# Multiproxy reconstructions of the North Atlantic Oscillation

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**Abstract.**

Multi-proxy ‘consensus’ reconstructions of North Atlantic Oscillation (NAO) indices are presented spanning the last three centuries. These consensus 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, ice cores) as well as long instrumental records. One consensus reconstruction based on all four series (R4) extends from 1750-1979 while another based on only three series (R3) extends from 1701-1979. Both consensus 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 consensus reconstructions, based on both proxy and long instrumental data, yield more optimal results than individual or consensus 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.

## 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 150 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*, 1997; *Cullen and deMenocal*, 1999a].

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 sea level pressure (SLP) or sea surface temperature (SST) to characterize the amplitude and phase of the NAO. In general, the indices are measures of the strength and position of maximum surface westerlies across the Atlantic and into Europe [*van Loon and Rogers*, 1978; *Rogers*, 1990]. These relatively short (130 year) instrumental time series 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 northern hemisphere circulation changes in recent decades [*Thompson and Wallace*, 1998; *Kerr*, 1999]. Regardless of the index chosen to represent this feature, extended records are essential to providing a long-term context for climate variability in the North Atlantic sector.

In this paper, we first describe four individual reconstructions of the NAO which employ tree rings, ice cores, and long instrumental data (Fig. 1). We also present results based purely on proxy data. Although these latter series exhibit significant reconstructive skill, we ultimately put forward the consensus reconstructions which also incorporate instrumental data, due to their greater resolved variance. The final consensus 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.

## Individual Reconstructions

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 Akuyreyri, 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 another 10 years. *Jones et al.* [1997] further extended the $NAO_{SLP}$ index to 1823, using early instrumental pressure observations from Gibraltar and south-west Iceland. *Cullen and deMenocal* [1999a] presented an NAO index which averages sea surface temperature (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 SOI index of the El Nino-Southern Oscillation. Coincidentally, both alternative indices for defining the phenomenon of interest (e.g. ENSO or the NAO) share about half their variance in common. **Figure 1.**

### Cook Reconstruction

*Cook et al.* [1998] reconstructed the December through February $NAO_{SLP}$ index of [*Rogers*, 1984] for the period AD 1701 to 1980 based on tree-ring width records from North America and Europe (Fig. 1a: open circles).

### D'Arrigo Reconstruction

*D'Arrigo and Cook* [1997] reconstructed December through March SST change associated with the NAO for the period AD 1701-1979 based on tree-ring width records from

North America, Europe, and the eastern Mediterranean (Fig. 1a: closed circles), as well as the updated historical Central England temperature record [see *Bradley and Jones*, 1993]. The instrumental $NAO_{SST}$ index used in calibration was that of *Cullen and deMenocal* [1999a].

### Appenzeller Reconstruction

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

### Mann Reconstruction

*Mann* [1999] produced an October through March $NAO_{SST}$ reconstruction for the period AD 1750-1980 based on multiproxy and instrumental data (global in distribution, but including many from the North Atlantic sector most relevant to the NAO (Fig. 1a: triangles)). This index was derived by first using the *Jones et al.* [1997] cold season (ONDJFM) $NAO_{SLP}$ index to calibrate an $NAO_{SST}$ series from the twentieth century instrumental surface temperature data used by *Mann* [1999]. An $NAO_{SST}$ reconstruction was then formed from the pre-20th century proxy-based surface temperature reconstructions of *Mann* [1999], using 19th century Jones $NAO_{SLP}$ for (conservative) verification of the reconstructed $NAO_{SST}$ index prior to the 20th century.

## Relationships among the Reconstructions

Figure 1b presents the global climate signature of the NAO with respect to SLP, SST, and SAT (the respective global data are from [*Kaplan et al.*, 1999, 1998; *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 $\pm 2\sigma$ (the

$\pm 2\sigma$ value of the *Hurrell* [1995] $NAO_{SLP}$ index for the time period 1864-1995 is $\pm 3.71$). A $\pm 2\sigma$ deviation was chosen in order to capture most of the NAO-related variability. Figure 1b shows the spatial extent of high response regions and with the associated response to a $\pm 2\sigma$ in the NAO in the range of $\pm 2^\circ$ C (SAT), $\pm 0.5^\circ$ C (SST), and 1.0 mb (SLP). Northern Europe and Scandinavia show cooling during a negative NAO year while, western Greenland, the Mediterranean, and Turkey, show warming. Figure 1b is then used as a means of comparing the performance of subsequent NAO reconstructions.

Table 1 summarizes the inter-correlations between the individual reconstructions. Table 2 presents correlations between the individual reconstructions and several of the most common instrumental NAO indices. Also included in Table 2 are 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 series used for this latter comparison are Bergen, Norway surface air temperature (B) and a Bermuda-Iceland index (BI) and the [*Jones et al.*, 1997]; $NAO_{SLP}$ index all date back reliably to about 1840.

As noted, 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. **Table 1.**

Figures 2a-d present the winter (December through March) average response of SLP, SST, and SAT to a $2\sigma$ 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 Figure 1b. Also presented, in the lower right-hand corner of Figures 2a-d, is the reconstructed time series compared to 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* [1999] reconstruction captures the southern extent of the Azores High SLP pattern shown in Figure 1b very well compared **Table 2.** **Figure 2.**

to the other reconstructions, due to the fact that the *Mann* [1999] reconstruction includes proxy data representation (tree rings) from as far south as Morocco. Certain indices tend to emphasize north-south North Atlantic circulation 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. **Figure 3.**

## The 'consensus' NAO Reconstructions

In anticipation that a linear combination of the individual reconstructions would improve calibration with instrumental NAO indices, we entered the four reconstructions into a principal components regression (PCR) [*Cook and Kairiukstis*, 1990]. To examine the potential frequency-domain strengths and weaknesses of different predictors, we include both low- and high-pass filtered versions of the four individual series as potential predictors in the PCR analysis.

Consensus reconstructions were initially developed for each of the 'target' instrumental $NAO_{SLP}$ and $NAO_{SST}$ indices. However, for brevity, we focus below on the widely used *Hurrell* [1995] $NAO_{SLP}$ index. Two sets of consensus reconstructions were produced, one based on all four individual series (1750-1979, R4); the other based on only three, excluding the shorter Mann reconstruction (1701-1979, R3). The spatial response plot of the R4 reconstruction is shown in Figure 3a. Figure 3b presents the estimated composite response to a 2$\sigma$ change in R42. Overall, the R4 pattern resembles the *Hurrell* [1995] $NAO_{SLP}$ (Fig.

1b) more closely than the individual series shown in Figures 2a-d and the non-instrumental composite shown in Figure 3b.

As indicated in Tables 1 and 2, both R4 and R3 exhibit correlations which are clearly 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 3). Table 3 demonstrates that the consensus series with instrumental data (R4/R3) outperform the consensus series without instrumental data (R42/32). These verification statistics further validate the usefulness of the consensus reconstructions and are an improvement over the statistics for the individual reconstructions (not shown). For example, *Cook et al.* [1998] resolves 41% of the variance, whereas R4/R3 resolves 56% (the period over which $R^2$ is calculated differs slightly).

The above comparisons suggest that the consensus series are superior in their general estimation of the NAO relative to the individual reconstructions. They further suggest that there is useful and non-overlapping information in each of the individual NAO reconstructions, such that when combined, they produce more robust estimates of the pre-instrumental behavior of the NAO. **Table 3.**

Figure 4 presents the two consensus reconstructions for the *Hurrell* [1995] $NAO_{SLP}$, **Figure 4.** which correlate at r = 0.95 (1750-1979). While we consider the R4/R3 consensus reconstructions presented here 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 almost certainly 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 consensus reconstructions based solely on proxy data (R42 and R32).

However, because our goal is to develop the most faithful long-term NAO reconstructions possible, we focus on the consensus reconstructions which include instrumental data, specifically on R4; which was found to be moderately better than R3.

The improved consensus 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 (SD) of R4 for both the pre-instrumental (1750-1873) and instrumental calibration periods (1874-1979; Table 4). An increase in variance by $\sim 30\%$ is seen when comparing the two intervals, despite the fact that the recent decades of strong positive trend are not included in the comparison. If one assumes that the amplitude in the record is stationary, this result suggests that the variance of the NAO has increased over time. An increase in SD in the recent period is also indicated in the R3, R42, and R32 series (Table 4). **Table 4.**

We then used the R4 series to evaluate whether the length of persistent positive or negative excursions in the NAO, comparable 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 six years (1823-1828). The most persistent negative excursion in the instrumental record is five years (1915-1919). There is a 20-year interval of negative values in the R4 series, from 1864-1883.

**Spectral Analysis of Consensus Reconstruction**

Next, we evaluated the frequency-domain properties of the R4 consensus NAO reconstruction. We employed the multi-taper 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 and reconstructed series show only a significant (99% level) spectral peak at 2.3 years for this interval (Fig. 5). The full instrumental record from 1874-1995 (including the recent decades of pronounced trend) exhibits statistically significant (95-99% level) spectral power concentrated in narrow frequency bands around 2.3, 7-8, and 70 years (Fig. 5). These same peaks are present and significant (95% level) in the R4 series over the full 1701-1979 interval. A roughly bi-decadal peak, previously identified in instrumental and proxy estimates of the NAO [e.g. *Rogers*, 1990; *Bradley and Jones*, 1993; *Plaut et al.*, 1995; *Hurrell and Van Loon*, 1997; *Jones et al.*, 1997; *Cook et al.*, 1998] and in globally distributed long-term climate proxy data [*Mann et al.*, 1995] is weakly significant (90% level) in R3.

As noted, a significant low frequency (70-yr) mode is present in R4 from 1750-1979 as well as in the instrumental record from 1874-1995. Both *Cook et al.* [1998] and *Appenzeller et al.* [1998] had observed that a similar low frequency feature was present in their reconstructions, but only when the instrumental period (since 1874) is included in the analysis. *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 over several centuries in long-term NH climate proxy data [*Schlesinger and Ramankutty*, 1994; *Mann et al.*, 1995, 1998a] and is observed in millennial reconstructions of the 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* [1999] have shown that robust multidecadal oscillatory climate 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 [see *Delworth et al.*, 1993, ????]. It is worthy of note that *Mann et al.* [1995] provide evidence suggesting that the strong secular trends of the 20th 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 20th century is highly non-trivial, and cannot be accomplished by the analysis of single time series, requiring instead the analysis of climate fields [*Mann and Park*, 1994, 1996]. **Figure 5.**

### Coherency Analysis of Consensus 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 (Fig. 6) indicate that there is broad and highly significant coherency at interannual to decadal time scales. 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. **Figure 6.**

## Discussion

Based on the analyses presented herein we consider the new consensus reconstructions to be considerably 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 consensus 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.

The consensus reconstructions can be used to evaluate how the NAO has varied over the past several centuries relative to the recent instrumental period. *Grassl* [1997] had noted that the amplitude of decadal variability associated with the NAO appears to have increased in recent decades [*Grassl*, 1997]. Our analysis of the SD of the consensus 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 [i.e., *Kerr*, 1999].

Another recent reconstruction of $NAO_{SLP}$, based on tree-ring records from Morocco and Finland, as well as Greenland ice core data, extends over 550 years [*Stockton and Glueck*, 1999]. They 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, perhaps, other proxy reconstructions. 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 complimentary time and frequency-domain attributes. This method presents a promising approach for obtaining improved reconstructions of the NAO and other key climate indices.

## Summary

We have presented multiproxy consensus reconstructions of the NAO, extending as far back as AD 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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## Figure Captions

**Figure 1.** a.) Location map of proxy and long instrumental records used in each of the four individual reconstructions and b.) the spatial response of winter (DJFM) SLP, SST, and SAT to a $2\sigma$ change in the *Hurrell* [1995] $NAO_{SLP}$ index.

**Figure 2.** Spatial response maps of winter (DJFM) SLP, SST, and SAT to a $2\sigma$ 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* [1999] $NAO_{SST}$ index [*Kaplan et al.*, 1999, 1998; *Baker et al.*, 1995].

**Figure 3.** Spatial response maps of winter (DJFM) SLP, SST, and SAT to a $2\sigma$ change in the a). R4 reconstruction NAO index, and b). R42 reconstruction NAO index [*Kaplan et al.*, 1999, 1998; *Baker et al.*, 1995].

**Figure 4.** The two consensus reconstructions, R4 (1750-1979) and R3 (1701-1979) for the *Hurrell* [1995] $NAO_{SLP}$ series, which correlate at 0.95 over 1750-1979.

**Figure 5.** Multitaper spectral analysis results of a). the *Hurrell* [1995] DJFM $NAO_{SLP}$ index over the periods 1874-1979 and b). 1874-1995; c). R4 over the periods 1874-1979 and d). 1750-1979

**Figure 6.** Coherency analysis (five $4\pi$ tapers were used) results 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.

# Tables

**Table 1.** Correlations between the NAO reconstructions for period 1874-1979 (unfiltered data). The term 'target' below refers to the instrumental NAO index against which each of the reconstructions is calibrated.

| | 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 |
| | PROXY | | | | | | | | | |

M is $NAO_{Mann}$ [*Mann*, 1999] using *Jones et al.* [1997] as a target.

M2 is $NAO_{App}$ [*Mann*, 1999] using *Jones et al.* [1997] as a target.

A is $NAO_{App}$ [*Appenzeller et al.*, 1998] using *Hurrell* [1995] as a target.

D is $NAO_{D'Arrigo}$ [*D'Arrigo et al.*, 1993] using *Cullen and deMenocal* [1999a] as a target.

D2 is $NAO_{D'Arrigo}$ [*D'Arrigo et al.*, 1993] using *Cullen and deMenocal* [1999a] as a target.

C is $NAO_{Cook}$ [*Cook et al.*, 1998] using *Rogers* [1984] as a target.

**Table 2.** Correlations between the NAO reconstructions and instrumental NAO and AO data for 1874-1979 (unfiltered data). The four final columns show the correlations with independent early instrumental data for 1840-1873 (see text).

| | 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 |
| | INSTR | | | | | | | | | EARLY-INSTR | | | |

H1 Hurrell winter (DJFM) $NAO_{SLP}$ from *Hurrell* [1995]

H2 Hurrell annual (Apr-Mar) $NAO_{SLP}$ (5-point smoothed) [*Appenzeller et al.*, 1998]

C1 Cullen winter (DJFM) $NAO_{SST}$ [*Cullen and deMenocal*, 1999b]

J1 Jones winter (DJF) $NAO_{SLP}$ [*Jones et al.*, 1997]

J2 Jones cold season (ONDJFM) $NAO_{SLP}$ [*Jones et al.*, 1997]

J3 Jones annual (Apr - Mar) $NAO_{SLP}$ [*Jones et al.*, 1997]

R1 Rogers winter (DJF) $NAO_{SLP}$ [*Rogers*, 1984]

R2 Rogers annual (Jan - Dec) $NAO_{SLP}$ [*Rogers*, 1984]

AO Thompson cold season (Nov - Apr) $AO_{800mb}$ [*Thompson and Wallace*, 1998]

B Bergen Winter (DJF) Temperature [*Baker et al.*, 1995]

BI Bermuda-Iceland winter (DJF) NAO (1862-65 years missing)

**Table 3.** Calibration (1900-1979) and verification (1873-1899) statistics for consensus reconstructions based on first differenced data [*Cook and Kairiukstis*, 1990]. Results are identical for R3 and R4, which are highly correlated at r = 0.95.

| | R3/R4 RECONSTRUCTION | | | | R32/R42 RECONSTRUCTION | | | |
|---|---|---|---|---|---|---|---|---|
| | CALIBRATION | VERIFICATION | | | CALIBRATION | VERIFICATION | | |
| 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 |
| | $aR^2$ | r | RE | ST | $aR^2$ | r | RE | ST |

$aR^2$= variance explained

r=Pearson correlation

RE = reduction of error

ST = Sign Test

**Table 4.** Standard deviation of the 4 reconstructions over selected time intervals.

| Period | stdev | Period | stdev | Period | stdev | Period | stdev |
|---|---|---|---|---|---|---|---|
| 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 |
| R4 | | R3 | | R42 | | R32 | |