AUXILIARY MATERIAL:

SUPPORTING INFORMATION

A signal of persistent Atlantic multidecadal variability in Arctic sea ice

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Auxiliary Text and Figures

Note 1. Sea ice time series

The materials used in this study are existing time series comprised of: (a) sea-ice records based on historical observations, (b) sea-ice reconstructions based on paleo-environmental records, and (c) Atlantic Multidecadal Oscillation (AMO) time series based on instrumental observations and paleo-environmental reconstructions. The reasons for using historical and paleo sea-ice reconstructions rather than modern datasets are that: (i) gridded sea-ice datasets based on satellite passive-microwave sensor data extend back less than four decades, and standard gridded datasets (e.g., HadSST) that extend back through the whole previous century are to a varying degree interpolated using climatology rather than real variability, particularly in winter [*Walsh et al*., 2011; *Semenov and Latif*, 2012] and (ii) longer, multi-century records are needed to be able to robustly establish the existence of multidecadal fluctuations. For descriptions of the capabilities and limitations of historical and proxy sea-ice records, see *Zakharov* [1997] and *Polyak et al.* [2010], respectively.

The historical records were chosen based on four criteria, as stated in the main paper: (i) longer than a century and a half in duration with seasonal-to-annual resolution and no substantial gaps, (ii) documented quality control for homogeneity, (iii) documented to represent sea ice regionally (not locally), and (iv) independence from the other records chosen. The first criterion excluded otherwise qualified sea-ice records from the Russian arctic seas [e.g., *Polyakov et al*., 2003] and Alaska. The second criterion is clearly essential, though in practice did not exclude any records except for a millennium-scale "Koch" index for Icelandic sea-ice incidence [*Koch*, 1945; *Bergthorsson*, 1969] in favor of a quality-assured record since 1600 [*Ogilvie*, 2005]. The third criterion excluded local/sub-regional records, e.g. W Baltic Sea, Gulf of Riga and port of Tallinn, in favor of the more regional Baltic Sea winter maximum ice extent [*Seina and Paluoso*, 2006]; note that although the Icelandic sea-ice indices are local, these have been demonstrated statistically [*Kelly et al.,* 1987] to represent sea ice in the Greenland Sea region and are therefore included. The fourth criterion was a factor for different time series derived from essentially the same Norwegian ice-chart source material. Here we a selected longer, more spatially- and temporally-detailed version [*Divine and Dick*, 2006] instead of the original version from *Vinje* [2001]; nonetheless, in Fig. 1 in the main paper we do show the original "E Nordic Seas" series [*Vinje*, 2001] for comparison to the reconstructed "W Nordic Seas" [*Macias Fauria et al*., 2010] and W Barents Sea series [*Divine and Dick*, 2006].

Figure S1 shows the approximate locations of the historical sea-ice records that were selected for analysis. The representativeness of each series is typically regional (100s of km). Temporally, the time series range from approximately one to three centuries. There are very few years with missing values, usually in the early part of the series. There is generally one value per year; however, the effective temporal resolution is sub-annual, typically representing a seasonal indicator.

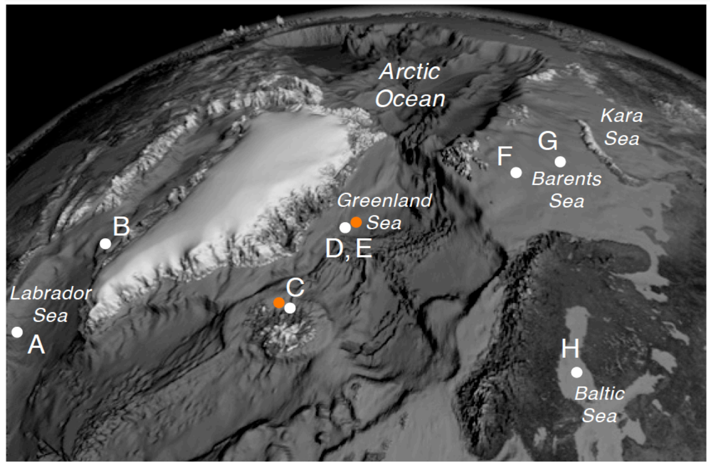

Figure S1. Location map of the historical and paleo proxy sea-ice time series analyzed here. White dots signify the approximate locations of the eight historical records, whereas brown dots signify the two sea-ice proxy records. Letters correspond to Table 1 and the panels in Fig. 1 in the main paper. Bathymetry and topography are shown in relief, and selected arctic marginal seas are indicated.

Two paleo proxy sea-ice records were also included in the analysis. As stated in the main paper, these records have been documented to represent regional sea-ice conditions from comparison / calibration against historical records from the same location, and have a temporal resolution of 25 years or better, in order to meet the Nyquist frequency that is necessary to resolve 50^{+}-year multidecadal variability. The records are: (1) an annually-resolved proxy for “W Nordic Seas” (i.e., Greenland Sea) winter sea-ice extent since 1200 [*Macias Fauria et al*., 2010], which has been calibrated against the *Vinje* [2001] historical sea ice, based on a combination of a regional tree-ring chronology from Fennoscandia and $\delta^{18}O$ from the Lomonosovfonna ice core in Svalbard, and (2) a high-resolution, full Holocene sea-ice proxy from marine core MD99-2269 north of Iceland (66°38 N, 20°51 W), based on quartz content [*Moros et al*., 2006]. Quartz content in Icelandic shelf sediments has been interpreted as a proxy for allochthonous drift ice transported there by the East Greenland Current and then the Northeast Iceland Current [*Andrews et al*., 2009]. The proxy is a semi-quantitative indicator of sea-ice severity. The MD99-2269 sea-ice proxy has been compared previously to Icelandic historical sea-ice incidence (the duration of the presence of sea ice along the Icelandic coast) and has been demonstrated [*Axford et al.,* 2011] to be consistent with other proxy data for sea ice and temperature near Iceland, including an independent sea-ice proxy based on the biomarker IP25 from nearby core MD-2275 [*Masse et al*., 2009].

The time series were left unaltered from the source, with no smoothing or resampling undertaken; the only exception was the MD2269 sea-ice proxy, which required resampling at regular intervals in order to identify signals using wavelet analysis – see Note 3. The sea-ice time series were also not standardized, except for the historical (1600–1860) [*Ogilvie*, 2005] and modern (1880–1996) [*Wallevík and Sigurjónsson*, 1998] parts of the Icelandic record. Further, no attempt was made to update the sea-ice records into the 2000s, in order to avoid introducing errors arising from differences in interpretation and indexing.

Note 2. Time-series analysis methods

The time-series analysis methods were primarily wavelet analysis. Decomposition of a time-series into wavelets – a set of localized rescaled and translated functions – allows highlighting of the variability features at different time scales. In contrast to the Fourier transform, the wavelet analysis can effectively visualize the frequency content of a signal as it varies through time [*Torrence and Compo*, 1998]. As a basis function for transform, we used Morlet wavelet, which is an optimal choice for providing a balance between time- and frequency-localization for features in the wavelet spectrum. The multidecadal components from the series were extracted using the weighted sum of the wavelet power spectrum over the range of scales that correspond to the equivalent Fourier periods between 50 and 120 years.

The choice of window was actually a choice of the width of the band pass filter with cut-off periods, given in terms of the respective gain function magnitude at filter edges, corresponding to 50 and 120 years. The choice of the width is optimal to isolate best the variability generally associated with the phenomenon our study was aimed at. The choice of these cutoffs prevents from leaking both the higher and lower frequency quasi-periodic variations where the covariance structure indeed might have a different character. The upper (lower frequency cutoff) limit also should not be too high to ensure minimization of edge effects of the transform, which is for the Morlet wavelet we used approximately corresponds to 120/sqrt(2) = 85 years. The limitations of the technique are similar to the ones associated with other spectral methods, like possible spectral leakage, edge effects etc. The general idea is always to find a trade-off between the biases and advantages of the technique employed. Wavelet transform in contrast to Fourier based techniques is convenient for the analysis of intermittent quasi-periodic variations as the wavelet filter has a local nature (compact support). The wavelet function we used, in turn, is considered to be optimal for our goals. It provides the balance between the time and scale (or period) localization and has a shape which resembles signals we have studied.

The amount of variance explained by the 50–120 year variability is given as percentage, although comparing the percentages between series is not straightforward, given differences in the noise inherent to the diverse indices. In contrast to the more common wavelet plot that depicts power as function of time on the x-axis and time scale on the y-axis, here we present the results as a wavelet-based bandpass filtered signal. This facilitates visualization and cross-comparison of the quasi-periodic behaviour (amplitude and phasing) of the analysed records. As an independent test for the wavelet-based multidecadal signal identified in the resampled MD-2269 data, we performed spectral analysis – see Note 3.

Note 3. Icelandic sea-ice proxy analysis

Prior to the band-pass wavelet filtering, we resampled the unevenly sampled MD99-2269 sea-ice proxy series to the regular time interval of 20 yr using linear interpolation. Figure S2 shows the results of the 50–120 year wavelet filter applied to the de-trended part of the series between 0–6 kyr BP which has a sufficient sampling density. Quasi-persistent multidecadal variability is apparent through the record, strongest in the past millennium, between 2–3 kyr BP, 3.6–4.2 kyr BP and 5.1–6.0 kyr BP. The quasi-persistence of the multidecadal signal is similar to that found in alkenone-reconstructed SSTs [*Sicre et al.,* 2009] from nearby core MD-2275 north of Iceland (66°33N; 17°42W), and in the $\delta^{18}O$ ice-core record from Renland in eastern Greenland (71°15N, 26°46W) – see the supporting online material from *Knudsen et al*. [2011].

Independent of the wavelet analysis, Fourier analysis of the MD99-2269 sea-ice proxy series was then carried out using the REDFIT technique [*Schulz and Mudelsee*, 2003]. The major advantage of the method is that it can provide the spectral estimate of the unevenly spaced time series via fitting the first-order auto-regressive process (AR1) directly to the data without its prior resampling. We used the de-trended part of the series between 0–6 kyr BP that has a sufficient sampling density and characteristics similar to an AR1 process. The appropriateness of the AR1 model to describe the analyzed data was tested using a non-parametric runs test embedded in the REDFIT package. In order to reduce the uncertainty in spectral estimate, we ran the analysis using a Welch spectral window and three WOSA (Weighted Overlap Segmented Averaging) segments. The results (Fig. S3) show a statistically significant peak between 60–70 years, thus corroborating the multidecadal signal isolated using the wavelets.

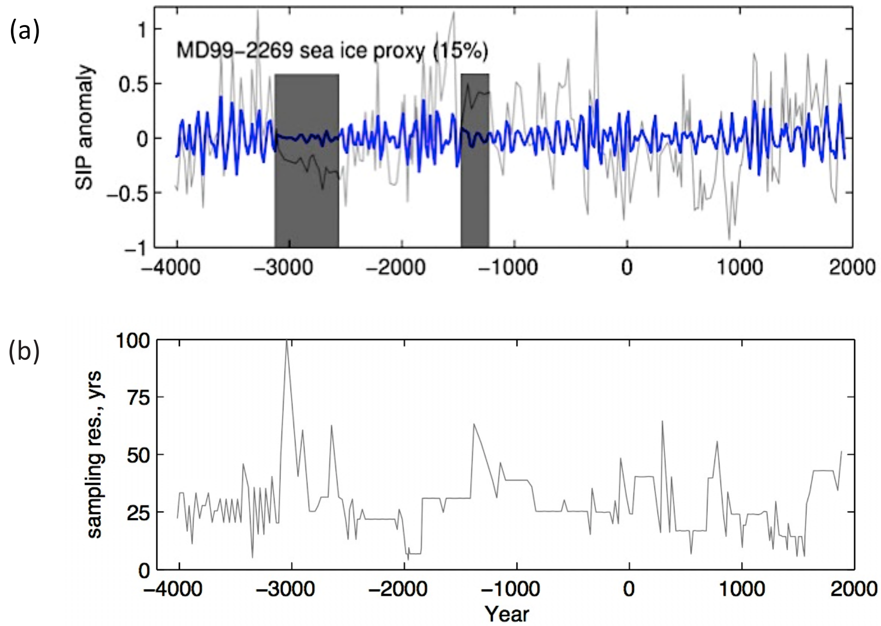

Figure S2. (a) Detrended MD99-2269-core sea-ice proxy (SIP) series (gray) and its multidecadal (50–120 year) component (blue). The wavelet bandpass-filtered component represents some 15% of the signal variance with respect to the variance of the resampled time series. (b) Sampling increment of the MD99-2269 sea-ice proxy series. The dark gray bars in (a) denote those parts of the record where the low-sampling increment precludes estimation of multidecadal variability.

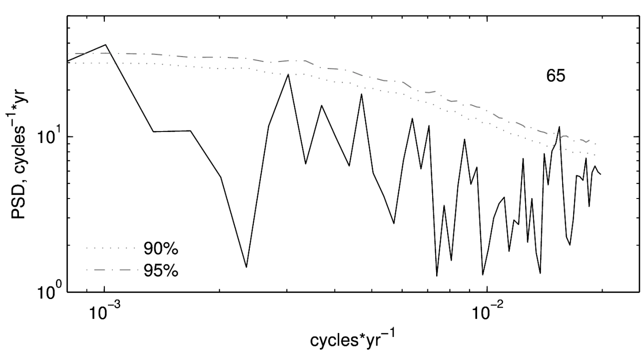

Figure S3. REDFIT estimates of the power spectral density function for the detrended MD99-2269 sediment core (0–6 kyr BP) series of sea-ice proxy (black solid lines); 95% and 90% ‘false alarm’ levels (gray dashed-dotted and dotted lines, respectively) for the theoretical AR(1) spectrum calculated from the percentiles of the Monte Carlo ensemble.

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