

# Climate related sea-level variations over the past two millennia

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**We present new sea-level reconstructions for the past 2100 y based on salt-marsh sedimentary sequences from the US Atlantic coast. The data from North Carolina reveal four phases of persistent sea-level change after correction for glacial isostatic adjustment. Sea level was stable from at least BC 100 until AD 950. Sea level then increased for 400 y at a rate of 0.6 mm/y, followed by a further period of stable, or slightly falling, sea level that persisted until the late 19th century. Since then, sea level has risen at an average rate of 2.1 mm/y, representing the steepest century-scale increase of the past two millennia. This rate was initiated between AD 1865 and 1892. Using an extended semiempirical modeling approach, we show that these sea-level changes are consistent with global temperature for at least the past millennium.**

climate | ocean | late Holocene | salt marsh

Climate and sea-level reconstructions encompassing the past 2,000 y provide a preanthropogenic context for understanding the nature and causes of current and future changes. Hemispheric and global mean temperature have been reconstructed using instrumental records supplemented with proxy data from natural climate archives (1, 2). This research has improved understanding of natural climate variability and suggests that modern warming is unprecedented in the past two millennia (1). In contrast, understanding of sea-level variability during this period is limited and the response to known climate deviations such as the Medieval Climate Anomaly, Little Ice Age, and 20th century warming is unknown. We reconstruct sea-level change over the past 2100 y using new salt-marsh proxy records and investigate the consistency of reconstructed sea level with global temperature using a semiempirical relationship that connects sea-level changes to mean surface temperature (3, 4). The new sea level proxy data constrain a multicentennial response term in the semiempirical model.

## Results and Discussion

**Sea-Level Data.** Salt-marsh sediments and assemblages of foraminifera record former sea level because they are intrinsically linked to the frequency and duration of tidal inundation and keep pace with moderate rates of sea-level rise (5, 6). We developed transfer functions using a modern dataset of foraminifera (193 samples) from 10 salt marshes in North Carolina, USA (7). Transfer functions are empirically derived equations for quantitatively estimating past environmental conditions from paleontological data (8). The transfer functions were applied to foraminiferal assemblages preserved in 1 cm thick samples from two cores of salt-marsh sediment (Sand Point and Tump Point, North Carolina; Fig. 1) to estimate paleomorph elevation (PME), which is the tidal elevation at which a sample formed with respect to its contemporary sea level (9). Unique vertical errors were calculated by the transfer functions for each PME estimate and were less than 0.1 m. Composite chronologies were developed using Accelerator

Mass Spectrometry (AMS) <sup>14</sup>C (conventional, high-precision, and bomb-spike), a pollen chrono-horizon (increased *Ambrosia* at AD 1720 ± 20 y), <sup>210</sup>Pb inventory, and a <sup>137</sup>Cs spike (AD 1963). A probabilistic age-depth model (10) incorporating all dating results was generated separately for each core to reduce chronological uncertainty and provide downcore age estimates at 1 cm intervals with uncertainties that varied from ± 1 to ± 71 y for 95% of samples (Fig. 1).

Relative sea level (RSL) was reconstructed by subtracting transfer-function derived estimates of PME from measured sample altitudes (Fig. 2B). Agreement of geological records with trends in regional and global tide-gauge data (Figs. 2B and 3) validates the salt-marsh proxy approach and justifies its application to older sediments (11, 12). Despite differences in accumulation history and being more than 100 km apart, Sand Point and Tump Point recorded near identical RSL variations. This agreement suggests that local-scale factors including tidal-range change and sediment compaction were not important influences on RSL in the region over the past two millennia. Accord between the age and altitude of basal and nonbasal samples (13, 14) provided further evidence that both records were free of detectable compaction.

To extract climate-related rates of sea-level rise (Fig. 2C), we applied corrections for crustal movements associated with spatially variable and ongoing glacial isostatic adjustment (GIA). A constant rate of subsidence (with no error) was subtracted from the Sand Point (1.0 mm/y) and Tump Point (0.9 mm/y) records. These rates were estimated from a US Atlantic coast database of late Holocene (last 2000 y) sea-level index points (13, 15). Use of a constant rate is appropriate for this time period given Earth's rate of visco-elastic response (14). The resulting records are termed "GIA-adjusted," expressed relative to mean sea level from AD 1400–1800 and visually summarized by an envelope (Fig. 2C). Using Bayesian multiple change-point regression (16), we identified four intervals (successive linear trends) of long-term (century scale), persistent sea-level variations with 95% confidence (Fig. 2C). Within the error bounds of reconstructed sea level, greater variability in rates at subcentennial time scales can be accommodated. From at least BC 100 until AD 950, sea level was stable (0.0 to + 0.1 mm/y). Between AD 850 and 1080 the rate of sea-level rise increased to 0.6 mm/y (0.4 to 0.8 mm/y)

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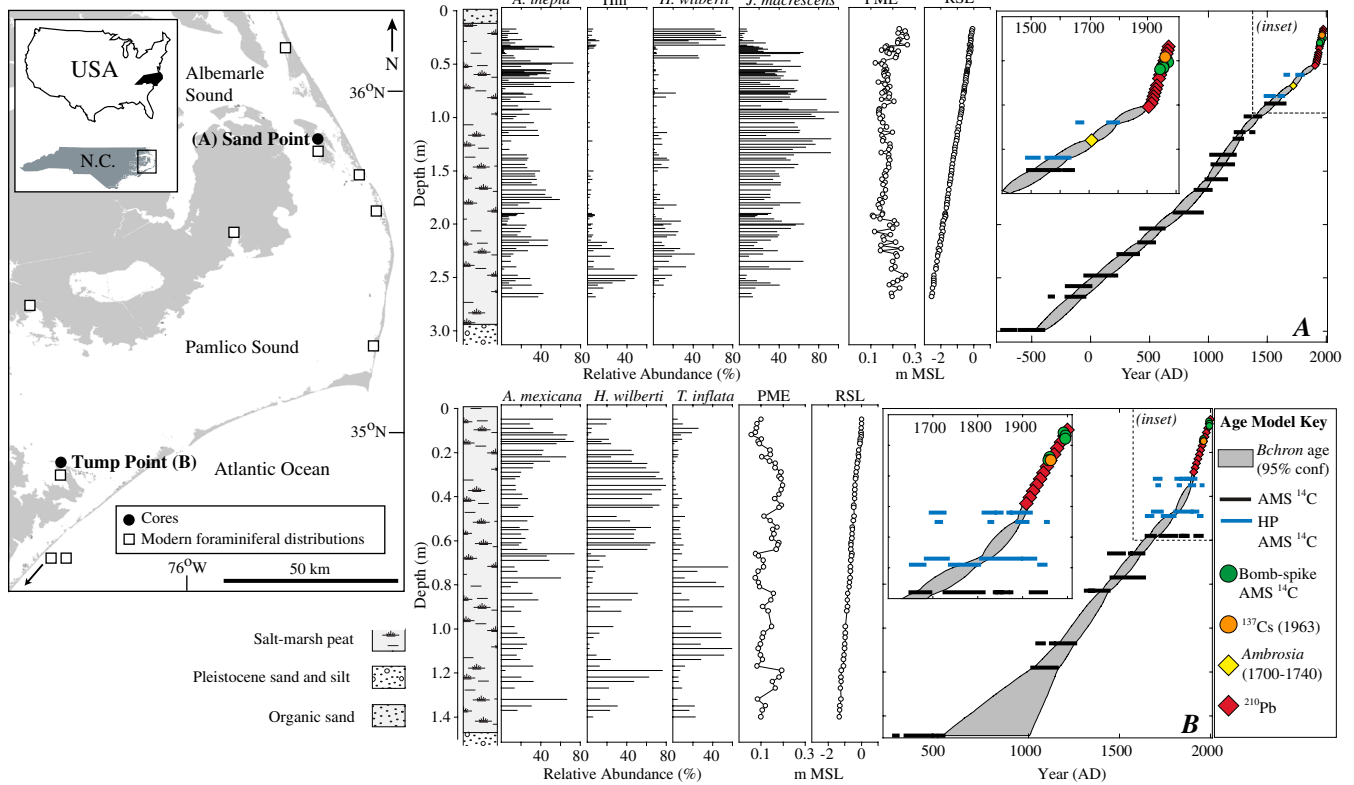
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**Fig. 1.** Litho-, bio-, and chrono-stratigraphy of the Sand Point (A) and Tump Point (B) cores (North Carolina, USA). Chronologies were developed using AMS  $^{14}\text{C}$  dating (conventional, high-precision, HP, and bomb-spike),  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$ , and a pollen horizon (*Ambrosia*). All dating results were combined to produce a probabilistic age-depth model for each core (10), shown as a gray-shaded area (95% confidence limits). This model estimated the age (with unique uncertainty) of samples at 1 cm resolution. Paleo marsh elevation (PME) above mean sea-level (MSL) was estimated for each sample by application of transfer functions to complete foraminiferal assemblages. Only the most abundant species are shown (Hm = *Haplophragmoides manilaensis*). RSL was estimated by subtracting PME from measured sample altitude.

for the following 400 y. A second change point at AD 1270–1480 marked a return to stable, or slightly negative, sea level ( $-0.2$  to  $0.0$  mm/y), which persisted until the end of the 19th century. Between AD 1865 and 1892 sea-level rise increased to a mean rate of  $2.1$  mm/y ( $1.9$  to  $2.2$  mm/y) (12). Sea-level variations in the last 2100 y did not exceed  $\pm 0.25$  m until the onset of the modern rise in the late 19th century. The modern rate of sea-level rise was greater than any century-scale trend in the preceding 2100 y; a conclusion that is independent of the GIA correction applied.

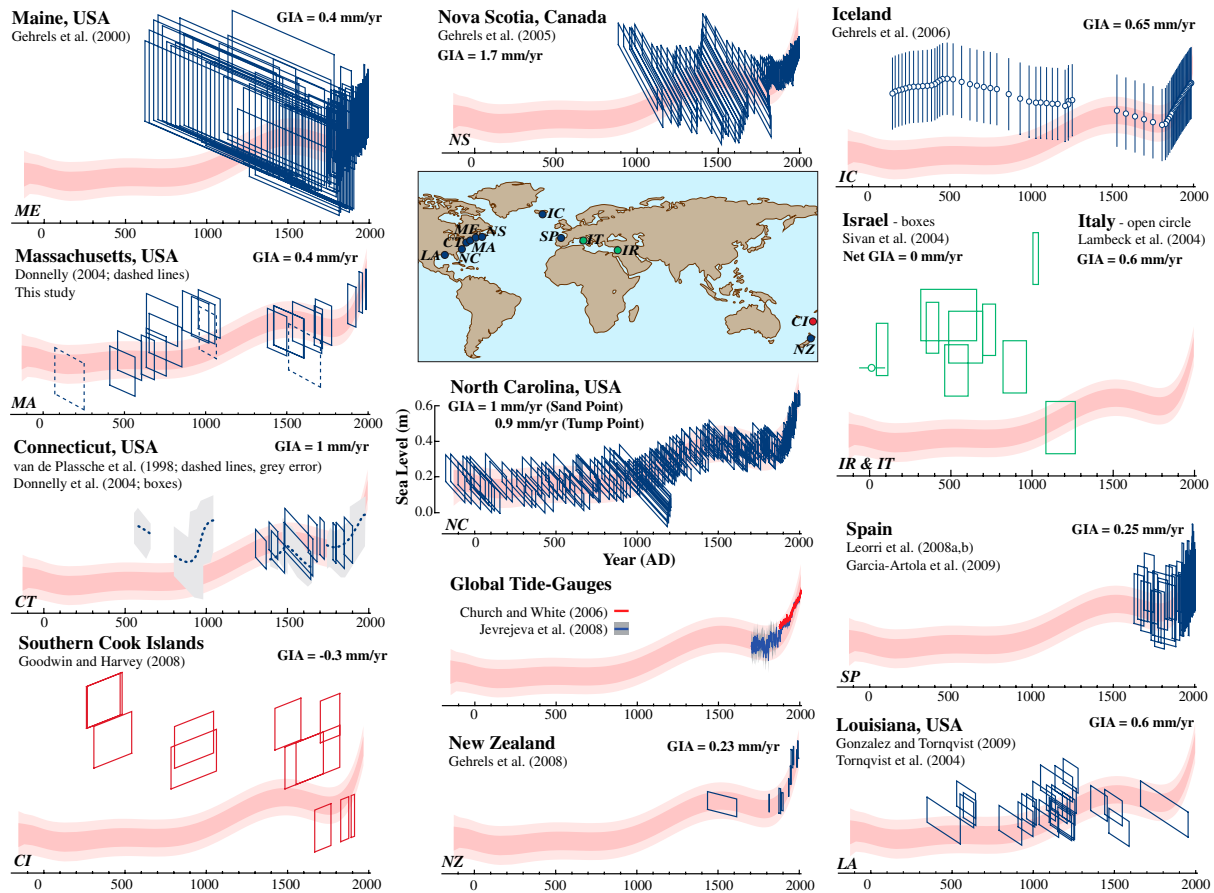
**Comparison with Other Proxy Sea-Level Reconstructions.** Most RSL reconstructions spanning the last 2000 y are from near- and intermediate-field regions affected by glacio-isostatic land movement because of their proximity to former ice sheets. To facilitate comparison among records, all sea-level reconstructions (including far-field regions) were adjusted for estimated GIA (Fig. 3). In Massachusetts, we developed a high-resolution reconstruction of RSL for the past 1500 y using macrofossils of common salt-marsh plants as sea-level indicators (Fig. S1). Sea level was stable prior to AD 500 and rose from AD 500 to 1000. The Massachusetts data agree with the North Carolina reconstruction, except for higher sea level between AD 700 and 1000 (although the uncertainty ranges overlap). There is a scarcity of high-resolution sea-level data covering the Medieval Climate Anomaly, particularly outside of North America (Fig. 3). Salt-marsh proxy records from the Gulf of Mexico (17, 18) show stable sea level until AD 1000, followed by rise to a peak at AD 1200. In Connecticut, sea level rose rapidly at AD 1000 (19), although this record may be compromised by sedimentary hiatuses from hurricane erosion (20, 21). In Iceland, sea level fell gradually from AD 500 to 1800,

possibly as a result of regional steric influences (22). All records from the Atlantic coast of North America, Gulf of Mexico, and New Zealand (23) show stable or falling sea level between AD 1400 and 1900 at the time of the Little Ice Age. A record from Connecticut (6) developed using salt-marsh plant macrofossils showed stable sea level between AD 1300 and 1800 (Fig. 3). The record from Maine (24) is inconclusive due to large uncertainties. In the Mediterranean Sea, archaeological evidence from Roman fish ponds in Italy located sea level 2000 y ago (50 BC to AD 100) at  $0.13$  m below present (25). In Israel, archaeological evidence compiled from coastal wells showed falling or stable sea level between AD 100 and 900 (26), including sea level above present from AD 300 to 700. There is some evidence for a 1 m sea-level oscillation at AD 1000. In the Cook Islands (far-field region), reconstructions from coral microatolls proposed falling sea level over the last 2000 y, including two low stands in the last 400 y separated by a high stand at AD 1750 indicating sea-level oscillations of up to  $0.6$  m (27), that are not observed in other proxy records. Atlantic reconstructions constrain the onset of modern sea-level rise to AD 1880–1920 (12) and are supported by salt-marsh records from Spain (28–30) and New Zealand (23). The Icelandic record suggests that local sea-level rise began earlier (AD 1800–1840). There are no reconstructions spanning the transition to modern rates of sea-level rise from the Mediterranean or far-field and these sea-level proxies have not been validated against instrumental records.

**Representation of Global Sea-Level Changes.** There is close agreement between reconstructed sea level in North Carolina and compilations of global tide-gauge data (31, 32) (Fig. 3; *SI Text*).







**Fig. 3.** Late Holocene sea-level reconstructions after correction for GIA. Rate applied (listed) was taken from the original publication when possible. In Israel, land and ocean basin subsidence had a net effect of zero (26). Reconstructions from salt marshes are shown in blue; archaeological data in green; and coral microatolls in red. Tide-gauge data expressed relative to AD 1950–2000 average, error from (32) in gray. Vertical and horizontal scales for all datasets are the same, and are shown for North Carolina. Datasets were vertically aligned for comparison with the summarized North Carolina reconstruction (pink).

In the following analysis, we kept the constraints established from instrumental sea-level data for AD 1880–2000 (4), which control the rapid response term (parameter  $b$ ) and the sum of the first two terms on the RHS of Eq. 2a. Compatibility with values for AD 1880–2000 implies that the parameters in Eqs. 1 and 2 are linked as follows to give the same total sea-level rise for this period from both equations:

$$a = a_1 + a_2 \quad \text{and} \quad T_0 = (a_1 T_{0,0} + a_2 \langle T_0 \rangle) / a, \quad [3]$$

where  $\langle T_0 \rangle$  is the average of  $T_0(t)$  over AD 1880–2000. If the resulting time scale  $\tau$  in Eq. 2 is multicentury,  $T_0(t)$  will vary little and sea-level curves for AD 1880–2000 will be almost identical to those shown in ref. 4. The parameter values found previously (3) for this time period were:

$$a = 0.56 \pm 0.05 \text{ cm/y/K}; \quad b = -4.9 \pm 1.0 \text{ cm/K}; \quad \text{and} \quad [4]$$

$$T_0 = -0.41 \pm 0.03 \text{ K}.$$

Hence two new parameters,  $a_2$  and  $\tau$ , together with an initial value  $T_{0,0}$ , are introduced, which need to be constrained from the new sea-level reconstruction. To do so, we forced the model with a global temperature record,  $T(t)$ , for AD 500–1850 (1). The two parameters were then constrained through Monte Carlo simulations combined with Bayesian updating from the North Carolina sea-level reconstruction (37).

**A Priori Solution.** We generated temperature curves using the Mann et al. (1) reconstruction (global land and ocean, Error-in-Variables, EIV) and its formal uncertainties. These data fulfilled our requirement of global (not just hemispheric) land and ocean coverage. For the instrumental period (temperatures based on HADCrutv3 dataset), we conservatively assumed error margins of  $\pm 0.06 \text{ K}$  for AD 1850–1950 and  $\pm 0.04 \text{ K}$  for AD 1950–2006 for decadal averages. These uncertainties formed a band surrounding the Mann et al. (1) temperature curve (Fig. 4A). Temperature curves were translated into corresponding sea-level curves using Eqs. 2 and 3. We described the prior uncertainties of the fit parameters  $a_1$ ,  $a_2$ ,  $b$ ,  $T_{0,0}$ ,  $T_0(t)$ , and  $\tau$ . For  $a$ ,  $b$ , and  $\langle T_0 \rangle$  we took the values given in Eq. 4 as true. Our a priori error distributions are presented in Table S3.

An ensemble of sea-level curves,  $T_0(t)$ , and its uncertainties were computed by integrating Eq. 2. Fig. 4B shows the a priori analysis with all parameters varied across their full a priori uncertainty ranges. Since AD 1000, reconstructed sea level from North Carolina was within the uncertainty bands for sea level predicted from the paleo-temperature data of Mann et al. (1), showing broad consistency among proxy sea level and proxy temperature data under the semiempirical relationship (Eq. 2).

**A Posteriori Solution.** We combined the two sources of data to constrain parameters and narrow uncertainty by using the North Carolina sea-level data to perform a Bayesian update on the a priori solution (SI Text). After constraining the parameters of the semiempirical model (Fig. 5), a good agreement among predicted



## Conclusions

We have presented a unique, high-resolution sea-level reconstruction developed using salt-marsh sediments for the last 2100 y from the US Atlantic coast. Post-AD 1000, these sea-level reconstructions are compatible with reconstructions of global temperature, assuming a linear relation between temperature and the rate of sea-level rise. This consistency mutually reinforces the credibility of the temperature and sea-level reconstructions. According to our analysis, North Carolina sea level was stable from BC 100 to AD 950. Sea level rose at a rate of 0.6 mm/y from about AD 950 to 1400 as a consequence of Medieval warmth, although there is a difference in timing when compared to other proxy sea-level records. North Carolina and other records show sea level was stable from AD 1400 until the end of the 19th century due to cooler temperatures associated with the Little Ice Age. A second increase in the rate of sea-level rise occurred around AD 1880–1920; in North Carolina the mean rate of rise was 2.1 mm/y in response to 20th century warming. This historical rate of rise was greater than any other persistent, century-scale trend during the past 2100 y.

## Materials and Methods

Sea level in North Carolina was reconstructed using transfer functions relating the distribution of salt-marsh foraminifera to tidal elevation (7, 12). Application of transfer functions to samples from two cores (at sites 120 km apart) of salt-marsh sediment provided estimates of PME with uncertainties

of <0.1 m. For each core a probabilistic age-depth model (10) was developed from composite chronological results and allowed the age of any sample to be estimated with 95% confidence. In Massachusetts, plant macrofossils preserved in salt-marsh sediment overlying a glacial erratic, were dated using AMS  $^{14}\text{C}$  and pollen and pollution chronohorizons (Fig. S1). The modern distribution of common salt-marsh plants was used to estimate PME. Sea level was reconstructed by subtracting estimated PME from measured sample altitude. Corrections for GIA were estimated from local (13) and US Atlantic coast (15) databases of late Holocene sea-level index points. Detailed methods are presented in *SI Text*.

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# Supporting Information

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## SI Text

**Reconstructing Relative Sea Level in North Carolina and Massachusetts.** In North Carolina, a modern dataset of 193 surface samples collected from 10 salt marshes (1) was used to develop transfer functions to quantify the relationship between foraminifera and elevation (2). We used these transfer functions to estimate paleomarch elevation (PME) at Sand Point and Tump Point, North Carolina. PME is the elevation at which a sample formed with respect to its contemporary sea level (3). Foraminifera preserved in 1 cm thick samples from the Sand Point and Tump Point cores provided the basis for estimating PME. To reconstruct relative sea level (RSL), estimated PME was subtracted from the measured altitude of each sample. Core-top elevations were established by leveling to geodetic benchmarks (Sand Point) and Real Time Kinematic (RTK) satellite navigation (Tump Point), thus sample altitude was derived from depth-in-core measurements. Foraminifera and PME estimates for the Sand Point and Tump Point cores are presented in Fig. 1. Transfer functions provide error estimates that are unique to each sample (4). Uncertainty from sampling (e.g., angle of bore hole, sample thickness, RTK error) was minimal and not included in the vertical sea-level errors.

At Wood Island (Massachusetts), salt-marsh plants were used as sea-level indicators (5). The modern mean elevation of *Juncus gerardii* (Jg), *Spartina patens* (Sp), and *Distichlis spicata* (Ds) was estimated by measuring stands at the Wood Island site. Multiple, stratigraphically ordered, samples were recovered along the boundary between a gently sloping granite erratic and overlying salt-marsh sediments. Identifiable remains of Jg, Sp, and Ds were used to provide an estimate of PME (Fig. S1).

**Developing Composite Chronologies for North Carolina and Massachusetts.** Original dating results for North Carolina and Massachusetts are provided in a separate file. A separate chronology was developed for the Sand Point and Tump Point cores, which were not combined or used to constrain one another in any way. The uppermost part of both cores was dated using a  $^{210}\text{Pb}$ -derived accumulation history. Sample ages were estimated using the constant supply constant flux model (6), which was independently corroborated by a  $^{137}\text{Cs}$  peak (corresponding to AD 1963) and bomb-spike  $^{14}\text{C}$  dates. Material prepared for bomb-spike  $^{14}\text{C}$  dating was analyzed using Accelerator Mass Spectrometry (AMS) with 15 repeats of 30,000 counts. Multiple samples were dated to facilitate calibration using the Northern Hemisphere Zone 2 dataset of Reimer et al. (7). High-precision  $^{14}\text{C}$  ages (8) were obtained by preparing duplicate or triplicate samples from the same depth interval and using a pooled mean (Calib 5.0.1 software program) for calibration. Radiocarbon activity was determined from 15 repeats of 30,000 counts to improve instrument-related precision. Calibration was undertaken using Calib 5.0.1, reported errors are  $2\sigma$ . An additional 15 samples at Sand Point and 7 at Tump Point were dated using conventional AMS  $^{14}\text{C}$ . Calibration was undertaken using Calib 5.0.1, reported errors are  $2\sigma$ . All samples were prepared for radiocarbon dating by cleaning under a binocular microscope to remove contaminating material. A pollen chronohorizon was identified in the Sand Point core by an increase in *Ambrosia* to 2% of total pollen, this change is indicative of land clearance during European settlement and was assigned an age of AD 1720  $\pm$  20 y (9).

The discreet dated samples from Sand Point and Tump Point were used to generate a probabilistic age-depth model for each of the cores separately using the statistical package *Bchron* (10)

executed in *R*. This approach used many thousands of iterations of the available data to provide an age-depth model with 95% confidence. This model was subsequently used to estimate the age (with a unique uncertainty) of every 1 cm thick sample in both cores, including those that were not directly dated. The uncertainty associated with estimating the age of individual 1 cm thick intervals ranged from  $\pm 1$  y (minimum) to  $\pm 193$  y (maximum), although more than 95% of samples had uncertainty of less than  $\pm 71$  y. In general, the smallest chronological errors were in the uppermost sections of each core (most recent), where age was constrained by techniques ( $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$ , bomb-spike  $^{14}\text{C}$ , and a pollen chrono-horizon) with small error terms. The chronologies (dates and age-depth models) for the Sand Point and Tump Point cores are presented in Fig. 1.

In Massachusetts, each of the samples used for estimating PME was also dated. 14 of the plant macrofossil samples were directly dated using AMS  $^{14}\text{C}$ . Pollen evidence of European land clearance (AD 1700 in this region) and the chestnut decline (AD 1930) were used to estimate the age of two samples. A peak in  $^{137}\text{Cs}$  associated with above ground testing of nuclear weapons was assigned an age of AD 1963 and an industrial horizon (AD 1875) was recognized by increased Pb and Cu concentrations and the occurrence of opaque spherules. The stratigraphical relationship between samples was used manually to better constrain the chronology derived from calibrated  $^{14}\text{C}$  ages and reduce uncertainty. The dates and age model for the Wood Island site are presented in Fig. S1. The elevation-depth model, developed using *Bchron* (10), supports the manual constraint of the chronology.

All sea-level data points are represented by boxes incorporating the elevational and chronological uncertainties associated with individual samples. This data is presented in Table S1 for North Carolina and for Massachusetts. Reconstructed sea level from the Sand Point and Tump Point cores for the last  $\sim 400$  y was presented by Kemp et al. (2). However, the data presented here spanning the last 400 y improve upon the existing record by introducing additional foraminiferal counts and new, statistically rigorous age-depth models developed using a newer technique.

In the main manuscript the data points reconstructing sea level in North Carolina are summarized using a 9 degree polynomial with  $1\sigma$  and  $2\sigma$  errors used to create a sea-level envelope which we have presented in pink. The purpose of this envelope is solely to provide a convenient visual summary of the data to aid the reader. The polynomial summary was not used for analysis of sea-level change in North Carolina.

**Estimating Vertical Land Movements Associated with Glacial Isostatic Adjustment (GIA).** Reconstructions of relative sea level are the net result of eustatic, isostatic, tectonic, and local factors. We assumed the tectonic factor to be zero in North Carolina and agreement between reconstructions from Sand Point and Tump Point (120 km apart) suggested that local factors were not a major influence. By assuming that the eustatic contribution to sea-level change over the last 2000 y was minimal (11), late Holocene sea-level reconstructions can be used to estimate the rate of GIA. A zero late Holocene sea-level eustatic function is a feature of most GIA models (12–14).

We used a standardized database of sea-level reconstructions collated for the US Atlantic coast to estimate the rate of GIA in North Carolina (15, 16). All data points that were not of base of basal or basal origin were excluded to negate the influence of sediment consolidation. Linear regression of the sea-level

data points over the last 2000 y (excluding changes since AD 1900) estimated the rate of GIA to be  $1.00 \pm 0.03$  mm/y in the region of Sand Point and  $0.90 \pm 0.02$  mm/y at Tump Point. This uncertainty is the  $2\sigma$  error of the regression line. Linear regression of midpoint sea-level reconstructions is appropriate for estimating rates of GIA in regions with sea-level histories constrained by a large number of data points with small age and vertical errors such as North Carolina (16). Model predictions support the use of a single linear rate of GIA over the late Holocene given Earth's rate of viscoelastic response (12–14). Predictions specifically for the areas around Sand Point and Tump Point show linear GIA for the last 2000 y (15). According to Engelhart et al. (16), there is 95% confidence that estimated rates of GIA (using this method) over the last 4000 y in North Carolina were within 0.10 mm/y of the values we have applied. GIA uncertainty has a propagating effect when used to adjust geological data because it becomes increasingly large further back in time. We did not include this effect as a stochastic error in our sea-level reconstruction (Figs. 2 and 3), but visually illustrate its influence by conservatively assuming a GIA uncertainty of  $\pm 0.15$  mm/y in Fig. 4.

Direct comparison among sea-level records is facilitated by correcting sea-level reconstructions for the effect of GIA. Uncertainty in estimating rates of GIA is therefore a possible cause for differences among records. All sites required correction for GIA. However, the location of a sea-level reconstruction (near, intermediate, or far field) does not influence the uncertainty of estimated GIA only its absolute value. In fact, uncertainty is proportionally less at sites experiencing high rates of GIA. Regional estimates of GIA have been derived from geological data or model predictions. Uncertainty is therefore dependent upon the quality of available geological data or the accuracy of model predictions which themselves have often been calibrated using sea-level data. The US Atlantic coast has one of the most detailed records of late Holocene sea level and sufficient, quality controlled data exists to identify regional GIA trends with confidence.

The rate of GIA for Wood Island and Revere, Massachusetts (0.4 mm/y) and Barn Island (5), Connecticut (1 mm/y) was estimated using the same approach as described for North Carolina. In Figure 3, all sea-level records presented have had estimated GIA removed. Other published studies of late Holocene sea-level change were adjusted for rates of glacio-isostatic adjustment (GIA) using estimates presented in the original publication [Maine (17), Nova Scotia (17, 18), Louisiana (19), Iceland (20), Israel (21), Italy (22), and the Cook Islands (23)], or from ref. 24 in the cases of Spain and New Zealand. No GIA correction was applied to the Israel data as the original publication states that the net effect was zero (21) because the rate of land subsidence was offset by ocean basin subsidence. In the Cook Islands, GIA is solely from subsidence of the ocean basin (23). In each example, except the record from Connecticut (25), sea-level data (and associated errors) were taken directly from the original publication or kindly provided by the author.

**Estimating Rates of Sea-Level Change.** Following adjustment for rates of GIA, we estimated rates of sea-level change for North Carolina. The datasets from Sand Point and Tump Point were only merged after this adjustment, by combining the age and sea-level estimates associated with individual data points into a single list. The sea-level data for North Carolina is complex because it consists of a large number of data points that are not spaced at regular temporal intervals and each of which has unique vertical and age uncertainties with an associated error distribution. Given the nature of the data, we used Bayesian change-point linear regression (26) to objectively and quantitatively identify discrete periods of GIA-adjusted sea-level change in North Carolina. We used the GIA-adjusted sea-level data points in this

analysis and not the summary polynomial sea-level curve (Figs. 2, 3, and 4). This technique is able to provide probabilistic estimates of rates and the timings of rate changes in complex data following many thousands of iterations. Three change-points gave a good fit to the data by providing four successive segments of sea-level change, each of which was described by a linear rate of change. The regression was forced through zero because RSL must equal zero at the time of core collection. The model takes account of calibrated radiocarbon uncertainty by approximating each calibrated age as a normal distribution; it also takes into consideration vertical errors.

This technique provides a most likely sea-level history given the distribution of the data points and the distribution of uncertainties within them. The fitted lines represent mean, long-term, sea-level change rates and have 95% upper and lower confidence intervals. The model is necessarily an approximation, as each of the four segments is linear, and changes are instantaneous rather than gradual. For the North Carolina reconstruction, sea level prior to the first change-point (AD 853–1076) was between  $-0.03$  and  $+0.06$  mm/y (95% confidence). From here until the second change-point (AD 1274–1476) sea level rose at  $0.37$ – $0.80$  mm/y (95% confidence interval). The third segment, until a change-point at AD 1865–1892, showed sea-level change of  $-0.16$  to  $+0.02$  mm/y (95% confidence). Since this most recent change-point sea level has risen at a rate of  $1.90$ – $2.20$  mm/y (95% confidence interval). These ranges represent the uncertainty in fitting a single best fit change-point regression through the proxy data. However, due to the age and vertical errors in the proxy sea-level data, shorter-lived sea-level changes (particularly at subcentennial time scales) exceeding the rates described can be accommodated. Indeed, any sea-level history is permissible with the confines of the error boxes although the results from change-point linear regression suggest that they are less likely than the sea-level changes we described.

Bayesian change-point analysis was not applied to the Massachusetts data (or other reconstructions of sea level as presented in Fig. 3) because of temporal gaps in the record of up to 400 y. We calculated a GIA-adjusted value of sea-level change during the 20th century from the mid points of AD 1899 (RSL =  $0.24 \pm 0.04$  m) and AD 2004 (RSL =  $0 \pm 0.04$  m).

#### Validating Sea-Level Reconstructions Using Tide-Gauge Records.

Instrumental records of sea-level variability provide a unique opportunity to independently check proxy-based reconstructions. Tide-gauge measurements are commonly averaged to reduce one year of data to a single point. Gauges with more than 50 y of data are considered to be the most representative of sea-level trends as the influence of annual-decadal scale variability is minimized (14, 16, 27). The distribution of such gauges is strongly biased toward the northern hemisphere. The longest tide-gauge records (such as Amsterdam, Liverpool, Brest, and Stockholm) are located in northern Europe (28, 29).

Sea-level reconstructions from salt marshes are developed using 1 cm thick slices of sediment from core material. The effect of this approach is twofold. Firstly, sea-level indicators on salt marshes such as plants and foraminifera do not respond to short-lived variability in sea level. Secondly, the 1 cm slices of sediment represent a period of time, which is dependent on the rate of sediment accumulation, but is on the order of years. Both of these factors serve to make salt marshes excellent archives of persistent paleo sea-level trends because short-lived and annual variability is naturally filtered out. Therefore it is unreasonable to expect sea-level reconstructions to resolve sea-level changes with the same resolution as tide gauges. In fact, this filtering means it is often easier to extract sea-level trends from salt marshes than from noisy tide-gauge records.

We consider reconstructed sea level to be in agreement with tide-gauge measurements when persistent trends can be seen



in both records and where tide-gauge measurements pass through sea-level reconstruction boxes incorporating age and vertical uncertainties. In Fig. 2B we show that tide-gauge data with annual resolution from North Carolina (since AD 1936) and Charleston, South Carolina (since AD 1920) are in agreement with the sea-level reconstructions from Sand Point and Tump Point. Compilations of tide-gauge records with global significance (28, 29) have recently been extended to AD 1700. In Fig. 3 we show that there is excellent agreement among these records and reconstructed sea level in North Carolina. For the period since AD 1880 the record of Church et al. (30) does not leave the summary sea-level envelope constructed for North Carolina and at no point does the midpoint of the Jevrejeva et al. record (28) covering the period since AD 1700 leave this envelope (Fig. 3). In Fig. S6 we compare the North Carolina sea-level reconstruction to the global tide-gauge-compilation of ref. 28, where the tide-gauge data was summarized using change-point regression. The largest difference between the two datasets was 6 cm which is less than the uncertainty for the North Carolina reconstruction and much of the tide-gauge data. This agreement provides confidence that salt marshes in North Carolina provide accurate reconstructions of long-term, persistent changes in sea level during the late Holocene.

**High-Resolution Numerical Modeling of Tidal-Range Change from Barrier Breaching in the Albemarle–Pamlico Estuarine System of North Carolina.** If tidal range has changed through time, sea-level reconstructions based upon tide-level indicators will differ from the “true” sea-level curve. To investigate this influence for Sand Point and Tump Point we modeled the influence of barrier breaching on tidal range using the Advanced Circulation Model for Coastal Ocean Hydrodynamics (ADCIRC). The open boundary of the grid was forced with six tidal constituents and runs were carried out for 60 d of model time, with a 10 d ramp. The final 45 d of the simulations were used to perform a harmonic analysis of the results. This harmonic analysis yielded the amplitudes and phases of 23 tidal constituents. In turn, these constituents were used to determine major tidal datums, such as mean higher high water (MHHW), mean lower low water (MLLW). Tidal range was taken to be the difference between MHHW and MLLW. The modeled study area covered the Outer Banks area of North Carolina from Bogue Inlet in the south to the border of North Carolina and Virginia in the north. In this region there are currently six inlets. From north to south these are: Oregon Inlet, Hatteras Inlet, and Ocracoke Inlet, which lead into Pamlico Sound; Drum Inlet and Barden Inlet (at Cape Lookout), which lead into Core Sound; Beaufort Inlet and Bogue, which lead into Bogue Sound. The tidal range on the ocean-side of the Outer Banks ranges from about 0.75 m to 1.25 m. Once the tide propagates through the northern inlets, it is quickly damped in Pamlico and Albemarle Sounds to a range that is less than 0.25 m and in many places less than 0.15 m. In Core, Back, and Bogue Sounds, tidal range is lower than on the ocean-side of the Outer Banks, but ranges from 0.25 m to 1.1 m.

**Small inlet breaches.** For this study, eight additional inlets were added to the model domain. Each of these new inlets was set to an approximate center depth of 6 m. As with existing inlets, tidal range declined rapidly after the tide propagated through the inlets. Increasing the number of inlets caused tidal range at our study sites to increase on the order of 0.05 m, within the uncertainty band shown for our analysis.

**Large inlet breaches.** To simulate “catastrophic” collapse of the barrier islands, six huge sections of the Outer Banks were removed. The bathymetry that existed in the original grid on either side of the barrier islands was kept, and simply interpolated between these two to create a new depth in the area where

the island was supposed to have collapsed. The results from the model simulations show tidal range increases in the sound area. There was significant spatial variability, with larger increases near to Tump Point, and lower increases toward the Pamlico and Neuse River inlets, near the Sand Point site. These differences in tidal range would produce RSL reconstructions from Sand Point and Tump Point that would be different to one another. But the records have near identical sea-level variations. This agreement suggests that tidal-range change was not an important influence on sea level in the region over the past two millennia.

**Ice Sheet Gravity Effect on the Proxy Sea-Level Data.** In addition to the effect of GIA since the last deglaciation, there is also the gravity effect on the geoid of shrinking continental ice sheets, and thus on local sea level. This phenomenon causes local rates of sea-level rise to differ from the global average and has been termed fingerprinting (31). The values found by Mitrovica et al. (31) are provided in Table S2, for two different GIA modeling approaches. The first approach uses, as they explain, “the combination of ice and Earth models adopted in a number of earlier studies;” the second uses a modified GIA model, where lower mantle viscosity is increased from  $2 \times 10^{21}$  to  $5 \times 10^{21}$  Pa s (Pascal seconds), in order to better fit historical tide-gauge data along the US Atlantic coast (Table S2).

The “fingerprint” of sea-level rise in North Carolina due to melting of the Greenland Ice Sheet, defined as local sea-level rise expressed as a fraction of global average sea-level rise from this source, is 60% (from Fig. 1B in ref. 31). For small glaciers, the fingerprint is 95% (from Fig. 1C in ref. 31). If we assume a fingerprint of 100% for both Antarctica and “other” (mainly thermoteric rise), we find that the *total* sea-level rise in North Carolina, computed using the above tabulated contributions as weights, is 87% and 83% respectively under the two GIA scenarios (see Fig. 1A in ref. 31).

As there is no guarantee that relative contributions from the various continental ice sheets to sea-level rise have been constant over time, it is not feasible to correct the North Carolina record for this effect because the uncertainties are too great. We restrict ourselves here to a sensitivity study, where we assume local sea-level rise to be 83% of the global average (i.e., we multiply North Carolina sea-level values by  $1/0.83 = 1.2$ ) to compare with sea-level curves reconstructed from the temperature proxy data. This exercise is depicted in Fig. S2. It is seen that even a worst-case fingerprint effect of 83% leads only to a barely (if at all) visible deterioration of the quality of fit.

**Assumed Prior Information.** We assumed the statistics summarized in Table S2 for the reconstructed temperatures, model fit parameters, and integration constants.

**Bayesian Updating to Estimate the Model Parameters.** We used Bayes’ theorem in the following form:

$$P(\theta|x) = (P(x|\theta)/P(x))P(\theta) = L_x(\theta)P(\theta),$$

where we defined the likelihood function as

$$L_x(\theta) = \prod_{i=1}^n \exp((-1/2)(H(t_i; \theta) - H_i)^2/\sigma^2),$$

where  $H_i$  is a proxy-reconstructed sea-level value,  $\theta = \{\tau, a_1, a_2, H_0, \langle T_0 \rangle, T_0(\text{AD}500), T(t)\}$  is the unknown parameter vector for which our Bayesian update will produce a probability density distribution, and  $H(t_i; \theta)$  is sea level as predicted from temperature by our relationship for the epoch  $t_i$ . Standard error ( $\sigma$ ) is the formal uncertainty of the  $n$  sea-level proxy data points.  $H_0$  and  $T_0(\text{AD}500)$  are integration constants of Eq. 2.

Note that the above equation describes the goodness by which an individual sea-level curve as predicted by our relationship from a Monte Carlo generated temperature curve “fits through” the observed sea-level points  $H_j$ . Thus, in the Bayesian update step this quantity is used to update the a posteriori probability of this curve among the generated ensemble. These probabilities, for all ensemble members, are then used to generate a posteriori uncertainty bands.

The result of the Bayesian prediction is somewhat dependent on the choice of weighting for the sea-level proxy data; it is necessary to downweight them (or inflate their assumed variance) to take into account that they are subject to strong serial correlation. An appropriate choice for this factor would be 10. With this choice, we find it is not possible to obtain a reasonable a posteriori result for the entire data period: it is necessary to exclude the sea-level data before AD 1000 from the fit.

Fig. 5 shows the resulting probability density distributions for the unknown parameters and functions of interest, and some correlation point clouds. One sees that parameter  $a_1$  is constrained to 0–0.25 cm/K/y, and  $\tau$  to 0–1000 y, with likely values in the 100–500 y range.

**Computation and Plotting Details.** We generated the medial curves and uncertainty bands displayed in our plots in the following way. For plots marked a priori, we generated 1,000 samples, for plots marked a posteriori, 25,000 samples. The plotted curves were smoothed using Singular Spectrum Analysis (SSA) smoothing (32) with an “embedding dimension” of 15 y, compatible with Vermeer and Rahmstorf (33). A polynomial was fitted to the North Carolina sea-level reconstruction and was used as a visual summary of the data. A 9 degree polynomial (as opposed to one of higher or lower order) was used because it captured the main features of reconstructed sea-level behavior at the time scales we resolve. Raising the degree only marginally improved fit to the data.

Both temperatures and sea levels were plotted relative to a reference level equal to the average for the period AD 1400–1800 [for the Mann et al. (34) reconstructed temperatures and the North Carolina reconstructed sea levels, respectively], corresponding with a reasonable notion of “preindustrial.” In the plots, the reconstructed North Carolina sea levels are represented by a red curve with pink  $1\sigma$  and  $2\sigma$  uncertainty bands, cut away for visibility where appropriate.

**The values of  $a_1$  and  $T_{0,0}$ .** From the plots in Fig. 5 (in particular, the two bottom right ones) it is seen that, while  $a_1$  and  $T_{0,0}$  are not separately strongly constrained, nevertheless the product  $-a_1 \cdot T_{0,0}$  is constrained, and positive. As  $a_1$  approaches zero from above,  $T_{0,0}$  approaches minus infinity. This behavior is a direct consequence of the compatibility condition (35)

$$aT_0 = a_1T_{0,0} + a_2\langle T_0 \rangle$$

with the parameters found from the fit to the instrumental period (33). Our results thus suggest a positive value for the secular part of sea-level rise today.

**Weighting and fit for the early period (AD 500–1100).** To fit the sea-level proxy data back to AD 500 required down-weighting of the data and generated an inadequate fit with broad uncertainty bands, suggesting that the data is not compatible. Restricting the Bayesian update to only post-AD 1000 sea-level data markedly improved the fit (Fig. 3D), but increased divergence between sea-level proxy data and sea-level predicted prior to AD 1000. There is independent evidence (21, 22) that the steep sea-level rise predicted from temperatures between AD 500 and 1000 is unphysical, and thus that the sea-level proxy data from North Carolina for this period are more realistic. This

conclusion is supported by sea-level reconstructions from Massachusetts (36) and elsewhere (16, 37).

Lowering reconstructed temperature by 0.2 K for the period AD 500–1100 produced good agreement with the North Carolina sea-level reconstruction (Fig. S4). We studied the sensitivity of this fit to a range of temperature corrections (–0.1 K to –0.3 K). As shown in Fig. S5, the best agreement was for a –0.2 K correction. An error of this magnitude is not implausible as we used the global Mann et al. (34) reconstruction prior to AD 1100 and not the Northern-Hemisphere-only reconstruction in which Mann et al. (34) had greater confidence. For the period prior to AD 1100, availability of proxy temperature reconstructions is poor for the Southern Hemisphere and this is necessarily reflected in greater uncertainty for global estimates which can accommodate a 0.2 K reduction in temperature within their uncertainty. This reduction in reconstructed temperature would make the Medieval Climate Anomaly globally less pronounced than Mann et al. (34) suggested, and reduce by a half its temperature contrast with the Little Ice Age.

An alternative explanation is that reconstructed sea level is in error. This reasoning does not appear credible because no other sea-level reconstruction suggests a stronger sea-level rise before AD 1100 (Fig. 3), as warm temperatures would imply under our semiempirical model. More rapid sea-level rise prior to AD 1100 would be a feature of predicted sea level using the Mann et al. (34) global temperature record and our semiempirical model regardless of the correction made for GIA. Further, agreement between the Sand Point and Tump Point records, despite differences in accumulation history and being more than 100 km apart suggests that local-scale factors were not important influences on RSL.

While the Grinsted et al. (38) prediction of former sea level is somewhat similar to ours, it features large sea-level variations (greater than 0.5 m) during the last 2000 y (see Fig. S6). The magnitude of these predicted sea-level changes is dependent on the temperature reconstructions used as input and their uncertainties. Only for the post-AD 1700 period, for which Grinsted et al. (38) used tide-gauge data from northwestern Europe to calibrate their model, is there a good agreement with our result. This agreement implies that these extended tide-gauge records are representative of former sea level.

**Performance over the instrumental period.** We tested the performance of our relationship over the instrumental period, AD 1880–2000 (Fig. 6). For temperatures, taken from Mann et al. (34), this is essentially a test of the HadCRUTv3 temperature dataset. For instrumental sea level, we took Church and White (29), with an estimated contribution due to the artificial reservoir effect added as described in ref. 33.

**Loose parameter constraints.** We also produced a reconstruction in which we did not use the prior constraints on the parameters from ref. 33. Instead, we used the following, loose constraints, effectively producing near-ignorant priors:

$$a = 0.44 \pm 0.5 \text{ cm/K/yr}$$

$$b = 0 \text{ (exactly)}$$

$$T_0(\text{AD } 1880\text{--}2000) = -0.45 \pm 0.3 \text{ K.}$$

Furthermore we loosened the constraint of the integration constant  $H_0$  to be  $U(-10 \text{ cm}, 10 \text{ cm})$ . The reason for fixing  $b$  was, that it is not possible to simultaneously solve for  $a$  and  $b$  using only the paleo data, as we found this to be an ill-posed problem. Fixing  $b$  to another value will only change the value obtained for  $a$  and not produce any other significant changes to the solution.

For this run we used a sample size of 250,000 instead of the usual 25,000. We found the following posteriors:

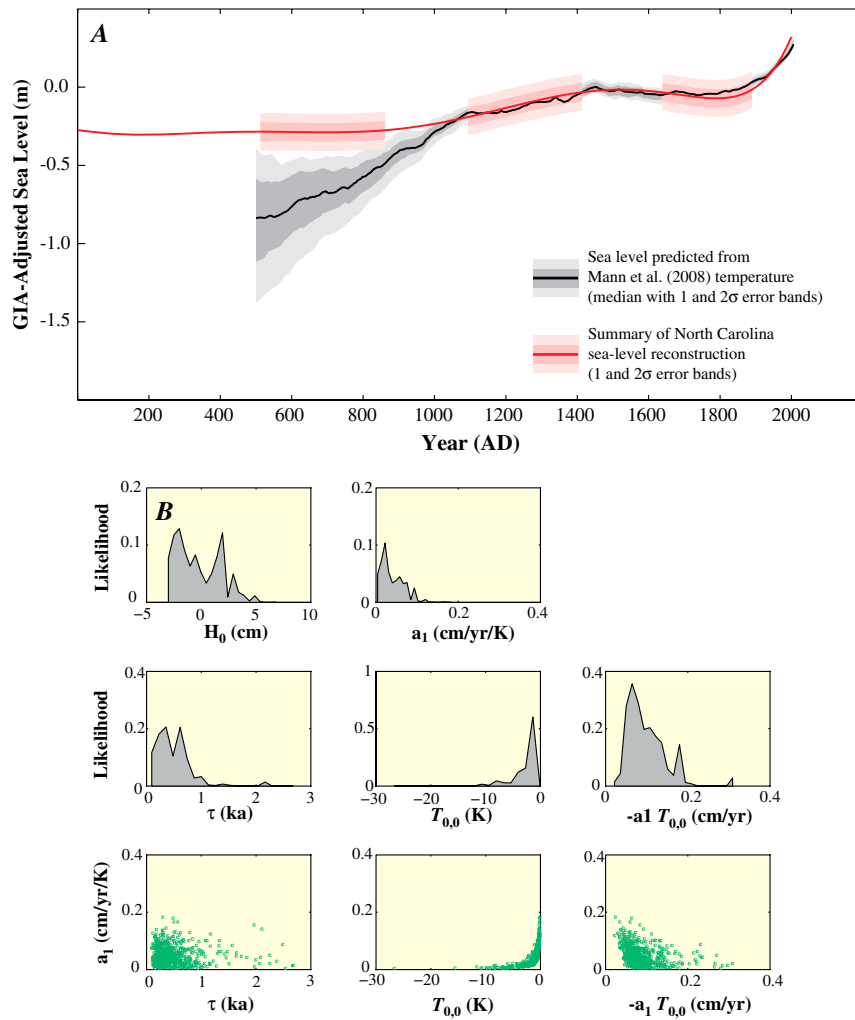
$$a = 0.60 \pm 0.15 \text{ cm/K/yr}$$
$$-a_1 \cdot T_{0,0} = 0.139 \pm 0.043 \text{ cm/yr}$$
$$\ln(\tau) = 5.83 \pm 0.78[\tau \text{ in years}].$$

From Fig. S3 we see that  $\tau$  is still robustly constrained to be finite. Also, remarkably,  $-a_1 \cdot T_{0,0}$ , a measure for long-term (intermillennial) sea-level rise, is seen to be very likely positive.

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**Fig. S2.** Sensitivity analysis for the ice sheet gravity effect in North Carolina. Shrinking ice sheets distort the geoid causing local sea-level changes to differ from the global average. (A) Sea-level reconstruction from paleo-temperature (gray) and proxy-reconstructed sea levels from North Carolina with uncertainties as cutaway color bands (pink). Scaled for a fingerprint in which North Carolina experiences 83% of global sea-level rise (computed in Table S2). GIA-adjusted sea level is expressed relative to AD 1400–1800 average. (B) Posterior probability density distributions and correlation point clouds for selected quantities; ka is thousand years.

















**Table S2. Fingerprints for North Carolina and other areas with proxy sea-level data**

	Greenland (mm/yr)	Antarctica plus others (mm/yr)	Meier (mm/yr)	Sum (mm/yr)				
Wt *	0.54	0.99	0.46	1.99				
Wt †	0.60	0.61	0.46	1.67	Factors relative to NC			
					For wt *	For wt †	x NC (1)	x NC (2)
Nova Scotia	0.20	1.00	0.90	0.76	0.69	1.14	1.21	
Massachusetts	0.30	1.00	0.90	0.79	0.72	1.10	1.15	
Connecticut	0.40	1.00	0.90	0.81	0.76	1.07	1.09	
North Carolina	0.60	1.00	0.90	0.87	0.83	1.00	1.00	
Louisiana	0.80	1.00	0.95	0.93	0.91	0.93	0.91	

\*uses ice and Earth models (1)

†uses a modified GIA model, where lower mantle viscosity is increased from  $2 \times 10^{21}$  to  $5 \times 10^{21}$  Pa s, in order to better fit to tide gauges on the US Atlantic coast (1)

1 Mitrovica JX, Tamisiea ME, Davis JL, Milne GA (2001) Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature* 409:1026–1029.

**Table S3. Assumed prior statistics**

Item	Distribution	Remarks
$T(t < \text{AD } 1850)$	$M(t) + N(0, (0.15 \text{ K})^2)$	decadal, uncorrelated; (2)
$T(\text{AD } 1850\text{--}1950)$	$M(t) + N(0, (0.06 \text{ K})^2)$	decadal, uncorrelated; (3)
$T(\text{AD } 1950\text{--}2006)$	$M(t) + N(0, (0.04 \text{ K})^2)$	decadal, uncorrelated; (3)
$a$	$N(0.56 \text{ cm/yr/K}, (0.05 \text{ cm/yr/K})^2)$	(1)
$\langle T_0(\text{AD } 1880\text{--}2000) \rangle$	$\langle T(\text{AD } 1951\text{--}1980) \rangle + N(-0.41 \text{ K}, (0.03 \text{ K})^2)$	(1) constrained $T_0$ for this interval
$a_1$	$U(0.01, 0.51) \text{ cm/yr/K}$	secular response part
$b$	$N(-4.9 \text{ cm/K}, (1.0 \text{ cm/K})^2)$	(1)
$\tau$	$400 \cdot \exp(U(-2, 2)) \text{ yrs}$	$\ln(\tau)$ uniformly distributed for $\tau = 135\text{--}7400$ years
$T_0(\text{AD } 500)$	$N(\langle T(\text{AD } 500\text{--}700) \rangle, (0.2 \text{ K})^2)$	starting value for $T_0$ integration
$H_0$	$C + U(-5, 5) \text{ cm}$	sea-level integration constant

$M(t)$  refers to the proxy-reconstructed paleotemperatures used;  $C$  is a constant chosen for computational reasons such that the prior will not constrain the posterior.  $N(\mu, \sigma^2)$  is the normal distribution of central value  $\mu$  and variance  $\sigma^2$ ;  $U(a, b)$  is the uniform distribution between  $a$  and  $b$ .  $K$  is Kelvin

1 Rahmstorf S (2007) A semiempirical approach to projecting future sea-level rise. *Science* 315:368–370.

2 Mann ME, et al. (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc Natl Acad Sci USA* 105:13252–13257.

3 Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J Geophys Res* 111:D12106.