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A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D.

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[1] We present a tree-ring based reconstruction of the Atlantic Multidecadal Oscillation (AMO) which demonstrates that strong, low-frequency (60–100 yr) variability in basin-wide (0–70°N) sea surface temperatures (SSTs) has been a consistent feature of North Atlantic climate for the past five centuries. Intervention analysis of reconstructed AMO indicates that 20th century modes were similar to those in the preceding $\sim$350 yr, and wavelet spectra show robust multidecadal oscillations throughout the reconstruction. Though the exact relationships between low-frequency SST modes, higher frequency ($\sim$7–25 yr) atmospheric modes (e.g., North Atlantic Oscillation/Arctic Oscillation), and terrestrial climates must still be resolved, our results confirm that the AMO should be considered in assessments of past and future Northern Hemisphere climates. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4221 Oceanography: General: Dendrochronology; 4263 Oceanography: General: Ocean prediction. **Citation:** Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson (2004), A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D., *Geophys. Res. Lett.*, *31*, L12205, doi:10.1029/2004GL019932.

1. Introduction

[2] Instrumental records of North Atlantic sea surface temperatures (SST) have included significant multidecadal variability over the previous 150 yr [*Schlesinger and Ramankutty*, 1994]. Both observations and model simulations implicate changes in the strength of the thermohaline circulation as the primary source of this multidecadal variability, and suggest a possible oscillatory component to this behavior [*Folland et al.*, 1986; *Griffies and Bryan*, 1997; *Delworth and Mann*, 2000]. The leading mode of low-frequency, North Atlantic (0–70°) SST variability has been termed the Atlantic Multidecadal Oscillation (AMO) [*Kerr*, 2000]. Over the instrumental period (1856-Present) the AMO exhibited a 65–80 yr cycle (0.4°C range), with warm phases at roughly 1860–1880 and 1930–1960 and cool phases during 1905–1925 and 1970–1990. The AMO appears to have returned to a warm phase beginning in the mid 1990s.

[3] The AMO has been linked to multi-year precipitation anomalies over North America, and appears to modulate El Niño-Southern Oscillation teleconnections over large portions of the Northern Hemisphere [*Enfield et al.*, 2001; *McCabe et al.*, 2004]. Multidecadal variability in the North Atlantic is also thought to play a role in Atlantic hurricane formation, African drought frequency, and winter temperatures in Europe [*Folland et al.*, 1986; *Goldenberg et al.*, 2001]. Instrumental observations capture only two full cycles of the AMO, so a need exists for developing longer proxies to assess low-frequency North Atlantic SST variations and their climatic effects. In stark contrast to the wealth of research employing reconstructions of Pacific Basin modes, only one previous study has used high-resolution proxies to examine multidecadal variability in the North Atlantic [i.e., *Delworth and Mann*, 2000].

[4] We developed a new reconstruction of the AMO spanning A.D. 1567–1990 using tree-ring records from eastern North America, Europe, Scandinavia, and the Middle East. This proxy record allowed us to evaluate the oscillatory nature of the AMO. We also compare modes of low-frequency behavior seen in the instrumental record with those of the preceding three centuries.

2. Methods

[5] We obtained tree-ring records (Figure 1) spanning at least A.D. 1600–1990 (http://www.ngdc.noaa.gov/paleo/treering.html) from regions known to border on strong centers of North Atlantic SST variability [*Enfield and Mestas-Nuñez*, 1999] and with climates (air temperatures or precipitation) strongly linked to these SST anomalies (e.g., eastern North America, Europe, Scandinavia, North Africa and the Middle East) [*Enfield et al.*, 2001; *McCabe et al.*, 2004; *Folland et al.*, 1986]. We detrended the raw tree-ring measurements using methods that preserve low-frequency variability (negative exponential or lines of zero or negative slope). Twelve total-ring-width records (see auxiliary material[1]) showed moderate to strong ($r < -0.25$ or > 0.25) correlations with annual North Atlantic SSTAs [from *Kaplan et al.*, 1998]. These chronologies were subjected to a principal components analysis (PCA), and the first five PCs (eigenvalues > 1; total variance explained = 66%) were retained for use in the reconstruction. We calibrated multiple-regression models on the 1922–1990 period that were verified against 1856–1921 data. Output from a model using PCs 1, 2, 4, and 5 was significantly correlated with observed values during the verification period ($r = 0.51$; $p < 0.001$), and exhibited the same sign as the observed data

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL019932.

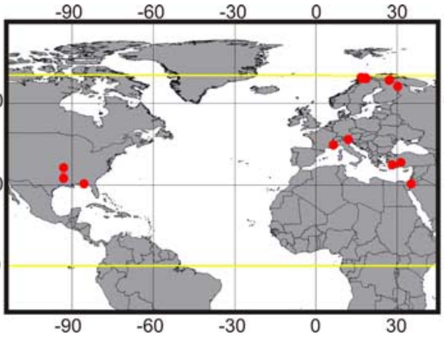

Figure 1. Map showing tree-ring chronologies (red circles) used to reconstruct the Atlantic Multidecadal Oscillation index. The AMO is indexed as the 10-year running mean of average-annual sea surface temperatures in the North Atlantic from 0–70°N (yellow lines).

73% of the time [*Fritts*, 1976]. The reduction of error statistic was 0.25, suggesting that the model possessed significant skill in estimating SSTA values outside the calibration period. We recombined the two subsamples to produce:

$$\textit{North Atlantic SSTA} = -0.0607 - 0.0566\,PC1 + 0.0703\,PC2 + 0.0528\,PC4 - 0.0679\,PC5 \qquad (1)$$

[6] Output from this model was well correlated with the annual observed data (r = 0.64). Correlations between 10-yr moving averages of estimated and observed SSTAs (the AMO index used by *Enfield et al.* [2001]) showed r = 0.81.

[7] In order to identify and compare regime-like behaviour in North Atlantic SSTs, we examined the AMO reconstruction using intervention analysis [*Box and Tiao*, 1975]. Positive or negative deviations of the indexed AMO (10-yr running average) from the long-term mean were considered potential regime shifts. To assess the significance of each potential regime, the entire reconstruction was fit with a univariate autoregressive moving average (ARIMA) model. Potential warm/cool regimes were then incorporated into a new ARIMA model as step-change variables. Step-change and univariate models were compared, and potential regimes whose model coefficient had $p < 0.05$ were considered significant. Results were similar using other common intervention model-types (e.g., ramp-change).

[8] We used a multi-taper method cross-spectral analysis (red noise assumptions) to evaluate the coherency of observed and reconstructed annual North Atlantic SSTA values in the frequency domain [*Mann and Lees*, 1996]. To examine the stationarity of low-frequency AMO behaviour through time, we performed a wavelet analysis on the full-length annual SSTA reconstruction [*Torrence and Compo*, 1998]. We employed a derivative of the Gaussian wavelet ("Mexican Hat") to highlight changes in the strength of modes over time, and padded the reconstruction with zeros to avoid "wraparound" effects. Significance was tested at the 95% confidence level against a red-noise background.

3. Results

[9] The AMO reconstruction captures thirteen complete >10 yr regimes over the 1567–1990 interval (Table 1 and Figures 2a–2c). Both observed and reconstructed AMO indices are marked by a persistent cool phase spanning 1903 to 1924 and a warm phase from 1925 through the 1960s (Figures 2a–2b). The proxy and observational records show a moderate to weak cool regime centred on the 1970s. The 1925–1970 warm phase is notable for its 46-yr duration, making it the third-longest regime in the proxy record (Table 1). The 1925–1970 warm phase was moderately strong, ranking as the fifth-most intense regime (warm or cool). A cool phase from 1789 to 1849 was the longest regime in the proxy record and also the second-most intense negative anomaly (Figures 2b–2c). The warm phase at 1656–1708 ranks as the second-longest regime of any sign. A pair of regimes at 1580–1596 and 1597–1632 is remarkable for being the most intense warm and cool phases in the proxy, respectively, though limited sample depth in the earliest portions of the reconstruction demands these regimes be interpreted cautiously.

[10] Our analysis also indicates that the North Atlantic switches between regimes by first entering an "organizational" phase where SST variability is dampened over multi-annual to decadal timescales (e.g., 1650s, early 1700s, 1970s; Figures 2b–2c). After a period of quiescence lasting some 5–10 yr, the system changes mean state to

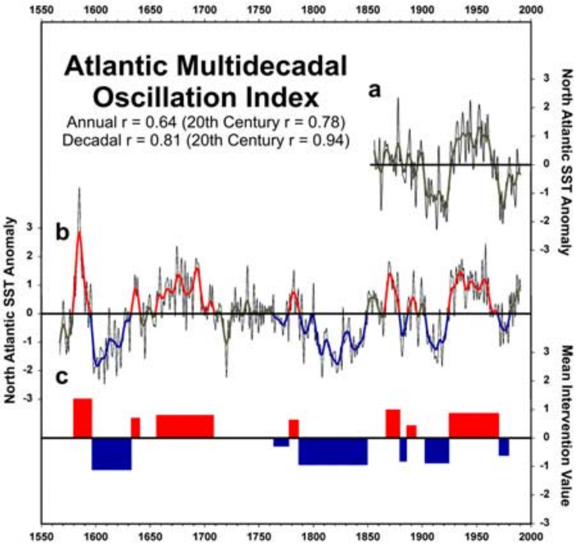

Figure 2. The Atlantic Multidecadal Oscillation (AMO) Index. (a) Observed values from *Kaplan et al.* [1998]. Annual North Atlantic sea surface temperature anomalies (SSTA) are shown as black lines and the AMO index (10-year running mean of SSTA) is shown in gray. The time series spans 1856–1990 A.D. (b) The 1567–1990 proxy record developed from tree-ring chronologies shown in Figure 1. Annual SSTA values are shown in black. Based on the results of intervention analysis [*Box and Tiao*, 1975], significant ($p < 0.05$) AMO warm regimes are shown in red, significant cool regimes in blue, and non-significant periods in gray. Agreement between the observed and reconstructed values increases in the 20th century, which is likely a result of better sampling of the SST field after ~1900 [*Kaplan et al.*, 1998]. (c) Mean intervention values (SSTA units) and durations of significant warm (red) and cool (regimes) identified in the intervention analysis.

Table 1. Results of Intervention Analysis Showing Significant Decadal-Scale and Longer Regimes in the Reconstructed AMO

Years	Phase	Mag.[a]	Intensity[b]
1580–1596	+	23.2	1.37
1597–1632	–	−39.9	−1.11
1633–1640	+	5.6	0.70
1641–1655	NS		
1656–1708	+	42.2	0.80
1709–1763	NS		
1764–1777	–	−4.0	−0.29
1778–1786	+	5.7	0.63
1787–1849	–	−58.5	−0.93
1850–1866	NS		
1867–1879	+	12.7	0.93
1880–1885	–	−4.9	−0.81
1886–1894	+	3.9	0.44
1895–1902	NS		
1903–1924	–	−19.2	−0.87
1925–1970	+	39.7	0.86
1971–1979	–	−5.4	−0.60

[a] Mag. = Magnitude; calculated by subtracting the long-term mean from each reconstructed annual SSTA value within a regime, and summing these values over the entire regime.

[b] Intensity = the ratio between magnitude and duration, equivalent to average magnitude for an event.

either a persistent warm or cool mode. Brief (~10 yr) periods of weak or non-significant AMO behaviour are seen between strong warm/cool regimes (Table 1). The only prominent breakdown in this oscillatory behaviour occurs during the 18th century. Over the entire period from 1709 to 1763 the indexed AMO does not differ significantly from the series mean (Figures 2b–2c) and, in terms of intensity, the subsequent cool phase at 1764–1777 is the weakest regime in the reconstruction (Table 1).

[11] MTM cross-spectral analysis of the observed and reconstructed time series (Figure 3a) highlights both the multidecadal nature of AMO variability during the instrumental period (1856–1990) and points to similarities in low-frequency behaviour between the records. The reconstructed AMO record shows strong coherence with the observed time series in a band from ~30–65 yr, while highly energetic peaks in both spectra overlap at 42.7 yr. The wavelet spectrum for the full reconstruction shows significant energy spread over a wide band from ~40–128 yr (Figure 3b), with little significant energy residing in the decadal to bidecadal ranges. From the late-1800s through the end of the reconstruction significant low-frequency variability is confined to a narrower band centred on ~40 yr but multidecadal power may be reduced by the effects of zero padding near the end of the record [*Torrence and Compo*, 1998]. The only noticeable breakdown in multidecadal behaviour occurs in the mid-18th century, coincident with the extended period where the indexed AMO does not differ significantly from the long-term mean (Table 1).

4. Discussion

[12] The network of tree-ring chronologies presented in this paper provides a new, well-replicated, statistically verified, and long-duration proxy for North Atlantic multidecadal variability. The use of long segments (mean segment length = 254 yr; see auxiliary material) facilitates comparisons between different periods in the reconstruction and, coupled with methods designed to preserve low-frequency signals, enables the examination of multidecadal signals [*Cook et al.*, 1995]. Our approach differs significantly from previous attempts at examining low-frequency North Atlantic variability on a multi-century basis. *Delworth and Mann* [2000] extracted an AMO-like signal from global surface-temperature reconstructions, whereas we targeted our proxy network on regions where the climate is known to have a high sensitivity to changes in North Atlantic SSTA. Our results are consistent with *Delworth and Mann's* [2000] work, however, in that both of these studies show strong, consistent multidecadal oscillations in the North Atlantic over the last three to five centuries.

[13] Confirmation of such natural, "long memory" processes in North Atlantic SST variability has a variety of implications for understanding the climate in regions surrounding the North Atlantic. The absence of significant power in the 7–25 yr bands of the observed and reconstructed time series (Figures 3a–3b) distinguishes the AMO from the primary modes associated with the North Atlantic

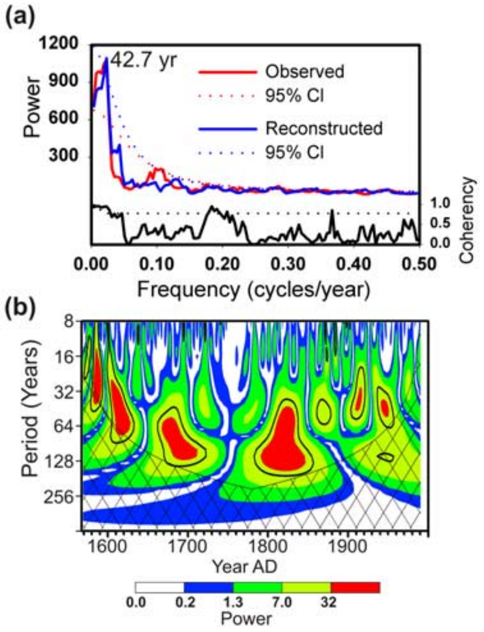

Figure 3. (a) Multi-taper method coherency spectra of the observed and reconstructed time series based on MTM analysis using red noise assumptions [*Mann and Lees*, 1996]. Both observed and reconstructed values were analyzed for the common period from 1856–1990 AD. Spectra show strong coherency between the observed and reconstructed values in a multidecadal band centred on 42.7 years. (b) Wavelet power spectrum for the full North Atlantic sea surface temperature anomaly reconstruction (1567–1990). From white to red the coloured intervals represent 5, 25, 50, and 75% of the wavelet power, respectively. Black contours in the power spectra represent the 95% confidence level based on a red-noise background. The cone-shaped net depicts areas of the spectrum susceptible to the effects of zero padding [*Torrence and Compo*, 1998]. The spectrum shows significant multidecadal (40 to >80 year) variability throughout the reconstruction with the exception of a brief period in the mid-18th century.

Oscillation (NAO) and Arctic Oscillation (AO), two related forms of sea surface pressure variability that drive wintertime climate in the Northern Hemisphere [*Hurrell*, 1995; *Thompson and Wallace*, 1998]. Observations and modelling studies, however, suggest that, in combination with tropical Pacific-Indian Ocean forcing [*Hoerling et al.*, 2001] and internal processes, NAO/AO variability is partially driven by North Atlantic SSTs [*Sutton and Hodson*, 2003]. North Atlantic SSTs may affect these atmospheric modes by altering evaporation, precipitation and ocean-atmosphere heat exchanges. As suggested by observations and simulation models, the AMO plays a role in North Atlantic climate outside of the winter months by producing anomalous geopotential heights over the fall and summer seasons [*Enfield and Mestas-Nuñez*, 1999]. Multidecadal variability in the North Atlantic might also be teleconnected with Pacific Basin modes via the AO and a hypothesized atmospheric bridge at high latitudes [but see *Honda et al.*, 2001]. Low-frequency variability similar to that in our AMO proxy appears in tree-ring based climate reconstructions from throughout western North America [*Gray et al.*, 2003] as well as in hemispheric-scale reconstructions of Pacific Basin air temperatures [*Delworth and Mann*, 2000].

[14] Such natural, low-frequency variations may also serve to alternately mask or amplify secular trends in the climate system [*Kerr*, 2000]. This is of particular concern when monitoring and modelling the effects of anthropogenic forcing on the Atlantic Thermohaline Circulation (THC). Previous studies propose that the effects of rising trace-gas concentrations might be sufficient to overwhelm internal, low-frequency processes in the North Atlantic [*Collins and Sinha*, 2003]. Because the AMO reconstruction is similar in the pre-and post-greenhouse eras, our results suggest that trace-gas forcing has yet to significantly affect the low-frequency component of THC variability. If the low-frequency components of THC variability continue to operate as they have for (at least) hundreds of years, the AMO and its impacts on Northern Hemisphere climate should be predictable over multiyear to decadal timescales [*Collins and Sinha*, 2003; *Griffies and Bryan*, 1997].

[15] In terms of both duration and magnitude, AMO variability observed in late-19th and 20th century instrumental records is typical of North Atlantic multidecadal behaviour over longer periods. Furthermore, the stationarity of these multidecadal oscillations throughout the reconstruction suggests that the mechanisms driving AMO variability have operated in a similar fashion for (at least) the previous ~500 yr. The AMO provides a potential means to help explain and possibly forecast persistent (10–100 yr) climate anomalies spanning wide geographic areas and multiple seasons that must be accounted for in assessments of pre- and post-greenhouse climates.

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