GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L15707, doi:10.1029/2006GL026656, 2006

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NAO influence on sub-decadal moisture variability over central North America

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Received 20 April 2006; revised 9 June 2006; accepted 15 June 2006; published 2 August 2006.

[1] A strong statistically significant spectral peak with a frequency of 7–8 years is computed for tree-ring reconstructed summer PDSI averaged at continental and regional scales over North America for the period 1645–1990. A similar, though non-significant spectral peak is computed for instrumental summer PDSI averaged over North America for the shorter period from 1900–1990. The winter NAO index (1781–2002) has a very strong spectral signature at this same 7–8 year sub-decadal frequency and is coherent with summer PDSI across a broad sector of the central U.S. Composite analyses confirm a PDSI response to extremes of the NAO over the central U.S., with drought prevalent during negative extremes, and wetness during positive extremes. The winter NAO index leads summer PDSI and a contingency table analysis indicates that extrema in the winter NAO index may have modest forecast value for the following spring-summer moisture regimes over the central U.S. **Citation:** Fye, F. K., D. W. Stahle, E. R. Cook, and M. K. Cleaveland (2006), NAO influence on sub-decadal moisture variability over central North America, *Geophys. Res. Lett.*, *33*, L15707, doi:10.1029/2006GL026656.

1. Introduction

[2] Interannual to decadal drought remains a significant socioeconomic problem [*National Research Council*, 1988]. A recent example is the moderate to exceptional drought over much of Texas, Oklahoma, and Arkansas during 2005 and continuing into 2006 (*Drought Monitor*, http://www.drought.unl.edu/dm). Rainfall amounts in 2005 were as much as 20 inches below normal in many areas with parts of Texas experiencing their worst drought in 50 years [*Kurt*, 2006]. The synoptic weather map and numerical model output may explain continuing drought on a day-to-day or week-to-week basis, but the origins of this drought and other long-term regional droughts remain unclear.

[3] Insight into the possible cause and duration of drought at sub-decadal to decadal time scales may be associated with modes of variability in the ocean-atmospheric climate system. Several external and internal forcings may influence temperature and/or precipitation over regions of the U.S., including the Hale solar magnetic cycle [*Mitchell et al.*, 1979; *Cook et al.*, 1997], the lunar nodal tidal cycle [*Currie*, 1981], the Pacific Decadal Oscillation [*Mantua et al.*, 1997], the North Atlantic Oscillation (NAO) [*Hurrel*, 1995; *Jones*, 1999], the El Niño/Southern Oscillation (ENSO) [*Trenberth*, 1997], and others. If an ocean-atmospheric mode of variability can be associated with sub-decadal patterns of drought and wetness, it may be possible to predict future drought/pluvial episodes and their duration over certain regions of the North American continent.

[4] Spectral analyses of indexed time series of these ocean-atmosphere modes of variability show a concentration of spectral power at several well-known frequencies (e.g., ~22, 18, 4–6, and 2 years). Similar spectral power can be identified in tree-ring reconstructions of the summer Palmer Drought Severity Index (PDSI) from 1645 to 1990 (Figure 1a) including the bi-decadal and ENSO-band (4–6 year) frequency components. However, the origin of the strongest statistically significant frequency component in the continent-wide PDSI reconstructions, with a period between 7–8 years, has not been determined even though it accounts for more than 5% of the overall significant variance in the PDSI spectrum. This recurring PDSI mode may be implicated with the current dry spell in the south-central U.S. We hypothesize that this mode of variability originates with the NAO on the basis of very strong spectral power at 7.8-years in the NAO's frequency spectrum (Figure 1b). We test this hypothesis using spectral, cross-spectral, composite map, and contingency table analyses of tree-ring reconstructed North American PDSI and the NAO.

2. Data

[5] The moisture variable used in this study is the PDSI, a soil moisture index derived from comparing mean monthly temperature and precipitation data with climatological means in a two-layer hydrological model [*Palmer*, 1965]. The PDSI index is zero-centered with "0" being "normal" and negative values representing drought and positive values indicating wetness.

[6] Moisture data analyzed in this study consisted of instrumental and tree-ring reconstructed summer (JJA) PDSI on a 286-point 2.5 × 2.5 degree latitude/longitude grid over most of North America. These gridded reconstructions of summer PDSI were developed by *Cook et al.* [2004] using a principal components regression analysis of annual proxies of drought and wetness provided by ~826 climatically sensitive tree-ring chronologies. The tree-ring data integrate a multi-seasonal moisture signal across North America that includes winter, spring, and especially summer climate conditions. These data provide a consistent, high quality, spatial and temporal history of drought and wetness across North America covering more than 700 years [*Cook et al.*, 2004]. We chose to restrict our analyses to the 1645 to 1990 period when all 286 North American grid points are fully populated.

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0094-8276/06/2006GL026656$05.00

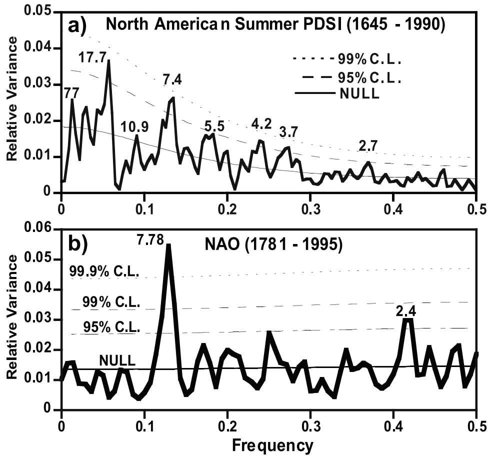

Figure 1. (a) Spectral power (relative variance) of a large-scale, North American average based on tree-ring reconstructed PDSI at 286 grid points from 1645 to 1990. The period in years of significant spectral peaks are annotated. (b) Same as Figure 1a but for the time series of the North Atlantic Oscillation (NAO) from 1781 to 1995 [*Jones*, 1999].

[7] We use the instrument-derived *Jones* [1999] NAO index extending from 1781 to 2002. The NAO is a dominant winter (DJFM) atmospheric circulation pattern over the extra-tropical North Atlantic [e.g., *Hurrell*, 1995] and is based on the meridional barometric pressure variation across the North Atlantic Ocean. The NAO index reflects the strength and position of the subtropical anticyclone over the North Atlantic and adjacent areas of North America. This subtropical anticyclone is known to influence the climate over much of the U.S. [*Trewartha*, 1981].

3. North American PDSI and NAO Spectra

[8] Spectral analyses were completed using Fourier analyses [*Blackman and Tukey*, 1958]. The spectral characteristics of North American-average tree-ring reconstructed PDSI from 1645 to 1990 are shown in Figure 1a. In this large-scale average, spectral power is concentrated in several expected frequencies, although some spectral peaks are not significant even at the 95% confidence level (Figure 1a). These spectral results are consistent with previous work. For example, *Cook et al.* [1997] found significant peaks at similar frequencies in a drought area index (DAI) over the western U.S. derived from the same data set used in this study. Peaks in the sub-decadal (7–8 year) band can also be seen in the spectral density of tree-ring reconstructed DAI reported by *Mitchell et al.* [1979] and *Stockton et al.* [1983]. The bi-decadal drought rhythm has been linked statistically to solar-lunar variability, the decadal to possible solar variability, the 3.0- to 6.0-year band to ENSO, and the biennial to winter QBO variability. However, the forcing of the 7–8 year frequency component has not been diagnosed, even though it exceeds all others in terms of significant (>95% C.L.) spectral power in the reconstructed PDSI averaged across North America (Figure 1a). Instrumental and reconstructed PDSI frequency analyses for the concurrent observational data period from 1900 to 1990 do not show such a strong response at 7–8 years (although a non-significant concentration of variance is present in both), but this may partly reflect the poor spectral resolution for this frequency with just 91 years of data. Only the higher-frequency 5-year ENSO peak is present in this truncated (1900–1990) analysis. From our analysis of the longer tree-ring reconstructed frequency analysis from 1645–1990, the NAO is implicated as a link in moisture variability over North America because the NAO index itself shows a very strong concentration of spectral variance in this same sub-decadal band centered at 7.78 years ($p < 0.0001$; Figure 1b).

4. Spatial Patterns of Spectral Power and Coherency

[9] Spectral analysis was performed on the reconstructed PDSI time series at each of the 286 grid points over the 1645 to 1990 time interval. For each grid point, relative variance was summed over the "sub-decadal" 7–8 year spectral band. These spectral power sums were then plotted at each of the 286 grid points and mapped (Figures 2a). Sub-decadal PDSI spectral power is concentrated in the central U.S. from the Texas-Louisiana coast to the Great Lakes and in the western U.S. (Figure 2a).

[10] Cross-spectral analysis was used to calculate the coherence and phase relationship between the NAO time series and the reconstructed PDSI at each North American grid point. Coherency is analogous to correlation between two time series in the frequency domain, and phase angle measures the lead and lag relationships between the time series [*Cook et al.*, 1997]. The squared coherency calculated between each PDSI grid point and the strongest frequency in the NAO time series (7.78 years, Figure 1b) was plotted and mapped (Figure 2b). This spatial analysis indicates that reconstructed PDSI over a large sector of the central U.S. is coherent with the NAO at this sub-decadal frequency, but the sub-decadal spectral power over the West is not (Figure 2b). Only the central U.S. PDSI variance is coherent with the NAO. Analyses of phase angle (not shown) indicate that PDSI and NAO are generally in phase (peak within the same year) over the central U.S.

[11] Cross spectral analyses between gridded reconstructed PDSI and indices of the SOI and PDO indicate low coherency over the central U.S. at the sub-decadal frequencies, but some marginal spatially discontinuous coherency with the SOI over portions of the western U.S. (not shown).

5. Composite Analyses

[12] Composite analyses were used to map the sign and strength of PDSI over North America during extremes of the NAO index (Figure 3a). Average reconstructed summer PDSI for the 69 years when the winter NAO index exceeded +0.5 standard deviations from the mean were mapped and indicate that positive extremes of the NAO index correspond to wet conditions over the central and western U.S. (Figure 3b). Dry conditions prevailed over the same areas during the 61-year composite of the negative phase of the winter NAO (<−0.5 SD, Figure 3c). A t-test comparing the means of the composite PDSI maps in Figures 3b, c

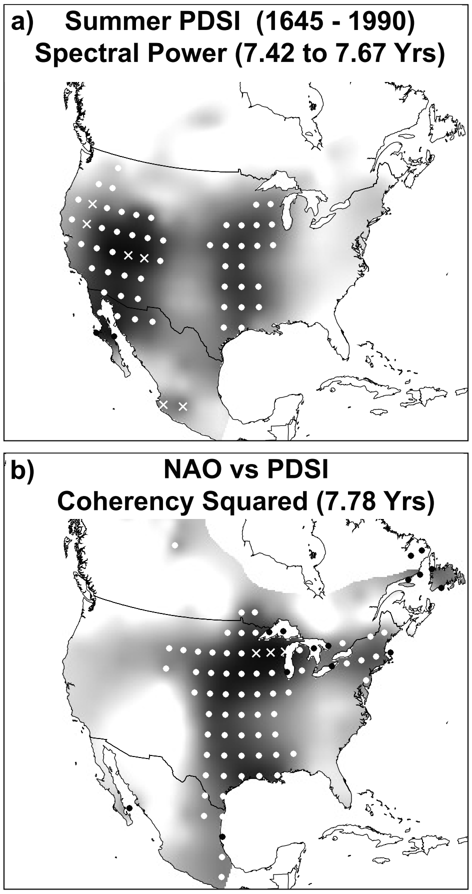

Figure 2. (a) Spectral power calculated for tree-ring reconstructed summer PDSI (1645 to 1990) at each grid point, summed over the 7.42 to 7.67 year interval, and mapped. Shading represents variation in spectral power (white = zero, black = 31%; dots = grid points where spectral density exceeds the 95% C.L., X's exceed the 99% C.L.). (b) Spectral coherence (biased coherency squared) between the NAO time series [*Jones*, 1999] and tree-ring reconstructed summer PDSI at each of the 286 grid points over the common 1781 to 1990 period. Shading represents coherency (white = zero, black = 0.6; significance symbols same as Figure 2a).

indicates significant differences in the central U.S. and to a lesser degree over portions of the West (Figure 3d).

[13] Similar composite analyses using instrumental PDSI (not shown) over the common time period with the NAO (1900 to 1990) confirmed the same pattern of wet conditions in the positive NAO phase and dry conditions in the negative NAO phase over the central U.S. When tested, the difference between the means of these composites was significant at $p \leq 0.01$ over an area extending from east Texas into the Ohio Valley.

6. Discussion

[14] These analyses indicate that the winter NAO (DJFM) can impact moisture conditions over the central U.S. during winter, spring, and perhaps persisting into early summer, with central U.S. moisture conditions measured by the summer PDSI which integrates temperature and precipitation effects on soil moisture during the winter, spring, and summer. Positive anomalies in the NAO tend to produce wetter than normal conditions over the central U.S. (Figure 3b) and the principal source of moisture in this region is probably the Gulf of Mexico. Moisture transport from the Gulf of Mexico can be critical to the extent, location, and duration of drought in North America [*Oglesby*, 1991]. The positive phase of the NAO also favors a strong Bermuda High in the western North Atlantic along with stronger than normal trade winds and evaporation across the Caribbean and Gulf of Mexico [*Kapala et al.*, 1998]. These warm, moisture-laden easterlies turn northward as they approach the northwestern Gulf and then flow into the southern Plains often as a low-level jet [*Helfand and Schubert*, 1995]. This is the well-known "Gulf moisture" that is particularly important during the spring and summer [*Trewartha*, 1981; *Oglesby and Erickson*, 1989]. This moisture flow, combined with reduced stability common in the western extremities of subtropical highs [*Trewartha*, 1981], favors increased spring and summer convective precipitation in the central U.S. region.

[15] Conversely, the negative phase of the NAO reflects a weak Bermuda high in the eastern Atlantic, weak trade winds, and an anomalously cold North America [*Kapala et al.*, 1998]. Weaker trades and a more easterly position of the Bermuda high would favor reduced winter-spring moisture flow into the central U.S. and relatively dry conditions [*Trewartha*, 1981; *Oglesby*, 1991] as indicated in Figure 3c.

[16] The positive phase of the NAO also displays a definitive sea surface temperature (SST) regime that may

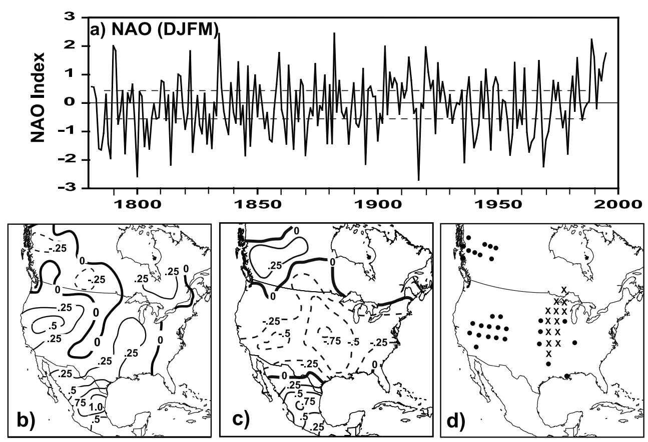

Figure 3. (a) The time series of the winter NAO index from 1781 to 1995 [*Jones*, 1999]. Dashed horizontal lines are the 0.5 standard deviations above and below the mean and were used as cutoffs for determining the "extreme" years to be used in the composite mapping of reconstructed summer PDSI. (b) A composite of reconstructed summer PDSI for years when the NAO index was in its positive phase and exceeded +0.5 standard deviations. Contours are in units of average PDSI with negative PDSI (dashed contours) representing drought and positive PDSI representing wet conditions (solid contours). (c) Same as Figure 3b but for years when the NAO index was in its negative phase (less than −0.5 standard deviations). (d) The results of a t-test between the means of Figures 3b and 3c at each grid point (dots = $p \leq 0.05$, X's = $p \leq 0.01$).

Table 1. A Contingency Table Comparing Three Equal Categories of the Winter NAO Index [*Jones et al.*, 1999] With Three Equal Categories of Tree-Ring Reconstructed Summer PDSI Over the Central U.S. (Latitude 30.0 to 47.0; Longitude 88.0 to 98.0)[a]

	NAO			
PDSI	Low	Medium	High	Total
Low	33	19	18	70
Medium	22	25	23	70
High	15	26	29	70
Total	70	70	70	210

[a]The three categories for the NAO index were <−0.53 (low), ≥−0.53 to ≤0.31 (medium), and >0.31 (high); and for the summer PDSI were <−0.723 (low), ≥−0.723 to ≤0.626 (medium), and >0.626 (high). The computed χ^2 of 10.89 for 4df is significant at $p < 0.05$ [*Panofsky and Brier*, 1965].

help explain the increased moisture flow into the central Plains. Composites of DJF SSTs over the Atlantic corresponding to the stronger positive years of the NAO reveal a three-cell pattern in the North Atlantic as described by *Wallace et al.* [1990]. This pattern consists of anomalously warm temperatures extending in a band across the central North Atlantic into the Gulf of Mexico and bounded on the north and south by colder Atlantic water (not shown). This pattern favors a stronger Bermuda High, stronger trade winds [*Wallace et al.*, 1990], greater evaporation, and enhanced moisture advection into the central U.S. During the negative phase of the NAO, the SST regime reverses with cooler SSTs in the central Atlantic, and warmer SSTs in the tropical Atlantic region resulting in a weaker Bermuda High and weaker trade winds [*Wallace et al.*, 1990; *Schubert et al.*, 2004]. This SST pattern does not favor a strong moisture flux into the central U.S. *McCabe et al.* [2004] have shown that a warm North Atlantic as indexed by the Atlantic Multidecadal Oscillation (AMO) and corresponding to a negative NAO was associated with both the 1930s Dust Bowl drought and the 1950s drought centered in the Texas region. A warm North Atlantic (negative NAO) also appears to be related to increased hurricane frequency in the Atlantic [*Elsner et al.*, 1999]. *Oglesby* [1991] hypothesizes that increased tropical storm activity may effectively intercept moisture inflow to the central U.S. It may not have been coincidental that Atlantic hurricane maxima (*HURDAT*, http://www.aoml.noaa.gov) occurred during several years of the Dust Bowl and 1950s droughts when the NAO was primarily negative.

[17] Because the winter NAO index leads much of the hydroclimatic variability represented in the summer PDSI, extremes in the NAO index may have some forecast value for late spring-summer moisture conditions over the central U.S. A contingency table analysis was used to test this hypothesis (Table 1). The NAO index [*Jones et al.*, 1999] and reconstructed summer PDSI over the central U.S. were each divided into three equal categories over their common period from 1781–1990. Dry conditions were prevalent during low NAO regimes, and moist conditions were prevalent during normal to high NAO regimes (χ^2 of 10.89, df = 4, $p < 0.05$; Table 1). These associations were most pronounced during low NAO regimes (Table 1), and indicate that the probability of central U.S. drought during the spring-summer may be dependent, in part, on conditions in the North Atlantic during the preceding winter-early spring.

7. Conclusion

[18] An association between moisture anomalies in the central U.S. with extremes of the NAO is supported by cross spectral analyses which indicate that the strong sub-decadal (7–8 year) frequency component seen in reconstructed summer PDSI may arise from modulation of moisture advection by the NAO. This association is computed for the winter-time index of the NAO (DJFM) and the summer average PDSI (JJA), which integrates moisture conditions over the late winter, spring, and summer. The sub-decadal frequency component accounts for only 5% of the variance in the large-scale North American average summer PDSI (e.g., the sum of the two significant peaks at 7 years in Figure 1a), but this variance fraction increases to 13.0% when computed for just the central U.S. region with strongest coherence with the NAO (Figure 2b). These results support previous work and indicate the phases of the winter NAO may have some modest forecast value for subsequent growing season moisture conditions over the central U.S.

[19] A weaker link between the winter NAO and summer PDSI is evident in the instrumental data available for the period 1900–1990, but is more robust in the reconstructed summer PDSI and NAO data available for 1781–1990. The results would not have been possible without the new long record of the NAO developed by *Jones et al.* [1999] and the tree-ring reconstructed summer PDSI for North America [*Cook et al.*, 2004].

[20] **Acknowledgment.** This research was sponsored by the NSF Earth System History Program (Grant ATM-0400713) and Lamont-Doherty Earth Observatory Contribution 6944.

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