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A signal of persistent Atlantic multidecadal variability in Arctic sea ice

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Key Points:
- Multidecadal variability is evident in Atlantic Arctic sea-ice reconstructions
- Sea-ice variability is linked to the Atlantic Multidecadal Oscillation

Supporting Information:
- Auxiliary Text
- Figure S1
- Figure S2
- Figure S3

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Abstract Satellite data suggest an Arctic sea ice-climate system in rapid transformation, yet its long-term natural modes of variability are poorly known. Here we integrate and synthesize a set of multicentury historical records of Atlantic Arctic sea ice, supplemented with high-resolution paleoproxy records, each reflecting primarily winter/spring sea ice conditions. We establish a signal of pervasive and persistent multidecadal (~60–90 year) fluctuations that is most pronounced in the Greenland Sea and weakens further away. Covariability between sea ice and Atlantic multidecadal variability as represented by the Atlantic Multidecadal Oscillation (AMO) index is evident during the instrumental record, including an abrupt change at the onset of the early twentieth century warming. Similar covariability through previous centuries is evident from comparison of the longest historical sea ice records and paleoproxy reconstructions of sea ice and the AMO. This observational evidence supports recent modeling studies that have suggested that Arctic sea ice is intrinsically linked to Atlantic multidecadal variability. This may have implications for understanding the recent negative trend in Arctic winter sea ice extent, although because the losses have been greater in summer, other processes and feedbacks are also important.

1. Introduction

There is consensus among theoretical and numerical models that global warming should be amplified in the Arctic [*Holland and Bitz*, 2003], with a multitude of climate system impacts including a diminished sea-ice cover [*Intergovernmental Panel on Climate Change*, 2007; *Serreze et al.*, 2007]. Satellite data analyses have established a significant negative trend in hemispheric sea-ice extent, presently -0.40×10^6 km^2 decade^{-1} (or ~3% decade^{-1}) in winter (March) and -0.89×10^6 km^2 decade^{-1} (or ~12% decade^{-1}) in summer (September) from 1979 to 2013 (using 1981–2010 as the base period). This has reduced the amount of older, perennial sea ice and suggesting a transformation toward a seasonal ice cover. The record low sea-ice extent ~3.4×10^6 km^2 reached in September 2012 was the latest step in that direction (National Snow and Ice Data Center, 2012, http://nsidc.org/arcticseaicenews/). The observed reduction in sea-ice extent has been significantly faster than projected by most numerical models using realistic anthropogenic increases in greenhouse gases [*Stroeve et al.*, 2012]. The mismatch between observations and models can arise from the following: model underestimation of the sensitivity of sea ice to radiatively forced climate change, incorrect or missing types of radiative forcing, and/or nonmodeled natural variability [*Kattsov et al.*, 2011]. Observational research on the latter aspect has focused primarily on interannual to decadal modes of variability such as the Northern Annular Mode and North Atlantic Oscillation, whose atmospheric circulation patterns have been found to be strongly imprinted on Arctic sea-ice concentration [*Serreze et al.*, 2007]. However, possible modes of variability on multidecadal timescales have not been examined extensively, owing largely to deficiencies in sea-ice data prior to the satellite era. Standard century-scale hemispheric data sets such as HADISST [*Rayner et al.*, 2003] indicate a monotonic decrease in Northern Hemispheric sea-ice extent until the latter part of the twentieth century, when the decreases accelerated concurrently with increases in greenhouse gas (GHG) forcing. There is no indication of multidecadal variability or reduced sea ice during the well-documented early twentieth century warming (ETCW) in the Arctic during the 1920s and 1930s in HADISST (Figure S2 in the supporting information). However, there are local and regional historical observations that do show reduced sea ice during the ETCW [*Johannessen et al.*, 2004], and a multidecadal mode of variability has been suggested [e.g., *Polyakov et al.*, 2003], though the evidence has remained fragmentary. Recent advances in developing longer sea-ice time

Table 1. Sea-Ice Time Series Included in the Analysis, Arranged From West to East[a]

Map ID	Region Name (Approx. Location)	Variable Type (Units)	Sampling or Season	Start Year	Source
A	Newfoundland (40°N–55°N, 50°W)	Ice extent maximum ($10^3 km^2$)	Winter	1810	*Hill* [1999]
B	SW Greenland (62°N–69°N, 50°W)	Ice export (km^3) through Fram Strait, reconstructed	Annual	1820	*Schmith and Hansen* [2003]
C_1	Iceland (66°N, 20°W)	Ice severity (seasons × regions/yr, sigma units)	Annual (winter-spring)	1600	*Oglivie* [2005]
C_2	Iceland (66°N, 20°W)	Ice incidence (weeks/yr, sigma units)	Annual (winter-spring)	1890	*Wallevík and Sigurjónsson* [1998]
C_3	N Iceland shelf (66°N, 21°W)	Ice severity paleoproxy	20–25 year	11,500 years BP	*Moros et al.* [2006]
D	Greenland Sea (70°N, 20°W)	Ice-edge anomaly (km)	Winter-spring (April)	1754	*Divine and Dick* [2006]
E	W Nordic Seas (70°N, 20°W)	Ice-extent ($10^3 km^2$) paleoproxy	Winter-spring (April)	1200	*Macias Fauria et al.* [2010]
F	W Barents Sea (75°N–80°N, 15°E)	Ice-edge anomaly (km)	Winter-spring (April)	1754	*Divine and Dick* [2006]
G	E Nordic Seas (75°N–80°N, 20°E)	Ice extent ($10^3 km^2$)	Winter-spring (April)	1864	*Vinje* [2001]
H	Baltic Sea (65°N, 20°E)	Ice extent, max. (0–1 scale)	Winter	1720	*Seina and Paluoso* [2006]

[a]Map ID corresponds to Figure S1 in the supporting information and the panels in Figure 1.

series from historical [e.g., *Schmith and Hansen*, 2003; *Divine and Dick*, 2006] and high-resolution paleoenvironmental proxy records [e.g., *Moros et al.*, 2006; *Macias Fauria et al.*, 2010; *Kinnard et al.*, 2011] provide an opportunity to (1) robustly identify and track multidecadal sea-ice variability and (2) establish linkages to known climate system fluctuations on a multidecadal timescale [e.g., *Delworth and Mann*, 2000].

Here we present observational evidence for pervasive and persistent multidecadal sea ice variability, based on time-frequency analysis of a comprehensive set of several long historical and paleoproxy sea ice records from multiple regions. Moreover, through explicit comparisons with instrumental and proxy records, we demonstrate covariability with the Atlantic Multidecadal Oscillation (AMO). The AMO is a coherent pattern of basin-wide sea surface temperature (SST) variations with a period of roughly 60–90 years. The AMO index can be considered as one representation of Atlantic multidecadal variability (AMV). Paleoenvironmental studies suggest that the AMO has persisted through previous centuries [*Gray et al.*, 2004] and even millennia [*Knudsen et al.*, 2011]. Modeling studies [e.g., *Delworth and Mann*, 2000; *Knight et al.*, 2005] have identified the Atlantic meridional overturning circulation (AMOC) as a probable mechanism for this variability, although there are between-model uncertainties in the phasing and strength of the AMO-AMOC covariability [*Medhaug and Furevik*, 2011]. It is thus suggested that the AMO represents natural internal climate system variability; however, external forcing (volcanic aerosols and/or solar variability) may play a role [*Otterå et al.*, 2010; *Booth et al.*, 2012]. The AMO has been found to impact climate variability not only in the low and midlatitudes [*Sutton and Hodson*, 2009]—i.e., within the 0°N–60°N AMO index boundary—but also into the Arctic [*Lamoureux et al.*, 2006; *Chylek et al.*, 2009; *Levitus et al.*, 2009]. Modeling experiments have recently suggested that sea ice extent in the Arctic is also influenced by the AMO [*Mahajan et al.*, 2011; *Day et al.*, 2012]. However, strong observational evidence of a sea ice–AMO connection has been elusive, in part, because century-scale data sets are not commensurate to tracking more than one complete "cycle."

2. Data and Methods

In order to identify patterns of multidecadal variability of sea ice, we evaluated about 20 existing historical records and then selected altogether eight records, based on four criteria: (1) longer than a century and a half in duration with seasonal-to-annual resolution and no substantial gaps, (2) documented quality control for homogeneity, (3) documented to represent sea ice regionally, and (4) independence from the other records chosen. The selected historical records span the subarctic–Arctic Atlantic from the Labrador Sea to the Barents Sea (Table 1 and Figure S1).

These records are supplemented with high-resolution paleoproxy records colocated with two of the historical records, thereby providing independent evidence of any signals. The proxy records for sea ice were chosen based on availability and two criteria: (1) documented to represent regional sea-ice conditions from comparison/calibration against historical records from the same location and (2) temporal resolution of 25 years or better, in order to resolve multidecadal variability. The paleodata analyzed are an annually resolved proxy for "Western Nordic Seas" (i.e., Greenland Sea) winter sea-ice extent since 1200 [*Macias Fauria et al.*, 2010], calibrated using a combination of a regional tree ring chronology from Fennoscandia and $\delta^{18}O$ from the Lomonosovfonna ice core in Svalbard, and a high-resolution, full Holocene sea-ice proxy from marine core MD99-2269 north of Iceland, based on quartz mineralogy [*Moros et al.*, 2006]. In contrast to the recent multiproxy reconstruction of summer sea-ice extent [*Kinnard et al.*, 2011], most of the historical and paleorecords analyzed here reflect conditions in the dynamic cold season (winter–spring), when multidecadal climate variability (e.g., the ETCW) is most pronounced in the Arctic.

A consistent time series analysis of each of the records was performed using time and time-frequency domain methods, primarily wavelet analysis [*Torrence and Compo*, 1998]. Decomposing a time series using wavelets highlights the variability of features on different timescales. Wavelet analysis is widely used to study climate system oscillations, because this method isolates not only amplitudes and phasing as functions of frequencies as in traditional spectral analysis but also reveals how these vary through time. Here we isolate and track multidecadal variability, using a broad 50–120 year wavelet filter. 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. As a basis function for the transform, we used the Morlet wavelet, which is an optimal choice for providing a balance between time and frequency localization for features in the wavelet spectrum—see supporting information.

3. Results: Multidecadal Sea-Ice Signal

The salient feature is the presence of pervasive multidecadal variability, upon which interannual-to-decadal fluctuations are superposed (Figure 1). Four aspects should be noted: (1) less sea ice is generally seen in most recent decades—despite the fact that these series do not extend into the 2000s—however, a common characteristic amongst several of the records (Figures 1a–1e) is sharply reduced sea ice at the onset of the ETCW, heralding the termination of the Little Ice Age in the region; (2) multidecadal variability is apparent in all of the records, except for the Baltic Sea. The wavelet-filtered signals (bold lines in Figure 1) have predominately 60–90 year timescales; e.g., the 400 year Iceland and "Western Nordic Seas" series have five successive peaks and troughs; the multidecadal fluctuations amongst the records are broadly consistent in their periods and in phase (though offset several years for the Newfoundland and the Barents Sea); (3) the multidecadal signal is persistent in all records where it is found—in no cases does the signal disappear through time; and (4) multidecadal signals are strongest in the Greenland Sea region (Figures 2b–2e) and weaker on either side, i.e., Newfoundland and the "Eastern Nordic Seas" (i.e., Barents Sea). Further, this is consistent with findings from twentieth century records from the Russian Arctic seas [*Polyakov et al.*, 2003], which indicate that a multidecadal fluctuation dissipates eastward from the Kara Sea, supporting the notion that the North Atlantic is the source of this variability. Further, our observational results agree with model studies of climate system variability that suggest the Greenland Sea to be of central importance for AMV [*Delworth et al.*, 1997; *Delworth and Mann*, 2000].

4. Results: Linking Sea Ice to Atlantic Multidecadal Variability

These temporal and spatial features suggest that multidecadal sea-ice variability is a robust feature that may be related to AMV such as expressed as the AMO. The possible AMO connection has been mentioned previously in sea-ice reconstructions [*Divine and Dick*, 2006; *Macias Fauria et al.*, 2010], although the authors only pointed out the similar timescale. Here for the first time, we explicitly compare sea-ice variability and the AMO over several centuries, thereby linking the two. We focus further on three independent sea-ice records from the Greenland Sea region, together with two AMO indices. The sea-ice records are the 180 year series Fram Strait ice export reconstruction, the 400 year historical series from Iceland, and the 800 year paleoproxy reconstruction of the Western Nordic Seas. The AMO records used for comparison are an instrumental-based series (National Oceanic and Atmospheric Administration, http://www.esrl.noaa.gov/psd/data/ time series/AMO/, 2012) and an AMO proxy reconstruction based on tree rings extending back more than 400 years [*Gray et al.*, 2004]. All three of the above mentioned sea-ice records overlap the whole 150 year instrumental AMO record, and two overlap the whole AMO proxy record.

The instrument-based AMO index for the past 150 years is characterized by two well-known cold (negative) phases and two warm (positive) phases (Figure 2a). The most recent cold phase occurred from the 1960s to the 1980s, while the earlier cold phase occurred in the late nineteenth century to early twentieth century, both associated with enhanced sea-ice export through Fram Strait [*Schmith and Hansen*, 2003; *Dima and Lohmann*, 2007], negative SST anomalies, and increased sea ice in the subpolar Atlantic (Figures 2c–2e). The most recent warm phase occurred from the 1990s through the present (W1 in Figure 2), while an earlier one occurred in the 1930s through the 1950s (W2 in Figure 2). The earlier warming initiated with an abrupt rise in SSTs around 1920 (heralding the onset of the ETCW) and terminated with an abrupt drop in the late 1960s,

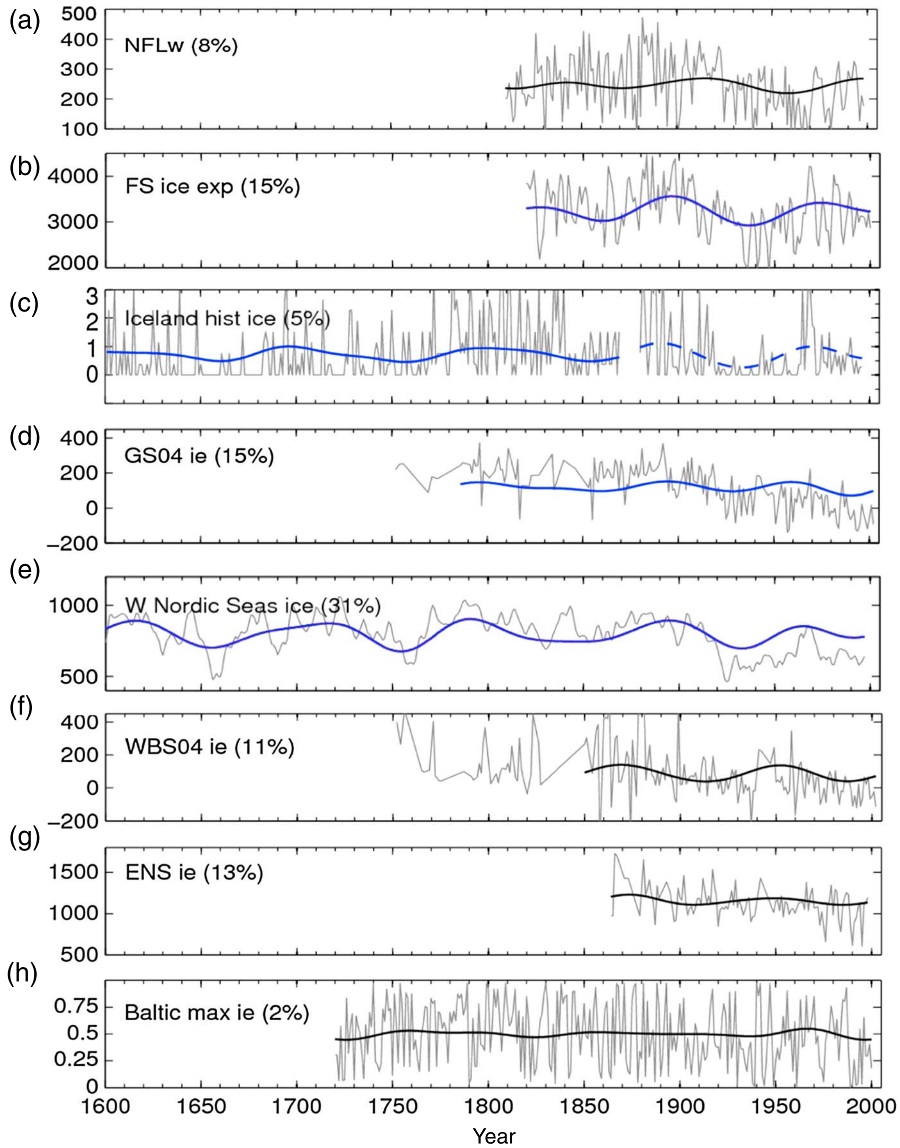

Figure 1. Multidecadal fluctuations in sea ice during the past 150–400 years. Original nonsmoothed time series (gray) and multidecadal (50–120 years) component (thick line) reconstructed from wavelet decomposition, with regions arranged from west to east: (a) Newfoundland regional winter sea-ice extent. (b) Fram Strait annual ice export reconstructed from historical Arctic sea-ice observations along SW Greenland. (c) Icelandic historical sea-ice severity index (1600–1870) and sea-ice incidence index (1880–2000), both standardized. (d) Greenland Sea (April) ice-edge anomaly. (e) Western Nordic Seas (i.e., Greenland Sea) ice-extent paleoproxy reconstruction. (f) Western Barents Sea ice-edge anomaly. (g) Eastern Nordic Seas (i.e., Barents Sea) historical ice extent. (h) Baltic Sea historical ice extent. The pronounced multidecadal signals in the Greenland Sea region are highlighted in blue. The numbers in parentheses indicate the amount of variance in the original nonsmoothed time series that is explained by the multidecadal component. See Table 1 and supporting information for details.

both punctuated with abrupt changes in sea ice in the Greenland Sea/Iceland region (Figure 2c–2e). Extending the comparison further back using an AMO proxy (Figure 2b), it is evident that the wavelength and phasing of the wavelet-filtered signals of the sea-ice records and the AMO are generally consistent and have the expected sign, with reduced sea ice (denoted W1–6 in Figure 2) during the warm AMO^+ phases and vice versa. For example, the lowest sea-ice values before the twentieth century occurred in the middle to late 1600s (W5 in Figure 2), as shown here in the Icelandic historical record and the Western Nordic Seas proxy (Figures 2d and 2e) and in a pan-Arctic summer sea-ice reconstruction [*Kinnard et al*., 2011]. This period coincided with a period of high AMO-proxy index values (Figure 2b). Moreover, the three highest sea-ice values (e.g., early 1600s, late 1700s to early 1800s, and late 1800s–1920) occurred during the three lowest

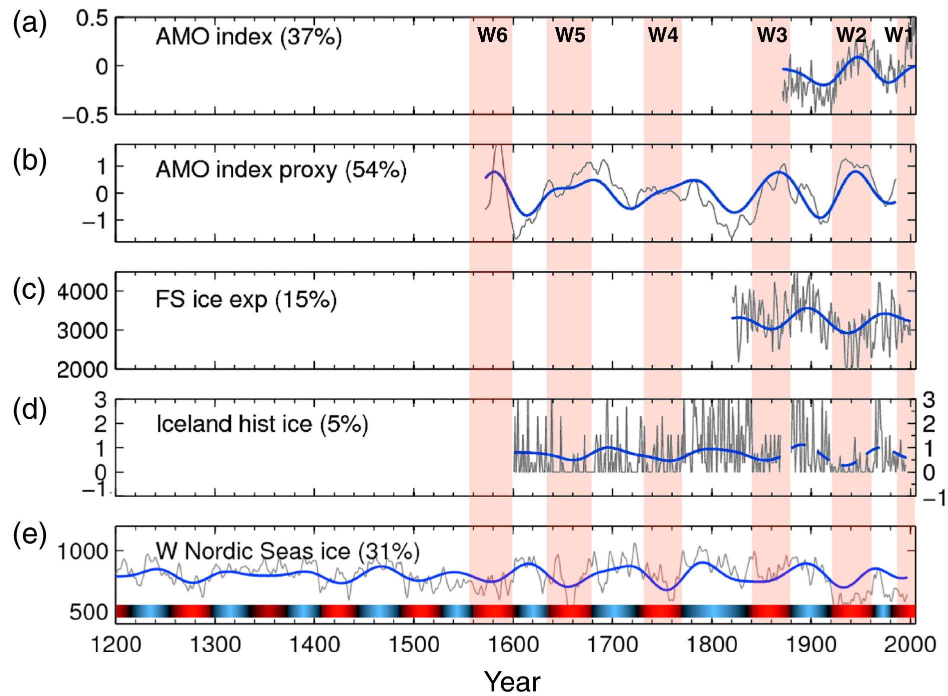

Figure 2. Persistent multidecadal fluctuations in sea ice linked to the AMO. Original time series (gray) and multidecadal 50–120 year component (blue) reconstructed from wavelet decomposition: (a) AMO modern index, not detrended, i.e., North Atlantic SST anomaly. (b) AMO proxy index, not detrended, 10 year running average [*Gray et al*., 2004]. (c) Fram Strait ice export reconstructed from historical observations along SW Greenland. (d) Icelandic sea-ice severity index (1600–1870) and sea-ice incidence index (1880–2000) (sigma units). (e) Western Nordic Seas sea-ice extent proxy reconstruction. The numbers in parentheses indicate the amount of variance in the nonsmoothed time series that is explained by the multidecadal component. The color bar in Figure 2e indicates periods with reduced ice (red) and cold periods with increased ice (blue) inferred from the wavelet-filtered signal. The reduced ice periods (labeled W1–W6) inferred from Figure 2e are projected (light red shading) onto the other series and are seen to correspond to warm AMO periods.

AMO index values on record, thus demonstrating persistent covariability. Further, wavelet results for the 800 year sea-ice proxy (Figure 2e) highlight the presence of multidecadal variability throughout the record, with 10 peaks and troughs, albeit with weaker amplitude prior to about 1500. Although this AMO proxy is not long enough to compare against the earlier part of the 800 year sea-ice series, inspection of a longer reconstruction of the AMO [*Mann et al*., 2009] points to pronounced negative AMO excursions in the mid-1300s and mid-1400s, which here are reflected as positive sea-ice anomalies.

A relevant question is whether the AMO-related variability evident in the sea-ice series from the Greenland Sea/Iceland over several centuries may be evident in even longer sea-ice records. Holocene sea-ice proxies are based on marine sediments, and as such there are few records whose resolution is high enough to resolve multidecadal variability. Here we analyze one such high-resolution sea-ice proxy from marine core MD-2269 from the North Icelandic shelf [*Moros et al*., 2006]. Based on allochthonous quartz content, this sea-ice proxy has been previously compared to historical Icelandic sea-ice occurrence and multiple paleoenvironmental proxies from around Iceland, including the sea-ice biomarker IP25—see supporting information. Because marine records inherently have uneven temporal sampling as well as dating uncertainties, the MD-2269 data cannot be as precisely compared to the other sea ice or AMO records, which are annually resolved. Here the existence of multidecadal fluctuations was tested using wavelet filtering and spectral analysis applied to those parts of the record with sufficient resolution, e.g., 0.5–6 kyBP. A distinct multidecadal signal (~60–70 year) is apparent through several millennia, albeit weaker in some intervals, e.g., between ~2.5 and 3.4 kyBP. This quasipersistence is similar to the modulation of possible AMO-related signals found previously [*Knudsen et al*., 2011] in other paleorecords from the region, notably $\delta^{18}O$ from the Renland ice cap in eastern Greenland and reconstructed SSTs from core MD-2275 north of Iceland, in proximity to the MD-2269 sea-ice record—see supporting information. The presence of multidecadal variability in this multimillennial sea-ice proxy offers independent support for the robustness of the signal seen in the shorter records from the Greenland Sea region.

5. Discussion and Conclusions

The pervasive multidecadal variability in observed sea ice is here not considered to represent truly oscillatory cycles but rather irregular, broadly multidecadal fluctuations between warmer (colder) periods with less (more) ice that are related to AMV. This is in general agreement with *Wood et al*. [2010], although the longer-term evidence of a persistent signal put forth here modifies their view that these are singular episodes rather than quasicyclic. Further, our conceptual model does not preclude abrupt sea ice–SST fluctuations such as those clearly seen at the onset of the ETCW and in the late 1960s [e.g.,*Thompson et al*., 2011] and antecedent cases seen here, e.g., early 1600s, 1660s, and 1760s. Indeed, such abrupt features may be intrinsic parts of the AMO-related behavior, enhanced through nonlinear atmosphere-ice-ocean interactions. Further, sea ice may not merely respond passively to changes in the North Atlantic Ocean but may itself be a fundamental and interactive component of AMO/AMOC variability, set into effect through anomalous sea-ice and freshwater pulses through Fram Strait, such as those evident in the 1880s–1910s and the 1960s immediately prior to a drop in the AMO (Figure 2c)—if so, a pertinent, unresolved question is how future reductions in Arctic sea ice could affect ice export and thereby possibly influence the AMO/AMOC.

Regardless of the uncertainties in the underlying principal mechanisms of the sea ice-AMO-AMOC linkages, it is clear that multidecadal sea-ice variability is directly or indirectly related to natural fluctuations in the North Atlantic. This study provides strong, long-term evidence to support modeling results that have suggested linkages between Arctic sea ice and Atlantic multidecadal variability [*Holland et al*., 2001; *Jungclaus et al*., 2005; *Mahajan et al*., 2011].

These results imply that the AMO may be an important factor in the faster-than- projected decreases in sea ice, in qualitative agreement with a recent modeling–satellite-data analysis [*Day et al*., 2012] that attributes up to 5–30% to the satellite era (1979–2010) summer sea-ice decrease to the concurrent AMO warm phase, and an even higher proportion for the winter sea ice. Given the demonstrated covariability between sea ice and the AMO, it follows that a change to a negative AMO phase in the coming decade(s) could—to some degree—temporarily ameliorate the strongly negative recent sea-ice trends. There are, however, caveats: (1) multidecadal fluctuations in Arctic–subarctic climate and sea ice appear most pronounced in the Atlantic sector, such that the pan-Arctic signal may be substantially smaller [e.g., *Polyakov et al*., 2003; *Mahajan et al*., 2011]; (2) the sea-ice records synthesized here represent primarily the cold season (winter–spring), whereas the satellite record clearly shows losses primarily in summer, suggesting that other processes and feedback are important; (3) observations show that while recent sea-ice losses in winter are most pronounced in the Greenland and Barents Seas, the largest reductions in summer are remote from the Atlantic, e.g., Beaufort, Chukchi, and Siberian seas (National Snow and Ice Data Center, 2012, http://nsidc.org/Arcticseaicenews/); and (4) the recent reductions in sea ice should not be considered merely the latest in a sequence of AMO-related multidecadal fluctuations but rather the first one to be superposed upon an anthropogenic GHG warming background signal that is emerging strongly in the Arctic [*Kaufmann et al*., 2009; *Serreze et al*., 2009]. Thus, the observed decreases in the Arctic sea-ice cover, especially in summer, may continue largely unabated as the GHG signal strengthens further.

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