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A Search for Scale in Sea-Level Studies

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ABSTRACT

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Many researchers assume a proportional relationship among the atmospheric CO_2 concentration, temperature, and sea level. Thus, the rate of sea-level rise should increase in concert with the documented exponential increase in CO_2. Although sea surface temperature has increased in places over the past century and short-term sea level rose abruptly during the 1990s, it is difficult to demonstrate a proportional relationship using existing geologic or historic records. Tide gauge records in the United States cover too short a time interval to verify acceleration in the rate of sea-level rise, although multicentury tide gauge and staff records from the Netherlands and Sweden suggest a mid-19th-century acceleration in sea-level rise. Reconstructions of sea-level changes for the past 1000 years derived using benthic foraminifer data from salt marshes along the East Coast of the United States suggest an increased rate of relative sea-level rise beginning in the 1600s. Geologic records of relative sea-level rise for the past 6000 years are available for several sites along the US East Coast from ^{14}C-dated basal peat below salt marshes and estuarine sediments. When these three scales of sea-level variation are integrated, adjusted for postglacial isostatic movement, and re-plotted, the range of variation in sea level suggested by basal peat ages is within ± 1 meter of the long-term trend. The reconstruction from Long Island Sound data shows a linear rise in sea level beginning in the mid-1600s at a rate consistent with the historic record of mean high water. Long-term tide gauge records from Europe and North America show similar trends since the mid–19th century. There is no clear proportional exponential increase in the rate of sea-level rise. If proportionality exists among sea level, atmospheric CO_2, and temperature, there may be a significant time lag before an anthropogenic increase in the rate of sea-level rise occurs.

ADDITIONAL INDEX WORDS: *Relative sea level, atmospheric CO_2, sea-level rise, basal peat, temperature reconstruction, global temperature, isostatic rebound, climate change.*

INTRODUCTION

Current studies of accelerated rates of sea-level rise have their roots in the documented increase in atmospheric CO_2 during the latter half of the 20th century (KEELING, 1960; KEELING *et al.*, 1976; KEELING, BACASTOW, and WHORF, 1982). A linkage between CO_2 and climate has been discussed for more than a century, and concentrated efforts to understand this linkage and its anthropogenic causes have been made by the US Department of Energy (USDOE, 1980) and subsequently by the National Research Council (NRC, 1983, 1990). The response of sea level to climate was explored as part of these studies. The NRC also addressed the engineering implications of an accelerated rate of sea-level rise on coasts (NRC, 1987). An influential collection of papers by BARTH and TITUS (1984) called attention to climate-related sea-level rise and future flooding of coastal lowlands in response to increases in "greenhouse" gases and an apparent exponential increase in CO_2 and global temperature. HOFFMAN, KEYES, and TITUS (1983) and HOFFMAN (1984) proposed a proportional linkage between CO_2, temperature, and warming oceanic waters resulting in steric expansion, increased water volume, and hence an exponential rate in future sea-level rise, constructs used by the Intergovernmental Panel on Climate Change (IPCC, 2001) as well. The concept of proportionality between CO_2 and sea level implies that the rate of sea-level rise accelerates in tandem with an exponential increase in CO_2 and atmospheric temperature. This simple concept has been used to argue that the rate of sea-level rise was low over the past 6000 years, began to increase during the 19th century, and will continue to increase during the next century (LEATHERMAN *et al.*, 1995; NRC, 1987).

Although sea surface temperature can be shown to have increased at certain locations during the past century on the basis of historic ship's data through the National Oceanographic and Atmospheric Administration's Comprehensive Ocean-Atmosphere Data Set and for the past 35–45 years (LEVITUS *et al.*, 2001) accompanied by an abrupt rise in sea level during the 1990s (PARK *et al.*, 1998), it is difficult to demonstrate a proportional relationship using existing geologic or historic records. DOUGLAS (1991, 2000) argues that tide gauge records cover too short a time interval to verify acceleration in the rate of sea-level rise but that multicentury tide gauge and staff records from the Netherlands demonstrate acceleration in sea-level rise between the 18th and 19th centuries attributable to anthropogenic warming. The

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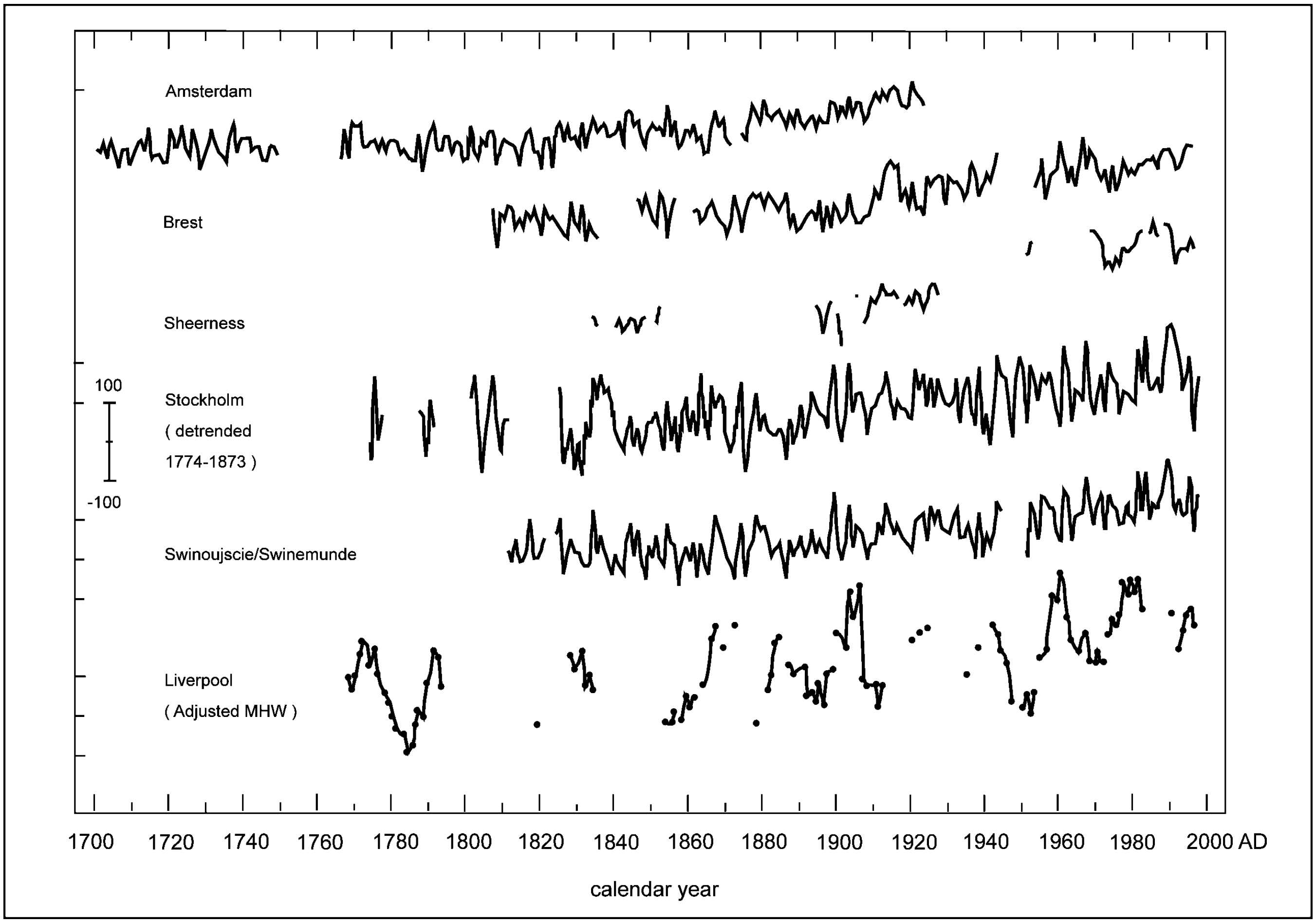

Figure 1. Time series of relative sea level for the past 300 years from Northern Europe. The scale bar indicates ±100 millimeters. Source: IPCC, 2001.

IPCC (2001) also compares long tide gauge records from Europe that show divergence from an apparent background rate in the 19th century, but at points of deflection separated by decades (Figure 1). Although reference is made to long-term sea-level time series, these are not integrated into discussions of accelerated sea-level rise. A critical integrated temporal scale is apparently lacking.

LONGER-TERM RATES OF SEA-LEVEL RISE

Late Holocene Sea Level

The most reliable records of Holocene sea-level rise are derived from radiocarbon-dated organics from basal peat deposits along stable or apparently subsiding coasts. Basal peat and especially those identified as formed from upper salt marsh species (*e.g., Spartina patens*) are invaluable indicators of the initial inundation of coastal areas by rising sea level. They are generally deposited on terrestrial surfaces that have undergone prior consolidation. Thus, age dating of basal peat furnishes two critical markers: first, the present depth to an inundated land surface, and second, the position of the contemporaneous mean high water (MHW). When radiocarbon ages are calibrated to calendar years (STUIVER, REIMER, and BRAZIUNAS, 1998), age *vs.* depth plots of basal peat provide a record of the former position of MHW through time. Regression analysis of a data set allows the rate of relative sea level (RSL) rise to be plotted on a regional basis. Regional comparisons of RSL curves allow the position of sea level to be decoupled from past and present vertical movement of the land. PELTIER and TUSHINGHAM (1991) have formulated significant numerical models of crustal movement as well as eustatic sea-level position for the past 18,000 years. Their models utilize RSL curves derived from basal peat ages for the East Coast of the United States; however, these records rarely extend beyond 6,000 years before the present (BP). Significant basal peat records of RSL rise for the past 6000 years are available for Chesapeake Bay, Long Island Sound, Cape Cod Bay, and Delaware Bay. With the exception of Delaware Bay, a comparison of these 6000-year trends (Figure 2) shows rates of RSL rise on the order of 1.3 to 1.4 mm/y. Delaware Bay data show a more rapid rate, 2.0 mm/y, potentially indicating greater regional subsidence (BELKNAP and KRAFT, 1977; CRONIN *et al.*, 1981; NIKITINA *et al.*, 2000).

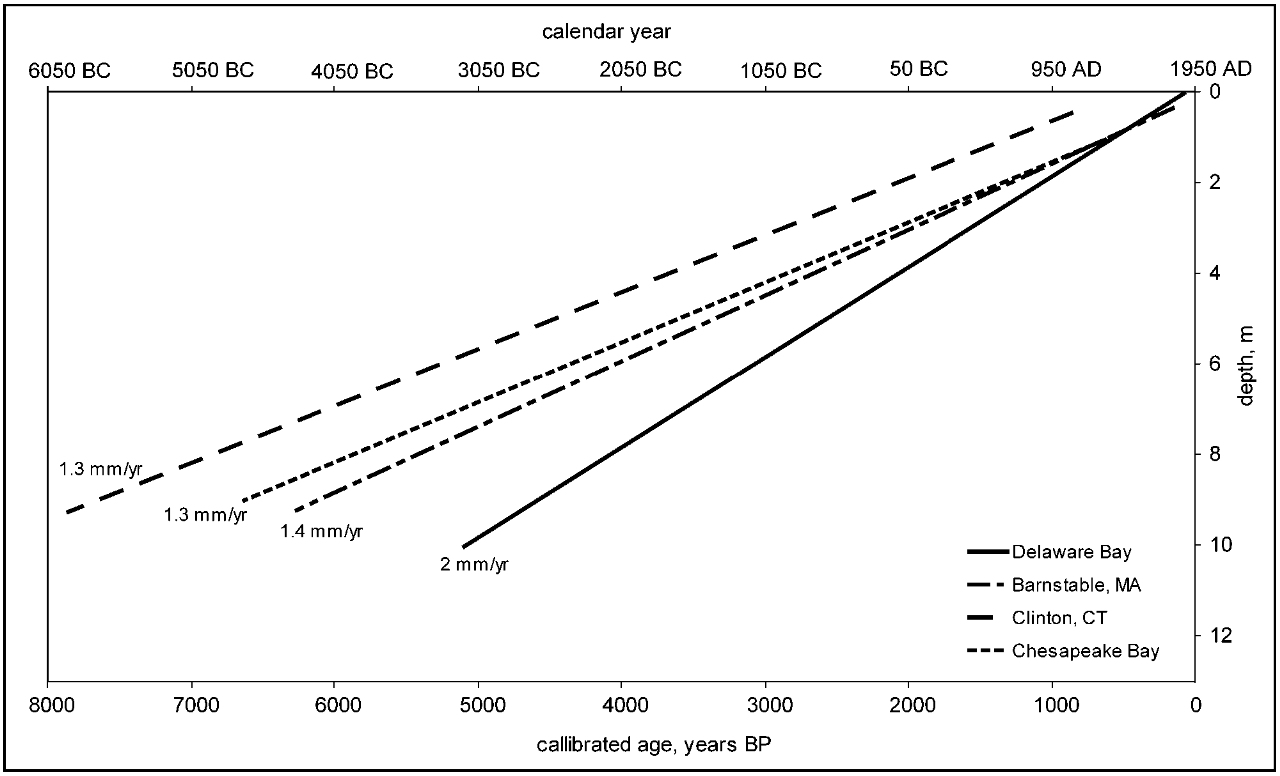

Figure 2. Relative long-term sea-level trends for Delaware Bay; Clinton, Connecticut; Barnstable, Massachusetts; and Chesapeake Bay.

The Past 1000 Years

Reconstruction of the rate of sea-level rise for the past 1000 years has been both aided and complicated by calibration of radiocarbon ages for natural fluctuations in atmospheric ^{14}C as well as an increase in ^{14}C due to nuclear testing. Nonetheless, attempts at defining RSL change over this period were made by KEARNEY (1996) for Chesapeake Bay, by THOMAS and VAREKAMP (1991) and VAREKAMP and THOMAS (1992, 1998) for both Long Island Sound and Delaware Bay, and by GEHRELS (1999) and GEHRELS *et al.* (2002) for the Gulf of Maine. KEARNEY's (1996) reconstruction is derived from a small sample of basal peat samples from Chesapeake Bay marshes in Maryland. He attempted to define the rate of RSL by regression analysis of these few points and concluded that the rate was extremely low during this time interval. He then compared the historic tide gauge record for Baltimore (*ca.* 1900 to the present) with a relative rate of sea-level rise of 3.0 mm/y by extending this rate into the past. On this basis, he concluded that a change from an ambient background rate had occurred at some time during the 19th century, a conclusion consistent with the HOFFMAN, KEYES, and TITUS (1983) and HOFFMAN (1984) model of RSL rise in proportion with atmospheric CO_2.

THOMAS and VAREKAMP (1991) and GEHRELS (1999) presented detailed RSL curves for the past 1000 years reconstructed from benthic foraminifers from salt marshes along the US East Coast. By defining the depth and salinity ranges of specific foraminifers in the marshes studied, they were able to date the changing position of MHW. Age dating was performed by a combination of ^{14}C, ^{210}Pb, and ^{137}Cs isotopic methods. Although the method adopted by these authors has been criticized, because factors other than seawater depth affect salinity, these high-quality and detailed reconstructions of RSL position are the best available geologic records. For both Long Island Sound and Delaware Bay, the former authors show an increased rate of RSL rise beginning as early as the 1600s. GEHRELS (1999), working in a more complex postglacial isostatic-rebound area, suggests an increased rate of RSL over the past two centuries. The THOMAS and VAREKAMP (1991) and VAREKAMP and THOMAS (1992, 1998) studies contrast with that of KEARNEY (1996) for the Chesapeake Bay and argue that the rate of RSL rise predated the Industrial Revolution, hinting at an underlying natural cause. With the exception of GEHRELS (1999), none of these researchers sought to integrate their data and conclusions with the 6000-year and historic tide gauge records.

The Historic Record

Tide gauges installed at harbors along world coasts record movements in sea level on hourly, daily, monthly, and annual bases. When viewed statistically over an agreed-upon time, these data are used to define tidal ranges and mean navigational datums such as mean lower low water, mean low water, mean sea level, and MHW. Over longer periods, these

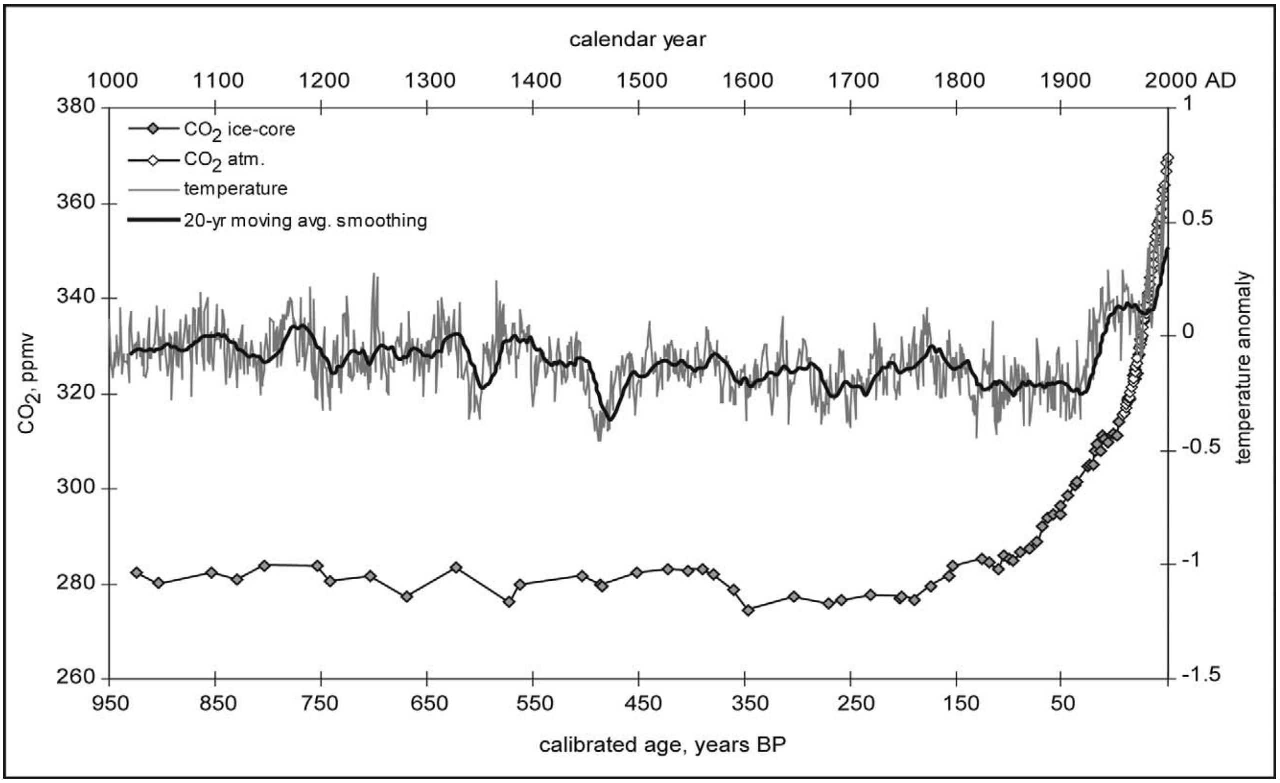

Figure 3. Millennial temperature reconstruction (Mann *et al.*, 1999) compared to CO_2 data from ice cores (Taylor and Law Domes) and atmosphere (Mauna Loa).

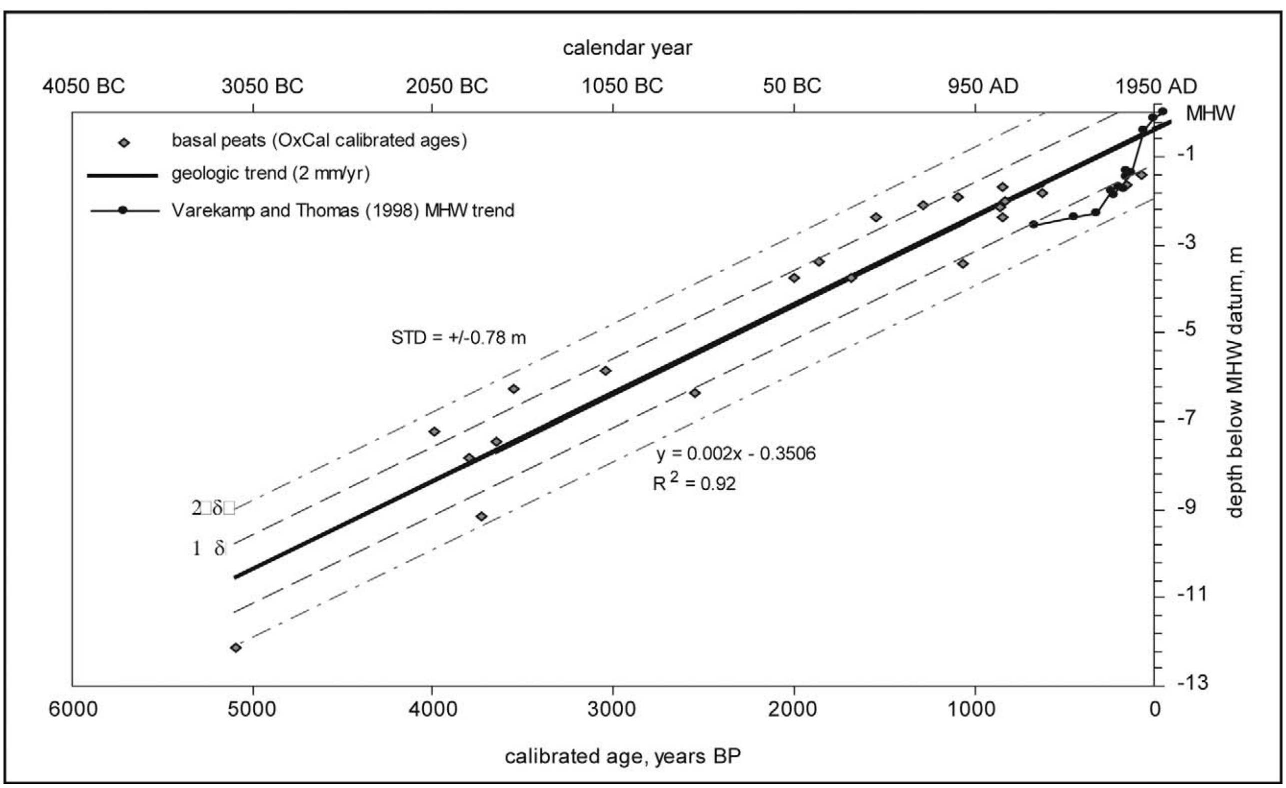

Figure 4. Relative 6000-year MHW trend for Delaware Bay (Nikitina *et al.*, 2000) *vs.* MHW trend over the last millennium.

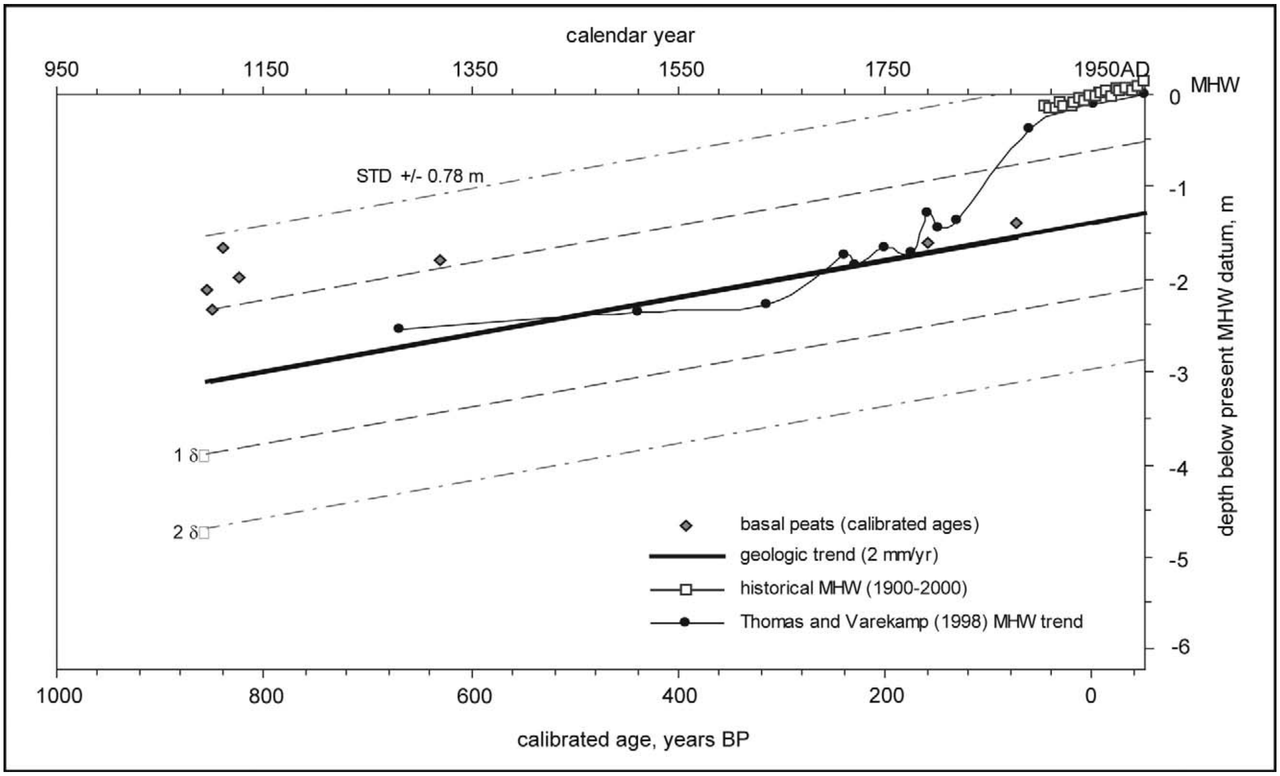

Figure 5. Relative MHW trends for Delaware Bay (Nikitina *et al.*, 2000; Varekamp and Thomas, 1998) compared with present MHW at Philadelphia, Pennsylvania.

data reflect trends that show decadal changes in sea level as well as longer-term regional and local sea-level variation. When the historic record is sufficiently long, tide gauges help to define relative movement of the land surface upon which the gauge is located. Thus, the record of sea level is relative to land movements as well. DOUGLAS (1991, 2000) and PELTIER (1996) argue on the basis of comparative historic sea-level records that the ongoing rate of sea-level rise on a worldwide basis is on the order of 1.9 to 2.0 mm/y. Postglacial readjustments of the Earth's crust create variations in the vertical movement of the land surface, as do anomalous areas of human-induced subsidence attributed to groundwater or petroleum withdrawal. Thus, the sum of vertical movement and global sea-level change shows movement of the sea surface relative to the land surface at each tide gauge.

Ideally, long-term records may show the possible divergence of relative sea level from a background trend dominated by geologic variables. The IPCC (2001) as well as DOUGLAS (2000), for example, argue that such a divergence in European tide gauge records occurred in the mid–19th century and indicate human-induced eustatic and steric changes in sea level due to atmospheric temperature rise over the same period. Unfortunately, US tide gauge records are insufficiently long to identify any acceleration in rate of sea-level rise from a background state. Along the US East Coast, the longest continuous historic records are confined to harbors in New York, Philadelphia, and Baltimore. Because of the potential for subsidence below many of the tide gauge sites along the Atlantic Coastal Plain due to compaction of the underlying sediments by natural or anthropogenic means, sites founded on crystalline rocks near the inner edge of the coastal plain provide the most reliable records of relative sea level.

THE RECORD OF ATMOSPHERIC CO_2

KEELING's (1960) important initial observations of increasing atmospheric CO_2 concentrations since 1958 triggered vast amounts of research into the linkage between its increase and rising global temperature over the same time interval. Carbon dioxide clearly increased in concentration during the latter half of the 20th century. These findings gave credence to REVELLE and SUESS's (1957) claim that the oceans could not absorb CO_2 at the rate at which it was being added to the atmosphere by burning of fossil fuels. REVELLE (1983) considered the impact of rising temperature on present ice sheets and suggested that melting glacier ice could add 40 centimeters to the height of sea level during the next century, with warming of ocean waters adding an additional 30 centimeters. Although not defining the pattern of such a future rise, REVELLE (1983) noted a probable 70-centimeter total rise. Subsequent research has yielded millennial, centennial, and decadal values for CO_2 preserved in Arctic and Antarctic ice cores. Clearly, there are linkages among major climate events, temperature, and global CO_2 concentration. In simple

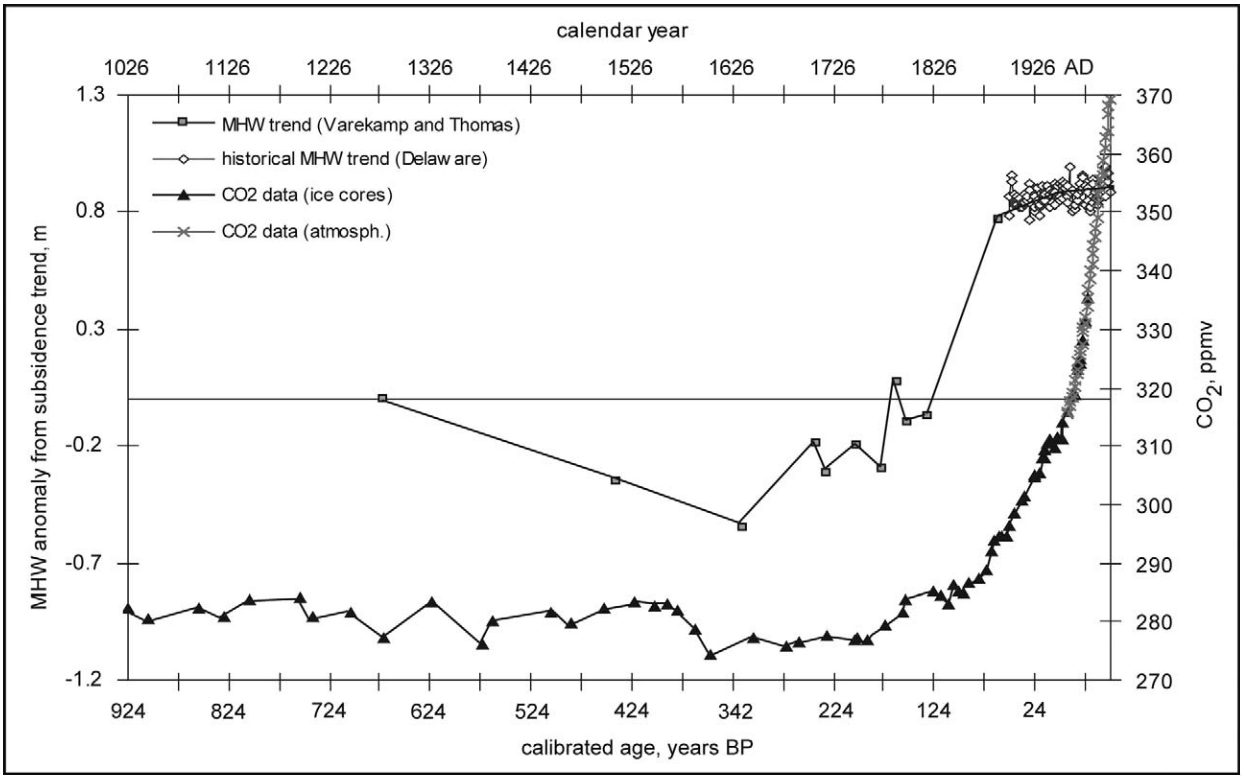

Figure 6. Comparison of CO_2 trends for the last millennium and MHW trends for Delaware Bay (Varekamp and Thomas, 1998, and historic record) adjusted for subsidence (2 mm/y).

terms, global CO_2 content is lower during full glacial periods, when sea levels are eustatically lowered, and then rises with postglacial warming and a return to interglacial conditions. Sea level rises as water is returned to the ocean basins; thus, in general terms, there is a clear correspondence between sea level and CO_2.

Linking the long- and short-term historic records of CO_2 concentration is also a certainty. The record of CO_2 preserved in Antarctic ice for the past 1000 years (ETHERIDGE *et al.*, 2001; INDERMUHLE *et al.*, 1999) is consistent with the data recorded at the Mauna Loa observatory over the past 50 years. The combined record shows an apparent exponential increase in concentration diverging from an ambient background level during the 19th century. Independent verification of a relationship between global temperature and atmospheric concentration of CO_2 was presented by MANN, BRADLEY, and HUGHES (1999), who presented a reconstruction of global temperature change for the past 1500 years derived from an array of tree-ring records. MANN, BRADLEY, and HUGHES's (1999) reconstruction points to a marked divergence in temperature from cooler past temperatures over the past century. A comparison of these reconstructed records is shown in Figure 3. One possible point of disagreement in the data is a slight time lag between temperatures as shown by tree rings and the CO_2 record. Dissimilar dating techniques might account for this lag.

LINKING SEA LEVEL TO THE CO_2 RECORD

The U.S. East Coast Record

Given the extant geologic records for sea-level rise along the U.S. East Coast, as well as the suitably long historic records from key tide gauges along the coast, it should be possible to demonstrate acceleration in the rate of sea-level rise reflecting both the exponential increase in CO_2 and temperature. Of the records of sea-level rise during the past 1500 years discussed above, only two of these display enough similarity in both method and area of postglacial crustal movement. KEARNEY's (1996) study of Chesapeake Bay sea-level rise is derived from basal peat ages and lacks sufficient detail. GEHRELS's (1999) benthic foraminifer record from the Gulf of Maine is suitably detailed, but the region is one of postglacial isostatic transition from a rising to a subsiding crust. It is difficult to separate the record of crustal movement from relative sea level in this location. Thus, determining a pure sea-level component here presented uncertainty. Only the studies by NYDICK *et al.* (1995) and VAREKAMP and THOMAS (1998) from Guilford, Connecticut, and Dennis Creek, New Jersey, present suitable data for comparison in method and setting.

Sea-Level Reconstruction for Delaware Bay

The Holocene sea-level history of Delaware Bay is well known through the work of BELKNAP and KRAFT (1977) and

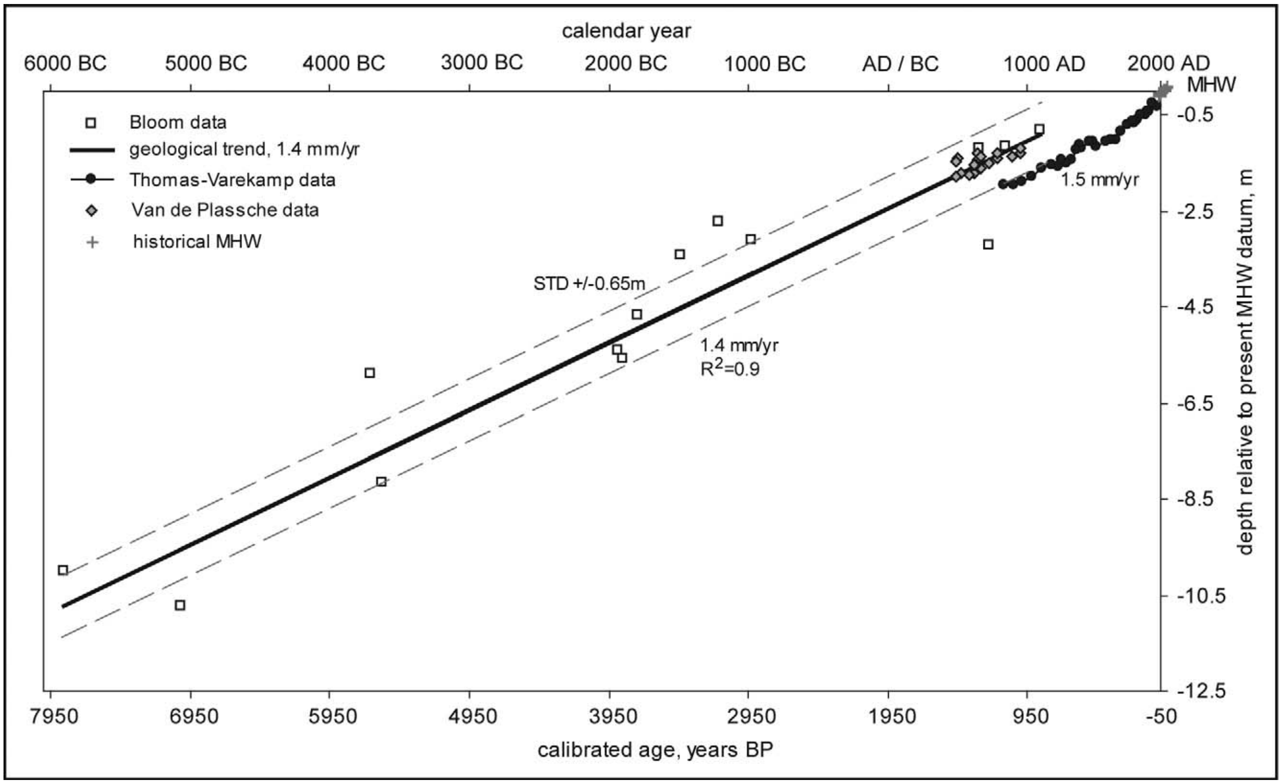

Figure 7. Sea-level curve for Clinton, Connecticut (Bloom and Stuiver, 1963; Van de Plassche *et al.*, 1998) and Guilford, Connecticut (Nydick *et al.*, 1995) compared to historical MHW record at Newport, Rhode Island.

NIKITINA *et al.* (2000). Their combined research is largely derived from basal peat ages from studies in salt marshes near the mouth of Delaware Bay. Important for our comparison is an agreement in reconstructed sea-level datums. Both basal peat and benthic foraminifer reconstructions generate the former position of MHW through time. Thus, the historic record of MHW of the past century can be directly compared with both the 6000-year and the 1500-year records. More important, we can integrate the time scales of these records—linking past with present.

Figure 4 is a composite of the three time scales. The Holocene trend is defined by a least squares regression of the calibrated ages for basal peat samples as compiled by NIKITINA *et al.* (2000). Although BELKNAP and KRAFT (1977) presented a curvilinear trend, we found a linear fit to the data shown to be more appropriate. The trend shows a mean rate of rise of 2.0 mm/y over the past 5000 years within a standard deviation range of ±78 centimeters about the mean. VAREKAMP and THOMAS's (1998) data have not been published in detail but are presented as curves in this source. We enlarged these reconstructions and scaled them accordingly. Their reconstructed trend for Dennis Creek is plotted on our 5,000-year trend adjusted to present MHW. For a historical comparison, we plotted the trend through the AD 1350 to 1800 data to show the close agreement in rate. Also shown is the historic tide gauge record of MHW for Philadelphia—a bedrock-floored gauge. Strikingly, both the calculated mean long-term trend and the historic MHW record show similar slopes, but the benthic foraminifer reconstruction shows marked divergence. Here, the earlier part of the Dennis Creek reconstruction shows general agreement with the long-term rate of RSL rise at 2.0 mm/y until about AD 1750. The RSL trend then rapidly rises until the early 20th century, when it slows and tends to parallel the historic tide gauge record of 2.6 mm/y. Because of marked increase in the rate of RSL rise in the Dennis Creek foraminifer record, the error range for the calculated 5000-year trend was increased to two standard deviations, or ±1.56 meters. Figure 5 shows the Dennis Creek reconstruction in more detail and shows the close similarity between the historic data and the early RSL history of this Delaware Bay salt marsh with respect to the long-term trend. Both early and late portions of the reconstruction show close agreement, whereas the historic period between AD 1800 and 1900 appears anomalous.

The long-term RSL trend for Delaware Bay is generally taken to be the rate of crustal subsidence in either the PELTIER (1996) or DOUGLAS (1991) postglacial adjustment models, so this 2.0-mm/y trend can be deleted from the composite RSL curve to detrend the data. This is presented in Figure 6 juxtaposed with the CO_2 record of the same time period. Unlike the MANN, BRADLEY, and HUGHES (1999) reconstruction of global temperature from tree-ring records, there is no discernible divergence in the rate of sea-level rise over the past two centuries to suggest a connection with the documented

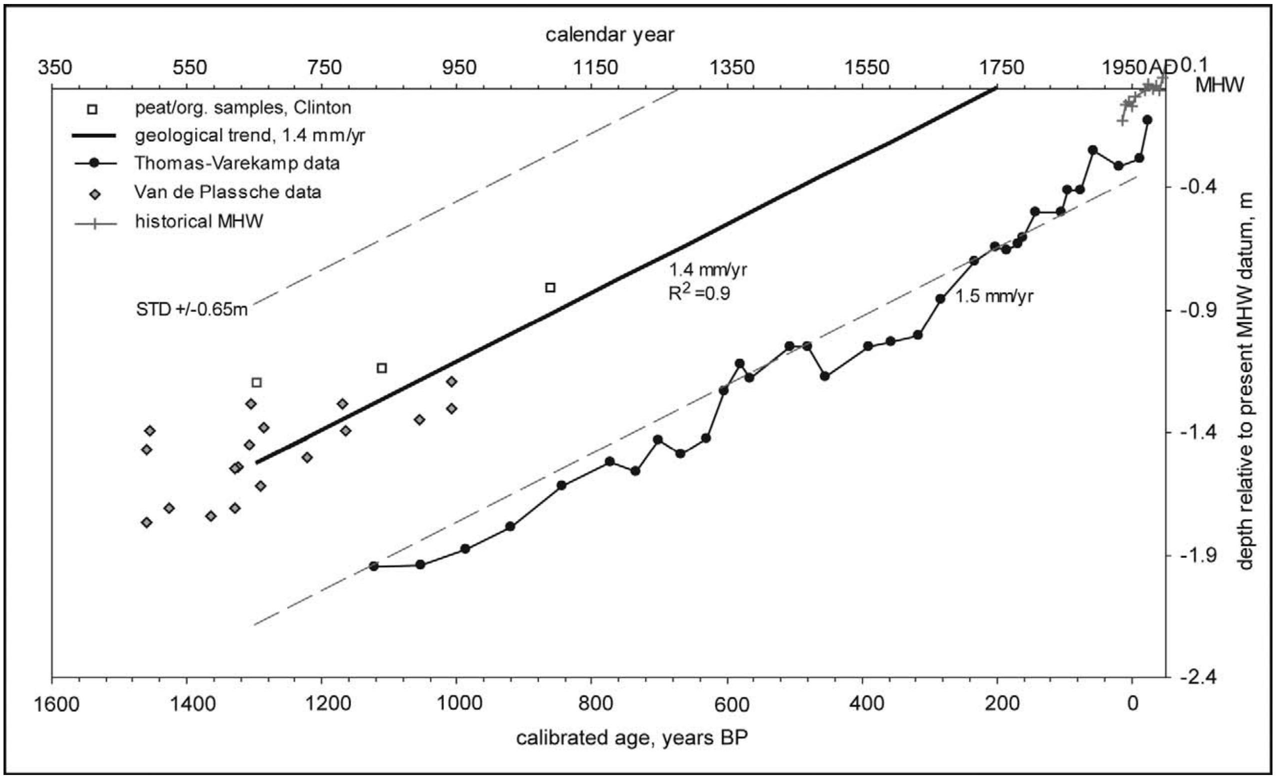

Figure 8. The 1500-year sea-level curve for Clinton, Connecticut (Bloom and Stuiver, 1963; Van de Plassche *et al.*, 1998) and Guilford, Connecticut (Nydick *et al.*, 1995) compared to historical MHW record at Newport, Rhode Island.

increase in atmospheric CO_2 concentration. On the contrary, if the historic rate of RSL rise over the past century, determined from the Philadelphia tide gauge, is taken to be 2.7 mm/y, then the suggested rate of current sea-level rise is on the order of 0.7 mm/y, a clear departure from DOUGLAS's (1991) and PELTIER's (1996) comparable rates of 1.9 to 2.0 mm/y. The lack of consistency in the Dennis Creek record suggests a possible unknown perturbation in the local stratigraphic record or an error in plotting the field data. Most significant is the clear similarity between the historic tide gauge record of the past century, the same interval reconstructed by VAREKAMP and THOMAS (1998), and the historic record between AD 1200 and 1800, which shows little variation from the background rate of sea-level rise.

The Reconstructed Sea-Level Record of Long Island Sound

NYDICK *et al.* (1995) and VAREKAMP and THOMAS's (1998) most complete and well-studied marsh cores and RSL construction is from the extensive salt marshes of Guilford, Connecticut. For comparative purposes, the nearby marshes at Clinton, Connecticut, were among the first deposits cored to obtain a long-term history of marine transgression. BLOOM and STUIVER (1963) did extensive and detailed age dating of basal peat at this location. VAN DE PLASSCHE, VAN DE BORG, and DE JONG (1998) also investigated these marshes and provided additional basal peat dates. The resultant long-term record of RSL rise extends from 7000 BP to present. The rate of rise over the long-term period was calculated to be 1.4 mm/y by linear regression (the best-fit analysis). Here, the standard deviation about the long-term mean trend was ±65 centimeters. Figure 7 shows the integrated composite of long-term, mesoscale, and historic sea-level records adjusted to local MHW. In this case, the reconstructed RSL history for the past 1500 years shows a comparable 1.4-mm/y trend until about AD 1630, when a change in rate occurs. After AD 1630, sea level appears to rise at a linear rate, continuing to and linking with the historic tide gauge data. A more detailed view of the past 1500 years is shown in Figure 8. Note that all change in the position of sea level is confined within a single standard deviation of the mean long-term trend. When the Guilford marsh reconstruction of VAREKAMP and THOMAS (1992) is detrended and compared to the CO_2 record of the same period (Figure 9), there is no indication of an exponential increase in the rate of sea-level rise. Worth note, however, are similarities in the pattern of sea-level rise and the CO_2 fluctuations in the ice-core record until the mid–19th century. After this period, any similarity with the atmospheric record ends. A linear rise in sea level is documented beginning in the 17th century and continues at a rate between 0.8 and 0.9 mm/y until the present time and with a range of variation comparable to that shown on the nearby tide gauge.

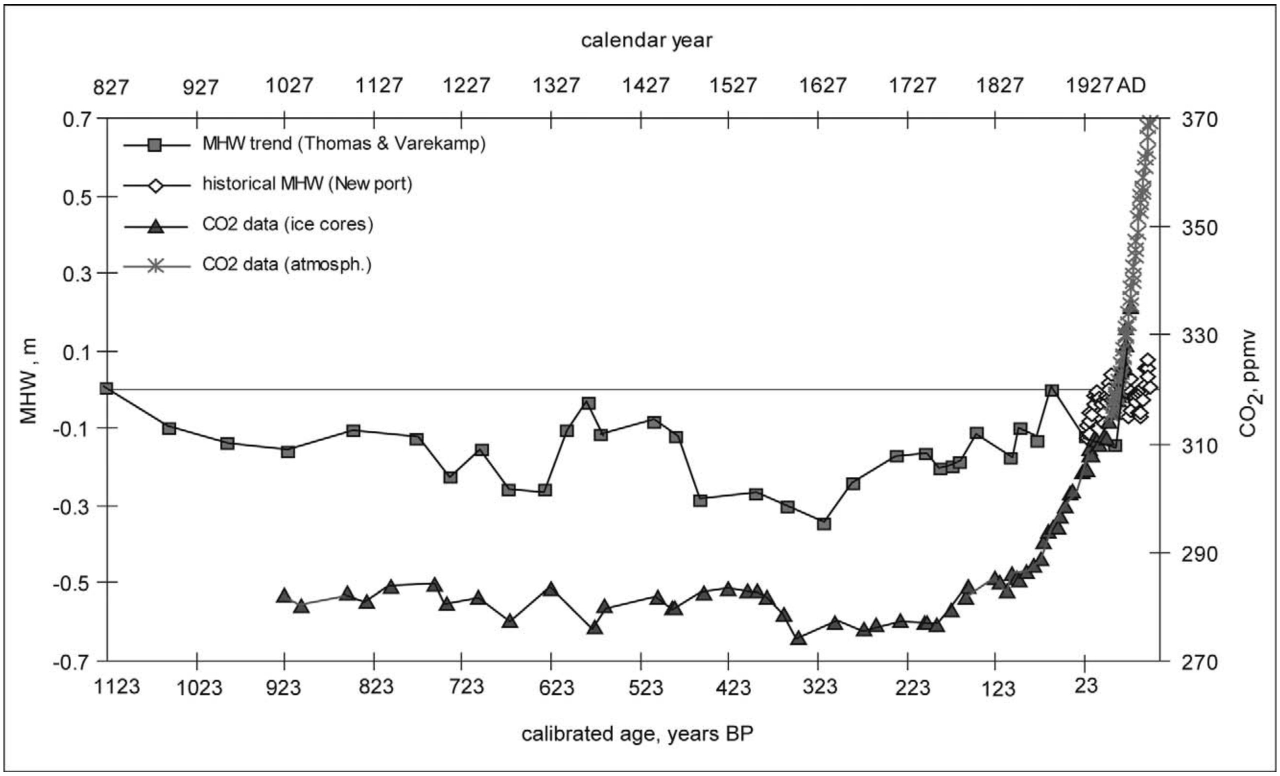

Figure 9. Comparison of CO_2 trends for the last millennium (Taylor and Law Domes, Mauna Loa) and MHW trend for Connecticut (Varekamp and Thomas, 1998, and historic record) adjusted for subsidence.

Least squares analysis of MHW at the Newport, Rhode Island, tide gauge provides a 0.9-mm/y rate as well. The residual sea-level trend shows no apparent agreement with that of atmospheric CO_2.

DISCUSSION

At this juncture, there are only three published mesoscale records of RSL for the past 1500 years that use similar methods that can be used for comparison. As mentioned above, the research performed by GEHRELS (1999) was done in a more complex area of postglacial isostatic adjustment. Thus, it is difficult to factor out differential crustal movement to detrend the mesoscale sea-level record. Guilford and Dennis Creek remain the only detailed reconstructions suitable for integrated analysis. As we have shown, the Dennis Creek data show an anomalous rise in sea level both preceded and postdated by periods with rates of rise little different from the background long-term rate attributed to isostatic fore bulge collapse. If such subsidence is indicated and the rate of long-term RSL rise is taken as the subsidence rate, then it is reasonable to consider the difference between that rate, 2.0 mm/y, and the historic rate of rise at Philadelphia, 2.7 mm/y, to be a rate of ongoing sea-level rise at less than 1.0 mm/y. There seem to be unresolved problems with the anomalous rise in sea level in the 1800 to 1900 interval. Nonetheless, the detrended rate of sea-level rise occurring historically is clearly less than 1.0 mm/y and is comparable to the detrended rate for Guilford, Connecticut, over the past 400 years. This is inconsistent with DOUGLAS's (1991) and PELTIER's (1996) calculated rates of approximately twice this amount.

An obvious problem with the integrated comparison of three time scales of sea-level records is the paucity of comparable studies. Only two detailed reconstructions are available, raising questions regarding their validity for evaluating linkages with the atmosphere and global temperature. In terms of other longer-term records, however, Figure 1 shows only four tide gauge records with suitable time depth to reflect sea-level rise acceleration since the 19th century. Two of these are in the Baltic Sea, and the others are in Amsterdam, Netherlands, and Brest, France. All are in areas of postglacial isostatic recovery, although MÖRNER (1980) considers Brest to be isostatically stable. One test of the validity of the benthic foraminifer method of sea-level reconstruction is to attempt to calculate exponential trends to the tide gauge records from Europe. Of the four records included by the IPCC (2001) as examples of accelerated sea-level rise in the 19th century, we have chosen the Stockholm record for comparison. This choice was made on the basis of a known and detailed record of postglacial isostatic uplift of raised shorelines (MÖRNER, 1980) that is independent of the Peltier numerical model. Thus, the uplift rate for Stockholm is taken to be

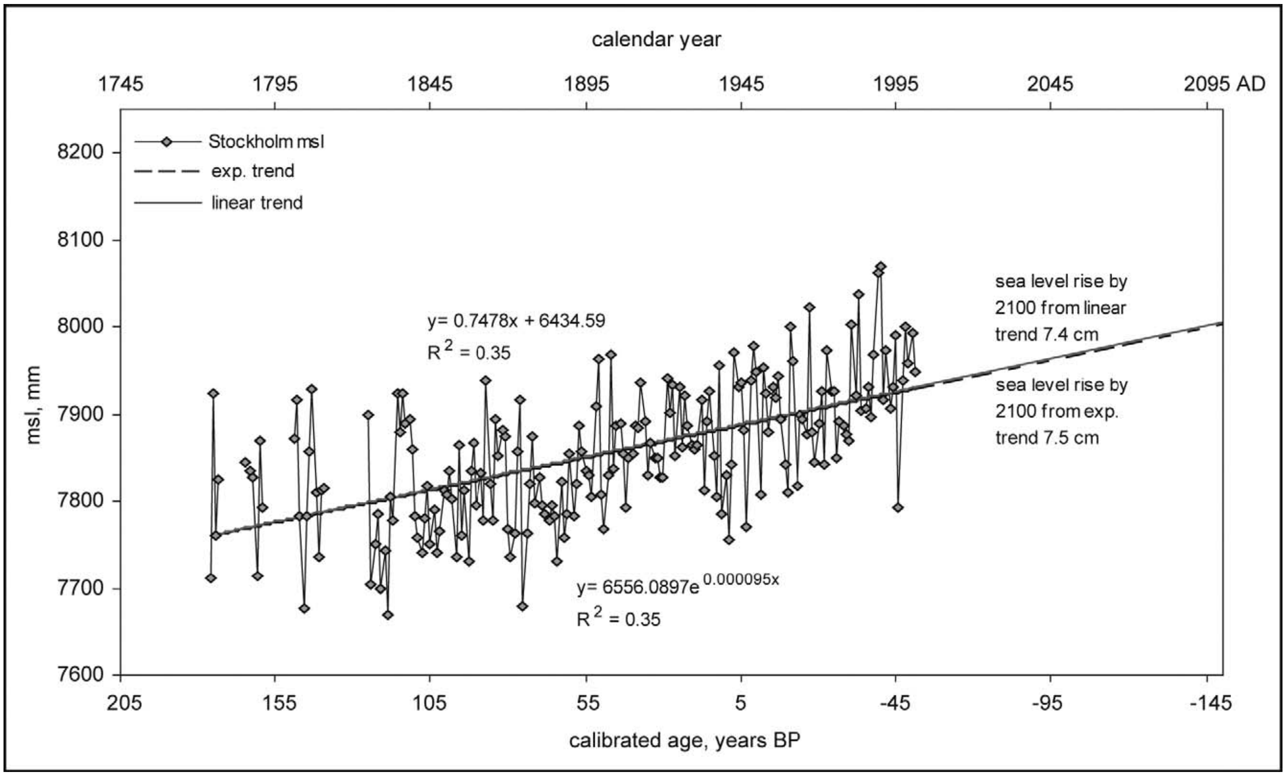

Figure 10. Stockholm historic sea-level trend (adjusted for uplift of 4.9 mm/y; Mörner, 1980) extrapolated to the year 2100.

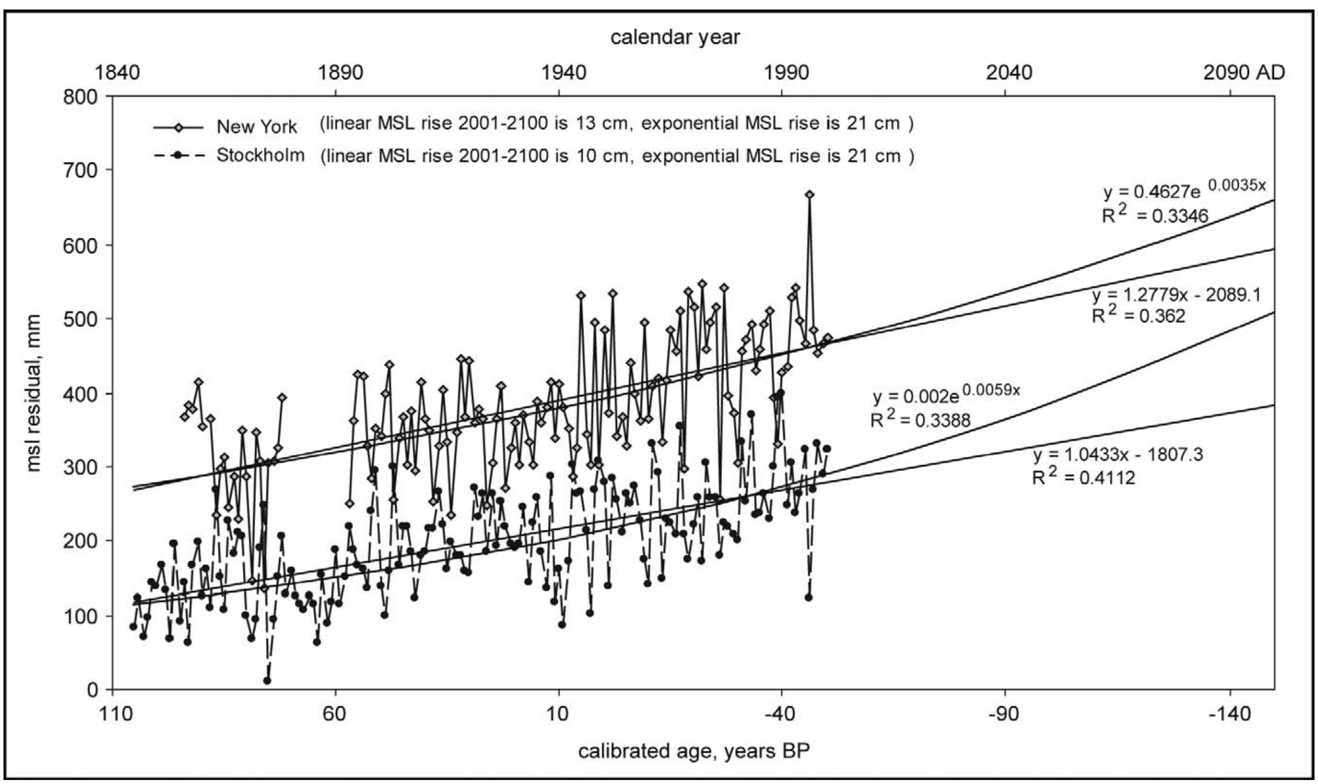

Figure 11. Comparison of mean sea level (MSL) residuals for Stockholm, Sweden, and New York, New York (uplift and subsidence adjusted).

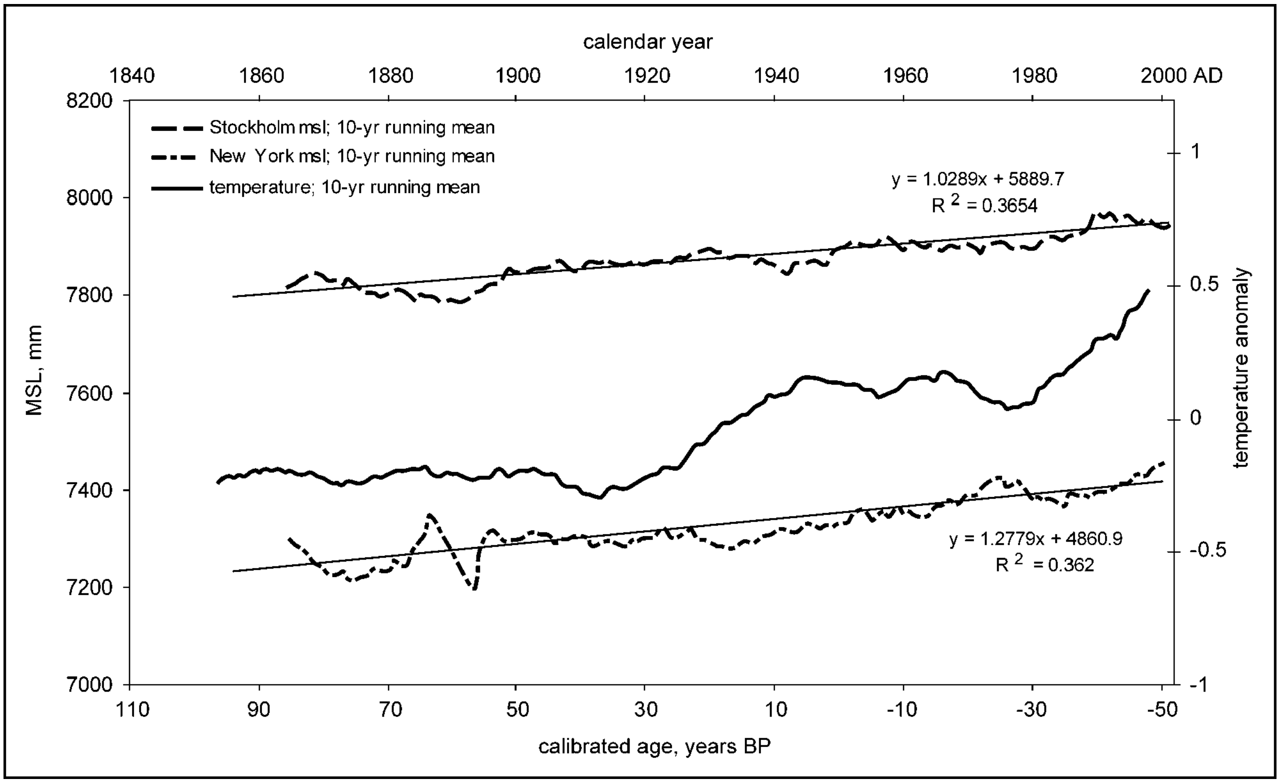

Figure 12. Comparison of temperature reconstruction (Mann *et al.*, 1999) and mean sea level (MSL) 10-year running means for Stockholm, Sweden, and New York, New York.

MÖRNER's (1980) value, 4.9 mm/y. The tide gauge record adjusted for uplift is shown in Figure 10 and extrapolated to provide an expected rise in level by the end of the century. Both linear and exponential functions are fitted to the entire data set. Both trends are nearly identical and suggest first, that the rate of ongoing sea-level rise is less than 1 mm/y, and second, that the extrapolated rise by the end of the century is between 7.4 and 7.5 centimeters. Unlike the CO_2 record, which has a clear exponential signal, the long-term tide gauge from Stockholm does not, and in fact, it shows a linear rate of ongoing sea-level rise broadly comparable with that of Long Island Sound. On the other hand, these data might be interpreted to show post-1940 acceleration in rate.

To address the historic records in more detail, we examined the post-1840 data for Stockholm and again calculated the best-fit regressions for only that portion of the data considered to diverge from a background rate of sea-level rise. In addition, by focusing on the 19th century, we are able to compare the longest US tide gauge record for New York with Stockholm and view records from opposite sides of the Atlantic. Like the Baltic records that we have adjusted to the isostatic uplift rate of 4.9 mm/y, we have detrended the New York data for a regional subsidence rate of 1.4 mm/y, as demonstrated by the consistent rates shown in Figure 2. Both data sets are shown as residual variations relative to their trends rather than as fixed datums. A comparison of these records is shown in Figure 11. Both exponential and linear functions were calculated for these data, and again, there is little difference between the functions, with linear trends showing slightly better correlation coefficients. More striking is the similarity in the linear rates of sea-level rise shown for both Stockholm and New York, 1.03 mm/y and 1.3 mm/y, respectively. Extrapolating either linear or exponential trends to the end of the century projects similar increases in sea level.

The linearity in the historic rate of sea-level rise is emphasized in Figure 12, which compares the 10-year running means for these tide gauge records with the 10-year running means of MANN, BRADLEY, and HUGHES's (1999) global temperature reconstruction (Figure 3). Foremost, the rate of sea-level rise has been linear over this time period and shows no indication of the pronounced mid-20th-century increase in temperature indicated by MANN, BRADLEY, and HUGHES (1999). Neither is there a relationship to the atmospheric CO_2 record shown in Figure 3. Worthy of note is the apparent opposite direction of the sea-level trends for the past few decades, which show rise in North America and fall in the Baltic, thus arguing against recent acceleration in sea-level rise.

An obstacle now is to relate and understand these comparisons in light of global atmospheric and oceanic models presented by the IPCC (2001). One possibility in the interpretation presented here is that our search for scale in sea-level studies is incorrect. A second is that the benthic foraminifer reconstructions are incorrect as well. A third possibility, however, is that we are correct in integrating three important time scales of sea-level change to view a composite of 5000 to 6000 years of geologic history and by so doing have identified a potential lack of proportionality between the CO_2 record and sea-level rise during the past two centuries. Clearly, we cannot deny anthropogenic increase in the rate of greenhouse gas loading over this time period or the accompanying increased rise in global temperature. Nonetheless, our study may point to a significant time lag between the atmospheric and oceanic systems that might suggest that we have not yet seen (or are only beginning to see) the impact of CO_2 on global sea level.

CONCLUSION

One of the conclusions of our study is that there has been a tendency to splice together rates of sea-level rise with little regard to the suitability of scale and to derive curves that show steadily increasing rates of sea-level rise. By integrating our time scales and confining ourselves to comparable data sets, we view the historic record as a continuation of the past rather than as a perturbation. In addition, by using data that can be keyed to MHW, we define a data set that shows the records of sea-level change to be included within a single standard deviation of the calculated trend. All basal peat-dated sea-level records we have studied thus far show mean trends within a range of $\pm$1.0 meter. In the problem of understanding sea-level history and applying it to ongoing climate change scenarios, there is clearly a lack of suitable detailed records for sea-level rise over the past 1000 years. There is a need for studying sea-level histories at all scales and especially the most recent geologic history. Methods similar to those of Thomas and Varekamp (1991) and Gehrels (1999) utilizing benthic foraminifers have promise, perhaps in conjunction with studies of pollen and sediment chemistry as well as differences in fauna due to local differences in salinity. It may be more informative to conduct such studies in areas of known and independently dated long-term basal peat records rather than relying solely on current numerical models for calibration. Finally, it is useful to integrate temporal data as we have done and to avoid a temptation to fit data to existing models.

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