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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

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[1] We construct a high-resolution relative sea-level record for the past 700 years by dating basal salt-marsh peat samples above a glacial erratic in an eastern Connecticut salt marsh, to test whether or not the apparent recent acceleration in the rate of sea-level rise (SLR) is coeval with climate warming. The data reveal an average SLR rate of 1.0 ± 0.2 mm/year from about 1300 to 1850 A.D. Coupling of the regional tide-gauge data (1856 to present) with this marsh-based record indicates that the nearly three-fold increase in the regional rate of SLR to modern levels likely occurred in the later half of the 19th century. Thus the timing of the observed SLR rate increase is coincident with the onset of climate warming, indicating a possible link between historic SLR increases and recent temperature increases. *INDEX TERMS:* 4556 Oceanography: Physical: Sea level variations; 4546 Oceanography: Physical: Nearshore processes; 1620 Global Change: Climate dynamics (3309); 3020 Marine Geology and Geophysics: Littoral processes; 4235 Oceanography: General: Estuarine processes. **Citation:** Donnelly, J. P., P. Cleary, P. Newby, and R. Ettinger (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, *Geophys. Res. Lett.*, *31*, L05203, doi:10.1029/2003GL018933.

1. Introduction

[2] To more accurately project future sea-level rise (SLR) changes and mitigate socio-economic impacts we must better understand the causes of sea-level change and how these changes may be linked to climate variability. To achieve these goals we must distinguish between natural and human-induced climate and sea-level changes. Tide-gauge records of sea-level change in eastern North America reach back only to the later part of the 19th century [*NOAA/NOS/CO-OPS*, 2003] when the rate of sea-level change may already have been influenced by human activity. Therefore, in order to examine possible links between sea level and climate change, it is necessary to extend the tide-gauge record of sea-level change further into the past.

[3] Salt-marsh sediments are ideal for reconstructing past sea-level changes as they are intrinsically linked to the magnitude, frequency, and duration of tidal inundation and can keep pace with moderate rates of SLR [*Redfield*, 1972; *Orson et al.*, 1998]. Several attempts have been made recently to reconstruct sea-level curves from Connecticut marsh sediments [e.g., *Varekamp et al.*, 1992; *Nydick et al.*, 1995; *van de Plassche et al.*, 1998; *Varekamp and Thomas*, 1998; *van de Plassche*, 2000]. These studies used single- or multiple-core stratigraphic analyses including identification of foraminifera and vegetation assemblages with age control provided primarily by C-14 methods, which limit their ability to adequately constrain historic fluctuations in sea level. The results have been interpreted to indicate that the recent increase in the rate of SLR initiated in the 16th century A.D. and accelerated around 1800 A.D. [e.g., *Varekamp and Thomas*, 1998]. However, these studies have been criticized for not accounting for vertical displacement due to peat autocompaction [*Gehrels*, 1999; *Kelley et al.*, 2001]. Differential compaction of peat and/or local water-level changes may explain why many of the sea-level patterns inferred using these methods cannot consistently be reproduced [*van de Plassche et al.*, 1998; *Varekamp and Thomas*, 1998].

2. Methods and Results

[4] Here we reconstruct past sea-level changes at Barn Island, Connecticut (41°19′54″N, 71°51′50″W; see auxiliary Figure A)[1] using contiguous basal stratigraphic sections of peat excavated from marsh sediments overlying a gently-sloping glacial erratic (Figure 1). Peat retrieved from such a basal contact is unlikely to have been significantly vertically displaced by autocompaction [e.g., *Bloom*, 1964; *Gehrels*, 1999]. Like the single core approach, this method has the benefit of yielding samples from a continuous stratigraphic column for analysis versus point samples retrieved from a series of cores.

[5] All basal peat samples contained *Spartina patens* (*Sp*) or both *Juncus gerardi* (*Jg*) and *Sp* remains. We estimated the relationship of these samples to mean high water (MHW) based on the elevation distribution of modern flora ("indicative meaning" [see *van de Plassche*, 1986]). Water-level changes at Barn Island were measured every 12 minutes from March 19–May 28, 2002 with a digital water-level recorder. We computed a cross-correla-

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018933.

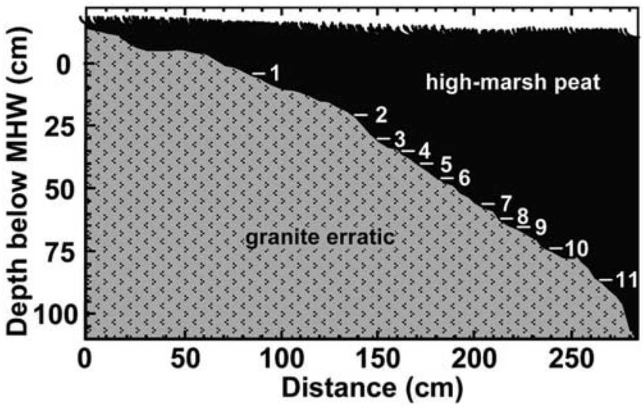

Figure 1. Cross-section of trench. Numbers indicate the location of C-14 dated samples (see Table 1 and Figure 2).

tion matrix between this water-level record and the New London tide-gauge record (20 km west of Barn Island) and compared average high- and low-water levels. No offset in tidal amplitude was evident between the two records (at 0.95 confidence), so we applied the MHW NOAA-defined datum from New London to the study site. All samples' elevations are presented here relative to MHW as defined by the NOAA tidal epoch (1983–2001). We determined modern elevation ranges of vegetation adjacent (within 50 cm) to exposed erratics by surveying 137 points with a Leica TC800 Total Survey Station. The resulting elevations and vertical uncertainties (at 2σ) of each vegetation type (*Jg*, *Jg/Sp*, and *Sp*) provide the basis for estimating the indicative meaning (or paleo-MHW) of the fossil samples (see auxiliary Figure B)[1]. Measurements of stands of *Jg* (n = 40) revealed a mean elevation of 4.6 ± 10.6 cm above MHW. Similarly, mixed *Jg* and *Sp* stands (n = 52) have a mean elevation of 6.7 ± 10.4 cm above MHW. Measurements in stands of *Sp* (n = 45) indicate a mean elevation of 4.0 ± 7.8 cm above MHW.

[6] Eleven samples from the marsh/erratic contact were C-14 dated by accelerator mass spectrometry (Figure 1; 1 cm^3 subsamples were carefully selected and screened to minimize contamination from root penetration and detrital remains). The C-14 results (calibrated to calendar years at 2σ) provide age estimates for fossil MHW indicators (Table 1; Figure 2). Due to the nonlinear C-14 calibration curve [*Stuiver et al.*, 1998] multiple calendar age ranges can arise from the calibration of one C-14 age (e.g., sample 9 yields 1306–1356, 1357–1365, and 1386–1440 A.D.). In some cases we can use the Principle of Superposition to determine which range most likely represents the age of the sample. For example sample 9 should be younger than sample 10 (since sample 9 was recovered 3.5 cm above sample 10), so we eliminate the two older ranges (1306–1356 and 1357–1365 A.D., gray on Figure 2); the youngest range from sample 9, 1386–1440 A.D., best represents the age of that sample.

[7] To further refine our C-14 chronology, we used fossil pollen evidence of European clearance/agriculture and industrial revolution-related heavy metal pollution horizons (Figure 3). Peat samples for pollen and metals analysis were also taken from just above the contact with the erratic. The initial rise in *Rumex spp*. pollen (a native weed) (−46.5 to −50.5 cm) coincides with land clearance for agriculture between 1650 and 1700 A.D. [*Clark and Patterson*, 1985; *Donnelly et al.*, 2001]. An uncertainty box has been plotted (light gray) based on the presence of *Jg* and *Sp* remains at this interval (indicative meaning of 6.7 ± 10.4 cm above MHW) and the time interval of initial land clearance (box with diagonal line fill; Figure 2). The combination of the indicative meaning of the sample (including 2σ uncertainty) with its accepted age range yields boxes representing the most likely elevation of MHW in the past (Figure 2). The appearance of *Plantago lanceolata* (an introduced species) between −32.5 and −35.5 cm (Figure 3) suggests deposition in the early 19th century [*Clark and Patterson*, 1985]. Based on the presence of *Jg* and *Sp* remains at this interval we plotted a box representing the indicative meaning of this interval (vertical line fill) and the associated uncertainty box (light gray) (Figure 2).

[8] Increases in the concentration of Pb and Cu at −23.5 to −27.5 cm (Figure 3) suggest that this interval was deposited during the onset of the industrial period (1850–1900 A.D.) [*Bricker-Urso et al.*, 1989; *Donnelly et al.*, 2001]. As *Jg* and *Sp* remains were also identified in these samples, we have plotted a box representing the indicative meaning of this interval (horizontal line fill) and the associated uncertainty box (light gray) (Figure 2).

[9] Given these independent stratigraphic dates we can better constrain the chronology derived from the calibrated C-14 ages. For instance, the C-14 age result from Sample 4 has three age ranges (1519–1593, 1622–1670, and 1780–1797 A.D.) when calibrated at 2σ. As this interval was

Table 1. Radiocarbon Ages and Indicative Meaning

No.	Lab No.	^{14}C Age	2σ calendar ages (A.D.)[a] Calibrated using Calib 4.3-method B [*Stuiver et al.*, 1998] (probability)	sample depth[b] *species*[c]*sampled* [indicative meaning (cm)] (2σ range)
1	OS-27763	>Mod.	-	−4.5 Sp/Jg [−11.2] (−0.8 to −21.6)
2	OS-27761	>Mod.	-	−20.5 Sp/Jg [−27.2]
3	OS-29650	>Mod.	-	−30.0 Sp/Jg [−36.7]
4	OS-26454	265 ± 30	*1519–1593 (0.359)* *1622–1670 (0.572)* 1780–1797 (0.069)	−35.0 Sp/Jg [−41.7] (−31.3 to −52.1)
5	OS-29654	15 ± 40	1700–1726 (0.176) *1813–1848 (0.175)* *1868–1918 (0.519)* *1949–1955 (0.129)*	−40.0 Sp/Jg [−46.7] (−36.3 to −57.1)
6	OS-27765	240 ± 35	*1523–1565 (0.097)* 1628–1681 (0.518) *1735–1806 (0.338)* *1932–1947 (0.047)*	−46.0 Sp/Jg [−52.7] (−42.3 to −63.1)
7	OS-26452	305 ± 40	1484–1656 (1.000)	−56.5 Sp/Jg [−63.2] (−52.8 to −73.6)
8	OS-29653	330 ± 35	1479–1643 (1.000)	−65.0 Sp [−69.0] (−61.2 to −76.8)
9	OS-27764	540 ± 40	*1306–1356 (0.337)* *1357–1365 (0.024)* 1386–1440 (0.640)	−74.0 Sp [−78.0] (−70.2 to −85.8)
10	OS-33644	475 ± 40	1400–1482 (1.000)	−77.5 Sp [−81.5] (−73.7 to −89.3)
11	OS-29652	570 ± 35	1303–1369 (0.596) *1382–1426 (0.404)*	−86.5 Sp [−90.5] (−82.7 to −98.3)

[a] calibrated age ranges in italics have been rejected based on stratigraphic arguments.
[b] mean sample depth in cm relative to local mean high water.
[c] Sp = *Spartina patens*, Jg = *Juncus gerardi*.

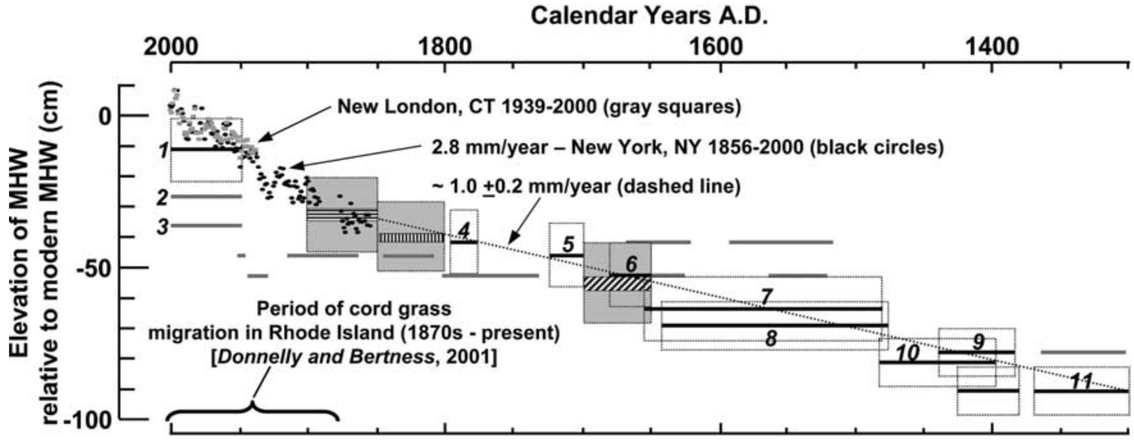

Figure 2. Mean high water reconstruction from Barn Island, CT. Numbers refer to C-14 sample numbers in Table 1. The corresponding calibrated calendar age ranges (at 2σ) for each C-14 date are shown as bars. Gray bars are age ranges excluded based on stratigraphic arguments. The boxes represent the uncertainty range of the sample given the accepted age range and the 2σ vertical range of the indicative meaning estimates. The indicative meaning of the interval where *Rumex* initially increases (1650 and 1700 A.D.; Figure 3) is plotted as a box with diagonal line fill. The box with vertical line fill represents the indicative meaning of the interval where *P. lanceolata* pollen appears in the stratigraphy (early 1800s A.D.; Figure 3). The indicative meaning of the interval where the concentration of Pb and Cu initially increase (1850–1900 A.D.; Figure 3) is plotted as a box with horizontal line fill. The light gray boxes indicate the 2σ uncertainty associated with the indicative meaning of the intervals that correspond to the increase in *Rumex, P. lanceolata,* and heavy metals. Annual mean MHW data from the NYC (black circles) and New London, CT tide gauges (small solid gray squares) are also plotted on the age/elevation plot. Dashed black line indicates a linear rate of SLR of 1.0 ± 0.2 mm/year that intersects all uncertainty boxes between 1300 and 1850 A.D. Bracket at bottom indicates the interval of cordgrass migration into the Rhode Island high marshes.

deposited after the increase in *Rumex* pollen (1650–1700 A.D.), and is just below the interval containing *P. lanceolata* pollen (~1800 A.D.), it dates to the later half of the 18th century. Therefore, the two older ranges can be eliminated, leaving the 1780–1797 A.D. range.

[10] Sample 5 has four possible calibrated C-14 ages (1700–1726, 1813–1848, 1868–1918, and 1949–1955 A.D.). The lack of Pb and Cu as well as *P. lanceolata* at this interval indicates deposition prior to the 19th century. Thus the three younger ranges (1813–1848, 1868–1918, and 1949–1955 A.D.) can be eliminated, leaving the 1700–1726 A.D. range.

[11] Calibration of the C-14 date obtained for Sample 6 also yields four ranges (1523–1565, 1628–1681, 1735–1806, and 1932–1947 A.D.). Since this sample comes from the interval just above the rise in *Rumex* pollen (1650–1700 A.D.), the oldest range (1523–1565 A.D.) and part of the second oldest range (1628–1650 of the 1628–1681 A.D. range) can be eliminated. Likewise, given that the interval occurs before the rise in Pb and Cu concentrations and *P. lanceolata* pollen; the youngest range (1932–1947 A.D.) can also be eliminated. This leaves the intervals 1650–1681 and 1735–1806 A.D. as possible age ranges. However, given that the accepted age range for Sample 5 (6 cm above Sample 6) is 1700–1726 A.D., the 1735–1806 A.D. range for Sample 6 is likely too young. Therefore the most appropriate age range of Sample 6 is 1650–1681 A.D.

[12] The three upper-most C-14 samples (samples 1, 2, and 3) yielded modern ages (>1950 A.D.). Annually averaged sea-level data (1856-present) from the New York City (NYC) tide gauge indicate that MHW was about 33 cm below modern MHW in the mid-19th century [*NOAA/NOS/CO-OPS*, 2003]. This matches the estimate derived from the marsh sediments that date to this interval (where Cu and Pb levels increase; Figure 2). Agreement between water-level measurements recorded at New London, CT and NYC since 1939 supports application of the NYC tide gauge to Barn Island. The uncertainty box for Sample 1 overlaps with the tide-gauge records (Figure 2). Given the instrumental record and the rise in heavy metals, samples 2 and 3 are too young and were likely contaminated by 'bomb' C-14.

3. Discussion and Conclusions

[13] This 700-year record from Barn Island provides a SLR estimate free of vertical displacement due to autocompaction of the peat column. A linear rate of rise of 1.0 ± 0.2 mm/year intersects all the 2σ uncertainty boxes of the record from the 14th to the mid-19th century (Figure 2). Linear regression of the NYC tide-gauge data reveals an average rate of SLR of 2.8 mm/year from 1856–2001 A.D. Coupling the Barn Island record and regional tide-gauge data indicates that the rate of SLR increased to modern levels in the 19th century (Figure 2). However, given that the center of each uncertainty box has the highest probability the most conservative interpretation of the data is that the SLR increase to modern values occurred in the late 19th century (Figure 2). The NYC tide-gauge data further support the late 19th century timing of the SLR increase. Linear regression of segments of the NYC tide-gauge data indicate an increase in the rate of SLR from about 1.0 mm/year between 1856 and 1878 to 2.4 mm/year between 1893 and 1921 A.D. [*Donnelly and Bertness*, 2001]. An increase in the rate of SLR at this time is also supported by the onset

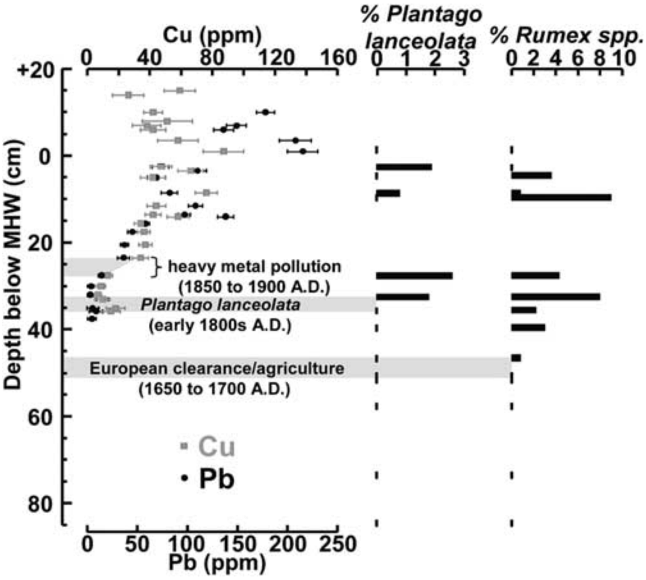

Figure 3. Heavy metal pollution and historic pollen stratigraphic ages (gray bars). Pollen grains within each sample were counted until a minimum of 100 regional pollen grains were identified, and the taxon percentages were calculated based on these regional (tree and shrub) pollen types. The interval where *Rumex* initially increases corresponds to the onset of European agriculture/clearance between 1650 and 1700 A.D. The first occurrence of *P. lanceolata* pollen dates to the introduction of this species to eastern North America in the early 19th century. We measured the concentration of Pb and Cu in selected samples by X-ray fluorescence spectrometry [*Klockenkamper*, 1997]. The interval where the concentration of Pb and Cu initially increase corresponds to the onset of the Industrial Revolution in the region between 1850 and 1900 A.D. The vegetation at each of these dated intervals consists of a mix of *J. gerardi* and *S. patens* and these stratigraphic ages are plotted on Figure 2 based on their indicative meaning.

of transgressive migration of low-marsh cordgrass (*Spartina alterniflora*) into the high marsh in the region [*Donnelly and Bertness*, 2001]. This evidence of an increase in the rate of SLR in the late 19th century differs from previous findings of "single core" studies from Connecticut marshes that argued for an initiation of higher SLR rates prior to the 19th century [e.g., *Nydick et al.*, 1995; *Varekamp and Thomas*, 1998].

[14] The likely increase in the rate of SLR in the late 19th century A.D. is roughly coincident in time with climate warming observed in both instrumental and proxy records [e.g., *Mann et al.*, 1998; *Pollack et al.*, 1998]. The results indicate that this recent increase in the rate of SLR may be associated with recent warming of the global climate system.

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