Ice-core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation

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Received 21 March 2011; revised 8 May 2011; accepted 13 May 2011; published 6 July 2011.

[1] Using five ice core data sets combined into a single time series, we provide for the first time strong observational evidence for two distinct time scales of Arctic temperature fluctuation that are interpreted as variability associated with the Atlantic Multidecadal Oscillation (AMO). The dominant and the only statistically significant multidecadal signal has a time scale of about 20 years. The longer multidecadal variability of 45–85 years is not well defined and none of the time scales in this band is statistically significant. We compare these observed temperature fluctuations with results of coupled climate model simulations (HadCM3 and GFDL CM2.1). Both the 20–25 year and a variable longer AMO time scale are prominent in the models' long control runs. This periodicity supports our conjecture that the observed ice core fluctuations are a signature of the AMO. The robustness of this short time scale period in both observations and model simulations has implications for understanding the dominant AMO mechanisms in climate. **Citation:** Chylek, P., C. K. Folland, H. A. Dijkstra, G. Lesins, and M. K. Dubey (2011), Ice-core data evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *38*, L13704, doi:10.1029/2011GL047501.

1. Introduction

[2] The recent rapid warming of Greenland and the Arctic is a combination of anthropogenic warming and natural climate variability [*Polyakov and Johnson*, 2000; *Chylek et al.*, 2010]. To separate these influences an understanding of the time scale of the Atlantic climate variability characterized by the AMO [*Delworth and Mann*, 2000; *Knight et al.*, 2005] is needed. Here we present an analysis of five ice core annual mean δ^{18}O data sets (each data set of 559 years), which provides strong observational evidence of two distinct time scales of the AMO fluctuations. The only statistically significant multidecadal signal, has a time scale of approximately 20 years. The often reported longer multidecadal variability between 45–85 years is not well defined and none of the time scales in this band is statistically significant. We compare these observed temperature fluctuations with results of coupled climate model simulations (HadCM3 and GFDL CM2.1). Two prominent AMO time scales (close to 25 years and a variable longer AMO time scale) observed in long control model simulations are identified as time scales observed in ice core records. This supports our claim that the observed ice core δ^{18}O fluctuations are a signature of the AMO. The coupled atmosphere ocean general circulation model simulations as well as simplified ocean physics studies [*Frankcombe et al.*, 2010] attribute the 20–30 year periodicity to an internal ocean mode involving the variability of the Atlantic Meridional Overturning Circulation. The longer time scale, not statistically significant but clearly visible in the 20th century instrumental data (see references in the next paragraph), may reflect a larger spatial scale associated with a slower deep circulation in the Atlantic Ocean or alternatively with a coupling of the Arctic and Atlantic circulations.

[3] Decadal and multi-decadal climate fluctuations have been identified in various indicators of the North Atlantic region with periodicity bands centered near 20–30 years and near 45–85 years. Variability in the 45–85 year time range was found in the instrumental records of the Atlantic SST [*Delworth and Mann*, 2000; *Schlesinger and Ramankutty*, 1994] sea ice extent [*Polyakov et al.*, 2003], Arctic temperature [*Polyakov and Johnson*, 2000; *Chylek et al.*, 2009], and Atlantic hurricane activity [*Goldenberg et al.*, 2001; *Chylek and Lesins*, 2008]. A shorter quasi-cyclic variation of around 20 years has been identified in global nighttime marine air temperature [*Folland et al.*, 1984], Central England temperature [*Folland*, 1983], the North Atlantic Oscillation index, and North Atlantic sea surface height [*Frankcombe and Dijkstra*, 2009]. Analysis of Greenland ice cores [*Johnsen et al.*, 1972; *Stuiver et al.*, 1995] suggested the presence of several quasi-cyclic multidecadal bands as well as a set of sub-decadal frequencies between 2.2 and 7.5 years.

2. Ice Core Data

[4] The temporal variability in δ^{18}O preserved in ice cores has long been used to reconstruct temperature changes in the polar regions [*Picciotto et al.*, 1960]. Although spectral analysis of the oxygen isotope δ^{18}O ice core data has been performed previously, usually a single ice core was analyzed and the observed spectral peaks were often not statistically significant [*O'Sullivan et al.*, 2002]. Here we analyze annual δ^{18}O data by combining five annually resolved Arctic ice cores with overlapping records between the years 1303 and 1961.

[5] An individual ice core location is influenced by both Arctic-wide climate variability and local weather patterns.

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0094-8276/11/2011GL047501

Figure 1. Locations of ice core sites used in this study.

At times, the latter can dominate the regional signal. To detect a reliable regional multi-decadal signal, it is advantageous to combine the signals from ice core records taken from multiple sites distributed over a wider area. A multi-century composite of several individual records is more likely to pick up a genuine regional multidecadal variability signal as the signal to noise ratio is improved.

[6] We analyze five geographically distributed Arctic ice cores (Figure 1) with overlapping time series from 1303–1961. Our composite time series includes annual δ^{18}O data from four Greenland ice cores: GISP2 [*Picciotto et al.*, 1960; *Steig et al.*, 1994; *Stuiver et al.*, 1995], Milcent [*Clausen et al.*, 1988], Crete [*Clausen et al.*, 1988], and Camp Century [*Johnsen et al.*, 1972], and one ice core from Ellesmere Island Agassiz Ice Cap [*Fisher et al.*, 1995]. The ice core data are archived and available at the NOAA Paleoclimate data website (http://www.ncdc.noaa.gov/paleo/data.html). An average of the δ^{18}O anomaly of the five ice cores is displayed in Figure 2a.

3. Method and Results

[7] We first calculate the δ^{18}O anomalies for individual ice cores by subtracting the 1303–1961 average. Then each time series is detrended, normalized to unit variance and padded by zeroes to complete the 1024 years that are used for the Fast Fourier Transform (FFT). After that five individual periodograms were averaged to obtain the spectrum of the five ice core composite. In the raw composite periodogram (gray line in Figure 2b), two multidecadal time scales are prominent: one centered near 20 years and another broader peak centered near 55 years. We note that each of the five individual periodograms (not shown) exhibit a peak between 19.7 and 20.9 years as well as a peak between 53.9 and 56.9 years.

[8] Not all peaks in FFT represent real periodicity [*Wunsch*, 2000]. Determination of statistical significance requires appropriate smoothing of the periodogram. A typical conservative choice for smoothing is to average over L ~ N/100 spectral components, which leads us to select L~10 (N = 1024 years). Accordingly we use a symmetrical Hamming filter with L = 11; other possible filter lengths or types give similar results for statistical significance. The smoothed periodogram (Figure 2b thick red line) shows that the approximate 20 year cycle remains prominent while the 50–60 year peak has been significantly reduced. The thick black line shows the estimated 95% confidence level assuming a Markov process for the combined ice core data which fits the mean spectrum well. The 20 yr peak is the only multidecadal periodicity that exceeds the 95% significance level, while energy of a longer cycle is spread between 40 and 80 years with no definite significant periodicity (Figure 2b). Essentially identical results are obtained by the FFT analysis of the average of the five δ^{18}O time series (compared to our procedure of averaging five FFTs of individual samples).

[9] We can gain further insight from a single ice core that spans a longer period, remembering that the signal to noise ratio will be lower and local noise may contaminate the spectral details. A similar spectral analysis of the Dye3 (Figure 2c) ice core data, available at annual resolution from 1899 BC-1872 AD, confirms that the 20 year time scale is the most prominent and persistent multidecadal mode, although its strength is somewhat weaker than in the five cores composite due to noise and interference from local climatic signals.

[10] The order 6 Morlet wavelet analysis of the average ice core δ^{18}O time series (Figure 3) shows an intermittent strong temporal variance at 20 year as well as at 50–60 year time scales.

[11] We associate the 20 year periodicity and the less well defined longer time scale found in the ice core data with the approximate 25 year and near century time scales found in the coupled atmosphere-ocean general circulation model HadCM3 1400 year simulation [*Knight et al.*, 2005]. Similar 20–30 yr as well as longer oscillation periods have been found in the GFDL CM2.1 model 1000 year control run [*Zhang*, 2008]. Changes in the AMO as indicated by modeled Atlantic Meridional Overturning Circulation (MOC) lead to major changes of the SST around Greenland. Therefore associated changes in our ice core temperature are expected at all five ice core sites. A wavelet analysis of the AMO in the HadCM3 model [*Knight et al.*, 2005] shows that the near 25 year and the near century time scale fluctuations vary greatly in intensity, occasionally disappearing altogether and reappearing. Similar non-stationary signals exists in our wavelet analysis of ice core data (Figure 3).

[12] In HadCM3 the two AMO time scales are associated with different spatial scales of the Atlantic MOC. The 25 year scale is associated with overturning within the North Atlantic basin while the century time scale is associated with overturning extending well into the South Atlantic. Finally we note that the 50–70 year timescale of the AMO is clearly manifested in Arctic temperatures of the last century and is likely responsible for a substantial fraction of the recent (1970–2010) Arctic warming [*Chylek et al.*, 2010].

[13] To support the δ^{18}O record as a proxy for the AMO we compare the broad features of the our five ice core composite δ^{18}O anomaly with the AMO index deduced from multiple proxy data [*Delworth and Mann*, 2000] and with the instrumental AMO index [*Parker et al.*, 2007] (Figure 2d). The Delworth-Mann proxy derived AMO (green curve in Figure 2d) deviates significantly from the

instrumental record AMO (black curve) after about 1910, while our AMO proxy (red curve) based on the five ice core δ^{18}O analysis follows the instrumental record AMO very accurately.

4. Discussion and Summary

[14] Our analysis shows that the only statistically significant periodicity in the Arctic ice cores and likely in the AMO is the periodicity of about 20 years. The coupled atmosphere ocean general circulation model simulations as well a simplified ocean physics model studies, indicate that external forcing may not be necessary to maintain a 20 year cycle. Thus, consistent with models the 20–30 year variability is attributed to a thermal Rossby (internal) ocean mode involving the variability of the Atlantic meridional overturning circulation [*Schlesinger and Ramankutty*, 1994; *Dijkstra and Ghil*, 2005; *Frankcombe and Dijkstra*, 2009]. The time scale of this mode depends on the equator-to-pole sea surface temperature gradient, the zonal extent of the Atlantic basin, and the speed of the zonal currents in the Atlantic. As long as these conditions do not change substantially over time, a near 20 yr variability, as observed in the ice-core data, can be maintained by the coupled ocean-atmosphere system. Atmospheric noise is likely to modulate the amplitude of such variability. The longer AMO time scale (not statistically significant, but clearly present in the 20th century instrumental records) may reflect a larger spatial scale mode associated with a slower deep circulation in the Atlantic Ocean or alternatively with a coupling of the Arctic and Atlantic circulations, as suggested by an idealized model [*Frankcombe et al.*, 2010].

[15] Our results (Figure 2) support that both natural quasi-periodic climate variability of the Arctic and secular anthropogenic increases of atmospheric concentration of greenhouses gases share the responsibility [*Chylek et al.*, 2010] for recent rapid Arctic warming.

[16] Occasional in phase coincidence of the two AMO modes might contribute to sudden changes in the AMO, and faster than normal changes of sea surface temperature [*Baines and Folland*, 2007; *Thompson et al.*, 2010]. We conclude that, in addition to longer time scales of variation, the AMO has maintained over thousands of years a close to 20 year time-scale as recorded in ice core data. This feature also stands out in long runs of the HadCM3 and GFDL CM2.1 models (at a slightly longer 25 year time-scale). A 6000 year control run of the HadCM3 model is now being analyzed for both time scales of AMO fluctuations, as well

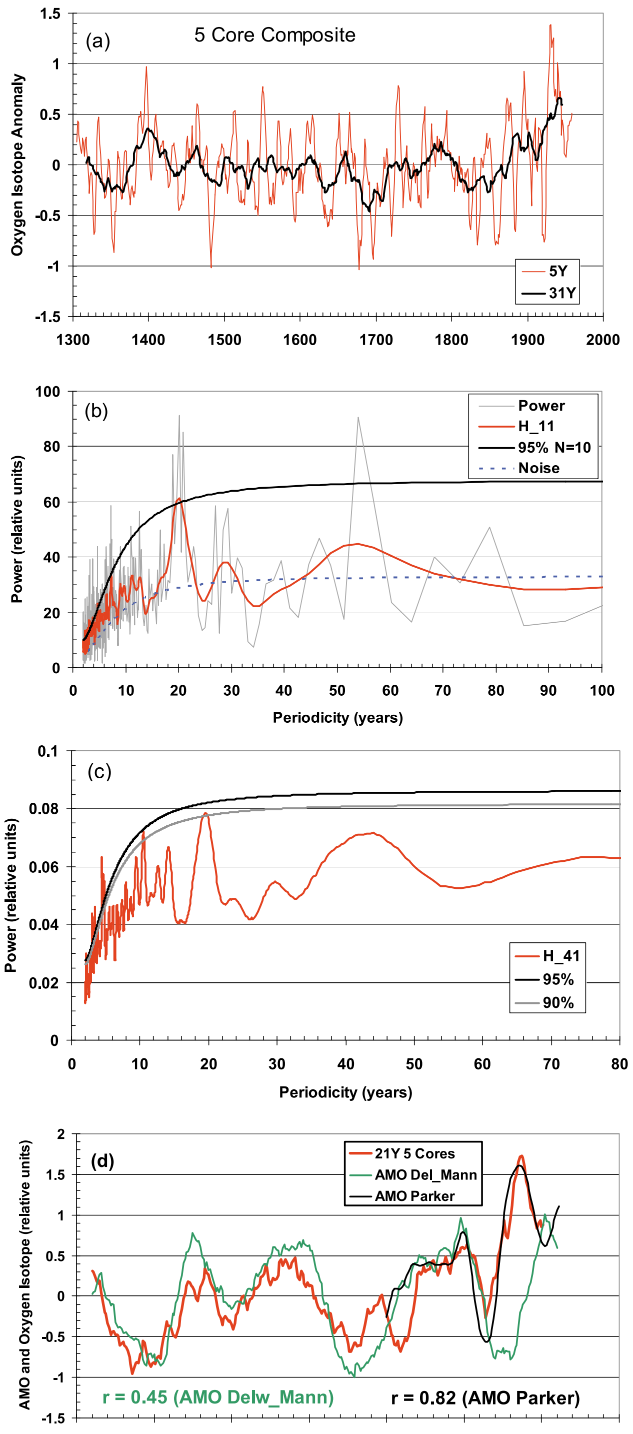

Figure 2. (a) The five ice core average oxygen δ^{18}O anomaly smoothed by an 5 yr moving average (red) and 31 yr moving average (black). (b) Combined periodogram of the δ^{18}O anomaly (gray line) shows prominent peaks centered near a period of 20 and 55 years. Averaging using 11 weight Hamming filter (red line) preserves the 20 year periodicity as the only statistically significant multidecadal periodicity. The blue dotted line is an estimated noise of the AR1 process. The 95% (thick black line) significance level for the Hamming filtered FFT spectrum was estimated using ten degrees of freedom. (c) Periodogram for the Dye3 δ^{18}O annual data (from 1899 BC to 1860 AD) smoothed by a 41 weight Hamming filter (red line) and estimated 95% significance level (black line) for a system with 54 degrees of freedom. (d) The AMO index (green) deduced by *Delworth and Mann* [2000], average δ^{18}O of the five Arctic ice cores (red) smoothed by a 21 yr moving mean, and the Parker AMO index (black line). The correlation coefficients shown are between our five ice core δ^{18}O time series and the Parker AMO (black), and the Delworth and Mann AMO proxy (green).

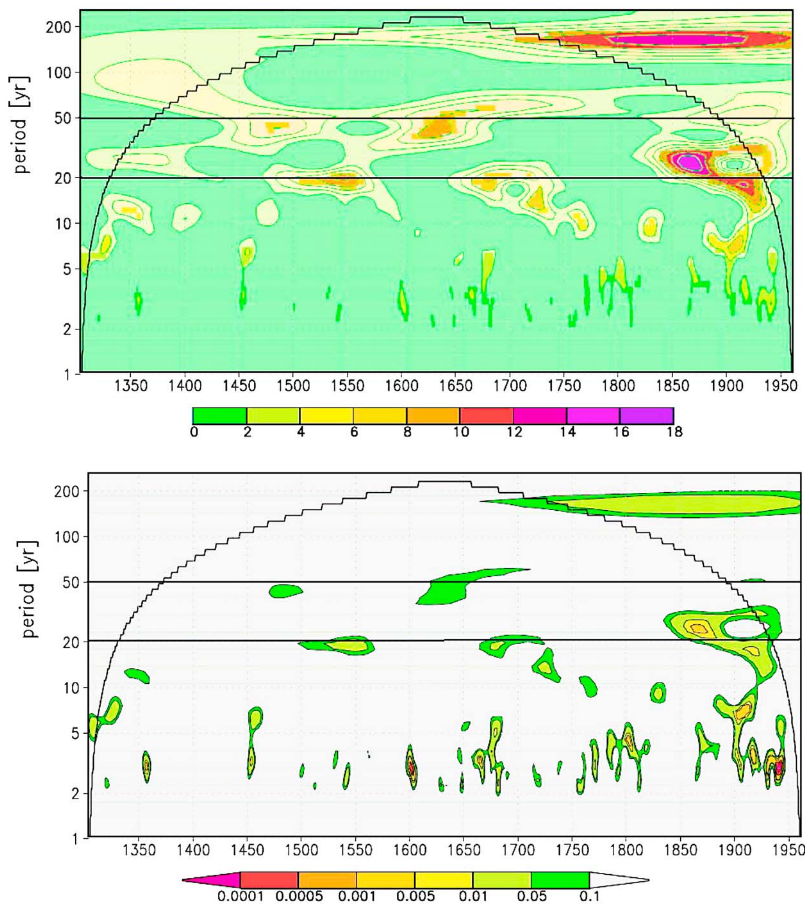

Figure 3. Wavelet analysis of the average of five ice core δ^{18}O time series (1302–1961). (top) The intermittency of the power of near 20 year periods and longer periods centered near 55 years over the composite ice core record. (bottom) The significance. The area outside a jagged semicircle is a method artifact with no statistical significance.

as for sudden changes in the AMO and Atlantic sea surface temperature.

[17] **Acknowledgments.** Reported research (LA-UR 11-01364) was supported in part by the DOE OBER, Climate and Environmental Sciences Division, by the LANL branch of the Institute of Geophysics and Planetary Physics, and by Joint UK DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). We thank Thomas Delworth for providing numerical data used in Figure 2 and two anonymous reviewers for helpful comments and suggestions. We also thank Geert Jan van Oldenborgh of the Netherlands Meteorological Institute for help with the wavelet analysis and Jeff Knight of the UK Met Office for useful comments. This paper is also UK Crown Copyright through the contribution of the second author.

[18] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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