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SUPPLEMENTARY INFORMATION

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Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation

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Alternative formulation of the AMOC index

In the AMOC index the effect of the AMOC on subpolar SST is isolated by removing the effect of forced, large-scale climate changes, e.g. in the 20th Century the "global warming signal". We do this by removing the mean surface temperature change of the Northern Hemisphere. Alternatively, the mean Northern Hemisphere sea surface temperature (SST) could be used; an argument in favor of this would be to avoid the effect of enhanced continental warming as compared to the ocean. Both versions of the index are compared in *Figure S1*.

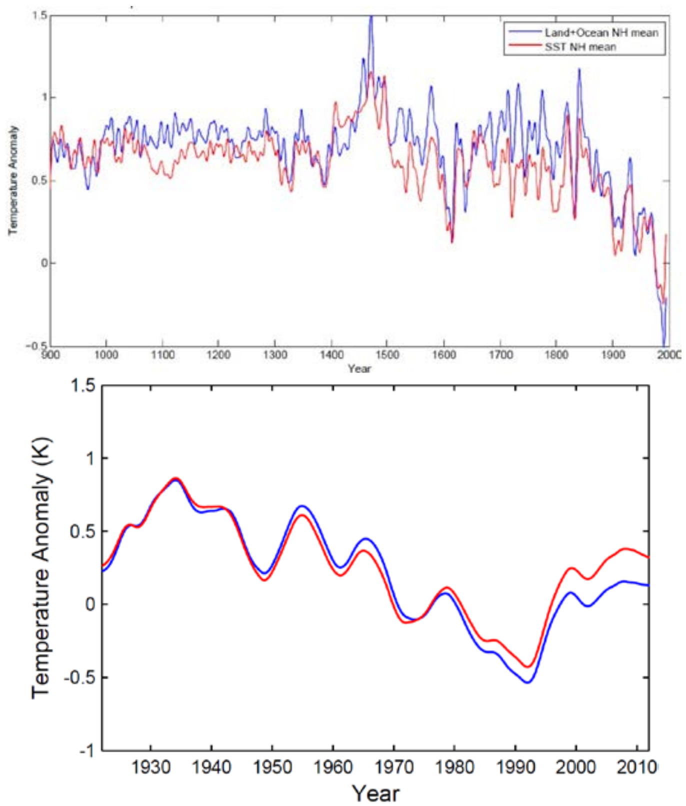

Figure S1. Two versions of the AMOC index: subpolar gyre SST with subtraction of either the Northern Hemisphere average SST (red) or the overall Northern Hemisphere surface temperature changes (blue). **(Top)** Proxy data and **(Bottom)** instrumental data. Blue curves are the same as Figs. 3 and 5 of the paper, respectively.

The difference in the proxy data is larger due to their greater reconstruction uncertainty, especially given the fact that the reconstruction for the whole Northern Hemisphere is by a simpler and more robust method than the reconstruction for individual grid points which is used in computing the mean northern hemisphere SST.

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While both curves are very similar and the conclusions of our paper do not depend on which one is used, there is the question of which version of the index is “better”. Using the entire NH temperature to normalize the index includes the effect of continental warming. However, the Atlantic subpolar gyre region is under strong influence of continental air from North America brought in by the westerlies (and our Fig. 1 shows a particularly large warming trend right to the west of the subpolar gyre cold patch) so arguably including continental temperatures in the mean is not unrealistic.

Examination of a global map of temperature trends for 1970-1990 (an interval during which the two indices diverge particularly strongly) shows that it is not only continental warming over North America and Asia which causes the difference but also a widespread SST cooling in the North Pacific that happens to coincide with the cooling in the North Atlantic subpolar gyre, although it is most likely physically unrelated. Using only SST in normalization is dominated by North Pacific SST, which has its problems due to the effect of the Pacific Decadal Oscillation, and it also gives greater influence to the North Atlantic SST outside the subpolar gyre region which arguably is also affected by the AMOC to some extent, leading to underestimation of the signal.

We have also examined a third possible index in which the mean surface temperature over the entire latitude belt of the subpolar gyre was subtracted. This again gave very similar results, however the statistical validation of the proxy series was less favorable in this case so the reconstructed curve was found to be less robust based on this measure.

Averaging over as large an area as possible, namely the entire Northern Hemisphere, has the advantage of minimizing local effects on the index and is thus our preferred choice.

Validation of the proxy reconstructions of temperature

To validate the proxy reconstructions of temperature we use standard techniques developed during the past two decades in the paleoclimate community.

Validation of the subpolar gyre temperature reconstruction was performed on each proxy network used in the composite reconstruction (900AD, 1400AD, 1500AD, 1600AD, 1700AD, 1800AD). (See Mann et al. 2009[1] for details on the selection of proxy networks used in the composite reconstruction.) The validation procedure calibrates the proxies against the instrumental data from 1896 to 1995 AD and then compares the proxy-based reconstruction to previously withheld instrumental data from 1850 to 1895 AD. In this way we can compare the reconstruction to the instrumental data from 1850 to1895 AD and assess the skill of the proxy-based reconstruction using a red-noise null hypothesis.

The series for the validation-period (1850-1895 AD) are shown in *Figure S2* and the Reduction of Error (RE) and the Coefficient of Efficiency (CE) skill scores calculated on the regional mean series are summarized in *Table S1*. In addition, the calibration period (1896-1995) RE scores were calculated (*Table S1*) and the reconstructions of the calibration period (network of 1800 AD) are shown in Figure 2 of our paper. Significance of the validation scores was evaluated using the procedure of Mann et al. 2007[2], section 3.5.

Calibration-period reconstructions are produced by applying the regression weights calculated by RegEM in calibration to the proxies over both the reconstruction and calibration time periods. The result is a continuous, proxy-based reconstruction from 900 to1995 AD.

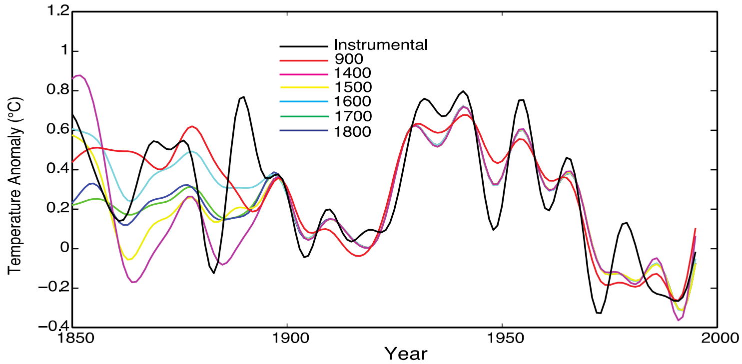

Figure S2. Validation series for the subpolar gyre. Validation series for the six proxy networks used to reconstruct different time intervals of the subpolar gyre temperature reconstruction. The 900 network is used to reconstruct 900-1399, the 1400 network, 1400-1499 and so on. The validation period is 1850-1895 AD. The series shown over the calibration period (1896-1995 AD) give a sense of a "perfect reconstruction", where the proxies perfectly reconstruct the principal components retained (see also supplementary information of Mann et al. 2009[1]).

Table S1. Validation-period and calibration-period decadal (10-year lowpass filtered) scores for the subpolar gyre and the NH mean. All scores are significant at the 95% significance level compared to a red-noise null.

	Subpolar Gyre		
Network	**Validation RE**	**Validation CE**	**Calibration RE**
1800	0.10	-0.12	0.60
1700	0.02	-0.23	
1600	0.44	0.30	
1500	0.33	0.16	
1400	0.10	-0.12	
900	0.04	-0.20	
	Northern Hemisphere Mean*		
700	0.70	-1.35	0.94

*Validation-period scores from Mann et al., 2008. The reconstruction used here employs the global, full-proxy network . See Mann et al., 2008 for details.

Statistical significance of the recent low AMOC index

To investigate whether the low AMOC index values seen in the late 20th Century could occur by random natural variability, we performed a series of Monte Carlo simulations. The time interval 900-1850 AD was chosen to characterize the natural variability of the AMOC index as we consider this pre-industrial period to be unaffected by anthropogenic climate change.

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The annually-resolved AMOC index from 900-1850 formed the basis for an ARMA(1,1) model from which 10,000 Monte Carlo series were constructed, since the autocorrelation function of the AMOC index is well described by an ARMA(1,1) process (*Figure S3*). We used the maximum likelihood estimate of the two ARMA parameters produced by the Matlab software. For each Monte Carlo series a 21-year running average was computed; ten examples are shown in *Figure S4* and compared to the 21-year running average of the proxy-based AMOC reconstruction (black).

The mean temperature anomaly of the proxy index during 900-1850 is 0.88 °C; the standard deviation of the 21-year averages is 0.13 °C. The observed AMOC depression during 1975-1995 (the last 21-year average available in the proxy data) is the greatest with a temperature anomaly of -0.13 °C, which is thus 8 standard deviations below the 900-1850 average.

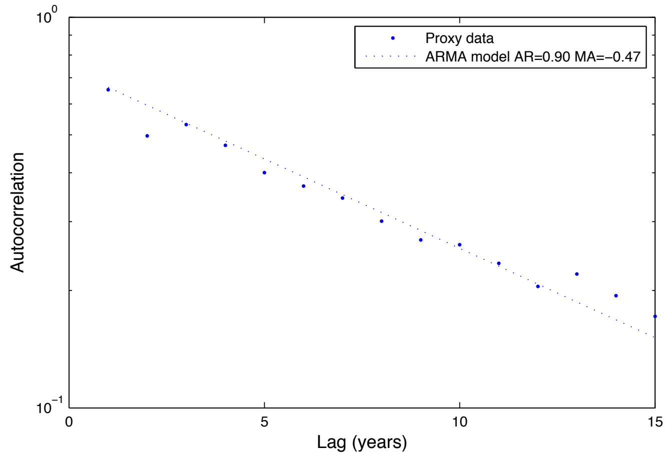

Figure S3. Lagged autocorrelation of the annually resolved proxy-based AMOC index and the fit to the autocorrelation obtained by an ARMA(1,1) process.

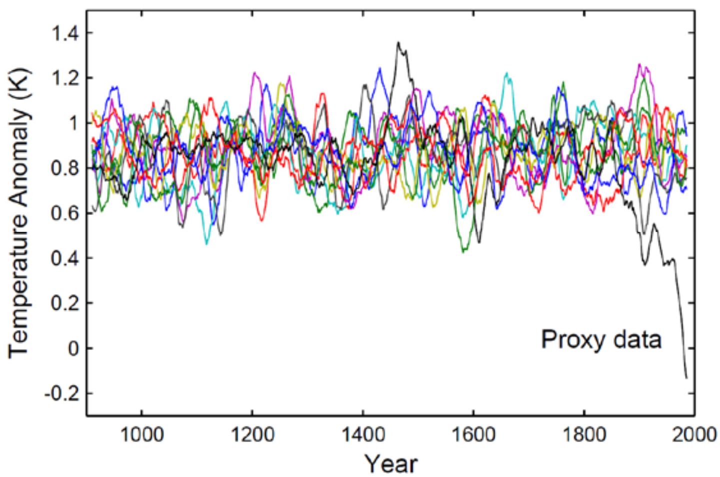

Figure S4. Comparison of our AMOC index (black) to ten example Monte Carlo series (colors) used to determine the significance of the 1975-1995 AMOC reduction. See text for specifics of Monte Carlo series generation.

To determine the statistical significance of the 1975-1995 AMOC reduction we also considered the data uncertainty of the proxy reconstruction, which for 21-year means has a standard deviation of 0.26 °C taking account of the error autocorrelation. The probability distribution of the lowest 21-year values of each Monte Carlo simulation is shown together with the lowest 21-year value of the proxy data and its uncertainty distribution in *Figure S5*. The probability to get a value as low as the observed 1975-1995 mean just by chance is thus the joint probability over the data uncertainty and the Monte Carlo distribution, i.e. the product of the two distributions shown, integrated over all temperature anomalies (i.e. the x-axis). For the data shown this number is 0.45%, which implies a 99.55% significance of the 1975-1995 AMOC reduction.

Note that this calculation is very conservative in that it is based solely on the proxy data, where the 0.45% chance of getting this lowering just from random natural variability is almost entirely due to the possibility that the actual 1975-1995 value is more than 2 sigma warmer than the best estimate from the proxy data, as can be seen in *Figure S5* from where the overlap of non-zero probabilities resides. However, the 20th Century decline in the proxy-based AMOC index closely follows that found also in the instrumental data with their much smaller uncertainty, so that the chances that the proxy data are that far off are in reality much smaller than their formal uncertainty range would suggest.

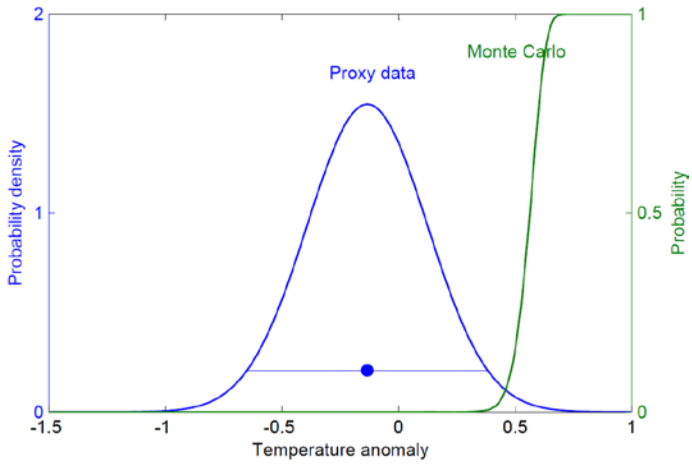

Figure S5. Uncertainty distribution for the mean AMOC index during 1975-1995 in the proxy data computed from the error model of Mann et al. 2009. The best estimate value of -0.13 °C (blue dot) is also shown together with the 2-sigma data uncertainty range (horizontal line). The green line shows the probability to find a given temperature anomaly *or lower* in any 21-year mean by chance in a Monte Carlo simulation as described above. Note that the overlap of non-zero values of the two distributions resides entirely in the far right tail of the proxy data uncertainty, as discussed in the text.

Discussion of other proxy data

We examined three sediment cores[3, 4] from the subpolar gyre region that have a sufficient resolution in time for our purposes but possess a considerable age uncertainty. Two of the cores[4] have annual-mean temperature estimates based on Mg/Ca ratios in planktonic foraminifera with different habitat preferences. For the third[3] a diatom-based transfer function is applied to reconstruct August SST. Reconciling these cores with each other and with the instrumental SST data proves difficult. The two Mg/Ca-based reconstructions have a statistical character unlike the instrumental data and they do not agree with the instrumental data from the same gridbox during the period of overlap (*Figure S6*). (Only one of them overlaps the instrumental data.)

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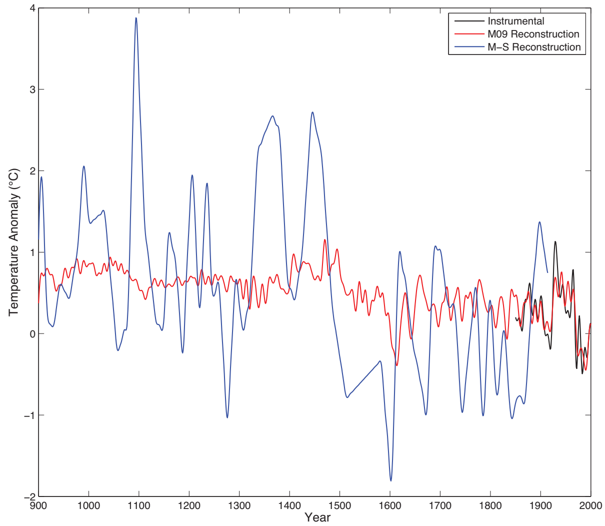

Figure S6. Temperature anomaly (°C) according to core RAPiD-35-25B (blue) from the southern tip of Greenland[4] compared to the Mann et al. 2009[1] reconstruction for the associated grid box (red) and the instrumental record for that grid box (black).

The diatom-based record[3] has a statistical character similar to the instrumental data, but the two have little correspondence during the period of overlap. Furthermore, the diatom-based reconstruction is different from the two foraminifera-based reconstructions (*Figure S7*).

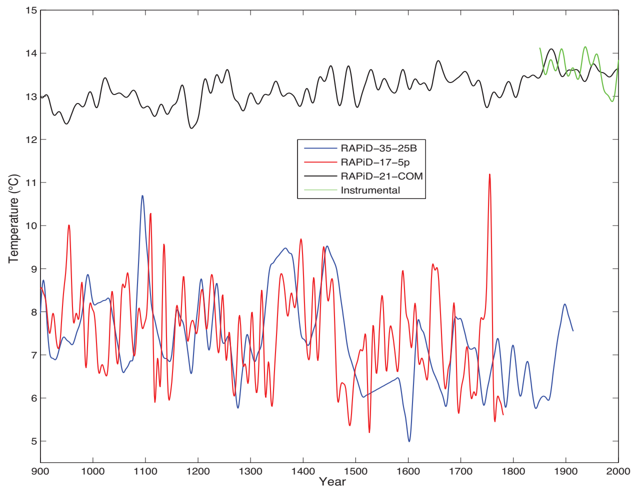

Figure S7. Comparison of temperature anomaly (°C) according to three sediment-core records on their original scales.

Finally, Wanamaker et al. 2012[5] claimed to have produced an AMOC reconstruction based on ^{14}C data taken from sea shells collected in shallow waters (81-83 m depth) near the northern coast of Iceland. They interpret these ^{14}C changes as indicative of ocean circulation changes, based on subtracting the local changes from a model-derived global ocean ^{14}C value. However, even if this difference is indicative of oceanic water mass changes at the study location, it is likely that changes in Arctic circulation, wind patterns and/or local currents may have more influence on this coastal site than the large-scale AMOC. One of their key results is that the AMOC "strengthened again after circa AD 1940", in contradiction to the conclusion of Dima and Lohmann 2010[6] who showed that the AMOC has been weakening since 1930, based on instrumental data.

In contrast to these proxy studies, our subpolar gyre reconstruction has been validated against the instrumental record and is very similar to it during the period of overlap (Figure 3 of our paper).

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