Geophysical Research Letters

Supporting Information for

A pre-industrial sea-level rise hotspot along the Atlantic coast of North America

W. R. Gehrels[1*], S. Dangendorf[2,3], N. L. M. Barlow[4], M. H. Saher[5], A. J. Long[6], P. L. Woodworth[7], C. G. Piecuch[8], and K. Berk[9]

1 Department of Environment and Geography, University of York, Heslington, York, YO10 5NG, United Kingdom

2 Research Institute for Water and Environment, University of Siegen, 57076, Siegen, Germany

3 Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, 4600 Elkhorn Avenue, Norfolk, VA23529, USA

4 School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom

5 School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, United Kingdom

6 Department of Geography, Durham University, Durham, DH1 3LE, United Kingdom

7 National Oceanography Centre, Liverpool, L3 5DA, United Kingdom

8 Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA

9 Department of Mathematics, University of Siegen, 57076, Siegen, Germany

*Corresponding author: Roland Gehrels (roland.gehrels@york.ac.uk)

Contents of this file

Additional Supporting Information (Files uploaded separately)

Introduction

Supplementary files include descriptions of all study sites, methods to derive the sea-level reconstructions, and all data that were used to reconstruct historical sea-level changes. The latter include chronological data and microfossil data on all cores, as well as modern foraminiferal data that formed the basis for the sea-level transfer functions. We also provide background on statistical correlations and climate models.

Text S1. Site descriptions.

Our main study site is located at Chezzetcook Inlet, a micro- to mesotidal embayment on the Atlantic coast of Nova Scotia (Figure S1). The mean spring tidal range at the mouth of the inlet is 2.14 m, but in the salt marsh at West Head, where we collected our cores, the mean spring tidal range is reduced to 1.86 m (Scott & Medioli, 1980). The marshes in Chezzetcook Inlet derive their sediment from eroding glacial deposits (Jennings et al., 1993). The salt marsh is dominated by a meadow of *Spartina patens* with fringes of *Juncus gerardii* along its landward edges. Chezzetcook Inlet has been the site of millennial-scale Holocene sea-level studies (Gehrels et al., 2004; Scott, 1977; Scott et al., 1987, 1995), while the Holocene evolution of Chezzetcook Inlet and its relationship with sea-level changes and sediment supply have also been extensively studied (Carter et al., 1992; Jennings et al., 1993, 1995; Orford et al., 1991, 1996). Gehrels et al. (2005) reported a doubling of the rate of relative sea-level rise around the beginning of the 20th century (from ~1.6 mm/yr to ~3.2 mm/yr). They also documented rapid rises of sea level between 1500 and 1550 CE and between 1700 and 1800 CE but, importantly, noted that these fluctuations could also be an artefact of radiocarbon calibration. By improving the chronology of this record, and by comparing it with records from Maine and Connecticut, we test in this paper the replicability of the 18th century sea-level oscillation.

The estuarine sediments in the upper reaches of Chezzetcook marsh in Nova Scotia are characterised by organic high salt-marsh facies. The oldest sections are about two metres deep (Figure S2) and four basal peats were dated that show that the sections date back about 1000 years (Gehrels et al., 2005). Salt-marsh accumulation has been rapid here, due to high rates of isostatic subsidence and relative sea-level rise (Gehrels et al., 2004), providing the highest resolution sea-level reconstruction from salt-marsh sediments in the North Atlantic region.

Our study site in Sanborn Cove (44°41'N, 67°24'W) in the town of Machiasport (Figure S1) fringes the tidal flats of Machias Bay, a macrotidal embayment in eastern Maine (mean tidal range is ca. 4 m). The salt marshes in this area derive their sediment from eroding bluffs of glaciomarine deposits that are especially abundant in the northern part of Machias Bay (Goodman et al., 2007; Wood et al., 1989). Sanborn Cove marsh exhibits a very clear plant zonation, with below the woodland edge a zone dominated by *Juncus gerardii*, followed by a middle zone of *Spartina patens* and a low marsh zone of *Spartina alterniflora*. Sanborn Cove contains the longest continuous sections of high-salt marsh sediments known in the northeastern USA (Figure S2), dating back almost 6000 years (Gehrels, 1999). Basal sea-level index points were previously collected along a slope of the Pleistocene glaciomarine sediments (Presumpscot Formation) that form the substrate of the marsh (Gehrels & Belknap, 1993; Gehrels et al., 1996; Gehrels, 1999). The basal facies is an organic mud and is dominated by *B. pseudomacrescens*, the most terrestrial of the foraminiferal species. The highly organic sediments contain the remains of the middle and upper marsh plants *Spartina patens* and *Juncus gerardi*. Previous studies established a middle and late Holocene sea-level record (Gehrels & Belknap, 1993; Gehrels et al., 1996; Gehrels, 1999). The late Holocene part of this record was refined and documented a 0.3-0.4 m rise of sea level since 1800 CE (Gehrels et al., 2002) as well as an oscillation in the 18th century which was also seen in the record from Wells in southwestern Maine. However, the record was noisy and it was suggested that "the eighteenth-century oscillation in Machiasport may be somewhat exaggerated by two 'outliers'". Our new record aims to test if the oscillations can be verified with improved chronology and higher vertical precision.

Our study site in Barn Island salt marsh, in eastern Connecticut (41°20'N, 71°52'W), is located on Narragansett Bay (Figure S1), which has a microtidal regime (mean tidal range is 0.8 m (Donnelly et al., 2004). The higher parts of Barn Island marsh are dominated by extensive meadows of *Spartina patens* and *Distichlis spicata*, while *Spartina alterniflora* occupies the lower marsh. Our site is located about 0.5 km north of the location from where Donnelly et al. (2004) produced a 600 year compaction free sea-level record based on the sampling of basal peat overlying a glacial erratic. Their major conclusion was that between 1850 and 1900 CE the rate of relative sea-level rise increased three-fold compared to the late Holocene trend of 1.0 mm/yr. However, due to the incremental nature of the sampling of basal peat, they were unable to resolve any sub-centennial fluctuations in the rate of sea-level change prior to the late 19th century. Our new record aims to achieve this.

Text S2. Paleosea-level reconstructions.

We use training sets comprising contemporary micro-organisms (foraminifera) to develop transfer functions for sea-level reconstructions, following approaches described by Gehrels et al. (2001) and Barlow et al. (2013). The transfer functions quantify the vertical relationship between elevation and micro-biota, thus allowing sea level to be expressed as a function of the microfossil assemblages preserved in sediments. We assess the fit between modern and fossil datasets using the Modern Analogue Technique (Birks, 1995; Juggins, 2003).

At each site we collected cores of salt-marsh sediment from the highest marsh zone, close to the upper limit of present tidal inundation and away from tidal creeks. We use a variety of dating methods, including AMS^{14}C, ^{210}Pb, ^{137}Cs, ^{206}Pb/^{207}Pb, tephra, pollen markers and trace metal markers to develop robust chronologies for our records. Our AMS^{14}C dating includes 'high-precision' dating (Marshall et al., 2007), i.e., the pooled mean of multiple age determinations on individual plant fragments at 2‰ precision (normal is 3‰). This significantly reduces the error of the ^{14}C ages for samples younger than ~300 calendar years (to between ±9 and ±17 ^{14}C yrs). Measurements of 'bomb-spike' AMS^{14}C in plant fragments are used to test model selection for ^{210}Pb analyses (Marshall et al., 2007). Age models are developed for cores using the Bayesian age-modelling software Bacon (Blaauw & Christen, 2011) which takes into account the stratigraphical position of the sample, thereby reducing the number of possible solutions for the calibrated ages of the samples.

We determine former sea-level positions by subtracting the elevation at which a fossil sample was originally deposited (calculated by the microfossil transfer function) from its present elevation (measured relative to national geodetic datums). We test the assumption that sediment compaction errors are insignificant in our sites (Brain et al., 2012) by comparing our reconstructed sea levels with sea-level data reconstructed from basal sediments that are unaffected by the effects of compaction (Engelhart & Horton, 2012; Gehrels, 1999).

We generated transfer functions for the reconstruction of sea-level changes based on foraminiferal assemblages from previously collected data sets and, in one site (Connecticut), added local foraminiferal data. We validated the model choice by checking the core-top predictions against the surveyed elevations and we also compared our reconstructions with sea-level observations from nearby tide gauges (Figure S7). Foraminiferal data used to generate the transfer functions are presented in Tables S7-S9. Fossil foraminiferal data are presented in Tables S10-S12.

For Chezzetcook marsh in Nova Scotia we used the local transfer function developed by Gehrels et al. (2005) from 46 foraminiferal samples collected by Scott & Medioli (1980) using Weighted-Averaging with Tolerance Downweighting regression. The main foraminiferal taxa include *Trochammina inflata*, *Tiphotrocha comprimata*, *Haplophragmoides manilaensis* and *Miliammina fusca*. Scott and Medioli (1980) grouped *Balticammina pseudomacrescens* and *Jadammina macrescens* together as *Trochammina macrescens*. We also combined these foraminifera in our training set because it was not possible to retrospectively split these taxa. Due to the small local tidal range the sampled vertical range of the foraminifera is relatively short, and as a consequence the match between observed and predicted assemblages is somewhat weak (Figure S 3). However, the largest residuals occur at the ends of the sampled range (Figure S 3), whereas our reconstructed values are all confined to the middle range. Hence, the transfer function is considered to perform adequately for the purpose of our sea-level reconstruction. The root mean squared error of prediction (RMSEP) of this transfer function is 0.06 m (which is taken as a 1 sigma error; (Barlow et al., 2013)). As both surface data and cores were tied to the same local datum and all sample sites were surveyed from the same vantage point no further datum and surveying uncertainties are considered and the 2 sigma vertical uncertainty associated with the reconstructed sea levels in Nova Scotia is taken as 0.12 m.

For the transfer function applied at Sanborn Cove in Maine (Figure S3) we used the regional Maine dataset of Gehrels (2000). Because our stratigraphy only contains high marsh facies we removed all low marsh and tidal flat samples from the dataset to avoid predictions by the transfer function that are outside the vertical range of the facies present in the core, leaving 44 samples containing the six primary agglutinated salt-marsh foraminiferal taxa (*B. pseudomacrescens*, *J. macrescens*, *T. inflata*, *Tiphotrocha comprimata*, *H. manilaensis* and *M. fusca*). To account for variations in tidal range along the Maine coast we produced a standardised water level index (SWLI) assuming in each marsh a vertical distance between local mean sea level (MSL) and the local highest astronomical tide (HAT) of 1m. The local HAT was determined from the highest occurrence of foraminifera, following Wright et al. (2011). We chose a Partial Least Squares (PLS) transfer function model as it performed well statistically (RMSEP = 0.06 SWLI) and was confirmed by Detrended Canonical Correspondence Analysis to adequately model the species distribution (Gehrels, 2000). Vertical uncertainty terms are calculated from the RMSEP, multiplied by the vertical distance between local MSL and HAT (2.82 m).

For the Connecticut transfer function (Figure S3) we used the dataset of Edwards et al. (2004) and included 26 new samples we collected from Barn Island (see supplementary data). We standardised the data using the same method as described above for Maine. The RMSEP of the Weighted Average – Partial Least Squares transfer function, calculated from 80 samples, is 0.09 SWLI.

In Maine and Connecticut uncertainty is introduced by datum selection and surveying errors (Gehrels et al., 1996; Gehrels et al., 2002) because data from multiple marshes in the region are combined. To account for this we added 0.10 m to the vertical error of the reconstructed sea levels. Our total (treated as 2 sigma) vertical uncertainty thus determined for the local sea-level reconstructions (re-calculated from the SWLIs) is 0.20 m in Maine and 0.16 m in Connecticut.

We base our sea-level reconstruction for Chezzetcook (Nova Scotia) on core CZ-25 (Figure S4). Typical for this marsh, the core contains high salt-marsh peat throughout, as shown by the presence of upper marsh foraminifera *B. pseudomacrescens* and *J. macrescens*. Only in a short core section between 0.4 and 0.6 m does *T. comprimata* reach levels above 20%. The foraminifera show that marsh sedimentation at this core site has persistently occurred within a very narrow vertical range of ~0.1 m, providing an ideal and stable sediment sequence for the reconstruction of sea-level changes. All foraminiferal assemblages have good analogues in the modern training set. Only four fossil assemblages have Minimum Dissimilarity coefficients over 10%, but are still considered 'close' analogues (Barlow et al., 2013; Watcham et al., 2013).

Our sea-level reconstruction for Maine (Sanborn Cove) is based on core SN-3.3 (Figure S5). Preserved foraminifera are typical of middle and upper marsh environments and are dominated by *B. pseudomacrescens* and *J. macrescens* with minor occurrences of *M. fusca*. In the upper 0.2 m we see the appearance of *T. comprimata*, followed by *T. inflata*. The bottom of the core contains very few foraminifera, which is indicative of a marsh-fringing freshwater facies. All fossil foraminiferal assemblages have good analogues in the modern training set.

Our sea-level reconstruction for Barn Island (Connecticut) is based on core BI-47.5 which is a metre in length (Figure S6). The core is representative of the overall stratigraphy of this part of the salt marsh, comprising a basal unit of humified organic mud, overlain by a *S. patens*/*J. gerardi* peat, which contains a thin unit of *S. alterniflora*/*S. patens* peat (Figure S2). The base of the salt-marsh section contains very few foraminifera and we therefore base our sea-level reconstruction only on the top 0.5 m of the core. Between 0.50 and 0.27 m, the foraminiferal assemblage is dominated by *J. macrescens*. A transgressive transition from *S. patens*- to *S. alterniflora*-dominated peat coincides with the appearance of a middle marsh fauna (*J. macrescens*, *T. comprimata* and *T. inflata*). From this level up, the tendency to lower paleomarsh conditions persists to the top of the core. Similar to our other sites, all fossil foraminiferal assemblages are well represented by their counterparts in the modern training set.

Text S3. Chronologies.

We dated thirty levels in the Chezzetcook (Nova Scotia) core by ^{14}C (Table S1, Figure S4). Of these, five levels were dated twice, providing one-sigma errors of as little as 11 ^{14}C years. The two highest ^{14}C analyses are bomb-spike dates. The rise of *Ambrosia* and *Rumex* pollen at 0.55 m reflects the settlement of the Chezzetcook area around 1780 (Gehrels et al., 2005). The top section of the core had been dated by ^{210}Pb (Gehrels et al., 2005), but we added two pollution markers. The swing in $^{206}Pb/^{207}Pb$ values at 0.3 m core depth represents the onset in lead pollution in eastern Canada around 1885 (Kylander et al., 2009). The pollution maximum at 0.06 m is dated to 1965 (Kemp et al., 2012), and is confirmed by the ^{137}Cs peak at the same level.

We dated nine levels in the Sanborn Cove (Maine) core with ^{14}C (Table S2, Figure S5), two with replicate analyses. At 0.28 m, the rise in *Ambrosia* and *Rumex* pollen signifies European settlement around 1760 (Gehrels et al., 2002). Two increases in Pb levels are linked to a middle 19th century increase of regional pollution (Kemp et al., 2012) and the use of leaded gasoline around 1930 (Graney et al., 1995). We find the 1965 ^{137}Cs spike at 0.06 m. The last hundred years are also dated by ^{210}Pb. Dates on woody plant fragments near the base of the core are much older than those obtained from overlying facies and demonstrate that the formation of the basal facies was either well above sea level (foraminifera are absent below 0.54 m), or the fragments were reworked. We did not use the three lowest dates for the sea-level reconstruction and our reconstruction only goes back to the middle 18th century.

The chronology of the Barn Island (Connecticut) core is provided by 13 ^{14}C dates (Table S3, Figure S6). Of these five are 'bomb-spike' dates, and five are high-precision (multiple) age determinations. We also used the 1965 nuclear bomb-testing maximum based on ^{137}Cs analyses, ^{210}Pb ages down to 0.15 m, as well as the onset of Cu and Pb pollution dated to 1875 (Bricker-Urso et al., 1989).The anomalously old basal age and two ages that were clearly out of sequence were ignored in the development of the age-depth model.

Text S4. Statistical significance of correlations.

The significance of correlations has been tested accounting for the temporal correlation structure in the underlying time series using a Fourier phase scrambling approach with 1000 simulations. The phase scrambling allows for a random generation multiple series with similar noise characteristics as the initial observational time series. Based on these random series bivariate correlations, which may appear just by chance, have been calculated and used as a basis for the assessment of statistical significance in observations.

Text S5. Climate models.

We use monthly sea-level output from five coupled atmosphere-ocean general circulation (climate) models participating in the Coupled Model Intercomparison Project Phase 5/ Paleoclimate Modelling Intercomparison Project Phase 3 (CMIP5/PMIP3) last millennium ("past1000") experiment (Schmidt et al., 2012): bcc-csm1-1, CCSM4, FGOALS-s2, MIROC-ESM, and MPI-EM-P. These models were chosen based on their availability in the Woods Hole Oceanographic Institution's CMIP5 Community Storage Server. We used output for sea-surface height above the geoid (the “zos” variable) for the period 850-1850 CE. Global-average values of zos were subtracted from the gridded fields, so as to remove any possible influences of global-mean sea-level changes arising from net freshwater input. Added to the zos variable was the corresponding model’s local inverted barometer response, computed as the additive inverse of the sea-level pressure field (the “psl” variable) and divided by a factor of ~10,000 kg m-2 s-2 to account for density and gravity. For eastern North America, we took the resulting (dynamic plus isostatic) sea-level time series closest to each of Nova Scotia, Maine and Connecticut, and averaged the three time series together, to create a single composite time series comparable to the first PC from EOF analysis of the tide gauges. We also took the sea-level time series from the model grid cell closest to Reykjavík, Iceland. The model’s NAO index was computed using psl as the sea-level pressure difference between the grid cells closest to the Azores and Iceland. Monthly model values were averaged annually to create a 1000-year time series of annual-mean values. Results shown in Figure S10 are based on time series with a 100-year Hamming filter applied, but similar results were found by applying a 50- or 200-year Hamming window.

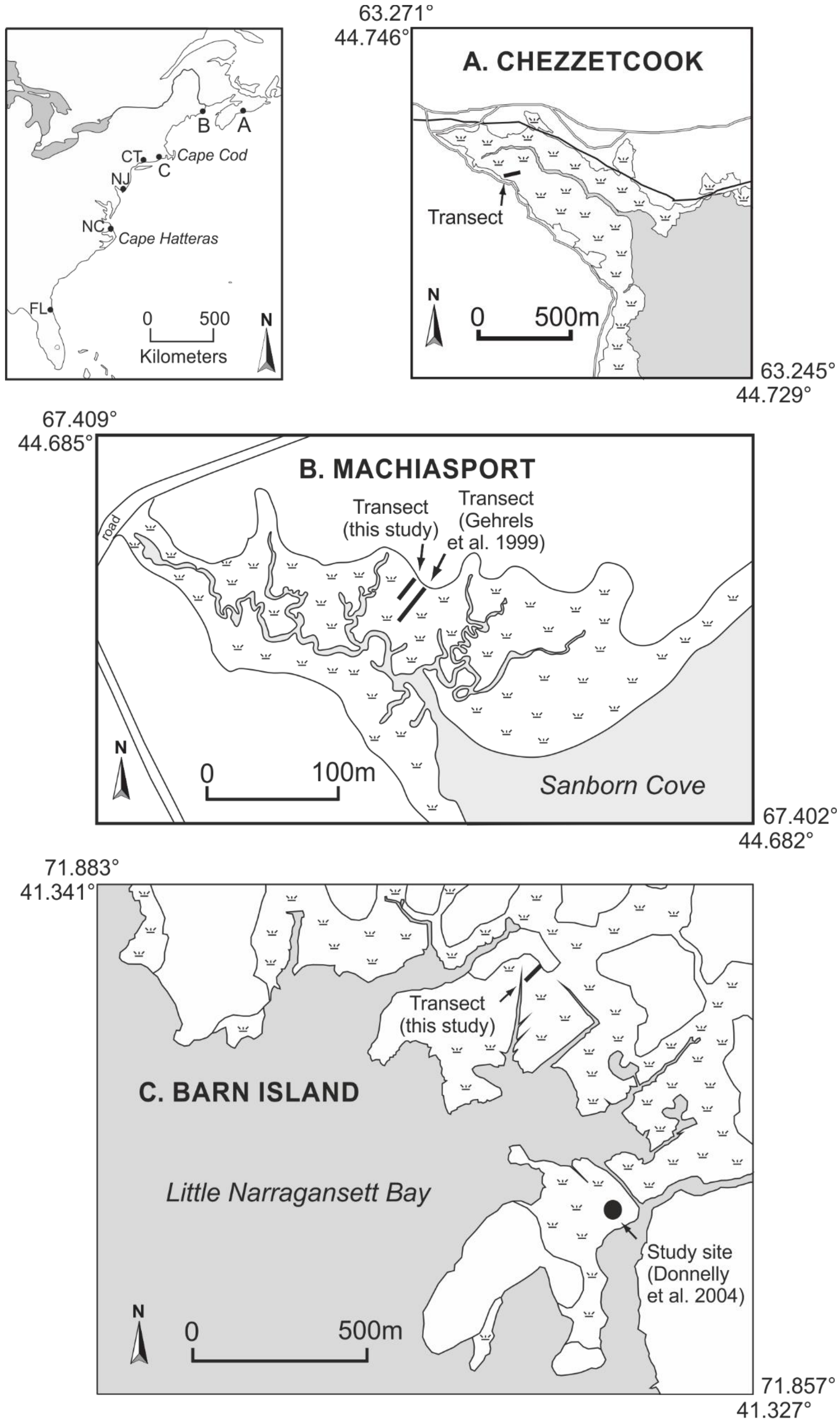


Figure S1. Locations of coring transects at Chezzetcook, Nova Scotia (A), Machiasport, Maine (B) and Barn Island, Connecticut (C).

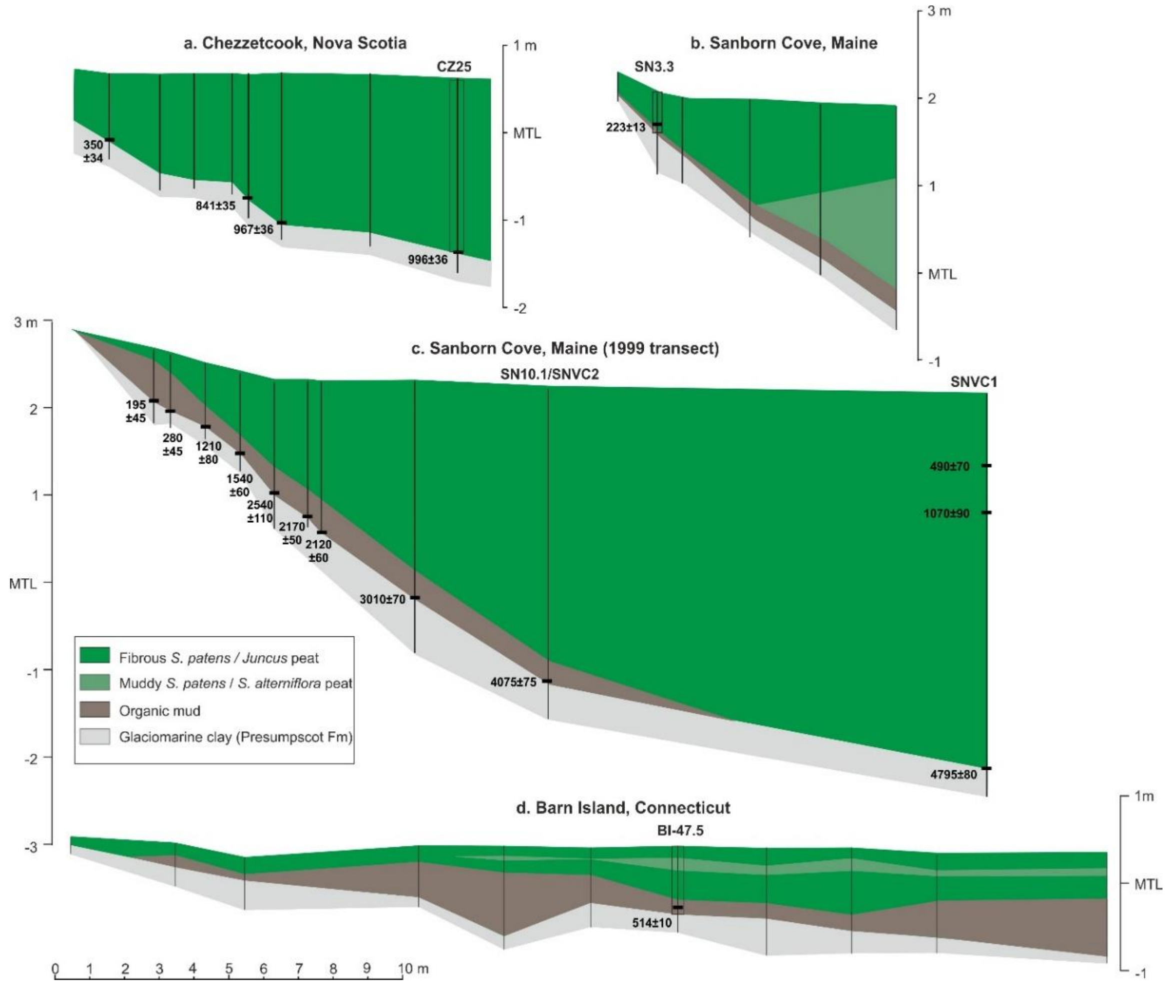
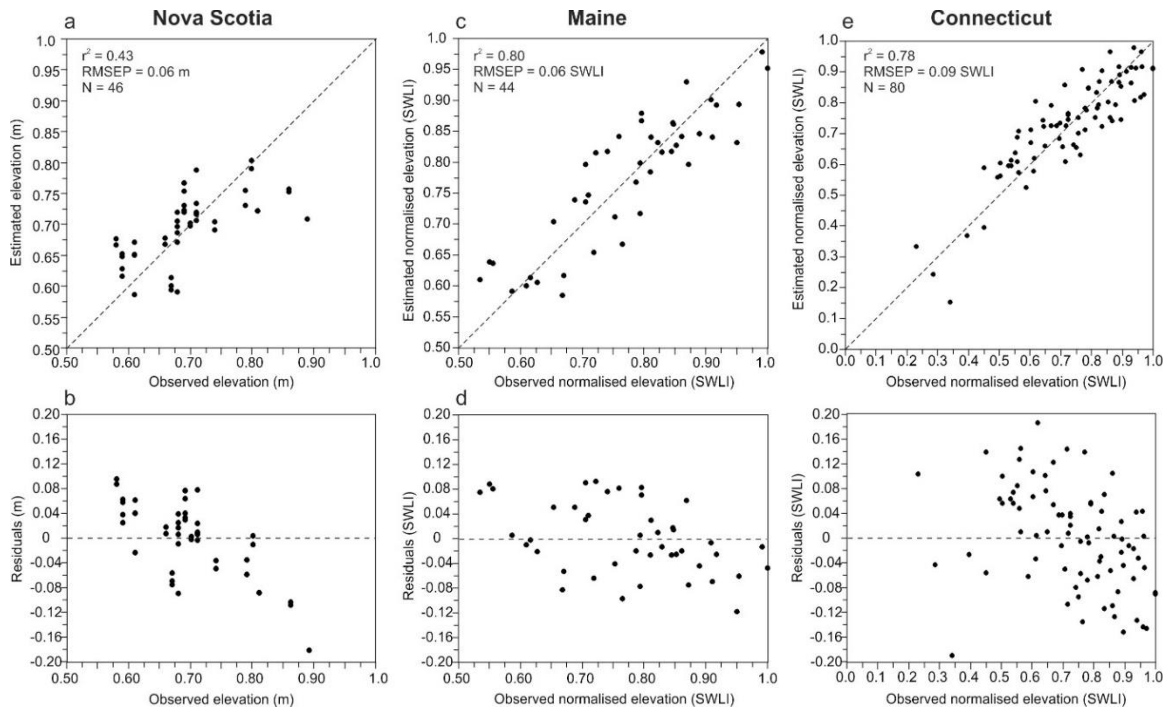


Figure S2. Stratigraphic cross sections through salt marshes at Chezzetcook (a), Sanborn Cove, Machiasport (b, c) and Barn Island (d). Sections b and d from this study. Section a is from Gehrels et al. (2005). Section c is from Gehrels (1999). MTL – mean tide level.



Supplementary Figure 3. Transfer function data for sea-level reconstructions based on distributions of modern foraminifera. The plots show observed vs. estimated elevations and residuals for Nova Scotia (a, b), Maine (c, d) and Connecticut (e, f). Foraminiferal training sets on which the transfer functions are based are in Tables S7-S9.

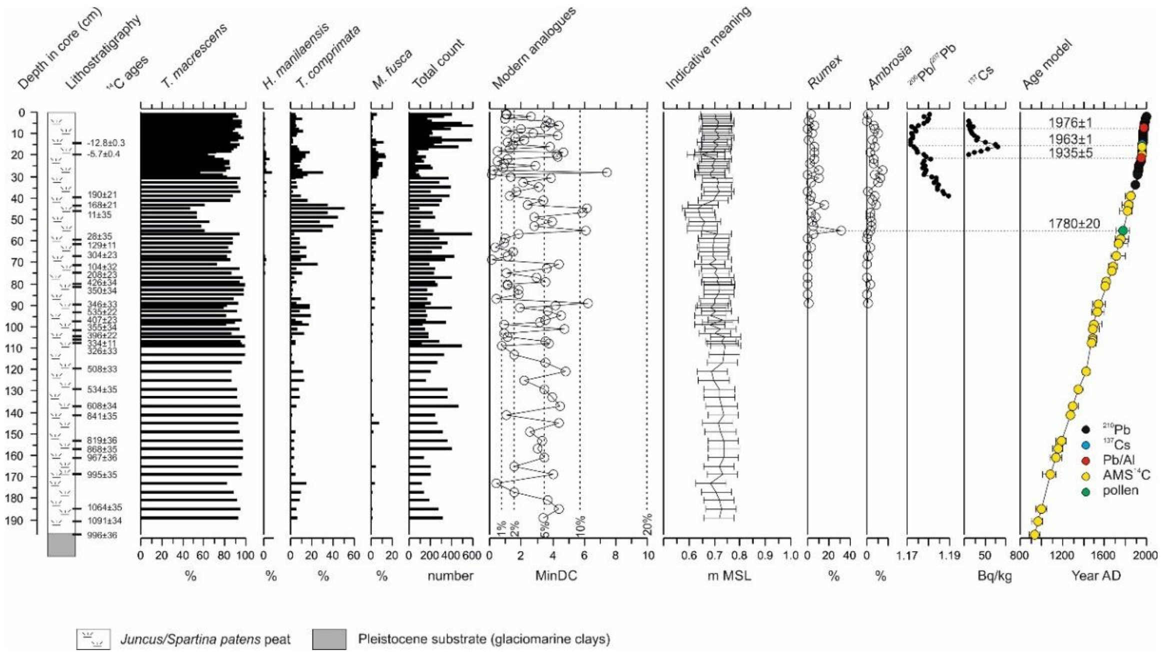


Figure S4. Microfossil and chronological data for core CZ-25 (Chezzetcook, Nova Scotia). See Table S1 for age data and Table S11 for foraminiferal data.

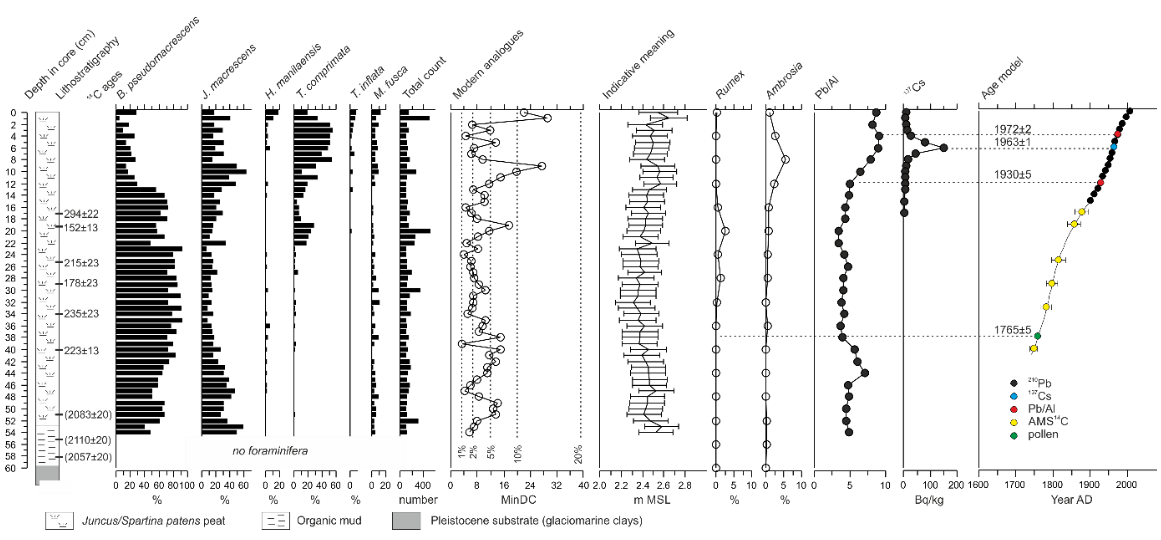


Figure S5. Microfossil and chronological data for core SN-3.3 (Sanborn Cove, Maine). See Table S2 for age data and Table S12 for foraminiferal data. The three oldest radiocarbon dates from the basal section were not used in the sea-level reconstruction.

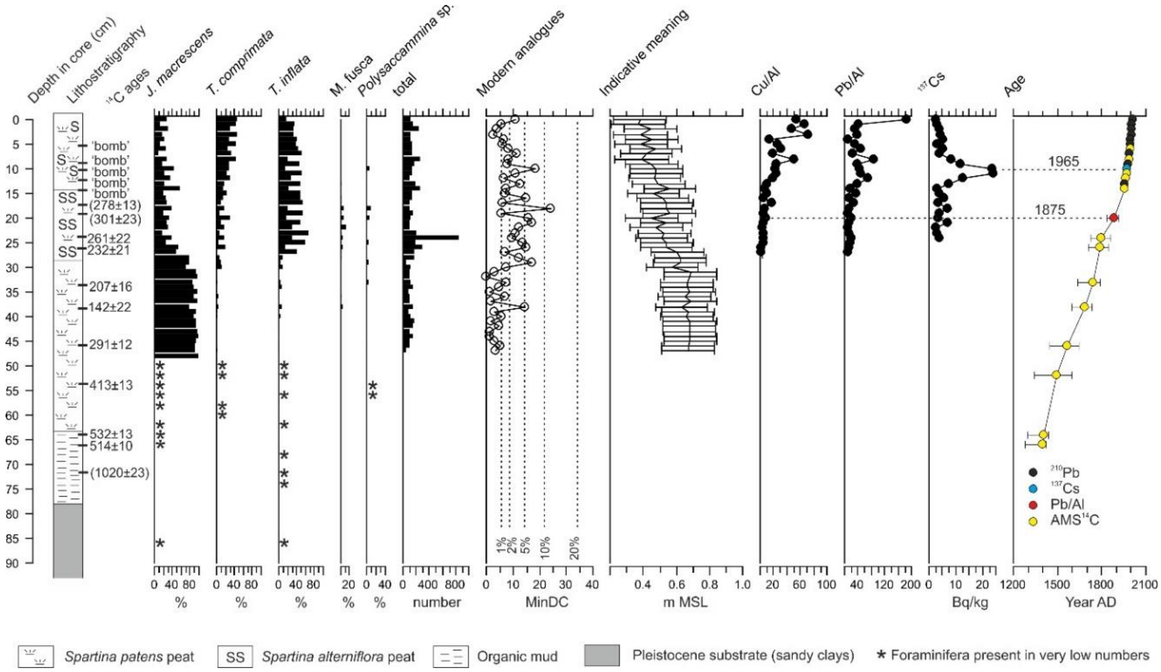


Figure S6. Microfossil and chronological data for core BI-47.5 (Barn Island, Connecticut). See Table S3 for age data and Table S13 for foraminiferal data. The old radiocarbon date from basal section was not used in the sea-level reconstruction.

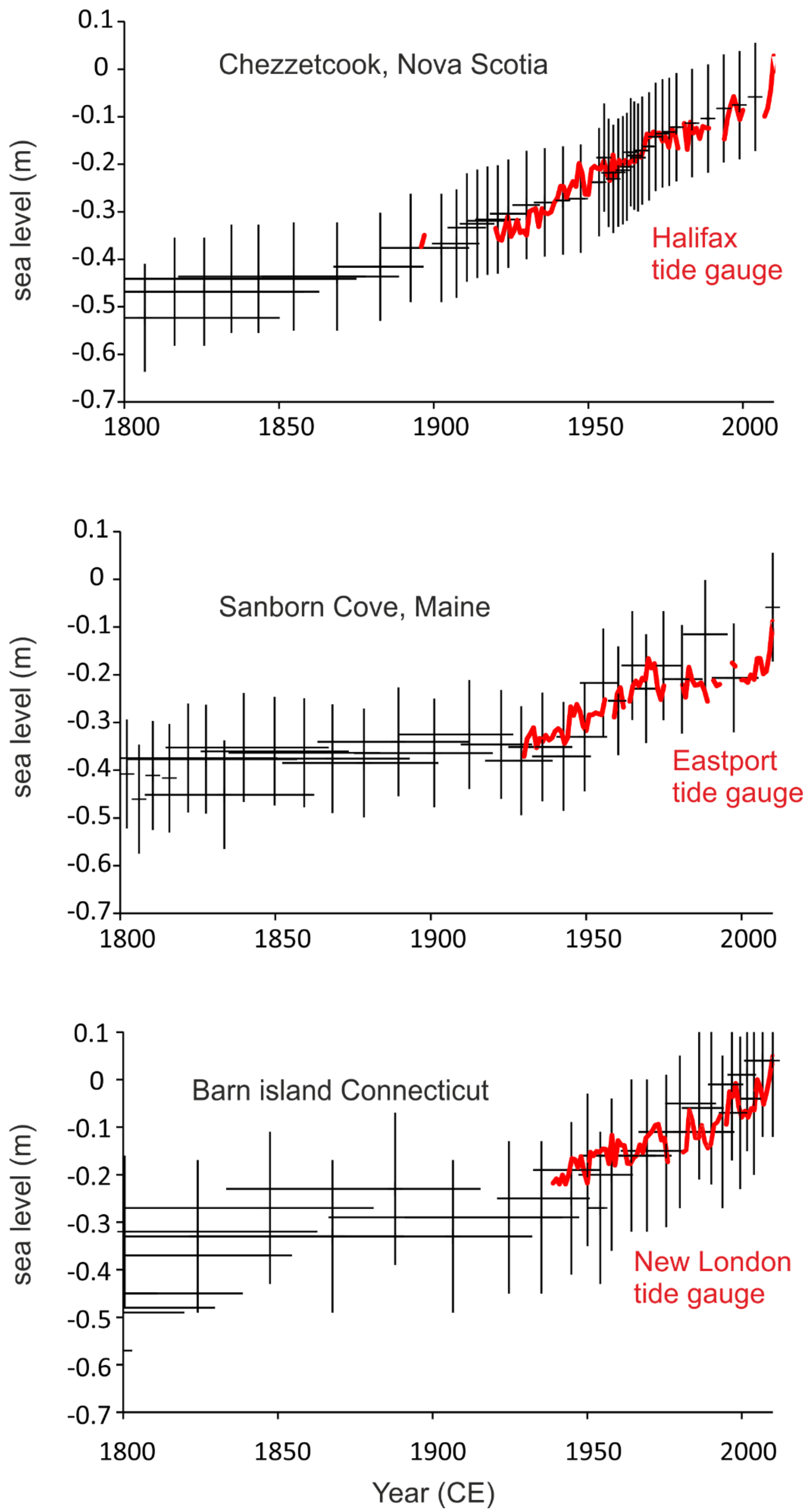


Figure S7. Comparison between proxy sea-level reconstructions (crosses) and nearby tide-gauge records.

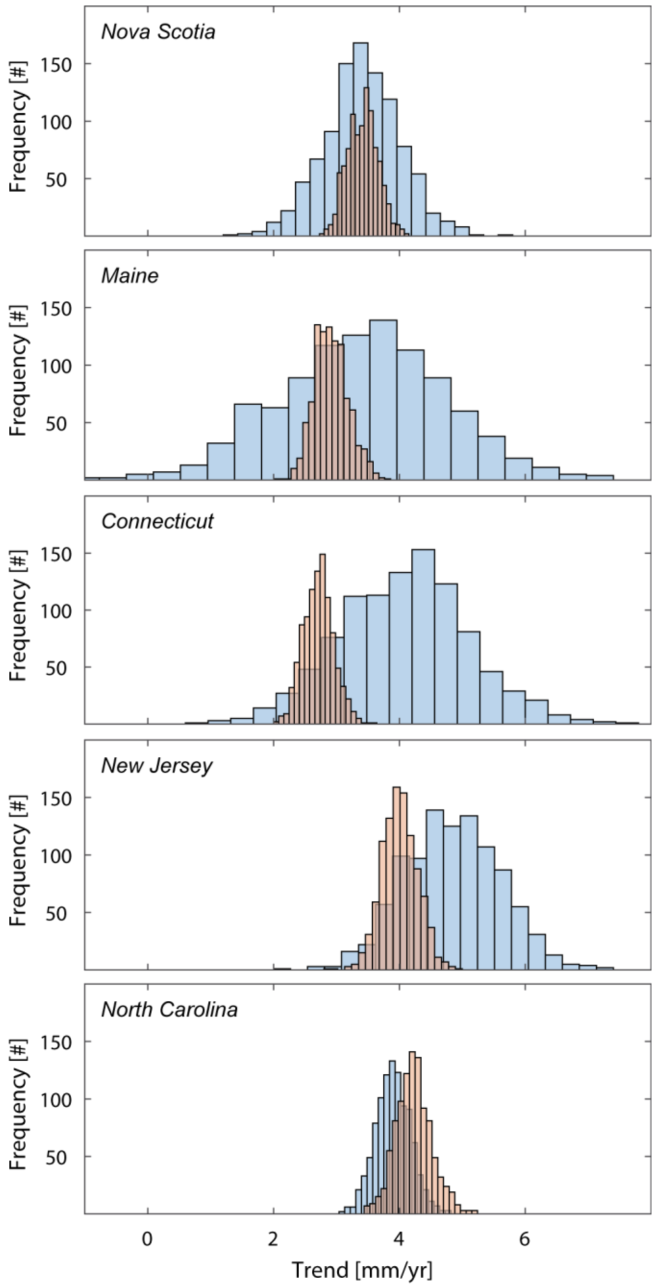


Figure S8. Comparison of 20th century (1900-2000) trends from salt-marsh reconstructions (blue) and tide gauges (red) under the consideration of their vertical and chronological uncertainties in 1000 Monte-Carlo simulations. Trends in tide-gauge records were only fitted to those observations which overlap with the respective saltmarsh index points and their uncertainties.

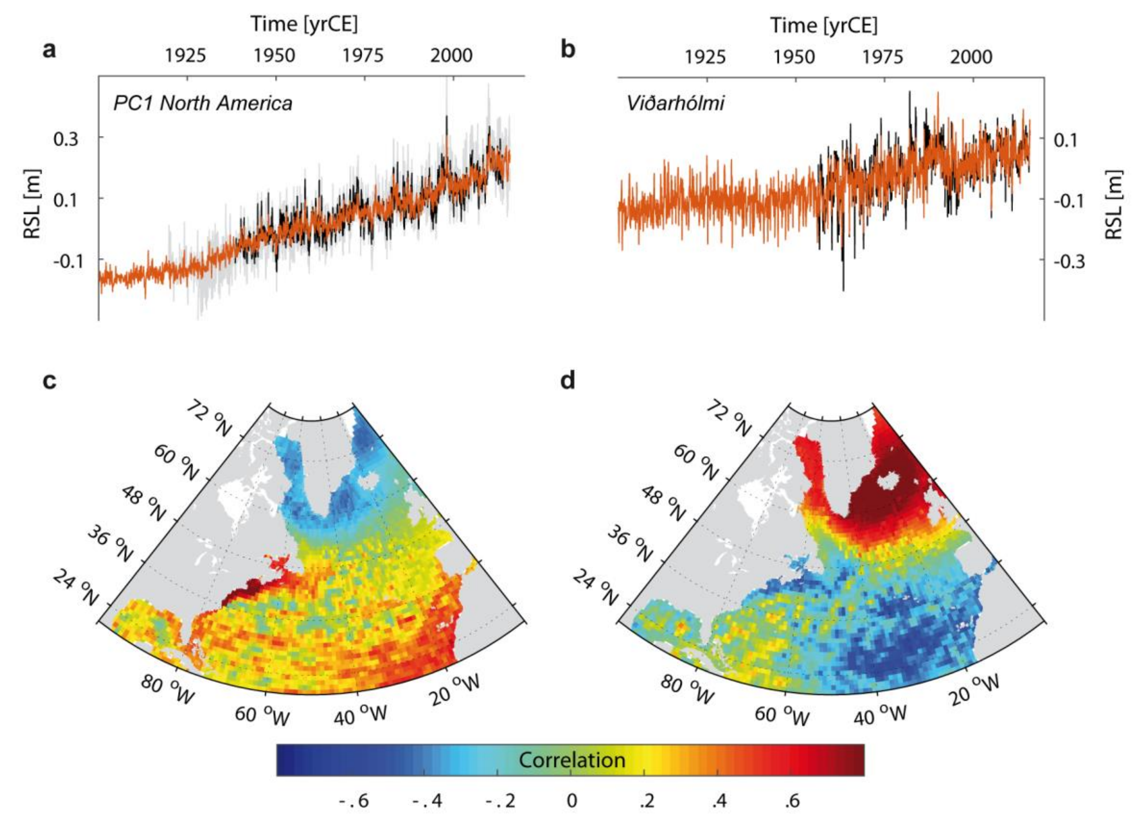


Figure S9. Representativity of the two sea-level records. **a** and **c**. Time series of the first PC of GCSL along the North American east coast from tide gauges at Halifax, Eastport and New London (black; individual records on which the first PC at the North American east coast has been built are shown in grey in **a**) and the spatial-temporal sea level reconstruction (Dangendorf et al., 2019) (red). The correlations between observations and the reconstruction are r ~ 0.87 and r ~ 0.85, respectively. **b** and **d**. Spatial correlations between the first PC of North American east coast GCSL (**b**)/ Viðarhólmi (**d**) and each grid point time series in the spatial-temporal sea level reconstruction (Dangendorf et al., 2019).

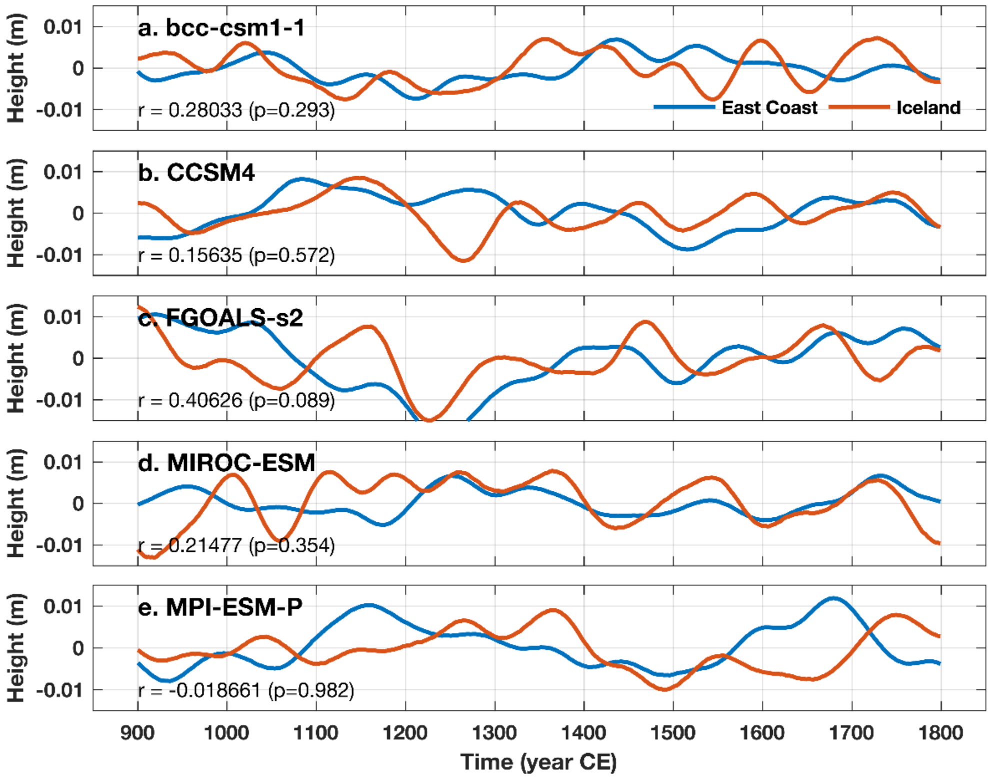


Figure S10. Sea-level variations along the North American east coast and Iceland and their correlations in five different PMIP models.

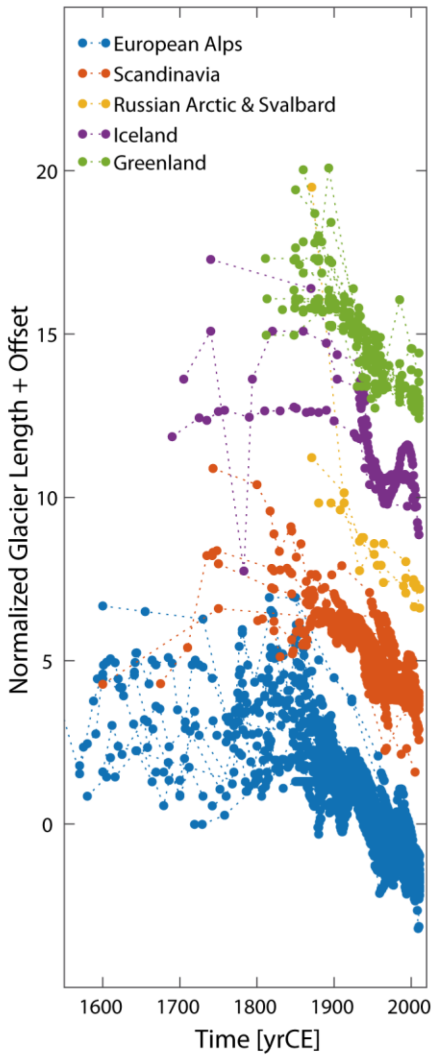


Figure S11. Glacier length records from Leclercq et al. (2014) from regions with data from before 1900 that have the potential to force an out-of-phase relative sea-level signal in Iceland and eastern North America. Records are normalised (i.e. mean removed and divided by their respective standard deviation).