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Multiproxy reconstructions of the North Atlantic Oscillation

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Abstract. Multiproxy composite reconstructions of North Atlantic Oscillation (NAO) indices are presented spanning the last three centuries. These composite time series draw on four nearly independent reconstructions derived from different combinations of global and North Atlantic sector climate proxy data (e.g., tree rings and ice cores) as well as long instrumental records. A composite reconstruction based on all four series (R4) extends from 1750 to 1979, while another version based on only three series (R3) extends from 1701 to 1979. Both composite reconstructions outperform the individual series based on correlation and verification statistics. These results suggest that each individual series reflects different aspects of the NAO, such that when combined, they yield more robust reconstructions. As to be expected, these composite reconstructions, based on both proxy and long instrumental data, yield more optimal results than individual or composite reconstructions based on proxy data alone. The reconstructions presented here provide an improved means of addressing features evident in the instrumental record with respect to those of prior centuries. One such feature evident in the reconstructions is an apparent increase in variance in the instrumental period relative to the past record.

1. Introduction

Much of the observed interannual to interdecadal climate variability in the Atlantic sector has been physically linked to a natural mode of variation known as the North Atlantic Oscillation (NAO) (see [*Hurrell,* 1995] and references therein). As one of the dominant modes of climate in the Northern Hemisphere (NH), the NAO accounts for roughly one third of the variance in sea level pressure (SLP) [*Wallace and Gutzler,* 1981] and 32% of Eurasian winter temperature variation over the past 60 years [*Hurrell,* 1996]. Growing evidence has demonstrated that the NAO has a profound impact on both marine and terrestrial ecosystems [*Fromentin and Planque,* 1996; *Alheit and Hagen,* 1997; *Beniston,* 1995; *Cullen and deMenocal,* 2000a]. The knowledge of how phenomena such as the NAO have varied in past centuries is of considerable interest to the paleoceanographic community. However, unlike the tropics, where abundant maritime proxy climate data (e.g., coral isotopes) are preserved for high-resolution reconstructions of patterns of sea surface temperature (SST) variability during past centuries, extratropical regions such as the North Atlantic are lacking these rich archives for reconstruction. In fact, some of the best proxy archives of information regarding this important pattern of variability come from terrestrial regions that experience the teleconnections of the substantial SLP dipole situated over the North Atlantic. These include, for example, tree ring records in Europe, North America, and the Middle East, historical records in Europe, and ice cores in the Arctic regions. Although the data we use herein to reconstruct the NAO are not strictly maritime proxies, they are a highly relevant addition to the network of paleoceanographic research aimed at understanding Atlantic sector climate variability.

In this paper, we first describe four individual reconstructions of the NAO which employ tree rings, ice cores, and long instrumental data (Figure 1) and then present composite series based on combinations of these individual versions. We also present results based purely on proxy data. Although these latter series exhibit significant reconstructive skill, we ultimately put forward the composite reconstructions which also incorporate instrumental data, owing to their greater resolved variance. The final composite reconstructions are then employed to begin to address questions regarding the nature of the NAO index, e.g., whether recent signs of increased variability [*Grassl,* 1997] and persistently high values in the past few decades [*Hurrell and Van Loon,* 1997] are unusual relative to the past several centuries.

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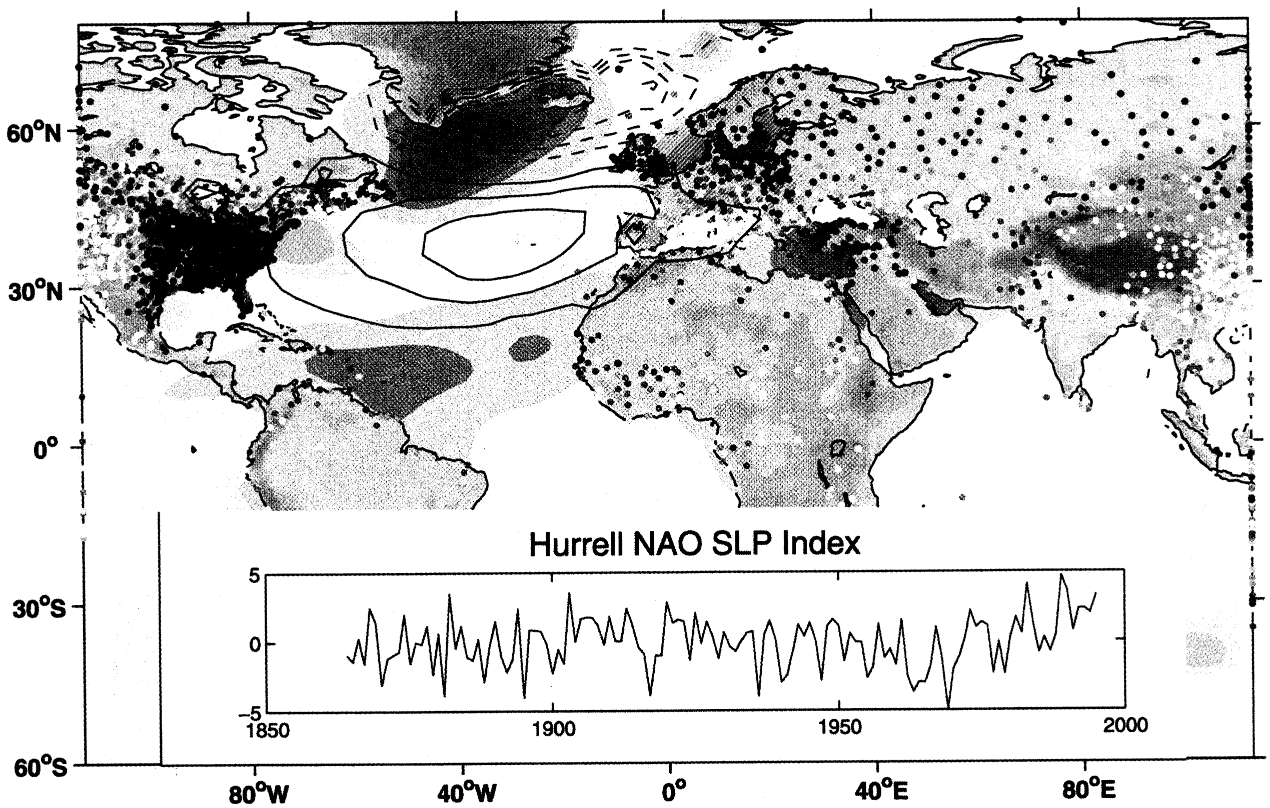


Plate 1. Spatial response of winter (December-March) sea level pressure (SLP), SST, and surface air temperature (SAT) to a 2σ change in the *Hurrell* [1995] North Atlantic Oscillation (NAO_{SLP}) index. The respective data are from *Kaplan et al.* [2000], *Kaplan al.* [1998], and *Baker et al.* [1995].

2. Indices of the NAO

Despite the fact that the physics behind the NAO have remained somewhat elusive, indices have been created to monitor its behavior over time. Currently, several instrumental indices have been developed using either SLP, SST, or surface air temperature (SAT) to characterize the amplitude and phase of the NAO. The first instrumental NAO index was defined by *Walker and Bliss* [1932]. *Rogers* [1984], simplifying this original series, constructed an NAO index starting in 1874 using SLP anomalies from Ponta Delgados, Azores, and Akureyri, Iceland, to represent the relative strengths of the Azores High and Icelandic Low. *Hurrell* [1995] then selected Lisbon, Portugal, and Stykkisholmur, Iceland, to extend the record back in time another 10 years. *Jones et al.* [1997] further extended the NAO_{SLP} index to 1823, using early instrumental pressure observations from Gibraltar and southwest Iceland. *Cullen and deMenocal* [2000b] presented an NAO index which averages SST over five Atlantic regions best correlated with the NAO_{SLP} index of *Hurrell* [1995] in order to capture the ocean component of the NAO, similar to the use of the NINO3 index as an alternative to the Southern Oscillation Index (SOI) of the El Niño-Southern Oscillation (ENSO). Coincidentally, both of these alternative indices share about half their variance in common with the specific SST regions.

These relatively short (130 year) instrumental indices, which measure the strength and position of maximum surface westerlies across the Atlantic and into Europe [*van Loon and Rogers,* 1978; *Rogers,* 1990], all exhibit weakly red spectra with enhanced energy in the interannual and decadal frequency bands and a suggestion of lower-frequency power in the more recent part of the record [*Hurrell and Van Loon,* 1997]. Certain researchers favor an alternative Arctic Oscillation (AO) index to describe the dominant NH circulation changes in recent decades [*Thompson and Wallace,* 1998; *Kerr,* 1999]. *Deser* [2000] currently reviews the supposed annularity of the AO and suggests that the Arctic and Atlantic components of the AO are strongly linked, whereas associations with the Pacific sector are weak. Regardless of the index chosen to represent this feature, extended records are essential for providing a long-term context for climate variability in the North Atlantic sector.

3. Individual Reconstructions

Below we briefly describe the individual reconstructions based on different time series of the NAO.

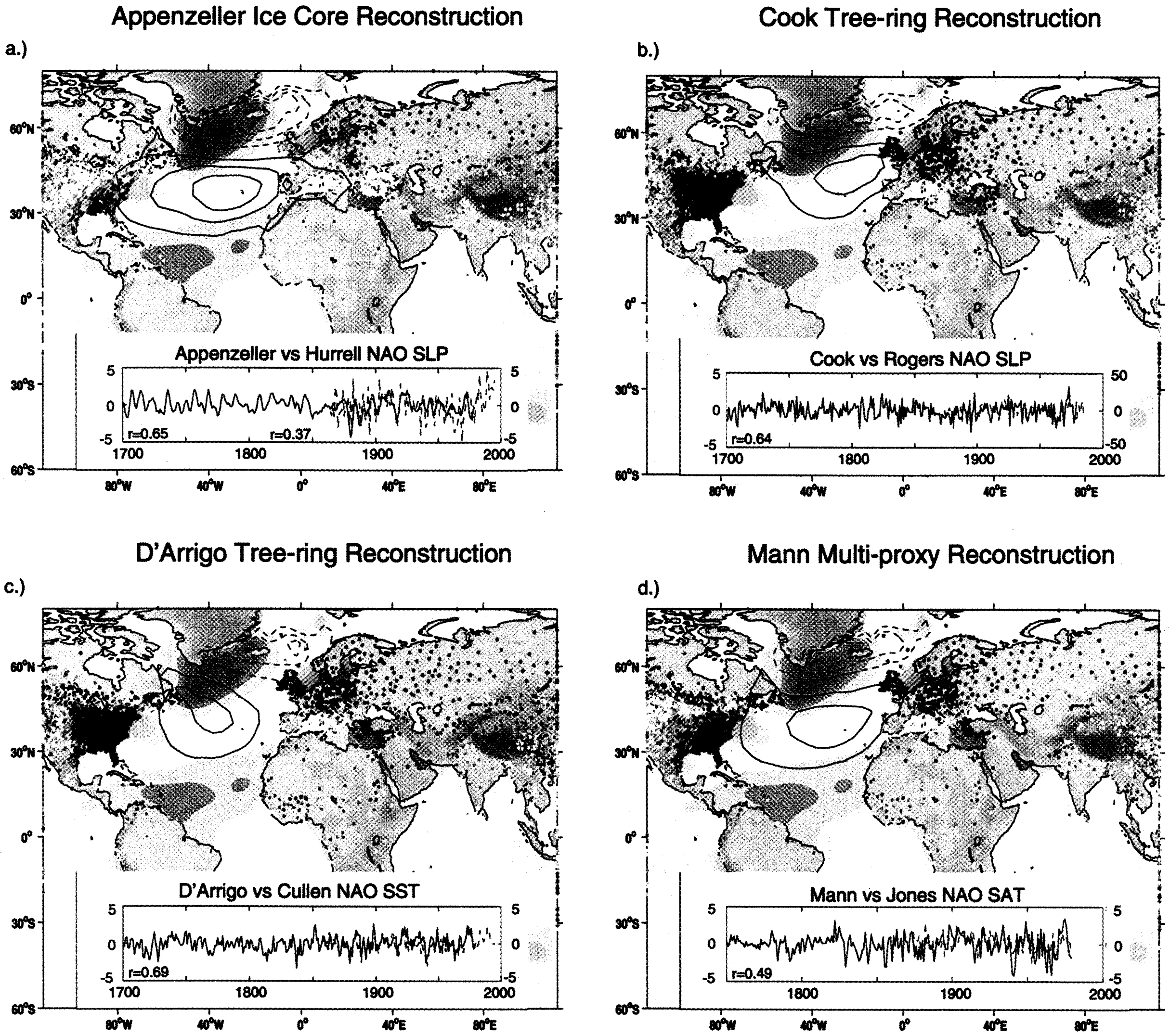


Plate 2. Spatial response maps of winter (December-March) SLP, SST, and SAT to a 2σ change in the (a) *Appenzeller et al.* [1998] NAO_{SLP} index, (b) *Cook et al.* [1998] NAO_{SLP} index, (c) *D'Arrigo and Cook* [1997] NAO_{SST} index, and (d) *Mann* [2000] NAO_{SST} index. The respective data are from *Kaplan et al.* [2000], *Kaplan et al.* [1998], and *Baker et al.* [1995].

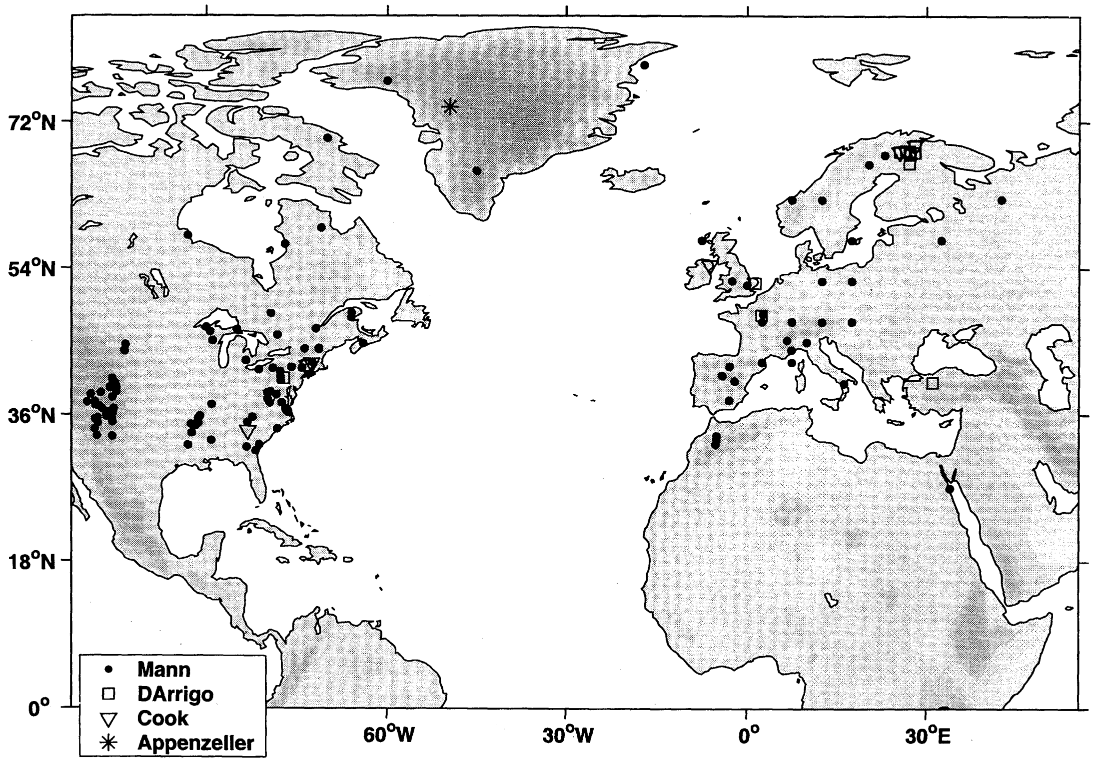


Figure 1. Location map of proxy and long instrumental records used in each of the four individual reconstructions.

3.1. Cook Reconstruction

Cook et al., [1998] reconstructed the December through February NAO_{SLP} index of [*Rogers,* 1984] for the period A.D. 1701-1980 based on tree ring width records from North America and Europe (Figure 1, triangles).

3.2. D'Arrigo Reconstruction

D'Arrigo and Cook [1997] reconstructed December through March SST change associated with the NAO for the period A.D. 1701-1979 based on tree ring width records from North America, Europe, and the eastern Mediterranean (Figure 1, squares) as well as the updated historical central England temperature record [*Bradley and Jones,* 1993]. The instrumental NAO_{SST} index used in calibration was that of *Cullen and de-Menocal* [2000b].

3.3. Appenzeller Reconstruction

Appenzeller et al. [1998] reconstructed an annual (April-April) NAO_{SLP} index for the period A.D. 1650-1980 based on a record of Greenland ice accumulation (Figure 1, stars). The instrumental NAO_{SLP} index used in calibration was that of *Hurrell* [1995]. This reconstruction has been smoothed using a 5-point binomial filter.

3.4. Mann Reconstruction

Mann [2000] produced an October through March NAO_{SST} reconstruction for the period A.D. 1750-1980 based on multiproxy and instrumental data (global in distribution but including many from the North Atlantic sector most relevant to the NAO (Figure 1, circles). This index was derived by first using the *Jones et al.* [1997] cold season (October-March) NAO_{SLP} index to calibrate an NAO_{SST} series from the twentieth century instrumental surface temperature data used by *Mann* [2000]. An NAO_{SST} reconstruction was then formed from the pre-twentieth century proxy-based surface temperature reconstructions of *Mann* [2000], using nineteenth century Jones NAO_{SLP} for conservative verification of the reconstructed NAO_{SST} index prior to the twentieth century.

Both the D'Arrigo and Mann series include some instrumental and/or historical data, which may inflate the calibration/verification statistics due to the statistical dependence between the predictor (proxy and a few instrumental series) and predictand (instrumental) NAO series. Therefore we also present results for alternative versions of these two reconstructions, which are based only on proxy data (M2 and D2) in the tables below.

4. Relationships Among the Individual Reconstructions

4.1. Spatial Response

Plate 1 presents the Atlantic sector climate signature of the NAO with respect to SLP, SST, and SAT (the respective data are from *Kaplan et al.* [2000], *Kaplan et al.* [1998], and *Baker et al.* [1995]. The response of SLP, SST, and SAT to a $\pm 2\sigma$ change in the NAO was calculated by means of linearly regressing SLP, SST, and SAT against the *Hurrell* [1995] NAO_{SLP} index. All data were normalized prior to analysis, and the slope of the line was then multiplied by 2 to obtain the $\pm 2\sigma$ response. A $\pm 2\sigma$ deviation was chosen in order to capture most of the NAO-related variability. Plate 1 shows the associated spatial response to a $\pm 2\sigma$ in the NAO, which is in the range of ±2° C (SAT), ±0.5° C (SST), and 1.0 mbar (SLP). Northern Europe and Scandinavia show cooling (warming) during a negative (positive) NAO year, while western Greenland, the Mediterranean, and Turkey show warming (cooling). Plate 1 is then used as a means of comparing the performance of subsequent NAO reconstructions.

4.2. Intercorrelations

Table 1 provides a listing of the NAO indices, both instrumental and proxy-based, as well as the abbreviations used herein. The "target" index refers to the instrumental NAO index against which each of the reconstructions is calibrated. Table 2 summarizes the intercorrelations between the individual reconstructions and the composite indices. Table 3 presents correlations between the individual NAO reconstructions and several of the most common instrumental NAO indices. The last four columns of Table 3 provide correlations with independent instrumental data related to the NAO over the period 1840-1873, an interval not used by any of the reconstructions for calibration purposes. The time series data used in these latter comparisons are Bergen, Norway, SAT (B), a Bermuda-Iceland index (BI), and the *Jones et al.* [1997] NAO_{SLP} index (J1 and J3). All date back reliably to ~ 1840.

Plate 2 presents the winter (December through March) average response of SLP, SST, and SAT to a 2σ change in each of the four individual NAO reconstructions, with the goal of expressing the comparative performance of each reconstruction to that of the *Hurrell* [1995] NAO_{SLP} index shown in Plate 1. The lower right-hand corner of Plates 2a-d presents the reconstructed time series and its respective "target" index.

All four reconstructions show quite similar SST patterns, but the differences are more pronounced when looking at the SLP projections. For example, the *Mann* [2000] reconstruction captures the southern extent of the Azores High SLP pattern shown in Plate 1 very well compared to the other reconstructions, perhaps because of the fact that the *Mann* [2000] reconstruction includes proxy data representation (tree rings) from as far south as Morocco. Certain indices tend to emphasize north-south North Atlantic circulation

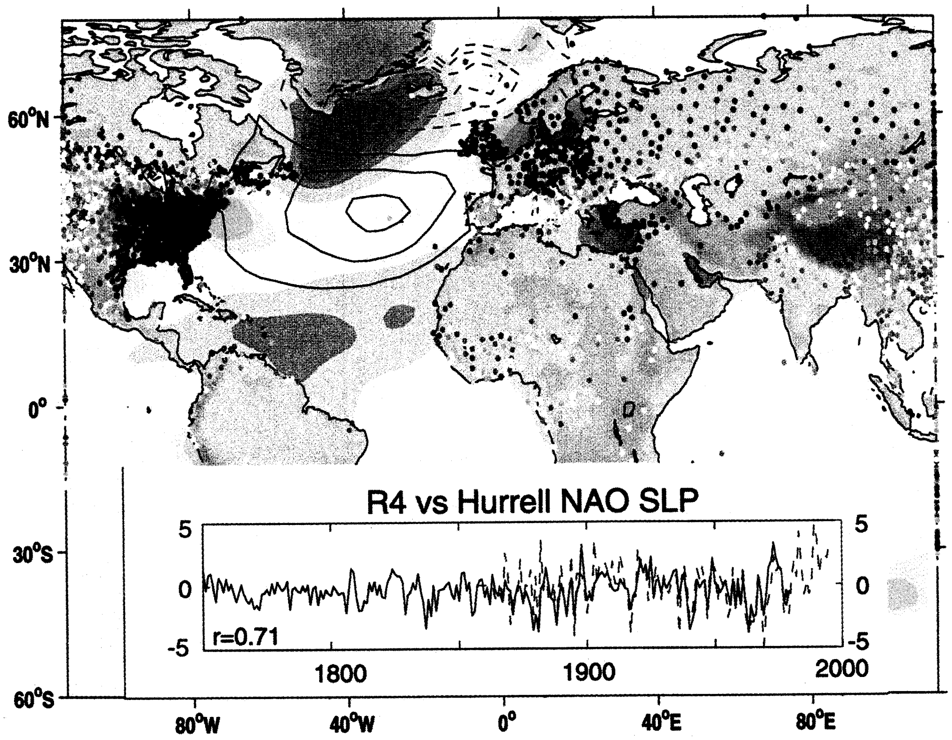
Table 1. Listing of All Indices and Abbreviations[a]

	Proxy			
	Reconstruction	Target	Source	Length
M	*Mann* [2000]	*Jones et al.* [1997]	multiproxy/instrumental	1750-1995
M2	*Mann* [2000]	*Jones et al.* [1997]	multiproxy/instrumental	1750-1995
A	*Appenzeller et al.* [1998]	*Hurrell* [1995]	ice cores	1650-1998
D	*D'Arrigo et al.* [1993]	*Cullen and deMenocal* [2000b]	tree rings/instrumental	1701-1979
D2	*D'Arrigo et al.* [1993]	*Cullen and deMenocal* [2000b]	tree rings	1701-1979
C	*Cook et al.* [1998]	*Rogers* [1984]	tree rings	1701-1979
R4	multiproxy	*Hurrell* [1995]	multiproxy/instrumental	1750-1979
R3	multiproxy	*Hurrell* [1995]	multiproxy/instrumental	1701-1979
R42	multiproxy	*Hurrell* [1995]	multiproxy	1750-1979
R32	multiproxy	*Hurrell* [1995]	multiproxy	1701-1979
	Instrumental			
	Index	Season	Field	Length
H1	*Hurrell* [1995]	Dec.-Mar.	SLP	1864 to present
H2	*Hurrell* [1995]	Apr.-Mar.	SLP	1864 to present
C1	*Cullen and deMenocal* [2000b]	Dec.-Mar.	SST	1856 to present
J1	*Jones et al.* [1997]	Dec.-Feb.	SLP	1821 to present
J2	*Jones et al.* [1997]	Oct.-Mar.	SLP	1821 to present
J3	*Jones et al.* [1997]	Apr.-Mar.	SLP	1821 to present
R1	*Rogers* [1984]	Dec.-Feb.	SLP	1864 to present
R2	*Rogers* [1984]	Jan.-Dec.	SLP	1864 to present
AO	*Thompson and Wallace* [1998]	Nov.-Apr.	800 mb	1864 to present
B	Bergen, Norway	Dec.-Feb.	SAT	1816 to present
B1	Bermuda-Iceland	Dec.-Feb.	SLP	1840 to present

[a] The term "target" below refers to the instrumental NAO index against which each of the reconstructions is calibrated.

R4 NAO Reconstruction

a.)



R42 NAO Reconstruction

b.)

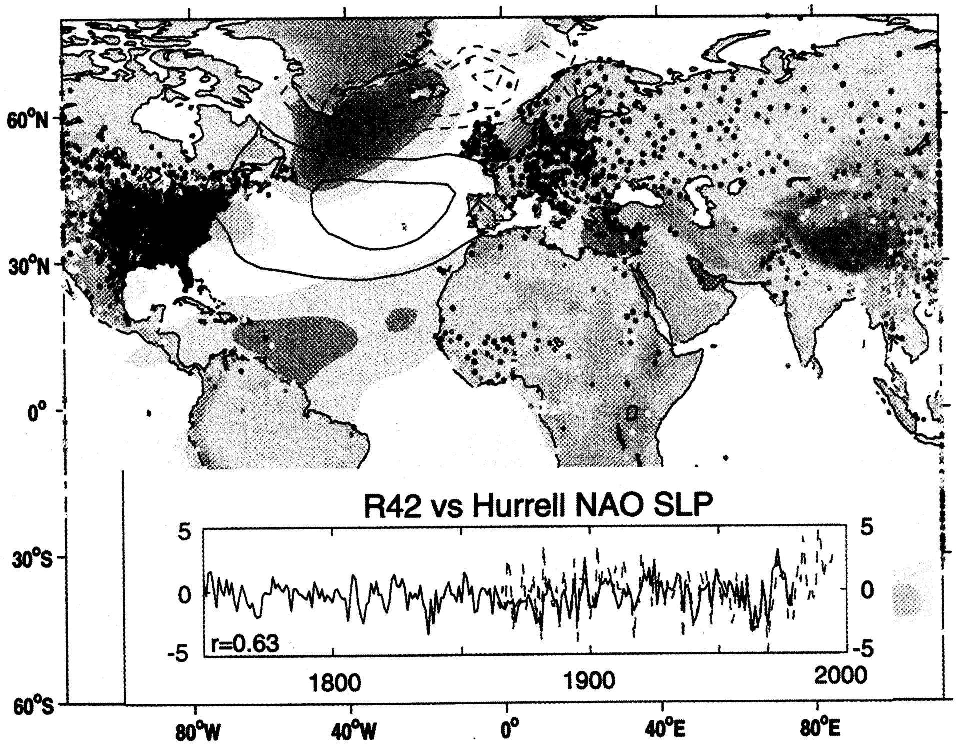


Plate 3. Spatial response maps of winter (December-March) SLP, SST, and SAT to a 2σ change in the (a) R4 reconstruction NAO index and (b) R42 reconstruction NAO index. The respective data are from *Kaplan et al.* [2000], *Kaplan et al.* [1998], and *Baker et al.* [1995].

Table 2. Correlations Between the Four NAO Reconstructions and the New Multiproxy Reconstructions (1874-1979)

	M	M2	A	D	D2	C	R4	R3	R42	R32
M	1.00	0.62	0.27	0.54	0.53	0.45	0.75	0.56	0.65	0.53
M2	···	1.00	0.08	0.26	0.21	0.16	0.38	0.22	0.44	0.20
A	···	···	1.00	0.38	0.28	0.26	0.58	0.55	0.53	0.45
D	···	···	···	1.00	0.91	0.58	0.86	0.88	0.81	0.81
D2	···	···	···	···	1.00	0.72	0.84	0.88	0.87	0.91
C	···	···	···	···	···	1.00	0.78	0.86	0.84	0.92
R4	···	···	···	···	···	···	1.00	0.95	0.96	0.92
R3	···	···	···	···	···	···	···	1.00	0.95	0.97
R42	···	···	···	···	···	···	···	···	1.00	0.95
R32	···	···	···	···	···	···	···	···	···	1.00

anomaly patterns (e.g., Appenzeller), while others emphasize a more southwest-northeast North Atlantic circulation anomaly pattern (e.g., D'Arrigo). This reflects the fact that there is more than one spatial degree of freedom to interannual and longer timescale circulation anomalies in the North Atlantic, suggesting that different indices tend to emphasize different combinations of the north-south and east-west degrees of freedom in SLP variations. The Appenzeller series does not capture the SAT pattern as well as the other reconstructions, possibly because it is based on data from only one site. Thus the individual reconstructions each have their strengths and weaknesses with regard to their ability to faithfully reproduce the large-scale patterns observed in the instrumental record.

5. "Composite" NAO Reconstructions

In anticipation that a linear combination of the individual reconstructions would improve calibration with instrumental NAO indices, we entered the four individual reconstructions into a principal components regression (PCR) [*Cook and Kairiukstis,* 1990]. In PCR the number of predictors is reduced by substituting a set of uncorrelated but equivalent variables, or principal components, prior to regression [*Cook and Kairiukstis,* 1990]. To examine the potential frequency domain strengths and weaknesses of different predictors, we included both low- and high-pass filtered versions of the four individual series as potential predictors in the PCR analysis.

Composite reconstructions were developed for each of the target instrumental NAO_{SLP} and NAO_{SST} indices listed in Table 1. However, for brevity, we focus below on the widely used *Hurrell* [1995] NAO_{SLP} index. Two sets of composite reconstructions were produced, one based on all four individual series (1750-1979, R4) and the other based on only three, excluding the shorter Mann reconstruction (1701-1979, R3). The spatial response plot for the R4 reconstruction is shown in Plate 3a, while Plate 3b presents the estimated composite response to a 2σ change in R42. Overall, the R4 composite pattern resembles the *Hurrell* [1995] NAO_{SLP} (Plate 1) somewhat more closely than the individual series shown in Plates 2a-d and the noninstrumental composite shown in Plate 3b.

As indicated in Tables 2 and 3, both R4 and R3 exhibit correlations which are in general improved relative to the individual series, with R4 performing moderately better than R3. R4 and R3 are further evaluated using statistical tests commonly used to verify dendroclimatic reconstructions [*Cook and Kairiukstis,* 1990] (Table 4). Table 4 demonstrates that the composite series with instrumental data (R4/R3) outperform the composite series without instrumental data (R42/R32). These statistics further validate the usefulness of the composite reconstructions and are an improvement over the statistics for the individual reconstructions. Although not directly comparable, the levels of variance accounted for in the composite reconstruction models appear to be as good or better than those for the individual series. For example, the model of *Cook et al.,* [1998] accounted for 41% of the variance in the Rogers instrumental NAO, whereas the composite R4/R3 series resolved 56% for this variable (R1 in Table 4; the time period for which the variance is calculated differs slightly).

The comparisons with early instrumental data (1840-1873) in Table 3 provide an additional independent means of verification of the various reconstruction models. In general, the composite series show higher correlations than the individual records in this comparison, particularly for R4/R3, which include some instrumental data. The composite series are further evaluated using statistical tests routinely employed to verify dendroclimatic reconstructions [*Cook and Kairiukstis,* 1990] (Table 4). Table 4 demonstrates that the composite series which include instrumental data (R4/R3) outperform those without instrumental data (R42/R32). They further suggest that there is useful and nonoverlapping information in each of the individual NAO reconstructions, such that when combined, they produce more robust estimates of the preinstrumental behavior of the

Table 3. Correlations Between the NAO reconstructions and Instrumental NAO and AO data (1874-1979)[a]

	H1	H2	C1	J1	J2	J3	R1	R2	AO	B	BI	J1	J3
M	0.59	0.37	0.65	0.53	0.55	0.43	0.55	0.58	0.42	0.62	0.42	0.38	0.22
M2	0.38	0.19	0.38	0.31	0.34	0.29	0.30	0.30	0.29	0.24	0.22	0.36	0.18
A	0.40	0.65	0.42	0.39	0.34	0.41	0.46	0.49	0.14	0.06	0.00	-0.10	-0.09
D	0.59	0.55	0.71	0.63	0.56	0.54	0.63	0.55	0.50	0.46	0.41	0.51	0.19
D2	0.50	0.45	0.64	0.52	0.46	0.42	0.61	0.53	0.43	0.31	0.19	0.21	0.04
C	0.60	0.33	0.49	0.56	0.54	0.40	0.64	0.62	0.39	0.31	0.36	0.40	0.21
R4	0.72	0.62	0.75	0.70	0.66	0.58	0.76	0.74	0.49	0.65	0.33	0.50	0.27
R3	0.69	0.57	0.70	0.69	0.64	0.57	0.75	0.70	0.49	0.47	0.25	0.37	0.21
R42	0.66	0.57	0.69	0.62	0.59	0.51	0.73	0.70	0.45	0.39	0.26	0.35	0.16
R32	0.63	0.49	0.64	0.62	0.57	0.50	0.71	0.67	0.45	0.37	0.20	0.27	0.12

[a] The last four columns show the correlations with independent early instrumental data for 1840-1873.

NAO. The above comparisons suggest that the composite series are generally superior in their estimation of the NAO relative to the individual reconstructions.

Figure 2 presents the two composite reconstructions for the *Hurrell* [1995] NAO_{SLP}, which correlate at $r = 0.95$ (1750-1979). While we consider these R4/R3 composite reconstructions to be more optimal estimates of the NAO, we readily note that the inclusion of instrumental data in the reconstructions tends to positively bias the verification statistics, though improving the statistical model. Hence we provide statistics in Tables 1-3 for the individual Mann and D'Arrigo reconstructions without instrumental data (M2 and D2) as well as for composite reconstructions based solely on proxy data (R42 and R32). Because our goal is to develop the most faithful long-term NAO reconstructions possible, we focus for the rest of this paper on those composite reconstructions which include instrumental data, specifically on R4, which was found to be moderately better than R3.

5.1. Spectral Analysis of Composite Reconstruction

Next, we evaluated the frequency domain properties of the R4 composite NAO reconstruction. We employed the multitaper method (MTM) of spectral analysis, which has several advantages over single-taper methods including reduced bias from data leakage and better tradeoff between spectral resolution and statistical variance [*Thomson*, 1982; *Percival and Walden*, 1993; *Mann and Lees*, 1996]. We used the robust noise estimation and significance determination procedure of *Mann and Lees* [1996] to isolate spectral peaks which are significant relative to the null hypothesis of red noise.

The power spectrum of the R4 series captures the characteristic band-limited variability seen in the *Hurrell* [1995] NAO_{SLP} over the common period 1874-1979. Both the instrumental (Figure 3a) and reconstructed (Figure 3b) series show only one significant (99% level)

Table 4. Calibration (1900-1979) and Verification (1873-1899) Statistics for Composite Reconstructions Based on First Differenced Data[a]

	R3/R4 Reconstruction				R32/R42 Reconstruction			
	Calibration	Verification			Calibration	Verification		
	aR^2	r	RE	ST	aR^2	r	RE	ST
H1	0.49	0.78	0.57	23/2	0.46	0.75	0.47	22/3
H2	0.57	0.64	0.38	16/9	0.45	0.52	0.25	19/16
C1	0.45	0.68	0.46	19/6	0.46	0.61	0.36	19/6
J1	0.49	0.78	0.58	24/2	0.41	0.75	0.53	22/3
J3	0.25	0.80	0.52	19/6	0.21	0.77	0.48	21/4
R1	0.56	0.79	0.60	22/3	0.52	0.75	0.51	19/6
R2	0.43	0.74	0.47	20/5	0.45	0.77	0.49	19/6
AO	0.29	0.58	0.34	21/4	0.25	0.52	0.27	21/4

[a] Data are from [*Cook and Kairiukstis*, 1990]. Results are identical for R3 and R4, which are highly correlated at $r = 0.95$. Here aR^2 is variance resolved and r is Pearson correlation coefficient. Positive values of the RE (Reduction of Error) statistic indicate skill in the model estimates [*Fritts*, 1976; *Cook and Kairiukstis*, 1990]. The sign test (ST) tracks the number of times the proxy-based estimates are in agreement with the meteorological data on the direction of change from year to year [*Fritts*, 1976].

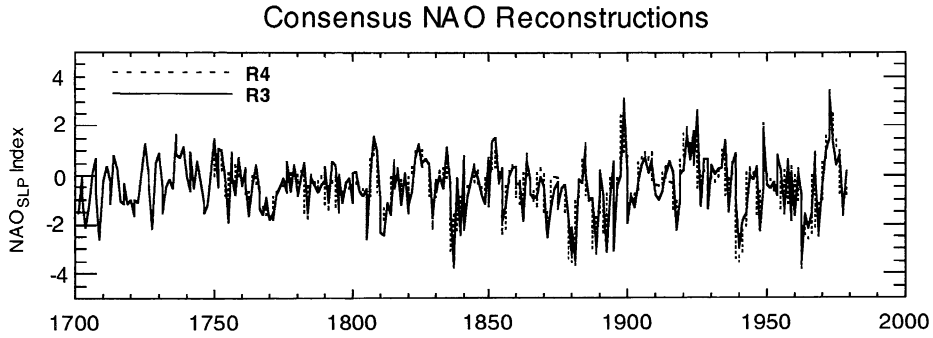


Figure 2. The two composite reconstructions, R4 (1750-1979) and R3 (1701-1979), for the *Hurrell* [1995] NAO_{SLP} series, which correlate at 0.95 over 1750-1979.

spectral peak at 2.3 years. This peak is likely associated with the quasi-biennial oscillation (QBO) [*Saravanan,* 1990]. The full instrumental record from 1874-1995 (which includes the recent decades of pronounced trend) exhibits statistically significant (95-99% level) spectral power concentrated in narrow frequency bands around 2.3 (QBO), 7-8 years (possible Pacific-Atlantic connection; Figure 3c). The 2.3 and 7-8 year peaks are also present and significant (99% level) in the R4 series over the full 1750-1979 interval. Also exceeding the 99% level is a peak centered on 12.5 years. This peak may relate to a dominant mode of Atlantic variability believed to be driven by coupled tropical ocean-atmosphere dynamics [*Black et al.,* 1999].

The low-frequency (70 year) mode is not present in R4 from 1750 to 1979 or in the instrumental record from 1874 to 1995. Both *Cook et al.* [1998] and *Appenzeller et al.* [1998] had observed a low frequency (70 year) feature in their individual reconstructions but only when the instrumental period (since 1874) was included in their analyses. *Stockton and Glueck* [1999] also reported a spectral peak in the 60-70 year range in their 550 year reconstruction, although it is not clear whether it is robust over this entire interval. In contrast, a 50-70 year pattern of North Atlantic variability is robust in the instrumental record [*Schlesinger and Ramankutty,* 1994; *Mann and Park,* 1994] and over several centuries in long-term NH climate proxy data [*Mann et al.,* 1995,1998], and is observed in millennial reconstructions of NH mean annual surface temperature [*Mann et al.,* 1999]. The presence of a 70 year term in some NH climate series and not in others is not necessarily contradictory. *Delworth and Mann* [2000] have shown that robust multidecadal oscillatory climate

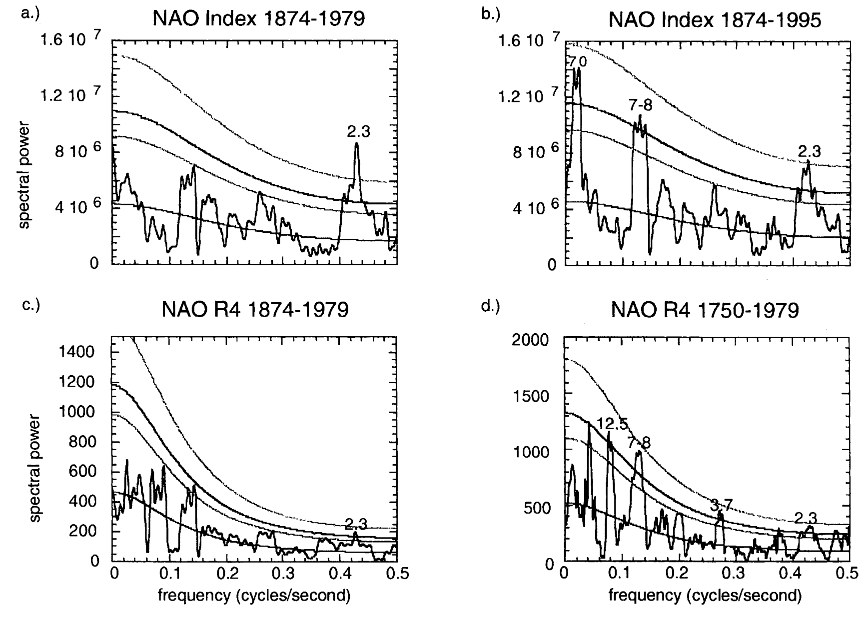


Figure 3. Multitaper spectral analysis results of the *Hurrell* [1995] December-March NAO_{SLP} index over the periods (a) 1874-1979 and (b) 1874-1995 and R4 over the periods (c) 1874-1979 and (d) 1750-1979. The respective confidence limits are 90, 95, 99, and 99.9%.

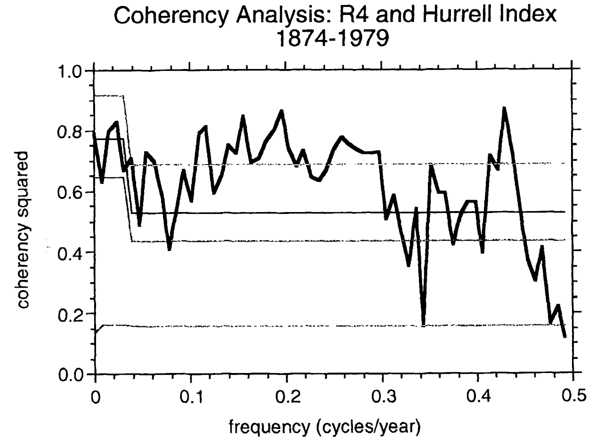


Figure 4. Coherency analysis using five 4π tapers of a) the *Hurrell* [1995] NAO_{SLP} index over the periods 1874-1979 and b) 1874-1995; c) R4 over the periods 1874-1979 and d) 1750-1979.

behavior in both model and observations is associated with ocean-atmosphere processes in the North Atlantic that project onto an NAO pattern only at certain phases of the signal evolution and then only during the cold season. In this sense, the NAO may not be a good characterization of the dominant mode of multidecadal natural variability in the North Atlantic [*Delworth et al.*, 1993;1997]. It is worthy of note that *Mann et al.* [1995] provide evidence suggesting that the strong secular trends of the twentieth century act to complicate the identification of multidecadal oscillatory behavior in climate during precisely this interval of time. Indeed, the signal separation of multidecadal oscillatory variability from secular trend during the twentieth century is highly nontrivial and cannot be accomplished by the analysis of single time series, requiring instead the analysis of climate fields [*Mann and Park,* 1994;1996].

5.2. Coherency Analysis of Composite Reconstruction

MTM coherency analysis [*Mann and Lees,* 1996] was also performed to compare the R4 series to the *Hurrell* [1995] NAO_{SLP} for the 1874-1979 common interval. Results (Figure 4) indicate that there is broad and highly significant coherency at interannual to decadal timescales. The coherency drops significantly near the Nyquist frequency, which may indicate differences between the two records at unresolved seasonal or shorter timescales that are aliased owing to the annual sampling. These coherency results are very encouraging and strongly suggest that the reconstruction is faithfully capturing the intrinsic interannual to decadal variability of the NAO.

6. NAO Variability

We used the R4 series to evaluate whether persistent positive or negative excursions in the NAO, comparable in length to those of recent decades, have occurred previously. The longest excursion of consistently positive values in the instrumental NAO series is 8 years (1988-1995). By comparison, the longest such positive interval in the reconstruction is only 6 years (1823-1828). The most persistent negative excursion in the instrumental record is 5 years (1915-1919); there is a 20 year interval of negative values in the R4 series, from 1864 to 1883.

The improved composite reconstructions can be used to evaluate how the nature of the NAO has varied over the past several centuries, possibly due to anthropogenic influences. As one means of evaluating possible changes in variability of the NAO, we calculated the standard deviation of R4 for both the preinstrumental (1750-1873) and instrumental calibration periods (1874-1979; Table 5). An increase in variance by ~ 30% is seen when comparing the two intervals despite the fact that the recent decades of strong positive trend are not included in the comparison. An increase in standard deviation in the recent period is also indicated in the R3, R42, and R32 series (Table 5).

Grassl [1997] had noted that the amplitude of decadal variability associated with the NAO appears to have increased in recent decades. Our analysis of the SD of the composite series suggests that the variability of the NAO has increased from 1750-1979, despite the fact that recent decades are excluded from this interval. Evaluation of the R3 series also suggests that the level of persistence in the recent period has been equalled or exceeded previously for negative departures but not for positive departures. Whether this apparent increase in NAO variability and persistent nature of positive recent trend are related to the anthropogenic increase in trace gases is still to be determined [*Kerr,* 1999].

Two other reconstructions of the NAO have recently been developed [*Stockton and Glueck,* 1999; *Luterbacher et al.,* 1999]. The first, a reconstruction of the NAO_{SLP} index based on tree ring records from Mo-

Table 5. Standard Deviation (s.d.) of the Four Reconstructions Over Selected Time Intervals

R4		R3		R42		R32	
Period	s.d.	Period	s.d.	Period	s.d.	Period	s.d.
1701-1979	1.16	1750-1979	1.13	1701-1979	1.09	1750-1979	1.03
1701-1873	0.90	1750-1873	0.98	1701-1873	0.95	1750-1979	0.93
1874-1979	1.40	1874-1979	1.34	1874-1979	1.24	1750-1979	1.17

rocco and Finland as well as Greenland ice core data, extends over 550 years [*Stockton and Glueck,* 1999]. The authors found that periods of consistently high or low index values in their reconstruction were comparable in length to those of the instrumental period. However, they note that extremes seen in the recent record were unmatched in magnitude (if not in persistence) and hence might be considered unique. An important consideration, however, is that such underestimation is typical of tree ring and other proxy reconstructions. The second combines instrumental station pressure, temperature, and precipitation measurements as well as proxy data to statistically reconstruct monthly time series of the NAO index back to 1675. Wavelet analysis suggested significant low-frequency variability, especially for the spring, summer and annual averaged indices.

7. Discussion

The "multiproxy" means of climate field reconstruction [*Bradley and Jones,* 1993; *Mann et al.,* 1998b], such as is described in the present study, seeks to combine instrumental data with complementary time and frequency-domain attributes. On the basis of the analyses presented herein we consider the new composite reconstructions to be improved over the individual series previously available. One likely explanation is that there is independent information within each of the individual series. In addition, the composite reconstructions may reduce a portion of the noise inherent to each individual series, thereby yielding better reconstructions. As demonstrated, the best models were obtained when the proxy and long instrumental series were combined.

Recently, some doubts have been raised by *Schmutz et al.* [2000] concerning the value of proxy-based estimates of the winter NAO index produced by different researchers using tree ring and ice core data. Among the proxy records examined were those of *Appenzeller et al.* [1998] and *Cook et al.* [1998] used in this study. To demonstrate their case, *Schmutz et al.* [2000] compared the proxy NAO index reconstructions with one produced by *Luterbacher et al.* [1999] based on long instrumental climate records from western Europe. These proxy and nonproxy NAO index reconstructions were then compared with the extended Iceland-Gibraltar winter NAO index produced by *Jones et al.* [1997] back to 1824 using early pressure data. In so doing, *Schmutz et al.* [2000] showed that the Luterbacher reconstruction agreed much better with the Jones index than did any of the proxy-based reconstructions. The loss of skill in the proxy series prior to 1850 was attributed to nonstationarity in the relationships between the proxies and the NAO. Thus *Schmutz et al.* [2000] cast serious doubt on the validity of the proxy-based NAO index reconstructions examined by them, including those used here. There are reasons to suspect that the analyses of *Schmutz et al.* [2000] were inadvertantly biased toward the results described therein. It would be expected that the Luterbacher NAO index reconstruction, based on western European instrumental data, is most highly correlated with the Iceland-Gibraltar index because of the close proximity of these records in a well-correlated climate space. In contrast, the proxy-based reconstructions of the NAO index examined by them included ice core data from Greenland and tree ring data from eastern North America and Morocco. These proxies potentially contain additional climate information on NAO variability not found in the western European records used by *Luterbacher et al.* [1999]. In addition, it is not clear that the NAO index based on Iceland-Gibraltar is an unbiased expression of the spatial teleconnectivity of the NAO over that portion of the North Atlantic sector containing the proxies. This point was indirectly raised by *Deser,* [2000, p. 782], who stated that the traditional two-station index used (Iceland-Azores in her case) was "not the optimal representation of the spatial pattern associated with it." We do not claim that the results of *Schmutz et al.* [2000] are necessarily wrong. Rather, we feel that any conclusions drawn from their results vis-á-vis trusting proxy-based NAO index reconstructions need to be carefully weighed against the more spatially complete information that such proxy records may contain. More work needs to be done to improve the proxy-based reconstructions. However, until these issues of bias and spatial completeness are resolved, it is premature to accept the Luterbacher NAO index reconstruction as the reference series for "long-term testing of proxy-based indices on the monthly to decadal timescales," as advocated by *Schmutz et al.* [2000, p. 137].

Overall, this method presents a promising approach for obtaining improved reconstructions of the NAO and other key climate indices. Future work will include comparison with model integrations of the NAO [*Osborn et al.,* 2000]. In general, more, long time series data of high resolution and quality are needed to successfully develop longer reconstructions. This is especially true in data-poor, yet climatically sensitive areas such as the Middle East.

8. Conclusions

We have presented multiproxy composite reconstructions of the NAO, extending as far back as A.D. 1701. Statistical evaluations suggest that these combined series are improved over the four individual reconstructions previously available, with the R4 series performing moderately better (albeit shorter) than the R3 series. These reconstructions, based on combined proxy and long instrumental data, were found to provide the best results in our analyses. Evaluation of the improved reconstructions suggest that the variability of the NAO may have increased over the past several hundred years, and that the length of the period of consistently high NAO values seen in the instrumental record of recent decades may exceed those reconstructed for the past several centuries.

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References

Alheit, J., and E. Hagen, Long-term climate forcing of European herring and sardine populations, *Fish. Oceanogr., 6,* 130-139, 1997.

Appenzeller, C., T.F. Stocker, and M. Anklin, North Atlantic Oscillation Dynamics Recorded in Greenland ice cores, *Science, 282,* 446-449, 1998.

Baker, C.B., J.K. Eischeid, T.R. Karl, and H.F. Diaz, The quality control of long-term climatological data using objective data analysis, paper presented at Ninth Conference on Applied Climatology, Am. Meteorol. Soc., Dallas, Tex., Jan. 15-20, 1995.

Beniston, M., Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings, *Clim. Change, 36,* 281-300, 1997.

Black, D.E., L.C. Peterson, J.T. Overpeck, A. Kaplan, M.N. Evans, and M. Kashgarian, Eight centuries of North Atlantic ocean atmosphere variability, *Science, 286,* 1709-1713, 1999.

Bradley, R.S., and P.D. Jones, Little Ice Age summer temperature variations: Their nature and relevance to recent global warming trends, *Holocene, 3,* 367-376, 1993.

Cook, E.R., and L. Kairiukstis, *Methods of Dendrochronology,* 1st ed., Kluwer Acad., Norwell, Mass., 1990.

Cook, E.R., R.D. D'Arrigo, and K.R. Briffa, The North Atlantic Oscillation and it's expression in circum-Atlantic tree-ring chronologies from North America and Europe, *Holocene, 8,* 9-17, 1998.

Cullen, H.M., and P.B. deMenocal, North Atlantic influence on Tigris-Euphrates streamflow, *Int. J. Climat., 20,* 853-863, 2000a.

Cullen, H.M., and P.B. deMenocal, North Atlantic influence on Middle Eastern climate and water supply: An analysis using an SST-based NAO index, *Clim. Change,* in press, 2000b.

D'Arrigo, R.D., and E.R. Cook, North Atlantic sector tree-ring records and SST variability, paper presented at Meeting on Atlantic Climate Variability, Lamont-Doherty Earth Obs., Palisades, NY, 10964, 1997.

D'Arrigo, R.D., E.R. Cook, G.C. Jacoby, and K.R. Briffa, NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector, *Quat. Sci. Rev., 12,* 431-440, 1993.

Delworth, T.L., and M.E. Mann, Observed and Simulated Multidecadal Variability in the Northern Hemisphere *Clim. Dyn., 16,* 661-676, 2000.

Delworth, T.L., S. Manabe, and R.J. Stouffer, Multidecadal climate variability in the Greenland Sea and surrounding regions: A coupled model simulation, *Geophys. Res. Lett., 24,* 257-260, 1997.

Delworth, T., S. Manabe, and R.J. Stouffer, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, *J. Climate, 6,* 1993-2011, 1993.

Deser, C., On the teleconnectivity of the "Arctic Oscillation", *Geophys. Res. Lett., 27,* 779-782, 2000.

Fritts, H., *Tree Rings and Climate,* 1st ed., Academic, San Diego, Calif., 1976.

Fromentin, J.M., and B. Planque, Calanus and environment in the eastern North Atlantic: Influence of the North Atlantic Oscillation on C-finmarchicus and C-helgolandicus, *Mar. Ecol. Prog. Ser., 134,* 111-118, 1996.

Grassl, H., A research program on climate variability and prediction for the 21st century, World Climate Research Program, *CLIVAR,* Hamburg, 1997.

Hurrell, J.W., Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation, *Science, 269,* 676-679, 1995.

Hurrell, J.W., Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature, *Geophys. Res. Lett., 23,* 665-668, 1996.

Hurrell, J.W., and H. Van Loon, Decadal Variations in Climate Associated with the North Atlantic Oscillation, *Clim. Change, 36,* 301-326, 1997.

Jones, P.D., T. Jonsson, and D. Wheeler. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and southwest Iceland *Int. J. Climatol., 17,* 1433-1450, 1997.

Kaplan, A., M.A. Cane, Y. Kushnir, A.C. Clement, M.B. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1956-1991, *J. Geophys. Res., 103,* 18567-18589, 1998.

Kaplan, A., Y. Kushnir, and M.A. Cane, Reduced space optimal interpolation of historical marine sea level pressure: 1854-1992, *J. Clim., 13,* 2987-3002, 2000.

Kerr, R.E., A new force in high-latitude climate, *Science, 284,* 241-242, 1999.

Luterbacher, J., C. Schmutz, D. Gyalistras, and E. Xoplaki, and H. Wanner, Reconstruction of monthly NAO and EU indices back to AD 1675, *Geophys. Res. Lett., 26,* 2745-2748, 1999.

Mann, M.E., Large-scale climate variability and connections with Middle East during the past few centuries, *Clim. Change,* in press, 2000.

Mann, M.E., and J.M. Lees, Robust estimation of background noise and signal detection in climatic time series, *Clim. Change, 33,* 409-445, 1996.

Mann, M.E., and J. Park, Global-scale modes of surface-temperature variability on interannual to century timescales, *J. Geophys. Res., 99,* 25819-25833, 1994.

Mann, M.E., and J. Park, Joint spatiotemporal modes of surface temperature and sea level pressure variability in the Northern Hemisphere During the Last Century, *J. Clim., 9,* 2137-2162, 1996.

Mann, M.E., J. Park, and R.S. Bradley, Global interdecadal and century-scale oscillations during the past five centuries, *Nature, 378,* 266-270, 1995.

Mann, M.E., R.S.Bradley, and M.K. Hughes, Global-scale temperature patterns and climate forcing over the past six centuries, *Nature, 392,* 779–787, 1998a.

Mann, M.E., R.S. Bradley, M. K. Hughes, and P.D. Jones, Global Temperature Patterns, *Science, 280,* 2029-2030, 1998b.

Mann, M.E., R.S. Bradley, and M.K. Hughes, Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett., 26,* 759-762, 1999.

Osborn, T., K.R. Briffa, S.F. Tett, and P.D. Jones, and R.M. Trigo, Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model, *Clim. Dyn.*, in press, 2000.

Percival, D.B., and A.T. Walden, ***Multitaper Spectral Estimation. Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques,*** 1st ed., Cambridge Univ. Press, New York, 1993.

Rogers, J.C., The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere, *Mon. Weather Rev., 112,* 1999-2015, 1984.

Rogers, J.C., Patterns of low-frequency monthly sea-level pressure variability (1899-1986) and associated wave cyclone frequencies, *J. Clim., 3,* 1364-1379, 1990.

Saravanan, R., A multiwave model of the quasi-biennial oscillation, *J. Atmos. Sci., 57,* 2465-2474, 1990.

Schlesinger, M. E., and N. Ramankutty, An oscillation in the global climate system of period 65-70 years, *Nature, 367,* 723-726, 1994.

Schmutz, C., J. Luterbacher, D. Gyalistras, E. Xoplaki, H. Wanner, Can we trust proxy-based NAO index reconstructions?, *Geophys. Res. Lett., 27,* 1135-1138, 2000.

Stockton, C.W., and M.F. Glueck, Long-term variability of the North Atlantic Oscillation, paper presented at 10th Symposium on Global Change Studies, Am. Meteorol. Soc., 1999.

Thompson, D.W., and J.M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett., 25,* 1297-1300, 1998.

Thomson, D.J., Spectrum estimation and harmonic analysis, *Proc. IEEE, 70,* 1055-1096, 1982.

van Loon, H., and J.C. Rogers, The seesaw in winter temperatures between Greenland and northern Europe, Part I, Winter, *Mon. Wea. Rev., 104,* 365-380, 1978.

Walker, G.T., and E.W. Bliss, World Weather V, *Mem. R. Meteorol. Soc., 4,* 53-84, 1932.

Wallace, J.M., and D.S. Gutzler, Teleconnections in the geopotential height field during the Northern Hemisphere winter, *Mon. Weather Rev., 109,* 784-812, 1981.

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