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Calibrating a sedimentary record of overwash from Southeastern New England using modeled historic hurricane surges

Katherine V. Boldt [a], Philip Lane [b], Jonathan D. Woodruff [c], Jeffrey P. Donnelly [d,*]

[a] University of Washington, School of Oceanography, Marine Geology and Geophysics, Seattle, WA 98195, USA
[b] Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program in Oceanography, Woods Hole, Massachusetts 02543, USA
[c] Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
[d] Geology and Geophysics Department, MS 22, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

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ABSTRACT

We present a 2000-year record of overwash deposits preserved in a backbarrier salt marsh from southeastern New England. The timing of recent deposits matches well with large hurricane-induced storm surge events documented by local tide gauges in 1991, 1960, 1954, and 1938. Storm surge modeling is used to evaluate the flooding history at the site as well as to assess the pre-instrumental historical record. Storms in 1815, 1727, and 1635 likely caused significant surge that overtopped the barrier, with the timing of coarse-grained overwash deposition correlating well with these events. We infer that twenty-three prehistoric layers mapped across the site were likely also deposited by landfalling hurricanes. Additional records from the area will help to evaluate whether or not temporal trends at the site are a robust representation of hurricane activity for the region. The frequency of overwash at Mattapoisett Marsh, on average 1.5 events per century, is significantly higher than many other overwash-based reconstructions from the western North Atlantic. Further, the Mattapoisett Marsh record does not contain significant multi-centennial gaps in overwash layers. This initial comparison of the data from Mattapoisett marsh with other reconstructions from the western North Atlantic may point toward relatively constant tropical cyclone frequency over the last 2000 years with significant variation in the number of intense tropical cyclones.

1. Introduction

Historical documentation of hurricane strikes in New England extends back to the time of European settlement around AD 1620 (Ludlum, 1963; Boose et al., 2001), though more complete records have been compiled by the National Oceanic and Atmospheric Administration (NOAA) since the mid 1800's (Landsea et al., 2004; Neumann et al., 1993). The rarity of hurricane landfalls and the short and sometimes incomplete nature of the documentary record necessitate the development of proxy hurricane records in order to elucidate meaningful changes in storm activity on long timescales. This gap in knowledge is being addressed through the study of the long-term (100's to 1000's of years) sedimentary evidence of overwash from coastal environments, notably salt marshes and coastal ponds (Emery, 1969; Warren and Niering, 1993; Donnelly et al., 2001a,b; Donnelly and Webb, 2004; Liu and Fearn, 2000; Donnelly, 2005; Buynevich and Donnelly, 2006; Donnelly and Woodruff, 2007; Scileppi and Donnelly, 2007; Woodruff et al., 2008a,b, 2009). When a severe storm or hurricane makes landfall, the associated storm surge and waves will often overrun sandy barriers, transporting and depositing allochthonous sediment atop *in situ* organic-rich silt or marsh peat. This overwash layer is later covered again by autochthonous fine-grained organic material, and stratigraphically preserved as geologic evidence of the event.

Determining the nature of deposits resulting from historical events provides a means of assessing the sensitivity of the site to overwash. This modern analog approach has often been used to constrain the nature and magnitude of prehistoric events (Donnelly et al., 2001a,b; Donnelly et al., 2004a; Donnelly and Webb, 2004; Donnelly, 2005; Donnelly and Woodruff, 2007; Scileppi and Donnelly, 2007; Woodruff et al., 2008b). Unfortunately, site specific information regarding historic storm impacts is often unavailable. High-resolution numerical surge and wave modeling provides a means of evaluating the susceptibility of coastal areas to overtopping and breaching for a given suite of storm parameters (Cheung et al., 2007), however these approaches are computationally intensive, and uncertainties increase significantly as they are extended to earlier periods.

Here we use a simple, regional-scale surge model, the Sea, Lake, and Overland Surges from Hurricanes model (SLOSH) (Jelesnianski et al., 1992), to estimate the storm surge levels at Mattapoisett Marsh, (41°39′8″ N, 70°47′12″ W), a small coastal tidal marsh located in southern New England (Figs. 1 and 2). The marsh is situated toward

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* Corresponding author.
E-mail address: jdonnelly@whoi.edu (J.P. Donnelly).

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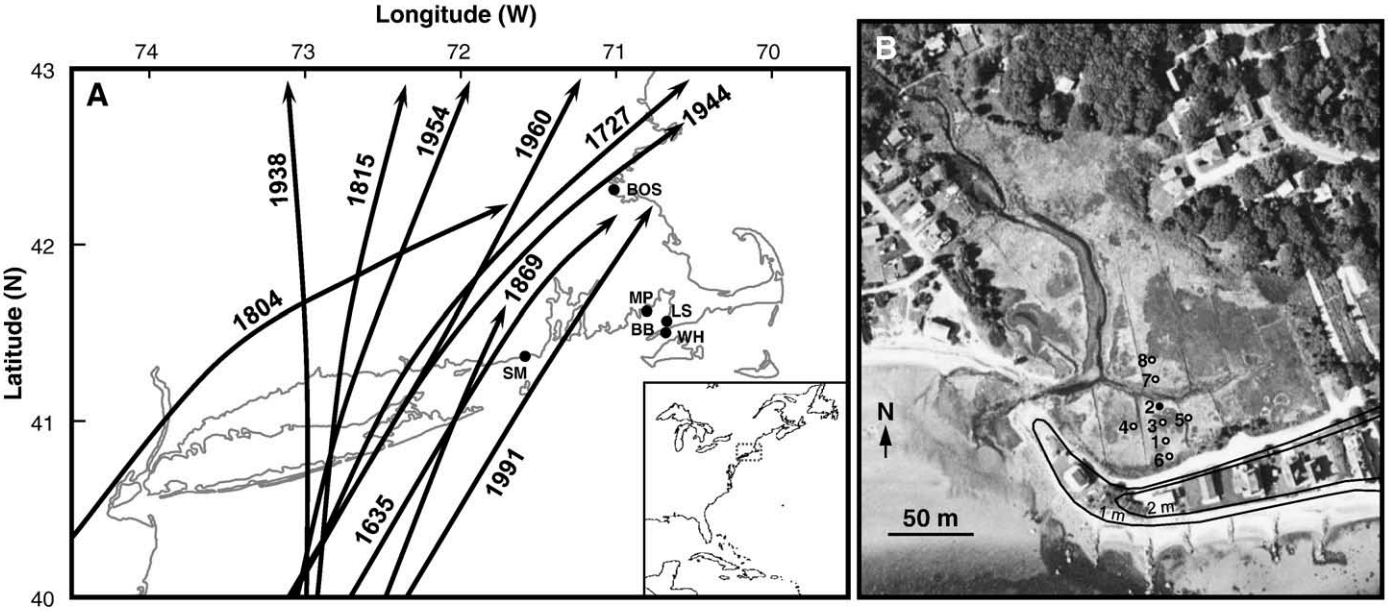

Fig. 1. A) map of southern New England with approximate storm tracks of notable hurricane landfalls. MP = Mattapoisett Marsh; WH = Woods Hole tide gauge; LS = Little Sippewissett Marsh; SM = Succotash Marsh; BB = Buzzards Bay; BOS = Boston. Inset shows the location of the study site in the western North Atlantic. B) Aerial photo of Mattapoisett Marsh. Cores locations are noted with circles. The location of Matt2 is noted in black.

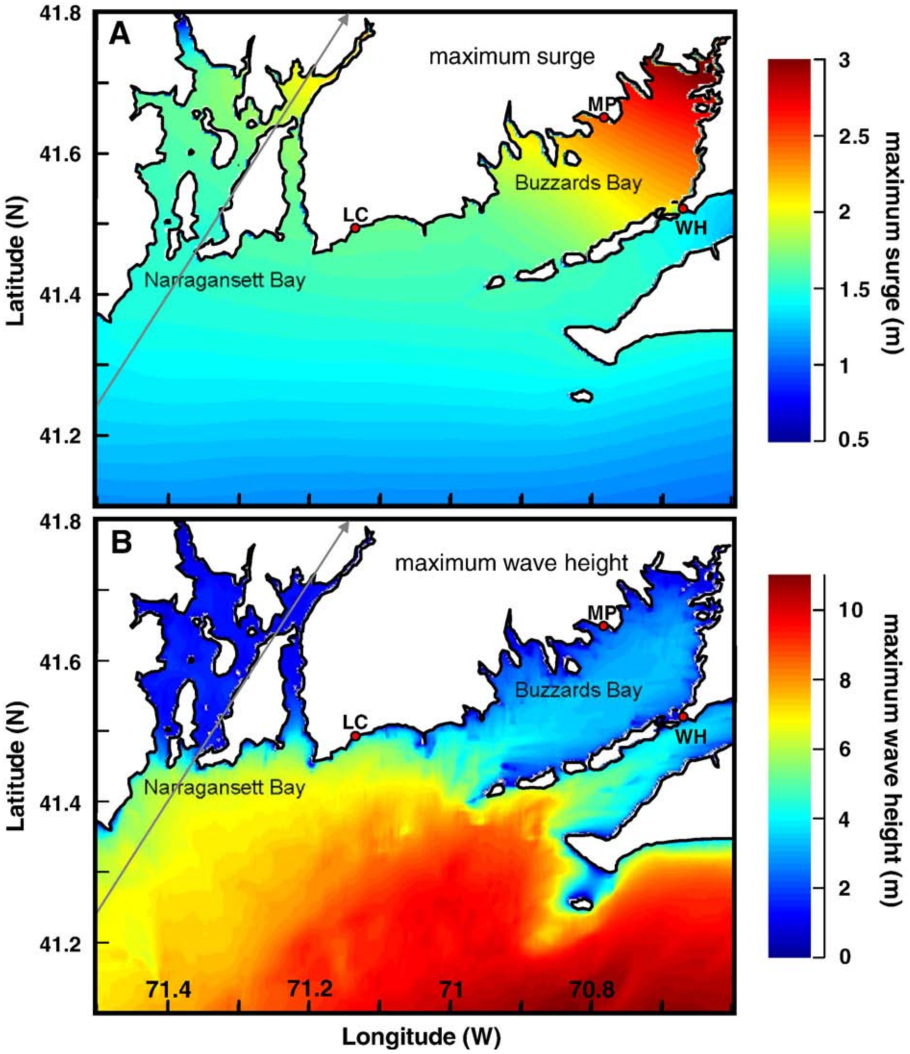

Fig. 2. Peak surge (A) and wave heights (B) simulated for Hurricane Bob, which struck southern New England on August 19, 1991 (after Cheung et al., 2007). The track of the center of Hurricane Bob is noted with a gray arrow. MP = Mattapoisett Marsh; WH = Woods Hole; LC = Little Compton, RI.

the head of Buzzards Bay, a long, semi-enclosed embayment, which provides shelter from storm waves but substantially amplifies hurricane-induced storm surge (Fig. 2A; also see Redfield and Miller, 1957; Cheung et al., 2007). A history of barrier overwash events at Mattapoisett Marsh is developed by assembling historical documentation for peak storm related water levels near the site since 1635 AD, and combining this historic record with SLOSH simulations for individual hurricanes. A comparison of this storm flooding history with recent sediment chronologies developed for Mattapoisett Marsh indicates that coarse grained deposits interbedded within the site's marsh peat sequence are contemporaneous with extreme (≥2 m above mean high water) hurricane-induced flooding. Supported by this modern analogue, we provide a sedimentary archive of likely hurricane-induced overwash extending back over 2000 years. This reconstruction is at present the longest and most complete reconstruction of hurricane-induced overwash for New England, and provides a record for which future reconstructions from the area can be compared in order to better assess variability in regional hurricane activity over the last few millennia.

2. Site description and methods

2.1. Study site

Mattapoisett Marsh is situated on the western side of Buzzards Bay (Figs. 1 and 2) on a till of late Wisconsinan age (Larsen, 1982). The elevation of the marsh is approximately at mean high water (MHW) and the mean tidal range at the site is ~1.2 m (NOAA, 2009). The marsh is separated from Buzzards Bay by an east-west barrier, ~50-m wide and 1.5-m to 2.5-m high, and composed primarily of sand and gravel with some boulders (Fig. 1B). Long shore drift is predominantly toward the west, with sandy till located to the east supplying material to the barrier. The marsh contains a small tidal creek network which empties through a narrow 5 m wide inlet located at the far west side of the barrier. The barrier and inlet have remained relatively stable over the documented record with USGS topographic maps surveyed in 1885 and 1936 showing no change in the barrier and inlet position over the last 125 yrs. Further, the 7.5 min quadrangle surveyed in 1936 shows that, similarly to today, the barrier elevation is less than 3 m (below the 10 foot contour).

2.2. Field and lab methods

In order to map out any coarse grained storm-induced deposits from Mattapoisett Marsh, eight vibracores (Matt1–Matt8) were collected in two crossing transects, one parallel and the other perpendicular to the shoreline (Fig. 1B). All cores consisted of organic-rich brown high-marsh peat interbedded with distinct coarse-grained and relatively dense sand layers. Sand layers were identified using contrasting sediment density from high-resolution (200 µm) digital radiographs of the cores and grain-size analysis of Matt2. Grain-size analysis was carried out every contiguous centimeter by combusting the organic matter at 550 °C for an hour and then running the residual ash through a Beckman–Coulter LS13320 laser diffraction particle size analyzer. Event layers were defined based on peaks in D_{90} grain size and corresponding dense layers evident in radiographs, and tracked across all cores.

The chronology for Matt2 is based on a combination of ^{14}C, ^{137}Cs, and an industrial revolution related increase in lead pollution following an approach similar to that used in previous studies (e.g., Donnelly et al., 2001a; Scileppi and Donnelly, 2007; Donnelly and Woodruff, 2007). Measurements of the activity of ^{137}Cs (a product of atmospheric nuclear weapons testing) were conducted using a high-resolution, germanium well gamma detector. Previous work has shown that the initial increase in bulk lead in core sediments from the Northeast corresponds to the onset of the industrial revolution, providing an additional stratigraphic marker of dating to the late 19th century (e.g., Donnelly et al., 2001a; Scileppi and Donnelly, 2007). To identify this lead pollution horizon, core halves were run through a non-destructive automated X-ray fluorescence (XRF) core scanner, which obtains millimeter to sub-millimeter resolution measurements of the sediment's elemental composition based on methods described by Croudace et al. (2006). All samples were run with a 3 kW Molybdenum (Mo) target tube with a 10 s exposure time and at a resolution of 1 mm. The remainder of the age constraint for Matt2 is based on ^{14}C dates calibrated to calendar ages at 1sigma using the Intcal09 data set (Reimer et al., 2009; see Table 1). Radiocarbon dates were obtained from the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution.

2.3. Historical water level observations

To assess the sensitivity of the barrier to hurricane-related overwash and resulting deposition of sand in Mattapoisett Marsh we first examined historical and instrumental data for coastal flooding in the Buzzards Bay region (Figs. 1A and 3) (Boose et al., 2001; Ludlum, 1963; Landsea et al., 2004; NOAA, 2009). Maximum monthly high water measurements recorded at the closest long-term tide gauge to Mattapoisett at Woods Hole, MA (Fig. 1) are available back to AD 1932. Records from the Woods Hole tide gauge indicate that hurricanes making landfall to the west caused the most extreme coastal flooding over the last 79 years, with five hurricanes resulting in storm surge of about 1.5 m or greater since AD 1932 (referenced to MHW); namely Bob (1991), Donna (1960), Carol (1954), as well as hurricanes in 1944, and 1938. These large levels of surge result from extreme southerly winds close to the time of landfall (Redfield and Miller, 1957). Conversely, although winter storms result in higher water levels on the east and north facing shoreline of New England, these types of storm events have resulted in relatively minor coastal flooding within the Buzzards Bay (≤1 m above MHW at Woods Hole, Fig. 3), whose southwestern facing orientation provides shelter from the predominantly northeast winds occurring during winter storms. In contrast to the large hurricane-induced levels of surge recorded in the Woods Hole tide gauge (Fig. 3), water levels for thirty winter storms recorded in the Boston tide gauge exceed the level of the highest hurricane-induced surge, 0.95 m above MHW in Hurricane Carol in AD 1954 (NOAA, 2009). And similar to the relatively modest winter storm related high water levels observed at the Woods Hole gauge, coastal flooding associated with winter storms in Boston since 1922 have not exceeded 1.6 m above MHW (NOAA, 2009). Thus, based on the instrumental record the south facing shoreline of New England is particularly vulnerable to extreme storm surge events resulting from landfalling hurricanes approaching from the south. Unfortunately, few direct observations of hurricane-induced flooding levels are available from western Buzzards Bay and, given the amplification of surge in the bay, the measurements from the Woods Hole gauge are likely less than those experienced at Mattapoisett Marsh.

2.4. Modeling storm surge at the site

To estimate storm flood levels at Mattapoisett Marsh for historical hurricanes, we employ the SLOSH storm surge model along with hindcasts of astronomical tides back to AD 1800. Details of the SLOSH model are presented in Jelesnianski et al. (1992), but here we provide a brief description. SLOSH is a numerical model used to simulate the storm surge generated by the extreme wind and pressure anomalies that accompany tropical cyclones. SLOSH requires a time series of six meteorological variables: (1) latitude and (2) longitude of the storm center, (3) the translation speed and (4) the bearing of the storm's motion, (5) the difference between the barometric pressure of the storm's ambient environment and the low barometric pressure of the

Table 1
Radiocarbon ages.

Lab number	Depth (cm)	^{14}C Age	1σ calendar ages (yrs B$_{1950}$.) Calibrated using Calib 5.0.1 [Reimer et al., 2009] (probability)	Cal age (yrs B1950)	Material
OS-68917	45	295 ± 30	**302-324** (0.303843) 363-366 (0.016921)[a] 376-428 (0.679236)[a]	**310**	*Distichlis spicata* rhizome
OS-68471	50–51	285 ± 35	294-324 (0.366939)[a] 362-366 (0.029303)[a] **376-428** (0.603758)	**400**	rootlets (1–2 mm)
OS-69008	50–51	325 ± 70	308-341 (0.217752)[b] 347-460 (0.782248)[b]	400	fine rootlets (>1 mm)
OS-67477	60–60.5	450 ± 30	**498–521** (1.)	**510**	fine rootlets (>1 mm)
OS-68726	72–73	580 ± 30	**543**–561(0.327446) 597-**633** (0.672554)	**620**	fine rootlets (>1 mm)
OS-68995	72–73	775 ± 35	679-725 (1.)[c]	700	*Distichlis spicata* rhizome (2 fragments)
OS-65601	82–83	930 ± 30	**796**-834 (0.431242) 841-876 (0.384549) 892-**909** (0.184209)	**815**	rootlets (>2 mm)
OS-67475	100–100.5	1050 ± 35	**928**-978 (0.978949) 1040-**1041** (0.021051)	**950**	fine rootlets (>1 mm)
OS-68725	125.5–126.5	1230 ± 25	**1089**-1109 (0.164803) 1126-1163 (0.365216) 1166-1182 (0.181874) 1206-**1235** (0.288107)	**1145**	fine rootlets (>1 mm)
OS-67476	135–136	1280 ± 25	**1181**-1208 (0.442329) 1231-**1268** (0.557671)	**1250**	fine rootlets (>1 mm)
OS-67474	165.5–166.5	1730 ± 25	**1606**-1638 (0.368858) 1645-**1695** (0.631142)	**1670**	rootlets (>2 mm)
OS-68916	177.5–178.5	1775 ± 45	**1614**-1679 (0.47852) 1682-1739 (0.434887) 1759-**1776** (0.086593)	**1710**	fine rootlets (>1 mm)
OS-65604	181.5–182.5	2010±25	1933-1990 (1.)[d]	1960	rootlets (>2 mm)
OS-65604	213.5–214.5	2030 ± 30	**1932**-2004 (0.932431) 2027-**2036** (0.067569)	**1970**	rootlets (>2 mm)

Bolded ages are those used in the age model (1σ max and min and cal age).

[a] Calibrated age ranges omitted based on stratigraphic position relative to ^{14}C date below.

[b] Age not included in plot on Fig. 2 given it has greater uncertainty than the replicate date from 50–51 cm.

[c] Age omitted from age model under the assumption that the older of the two replicate dates from 72–73 cm contained reworked plant fragments.

[d] Age omitted from age model as it is older than would be expected based on other ^{14}C dates in sequence.

storm's center (ΔP), and (6) the radius of maximum wind ($R_{\max}$) of the storm. These values are used to generate a parameterized model of the forces that act upon the ocean's surface during a tropical cyclone. SLOSH uses these forces, together with topographic and bathymetric maps of a coastal region, to solve the continuity and momentum equations for a fluid on a rotating sphere and determine the water column height anomaly (storm surge) at each grid cell in the model domain.

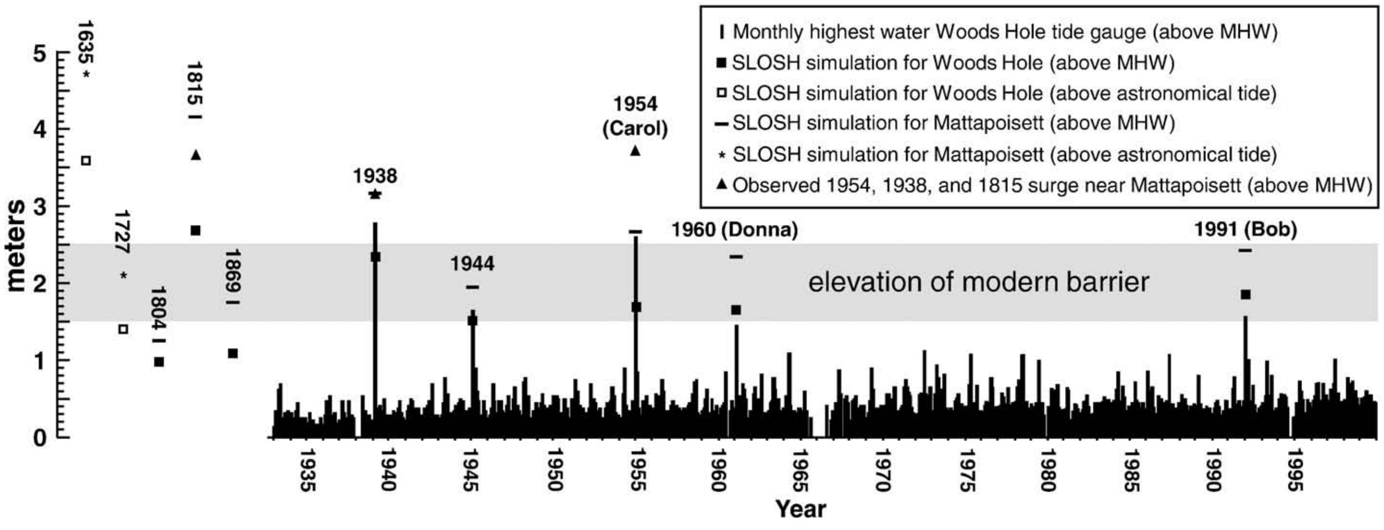

Fig. 3. Maximum monthly water levels above MHW from the Woods Hole tide gauge with SLOSH-based water level estimates for Woods Hole and Mattapoisett. Left are SLOSH predictions for hurricane event in 1869, 1815, 1804, 1727, and 1635 (SLOSH surge estimates post AD 1800 have been corrected for astronomical tide at the time of landfall). Observed water levels near Mattapoisett for hurricanes in 1954 (Carol), 1938, and 1815 are indicated with solid triangles. The modern elevation range of the barrier fronting Mattapoisett Marsh is noted (see also Fig. 1B).

In order to model the storm surges associated with historic storms in New England, we used two datasets of storm observations. For post-AD 1851 storms, we used the Best Track Reanalysis Data (here after "Best Track data"), which is available through the National Hurricane Center (Landsea et al., 2004; Neumann et al., 1993). The Best Track data include latitude, longitude, and maximum wind speed at discrete ($\Delta t = 6$ h) time increments. To model events occurring prior to AD 1851, we used the Boose et al. (2001) reconstructions, which provide estimates of storm latitude, longitude, and maximum wind speed at variable (but provided) time increments. The Boose et al. analysis provides estimates of meteorological data based on observations and damage reports for tropical cyclones that have significantly affected New England since AD 1635. Time stamped storm positions are reported directly in each dataset; however, variables other than position and maximum wind speed were inversely calculated based on technique described below.

Storm forward speed was determined first by using consecutive storm positions to solve the Haversine formula for the distance traveled along a spherical earth. This distance was then divided by the time increment (Δt) to solve for storm translation speed. The bearing, or compass direction in degrees, of each storm's motion was similarly calculated from successive latitude and longitude observations.

Though estimates of storm intensity are likely more accurate in the more recent years of each dataset, both the Best Track and Boose et al. data report the maximum wind speed ($V_{\max}$) for the entire duration of each storm track. SLOSH does not use $V_{\max}$ as an input variable directly, but instead uses ΔP and the $R_{\max}$ to construct a storm wind field. SLOSH's parameterized wind field is similar to the Rankine vortex model (Jelesnianski et al., 1992) in which rotary wind speeds increase linearly and rapidly as one moves from the storm center to the radius of maximum wind and then decline more gradually (proportional to 1/radius) at greater distances. The storm translation speed is added vectorially to this otherwise axisymmetric wind field, in order to provide a more realistic asymmetry to a storm's modeled wind field.

Neither ΔP nor $R_{\max}$ are supplied in the Best Track or Boose et al. datasets so we exploited published, empirical relationships among ΔP, $R_{\max}$ and $V_{\max}$ in order to leverage available storm data into the information required by the SLOSH model. As part of its parameterized wind field, SLOSH uses a linear model that relates $R_{\max}$ to $V_{\max}$. The slope and y-intercept of this model have been found empirically to depend on ΔP, and specific values of the linear model coefficients are indexed within the SLOSH code by integer values of ΔP (Jelesnianski and Taylor, 1973).

Central pressure (Pc) readings for many of the 19th and 20th century storms affecting New England are available in the Best Track dataset. We used these Pc values, along with a typical ambient barometric pressure of 1010 mb, to approximate ΔP and rephrased the ΔP, $R_{\max}$ and $V_{\max}$ relationships in SLOSH to solve for $R_{\max}$ — the final variable needed to run the SLOSH model (Fig. 4). It is unlikely that the Best Track dataset, with a temporal resolution of 6 h, captures the Pc and $V_{\max}$ at the time of landfall. In order to estimate the $R_{\max}$ at landfall, we used the values for these variables at the 6-hour observation nearest landfall containing both $V_{\max}$ and Pc measurements. These data, along with the $R_{\max}$ estimates, are shown in Fig. 4. The values of ΔP, $R_{\max}$ and $V_{\max}$ interpolated to the time of landfall are shown in Table 2.

The Boose et al. storms that affected New England lack data regarding both barometric pressure (ΔP or Pc) and $R_{\max}$. This significantly complicates accurate modeling of the storm surge associated with these storms because $R_{\max}$ strongly affects the magnitude and distribution of coastal flooding. When comparing two storms with equal intensity (according to $V_{\max}$) but different $R_{\max}$'s, one finds that in general the larger of the two will result in a greater surge. The reasons for this difference in surge are numerous. The greater surge results in part from the longer fetch and the longer time over which that the storm's winds act on the ocean surface. Moreover, the larger storm will require a deeper pressure (greater ΔP) in order to maintain the same pressure gradient and $V_{\max}$ of the smaller storm. This lower central pressure will contribute to the high water anomaly in the vicinity of the storm center through the "inverted barometer" effect. However, the pressure-driven surge, which is on the order of about 1 cm surge for every 1 mb increase in ΔP, is small compared to the wind-driven surge.

The sensitivity of the modeled surge to the size of the storm demands the use of a reasonable value for the $R_{\max}$. Since there are no standardized records of $R_{\max}$ for many of the storms that have impacted New England over the last four centuries, we chose to use observational datasets of Atlantic hurricane $R_{\max}$ to estimate the most likely value of this variable for specific early American storms. We used the Kossin et al. (2007) dataset, which contains ~12,000 satellite-based estimates of $R_{\max}$ for Atlantic tropical cyclones occurring between 1983 and 2005, to develop relationships between the data available in the Best Track and Boose et al. datasets and $R_{\max}$. Through multiple linear regression, we developed a model to estimate $R_{\max}$ from storm latitude and $V_{\max}$ alone. Comparing the observations in the Kossin dataset with the modeled values using our regression produces an R^2 of 0.80 with residuals that are normally distributed

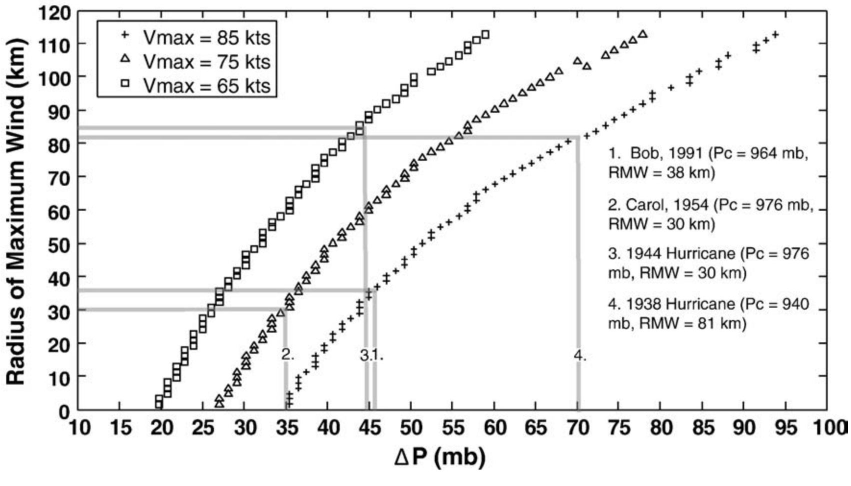

Fig. 4. SLOSH relationship between radius of maximum winds ($R_{\max}$) and ΔP for specific $V_{\max}$ values for 41° N latitude. This relationship was used to estimate the $R_{\max}$ of historic hurricanes like Bob, Carol, 1938 and 1944 using Best Track central pressure readings near landfall.

Table 2
SLOSH input parameters at landfall and results for Woods Hole (WH) and Mattapoisett (Matt).

Storm (year)	Latitude (°N)	Longitude (°W)	Forward speed (km/hr)	Bearing (degrees from N)	V_{max} (knots)	Pc (mb)	ΔP (mb)	R_{max} (km)	WH SLOSH surge (m)[a]	Tidal corr (m)	WH storm tide (m) [a]	Matt SLOSH surge (m) [a]	Tidal corr (m)	Matt storm tide (m) [a]
1991	41.82	71.12	50	34.78	81	967	43	37	1.98	−0.15	1.831	2.89	−0.5	2.41
1960	40.98	72.52	66	31.54	85	952	58	63	1.77	−0.11	1.665	2.8	−0.4	2.35
1954	41.13	72.52	56	21.54	82	963	47	48	1.68	0	1.684	2.59	0.09	2.68
1944	41.05	72.43	52	38.46	70	961	49	82	1.43	0.07	1.5	1.98	0.01	1.99
1938	40.58	73.08	66	358.00	80	947	63	84	2.41	−0.1	2.313	3.69	−0.5	3.15
1869	41.46	71.68	81	22.93	87	966	44	24	1.77	−0.67	1.096	2.65	−0.9	1.74
1815	40.90	72.80	68	15.01	110	925	85	50	2.62	0.07	2.686	4.08	0.08	4.16
1804	42.51	70.78	50	68.65	90	946	64	61	1.16	−0.18	0.976	2.04	−0.8	1.26
1727	40.85	72.87	45	45.68	88	949	61	61	1.43 [b]	NA	NA	2.1 [b]	NA	NA
1635	41.70	71.20	51	33.85	110	924	86	50	3.6 [b]	NA	NA	4.72[b]	NA	NA

[a] Relative to contemporaneous mean high water (MHW).

[b] Relative to astronomical tide (i.e. no tidal correction).

with a standard deviation of ~7 km (Fig. 5). In this way, we used the latitude and V_{max} provided in the Best Track data and Boose et al. records to assign a mean value of R_{max} for historic storms based on their intensity and location. This climatological mean value of R_{max} was then used, together with the V_{max}, to determine the ΔP, according to the previously discussed linear model relating ΔP, R_{max} and V_{max} in SLOSH. Once a time series for each required variable was assembled, the data were interpolated to 1-hour resolution, as required by SLOSH. Latitude and longitude were interpolated using a cubic-spline method to produce smooth tracks. Translation speed, bearing, ΔP, and R_{max} were all interpolated using a simple linear method.

2.5. Sensitivity assessment for wave induced flooding relative to storm surge

In addition to storm surge, waves can also contributed significantly to the overall storm tide — the total water level resulting from the combined effects of wind-induced surge, astronomical tide, wave setup and wave run up (e.g., Stockdon et al., 2006, Woodruff et al., 2008). Given the sites sheltered location within Buzzards Bay, however, the additional rise in water height due to waves is likely small relative to storm surge. A comparison of modeled surge and wave climates for Hurricane Bob in 1991 supports this assessment (Cheung et al., 2007; Fig. 2). Computed maximum offshore wave heights exceeded 10 m, while maximum wave heights in the middle of Buzzards Bay towards Mattapoisett were closer to 2 m. On the open coast in Little Compton, RI, significant wave heights were 5.46 m versus a storm tide of 1.66 m above mean sea level. In the vicinity of Mattapoisett Marsh significant wave heights were likely less than 2 m and the storm tide was about 2.5 m. The Hurricane Bob simulation shows the dispersion and sheltering of wave energy near the head of Buzzards Bay and an additional reduction in wave height along the coastline of Mattapoisett Harbor and Marsh (Cheung et al., 2007). Similar sheltering is evident in simulations of waves and surge in Chesapeake Bay during Hurricane Isabel in 2003 (Sheng et al., 2010). Given the relatively low wave heights at Mattapoisett Marsh during hurricane events such as Hurricane Bob and the accentuated surge in Buzzards Bay, the level of surge likely plays a key role in determining which storms are capable of overtopping the Mattapoisett barrier.

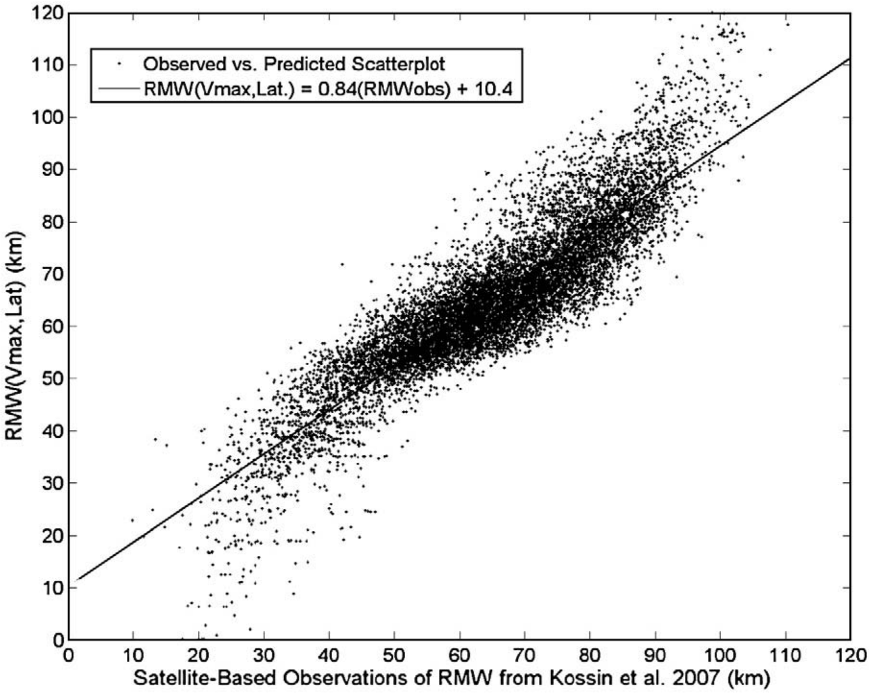

Fig. 5. Radius of maximum wind (R_{max}) predictions from linear model versus R_{max} observations from Kossin et al. (2007). $R^2 = 0.80$.

3. Results

3.1. Surge modeling

The SLOSH simulations compare well with observations of surge from the Woods Hole tide gauge (Fig. 3; Table 2). The one exception is the 1954 Hurricane Carol, where the SLOSH simulation underestimates the surge at Woods Hole by nearly 1 m. SLOSH results are also consistent with surge being amplified at Mattapoisett Marsh compared to Woods Hole. This amplification is consistent with storm observations taken directly from Mattapoisett Harbor, which place high water levels for 1938 Hurricane and Hurricane Carol in 1954 at 3.2 m 3.7 m respectively (Redfield and Miller, 1957), compared to water levels above MHW of 2.8 m and 2.5 m at the Woods Hole tidal gauge. The SLOSH model run for the 1938 hurricane accurately estimates the surge level at Mattapoisett, while the SLOSH result again underestimates the surge at Mattapoisett for Hurricane Carol by about a meter. Regardless of this single discrepancy, both observations and SLOSH modeling results indicate the water levels at Mattapoisett Marsh equaled or exceeded the 1.5–2.5 m barrier during Hurricane Carol, as well as hurricanes in 1938, 1944, 1960, and 1991 (Fig. 3; Table 2).

3.2. Mattapoisett marsh chronology

To examine the timing of storm-induced deposition in Mattapoisett Marsh and determine which historical storms may have deposited them, we a developed an age model for the upper 60 cm of Matt2 (Fig. 6). A well defined peak in ^{137}Cs activities was observed at 8.5 cm in sediments measured at this coring site. This ^{137}Cs peak most likely corresponds to the timing of maximum atmospheric deposition of bomb test Cesium in AD 1963, with an estimated modern sedimentation rate of approximately 2.0 mm/yr during the late 19th century based on this chronological constraint. XRF analyses of Matt2 reveal an increase in bulk lead (Pb) levels towards the surface of the core, with the onset of this Pb increase beginning at depths between 22 cm and 28 cm. Previous work has shown that heavy metal pollution increased substantially in the Northeastern U.S. during the onset of the industrial revolution between AD 1850 and AD 1900, resulting in unnaturally high levels of lead accumulating in the regions ponds and marshes (McCaffrey and Thomson, 1980; Bricker-Urso et al., 1989; Donnelly et al., 2001a). The increase in bulk Pb between 22 cm and 28 cm likely therefore corresponds to an age of between AD 1850 and AD 1900, which is consistent with the deposition rate of 2.0 mm/yr obtained using ^{137}Cs. This sedimentation

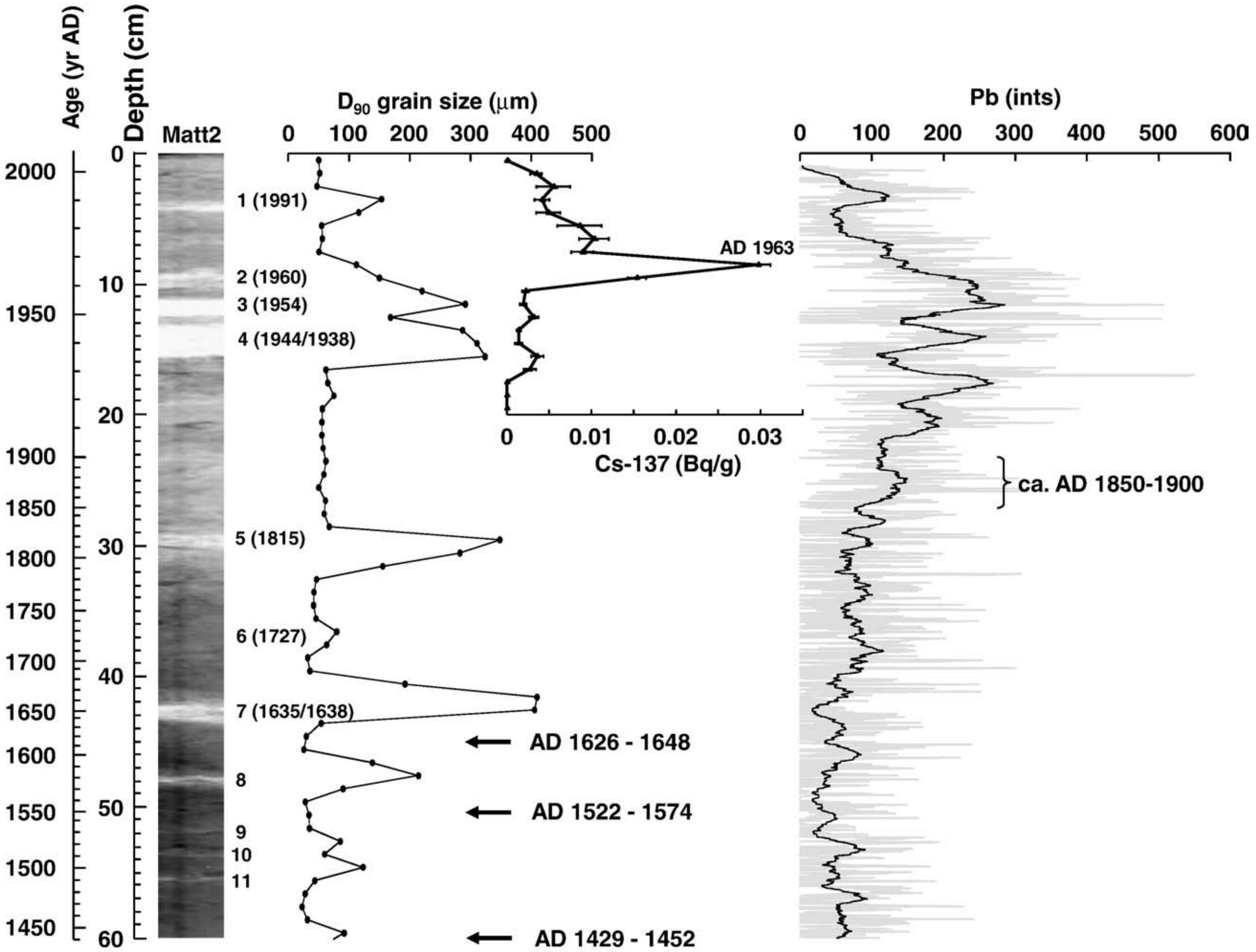

Fig. 6. Sedimentological and chronostratigraphic data from the upper 60 cm of core Matt2. By convention D_{90} defines the grain size at which 90% of the sample is finer. Radiograph (far left) shows density contrasts (lighter being more dense). D_{90} grain size data shows peaks in grain size that correlate with dense layers. The peak in ^{137}Cs activity at about 9 cm likely dates to the peak in atmospheric nuclear weapons testing in AD 1963. Bulk Pb levels (right) indicate an increase in Pb pollution initiating between about 23 and 27 cm associated with the onset of the Industrial Revolution between AD 1850 and AD 1900. Bulk Pb data is measured every mm using scanning XRF (dark line indicates 11 point moving average). Calibrated ^{14}C age ranges are noted with arrows (see supplemental table). The time scale noted on the left axis is derived from our age model displayed in Fig. 3. The historical storms attributed to events numbered 1–7 are noted to the right of the radiograph.

rate is also similar to the local rate of sea-level rise (~2.6 mm/yr) indicated by both the Woods Hole tide gauge and other marsh reconstructions (e.g., Orson et al., 1998; Donnelly and Bertness, 2001), a finding consistent with New England high marsh sediments closely track local rates of sea-level rise (e.g., Orson et al., 1998; Donnelly et al., 2004).

Long-term accumulation rates prior to the 19th century are closer to 1 mm/year based on calibrated radiocarbon results (Fig. 7), which are consistent with accumulation rates published previously for similar southern New England marsh environments (Donnelly and Bertness, 2001; Donnelly et al., 2004b). Two radiocarbon dated samples collected at 72–73 cm and 181.5–182.5 cm are slightly older than the trend. These two anomalously old dates likely contain reworked older carbon and were therefore not used for the age model of Matt2 (gray on Fig. 7).

3.3. Age estimates for recent overwash deposition

At least four dense layers are evident in the high-resolution radiographic image of Matt2 during the last 100 years based on ^{137}Cs and bulk Pb chronologies (Fig. 6). These dense layers (events 1–4) also correspond to peaks in D_{90} grain size, though the 1 cm sampling resolution does not delineate two separate grain size peaks for events 2 and 3. Events 1–4 occur at a depth of about 4, 9, 11.5, and 14 cm, and based on an average accumulation rate of 2 mm/yr, yield ages of approximately 1988, 1963, 1953, and 1938 respectively. Accounting for age uncertainties, these dates are consistent with deposition during the four or five most extreme surge events that exceeded or equaled the modern barrier height over this interval (1991, 1960, 1954, 1938, and potentially 1944; Fig 3). SLOSH simulations suggest that the 1944 hurricane likely resulted in enough surge to overtop at least portions of the barrier, thus it is possible that event 4 is a combination of coarse grained deposition from both the 1938 and 1944 hurricanes.

No coarse grained deposits are present in the interval that dates to the last half of the 19th century, despite the fact that an intense hurricane struck the region on September 8, 1869 (Ludlum, 1963; Boose et al., 2001, Donnelly and Webb, 2004; Landsea et al., 2004; Neumann et al., 1993). The small size of the storm (radius of maximum winds of ~25 km) and the fact that it struck at a low tide suggests that storm surge was likely minimized during the event (Ludlum, 1963). The SLOSH simulation estimates that Mattapoisett Harbor experienced 1.74 m of surge above MHW during this AD 1869

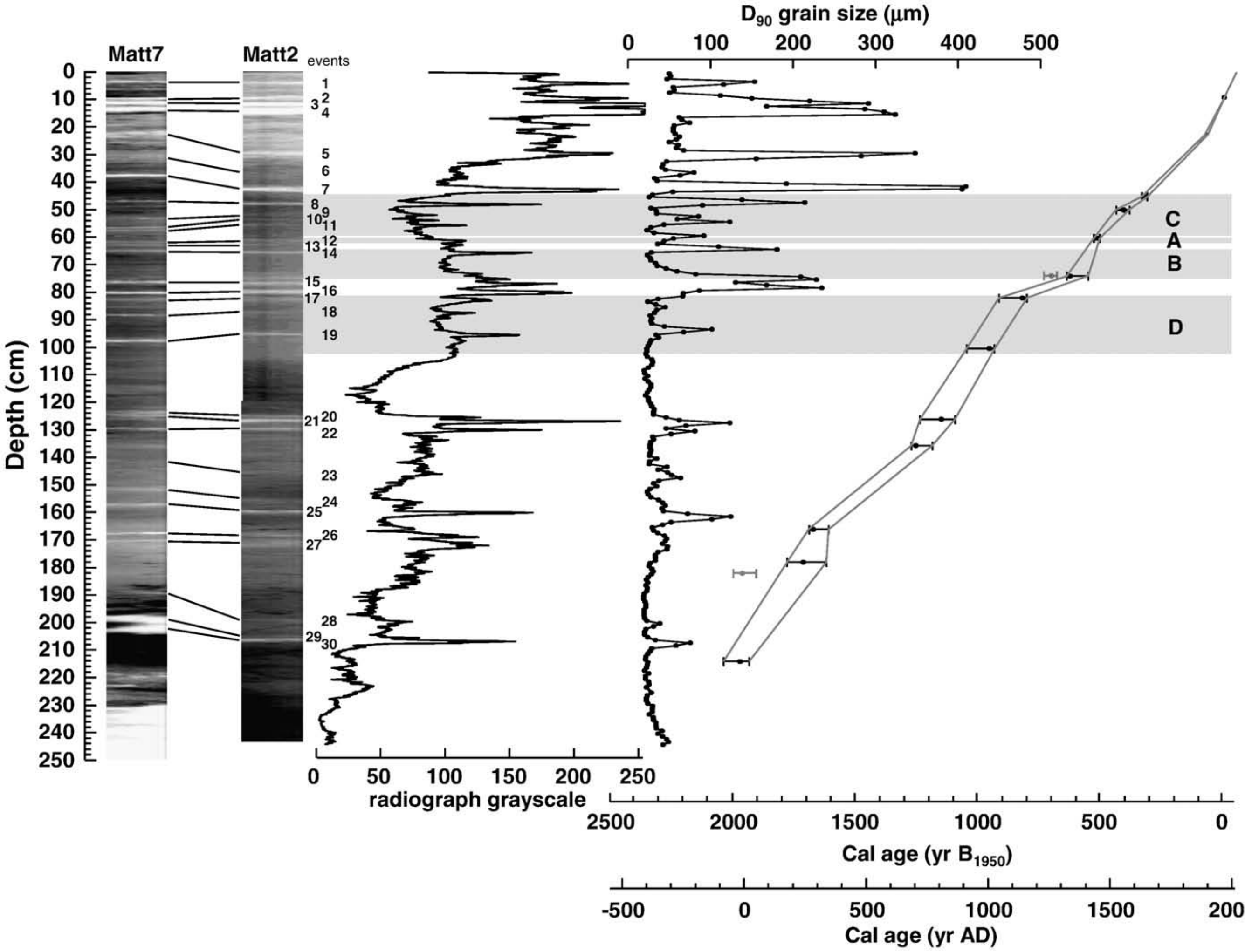

Fig. 7. Radiographs of cores Matt2 and Matt7 (left two panels; lighter is more dense). Correlations between layers in Matt2 and Matt7 are shown with lines. Full correlations between layers in all cores on this transect are shown in Figs. 7 and 8. Radiograph grayscale derived from Matt2 is shown just to the right of radiograph images, and provides a relative measure for density variations. D_{90} grain size data is also from Matt2 with peaks correlating to dense layers. Event layers 1–30 are noted. (Far right panel) Age depth plot; age controls below 40 cm are from calibrated ^{14}C dates with error bars representing maximum and minimum 1σ uncertainties (see Table 1). AD 1963 ^{137}Cs peak at 9 cm, and the AD 1850–1900 bulk Pb pollution increase at 23–27 cm are also noted. Horizontal grey shading denote timing of prehistoric overwash deposits documented at Succotash Marsh (A and B) and Little Sippewissett Marsh (C and D) and the corresponding depth in Matt2.

event (Fig. 3), which if it occurred today would only inundate the lower most portions of the barrier near the small tidal inlet at the far west side of the barrier. Unfortunately no accounts of surge levels at Mattapoisett for this event have been discovered; however, accounts of modest surge from nearby New Bedford, MA are consistent with the SLOSH simulation of low storm surge during the event (supplemental data in Boose et al., 2001).

One event layer was deposited at Mattapoisett Marsh in the first half of the 19th century (event 5). Historical documents indicate that two hurricanes made landfall to the west of the site during this interval on October 9, 1804 and September 23, 1815 (Boose et al., 2001; Ludlum, 1963). SLOSH simulations of surge at Mattapoisett Harbor for these events estimate that the 1815 hurricane resulted in over 4 m of surge above MHW, while the 1804 hurricane resulted in about 1.25 m of surge above MHW. The extreme surge in the Mattapoisett area for the 1815 hurricane is verified by historical accounts of over 3.5 m of surge above MHW in neighboring Fair Haven, MA and other nearby communities (supplemental data in Boose et al., 2001). Conversely, no accounts of extreme surge are noted in compilations of historical documents for the 1804 storm (Ludlum, 1963; Boose et al., 2001). On the basis of these observations we conclude that event 5 is likely a result of the more intense 1815 event.

A modest peak in D_{90} grain size at about 37 cm in Matt2 (event 6), dates to the early 18th century. A distinct, dense layer is not evident in the Matt2 radiographic image associated with this layer, however, most other cores contain a faint dense layer at this stratigraphic position (Figs. 7–9). Only one severe hurricane landfall is documented in the early 18th century on September 27, 1727 (Ludlum, 1963; Boose et al., 2001). The SLOSH simulation for this event estimates surge of about 2.1 m at Mattapoisett (uncorrected for astronomical tide), and are consistent with that this event having the capacity to inundate at least the lower segments of the barrier at the site.

A significant overwash layer occurs at 43 cm in Matt2 and dates to the early 17th century (event 7; Fig. 6). One of the most infamous hurricanes in New England struck in August of 1635 (Ludlum, 1963; Boose et al., 2001). The combination of historical data and SLOSH simulations of the 1635 hurricane indicate extreme surge in Buzzards Bay during this storm. Our SLOSH simulation suggests surge in access of 4.5 m (uncorrected for astronomical tide) at Mattapoisett. This AD 1635 deposit also exhibits some of the largest grain sizes observed at Matt2 (Fig. 7), which is consistent with the hurricane being one of the most intense events to affect Buzzards Bay during the historical record.

3.4. Prehistoric hurricane chronology at mattapoisett

Twenty three additional prehistoric dense, coarse-grained deposits are preserved in cores recovered from Mattapoisett Marsh, with the earliest event occurring about 2000 cal. yrs. before AD 1950

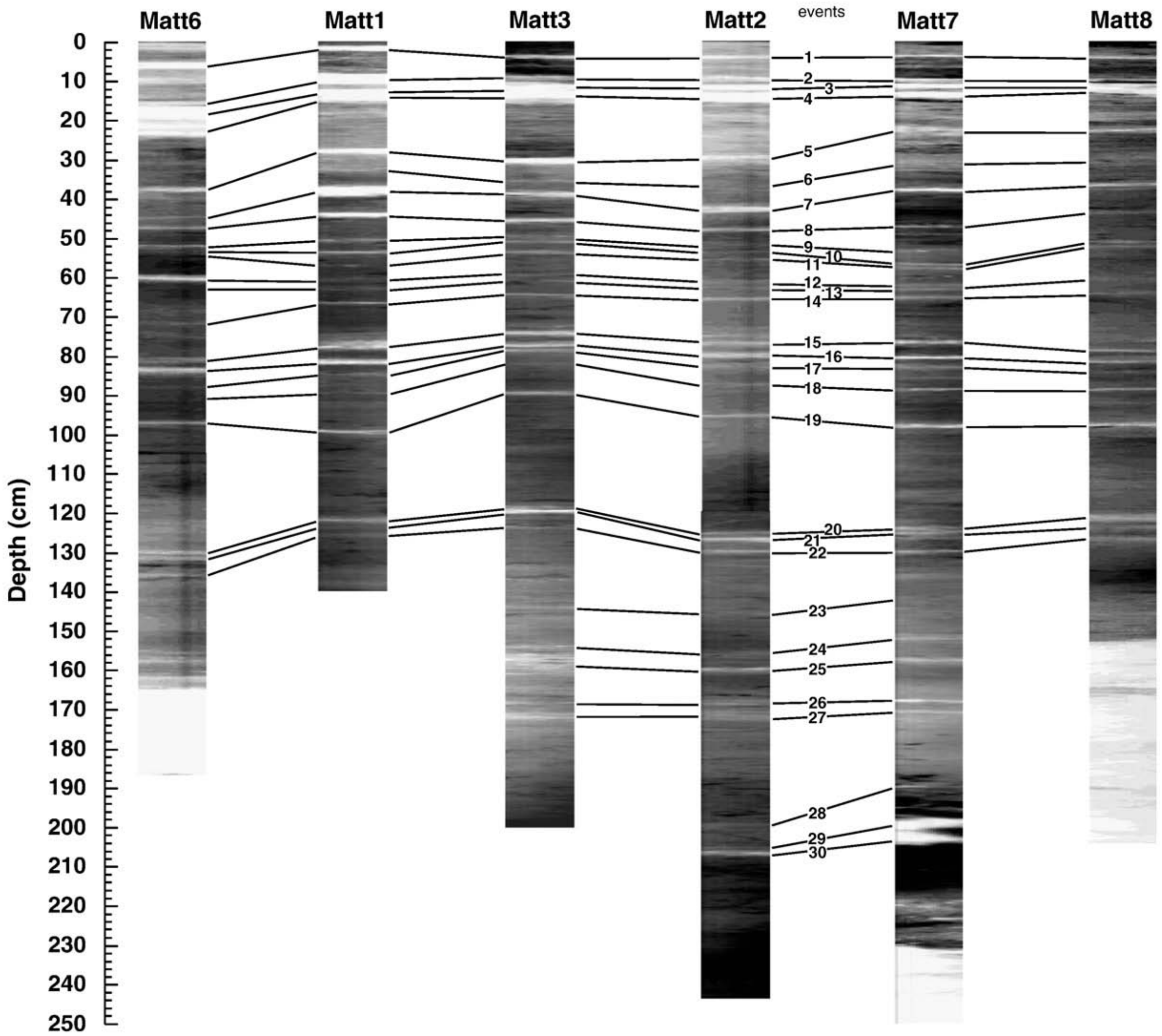

Fig. 8. Radiographic images of six cores on north/south oriented transect (see Fig. 1B) with inferred correlation lines.

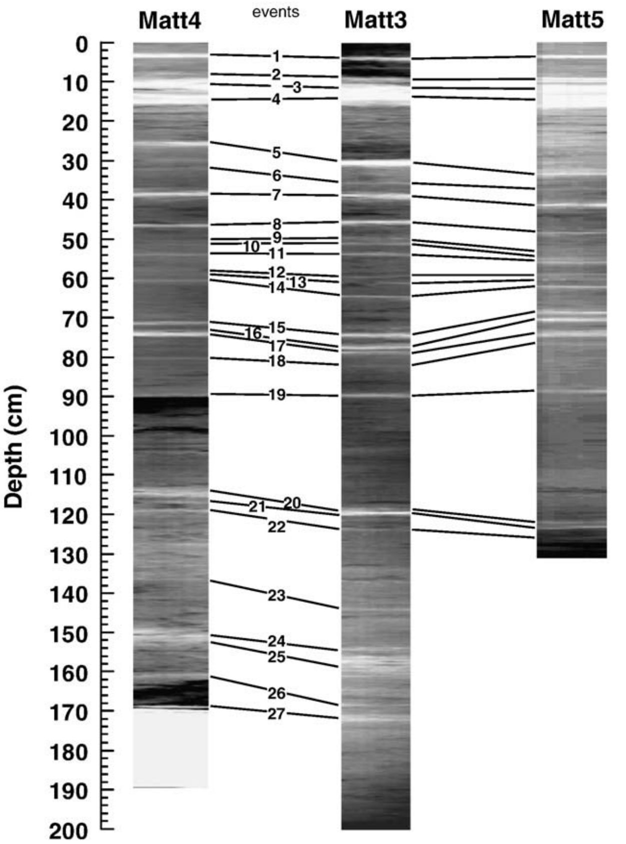

Fig. 9. Radiographic images of three cores on east/west oriented transect (see Fig. 1B) with inferred correlation lines.

(B_{1950}) (Figs. 7 and 10). Based on similar sedimentary characteristics between modern hurricane deposits and the coarse layers occurring further down core, we infer that prehistoric coarse units were deposited under similar storm-induced flooding conditions. Layers below ~80 cm (earlier than ~800 cal yrs B_{1950}) generally exhibit a smaller D_{90} grain-size, although the thickness and density of these older layers are comparable to those observed for the more recent deposits (Fig. 7).

4. Discussion

4.1. Flooding assessment for 20th century hurricanes

SLOSH model simulations produce surges similar to those recorded by tide gauge measurements and additional documentation for recent storms. Further SLOSH results for early historical storms prior to the instrumental record generally agree with historic accounts of storm surge. The one storm analyzed with SLOSH where the model result did not produce surge values similar to the instrumental record was Hurricane Carol in 1954. For this event SLOSH underestimates the surge at both Woods Hole and Mattapoisett by about 1 m. The mismatch between modeled and observed storm surge for this event may be due to the NOAA Best Track data underestimating the intensity of this storm at landfall. The Best Track data currently lists the sustained winds as 85 knots at landfall on Long Island (40.8° North) and provides a pressure reading of 976 millibars well after landfall at 43.1° North latitude (used in our analysis). However, observations near landfall from the Suffolk County Airport indicate a minimum pressure of 960 mbar (Vallee and Dion, 1998; Jarrell et al., 2001). This pressure is more consistent with a category 3 storm with sustained winds of 96–112 knots. A SLOSH simulation for this event assuming 95 knots sustained winds and an $R_{\max}$ of 40 km produces surge magnitudes

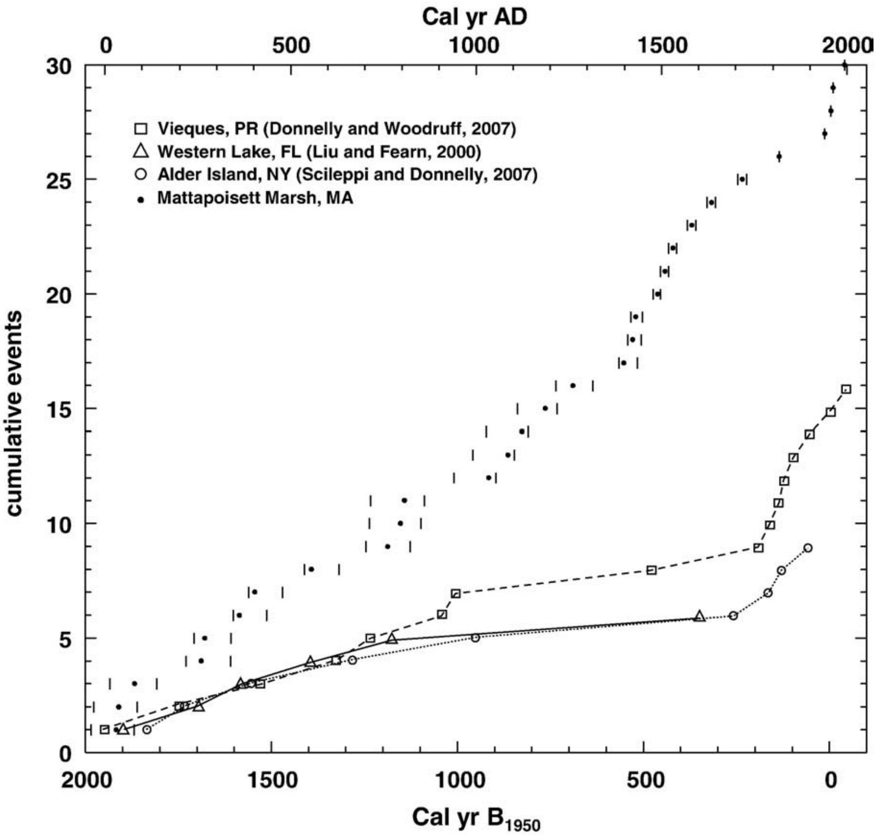

Fig. 10. Cumulative frequency plot of events from Mattapoisett Marsh, MA, Vieques, PR (Donnelly and Woodruff, 2007), Alder Island, NY (Scileppi and Donnelly, 2007), and Western Lake, FL (Liu and Fearn, 2000).

similar to observed values and is consistent with Carol being slightly more intense in the region than documented by the NOAA Best Track dataset.

Recent deposits correlate well with documented 20th century hurricane landfalls and are thus interpreted as event layers attributable to landfalling hurricanes in 1991, 1960, 1954, and 1938. SLOSH results indicate that each of these events likely resulted in storm tides exceeding 2.3 m above MHW at the site. The 1944 hurricane likely resulted in a surge of just under 2 m above MHW at Mattapoisett. As no distinct sand layer is discernable for this storm, it may not have overtopped the barrier. However, given that it occurred only six years after the 1938 hurricane, it is possible that sand deposited during the 1944 event was added to the 1938 sand layer before sufficient peat could accumulate to allow differentiation of the two deposits. Yet, if our attribution of layers is correct, deposits resulting from hurricanes Carol (1954) and Donna (1960), also six years apart, are clearly distinguishable. Radiographs of the core closest to the barrier (Matt6) and closest to the inlet (Matt4) may indicate two separate dense layers at the interval designated event 4 (Figs. 8 and 9). Thus the 1944 hurricane may have only overtopped the barrier at its western end where modern elevations reach about 1.5 m. Of the 20th century storms recorded at Mattapoisett Marsh, only 1954 and 1938 deposited overwash fans at Succotash Marsh, RI (SM), about 68 km to the southwest of Mattapoisett Marsh (Donnelly et al., 2001a), an observation consistent with Mattapoisett being more sensitive in recording overwash for the less intense events in 1991, 1960 and potentially also in 1944.

4.2. Evaluation of early historical hurricanes

Prior to the instrumental record, we must rely on a more incomplete documentary record to assess the event deposit history of the site. However, intense hurricane strikes that cause significant damage are well represented in historical archives (Ludlum, 1963; Boose et al., 2001). The most notable of these occurred in 1869, 1815, 1804, 1727, and 1635.

The 1869 storm is the earliest documented intense hurricane to strike the region within the Best Track data set, however, it does not appear to have left a deposit at Mattapoisett Marsh. It is possible that natural or anthropogenic modifications to the site could have increased the barrier height reducing the susceptibility of the site to overtopping during the second half of the 19th century; however, a U.S. Coast and Geodetic Survey Map surveyed in AD 1885 shows the site in a similar configuration as today, only without human development.

SLOSH simulations of the 1869 hurricane suggest that the small size ($R_{\max}$ of ~25 km), rapid forward speed, and low tidal stage at the time of landfall resulted in only modest surge levels of approximately 1.7 m above contemporary MHW at the Mattapoisett Marsh (Fig. 3). As a result, much of the barrier was likely not overtopped during this event. Surge may have overtopped the lower portion of the barrier to the west, but the lack of any event layer in Matt4 indicates that overwash was likely minimal. The reconstruction from Succotash Marsh, RI also does not contain any evidence of the 1869 hurricane (Donnelly et al., 2001a). A surge of only 2 meters above the normal high-tide level was noted at Bristol, RI, approximately 40 km to the west of our study site (Ludlum, 1963).

Event 5, at 30 cm in Matt2, dates to the early 19th century and could have been deposited by either the 1804 or 1815 storm. However, both historical accounts (Boose et al., 2001; Ludlum, 1963) and the SLOSH simulations indicate that surge from the 1804 event was relatively modest (~1.2 m above contemporary MHW) and likely did not overtop the barrier at Mattapoisett Marsh. Conversely, surge associated with the 1815 event was extreme, resulting in water levels over 4 m above contemporary MHW, more than sufficient to overtop the barrier. Thus we attribute event 5 to the 1815 storm. A deposit associated with the 1815 hurricane was also identified at Succotash Marsh, RI (Donnelly et al., 2001a). Similarly, event 6, a relatively modest peak in grain size at about 37 cm in Matt2, was likely deposited during the 1727 hurricane, which resulted in about 2.1 m of surge (above astronomical tide levels). The absolute height of the 1727 surge relative to MHW could have exceeded 2.5 m if the storm struck at a high astronomical tide. Like the less intense hurricanes in the Best Track data (i.e. 1991, 1960 and 1944), this 18th century event is also not recorded at Succotash Marsh, RI (Donnelly et al., 2001a).

The layer at about 43 cm in Matt2 (event 7) dates to the early 17th century and is most likely related to the 1635 hurricane. SLOSH simulations suggest that water levels at Mattapoisett Marsh during this event were close to 4.7 m above astronomical tide levels and historical accounts indicate surge may have reached as high as 6 m at the head of Buzzards Bay (Ludlum, 1963). In addition to the 1635 event, two more hurricanes struck the region in 1638, with one account indicating about 4 m of surge in Narragansett Bay (about 40 km west of Mattapoisett Marsh) (Ludlum, 1963). Unfortunately the sparse historical documentation of these 1638 storms precludes the use of SLOSH to evaluate the surge associated with these events. The 1-cm resolution of the grain-size data from Matt2 does not differentiate more than one event layer, but the higher resolution radiograph hints at the possibility of two layers (Fig. 6), one deposited in 1635 and the other perhaps attributable to one or both of the 1638 storms. Radiographic images of event 6 from cores Matt3, Matt4, and Matt8 may also provide evidence of two distinct layers, although the remaining cores contain only one dense layer at this interval (Figs. 7–9). Thus, whether or not the sedimentary record contains evidence of more than one event in the early 17th century remains equivocal.

4.3. Prehistoric hurricanes

The prehistoric record (prior to 1630 AD) extends back to approximately 2200 cal yrs B_{1950} and contains 23 additional dense coarse-grained layers. Only a small number of prehistoric events have been identified in earlier work in this region (Donnelly et al., 2001a; Buynevich and Donnelly, 2006). Two events that date to AD 1423–1439 (A on Fig. 6) and AD 1309–1391 (B on Fig. 7), respectively, were documented at Succotash Marsh, RI (Donnelly et al., 2001a). At Mattapoisett Marsh three events (12, 13 and 14; see grey shading A and B on Fig. 7) are recorded at about this time, possibly indicating that one of the event layers identified at Succotash Marsh could have been deposited by two storms. Similarly, at Little Sippewissett Marsh (LS), 16 km to the southeast of Mattapoisett Marsh, two prehistoric overwash layers were documented at AD 1443–1618 (C on Fig. 7) and AD 994–1149 (D on Fig. 7), respectively (Buynevich and Donnelly, 2006). At Mattapoisett Marsh, four events are recorded between AD 1443 and 1618 (events 8–11; see grey shading C on Fig. 7) and three events between AD 995 and 1149 (events 17–19; see grey shading D on Fig. 7).

Two possible explanations exist for the differences between the Mattapoisett Marsh record and the reconstructions from Succotash and Little Sippewissett Marshes. Either overwash layers at Succotash and Little Sippewissett were, in some cases, deposited by multiple events, or some of the events recorded at Mattapoisett Marsh did not leave sedimentological evidence at the other sites. Only the two most extreme storm surge events of the 20th century deposited overwash layers at Succotash Marsh (AD 1954 and AD 1938; Donnelly et al., 2001a) compared to at least 4 events recorded at Mattapoisett Marsh during the same interval, indicating that at least over the past century Mattapoisett Marsh has been more sensitive to overwash. This is consistent with Mattapoisett Marsh being susceptible to deposition associated with weaker events, perhaps due to its lower barrier (e.g., the modern Succotash Marsh barrier is ~3 m high), and/or potentially because the size and track of a particular storm resulted in higher surge at Mattapoisett relative to the other sites.

4.4. Limitations

Given that only 3 years separated the AD 1635 event from the two events in AD 1638, event layer 6 may reflect deposition by two or possibly three storms. This result highlights a potential limitation of depositional archives of past flooding events in that layers deposited in close temporal succession may appear as one indistinguishable unit. Only one overwash layer was attributed to this time interval at Succotash Marsh (Donnelly et al., 2001a). The resolution of these types of archives is in large part controlled by sedimentation rates, deposit thickness, and the frequency of the events (Donnelly and Webb, 2004; Woodruff et al., 2008a). As a consequence, reconstructions of hurricane landfalls based on sediment records may be biased by undercounting. Overall, however, the age of each layer in the upper sediments is consistent with a vast majority, if not all, of the severe historical hurricanes that produced more than 2 m in storm surge at the site (Figs. 1 and 3).

A storm's capacity to overtop the barrier and deposit a sandy layer in the backbarrier environment depends on factors such as the height and width of the barrier beach, dune vegetation or lack thereof, the tidal phase during the storm, wave height and direction, wind velocity and direction, storm surge height and duration, as well as near and offshore bathymetry (Donnelly and Webb, 2004; Cheung et al., 2007). Over longer time scales, sea-level rise can cause barriers to migrate landward. This landward transgression can affect the susceptibility of a backbarrier core site to coarse-grained deposition and may imply that layers further down core were transported farther from the source than more modern layers (Donnelly and Webb, 2004). Over the last ~375 years only historical hurricanes with surges of at least ~2 m are preserved in the Mattapoisett Marsh sediments. Given that this threshold does not appear to have changed over the historic interval, we infer that the site's barrier has not changed significantly since ~1620 AD. Changes in barrier morphology may have affected overwash further down in the Mattapoisett Marsh record, as event layers deeper than ~80 cm contain smaller grain sizes than those in more recent sediments (Fig. 7). The coarser event layers in the top third of the record, relative to the event layers in the bottom two-thirds of the reconstruction (i.e., layers below ~80 cm or before ~800 cal yrs B_{1950}), likely indicate that the barrier was farther from the core sites in the earlier part of the record. As a result, the finer sand grains that make up the event layers in the bottom part of the reconstruction may have been transported a greater distance, assuming that the grain size of sediments available for transport by storms has been constant through time. If particles in the older layers traveled significantly farther than those in more recent layers, it could imply that the older event deposits represent only the most intense storms. Thus, less intense events, such as the AD 1727 hurricane, may not necessarily be recorded within the older pre-historic sediments at the site.

4.5. Paleo-hurricane proxy comparisons

Assuming that local changes to the morphology of the site have not significantly affected the sensitivity of the site to overwash over the last 2000 years, we provide an initial comparison of the Mattapoisett hurricane reconstruction to other records from the western North Atlantic. Previous reconstructions have suggested an inactive interval lacking intense hurricane strikes after 1000 cal yrs B_{1950} (Liu and Fearn, 2000; Donnelly and Woodruff, 2007; Scileppi and Donnelly, 2007; Woodruff et al., 2008b; Fig. 10). No such pattern is evident in the Mattapoisett data. The differences between the Mattapoisett data and other reconstructions from this basin may be due to the apparent higher sensitivity of Mattapoisett Marsh to overwash. Nearly all New England hurricane landfalls to the west of the Mattapoisett site during the 20th century resulted in preserved overwash deposits in the marsh. Further the rate of overwash occurrence over the last 2000 years has been two to five times greater at Mattapoisett Marsh than that observed in other reconstructions from the western North Atlantic (Fig. 10). Thus, the record from Mattapoisett Marsh likely reflects a spectrum of storms of varying intensities. Estimates of intensity thresholds inferred for other reconstructions in the basin range from strong category 2 storms at Alder Island, NY (Scileppi and Donnelly, 2007) to category 4 and 5 storms at Western Lake, FL (Liu and Fearn, 2000). The combined data from all these reconstructions could point toward relatively constant tropical cyclone frequency over the last 2000 years (e.g., the Mattapoisett reconstruction) with significant variation in the number of intense tropical cyclones, with the latter only being detected at sites with high sensitivity thresholds.

Some variability exists in the frequency of hurricane landfalls as revealed in the Mattapoisett reconstruction, though the degree to which this variability is statistically significant remains uncertain. One of the most active intervals in the reconstruction spans the 15th and 16th centuries, during which 7 event deposits are identified (Fig. 10). Other records from the northeastern U.S. reveal evidence of a number of intense hurricane strikes in the 16th and 15th centuries (Donnelly et al., 2001a,b; Buynevich and Donnelly, 2006). A recent synthesis of available reconstructions from the entire basin, including the one presented here, indicates three intervals of increased hurricane activity from AD 900 to 1250, AD 1350 to 1450, and AD 1750 to 1850 (Mann et al., 2009). Climate forcing of the later two active intervals remains enigmatic, however the earlier active interval may have resulted from a combination of warm sea surface temperatures and more La Niña-like conditions. More hurricane reconstructions and paleoclimatic work is required in order to further address potential climatic forcing. Additional records from near Mattapoisett Marsh will also help evaluate whether or not temporal variations in hurricane-induced overwash at the site are robust throughout the region.

5. Conclusions

The record of sedimentary overwash event deposits from Mattapoisett Marsh provides the most detailed overwash reconstruction of hurricane strikes available for the northeastern United States. Event layers deposited during historic time match well with known severe hurricane strikes, and indicate that flooding intensities exceeded the barrier threshold for 20th century hurricanes in 1991, 1960, 1954, 1938, and potentially in 1944. Flooding levels measured during Hurricane Carol in 1954 are ~1 m higher than those predicted by SLOSH suggesting that the Best Track data may underestimate the intensity of the event at landfall. Earlier historical hurricanes evident in the record include storms in 1815, 1727, 1635 and potentially 1638. Historical hurricanes occurring in 1869 and 1804 did not leave an identifiable deposit at the site suggesting that the flooding for these storms was less intense and incapable of inundating the barrier. The 15th and 16th centuries are among the most active of the last 2000 years with seven events occurring over that time. The data presented here combined with other reconstructions from the western North Atlantic may indicate significant variation in the number of intense tropical cyclones, but relatively constant tropical cyclone frequency over the last 2000 years. More detailed, long-term records of hurricane-induced overwash are needed in order to confirm trends observed. In addition, future work should include efforts to quantify the relative intensity of surge events so we might better determine the full character of tropical cyclone activity over the last few millennia.

Acknowledgments

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