Tree-ring reconstructions of temperature and sea-level pressure variability associated with the warm-season Arctic Oscillation since AD 1650

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[1] Arctic Oscillation (AO) changes are inferred from a tree-ring reconstruction of a warm-season temperature index. The reconstruction covers AD 1650–1975 and is based largely on chronologies from circumpolar-Arctic and circum-North Atlantic areas. It accounts for 48% of the variance in the instrumental AO record from 1900 to 1975, verifies using independent data, and exhibits its largest variance at low frequencies. Positive levels during 20th century periods equal or exceed values back to AD 1650. Trends (including lower values during 'Little Ice Age' periods) resemble those of Arctic temperature reconstructions, reflecting some data overlap, but also the strong link between the AO and northern temperatures. A reconstruction of an AO summer sea level pressure index shows similar trends. Comparison of these reconstructions with proxies of the North Atlantic Oscillation (NAO) and other indices can help clarify relationships between the AO and NAO, at least during the boreal warm season. *INDEX TERMS:* 4221 Oceanography: General: Dendrochronology; 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9315 Information Related to Geographic Region: Arctic region. **Citation:** D'Arrigo, R. D., E. R. Cook, M. E. Mann, and G. C. Jacoby, Tree-ring reconstructions of temperature and sea-level pressure variability associated with the warm-season Arctic Oscillation since AD 1650, *Geophys. Res. Lett.*, *30*(11), 1549, doi:10.1029/2003GL017250, 2003.

1. Introduction

[2] The Arctic Oscillation (AO) is a key aspect of climate variability in the higher latitudes of the Northern Hemisphere (NH). It has been identified as the dominant empirical orthogonal function (EOF) of winter sea-level pressure (SLP) variability for the NH poleward of 20°N [*Thompson and Wallace*, 1998]. It is characterized by an alternation of atmospheric mass between the Arctic and middle latitudes. The more regional North Atlantic Oscillation (NAO) features an alternation of mass between the North Atlantic subpolar and lower middle latitudes and subtropics [*Hurrell*, 1995].

[3] The AO's primary center of action covers a larger, more zonally symmetric region of the Arctic, and accounts for a significantly larger fraction of the variance in NH surface air temperatures than the NAO, with which it is highly correlated [*Thompson and Wallace*, 1998; *Deser*, 2000]. Most studies have focused on winter and/or cold-season variations during which the extratropical NH storm tracks, and hence the AO and NAO which measure the variability therein, are best defined. The winter AO is more strongly coupled than the NAO with surface air temperatures over high latitudes, particularly in Eurasia [*Thompson and Wallace*, 1998]. Sustained positive trends in both modes in recent decades may be linked to large-scale warming and anthropogenic increase in trace gases [e.g., *Hurrell*, 1995; *Shindell et al.*, 1999], although some models yield contradictory results [e.g., *Zorita and Gonzalez-Rouco*, 2000].

[4] Considerable controversy exists as to whether or not the AO and NAO are distinct entities. *Wallace* [2000] and *Deser* [2000] argue that they are virtually indistinguishable. An alternative view, based on rotated principal components analysis (RPCA) of NH SLP data, is that the AO and NAO are distinct modes of circulation during the non-winter months [*Rogers and McHugh*, 2002]. In winter and annual average records, however, they do not appear distinct, a possible result of a shared winter storm track between the northeast Atlantic and Arctic [*Rogers and McHugh*, 2002].

[5] Detailed analysis of the AO and NAO is constrained by the length of instrumental record. *Jones et al.* [2001] stressed the critical need for developing longer records of such key climate variables from proxy series. Longer proxy series can be used to evaluate the long-term natural behavior of the AO and whether or not it is a separate mode of variation from the NAO. In so doing, these extended series can provide a long-term context for variability during the period of increasing trace gases, and for testing climate prediction models.

[6] A number of proxy reconstructions of the winter NAO have now been published, based on tree rings [e.g., *Cook et al.*, 1998, 2002], ice cores [*Appenzeller et al.*, 1998], instrumental and proxy records [*Luterbacher et al.*, 2002], and multiproxy data sets [*Cullen et al.*, 2001]; [and see *Hurrell et al.*, 2003]. To our knowledge no such reconstructions have been published on the AO, which, at least during the warm season, may be a distinct feature of the climate system [*Rogers and McHugh*, 2002]. We present a reconstruction of an AO temperature index (AD 1650–1975) for the warm season, when the AO is more likely to be distinct from the NAO. We evaluate its variability over time and relative to a similar reconstruction of AO SLP. These reconstructions are also assessed in relation to reconstructions of the NAO [*Cook et al.*, 2002; *Luterbacher et al.*, 2002] and Arctic temperatures [*Jacoby et al.*, 1999]; and an "NAO-free" AO index [*Rogers and McHugh*, 2002].

2. Data and Analysis

2.1. AO SAT and SLP Indices

[7] Tree-ring data were compared to two instrumental indices of the AO provided by *Thompson and Wallace*

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[2000]: one of AO-related surface air temperature (SAT) and the other of AO SLP. These indices correlate at $r = 0.57$ for the 1900–1996 period for April to September. We focus on the SAT index (as a longer data set is available for statistical testing), but also briefly present similar results for the SLP series. The SAT index targets the AO's impact on temperature of the middle to higher latitudes of the NH, and represents the expansion coefficient time series of the SAT pattern of anomalies associated with the AO [*Thompson and Wallace*, 2000]. We are aware that the spatial AO SLP pattern [*Thompson and Wallace*, 2000; *Thompson et al.*, 2000] is dominated by the cold season when variability is largest, and hence may not be the dominant mode of variability in the warm season reconstructed here. This consideration suggests the value of targeting a true warm season AO pattern in future work.

2.2. Tree-Ring Indices

[8] We first identified a set of primarily tree-ring width (and some maximum latewood density) chronologies which demonstrated a significant response to AO SAT. Simple correlation analysis was used to screen the AO SAT index against 129 candidate predictor chronologies from two data networks. One network represents the circumpolar Arctic treeline and adjacent areas; chronologies from this data set were used previously to reconstruct annual Arctic and NH temperatures [*Jacoby et al.*, 1999]. The other represents circum-North Atlantic land areas; chronologies from this data set were used to reconstruct the winter NAO [*Cook et al.*, 1998; *Cook et al.*, 2002]. All are exactly-dated records with demonstrated climate sensitivity (to temperature or precipitation) in AO/NAO sensitive regions [*Thompson and Wallace*, 1998].

[9] Initial correlation screening revealed a subset of 36 tree-ring chronologies out of the original 129 series which correlated significantly ($p < 0.10$ level, two-tailed test) with the AO SAT index over a common period from 1900 to 1975. These 36 series were retained for inclusion in the AO reconstruction model (Figure 1). Both Arctic and North Atlantic regions are represented, consistent with the observation that the AO primarily impacts the climate of the circumpolar Arctic, but is also correlated with the NAO [*Thompson and Wallace*, 1998; *Deser*, 2000]. The regression coefficients for the sites in Figure 1 indicate that the distribution of explanatory power is more or less evenly distributed across the Arctic and Atlantic regions. Spatial representation does not vary greatly between the periods of calibration and verification. The strongest correlations between the tree-ring data and the AO SAT index were found for the months of April to September (AMJJAS) of the current growth year. This season was then used to develop the reconstruction. Less dynamically active than in winter, the warm season is still of considerable interest, in part because the motion of Arctic ice pack and response to wind forcing is most sensitive at this time [*Thompson and Wallace*, 2000; *Thompson et al.*, 2000].

[10] Principal components regression analysis [*Cook and Kairiukstis*, 1990] was used to reconstruct the warm season AO SAT index based on the 36 predictor chronologies for A.D. 1810–1975. Only those principal components having eigenvalues >1.0 were retained in the regression. The ar^2 criterion was used to select the eigenvectors entered into the model [*Cook and Kairiukstis*, 1990]. A nested procedure allowed extension of the reconstruction back to AD 1709 based on 33 series, and to AD 1650, based on a subset of 25 longer series [*Cook et al.*, 2002].

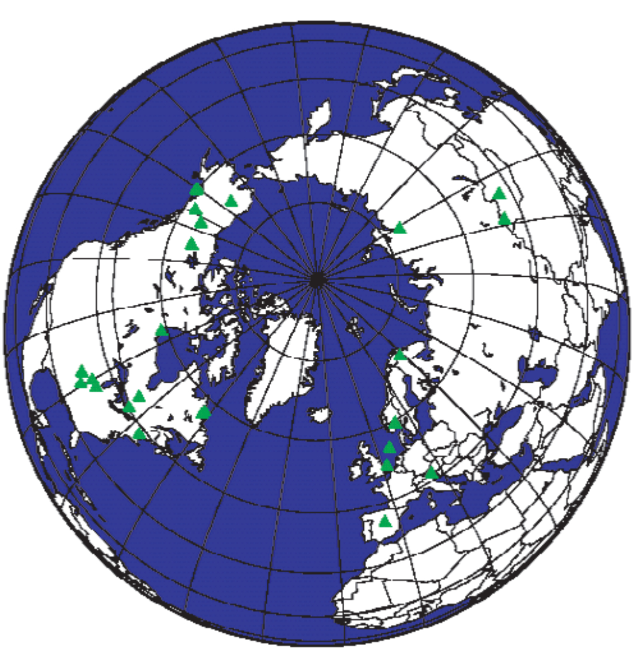

Figure 1. Map showing tree-ring sites (triangles) used to reconstruct the AO SAT index. The sites include Arctic and elevational treeline; and North Atlantic sector locations. Triangles may represent more than one site. Results similar for AO SLP index.

3. Results and Discussion

3.1. Tree-Ring Model

[11] The AO SAT regression model was developed over the 1900–1975 period used for calibration, with a 1860–1899 period reserved for verification. Over 48% of the variance in the instrumental AO was accounted for by this model (Figure 2). The tree-ring model verifies using several measures of common variance [*Cook and Kairiukstis*, 1990]. These include the Reduction of Error (RE), which is positive (0.16). The Pearson coefficient (0.33), sign test (26+14−) and cross products mean T-test (2.385) results are all significant at or above the 95% level [*Cook and Kairiukstis*, 1990]. The nested models also pass these tests but at lower levels. While these results indicate statistically significant skill, due to the relatively low level of variance in verification we offer this model as only a preliminary reconstruction of the AO, providing some tentative initial insights into the behavior of the phenomenon in past centuries. Figure 3 (top) presents the AO SAT reconstruction from AD 1650–1975. Values during the middle 20th century, overlapping with the anthropogenic increase in trace gases, equal or exceed those in the prior record. There are generally above average indices in the 1700s. Lower values are reconstructed for several colder periods within the so-called 'Little Ice Age' of the 15th–19th centuries [*Folland et al.*, 2001], including the early and late 1800s and within the Maunder Minimum (late 1600s–early 1700s; more pronounced in AO SLP reconstruction below).

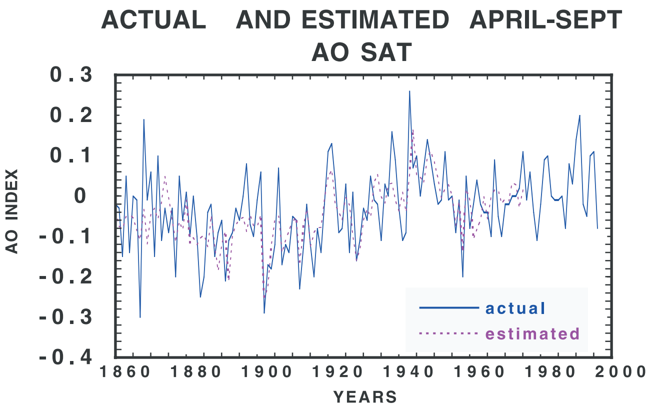

Figure 2. Actual (solid) and estimated (dashed) AO SAT index for 1860–1975. Tree-ring model accounts for 48% of the variance over the 1900–1975 calibration period.

3.2. Spectral Analysis

[12] Multi-taper method (MTM) spectral analysis was used to evaluate the reconstruction in the frequency domain [*Mann and Lees*, 1996] (Figure 4, top). The AO SAT reconstruction shows a dominance at lower frequencies, typical of many circum-Arctic tree-ring series [e.g., *Jacoby et al.*, 1999]. There is a broad 50–100+ yr peak (>99% significance) that overlaps with a ~70 yr oscillation observed in the global instrumental record [*Mann and Park*, 1994; *Schlesinger and Ramankutty*, 1994]. This period of enhanced power is still significant when only the pre- 20th century period is considered (Figure 4, bott). A persistent multi-decadal NH climate signal is observed in other proxy series of large-scale temperature variability [*Mann et al.*, 1995]. The timescale of the signal is in the range of the so-called 'Gleissberg' solar cycle, and some modeling evidence indeed supports the hypothesis of a solar-driven signal on this timescale [*Shindell et al.*, 2001; *Waple et al.*, 2002]. However, experiments employing a coupled ocean-atmosphere model suggest that a multidecadal signal similar to that seen in observations and paleo-reconstructions can be generated purely from internal coupled ocean-atmosphere variability [*Delworth and Mann*, 2000]. Peaks at ~2–3 yr, (95–99%), ~4.6–4.9 yr (99%), ~6–7 yr (95%) and ~21–25 yr (ns) were also identified and are broadly consistent with some observed in instrumental and proxy series of the NAO [e.g., *Rogers*, 1984; *Cook et al.*, 1998]. A ~11 yr peak (95%) may relate to solar effects, which can impact climate through AO forcing [*Shindell et al.*, 2001].

3.3. Comparisons With Related Climate/Tree-Ring Indices

[13] The reconstruction of the summer (JJA) AO SLP index is shown in Figure 3 (bott.) for 1650–1975. Results were improved for this season as compared to the April–Sept. season used for SAT. Trends are similar to those for AO SAT; correlation between the AO SAT and SLP reconstructions is r = 0.56. Trends in both series resemble those of a tree-ring reconstruction of Arctic annual temperatures (r = 0.46 with AO SAT; 0.51 with AO SLP [*Jacoby et al.*, 1999]. The similarities reflect some data overlap, but also the strong linkage between the AO and Arctic temperatures. There is still, however, considerable

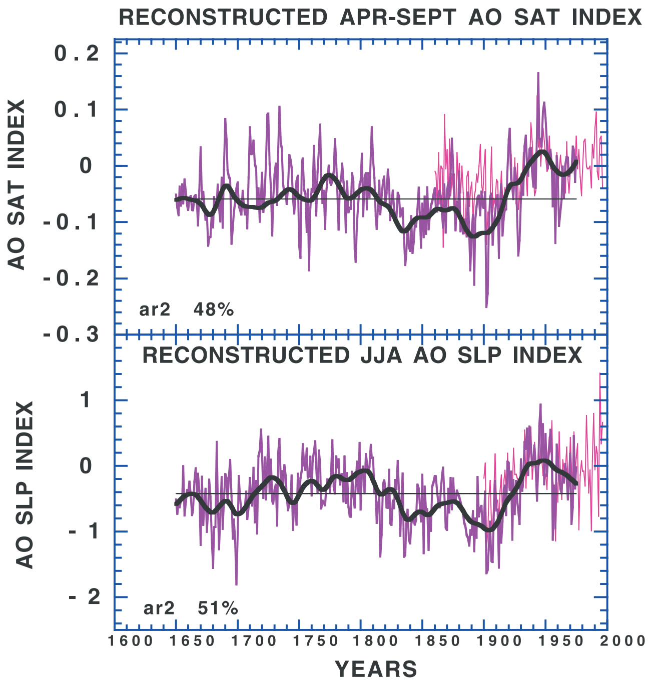

Figure 3. Top: Reconstruction of warm season AO SAT index for AD 1650–1975; annual (purple) and smoothed (black) lines. Red line is instrumental data; variance has been adjusted to correspond to tree-ring estimates. Mean line also indicated. Bottom: JJA AO SLP index. This model accounts for 51% of the variance and also verifies using several statistical tests (e.g., RE = .14).

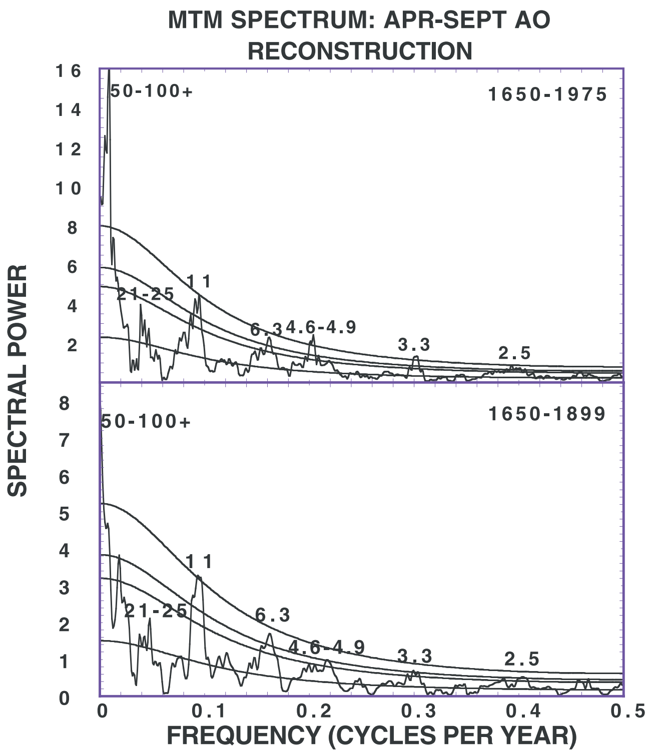

Figure 4. Multi-taper method (MTM) spectral analysis for AO SAT reconstruction. Black lines indicate null, 90%, 95%, and 99% levels of significance. Top: full period from 1650–1975; bottom: 1650–1899.

unshared variance between these reconstructions. Interestingly, correlation is weak (0.16, albeit significant, 99%, 1659–1975) between the AO SAT and *Luterbacher et al.* [2002] NAO reconstructions for the warm season (April–Sept), when the AO and NAO may be most distinct from each other [*Rogers and McHugh*, 2002]. There is strong correlation, however, between the *Cook et al.* [2002] NAO series and a tree-ring model of DJFM AO SLP (r = 0.68 for 1709–1977; not shown). Correlations between the AO reconstructions and the winter *Cook et al.* [2002] NAO SLP reconstruction are not statistically significant (similarly, correlation between instrumental winter NAO SLP and summer AO SAT for 1866–1966 is only 0.07; ns). Although based partly on overlapping data for the North Atlantic sector, the AO and *Cook et al.* [2002] reconstructions are for different variables (for AO SAT) and seasons. As noted, the AO reconstruction is dominated by lower frequencies, whereas the *Cook et al.* [2002] reconstruction best reflects a higher frequency range. *Cook et al.* [2002] used a longer period for calibration than previous NAO reconstructions. This method helped provide a more strongly verified model, since the longer calibration period included instrumental data preceding possible 20th century bias due to the contamination of the natural variability by anthropogenic climate influences. Since such longer instrumental time series do not exist for the AO, such potential bias is more difficult to guard against. However, since the tree-ring data used in the AO reconstructions cover a broader region, they may be less likely to show spatial bias due to any shift in the AO'S teleconnection with 20th century Arctic climate.

3.4. NAO-Free AO Index

[14] AO patterns during the non-winter months are clearly distinct from the NAO using RPCA, as previously shown [*Rogers and McHugh*, 2002]. Since the AO SAT/SLP indices were not generated as such, they may contain features of both the AO and the NAO. *Rogers and McHugh* [2002] found that the AO's (nonwinter) center of action is largely in the Eurasian Arctic, and is significantly linked to Siberian air temperatures. Consistent with this finding, there is strong agreement between a subset of the tree-ring records from the circum-Arctic (including Eurasia) and Atlantic sectors, and the *Rogers and McHugh* [2002] summer RPCA based "NAO-free" AO index for the 1946–1975 common period (ar^2 67%).

[15] It will be of value in future work to test, in more detail, proxy-based reconstructions such as this first effort against those based on independent long instrumental and proxy data [e.g., *Luterbacher et al.*, 2002]. Development of seasonally-optimal instrumental indices of the AO, and separate modeling of Arctic and North Atlantic tree-ring data sets, will also aid in clarifying whether the AO/NAO modes are in fact distinct prior to the period of instrumental data analysis.

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