Greenland ice core evidence for spatial and temporal variability of the Atlantic Multidecadal Oscillation

Petr Chylek,[1] Chris Folland,[2] Leela Frankcombe,[3] Henk Dijkstra,[3] Glen Lesins,[4] and Manvendra Dubey[5]

Received 5 February 2012; revised 20 March 2012; accepted 20 March 2012; published 3 May 2012.

[1] The Greenland δ^{18}O ice core record is used as a proxy for Greenland surface air temperatures and to interpret Atlantic Multidecadal Oscillation (AMO) variability. An analysis of annual δ^{18}O data from six Arctic ice cores (five from Greenland and one from Canada's Ellesmere Island) suggests a significant AMO spatial and temporal variability within a recent period of 660 years. A dominant AMO periodicity near 20 years is clearly observed in the southern (Dye3 site) and the central (GISP2, Crete and Milcent) regions of Greenland. This 20-year variability is, however, significantly reduced in the northern (Camp Century and Agassiz Ice Cap) region, likely due to a larger distance from the Atlantic Ocean, and a much lower snow accumulation. A longer time scale AMO component of 45–65 years, which has been seen clearly in the 20th century SST data, is detected only in central Greenland ice cores. We find a significant difference between the AMO cycles during the Little Ice Age (LIA) and the Medieval Warm Period (MWP). The LIA was dominated by a ∼20 year AMO cycle with no other decadal or multidecadal scale variability above the noise level. However, during the preceding MWP the 20 year cycle was replaced by a longer scale cycle centered near a period of 43 years with a further 11.5 year periodicity. An analysis of two coupled atmosphere-ocean general circulation models control runs (UK Met Office HadCM3 and NOAA GFDL CM2.1) agree with the shorter and longer time-scales of Atlantic Meridional Overturning Circulation (AMOC) and temperature fluctuations with periodicities close to those observed. However, the geographic variability of these periodicities indicated by ice core data is not captured in model simulations. **Citation:** Chylek, P., C. Folland, L. Frankcombe, H. Dijkstra, G. Lesins, and M. Dubey (2012), Greenland ice core evidence for spatial and temporal variability of the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *39*, L09705, doi:10.1029/2012GL051241.

1. Introduction

[2] The severity of the consequences of the current global warming depends considerably on how intense the warming is in the Arctic. Climate models (coupled atmosphere-ocean general circulation models) suggest [*Intergovernmental Panel on Climate Change*, 2007] that due to so called Arctic amplification [*Polyakov et al.*, 2002; *Chylek et al.*, 2009; *Kumar et al.*, 2010], Arctic warming will proceed faster than the global average. It is often assumed that most of the post 1970 Arctic warming is due to increasing concentration of CO_2 and other greenhouse gases (GHGs), without taking natural Arctic climate variability into consideration. However, the possibility that a non-negligible fraction of the recent Arctic warming has been caused by a multidecadal cycle of the Arctic climate [*Parker et al.*, 2007; *Semenov et al.*, 2010; *Chylek et al.*, 2010; *Polyakov et al.*, 2010, 2011; *Mahajan et al.*, 2011, 2012] linked to the Atlantic Multidecadal Oscillation (AMO), and to changes in the Atlantic Meridional Overturning Circulation (AMOC), is becoming increasingly likely. In this paper, we analyze annual data from six Arctic ice core δ^{18}O records (as a proxy for temperature variability), each about 660 years long, to determine cycles of Arctic natural (forced or unforced) climate change and its spatial and temporal variability.

2. Ice Core Data

[3] The ice core oxygen isotope ratio δ^{18}O has frequently been used as a proxy for temperature variability [*Picciotto et al.*, 1960; *Dansgaard et al.*, 1969]. In this study we provide a spectral analysis of the δ^{18}O records from six ice cores [*Clausen et al.*, 1988; *Dansgaard et al.*, 1969; *Fisher et al.*, 1995; *Grootes and Stuiver*, 1997; *Johnsen et al.*, 1970, 1972; *Stuiver et al.*, 1995] spanning the region from the southern Greenland Dye 3 site at latitude 62°N up to the most northern site at Canadian Agassiz Ice Cap at 84°N (Figure 1).

[4] Although the annual δ^{18}O is affected by several environmental factors, it has been generally accepted as a reasonable proxy for temperature. A high correlation between the instrumental era AMO index [*Parker et al.*, 2007] and average ice core δ^{18}O data [*Chylek et al.*, 2011], as well as a good agreement between the paleo AMO [*Delworth and Mann*, 2000] and δ^{18}O data justifies the use of annual δ^{18}O data as a proxy for AMO periodicity. Greenland temperature reconstructed from trapped air [*Kobashi et al.*, 2011] is also in a good agreement with δ^{18}O deduced temperature data.

[5] The δ^{18}O data for all six ice cores are available at the NOAA Paleoclimate website. Five of the ice cores have 659 years of a common time span from 1302 to 1961, and this time period is used in the analysis below. The Dye 3 δ^{18}O data ends in 1872, and consequently, for the Dye 3

[1]Space and Remote Sensing, Los Alamos National Laboratory, Los Alamos, New Mexico, USA.
[2]Met Office Hadley Centre, Exeter, UK.
[3]Institute for Marine and Atmospheric Research, Department of Physics and Astronomy, University of Utrecht, Utrecht, Netherlands.
[4]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada.
[5]Earth and Environmental Sciences, Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

Copyright 2012 by the American Geophysical Union.
0094-8276/12/2012GL051241

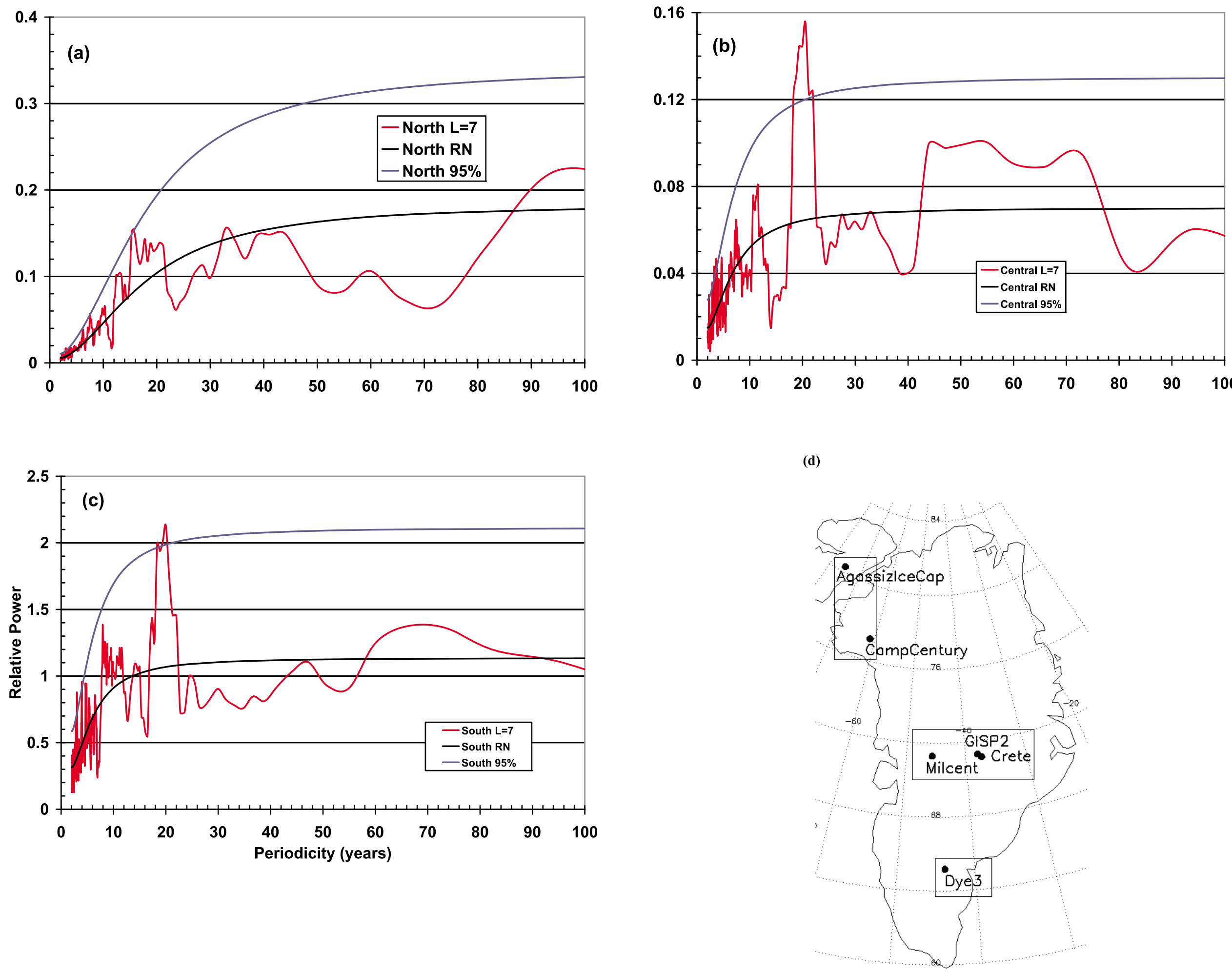

Figure 1. (a–c) Spectral analysis of 660 years of ice core δ^{18}O data for the three indicated geographical regions (averaged over L = 7 frequencies); estimated red noise (RN) and 95% confidence levels are also indicated. (d) A map of the ice core sites used in the study.

dataset the selected time period of 659 years will be 1213–1872.

3. Method

[6] To obtain latitudinal resolution, we group the ice cores into three regions (Figure 1) denoted as South (Dye 3), Central (GISP2, Milcent, and Crete), and North (Camp Century and Agassiz Ice Cap). The Dye 3 site is closest to the North Atlantic Ocean so the oceanic influence is largest there, while a diminished ocean influence is expected at the more northern locations.

[7] Since we are interested in periodicities rather than trends, we linearly detrended each δ^{18}O time series and normalized it to a unit variance. We averaged Fast Fourier Transforms (FFT) of individual series to obtain the average FFT for each region. Averaging the FFTs of individual time series (rather than the time series themselves) prevents a possible cancellation of coherent δ^{18}O signals due to timing errors in individual ice cores.

[8] To remove spurious peaks, the raw periodograms were averaged over several frequencies [*Shumway and Stoffer*, 2006]. Although the number of frequencies to be averaged cannot be unambiguously determined, a general practice is to average over about L = N/100 resolved frequencies where N is the number of data points in the series.

4. Regional Differences

[9] Figure 1a shows the resulting periodogram for the most northern region (Camp Century and Agassiz Ice Cap). No multidecadal periodicity is observed. The central region (GISP2, Milcent, and Crete) is dominated by a 20 year cycle (Figure 1b) that represents the only statistically significant multidecadal periodicity. Additional power is distributed within a broad band of longer time scales (40 to 70 years) that is, however, not statistically significant. This band contains the 60–70 years cycle which is observed in the 20th century North Atlantic region instrumental data [*Schlesinger and Ramankutty*, 1994; *Delworth and Mann*, 2000]. In the southern region (Dye 3 site) the

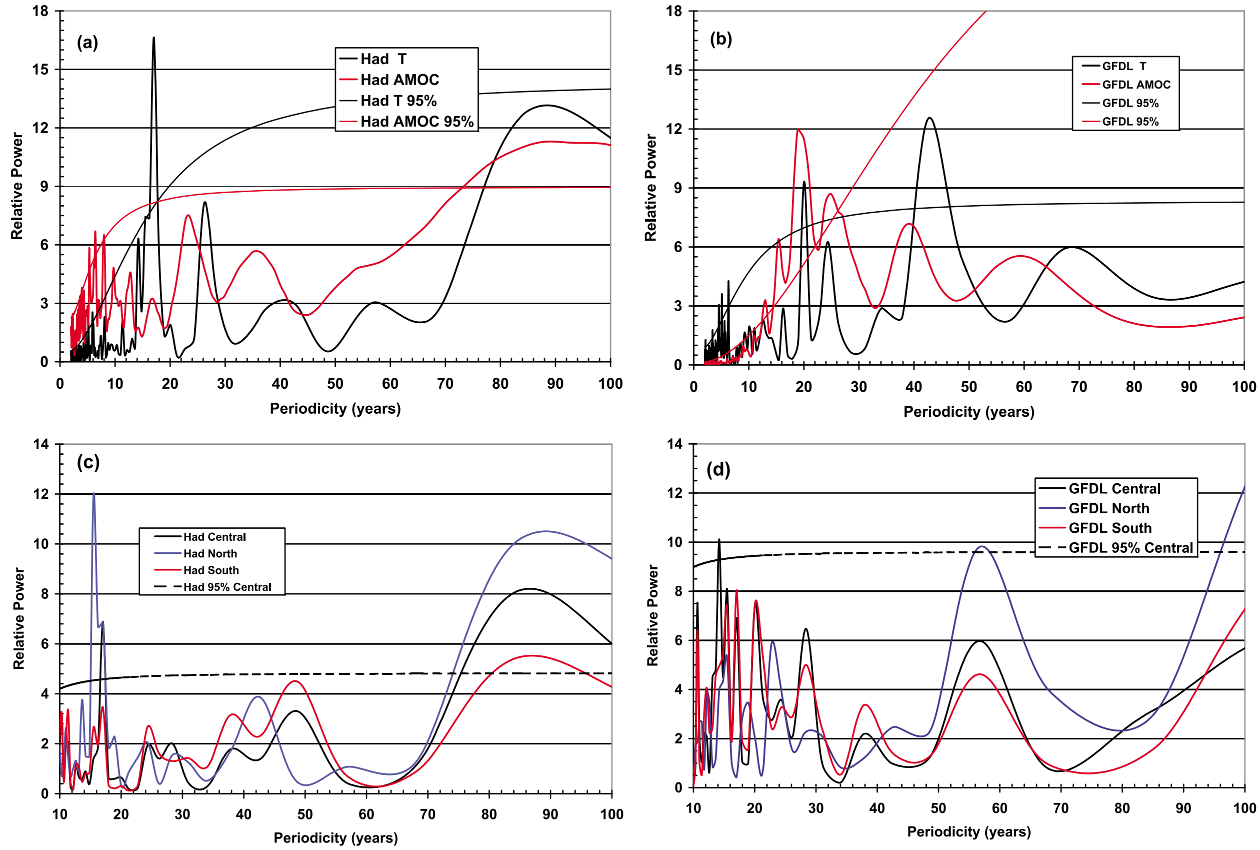

Figure 2. (a) North Atlantic temperature and AMOC periodograms for the HadCM3 model control run (with a constant pre-industrial forcing) smoothed using a Hamming filter (a three component filter for 340 years long temperature time series and 13 component filter for 1400 years AMOC time series). An estimate of 95% confidence level is also shown. (b) Same for the GFDL CM2.1 model control run (with a three component filter for 340 years long temperature time series and 9 component filter for 1000 years AMOC time series). (c and d) Model near surface air temperature integrated over the three regions (south: 64 to 68°N and 40 to 50°W; central: 70 to 74°N and 30 to 50°W; and north: 76 to 82°N and 60 to 80°W) show a longer scale periodicity appearing at all three location, in disagreement with ice core data. Estimated 95% confidence level for central Greenland is also shown.

dominant multidecadal periodicity is again ~20 years (Figure 1c).

5. Models

[10] A conceptual ocean model [*Frankcombe et al.*, 2010], as well as AOGCM studies [*Zhang*, 2008; *Dong and Sutton*, 2005, *Mahajan et al.*, 2011, 2012] connects a 20-year cycle to changes in the Atlantic Meridional Overturning Circulation (AMOC). Since the 20 year quasi-periodic signal originates in the Atlantic Ocean, it is expected that the signal strength will decrease with the distance from the ocean. A diminishing strength in the northern region is also affected by low snow accumulation rates and smoothing by diffusion processes [*Johnsen et al.*, 2000]. The origin of the 45–65 year cycle is less certain. While conceptual models [*Frankcombe et al.*, 2010; *Frankcombe and Dijkstra*, 2010, 2011] suggest that this longer scale of the AMO may originate in the Arctic, others have proposed a wider area of the Atlantic as a source region of this longer time scale variability [e.g., *Knight et al.*, 2005].

[11] We have used control runs of the two AOGCMs (HadCM3 and GFDL CM2.1) to compare the basic features of our ice core analysis with model simulations. In the HadCM3 control run (Figure 2a) we see a shorter periodicity

Figure 3. (a–d) Spectral analysis of the Dye3 annual ice core δ^{18}O data (1899 BC–1872 AD) for four equal length time spans, starting with the most recent and continuing backwards in time. Black and gray lines are estimates of red noise (RN) and 95% significance levels; (e and f) same for a Little Ice Age and Medieval Warm Period. During the Little Ice Age a 20 year cycle dominated, while during the warm period a 20 year cycle is suppressed and the power is shifted to a longer time scale. In addition, during the warm period we see a strong ~11.5 year band. (g) Wavelet analysis (relative power) of the Dye3 annual ice core δ^{18}O data for the years from 1899 BC–1872 AD. The most significant cycles are marked by rectangular boxes and numbered. The same numbers are used in Figures 3a–3d to indicate the corresponding cycles.

between 20 and 30 years and a longer cycle close to 90 years in both the AMOC (defined as by *Knight et al.* [2005] and *Mahajan et al.* [2012]) and the North Atlantic temperature (between 10–70° W and 10–60° N). The GFDL control run suggests periodicities of 19 and 24 years and a longer scale periodicity between 40 and 50 years (Figure 2b). Model surface air temperatures averaged over three regions (Figures 2c and 2d) show a longer scale periodicity

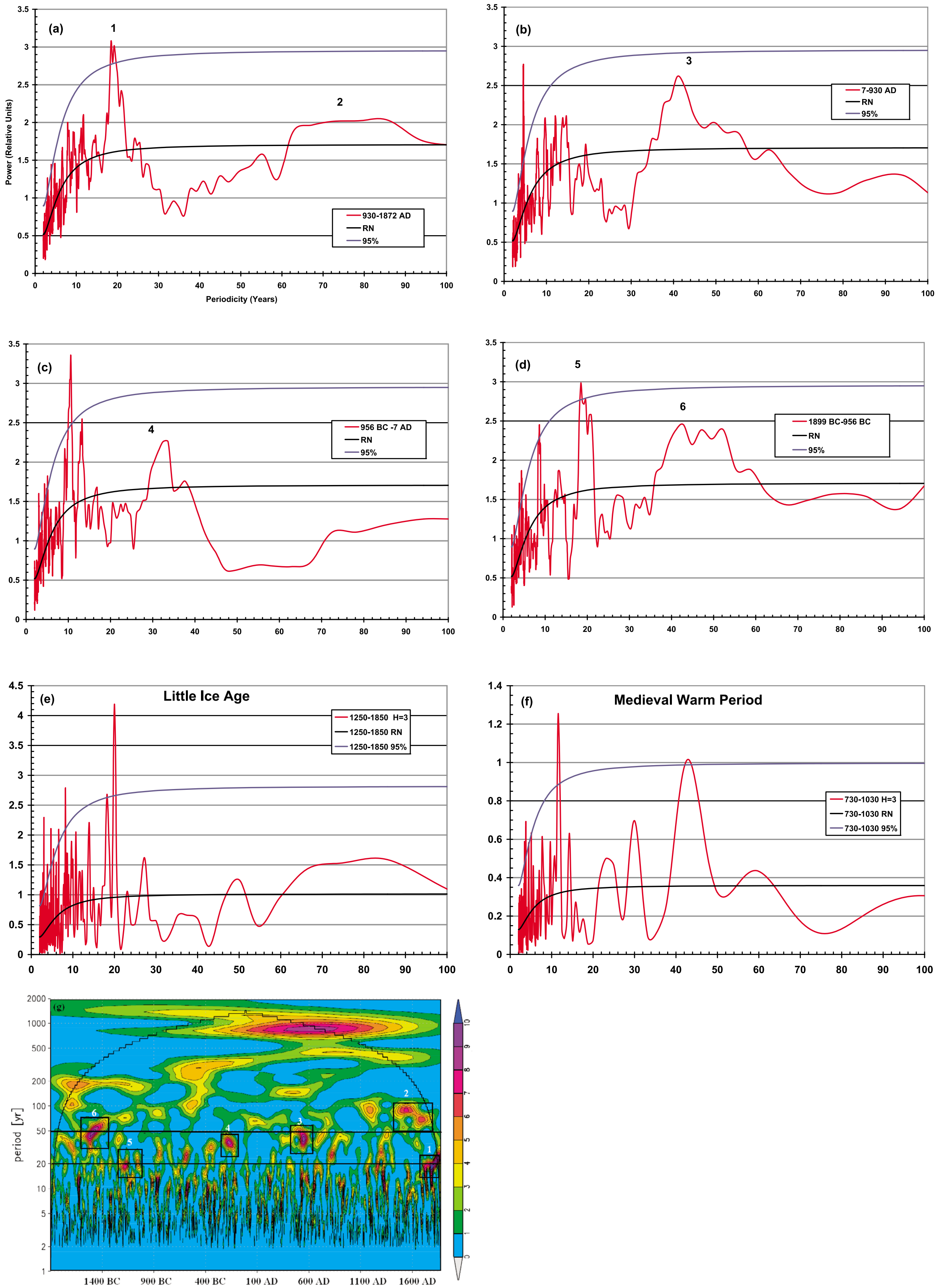

Figure 3

appearing at all three regions, in disagreement with the ice core data.

6. Long-Term Changes in Multidecadal Variability

[12] The longest ice core δ^{18}O record available at an annual resolution is the Dye 3 record which spans the period 1899 BC to 1872 AD. To capture the time variability in our FFT analysis we divide the Dye 3 record into four equal length segments of 983 years and perform the FFT on each segment. The raw periodograms are averaged over L = 9 spectral frequencies.

[13] The most recent segment (930–1872 AD) confirms the dominance of a 20 year cycle, with slightly elevated power within the longer multidecadal band (Figure 3a). The first millennium AD segment (7 to 930 AD) does not show any multidecadal highly statistically significant periodicity (Figure 3b). During the first millennium BC (956 BC to 7 AD) the only multidecadal periodicity elevated above the noise level is centered close to 32 years, although its significance remains below 80% level (Figure 3c). The earliest segment (1899 BC to 956 BC) is similar to the most recent one (930–1872 AD). Here the 20-year oscillation is significant at the 95% confidence level and the longer timescale oscillation approaches the 80% confidence level (Figure 3d). At all times we see also sub-decadal frequencies possibly related to NAO and ENSO.

[14] We note a significant difference between the Little Ice Age (LIA) dominated by a 20 year cycle, and Medieval Warm Period with multidecadal cycle between 40 and 50 years (Figures 3e and 3f). We note that the observed shorter time scale during the cold LIA period agrees with recent work [*Kobashi et al.*, 2010] using an independent temperature proxy.

[15] A wavelet analysis (Figure 3g) confirms the shifts of periodicities over millennia. If the AMO is a damped oscillatory internal ocean mode excited by atmospheric noise [*Frankcombe et al.*, 2010], then large differences in dominant variability time scales are not unexpected.

7. Discussion and Summary

[16] The regionally and temporally resolved spectral analysis of six Arctic annual ice core δ^{18}O time series points towards a considerable natural spatial and temporal variability of the Greenland climate and one of its driving forces the Atlantic Multidecadal Oscillation (AMO). The most dominant observed quasi-periodicity is that of $\sim$20 years followed by a longer multidecadal band between 45 and 65 years. The observed intermittency of these modes over the last 4000 years supports the view that these are internal ocean-atmosphere modes, with little or no external forcing. The Little Ice Age was dominated by a $\sim$20 year AMO cycle with no other decadal or multidecadal variability above the noise level. During the preceding Medieval Warm Period the 20 year cycle was replaced by a longer scale cycle centered near a period of 43 years and an additional $\sim$11.5 year periodicity.

[17] The observed large temporal variability of the AMO as captured by the ice core records points to the difficult task of capturing and forecasting these pronounced multidecadal quasi-oscillations in global and regional Arctic climate models for assessing future Arctic climate.

[18] **Acknowledgments.** The reported research (LA-UR-11-11228) was supported in part by the DOE OBER, Climate and Environmental Sciences Division, by the LANL branch of the IGPP, and by the Joint UK DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). We thank Jeff Knight and Salil Mahajan for providing HadCM3 and the GFDL CM2.1 data, respectively, and Louise Sime for helpful comments on early version of this paper.

[19] The Editor thanks the two anonymous reviewers for assisting in the evaluation of this paper.

References

Chylek, P., C. K. Folland, G. Lesins, M. K. Dubey, and M. Wang (2009), Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *36*, L14801, doi:10.1029/2009GL038777.

Chylek, P., C. K. Folland, G. Lesins, and M. K. Dubey (2010), Twentieth century bipolar seesaw of the Arctic and Antarctic surface air temperatures, *Geophys. Res. Lett.*, *37*, L08703, doi:10.1029/2010GL042793.

Chylek, P., C. K. Folland, H. A. Dijkstra, G. Lesins, and M. K. Dubey (2011), Ice-core evidence for a 20 year time-scale of the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *38*, L13704, doi:10.1029/2011GL047501.

Clausen, H. B., N. Gundestrup, S. Johnsen, R. Bindschadler, and J. Zwally (1988), Glaciological investigations in the Crete area, central Greenland: A search for a new deep-drilling site, *Ann. Glaciol.*, *10*, 10–15.

Dansgaard, W., S. Johnsen, J. Moller, and C. Langway (1969), One thousand centuries of climatic record from Camp Century on the Greenland ice sheet, *Science*, *166*, 377–380, doi:10.1126/science.166.3903.377.

Delworth, T. L., and M. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–676, doi:10.1007/s003820000075.

Dong, B., and R. T. Sutton (2005), Mechanism of interdecadal thermohaline circulation variability in a coupled ocean-atmosphere GCM, *J. Clim.*, *18*, 1117–1135, doi:10.1175/JCLI3328.1.

Fisher, D. A., R. Koerner, and N. Reeh (1995), Holocene climatic records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada, *Holocene*, *5*, 19–24, doi:10.1177/095968369500500103.

Frankcombe, L. M., and H. A. Dijkstra (2010), Internal modes of multidecadal variability in the Arctic Ocean, *J. Phys. Oceanogr.*, *40*, 2496–2510, doi:10.1175/2010JPO4487.1.

Frankcombe, L. M., and H. A. Dijkstra (2011), The role of Atlantic-Arctic exchange in North Atlantic multidecadal climate variability, *Geophys. Res. Lett.*, *38*, L16603, doi:10.1029/2011GL048158.

Frankcombe, L. M., A. S. von der Heydt, and H. Dijkstra (2010), North Atlantic multidecadal variability: An investigation of dominant time scales and processes, *J. Clim.*, *23*, 3626–3638, doi:10.1175/2010JCLI3471.1.

Grootes, P. M., and M. Stuiver (1997), Oxygen 18/16 variability in Greenland snow and ice with 10^3 to 10^5-year time resolution, *J. Geophys. Res.*, *102*, 26,455–26,470, doi:10.1029/97JC00880.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Johnsen, S. J., W. Dansgaard, H. Clausen, and C. Langway (1970), Climatic oscillations 1200–2000 A.D, *Nature*, *227*, 482–483, doi:10.1038/227482a0.

Johnsen, S. J., W. Dansgaard, H. Clausen, and C. Langway (1972), Oxygen isotope profiles through the Antarctic and Greenland ice sheets, *Nature*, *235*, 429–434, doi:10.1038/235429a0.

Johnsen, S. J., H. Clausen, K. Cuffey, G. Hoffmann, J. Schwander, and T. Creyts (2000), Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion, in *Physics of Ice Core Records*, pp. 121–140, Hokkaido Univ. Press, Sapporo, Japan.

Knight, J., R. Allan, C. Folland, M. Vellinga, and M. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GL024233.

Kobashi, T., et al. (2010), Persistent multi-decadal Greenland temperature fluctuation through the last millennium, *Clim. Change*, *100*, 733–756, doi:10.1007/s10584-009-9689-9.

Kobashi, T., K. Kawamura, J. P. Severinghaus, J.-M. Barnola, T. Nakaegawa, B. M. Vinther, S. J. Johnsen, and J. E. Box (2011), High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core, *Geophys. Res. Lett.*, *38*, L21501, doi:10.1029/2011GL049444.

Kumar, A., J. Perlwitz, J. Eischeid, X. Quan, T. Xu, T. Zhang, M. Hoerling, B. Jha, and W. Wang (2010), Contribution of sea ice loss to Arctic amplification, *Geophys. Res. Lett.*, *37*, L21701, doi:10.1029/2010GL045022.

Mahajan, S., et al. (2011), Predicting Atlantic meridional overturning circulation (AMOC) variations using subsurface and surface fingerprints, *Deep Sea Res., Part II*, *58*, 1895–1903, doi:10.1016/j.dsr2.2010.10.067.

Mahajan, S., R. Zhang, and T. Delworth (2012), Impact of the Atlantic meridional overturning circulation (AMOC) on Arctic surface air temperature and sea-ice variability, *J. Clim.*, doi:10.1175/2011JCLI4002.1, in press.

Parker, D., C. Folland, A. Scaife, J. Knight, A. Colman, P. Baines, and B. Dong (2007), Decadal to multidecadal variability and the climate change background, *J. Geophys. Res.*, *112*, D18115, doi:10.1029/2007JD008411.

Picciotto, E., X. De Maere, and I. Friedman (1960), Isotopic composition and temperature of formation of Antarctic snows, *Nature*, *187*, 857–859, doi:10.1038/187857a0.

Polyakov, I. V., G. V. Alekseev, R. V. Bekryaev, U. Bhatt, R. L. Colony, M. A. Johnson, V. P. Karklin, A. P. Makshtas, D. Walsh, and A. V. Yulin (2002), Observationally based assessment of polar amplification of global warming, *Geophys. Res. Lett.*, *29*(18), 1878, doi:10.1029/2001GL011111.

Polyakov, I., et al. (2010), Arctic Ocean warming contributes to reduced polar ice cap, *J. Phys. Oceanogr.*, *40*, 2743–2756, doi:10.1175/2010JPO4339.1.

Polyakov, I., et al. (2011), Fate of early 2000s Arctic warm water pulse, *Bull. Am. Meteorol. Soc.*, *92*, 561–566, doi:10.1175/2010BAMS2921.1.

Schlesinger, M., and N. Ramankutty (1994), An oscillation in the global climate system of period 65–70 yr, *Nature*, *367*, 723–726, doi:10.1038/367723a0.

Semenov, V., et al. (2010), The impact of the North Atlantic-Arctic multidecadal variability on Northern Hemisphere surface air temperature, *J. Clim.*, *23*, 5668–5677, doi:10.1175/2010JCLI3347.1.

Shumway, R., and D. Stoffer (2006), *Time Series Analysis and its Applications: With R Examples*, 2nd ed., 575pp., Springer, New York.

Stuiver, M., P. M. Grootes, and T. Braziunas (1995), The GISP2 ^{18}O climate record of the past 16,500 years and the role of the sun, ocean and volcanoes, *Quat. Res.*, *44*, 341–354, doi:10.1006/qres.1995.1079.

Zhang, R. (2008), Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation, *Geophys. Res. Lett.*, *35*, L20705, doi:10.1029/2008GL035463.

P. Chylek, Space and Remote Sensing, Los Alamos National Laboratory, MS B244, Los Alamos, NM 87545, USA. (chylek@lanl.gov)

H. Dijkstra and L. Frankcombe, Institute for Marine and Atmospheric Research, Department of Physics and Astronomy, University of Utrecht, Princetonplein 5, NL-3584 CC Utrecht, Netherlands.

M. Dubey, Earth and Environmental Sciences, Los Alamos National Laboratory, MS D462, EES-6, Los Alamos, NM 87545, USA.

C. Folland, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

G. Lesins, Department of Physics and Atmospheric Science, Dalhousie University, Dunn Building, Halifax, NS B3H 1Z0, Canada.