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Sea-level rise in New Jersey over the past 5000 years: Implications to anthropogenic changes

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ABSTRACT

We present a mid to late Holocene sea-level record derived from drilling the New Jersey coast that shows a relatively constant rise of 1.8 mm/yr from ~5000 to 500 calibrated calendar years before present (yrBP). This contrasts with previous New Jersey estimates that showed only 0.5 mm/yr rise since 2000 yrBP. Comparison with other Mid-Atlantic sea-level records (Delaware to southern New England) indicates surprising uniformity considering different proximities to the peripheral bulge of the Laurentide ice sheet, with a relative rise throughout the region of ~1.7–1.9 mm/yr since ~5000 yrBP. This regional sea-level rise includes both: 1) global sea-level (eustatic) rise; and 2) far-field geoidal subsidence (estimated as ~0.8–1.4 mm/yr today) due to removal of the Laurentide ice sheet and water loading. Correcting for geoidal subsidence, the U.S. east coast records suggest a global sea-level (eustatic) rise of ~0.4–1.0 mm/yr (with a best estimate of 0.7±0.3 mm/yr) since 5000 yrBP. Comparison with other records provides a best estimate of pre-anthropogenic global sea-level rise of <1.0 mm/yr from 5000 until ~200 yrBP. Tide gauge data indicate a 20th century rate of eustatic rise of 1.8 mm/yr, whereas both tide gauge and satellite data suggest an increase in the rate of rise to ~3.3 mm/yr from 1993–2006 AD. This indicates that the modern rise (~3.3 mm/yr) is significantly higher than the pre-anthropogenic rise (0.7±0.3 mm/yr).

1. Introduction

There are growing concerns about the rates and effects of sea-level rise along coastlines of the world, especially in view of anthropogenic global warming that will cause a more rapid rise due to steric (thermal expansion) effects and melting of ice sheets (e.g., Church et al., 2001). Tide gauge data from the 20th century indicate that sea level rose globally at a rate of 1.8±0.3 mm/yr (e.g., Cazenave and Nerem, 2004; White et al., 2005; Church and White, 2006). Relative sea levels, the combination of subsidence and eustatic change, have been significantly higher in many regions, threatening many low-lying coastlines. Extracting a eustatic estimate from relative sea-level change is challenging because there is no unequivocal geological reference frame for removing regional and local effects.

Post 1900 and post 1993 AD rates of eustatic change can be evaluated from tide gauge (e.g., White et al., 2005) and satellite data (e.g., Cazenave and Nerem, 2004; Rahmstorf et al., 2007), respectively. Tide gauge data for the U.S. Mid-Atlantic region (Fig. 1) shows a regional rate of approximately 3 mm/yr of sea-level rise in the 20th century (Psuty and Collins, 1996; this study) versus the 1.8 mm/yr global average (see also Peltier, 1996). Thus, ~1.2 mm/yr of rise in this region is due to coastal subsidence that is related to crustal rebound from the Laurentide ice-sheet removal and water-loading (Peltier, 1997). The rates are higher locally (~4 mm/yr) at Atlantic City and Sandy Hook, NJ due to sediment compaction (Fig. 1; Psuty and Collins, 1996); compaction at Atlantic City is caused by groundwater withdrawal, a similar mechanism that causes the high rates of subsidence observed in Venice, Italy (Gambolati et al., 1974; Rapaglia, 2005). Though tide gauge data constrain the 20th century sea-level changes (e.g., Fig. 1), anthropogenic warming due to CO_2 emissions potentially affected eustatic changes during this period (Church et al., 2001); to understand anthropogenic influences, the natural variability of sea-level change prior to 1900 AD must be assessed. Any anthropogenic influences (e.g., due to agriculture) prior to 1900 AD are assumed to be small relative to the post-industrial release of CO_2 (Broecker and Stocker, 2006).

Geological data are needed to place instrument (tide gauge and satellite) estimates into a longer term context. However, considerable debate and misunderstanding exist about mid–late Holocene (since 5000 yrBP) eustatic changes inferred from geological proxies. Many studies have assumed that global sea level has been essentially the

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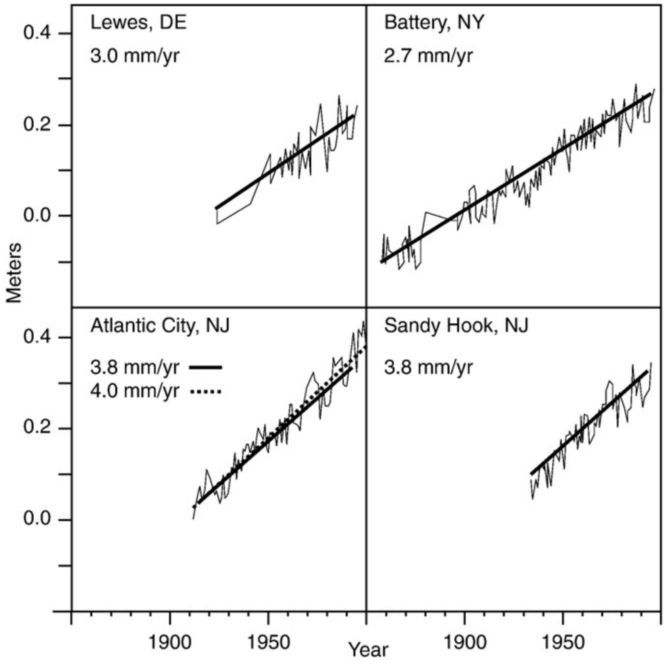

Fig. 1. Tide gauge data from Psuty and Collins (1996) along with more recent data provided by Psuty (personal communication) for Lewes, DE, Battery, NY, and Sandy Hook, NJ, and http://www.bodc.ac.uk/data/information_and_inventories/gloss_handbook/stations/220 for Atlantic City. We fit a linear regression to the Atlantic City data of 4.0 mm/yr from 1912 to 2000 (gray lines); Psuty and Collins (1996) regression of 3.8 mm/yr from 1912–1995 is shown for comparison.

same since 2000 yrBP (e.g., Munk, 2002; Church and White, 2006), whereas many others have argued for a global fall, not a rise in sea level since 5000 yrBP (e.g., Blum et al., 2001, Zong, 2004, Lessa and Masselink, 2006). Several studies have addressed Holocene sea-level rise on the New Jersey coastline (Stuvier and Daddario, 1963; Daddario, 1961; Meyerson, 1972; Psuty, 1986; Davis, 1987; Newman et al., 1987; Varekamp and Thomas, 1998) and the offshore region (Emery and Milliman, 1979), suggesting a rise of ~2 mm/yr from ~7000–2000 yrBP before present. Psuty (1986) interpreted a dramatic slow-down in the rate of rise in New Jersey to ~0.5 mm/yr from ~2500 yrBP to present (Fig. 3) (Psuty, 1986). Other regions (Asian margins, Australia, and the Gulf of Mexico) have recorded a mid-Holocene (~5000 yrBP) peak in relative sea level with sea level several m above present; whereas some of these regions showing this peak have strong tectonic overprint (e.g., Asian margins, Saito, 2005), others are from passive continental margins or other regions generally assumed to be tectonically stable (e.g., Gulf of Mexico; Blum et al., 2002; Thailand; Horton et al., 2005; Australia, Lessa and Masselink, 2006). Much of this apparent mid-Holocene highstand in the latter regions may be attributed to Glacial Isostatic Adjustment (GIA; Peltier, 1997) or regional flexural uplift (Simms et al., 2005). The Barbados sea-level curve of Fairbanks (1989) provides an excellent history of the last major eustatic lowstand (~20,000 yrBP) through the early Holocene rapid rise; it shows a lower rate after ~6000 yrBP (Fig. 3). However, the portion of the "Barbados curve" younger than 6400 yrBP is based on various western North Atlantic reef locations from different tectonic regimes (Lightly et al. (1982), not Barbados and thus may not have the fidelity of the Barbados record.

The surprising fact is that the rates of mid–late Holocene (past 5 kyr) global sea-level rise are poorly known and have been since Fairbridge (1961). Though the Laurentide ice sheets had largely retreated by 5 ka (Dyke, 2004), the effects of ice-sheet melting and warming on global sea level are not well constrained for this interval. There is considerable disagreement regarding the eustatic contribution to global sea-level rise in the last 7000 yr (Gehrels et al., 2006). Lambeck (1997) and Fleming et al. (1998) suggest a eustatic contribution of at least 3 m in the last 6000 ^{14}C yr. In contrast, Peltier (2002) suggests that there has not been any ice melt after 4000 yrBP. In addition, because the amount of sea-level rise during this interval is relatively small (~5 m), errors in subsidence and uplift history due to local and far field effects confound our understanding. For example, previous studies in the Gulf of Mexico have interpreted a highstand in the mid-Holocene that has been shown to be largely a result of regional loading and flexural uplift (Simms et al., 2005). We present new data obtained from several new sites cored on the New Jersey coastline, combined with data obtained from previous studies, that provide insight into pre-anthropogenic rates of sea-level rise and allows evaluation of the anthropogenic component versus natural influences on modern sea-level rise.

2. Methods

We provide mid–late Holocene (past 8000 yrBP) relative sea-level estimates from five coreholes on the New Jersey coast (Rainbow Island, Great Bay I, Great Bay II, Cape May, and Island Beach) (Fig. 2), plus one offshore vibracore (NJGS core 127). Conventional rotary coring with excellent recovery was conducted on the barrier island immediately behind dunes at Cape May and Island Beach (Miller et al., 1994); the other three holes were obtained with a Multi-twin G-30 Drill ("Sonic Metaprobe") mounted on a truck for drilling on the peninsula of Great Bay and a hovercraft for drilling offshore sedge islands at Rainbow Island. We analyzed lithofacies and benthic foraminiferal biofacies, interpreted paleoenvironments, and radiocarbon dated marsh and bay deposits (organic rich sediments comprising primarily peats).

Radiocarbon measurements were performed at the NOAMs Woods Hole facility and Geochron and are given here in radiocarbon years and calendar yrBP (Table 1 provides radiocarbon and calibrated ages; Figs. 2 and 3 show yrBP) with excellent error bars (average ± 57.2 yr for 1α variation for 15 measurements from Rainbow Island, Great Bay I, Great Bay II, Island Beach, Cape May, and core 127) that are generally within plotting error (2σ error bars shown in Fig. 3).

The calibrated calendar dates for the complete New Jersey sea-level database (i.e., including the published data) were calculated using CALIB 5.0.1 (Stuiver et al. 2005). We use a laboratory multiplier effect of 1 with 95% confidence limits and employ the dataset IntCal04 (which is confined to 0–26,000 yrBP). This dataset is recommended for most non-marine samples and is based on dendrochronologically dated tree-ring samples that cover the period from 0–12,400 yrBP. For the time interval 12,400–26,000 yrBP, data from marine records are converted to the atmospheric equivalent with a site-specific marine reservoir correction to provide terrestrial calibration. In instances where marine samples (such as shells and foraminifera) have been dated, the dataset Marine04 was employed. The marine calibration dataset incorporates a time-dependent global ocean-reservoir correction of about 400 yr but to accommodate local effects, the different Delta R in reservoir age of the local region of interest and the model ocean was determined (Stuiver and Reimer, 2004).

We have evaluated the fidelity of each data point in the New Jersey sea-level database using a method that was formalized during International Geological Correlation Program Projects 61 and 200 (e.g., van de Plassche, 1986; Shennan and Horton, 2002) (Table 1). In addition to calibration, we have defined the most reliable observations, with quantified uncertainty terms, as sea-level index points by two attributes: location and altitude (including quantification of errors in vertical range considering tidal range and depositional environment). The location attribute of a sea-level index point is simply the geographical coordinates of the site from which the sample was collected; we rejected samples where positions were not certain within 1 km.

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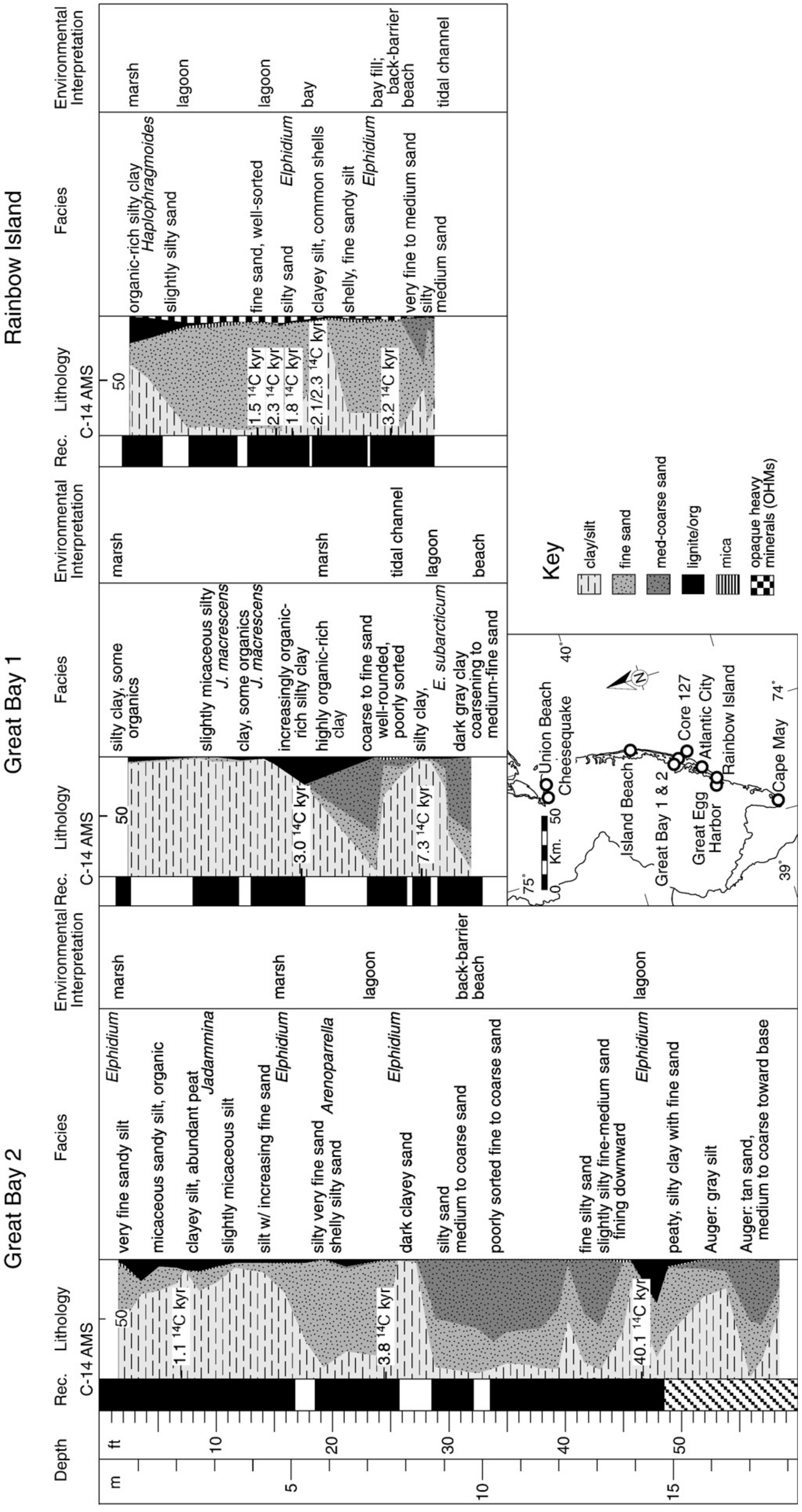

Fig. 2. New data from 3 New Jersey coreholes showing core recovery (black), lithology (key at right), radiocarbon ages, lithofacies, biofacies, and environmental interpretation. Inset: location map for all New Jersey localities and cores discussed here. Dates are calibrated radiocarbon years.

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Table 1

Samples/cores, latitude, longitude, carbon-14 lab code, carbon-14 age and errors (SD = standard deviation), elevation (MHW = Mean High Water, MHHW = Mean Higher High Water; MSL = Mean Sea level). The term Index Points is defined in text and all index points on Fig. 2 are circled. Unclassified/rejected samples were plotted but not circled. All data are derived here except for Meyerson (1972), Daddario (1961), and Pusty (Cheesequake, Union Beach, and Great Bay as noted). Cal = calibrated ages. RSL = relative sea level. HAT = highest astronomical tide

							Calibrated age ± 2SD													Calibrated 2SD		
Site	Latitude	Longitude	Lab code	^{14}C age	^{14}C error ± 1SD	Max.	Mean	Min.	Surface elevation (ft relative to MHW)	Surface elevation (m relative to MHHW)	Surface elevation (m relative to MSL)	Depth (ft)	Depth (m)	Elevation error (m)	RWL	RWL (m)	RWL error (m)	RSL (m)	RSL error (m)	Cal age	+Error	Notes
Index points																						
Great Bay 2	39 30′ 36.51″N.	74 19′ 11.35″W	NOSAM 34136	1200	35	1257	1133	1009	3.00	0.91	1.52	6.95	2.12	0.08	MHHW	1.40	0.20	−2.01	0.22	1133	124	RWL based on Jadammina macrescens
Great Bay 1	40 30′ 36.51″N.	75 19′ 11.35″W	NOSAMS 34134	2890	30	3156	3041	2926	3.00	0.91	1.52	18.95	5.78	0.08	MHHW	1.40	0.20	−5.66	0.22	3041	115	RWL based on Jadammina macrescens
Cap May	38 56′ 52″N	74 53′ 00″W	NOSAMS 8643	2740	30	2920	2823	2725	5.00	1.52	2.13	28.00	8.53	0.08	MHHW	1.66	0.20	−8.07	0.22	2823	98	RWL based on environmental interpretation
Island Beach	40 48′ 10″N	75 05′ 37″W	GX-19017	5625	200	6883	6415	5947	12.00	3.66	4.26	46.10	14.05	0.08	MHHW	1.40	0.20	−11.19	0.22	6415	468	RWL based on environmental interpretation
Great Bay Psuty				500	70	657	494	331	n/a	n/a	3.00	9.19	2.80	1.08	MHHW	1.40	0.20	−1.20	1.10	494	140	RWL based on environmental interpretation
Great Bay Psuty				3050	95	3448	3210	2972	n/a	n/a	3.00	24.60	7.50	1.08	MHHW	1.40	0.20	−5.90	1.10	3210	190	RWL based on environmental interpretation
Great Bay Psuty				4175	145	5264	4760	4256	n/a	n/a	3.00	27.70	8.44	1.08	MHHW	1.40	0.20	−6.84	1.10	4760	290	RWL based on environmental interpretation
Great Bay Psuty				4495	125	5565	5204	4843	n/a	n/a	3.00	27.10	8.26	1.08	MHHW	1.40	0.20	−6.66	1.10	5204	250	RWL based on environmental interpretation
Meyerson				1335	95	1411	1209	1006			3.00		3.00	1.08	MHHW	1.66	0.20	−1.66	1.10	1209	920	High marsh
Meyerson				2150	110	2352	2117	1882			3.00		7.00	1.08	MHHW	1.53	0.20	−5.53	1.10	2117	922	Low marsh
Core 127	39 24.9894N	74 15.3323 W		7690	50	8571	8486	8401	0.00	0.00	−1.00	51.90	15.82	0.08	MHHW	1.40	0.20	−18.22	0.22	8486	920	RWL based on environmental interpretation (basal peat)
Core 127	40 24.9894N	75 15.3323 W		7130	100	8170	7960	7749	0.00	0.00	−1.00	52.71	16.07	0.08	MHHW	1.40	0.20	−17.47	0.22	7960	921	RWL based on environmental interpretation (basal peat)
Freshwater limiting data																						
Great Bay 1	40 30′ 36.51″N.	75 19′ 11.35″W	NOSAMS 3415	7340	35	8287	8157	8027	3.00	0.91	1.52	28.45	8.67	0.08	MSL	0.68	2.06	−7.83	2.06	8157	130	RWL based on environmental interpretation
Island Beach	39 48′ 10″N	74 05′ 37″W	GX-19018-AMS	4532	58	5441	5209	4976	12.00	3.66	4.26	12.70	3.87	0.08	MSL	0.68	2.06	−0.29	2.06	5209	233	RWL based on environmental interpretation
Great Bay Psuty				6380	355	7932	7205	6477	n/a	n/a	3.00	29.63	9.03	1.08	MSL	0.68	2.06	−6.71	2.33	7205	710	RWL based on environmental interpretation
Cheesequake				6020	215	7413	6908	6403	n/a	n/a	1.00	28.38	8.65	1.08	MSL	0.79	2.29	−8.44	2.53	6908	430	Base of peat with Cedar ~fresh

Cheesequake				7325	195	8535	8145	7755	n/a	n/a	1.00	40.35	12.30	1.08	MSL	0.79	2.29	−12.08	2.53	8145	390	Peat below peat with Cedar ~freshwater
Cheesequake				6610	215	7929	7475	7020	n/a	n/a	1.00	37.50	11.43	1.08	MSL	0.79	2.29	−11.22	2.53	7475	430	Freshwater (cedar)
Cheesequake				6610	215	7929	7475	7020	n/a	n/a	1.00	37.50	11.43	1.08	MSL	0.79	2.29	−11.22	2.53	7475	430	Freshwater (cedar)
Meyerson				1760	120	1945	1675	1405	n/a	n/a	3.00		2.30	1.08	MSL	0.78	1.90	−0.08	2.19	1675	921	Freshwater
Meyerson				2840	110	3314	3033	2752	n/a	n/a	3.00		5.75	1.08	MSL	0.78	1.90	−3.53	2.19	3033	923	Freshwater
Meyerson				3030	130	3551	3206	2861	n/a	n/a	3.00		5.50	1.08	MSL	0.78	1.90	−3.28	2.19	3206	924	Freshwater
Meyerson				3145	120	3638	3322	3005	n/a	n/a	3.00		6.00	1.08	MSL	0.78	1.90	−3.78	2.19	3322	925	Freshwater
Union Beach				2695	145	3162	2763	2363	n/a	n/a	0.00	1.97	0.60	1.08	MSL	0.79	2.29	−1.39	2.53	2763	290	RWL based on environmental interpretation
Core 3	3 39′ 45.48″N	74 05′ 55″ W		8800	170	10242	9872	9502	n/a	n/a	0.00	12.50	3.81	1.08	MSL	0.68	2.06	−4.49	2.33	9872	920	RWL based on environmental interpretation
Marine limiting data																						
Great Bay 2	39 30′ 36.51″N.	74 19′ 11.35″W	NOSAM 34137	4260	40	4124	3842	3559	3.00	0.91	1.52	24.75	7.54	0.08	HAT	2.74	2.06	−8.77	2.06	3842	283	Marine limiting date based on *Elphidium* spp.
Rainbow Island I	39 18′ 17.04″N.	74 35′ 04.47″W	GX-30879-AMS	2580	30	2022	1775	1528	0.00	0.00	0.60	16.90	5.15	0.08	HAT	2.74	2.06	−7.29	2.06	1775	247	Marine limiting date based on *Elphidium* spp.
Rainbow Island I	39 18′ 17.04″N.	74 35′ 04.47″W	GX-30880-AMS	2880	30	2355	2114	1872	0.00	0.00	0.60	18.90	5.76	0.08	HAT	2.74	2.06	−7.90	2.06	2114	242	Marine limiting date based on *Elphidium* spp.
Rainbow Island I	39 18′ 17.04″N.	74 35′ 04.47″W	GX-30881-AMS	3770	40	3476	3207	2938	0.00	0.00	0.60	24.90	7.59	0.08	HAT	2.74	2.06	−9.73	2.06	3207	269	Marine limiting date based on *Elphidium* spp.
Rainbow Island II	39 18′ 13.16″N.	74 35′ 16.70″W	GX-31527	2330	70	1777	1520	1263	0.00	0.00	0.60	13.80	4.21	0.08	HAT	2.74	2.06	−6.34	2.06	1520	257	Marine limiting date based on *Elphidium* spp.
Rainbow Island II	39 18′ 13.16″N.	74 35′ 16.70″W	GX-31528-AMS	2980	40	2575	2279	1982	0.00	0.00	0.60	15.30	4.66	0.08	HAT	2.74	2.06	−6.80	2.06	2279	297	Marine limiting date based on *Elphidium* spp.
Rainbow Island II	39 18′ 13.16″N.	74 35′ 16.70″W	GX-31526	2960	70	2594	2263	1931	0.00	0.00	0.60	19.00	5.79	0.08	HAT	2.74	2.06	−7.93	2.06	2263	332	Marine limiting date based on *Elphidium* spp.
Cheesequake				4330	460	5989	4819	3649	n/a	n/a		37.07	11.30	1.08	HAT	3.07	2.29	−14.37	2.53	4819	920	Marine limiting date
Unclassified/reject																						
Daddario				1900	0	1824	1849	1874				5.25	1.60	0.08								Reject based on missing data
Daddario				2975	0	3080	3146	3212				12.14	3.70	0.08								Reject based on missing data
Daddario				3800	0	1450	2843	4235				11.15	3.40	0.08								Reject based on missing data
Daddario				4775	0	5477	5531	5584				30.51	9.30	0.08								Reject based on missing data
Daddario				5850	0	6641	6684	6727				39.21	11.95	0.08								Reject based on missing data
Great Bay Psuty				3035	120	3474	3177	2879	n/a	n/a	3.00	12.80	3.90	1.08	MHHW	1.40	0.20	−2.30	1.10	3177	240	Reject based on huge age reversal

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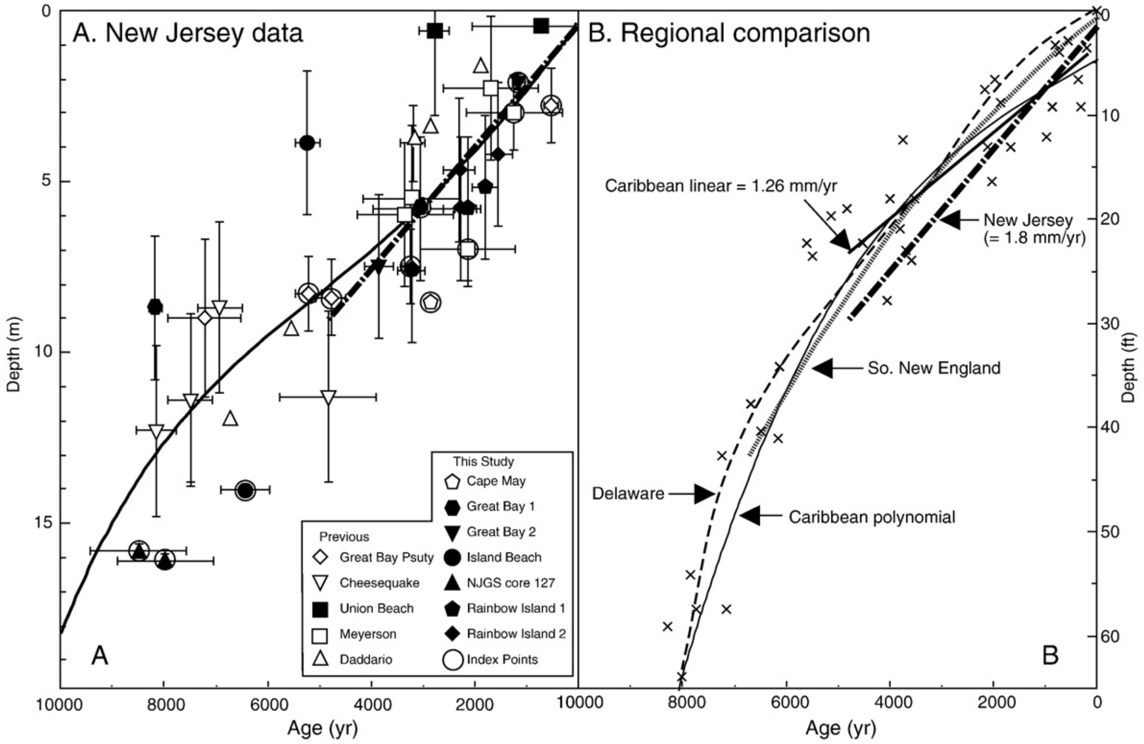

Fig. 3. Left panel A. Comparison of all ^{14}C dates for New Jersey localities (key on bottom right) with ages and error bars as specified in text. The linear regression of 1.8 mm/yr (thick dashed line) is fit to all of the data from 5000–0 yrBP. Black line is a polynomial fit to the data from 10000–0 yrBP. Note that the different regressions yield essentially the same record from 5000–0 yrBP. Data points with no apparent depth errors are from marsh deposits with 30 cm vertical errors. All data on Table 1 are plotted; index points are circled. Right panel B. Comparison of our sea-level data and regression (thick dashed line as in panel A) with the sea-level record of Fairbanks, 1989) (crosses) which is based on Lightly et al.'s (1982) western Atlantic reef data for ages less than ~6400 yrBP. Two regressions through the reef data are shown, the first is a third-order polynomial (thin solid line), the other is a linear regression for all Lighty et al., 1982) data younger than 5500 yrBP (thick solid line). The Delaware (thin dashed line) (Ramsey and Baxter, 1996) and Southern New England (dotted line) (Donnelly et al., 2005) sea-level records are shown for comparison.

None of the samples within the New Jersey database formed exactly at the mean of former sea level. Most come from environments within the upper part of the tidal range, but in total they cover the full tidal range and, for freshwater and marine limiting dates, beyond. In order to measure relative sea-level change, it is necessary to establish the relationship of the sample to a tidal level. The relationship of a sample to a tide level, and hence sea level, is called the "indicative meaning" (Preuss, 1979; van de Plassche, 1986; Shennan, 1986; Horton et al., 2000). It comprises two parameters, namely the reference water level (e.g., MHHW) and the indicative range (the vertical range over which the sample could occur). Facies analysis shows that 5 of our radiocarbon dates are on marsh deposits with a *Jadammina macrescens-Haplophragmoides* biofacies indicating deposition within ~40 cm of mean high water (Scott and Medioli, 1980; Horton and Culver, 2008). Ten dates are on back barrier lagoons based on facies successions and an *Elphidium* biofacies (Fig. 2); maximum modern depths in these lagoons/bay are ~3 m. To constrain the indicative meaning of other samples within our database, we used zonations of modern vegetation (e.g., Redfield, 1972; Niering and Warren, 1980; Gehrels, 1994; Orson et al., 1998; Morris et al., 2002).

We also included other factors that contribute to the height error of an index point (see Shennan, 1986; Woodroffe, 2006 for details). These include instrumental leveling of the site to a national datum and conversion to MSL. This is usually ±0.01 m for our detailed surveying, but may be as much as ±0.5 m for some of the published data where we had to estimate the elevation based upon their location. The precision for relating the leveling datum to local tide levels is typically ±0.1 m, but is as large as ±0.5 m for our offshore core. These errors exclude any influence of the change of tidal range through time. The total height error within our database is calculated from the expression:

$$E_h = \left(e_1^2 + e_2^2 \ldots + e_n^2\right)^{1/2}$$

where $e_1 \ldots, e_n$ are the individual sources of error.

The aim of the quality control is to include all radiocarbon dated samples (Fig. 3A). However, six of the data points are rejected from further analysis because of missing information (a fault which could possibly be reduced with further research), or because of uncertainty over the reliability of their relationship to a former sea level. In certain circumstances, samples from freshwater and marine environments provide important data that may be employed to test specific hypotheses because these environments must have formed inland/seaward of the paleo-coastline and above/below former sea level, respectively. After quality control twelve points qualify as index points (Fig. 3A), with precise vertical error estimates (c. ±0.2 m); 28 points place additional constraints on the position of sea-level, albeit with larger error estimates (typically ±1.1–2.5 m). Table 1 provides laboratory code, latitude, longitude, elevation for all of our data and a classification of index points.

3. Results

Results from Rainbow Island, Great Bay I, Great Bay II are shown here (Fig. 2); they are plotted along with corehole data from Island Beach (Miller et al., 1994), Cape May (Miller et al., 1996), and NJGS core 127 (Uptegrove, 2005; Fig. 3A). We compare our results with the previous New Jersey sea-level record of Psuty (1986) that includes

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Table 2

Pre-anthropogenic rates of eustatic sea-level rise (5000–200 yrBP)	Rate
1) Total rate of sea level rise from U.S. Mid Atlantic margin	1.8 mm/yr
GIA component	0.8–1.4 mm/yr
	0.4–1.0
Eustatic component based on NJ data	(0.7±0.3) mm/yr
2) Sea level rise based on data from Caribbean reefs	1.1 mm/yr
Subsidence rate of Caribbean reefs	0–0.25 mm/yr
Eustatic component based on Caribbean reef data	1.1–0.85
3) Eustatic component from Lambeck et al. (2002)	0.5 mm/yr
Conclusion: pre-anthropogenic rate of eustatic change	0.4–1.0 mm/yr
or	$\boxed{0.7\pm0.3}$ mm/yr
Modern rates of eustatic sea-level rise (~1900–2006)	
1) Eustatic estimate from ~1900–1993 AD (tide gauge data)	1.8 mm/yr
Preanthropogenic rate of eustaic change	0.8 mm/yr
Anthropogenic contribution to eustatic rise (~1900–1993 AD)	1 mm/yr
2) Eustatic estimate from 1993–2006 AD (satellite and tide gauge data)	3.2 mm/yr
Preanthropogenic rate of eustaic change	0.7 mm/yr
Anthropogenic contribution to eustatic rise (~1993–2006 AD)	2.5 mm/yr

dates from Union Beach, Great Bay and Cheesequake, NJ and data from other New Jersey coastline studies (Daddario, 1961; Meyerson, 1972) (Fig. 3A).

Comparison of sites throughout the New Jersey coast shows remarkably consistent results over the past 5000 yrBP. This is somewhat surprising because during glaciation and early stages of deglaciation, the northern New Jersey locations would have been within the influence of the peripheral bulge caused by loading of Laurentide ice, but by 5000 yrBP this effect is not noticeable, and only far field effects cause subsidence (see Discussion). Data older than ~5000 yrBP show more scatter, with 3 index points that are substantially deeper (5–7 m) than other points. We derived a relative sea-level record for data for the New Jersey dataset by: 1) fitting a 4th order polynomial to all the data that suggests a more rapid rise prior to 5000 yrBP and a slower rise since; and 2) a linear fit to the entire dataset from 500–5000 yrBP that shows a relative rise of 1.78 mm/yr (r^2 of 0.58; $n=38$), virtually identical to the higher-order fit in the interval of overlap. The two curves indicate a relatively constant rate of sea level rise for approximately the past 5000 yrBP and they lack the slowing down of rise at 2000 yrBP that was previously suggested (Fig. 3) (Psuty, 1986).

The fidelity of any sea-level estimate may be complicated by reworking of material and other processes such as storm transport. For example, recent work by Donnelly et al. (2005) has shown that certain areas along the New Jersey coastline have been impacted significantly by major storms (hurricanes and northeasters). The historic hurricane of 1821 AD likely deposited at least 50 cm of fine sand onto the Whale Beach Marsh site, south of Atlantic City. Given the localities used in the present study it is possible that this or other storms would have significantly impacted the study sites. The effect of "sediment dumps" by storms would be to overestimate sea-level change. Though processes such as storms and reworking may contribute to the scatter shown on Fig. 3, the consistent patterns seen in numerous cores in New Jersey (Fig. 3 panel A) and the consistency of the New Jersey records with other regional records (Fig. 3, panel B) testifies that we have captured the correct sea-level signal of ~1.8 mm/yr over the past 5000 yrBP.

4. Discussion: comparison with other geological records

Comparisons of the New Jersey data and two compilations of sea-level data from elsewhere in the U.S. Mid-Atlantic region suggest surprising uniformity in the rates of relative rise considering different proximities to the peripheral bulge of the Laurentide ice sheet. Ramsey and Baxter (1996) evaluated dates from nearby Delaware sites and provided a preferred relative sea-level curve that is indistinguishable from ours, with a mean rate of 1.7 mm/yr. A compilation of data from Southern New England (Donnelly et al., 2005) is also virtually indistinguishable from the New Jersey and Delaware records with a mean rate of 1.9 mm/yr. We conclude that from 5000 to ~500 yrBP relative sea level rose ~1.7–1.9 mm/yr for the region from Delaware to southern New England. This is about 1 mm/yr slower than regional rates of rise since 1900 AD (Fig. 1). Rates in Delaware and Southern New England were faster from 8000–5000 yrBP, though the rates in New Jersey are not well constrained for this interval.

Regional relative sea-level rise on the U.S. Mid-Atlantic margin includes both the global sea-level (eustatic) rise and GIA, which includes the effects of far-field geoidal subsidence due to removal of the Laurentide ice sheet and water loading (hydroeustasy). Peltier (1997) provided a global model of GIA and concluded that 0.8–1.4 mm/yr of subsidence is occurring in the U.S. Mid-Atlantic margin today. This suggests that about one half of the relative rise in sea-level observed on the U.S. Mid-Atlantic margin from 5000–500 yrBP was due subsidence and that ~0.4–1.0 mm/yr of the rise was due to eustasy (Table 2).

Comparison with the Fairbanks (1989) sea-level curve places additional constraints on the rate of eustatic rise over the past 6000 yr. The youngest dated coral from the Fairbanks (1989) Barbados compilation is 6400 yrBP. The portion of the sea-level curve younger than this is based on Lightly et al.'s (1982) western North Atlantic reef data (Fig. 3), including localities in Florida (7.1–9.4 kyr), Bahamas (3.5–4.6 kyr), Martinique (0.56–2.1 kyr), Panama (3.5–5.1 kyr), Puerto Rico (0.2–2.0 kyr), and St. Croix (0.3–9.1 kyr). Lightly et al. (1982) and Fairbanks (1989) fit polynomials to the data that showed a major decrease in the rate of relative rise from 12 mm/yr to ~1 mm/yr between 7000 and 5000 yrBP (Fig. 3B). We obtained linear regressions for their data of 1.1 mm/yr ($r^2=0.74$) since 5500 yrBP and 4.6 mm/yr for 6–9.4 yrBP ($r^2=0.74$; Fig. 3B). It is clear that both the Mid-Atlantic and Caribbean regions show a monotonic rise during the mid–late Holocene (Fig. 3B). Peltier (1997) estimated that the Caribbean reef localities experienced GIA effect of 0–0.25 mm/yr. This suggests that the western North Atlantic reef data provide a reasonable eustatic estimate for the Holocene, supported by our estimate of a eustatic rise of ~0.4–1.0 mm/yr from the U.S. Mid-Atlantic comparisons (Fig. 3B; Table 2).

Based on our comparisons (Fig. 3), we conclude that a eustatic rise of ~2–5 m has occurred from ~5000 yrBP (0.4–1.0 mm/yr; Fig. 3B) to our youngest dates (~500 yrBP in New Jersey; ~200 yrBP in the western Atlantic reef record). This range encompasses the global estimate of Lambeck (2002) who modeled a rise of ~3 m over the past 6 kyr (0.5 mm/yr). Lambeck (personal communication, 2005) attributes a greater GIA adjustment to the western Atlantic reef locations than Peltier (1997), in part explaining the higher rates in that region. Based on our assessment of errors, we conclude that the best estimate of eustatic rise over the period 5000 to ~200 yrBP was ~0.7± 0.3 mm/yr.

Our comparisons are consistent with a monotonic rise in sea level from 5000 yrBP to our youngest dates (~500 yrBP in New Jersey; ~200 yrBP in the western Atlantic reef record). However, higher order (up to millennial scale) variations cannot be precluded considering scatter in the data and the time between dated points in individual cores (typically 1000 yr or greater). In fact, detailed studies in Guilford, CT have documented several increases and decreases over the past 1500 yrBP superimposed on a general rise of 1.6 mm/yr (Varekamp and Thomas, 1998).

We suggest that the mid-Holocene sea-level high noted in previous studies (e.g., Blum et al., 2002; Saito, 2005; Horton et al., 2005; Lessa and Masselink, 2006) is an artifact of GIA or local uplift. For example,

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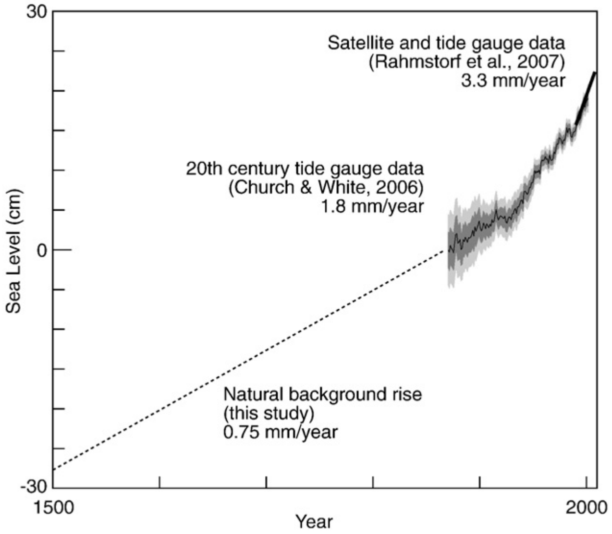

Fig. 4. Comparison of the pre-anthropogenic rise (this study) with tide gauge data (Church and White, 2006) and satellite data (Rahmstorf et al., 2007).

Simms et al. (2005) attributed the mid-Holocene highstand in the Gulf of Mexico to peripheral uplift associated with the sediment loading of the Mississippi delta. Today, much of the southern hemisphere is experiencing GIA uplift due to changes in the geoid resulting from deformation of the mantle by removal of the Laurentide ice sheet (Peltier, 1997; Lambeck, 2002). These GIA adjustments explain the relatively high sea level observed in the mid-Holocene in many regions.

5. Implications to instrument scale sea-level changes

Our constraints on the recent geologic history allow us to estimate the natural versus anthropogenic contributions to modern sea-level rise (Table 2). We show that the mean natural sea-level rise was 0.7± 0.3 mm/yr over the past 5000 yrBP (Table 2). Tide gauge data indicate a rise of ~1.8 mm/yr globally since 1900 AD (e.g., White et al., 2005), which suggests that less than one half of the 20th century rise was due to natural causes. The cause of the natural rise of 0.7±0.3 mm/yr during the mid–late Holocene is still debatable and could be attributed to natural global warming (steric effects) and/or continued melting of ice sheets. Given that most climate records suggest a mid-Holocene (~5000 yrBP) peak warmth (e.g., Kerwin et al., 1999), it seems likely that the continued rise must be attributable not to temperature, but to residual melting of ice sheets. Lambeck (2002) suggested that west Antarctic ice sheet melting was the major contributor to mid–late Holocene rise.

Comparison of geological and instrument (tide gauge and satellite) records admittedly combines two different measurement schemes with significantly different errors. Yet, as noted by Lambeck (2002), the dramatic rise in sea level observed in instrument records since ~1850 AD must be a very recent development or else it would be visible in older geological and archeological records. Though the geological estimates have large error bars relative to instrument records, it is clear that the pre-1750 AD rates of global rise were very slow, whether they are 0.4 mm/yr or 1.0 mm/yr (i.e., the range in estimates, Table 1). It is also clear that the rates of rise were much higher from 1850–1993 AD and have increased further since 1993 AD (Rahmstorf et al., 2007).

Instrument (tide gauge and satellite) records indicate a rise of ~3.3 mm/yr today (Rahmstorf et al., 2007), and thus requires ~2.5 mm/yr of change due to anthropogenic influences (Table 2). The cause of the anthropogenic rise has been debated. Munk (2002) noted that only ~0.3 mm/yr of rise could be explained by 20th century warming, and most glaciologist have previously argued for little or no net melting of continental ice sheets (Church et al., 2001), though mountain glaciers have been in retreat (Folland et al., 2001). However, new observations suggest significantly more melting of ice sheets in Greenland (Rignot and Kanagaratnam, 2006) and Antarctica (Velicogna and Wahr, 2006) than previously estimated, potentially explaining the higher rate (see also Kaser et al., 2006). Greenland ice sheet melting can potentially contributed up to 0.57 mm/yr (Stearns and Hamilton, 2007), and melting of mountain glaciers contributed ~0.6 mm/yr (Cazenave and Nerem, 2004). In addition, heat gain to the ocean was larger than previously believed, sufficient to explain ~1.6 mm/yr of rise (Willis, Roemmich, Cornuelle, 2004). In total, it appears that much (2.8 mm/yr) of the modern rise of 3.3 mm/yr can be explained by observed warming and melting (see Cazenave, 2006; Table 2).

The rate of sea level rise appears to be increasing (Fig. 4) from a pre-anthropogenic rate of 0.7±0.3 mm/yr and a 20th century rate of 1.8 mm/yr. Satellite observations indicate that the global rate was ~2.8±0.4 mm/yr from 1993–2003 (Cazenave and Nerem, 2004), whereas a reanalysis of global tide gauge data (Church and White, 2006) also show a similar increase in the global rate after 1993 AD (Fig. 4). A recent study by Rahmstorf et al., 2007) has suggested that the rate from 1993–2006 AD was 3.3 mm/yr, tracking the high end of the Intergovernmental Panel on Climate Change's estimate for sea level rise of 80 cm by 2100 AD. The geological record documents that the rate of rise observed in the 20th century (and apparently accelerating today), is anomalous and far exceeds the natural, pre-anthropogenic rate of rise of 0.7±0.3 mm/yr (Fig. 4).

6. Conclusions

Sea-level estimates from the U.S. Mid-Atlantic region show a uniform relative rise of 1.7–1.9 mm/yr over the past 5000 yrBP. Subtracting subsidence effects indicates that global sea level rose ~0.7±0.3 mm/yr from 5000 yrBP. Comparison with other records, suggests that the best estimate of the natural, background rate of eustatic rise was 0.7± 0.3 mm/yr since 5000 yrBP. Tide gauge data indicate a ~1.8 mm/yr eustatic rise in the 20th century, whereas satellite data and tide gauge data show that the rate has increased to ~3.3 mm/yr from 1993 to 1997. This suggests that anthropogenic influences are responsible for a eustatic rise of ~2.5 mm/yr over background.

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