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Climate Change and the Rise and Fall of Sea Level Over The Millennium

Johan C. Varekamp and Ellen Thomas

Average rates of relative sea level rise (RSLR) along the coast of the eastern United States were 1–2 mm/yr over the last 2,000 years. Higher rates have occurred in recent centuries, and their onset seems to have preceded the period of modern global warming. A modest rate increase started in the 17th century, well before the modern global warming of this century, but the highest rates have occurred during the last 200 years, with a major acceleration around 1800 A.D. No significant acceleration is apparently associated with the rapidly rising temperatures of the last 100 years.

How does one establish possible relationships between rates of sea level rise and climate fluctuations? Tide-gauge records are too short and noisy to derive a quantitative, empirical relationship between relative sea level rise rates and climate change [*Douglas,* 1992], and predictions of future rates of sea level rise are largely based on theory. The recent geological record can provide empirical insights, which can be applied toward the assessment of current rates and those predicted for the next century.

Salt Marsh Sequences

Average rates of RSLR over the last 5–10 millennia have been deduced from age-depth graphs generated from dated salt marsh peat sequences and estuarine deposits in many areas [*Gehrels et al.,* 1996]. Detailed RSLR curves covering the last 1,000 years can only be obtained through an approach with high spatial and temporal resolution. Salt marshes grow in the intertidal region and can be divided into facies subzones (low marsh, high marsh, highest high marsh, etc.) between mean sea level and the highest high tide level, which are characterized by floral and microfaunal assemblages, lithology, and sediment chemistry. Generally, marsh accretion keeps up with RSLR so that coastal marsh systems are in dynamic equilibrium with RSLR; temporary submergence of marshes occurs during periods with a high rate of RSLR but is counteracted by increased marsh accretion rates in the resulting low marsh. The marsh accretion will outpace RSLR during periods of slow rise, and a high marsh will be established where lower rates of accretion prevail.

Marsh submergences and emergences can be recognized from paleoenvironmental analyses of peat sequences and can be interpreted as indicators for fluctuations in the rate of RSLR. Marsh subenvironments can be reconstructed in core samples with microfaunal assemblages (agglutinated foraminifera) [*Scott and Medioli,* 1980] in conjunction with other sediment parameters. Individual marsh cores can be sliced in 2- to 5-cm samples, providing continuous records with all parameters determined on the same samples. The paleoenvironmental reconstructions are then summarized in marsh-paleoenvironmental (MPE) curves [*Thomas and Varekamp,* 1991], which show the vertical distance of the paleomarsh surface to a paleo sea level plane for each sample interval.

RSLR curves can be derived from MPE curves after establishing age-depth relations through a set of ^{14}C and ^{210}Pb dated points with the assumption of a continuous sedimentary record. Self-compaction is not a major concern in the upper few meters of marsh sediment. Radiocarbon ages of carefully picked remains of a single plant species can be calibrated into calendar years, which may increase the error from ± 50 years to about ± 80 years. It is thus implicit in the ^{14}C dating method that the absolute time frame cannot be established better than within about 100–150 years, and for the period younger than 300 BP, ^{14}C ages are ambiguous. The ^{210}Pb ages are more precise (±10–15 years) but do not extend into the time span older than 125 BP.

The principle of this method of RSLR curve construction (referred to here as the "single cores" approach) is shown in Figure 1, together with a hypothetical scenario of rising sea level with concurrent marsh accretion; a plot of the small offsets (1–6) versus depth would constitute a partial MPE curve of which a real example (Guilford Marsh, Conn.) is given in Figure 2. Uncertainties relate to the resolution of the age model and possible variations in tidal range, which will be read as variations in sea level. Data on metal pollution and pollen contents in marsh sediments may define isochronous horizons for the industrial revolution (about 1860 A.D. in New England) [*Nydick et al.,* 1995], and the land clearing related to early colonization (e.g., ragweed pollen peak, around 1650 A.D.), which can improve the age models.

A different approach in construction of RSLR curves is to determine age index points with "indicative meaning for sea level" from many different cores throughout a marsh [e.g., *van de Plassche,* 1991]. Such studies relate a regional stratigraphy to a regime of rising sea level and may provide a broader insight into the impact of changes in RSLR on sedimentary processes. Different marsh sections have different self-compaction trends, however, because the marsh top section is "taken along for the ride" with the compacting deeper sediments. Basal peat samples do not suffer from such compaction problems, but many of these are fresh water peats for which the position of paleo sea level is poorly constrained. The modern marsh topography must be accurately surveyed to refer the samples from different cores to a fixed datum level. These factors introduce uncertainties [*Gehrels et al.,* 1996]; more ^{14}C dates do not necessarily improve the precision of the RSLR record because the error boxes will overlap. The two approaches provide different types of sea level rise information; relatively short-term (several centuries) fluctuations in the rate of RSLR are possibly

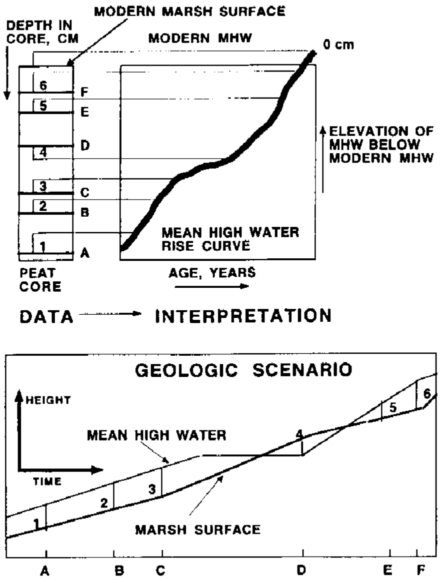

Fig. 1. Paleoenvironmental data from a peat core provide estimates of the vertical distance from the paleomarsh surface to paleo mean high water (MHW) level, indicated for core levels A–F with numbers 1–6. The elevation of MHW over time is transferred to a graph where the depth scale is replaced by age, resulting in an MHW rise curve. The geologic scenario provides hypothetical space-time trajectories for MHW and the paleomarsh surface, with the vertical distances 1–6 at times that A–F indicated. A continuous, high-resolution paleoenvironmental record is established by slicing cores in 2- to 5-cm samples.

For more information, contact Johan C. Varekamp (jvarekamp@wesleyan.edu) or Ellen Thomas (ethomas@wesleyan.edu), Department of Earth and Environmental Sciences, Wesleyan University, Middletown CT 06459-0139 USA.

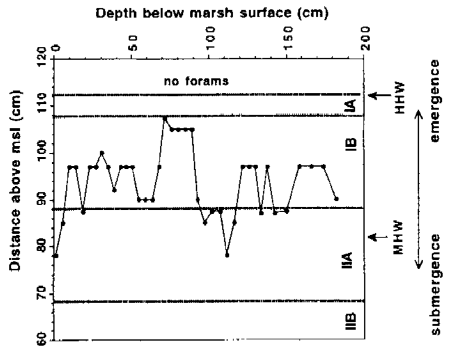

*Fig. 2. Marsh paleoenvironmental curves are derived from data on agglutinated benthic foraminifera [*Thomas and Varekamp, *1991]. The curve gives the position of the paleomarsh surface for each core slice with respect to mean sea level (MSL) at the time of deposition. Stippled lines indicate the faunal subzonal boundaries IA, IB, IIA and IIB; levels of mean high water (MHW) and highest high water (HHW) are also indicated. Excursions to the right indicate that marsh accretion outpaced the rate of RSLR; excursions to the left indicate relative marsh submergences. Data from Guilford Marsh, Conn. [*Nydick et al., *1995].*

best resolved with the single cores method. It is of course paramount for the latter method to establish continuous single core records from representative locations in a marsh, which can be selected only after extensive marsh-wide microstratigraphic studies.

Delaware Bay and Long Island Sound

Salt marsh sequences along Delaware Bay at Dennis Creek Marsh in New Jersey and along Long Island Sound in Connecticut accreted under different regimes of RSLR due to different rates of regional crustal rebound: forebulge collapse in the Delaware Bay region versus minor subsidence in Long Island Sound [*Peltier,* 1996]. RSLR curves, determined with the single cores approach, from the two regions can be used as averaged extensions of local tide gauge records. They show fluctuations at a variety of timescales, but the period from 1300 to 1650 A.D. is characterized by a relatively low rate of RSLR (0.3–1.6 mm/yr.; Figure 3). The curve segment since 1650 A.D. shows strong fluctuations at an overall steeper slope, with rates of 2.6–6.9 mm/yr. The recent rate of RSLR in Long Island Sound (2.6 mm/yr.; Fig. 3b), is in good agreement with the New London, Conn., tide gauge record.

The estimated rates of RSLR at each coring site depend on the rate of local crustal movements, which are usually related to glacial rebound processes [e.g., *Peltier,* 1996], on the compaction rate of the local marsh sequence, on the rate of true local sea level rise, and on local or regional changes in tidal range. All marsh-derived RSLR curves thus carry a strong local signature. To assess potential correlations between periods with anomalous rates of RSLR in different marshes and geographic areas, the data can be expressed as fractions from their local long-term average RSLR rates. The obtained deviations from the local average rates, expressed here as nondimensional rate ratios, provide evidence for periods in which the rates of RSLR were anomalous with respect to the local average rate. Such a procedure largely removes the local character of the curves and makes it possible to detect coherence in RSLR records from widely different areas.

The most striking feature of the rate ratio diagrams from these two eastern U.S. marshes is a strong increase in the rate of RSLR in the last few centuries (Figure 4); the acceleration appears to have been coeval in these two areas with widely different average absolute rates of RSLR. From about 1000 A.D. until 1600 A.D., RSLR occurred at a rate close to the long-term average, but this rate increased by a factor of 2 around 1650 ± 75 A.D. [*Nydick et al.,* 1995]. This acceleration was followed by a short, negative rate anomaly during the 18th century. The highest rates occurred over the last two centuries (from about 1800 A.D.). Details in some records over the last 100 years show evidence of human activities on the marsh environments. For example, the drainage of many marshes has been heavily modified since the late 19th century by mosquito ditching and flood control levee construction. The correlations in rate variations between the RSLR graphs is striking, however, and the eastern United States has seen enhanced rates of RSLR over the last 200–400 years.

Correlation Between RSLR and Climate?

The sea level rate ratio records can be compared with the highest summer temperature proxy record from the Greenland Ice Sheet Project 2 ice core [*Stuiver et al.,* 1995], which may represent an average Northern Hemispheric temperature signal, and shows the Medieval Warm Period (900–1250 A.D.), the Little Ice Age (1300–1800? A.D.), and the modern global warming since about 1850 A.D. (Figure 4).

These RSLR records do not show strong evidence for enhanced rates during the Medieval Warm Period, in agreement with earlier studies from Clinton Marsh, Conn. [*Varekamp et al.,* 1992]. The rate of RSLR was low during the early part of the Little Ice Age (1400–1650 A.D.); the first rise in temperature started around 1600 A.D., coinciding with the onset of the higher rates of RSLR along the eastern U.S. seaboard. The subsequent deceleration during the 18th century and rapid rise from the late 18th–early 19th century appear to correlate with the temperature record (Figure 4), although the age constraints between 1700–1900 A.D. probably lack the necessary precision to attach too much value to such a correlation. The period since 1800 A.D. (including the modern global warming for which climatologists have speculated on an anthropogenic cause) is associated with the highest rates of RSLR, but no acceleration in RSLR is evident (even discounting marsh records with anthropogenic disturbances) with the rapidly rising temperatures of the last 100 years, in agreement with the tide gauge records [*Douglas,* 1992; *Gornitz,* 1992]. The ^{210}Pb dates provide good age constraints for the end of the last century. It is quite certain, therefore, that the first acceleration occurred prior to this period.

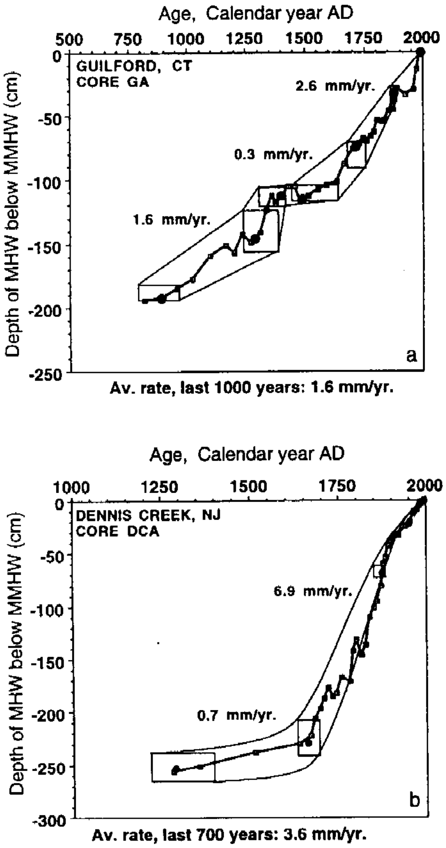

Fig. 3. RSLR curves for (a) Guilford, (Conn.), and (b) Dennis Creek, N.J., derived with methods after Varekamp et al. *[1992]. The vertical axes show the depth of MHW below the modern MHW level; dots represent dated samples, with boxes of 1σ error bars for the calibrated ages and estimates of vertical uncertainty, with an interpolated error envelope; squares are analyzed samples with interpolated ages. Average rates of RSLR are indicated for curve segments; the highest rates occur in the core tops, starting around 1600 A.D.*

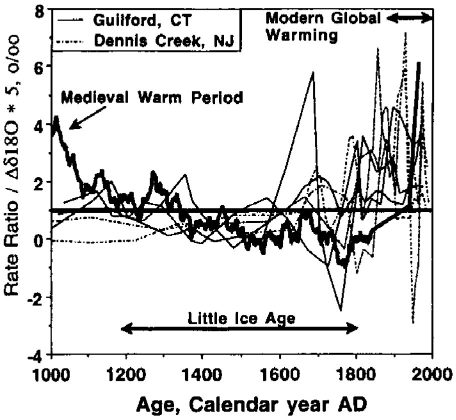

*Fig. 4. Sea level rate ratio curves from Connecticut (3 cores) and Delaware Bay (3 cores) with a climate proxy record (thick, black curve). The horizontal line at rate ratio equals 1 represents the 1,000-year average rates of RSLR for the different sites; rate ratio values 1 indicate periods of rapid sea level rise. The timescale of the Greenland Ice Sheet Project 2 highest summer temperature proxy record [*Stuiver et al., *1995] was adapted from the original timescale to calendar years A.D., with 1990 as the most recent date; the ice core isotope data are plotted as deviations in* δ^{18} *O from the period 1800–1840, multiplied by 5 to accommodate the different numerical scales. The highest rates occur in the period since about 1800 A.D., with a slight acceleration around 1650 A.D.*

The underlying reasons for the possible changes in sea level rise over the last 1,000 years are poorly understood. The combined effects of thermal expansion of sea water and relocation or changes in intensity of major ocean currents may be important causes for changes in the rates of sea level rise along the eastern U.S. seaboard [*Varekamp et al.*, 1992]. Increase in ocean water mass as a result of polar ice melting in response to these small climate variations is much less likely to influence the rates of RSLR at these timescales, but processes such as geoidal or earth rotational changes may have had effects as well. The calculated crustal subsidence rate in the Long Island Sound region is about 1 mm/a [*Peltier,* 1996]. Thus, the long-term rate of eustatic sea level rise over the last 1,000 years must have been close to zero until the recent acceleration.

These data do not indicate that further temperature rise in the next century will not result in an acceleration of the rate of RSLR. Neither the recent geologic record nor the tide gauge record of this century provides tools with the necessary precision to make exact predictions on the rates of RSLR for any temperature-forcing scenario for the next century. The RSLR records for the recent geologic past, however, show a broad coherence between the temperature record and rates of RSLR, except the Medieval Warm Period around 1000 A.D. Sudden rate changes have occurred, apparently in association with minor climate fluctuations, and such changes may happen again in the near future.

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