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A Revised Late Holocene Sea-Level Record for Northern Massachusetts, USA

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ABSTRACT

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Accelerator mass spectrometry (AMS) radiocarbon dating of basal high-marsh sediments from Romney Marsh, Revere, Massachusetts, provides a revised reconstruction of the late Holocene relative sea-level history of the region. After correction for changes in tidal amplitude, the sea-level change envelope reconstructed from five AMS radiocarbon dates of basal marsh sediments at Romney Marsh in Revere, Massachusetts, indicates a rise in mean sea level (MSL) of close to 2.6 m in the past 3300 years. The data indicate a possible decrease in the average rate of rise from 0.80 ± 0.25 mm/y between 3300 to 1000 YBP to a rate of 0.52 ± 0.62 mm/y between 1000 YBP and the past 150 to 500 years. An increase in the rate of sea-level rise is evident over the past few hundred years. A slowing of the rate of sea-level rise between 1000 YBP and historic times and the increase in the rate of rise to modern values is also evident in other sea-level records from Maine and Connecticut. The coherence between these sea-level records and concomitant climate changes in and around the North Atlantic indicates that regional-scale sea-level fluctuations in the region may be driven by climate forcing. However, earlier sea-level fluctuations correlated to sea-surface temperature variability are not well-resolved by this record or other records in the region and may indicate that changes in sea level are not tightly coupled with sea-surface temperature changes.

ADDITIONAL INDEX WORDS: *Salt marsh, halophytes, climate, global warming, sea-surface temperatures, subsidence.*

INTRODUCTION

Possible increases in eustatic sea level resulting from climate warming (IPCC, 2001) have sparked renewed interest in past sea-level variations. To more accurately project future changes and potentially mitigate socioeconomic impacts, we need to better understand the causes of past sea-level change. For example, it is important to determine what the relative contributions of melting land ice and warming sea-surface temperatures on past sea levels have been to better understand what may be driving current sea-level increases. Consequently, we need long-term proxy records of past sea levels at sufficient spatial and temporal resolution to explore potential linkages with past natural climate change that will provide a framework for evaluating projections of future changes in sea level. The relatively sparse late Holocene sea-level data from northern Massachusetts yield no coherent pattern, indicating that the ages of several of the data points may be erroneous. In this study, I use radiocarbon-dated, tidal salt-marsh deposits to construct a late Holocene sea-level history at Romney Marsh in Revere, Massachusetts (Figure 1) to refine the sea-level chronology for northern Massachusetts.

The distribution of salt-marsh communities are intrinsically linked to the magnitude, frequency and duration of tidal inundation (Chapman, 1960; Redfield, 1972). The zonal arrangement of vegetation in New England salt marshes is controlled by tolerance to physical stress (*i.e.,* flood and salt tolerance) and by interspecies competition (Bertness, 1991a, 1991b). The narrow vertical range of high-marsh flora within a few decimeters of mean high water (MHW) makes the remains of ancient marshes excellent proxies for past sea levels (Redfield and Rubin, 1962). Mudge (1862) and Davis (1910) recognized that coastal wetland deposits in the northeast United States provide a record of relative sea-level rise, based on their finding of high-marsh peat well below contemporary MHW. However, this archive could not be fully exploited and quantified until the development of radiocarbon-dating methods in the middle of the 20th century. The marshes that exist today in the northeastern United States developed in the past 4000 to 7000 years by accreting vertically to keep pace with relatively low rates of sea-level rise (Orson, Warren, and Niering, 1998; Redfield, 1972). These accumulations of marsh sediments provide a rich archive of how sea level has changed during the late Holocene (*e.g.,* Bloom and Stuiver, 1963; Redfield and Rubin, 1962; Stuiver and Daddario, 1963). However, vertical displacement of the peat column because of autocompaction (Bloom, 1964; Cahoon, Reed, and Day, 1995; Donnelly *et al.,* 2004; Gehrels, 1999; Kaye and Barghorn, 1964) necessitates the use of samples directly overlying hard substrate as sea-level indicators.

Redfield and Rubin (1962) developed the first late-Holocene sea-level record in the northeast United States based on radiocarbon-dated, basal high-marsh peat deposits from Barnstable, Massachusetts (Figure 1). Stuiver and Daddario (1963) and Bloom and Stuiver (1963) developed similar

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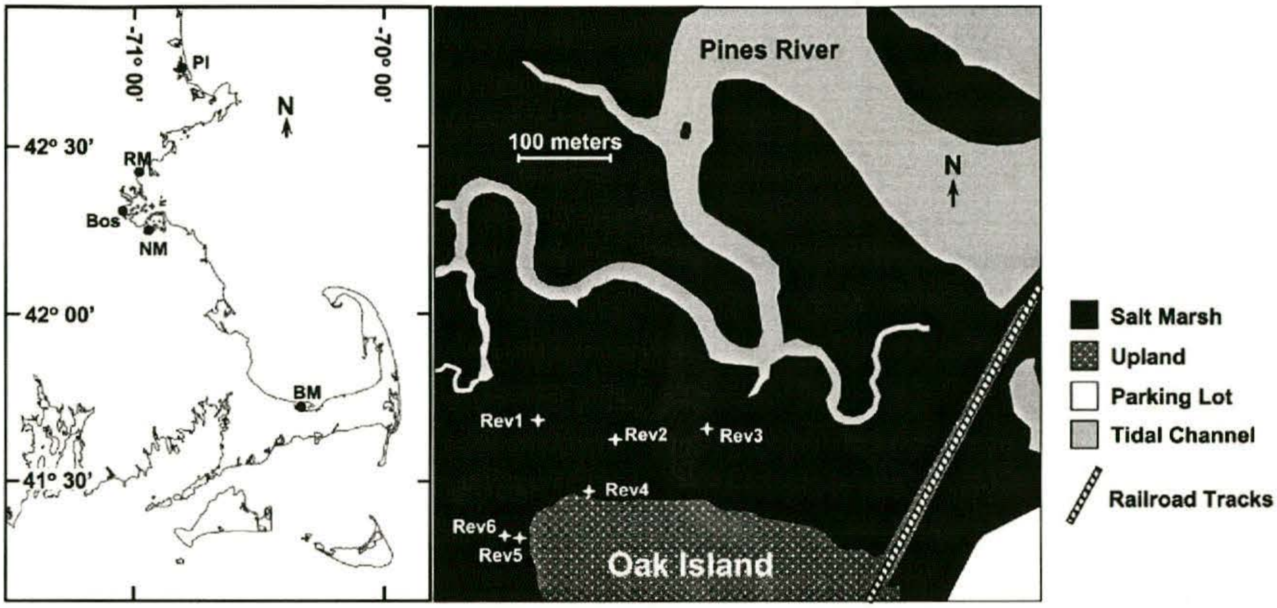

Figure 1. (left) Location map for Romney Marsh (RM) and previously published sea-level chronologies from Massachusetts: Neponset Marsh (NM); Barnstable Marsh (BM); Boston (Bos). (right) Romney Marsh study site north and northwest of Oak Island, Revere, Massachusetts. Core locations noted by stars (see Figure 3 for core cross-sections).

records from New Jersey and Connecticut, respectively. In addition, REDFIELD (1967), MCINTIRE and MORGAN (1964), and KAYE and BARGHORN (1964) constructed sea-level chronologies from northern Massachusetts. However, many of these earlier studies have radiocarbon-dated samples that do not conform to the overall general trend, even taking into account the large analytical uncertainties associated with many of these samples.

REDFIELD and RUBIN (1962) suggested that anomalous sample ages might be the result of contamination associated with sediment-core extraction. Early coring operations frequently employed piston corers of varying lengths that required multiple drives to obtain sediment samples from depth. When employing this approach, younger material can fall into the core hole and be incorporated in the sediment sample. Large samples of bulk sediment were required to yield enough carbon for conventional radiocarbon dates. These samples potentially contained organic matter with older or younger carbon. Older material can be reworked and incorporated in the growing surface of the marsh resulting in a bulk radiocarbon age determination significantly older than the high-marsh surface at the time of deposition. Basal samples can often contain organic matter from the submerged upland soil that may or may not have formed close to the time of submergence.

Several of the sea-level data points from the Hammock River Marsh in Clinton, Connecticut (BLOOM and STUIVER, 1963), were found to contain errors of this type. VAN DE PLASSCHE, MOOK, and BLOOM (1989) dated additional samples from this site after removing "a black amorphous organic material," interpreted as the weathered residue of a former peat deposit. These new samples yielded ages significantly younger than those initially dated by BLOOM and STUIVER (1963), and samples of the extracted black organic material yielded an age 500 radiocarbon years older than the accompanying sedge peat (VAN DE PLASSCHE, MOOK, and BLOOM, 1989).

The leaching of humic acids, particularly at an impermeable basal contact, can potentially introduce younger or older carbon to a sample. BELKNAP *et al.* (1987, 1989) dated both the humic acid fraction and nonhumic acid fraction from several samples from Addison, Maine, and found that the humic acid samples yielded ages significantly older and younger than the nonhumic acid fraction. They concluded that humic acids significantly redistribute both older and younger carbon within the marsh sediments.

In addition, radiocarbon dates from early studies were often reported with analytical uncertainty ranges of 300 years or more at one standard deviation (SD). Given all these potential sources of uncertainty, existing Late Holocene sea-level data from the region are ambiguous, and do not adequately constrain past sea level. Only eight previously published radiocarbon-dated basal high-marsh peat samples for northern Massachusetts are available for the past 3500 years (Table 1, Figure 2). Two samples were recovered from the Boylston Fish Weir site, Boston, Massachusetts (Figure 1; KAYE and BARGHORN, 1964), and six samples were recovered from Neponset Marsh in Milton, Massachusetts (REDFIELD, 1967). To refine the late Holocene history of relative sea-level rise in northern Massachusetts, I radiocarbon-dated five basal samples of high-marsh plant remains with accelerator mass spectrometry (AMS) radiocarbon methods.

Table 1. *Previously published radiocarbon-dated sea-level indicators for northern Massachusetts.*

Sample No.	Lab No.	^{14}C Age	2 SD Calendar Age (Method B; Stuiver *et al.*, 1998) (Probabilities)	Sample Depth (cm)*	Estimated Elevation Below Modern MHW (cm)
A1†	W-988	1700 ± 300	378 BC–895 AD (0.995) 924–938 AD (0.005)	−52	−60
A2†	O-1276	2750 ± 115	1263–758 BC (0.966) 685–663 BC (0.008) 638–549 BC (0.027)	−70	−78
A3‡	I-2275	1310 ± 95	560–900 AD (0.966) 918–958 AD (0.034)	−40	−37
A4‡	I-2216	1360 ± 105	438–524 AD (0.052) 525–894 AD (0.948)	−70	−67
A5‡	I-2217	1860 ± 100	48 BC-403 AD (1.000) 760–682 BC (0.027)	−101	−98
A6‡	W-1451	2100 ± 200	665–634 BC (0.008) 590–579 BC (0.003)	−113	−110
A7‡	W-1452	2790 ± 200	556 BC–342 AD (0.962) 1426–1418 BC (0.004) 1414–483 BC (0.981) 466–449 BC (0.008) 441–425 BC (0.004) 425–413 BC (0.004)	−174	−171
A8‡	W-1453	3110 ± 200	1866–1846 BC (0.006) 1774–892 BC (0.981) 879–839 BC (0.012)	−222	−219

* Depth is the mean depth of samples as reported in the original study.
† Boston, Massachusetts (Kaye and Barghorn, 1964) 8 cm added for MHW change since sampled.
‡ Neponset River Marsh, Milton, Massachusetts (Redfield, 1967) 8 cm added for MHW change since sampled and 11 cm subtracted as Redfield used the HM surface (likely ~11cm above contemporaneous MHW) as a local datum.

STUDY SITE AND METHODS

MUDGE (1862) first studied Romney Marsh in the middle of the 19th century and recognized that the preservation of high-marsh peat at depths below its modern habitat range indicated a relative rise in sea level. Romney Marsh was again the focus of scientific inquiry in the early 20th century when V. J. Chapman mapped the vegetation and examined the nature of tidal inundation at the site (CHAPMAN, 1940). The marsh exhibits the classic, nearly monospecific, floral zonation typical of New England salt marshes (MILLER and EGLER, 1950; REDFIELD, 1972). Tall cord grass (*Spartina alterniflora*) occupies the lower intertidal zone, between approximately mean sea level and MHW. The high-marsh zone occurs between MHW and mean highest high water (MHHW) with salt marsh hay (*Spartina patens*) and stunted cordgrass occupying lower elevations, and black rush (*Juncus gerardi*) dominating the terrestrial border. Spike grass (*Distichlis spicata*) often occupies disturbed areas in the high marsh (BERTNESS, 1991b).

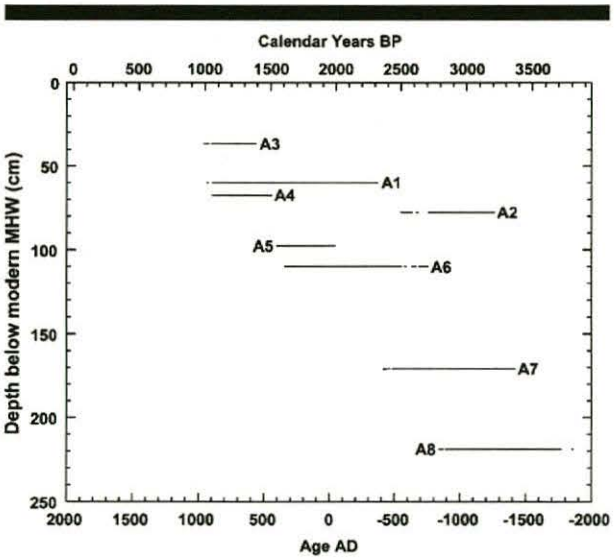

Figure 2. Elevation *vs.* calendar ages of previously published high-marsh basal samples (A1–A8) from northern Massachusetts (KAYE and BARGHORN, 1964; REDFIELD, 1967; see Table 1). Note one radiocarbon date often yields several possible calendar ranges when calibrated for secular changes in atmospheric radiocarbon concentrations.

Romney Marsh is located behind Revere Beach and is connected to Lynn Harbor and Massachusetts Bay via the Pines and Saugus Rivers. The portion of Romney Marsh that is the focus of this inquiry is located just north of Oak Island in Revere, Massachusetts (42°25′41″ N, 70°59′20″ W; Figure 1). The mean tidal range at Romney Marsh is approximately 2.8 m (NOAA/NOS/CO-OPS, 2004).

I extracted six vibracores off the northwest corner of Oak Island (Figure 1). Vibracores were wrapped in plastic to prevent desiccation and refrigerated at 4°C. Cores were described in the lab by sediment type, grain size, character of the transitions between zones, and color (based on the Munsell soil color charts). Plant macrofossils were identified to species when possible using the NIERING, WARREN, and WEYMOUTH (1977) rhizome key. Sediment types are defined by the species of plant remains preserved within the peat.

High-marsh peat contains *S. patens* and *D. spicata* remains. Highest high-marsh (HHM) peat contains *J. gerardi* or *Scirpus* spp. remains. Mud units contained fine-grained sediments with few *in situ S. alterniflora* remains.

Some compaction often occurs during the vibracoring operation. To account for this when illustrating stratigraphies and determining the elevation of the basal samples, I assume that all the compaction associated with the coring operation occurs within the "soft" sediment (peat and mud units), and none occurs within the basement sand and gravel. This assumption is likely valid in determining the elevation of the basal contact because the peat and mud units are much more likely to compact than the basement sand and gravel. Some errors may be expected with respect to the elevation of stratigraphic contacts within the soft sediment given the assumption of uniform compaction within the soft sediment column because some intervals within the peat or mud units may be more likely to compact than others. All depths presented here have been corrected for compaction associated with the vibracoring operation.

Dating

AMS radiocarbon dating of individual plant remains greatly reduces potential contamination from humic acids. Peat samples of 1–3 cm^3 were removed from suitable cores for radiocarbon analysis. The samples were sieved to $\geq$1 mm, and the remaining plant fragments sampled and, when possible, identified to species. Five basal vegetation samples were identified as good sea-level indicators and submitted to Beta Analytic Inc. (Miami, Florida) or the National Ocean Sciences AMS facility at Woods Hole, Massachusetts, for AMS radiocarbon dating (Table 2). One additional nonbasal sample (R3) was dated to establish the timing of a stratigraphic transition.

The new dates and the dates of previous studies from northern Massachusetts have been calibrated for secular changes in carbon-14 (C-14) concentrations (STUIVER *et al.*, 1998). The nonlinearity of the calibration curve can often result in multiple calibrated ranges. To quantify the probability that the age of any one sample is represented by each of its calibrated age ranges, Method B of the Stuiver *et al.* (1998) Calib 4 program was used. This method estimates the probability that any one calibrated age range represents the age of the sample based on how the normally distributed analytical error is projected across the calibration curve. Radiocarbon dates were calibrated with 2 SD associated with reported analytical uncertainty.

Modern Mean High-Water Datum

Using a digital water-level recorder (Model WL14, Global Water Instrumentation, Inc., Gold River, California), we measured water-level changes at Romney Marsh every 6 minutes from August 2, 2003 to October 25, 2003. A cross-correlation matrix was computed between the Romney Marsh water-level record and the Boston tide-gauge (NOAA Station 8443970) record (8 km to the southwest), and the MHW levels were compared. No offset in tidal amplitude was evident between the two records (at 0.95 confidence), enabling the MHW and MHHW NOAA-defined datum from the Boston, Massachusetts, station to be directly applied to the study site. The elevations of all samples are presented here relative to MHW as defined by NOAA tidal epoch (1983–2001).

Determining the Paleo-Mean High Water (Indicative Meaning)

The relationship of the dated basal samples to a reference tide level or the "indicative meaning" of these samples (GEHRELS, BELKNAP, and KELLY, 1996; VAN DE PLASSCHE, 1986) can be estimated based on modern relationships of the flora to tidal inundation. I assigned an elevation or indicative meaning (relative to modern MHW) for each basal sample based on the present day vertical range of the marsh vegetation species or combination of species found in the peat samples. I determined the modern elevation range of marsh vegetation by surveying 291 random points with a Leica TC800 Total Survey Station (Leica Geosystems, Heerbrugg, St Gallen, Switzerland). The vegetation composition was noted for a 50-cm diameter circle around each sample point. I used this modern distribution to estimate the relationship of vegetation identified within dated basal-peat samples to MHW in the past and construct envelopes of MHW change that incorporate uncertainties associated with both dating and elevation estimates.

RESULTS

Core REV1 was taken 100 m to the northwest of the western end of Oak Island (Figure 1). In this core, the high marsh (HM) peat dominated by *S. patens* plant remains extends from +11 cm to −199 cm, whereas the HHM peat containing *D. spicata, S. patens, J. gerardi,* and *Scirpus* spp. plant remains ranges from −199 cm to −216 cm. The basal unit in this core is a black-to-brown, muddy sand from −216 cm to −262 cm (Figure 3). A sample removed from the basal contact of the HHM unit at −213 cm to −216 cm in this core containing *J. gerardi, Scirpus* spp., and *S. patens* remains (R1) yielded a radiocarbon age of 3050 ± 50 (Table 2, Figure 4).

Core REV2 was extracted 90 m east–southeast of REV1 (Figure 1). A brown, muddy, HM peat containing *S. patens* and *D. spicata* plant remains is evident from +5 cm to −90 cm (Figure 3). From −90 to −160 cm a dark, olive-gray mud was recovered with numerous *S. alterniflora* remains in the top of the unit grading to no plant remains at the base of the unit. This unit unconformably overlies a brown, muddy, HM peat with *S. patens* and *D. spicata* remains from −160 cm to −200 cm. The basal unit consists of poorly sorted, fine-to-coarse sand from −200 cm to −238 cm. A large *in situ* root fragment is preserved within this unit at a depth of −202 cm to −210 cm. A sample containing *D. spicata* remains from the basal contact of the HM peat from −198 cm to −200 cm (R2) yielded a radiocarbon age of 2950 ± 60 YBP (Table 2; Figure 4). A sample containing *S. patens* remains from the −160 cm to −161 cm, at the contact between the basal HM peat and the mud unit (R3), yielded a radiocarbon age of 2510 ± 50 YBP.

Core REV3 was extracted 130 m northeast of REV4 (Figure 1). This core is similar to REV2 with a mud containing *S.*

Table 2. *Radiocarbon dated sea-level indicators from Romney Marsh, Revere, Massachusetts.*

Sample No.	Laboratory No.	Core	^{14}C Age	2 SD Calendar Age (Method B: Stuiver *et al.*, 1998) (Probabilities)	$u\delta\,^{13}C$ (%)	Sample Depth Below Modern MHW (cm)*	Species†	Relationship to Modern MHW (cm from MHW)	Change in MHW Related to Variations in Tidal Range (cm)‡	Estimated Elevation of MSL (cm)
R1	Beta-134753	REV1	3050 ± 50	1426–1419 BC (0.007) 1414–1207 BC (0.912) 1203–1189 BC (0.024) 1179–1155 BC (0.036) 1142–1130 BC (0.021)	−18.0	−213 to −216	Jg, Sp	−20 ± 12.8	−22	−256.5 ± 12.8
R2	Beta-134755	REV2	2950 ± 60	1374–1337 BC (0.039) 1319–997 BC (0.958) 986–982 BC (0.003)	−15.0	−200 to −192	Ds	−12 ± 15	−22	−225 ± 15
R3	Beta-134754	REV2	2510 ± 50	796–499 BC (0.925) 492–483 BC (0.012) 465–449 BC (0.026) 441–426 BC (0.022) 424–413 BC (0.016)	— −14.7	−156 to −157	Sp	−11 ± 12.2	−15	−182.5 ± 12.2
R4	Beta-134756	REV4	1900 ± 40	24–4 AD (0.059) 47–226 AD (0.941)	−24.8	−100 to −102	Jg, Sc, Sp	−20 ± 12.8	−8	−129 ± 12.8
R5	OS-24172	REV6	260 ± 50	1486–1681 AD (0.784) 1735–1806 AD (0.185) 1933–1947 AD (0.030)	−20.8	−35 to −36	Jg/Sp	−20 ± 12.8	−2.5	−58 ± 12.8
R6	Beta-138707	REV7	1040 ± 40	894–925 AD (0.120) 935–1040 AD (0.849) 1102–1116 AD (0.015) 1142–1151 AD (0.015)	−15.7	−57 to −58	Sp	−11 ± 12.2	0	−68.5 ± 12.2

* Depth corrected for compaction incurred during coring operation.
† Jg = *Juncus gerardi*, Sp = *Spartina patens*, Ds = *Distichlis spicata*, Sc = *Scirpus* spp.
‡ Tidal range corrections from GEHRELS *et al.*. (1995).

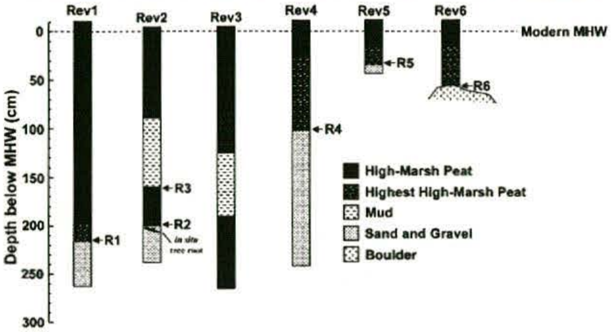

Figure 3. Stratigraphic cross-section of cores from Romney Marsh. Cores are plotted relative to modern mean high water (MHW). The locations of radiocarbon dated samples (see Table 2) are noted with arrows.

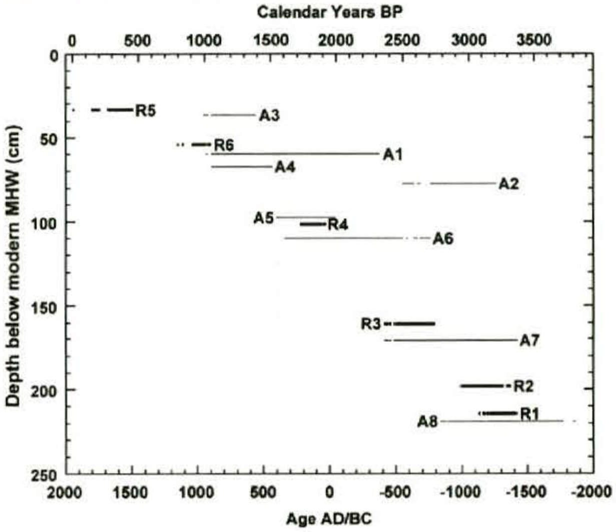

Figure 4. Elevation *vs.* calendar ages of radiocarbon dated high-marsh and highest high marsh samples from Romney Marsh (black bars R1–R5; see Table 2) and the calendar ages of previously published high-marsh samples from northern Massachusetts (grey bars A1–A8; see Table 1). Six of the eight previously published data points overlap with the trend apparent in the Romney Marsh data at 2 SD. Samples A2 and A3 are too old and were likely contaminated with older carbon.

alterniflora remains from −125 cm to −190 cm, overlying muddy HM peat. As in core REV2, the mud unit is capped by muddy HM peat from +6 cm to −125 cm. The basal contact was not recovered in this core because muddy HM peat extends −268 cm to the base of the core. Probing to refusal indicated the mineral basement was at a depth of approximately −290 cm at this location.

Core REV4 was taken 5 m north of the Oak Island (Figure 1). A brown, muddy, HM peat dominated by *S. patens* plant remains was recovered from +12 cm to −24 cm (Figure 3). A black, muddy, HHM peat containing *D. spicata, S. patens, J. gerardi,* and *Scirpus* spp. plant remains exists from −24 cm to −102 cm. These peat units overlie poorly sorted, fine-to-coarse sand. A sample from the base of the HHM peat containing *S. patens, J. gerardi* and *Scirpus* spp. remains at −102 cm to −104 cm (R4) yielded a radiocarbon age of 1900 ± 40 YBP (Table 2, Figure 4).

Cores REV5 and REV6 were taken a few meters off the western edge of Oak Island (Figure 1). Brown, HM peat containing *S. patens* remains was recovered from +13 cm to −17 cm in core REV5. This unit graded into a black, muddy, HHM peat that extends to a depth of −34 cm (Figure 3). The basal unit from −34 to −43 cm consists of brown, muddy sand with sparse plant remains. A sample containing *J. gerardi* and *S. patens* remains from the basal contact of the HHM peat from −33 cm to −34 cm (R5) yielded a radiocarbon age of 260 ± 50 YBP. Core REV6 met refusal with a hard substance at a depth of approximately −56 cm. Given that the local surficial geology consists of glacially derived sediments with numerous boulders, it is assumed that a boulder underlies this portion of the marsh. A brown, muddy, HM peat was recovered from +13 cm to −16 cm that grades into a black, muddy, HHM peat that extends to a depth of −56 cm (Figure 3). A sample from the base of this core at −55 cm to −56 cm containing *S. patens* remains (R6) yielded a radiocarbon age of 1040 ± 40 YBP (Table 2, Figure 4).

Comparison with Previously Published Data

To compare the results of previous studies with those from Romney Marsh, an estimate is needed of how the earlier samples relate to past MHW. Estimating those relationships is difficult because information regarding the type of material being radiocarbon-dated is often limited. KAYE and BARGHORN (1964) radiocarbon-dated freshwater peat, salt-marsh peat, and estuarine sediments from the Bolyston fish weir site in Boston, Massachusetts (Figure 1). Few of the samples dated were from basal contacts so a correction for autocompaction was necessary in many cases to reconstruct past sea levels. Only two radiocarbon dates from basal sediments containing HM remains were obtained, and these are included in this study (Figures 2 and 4, Table 1). Sample A1 from 60 cm below modern MHW yielded a radiocarbon age of 1700 ± 300 YBP (A1). Sample A2 from 78 cm below MHW yielded a radiocarbon age of 2750 ± 115 YBP (A2).

REDFIELD (1967) radiocarbon-dated six salt marsh samples (A3–A8; Figures 2 and 4, Table 1) from the Neponset River Marsh in Milton, Massachusetts (Figure 1). These samples were described simply as peat or silty peat with no information concerning their floral remains. The surface vegetation at the site was identified as *S. patens,* however, and for the purposes of this study, I assumed that these samples were *S. patens*–dominated HM peat.

I calibrated the radiocarbon dates from these earlier studies to calendar years in the same manner as the data presented here for Romney. In addition, to adjust the elevation of these previously published samples to the modern MHW datum, 8 cm have been added to the depth of these samples to account for the approximate increase in the level of MHW since these previous studies were conducted (Table 1). Both tide-gauge measurements and marsh-accretion rates determined from Cesium-137 (Cs-137) profiles (DONNELLY and BERTNESS, 2001; ORSON, WARREN, and NIERING, 1998) indicate a correction of between +7 cm and +9 cm since the 1960s is appropriate.

Furthermore, in the case of the Neponset samples (A3–A8), I assumed the local datum used by REDFIELD (1967) was the HM surface (dominated by *S. patens*). Given the relationship of modern marsh vegetation to MHW (see section below), I have estimated that the REDFIELD (1967) marsh datum was roughly 11 cm above contemporaneous MHW. Therefore, I applied a correction of +11 cm to the sample depths reported by REDFIELD (1967). Combined with the −8 cm discussed above for increases in MHW since this site was sampled, the total correction for the Neponset samples is −3 cm (Table 2). This correction is not necessary for the KAYE and BARGHORN (1964) samples because they used contemporaneous MHW as their datum.

The raw data from Romney Marsh and these previous studies is plotted in Figure 4 relative to the modern MHW datum. Six out of the eight previously published sea-level indicators are generally consistent with the five dated basal Romney Marsh samples, albeit with significantly large uncertainty ranges (Figure 4). Sample A2 from the Boston study by KAYE and BARGHORN (1964) and sample A3 from Neponset (REDFIELD, 1967) do not conform to the overall trend and are apparently too old.

Construction of Mean Sea-Level Envelope for Romney Marsh

I estimated the elevation of past MHW, relative to the dated basal samples, based on the modern relationship of marsh flora to MHW. The results of the survey of modern vegetation indicate that mixed stands of *J. gerardi* and *S. patens* (n = 86) occur at a mean elevation of 20 cm ± 12.8 cm above MHW at 2 SD (Figure 5). Samples R1, R4, and R5 contain both *J. gerardi* and *S. patens* remains, assuming that the modern relationship of these species to MHW also held true in the past, I estimated that MHW was 20 cm ± 12.8 cm below the elevation of samples R1, R4, and R5 (Table 2). Measurements of monospecific stands of *D. spicata* (n = 59) yielded a mean elevation of 12 cm ± 15 cm above MHW (Figure 5). Given the *D. spicata* remains in sample R2, MHW was likely 12 cm ± 15 cm below the elevation of this sample (−198 cm to −200 cm) or −211 cm ± 15 cm (Table 2). The survey of modern flora also yielded a mean elevation of 11 cm ± 12.2 cm (n = 129) above MHW for pure stands of *S. patens* (Figure 5). Therefore, as samples R3 and R6 both contained only *S. patens* remains, MHW was likely 11 cm ± 12.2 cm below those samples at the time of their deposition.

The MHW record derived from the marsh sediments may not directly mirror changes in mean sea level (MSL) because the tidal range has likely varied through time. GEHRELS *et al.* (1995) modeled changes in tidal amplitude in the Gulf of Maine (including Massachusetts Bay) and showed the tidal range has gradually been increasing throughout the Holocene. Their projections indicate that MHW has increased roughly 22 cm in the past 3300 years (3000 C-14 years) due solely to tidal amplification. I have applied a correction to the Romney Marsh data based on the GEHRELS *et al.* model results to estimate true changes in MSL (Table 2).

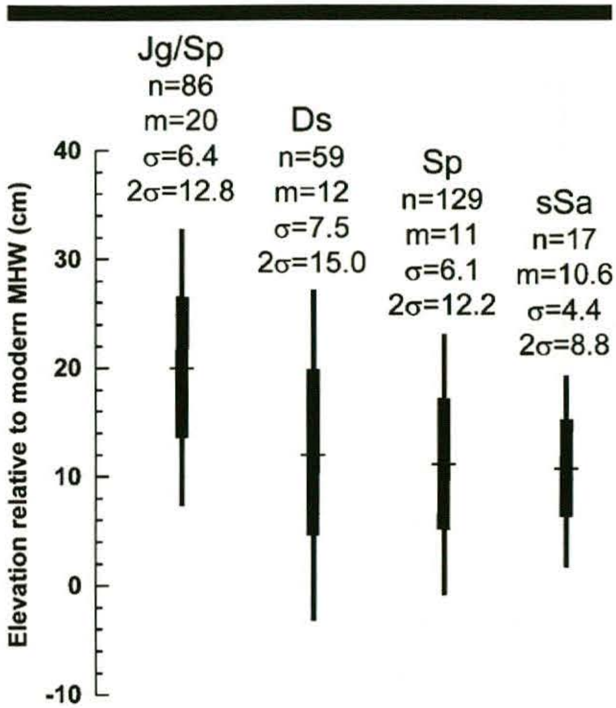

Figure 5. Distribution of marsh flora at Romney Marsh relative to modern mean high water (MHW) with associated statistics. Distributions at 2 SD are used to estimate the relationship of fossil samples to MHW in the past (see Table 2). Jg = *Juncus gerardi*; Sp = *Spartina patens*; Ds = *Distichlis spicata*; sSa = stunted *Spartina alterniflora*.

The tide gauge record at Boston, Massachusetts (NOAA/NOS/CO-OPS, 2004) indicates that MSL has increased by approximately 22 cm since 1922 AD at an average rate of 2.8 mm/y (Figure 6). Consequently, the MSL envelope generated from the Romney Marsh samples terminates at the 1922 AD MSL mark where the instrumental record begins (Figure 7). Five basal samples (R1, R2, R4, R5, and R6; Table 2) are used to construct a MSL chronology for Romney Marsh by creating an envelope of depth and age ranges that enclose the error boxes derived from radiocarbon dating and calibration as well as paleoelevation range estimates. Sample R3 is not from a basal contact and is not used to provide the MSL envelope.

The MSL envelope reconstructed from five AMS radiocarbon dates of basal marsh sediments at Romney Marsh reveal a rise in sea level of about 2.6 m in the past 3300 years (Figure 7). The data indicate a possible decrease in the average rate of rise from 0.80 mm/y ± 0.25 mm/y between 3300 YBP and 1000 YBP to a rate of 0.52 mm/y ± 0.62 mm/y between 1000 YBP and the past 150–500 years. Tide gauge measurements from Boston indicate an average rate of sea-level rise of 2.8 mm/y over the past 80 years (Figures 6 and 7).

DISCUSSION

The data from Romney Marsh constrain the history of past sea-level change much more precisely than have previous

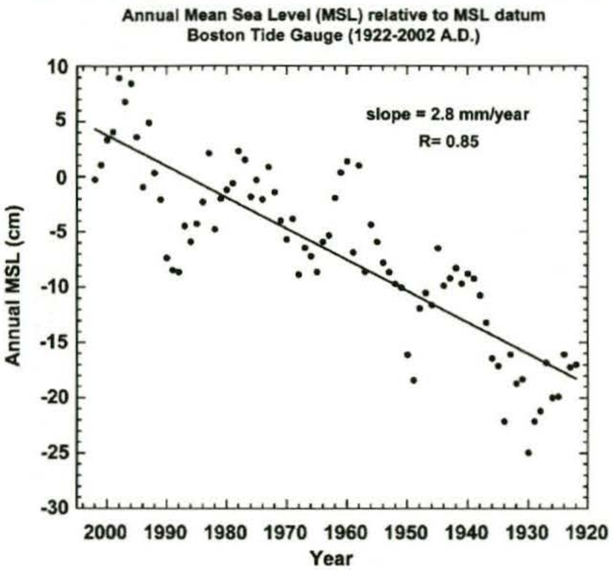

Figure 6. Annual average mean sea level (MSL) relative to the MSL datum recorded by the tide gauge at Boston, Massachusetts from 1922 to 2002 AD (Station 8443970; NOAA/NOS/CO-OPS, 2004). Linear regression indicates an average rate of submergence of 2.8 mm/y.

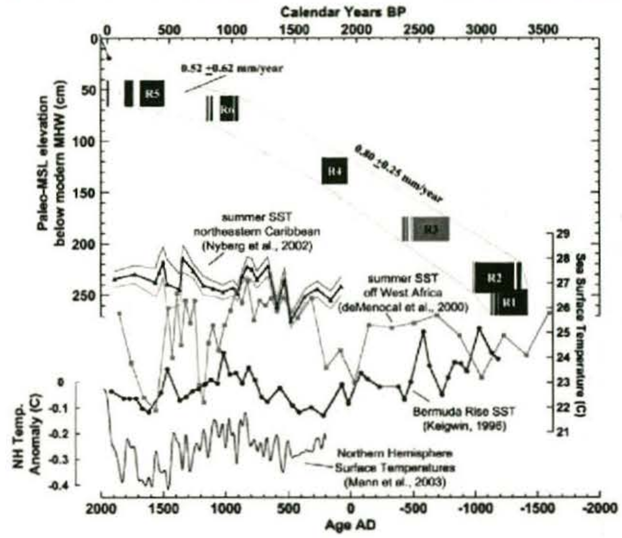

Figure 7. Mean sea level (MSL) envelope for Romney Marsh, Massachusetts (top). Samples have been corrected for changes in MHW (see Table 2) related to predicted changes in tidal range (GEHRELS *et al.,* 1995). Black boxes represent uncertainty range associated with radiocarbon age determinations and estimated relationship of the sample to paleo-MSL for basal samples. Sample R4 (gray boxes) is not from a basal contact and is not used to construct the MSL envelope, although it is generally consistent with the overall MSL envelope. The MSL envelope terminates at −19 cm and 1922 AD when the instrumental record (Boston Tide Gauge) begins. Estimated rates of sea-level change were derived by calculating the mean of the maximum and minimum linear rate of change that is possible within MSL envelope segments ~3300–1000 YBP and 1000–300 YBP. North Atlantic sea surface temperature (SST) estimates (bottom). Black circles are paleo-SST estimates derived from oxygen isotopes within foraminifera from a core from the Bermuda Rise (KEIGWIN, 1996). Gray squares are summer paleo-SST estimates derived from microfaunal communities from a sediment core off West Africa (DEMENOCAL *et al.,* 2000). Black triangles are summer paleo-SST estimates from the northeastern Caribbean (NYBERG *et al.,* 2002). Black curve at bottom is Northern Hemisphere surface temperature reconstruction (MANN and JONES, 2003).

studies. The use of AMS radiocarbon-dated macrofossils and vibracoring greatly reduced the chances for contamination of the ages by older carbon and provided age estimates with two to six times greater analytical certainty (Tables 1 and 2). The MSL reconstruction from Romney Marsh is similar to sea-level reconstructions from nearby Maine. Records from Wells, Maine; Phippsburg, Maine; Machiasport, Maine; and Gouldsboro, Maine all reveal approximately the same magnitude of submergence over the past 3300 years (~2.5 m; GEHRELS, BELKNAP, and KELLY, 1996) indicating that northern Massachusetts and coastal Maine are in a zone of similar vertical land movement.

An increase in the rate of submergence occurring sometime in the past few hundred years is evident in the Romney Marsh record. Higher resolution records in the region, from Machiasport, Maine (GEHRELS, 1999); Guilford, Connecticut (NYDICK *et al.,* 1995); Clinton, Connecticut (VAN DE PLASSCHE, 2000); and Barn Island, Connecticut (DONNELLY *et al.,* 2004) also indicate this recent acceleration. NYDICK *et al.* (1995) and GEHRELS (1999) argue that a portion of this recent increase in the rate of sea-level rise predated industrialization and the climate warming of the past 150 years. However, coupling of the regional tide-gauge data (1856 to present) with results of a high-resolution sea-level study from Barn Island, Connecticut, indicates that a threefold increase in the rate of sea-level rise there likely occurred in the late 19th century, concomitant with the initiation of recent climate warming (DONNELLY *et al.,* 2004). The documentation of significant changes in the composition of southern New England marsh vegetation likely associated with increased flooding frequency that initiated during this time (DONNELLY and BERTNESS, 2001) further supports that the acceleration in the rate of sea-level rise took place, and that the timing of this acceleration may have occurred in the late 19th century.

If the timing of this acceleration is a global- or regional-scale phenomenon, it may be associated with recent warming of the global climate system. For example, LEVITUS *et al.* (2000) showed that global sea-surface temperatures (SSTs) increased by 0.31°C in the past half of the 20th century, possibly as a result of anthropogenic greenhouse gas emissions (LEVITUS *et al.,* 2001). Modeling results indicate that sea level may increase on average by about 15 cm due solely to thermal expansion related to warming associated with a doubling of atmospheric carbon dioxide concentrations (BRYAN, 1996). Recent work suggests that the contribution of meltwater from land ice to increases in sea level over the past century may be significantly greater than the contribution from changing oceanic temperature and salinity (MILLER and DOUGLAS, 2004). In addition, contributions from melting continental ice may contribute significantly greater amounts of sea-level rise in a carbon dioxide–enriched climate (IPCC, 2001).

The Romney Marsh record may indicate a slowing in the rate of sea-level rise between approximately 1000 YBP and the historic period (Figure 7). An interval of reduced rates of sea-level rise at this time is also apparent in a sea-level record derived from Machiasport, Maine (GEHRELS, 1999), and Clinton, Connecticut (VAN DE PLASSCHE, VAN DER BORG, and DE JONG, 1998; VAN DE PLASSCHE, 2000) and Guilford, Connecticut (NYDICK *et al.,* 1995; VAREKAMP and THOMAS, 1998). The Barn Island record indicates an average sea-level rise rate of 1.0 mm/y ± 0.2 mm/y from about 1300 AD to 1850 AD (DONNELLY *et al.,* 2004). The roughly twofold greater rate of rise at Barn Island relative to Romney Marsh and Machiasport, Maine for this interval is the result of differential crustal subsidence likely related to glacioisostatic processes (DAVIS and MITOVICA, 1996; DONNELLY, 1998; PELTIER, 1996). VAN DE PLASSCHE, VAN DER BORG, and DE JONG (1998), VAN DE PLASSCHE (2000), and GEHRELS (1999) argued for a correlation between North Atlantic SST changes (KEIGWIN, 1996; Figure 7) and sea-level fluctuations at both Clinton, Connecticut, and Machiasport, Maine, respectively. They pointed out that the slow rates in sea-level rise between roughly 1000 YBP and historic times correspond to cooler SSTs at the Bermuda Rise (Little Ice Age; LIA) and suggested that the sea-level fluctuations may be, in part, because of steric changes in the North Atlantic. However, the Machiasport, Maine sea-level record neither resolves any significant sea-level variability associated with the warming of Bermuda Rise SSTs around 1500 AD, nor shows any reduction in the rate of sea level during earlier periods of cooling SSTs between 0 AD and 500 AD (Figure 7). The Clinton, Connecticut record (VAN DE PLASSCHE, VAN DER BORG, and DE JONG, 1998; VAN DE PLASSCHE, 2000) does yield sea-level fluctuations that roughly correlate with the SST record from the Bermuda Rise; however, it has been criticized for not taking into account peat autocompaction (KELLEY *et al.,* 2001).

More recent studies have reconstructed additional long-term records of SSTs for sites in the North Atlantic. For example, NYBERG *et al.* (2002) used oxygen isotopes to reconstruct SSTs for a site in the northeastern Caribbean, and DEMENOCAL *et al.* (2000) used faunal data from off West Africa to document millennial-scale fluctuations in SST (Figure 7). These records and the Bermuda Rise data indicate that SSTs were as warm as today or warmer during the Medieval Warm Period (MWP) about 1500 years to 900 years ago and again for a brief interval, interrupting the LIA, about 500–600 years ago.

These SST records are in general agreement with historical records (JONES and BRADLEY, 1995) and a record of Greenland land surface temperatures derived from ice sheet borehole temperatures (DAHL-JENSEN *et al.,* 1998). However, significant differences among these SST records are evident. For example, the warming into MWP in the Bermuda Rise record occurred several hundred years later than the West Africa Margin or the northeastern Caribbean records (Figure 7). In addition, the northeastern Caribbean record shows a 1.5°C cooling of SSTs between 0 AD and 500 AD whereas the West African Margin record indicates a 3°C warming during the same interval. Offsets in the timing of SST fluctuations evident in these records may reflect real spatial variability in SST fluctuations, changes in oceanic circulation patterns, and/or age model uncertainties.

MANN and JONES (2003) reconstructed surface atmospheric temperature estimates extending back 1800 years. The Northern Hemisphere temperature reconstruction is plotted in Figure 7. The MANN and JONES (2003) record shows the MWP warming centered about 1000 years ago followed by a overall cooling trend into the historic period. The modern interval of warming initiated in the 19th century. This pattern of atmospheric temperature change most closely resembles the SST record reconstructed from the Bermuda Rise. Given the differences among the SST records from the North Atlantic Basin and the fact that the contribution of warming SSTs may be relatively small, caution should be exercised when attempting to draw inferences from possible correlations between relatively small sea-level fluctuations, particularly if the SST variations are evident in only one record.

CONCLUSIONS

High-marsh sediments form at an elevation just above MHW (11 cm ± 12 cm) and provide a means of estimating past levels of MHW and sea level in general. The five AMS radiocarbon dates of basal marsh sediments at Romney Marsh in Revere, Massachusetts, significantly refine previous estimates of past sea level for this region. After correction for tidal amplitude changes, the sea-level change envelope reconstructed in this study indicates a rise in MSL of close to 2.6 m in the past 3300 years. The data indicate a possible decrease in the average rate of rise from 0.80 mm/y ± 0.25 mm/y between 3300 YBP and 1000 YBP to a rate of 0.52 mm/y ± 0.62 mm/y between 1000 YBP and the past 150–500 years. Tide gauge measurements from Boston indicate an average rate of sea-level rise of 2.8 mm/y over the past 80 years. A reduced rate of sea-level rise between 1000 YBP and historic times and the increase in the rate of rise to modern values are also evident in other marsh-derived sea-level records from Maine and Connecticut. The general coherence among these records suggests that the inferred sea-level fluctuations are, at least, a regional-scale phenomena.

The decrease in sea-level rise rates during the LIA (1000 YBP to ~150 YBP) and the acceleration in the rate of sea-level rise during recent climate warming may indicate climate forcing of sea-level variability over the past millennium. However, given that SSTs in the North Atlantic appear to have varied widely over the past few millennia, in some cases without any correlative fluctuations in sea level, this suggests that SST and sea level may not be tightly coupled. This may indicate that thermal expansion of the sea surface may not be as important in changing sea level as other factors such as melting land ice.

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LITERATURE CITED

BELKNAP, D.F.; ANDERSEN, B.G.; ANDERSEN, R.S.; ANDERSEN, W.A.; BORNS, H.W., JR.; JACOBSEN, G.W.; KELLEY, J.T.; SHIPP, R.C.; SMITH, D.C.; STRUCKENRATH, R., JR.; THOMPSON, W.W., and TYLER, D.A., 1987. Late Quaternary sea-level changes in Maine. *In:* NUMEDAL, D., PILKEY, O.H., JR., and HOWARD, J.D. (eds.), *Sea Level Fluctuations and Coastal Evolution,* Society of Economic Paleontologists and Mineralogists. Special publication 41, pp. 71–85.

BELKNAP, D.F.; SHIPP, R.C.; STUCKENRATH, R.; KELLEY, J.T., and BORNS, H.W., JR., 1989. Holocene sea-level change in coastal Maine. *In:* ANDERSON, W.A. and BORNS, H.W., JR. (eds.), *Neotectonics of Maine.* Maine Geological Survey Bulletin 40, pp. 85–105.

BERTNESS, M.D., 1991a. Interspecific interactions among high marsh perennials in a New England salt marsh. *Ecology,* 72, 125–137.

BERTNESS, M.D., 1991b. Zonation of Spartina patens and Spartina alterniflora in a New England salt marsh. *Ecology,* 72, 138–148.

BLOOM, A.L., 1964. Peat accumulation and compaction in a Connecticut coastal marsh: *Journal of Sedimentary Petrology,* 34, 599–603.

BLOOM, A.L. AND STUIVER, M., 1963. Submergence of the Connecticut coast. *Science,* 139, 332–333.

BRYAN, K., 1996. The steric component of sea level rise associated with enhanced greenhouse warming; a model study. *Climate Dynamics,* 12, 545–555.

CAHOON, D.R.; REED, D.J., and DAY, J.W., JR., 1995. Estimating shallow subsidence in microtidal salt marshes of the Southeastern United States: Kaye and Barghorn revisited. *Marine Geology,* 128, 1–9.

CHAPMAN, V.J., 1940. Studies in salt marsh ecology, VI and VII: comparison with marshes on the east coast of North America. *Journal of Ecology,* 28, 118–152.

CHAPMAN, V.J., 1960. *Salt Marshes and Salt Deserts of the World.* London: L. Hill Publishing, 392p.

DAHL-JENSEN, D.; MOSEGAARD, K.; GUNDESTRUP, N.; CLOW, G.D.; JOHNSEN, S.J.; HANSEN, A.W., and BALLING, N., 1998. Past temperatures directly from the Greenland Ice Sheet: *Science,* 282, 268–271.

DAVIS, C.A., 1910. Salt marsh formation near Boston and its geological significance. *Economic Geology,* 5, 623–639.

DAVIS, J.L. and MITROVICA, J.X., 1996. Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America. *Nature,* 379, 331–333.

DEMENOCAL, P.; ORTIZ, J.; GUILDERSON, T., and SARNTHEIN, M., 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science,* 288, 2198–2202.

DONNELLY, J.P., 1998, Evidence of late Holocene post-glacial isostatic adjustment in coastal wetland deposits of eastern North America. *Georesearch Forum,* 3–4, 393–400.

DONNELLY, J.P. and BERTNESS, M.D., 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proceedings of the National Academy of Sciences, 98, 14218–14223.

DONNELLY, J.P.; CLEARY, P.; NEWBY, P., and ETTINGER, R., 2004. Coupling instrumental and geological records of sea-level change: evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters,* 31, L05203.

GEHRELS, W.R., 1999. Middle and late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS ^{14}C dates on basal peat. *Quaternary Research,* 52, 350–359.

GEHRELS, W.R.; BELKNAP, D.F.; PEARCE, B.R., and GONG, B., 1995. Modeling the contribution of M2 tidal amplification to the Holocene rise of mean high water in the Gulf of Maine and the Bay of Fundy. *Marine Geology,* 124, 71–85.

GEHRELS, W.R.; BELKNAP, D.F., and KELLY, J.T., 1996 Integrated high-precision analysis of Holocene relative sea-level changes: lessons from the coast of Maine. Geological *Society of America Bulletin,* 108, 1073–1088.

[IPCC] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2001. *Climate Change 2001: The Scientific Basis.* New York: Cambridge University Press, 892p.

JONES, P.D. and BRADLEY, R.S., 1995. *Climate Since AD 1500.* London: Routledge, 695p.

KAYE, C.A. and BARGHORN, E.S., 1964. Late Quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat. *Geological Society of America Bulletin,* 75, 63–80.

KEIGWIN, L.D., 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science,* 274, 1504–1508.

KELLEY, J.T.; BELKNAP, D.F.; DALY, J.F., and VAN DE PLASSCHE, O., 2001. North Atlantic climate-ocean variations and sea level in Long Island Sound, Connecticut, since 500 cal yr A.D.; discussion and reply. *Quaternary Research,* 55, 105–111.

LEVITUS, S.; ANTONOV, J.I.; BOYER, T.P., and STEPHENS, C., 2000. Warming of the world ocean. *Science,* 287, 2225–2229.

LEVITUS, S.; ANTONOV, J.I.; WANG, J.; DELWORTH, T.L.; DIXON, K.W., and BROCCOLI, A.J., 2001. Anthropogenic warming of the Earth's climate system. *Science,* 292, 267–270.

MANN, M.E. and JONES, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters,* 30(15), 1820.

MCINTIRE, W.G. and MORGAN, J.P., 1964. *Recent Geomorphic History of Plum Island, Massachusetts and Adjacent Coasts.* Baton Rouge, Louisiana: Louisiana State University Press, 44p.

MILLER, L. and DOUGLAS, B.C., 2004. Mass and volume contributions to twentieth-century global sea level rise. *Nature,* 428, 406–409.

MILLER, W.R. and EGLER, F.E., 1950. Vegetation of the Wequetequock-Pawcatuck tidal marshes, Connecticut. *Ecological Monographs,* 20, 143–172.

MUDGE, B.F., 1862. The salt marsh formations of Lynn. Proceedings of the Essex Institute, 2, 117–119.

[NOAA/NOS/CO-OPS] NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION; NATIONAL OCEAN SERVICE, AND CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES, 2004. Verified Historical Water Level Data. http://www.opsd.nos.noaa.gov/data_res.html (accessed May 13, 2004).

NIERING, W.A.; WARREN, R.S., and WEYMOUTH, C.G., 1977. Our dynamic tidal marshes: vegetation changes as revealed by peat analysis. *Connecticut Arboretum Bulletin* 22, 12p.

NYBERG, J.; MALMGREN B.A.; KUIJPERS, A., and WINTER, A, 2002. A centennial-scale variability of tropical North Atlantic surface hydrography during the late Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 183, 25–41.

NYDICK, K.R.; BIDWELL, A.B.; THOMAS, E., and VAREKAMP, J.C., 1995. A sea-level rise curve from Guilford, Connecticut, USA. *Marine Geology,* 124, 137–159.

ORSON, R.A.; WARREN, R.S., and NIERING, W.A., 1998. Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. *Estuarine, Coastal Shelf Science,* 47, 419–429.

PELTIER, W.R., 1996. Global sea level rise and glacial isostatic adjustment: an analysis of data from the east coast of North America. *Geophysical Research Letters,* 23, 717–720.

REDFIELD, A.C., 1967. Postglacial change in sea level in the western North Atlantic Ocean. *Science,* 157, 687–692.

REDFIELD, A.C., 1972. Development of a New England salt marsh. *Ecological Monographs,* 42, 201–237.

REDFIELD, A.C. and RUBIN, M., 1962. The age of salt marsh peat and its relations to recent change in sea level at Barnstable, Massachusetts. *Proceedings of the National Academy of Sciences*, 48, 1728–1735.

STUIVER, M. and DADDARIO, J.J., 1963. Submergence of the New Jersey coast. *Science*, 142, 451.

STUIVER, M.; REIMER, P.J.; BARD, E.; BECK, J.W.; BURR, G.S.; HUGHEN, K.A.; KOMAR, B.; MCCORMAC, F.G.; PLICHT, J.V.D., and SPURK, M., 1998. INTCAL98 radiocarbon age calibration 24,000–0 cal BP. *Radiocarbon*, 40, 1041–1083.

VAN DE PLASSCHE, O., 1986. Introduction. *In*: VAN DE PLASSCHE, O., (ed.), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Norwich, Connecticut: Geo Books, pp. 1–26.

VAN DE PLASSCHE, O., 2000. North Atlantic climate-ocean variations and sea level in Long Island Sound, Connecticut, since 500 cal year AD *Quaternary Research*, 53, 89–97.

VAN DE PLASSCHE, O.; MOOK, W.G., and BLOOM, A.L., 1989. Submergence of coastal Connecticut 6000–3000 (^{14}C) years. *Marine Geology*, 86, 349–354.

VAN DE PLASSCHE, O.; VAN DER BORG, K., and DE JONG, A., 1998. Sea level-climate correlation during the past 1400 yr. *Geology*, 26, 319–322.

VAREKAMP, J.C. and THOMAS, E., 1998. Climate change and the rise and fall of sea level over the millenium. *Eos, Transactions, American Geophysical Union* 79, 69 and 74–75.