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

Kenneth G. Miller a,⁎, Peter J. Sugarman b, James V. Browning a, Benjamin P. Horton c, Alissa Stanley a, Alicia Kahn a, Jane Uptegrove b, Michael Aucott d

⁎ Corresponding author.

a Department of Earth and Planetary Sciences, 610 Taylor Road, Rutgers University, Piscataway, NJ 08854, United States
b New Jersey Geological Survey, Trenton, NJ 08625, United States
c Department of Earth and Environmental Science, University of Pennsylvania, 240 South 33rd Street, Philadelphia, PA 19104-6316, United States
d Dept. Environmental Protection, PO Box 409, Trenton, NJ 08625, United States

A R T I C L E  I N F O

Article history:
Received 8 June 2007
Accepted 14 March 2008
Available online 28 November 2008

Keywords:
Holocene
eustasy
relative sea-level
New Jersey
climate change

A B S T R A C T

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).

© 2008 Elsevier B.V. All rights reserved.

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 CO2 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 CO2 (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
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 (Stuiver 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 rate 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 14C 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 seagrass beds 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 NOAA Woods Hole facility and Gekochron 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 1σ 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.
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.
Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Lab code</th>
<th>%C age</th>
<th>%C error</th>
<th>Max.</th>
<th>MSL</th>
<th>MHHW</th>
<th>MHHW</th>
<th>Depth</th>
<th>Depth</th>
<th>Elevation</th>
<th>RWL</th>
<th>RWL</th>
<th>RWL</th>
<th>RWL</th>
<th>Elevation error</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayley points</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Great Bay 2</td>
<td>39° 30' 36.51'' N</td>
<td>74° 19' 11.35'' W</td>
<td>NOSAM 34136</td>
<td>1200</td>
<td>35</td>
<td>1237</td>
<td>1131</td>
<td>1009</td>
<td>3.00</td>
<td>0.91</td>
<td>1.52</td>
<td>6.95</td>
<td>2.12</td>
<td>0.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
</tr>
<tr>
<td>Great Bay 1</td>
<td>39° 30' 36.51'' N</td>
<td>75° 19' 11.35'' W</td>
<td>NOSAM 34134</td>
<td>2800</td>
<td>30</td>
<td>3115</td>
<td>1041</td>
<td>2926</td>
<td>3.00</td>
<td>0.91</td>
<td>1.52</td>
<td>18.95</td>
<td>5.78</td>
<td>0.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
</tr>
<tr>
<td>Barnegat Bay</td>
<td>38° 30' 52.72'' N</td>
<td>74° 53' 00'' W</td>
<td>NOSAM 34643</td>
<td>2740</td>
<td>30</td>
<td>2920</td>
<td>2823</td>
<td>2725</td>
<td>5.00</td>
<td>0.91</td>
<td>1.52</td>
<td>2.13</td>
<td>28.00</td>
<td>8.53</td>
<td>0.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
</tr>
<tr>
<td>Island Beach</td>
<td>40° 48' 10'' N</td>
<td>75° 05' 37'' W</td>
<td>CX-19057</td>
<td>5625</td>
<td>200</td>
<td>6881</td>
<td>6415</td>
<td>5947</td>
<td>12.00</td>
<td>0.91</td>
<td>1.52</td>
<td>4.60</td>
<td>16.05</td>
<td>0.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
</tr>
<tr>
<td>Great Bay Peaty</td>
<td>50° 70' 657</td>
<td>394</td>
<td>331</td>
<td>n/a</td>
<td>n/a</td>
<td>3.00</td>
<td>9.19</td>
<td>2.80</td>
<td>1.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>94</td>
<td>140</td>
<td>RWL based on environmental interpretation</td>
<td></td>
</tr>
<tr>
<td>Great Bay Peaty</td>
<td>3950</td>
<td>95</td>
<td>3448</td>
<td>3210</td>
<td>2972</td>
<td>n/a</td>
<td>n/a</td>
<td>3.00</td>
<td>24.60</td>
<td>7.50</td>
<td>1.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>3210</td>
<td>190</td>
</tr>
<tr>
<td>Great Bay Peaty</td>
<td>4075</td>
<td>145</td>
<td>5264</td>
<td>4500</td>
<td>4256</td>
<td>n/a</td>
<td>n/a</td>
<td>3.00</td>
<td>27.70</td>
<td>8.44</td>
<td>1.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>4500</td>
<td>200</td>
</tr>
<tr>
<td>Great Bay Peaty</td>
<td>4495</td>
<td>125</td>
<td>5565</td>
<td>5204</td>
<td>4843</td>
<td>n/a</td>
<td>n/a</td>
<td>3.00</td>
<td>27.00</td>
<td>8.26</td>
<td>1.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>5204</td>
<td>250</td>
</tr>
<tr>
<td>Meyerson</td>
<td>1135</td>
<td>141</td>
<td>1200</td>
<td>1006</td>
<td>965</td>
<td>n/a</td>
<td>n/a</td>
<td>3.00</td>
<td>3.00</td>
<td>1.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>1006</td>
<td>950</td>
<td>RWL based on environmental interpretation</td>
</tr>
<tr>
<td>Meyerson Corey</td>
<td>7600</td>
<td>50</td>
<td>8781</td>
<td>8486</td>
<td>8401</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>51.00</td>
<td>15.82</td>
<td>0.08</td>
<td>MHHW</td>
<td>1.40</td>
<td>0.20</td>
<td>0.09</td>
<td>0.22</td>
<td>8486</td>
<td>920</td>
</tr>
<tr>
<td>Cheesequake</td>
<td>6920</td>
<td>215</td>
<td>7413</td>
<td>6908</td>
<td>6403</td>
<td>n/a</td>
<td>n/a</td>
<td>1.00</td>
<td>28.38</td>
<td>8.65</td>
<td>1.08</td>
<td>MSL</td>
<td>0.79</td>
<td>2.29</td>
<td>0.09</td>
<td>0.22</td>
<td>6908</td>
<td>408</td>
</tr>
<tr>
<td>Cheesequake</td>
<td>7325</td>
<td>195</td>
<td>8535</td>
<td>8145</td>
<td>7755</td>
<td>n/a</td>
<td>n/a</td>
<td>1.00</td>
<td>40.35</td>
<td>12.10</td>
<td>1.08</td>
<td>MSL</td>
<td>0.79</td>
<td>2.29</td>
<td>0.09</td>
<td>0.22</td>
<td>8145</td>
<td>390</td>
</tr>
<tr>
<td>Freshwater limiting data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>Latitude</td>
<td>Longitude</td>
<td>Lab code</td>
<td>14C age</td>
<td>14C error ±1 SD</td>
<td>Max.</td>
<td>Min.</td>
<td>Surface elevation (ft relative to MHW)</td>
<td>Surface elevation (m relative to MSL)</td>
<td>Depth (ft)</td>
<td>Depth (m)</td>
<td>Elevation error (m)</td>
<td>RWL (m)</td>
<td>RWL error (m)</td>
<td>RWL (m)</td>
<td>RWL error (m)</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>----------</td>
<td>-----------</td>
<td>----------</td>
<td>---------</td>
<td>-----------------</td>
<td>------</td>
<td>------</td>
<td>---------------------------------------</td>
<td>---------------------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>---------------------</td>
<td>---------</td>
<td>-----------------</td>
<td>---------</td>
<td>-----------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Cheesequake</td>
<td>37.50</td>
<td>11.43</td>
<td>0.88</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Cheesequake</td>
<td>37.50</td>
<td>11.43</td>
<td>0.88</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>37.50</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Meyerson</td>
<td>30.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Meyerson</td>
<td>30.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Meyerson</td>
<td>30.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Meyerson</td>
<td>30.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>30.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Union Beach</td>
<td>20.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>20.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>20.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>20.15</td>
<td>1.00</td>
<td>20.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Core 3</td>
<td>3.08</td>
<td>45.48</td>
<td>74.05</td>
<td>55.00</td>
<td>0.88</td>
<td>0.88</td>
<td>1.00</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Marine limiting date</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Great Bay 2</td>
<td>31.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island I</td>
<td>31.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island II</td>
<td>31.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island II</td>
<td>31.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>31.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Cheesequake</td>
<td>41.15</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>41.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>41.15</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>41.15</td>
<td>1.00</td>
<td>41.15</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island I</td>
<td>13.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island II</td>
<td>13.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Rainbow Island II</td>
<td>13.16</td>
<td>10.70</td>
<td>1.40</td>
<td>0.88</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>13.16</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
<tr>
<td>Cheesequake</td>
<td>37.07</td>
<td>11.30</td>
<td>0.88</td>
<td>1.00</td>
<td>37.07</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.07</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>37.07</td>
<td>1.00</td>
<td>37.07</td>
<td>1.00</td>
<td>Freshwater</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Freshwater based on environmental interpretation; Freshwater based on environmental interpretation.
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; Sherman, 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:

\[ e_h = (e_1^2 + e_2^2 + \ldots + e_n^2)^{1/2} \]

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...
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 yr BP 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 yr BP, 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 (hydroseustasy). 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 yr BP 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 yr BP. The portion of the sea-level curve younger than this is based on Lighty 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 yr BP (Fig. 3B). We obtained linear regressions for their data of 1.1 mm/yr ($r^2 = 0.74$) since 5500 yr BP and 4.6 mm/yr for 6–9.4 yr BP ($r^2 = 0.74$; 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. We conclude that from 5000 to ~500 yr BP was ~0.4–0.7 mm/yr (Table 2).

Based on our comparisons (Fig. 3), we conclude that a eustatic rise of ~2–5 m has occurred from ~5000 yr BP (0.4–1.0 mm/yr; Fig. 3B) to our youngest dates (~500 yr BP in New Jersey; ~200 yr BP 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 yr BP was ~0.7 ± 0.3 mm/yr.

Our comparisons are consistent with a monotonic rise in sea level from 5000 yr BP to our youngest dates (~500 yr BP in New Jersey; ~200 yr BP 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 5000 yr BP 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,
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 rate 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.

Acknowledgements

N. Psuty pioneered study of the effects of sea-level change in New Jersey and encouraged us in this study. We thank the USGS ERMT drillers for obtaining cores from Great Bay and Rainbow Island, G.M. Ashley and R.E. Sheridan for comments, and J. Milliman, four anonymous reviewers. Supported by NSF EAR99-09179 and EAR03-017112 (Miller), a NJ DEP Mini-grant, and the New Jersey Geological Survey.

References


