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Reconstruction of monthly NAO and EU indices back to AD 1675

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Abstract. Instrumental station pressure, temperature and precipitation measurements and proxy data were used to statistically reconstruct monthly time series of the North Atlantic Oscillation (NAO) and the Eurasian (EU) circulation indices back to 1675. Systematic testing of the reconstruction procedure indicated generally reliable reconstructions throughout the entire period, except for summertime before about 1750. Predictive skill varied for different sub-periods depending on data availability. It was highest for autumn and winter and was generally better for the EU than for the NAO index. Wavelet analysis suggested significant low-frequency variability, especially for the spring, summer and annual averaged indices. The co-variability between the NAO and EU indices was found to exhibit large decadal to century timescale variations, indicating that climate variability over the continent is temporarily decoupled from the NAO.

Introduction

Reliable long-term reconstructions of circulation indices are of great importance for a better understanding of the low-frequency variability of the atmospheric circulation and the validation of global climate models [*WCRP*, 1998].

The North Atlantic Oscillation (NAO) presents one of the most prominent anomaly patterns in the Northern Hemisphere winter [*Wallace and Gutzler*, 1981; *Kushnir and Wallace*, 1989]. *Barnston and Livezey* [1987] showed that the NAO is the only pattern prevalent in all 12 months and that its centers of action exhibit pronounced seasonal variation. The associated circulation index correlates significantly with the NAO index provided by *Hurrell* [1995]. This suggests that pattern-based indices can be approximated by pressure differences between two geographically fixed locations. Apart from the NAO, the East Atlantic/Western Russia pattern (Eurasia-2 pattern EU2 [*Barnston and Livezey*, 1987]) is one of the most important modes for western Eurasia. The EU2 index measures the pressure difference across central Europe and thus is important in describing the variability of Eurasian climate, especially during wintertime [*Schmutz and Wanner*, 1998].

Simple instrument-based indices of the NAO behavior [*WCRP*, 1998] have been successively reconstructed back to 1865 (Lisbon-Stykkisholmur; *Hurrell* [1995]) and 1821 (Gibraltar-Reykjavik; *Jones et al.* [1997]). Based on tree-rings, *Cook et al.* [1998] reconstructed a winter NAO index back to 1701. Recently, *Stockton and Glueck* [1999] used tree-rings and ice core data for NAO index reconstructions back to the year 1429. A proxy NAO index has been reconstructed from ice accumulation records in Greenland for the past 350 years [*Appenzeller et al.*, 1998]. These reconstructions apply to the winter season or even refer to annual to multi-annual mean values, despite the fact that the variability and regional effects of the NAO show a strong annual cycle. Furthermore, the various proxy variables used in some of these studies do not resolve seasonal effects, and reflect climatic variations only over a limited range of timescales [*Jones et al.*, 1998]. To our knowledge, no attempts have been undertaken to reconstruct an EU index for previous centuries. In addition, studies about the co-variability of the NAO and EU indices are still lacking.

The aims of the present study are: i) to reconstruct monthly NAO and EU indices back to 1675; ii) to provide objective quantitative measures for the reliability of our reconstructions, and iii) to assess the low-frequency variability and co-variability of the two circulation indices in the last 315 years.

Data and Methods

Two different NAO and two EU indices were reconstructed (Fig. 1a). Each index was defined (cf. *Hurrell*, [1995]) as the difference between two standardized (1901-1980) SLP time series. With one exception (NAO2), the time series were based on SLP averaged from four adjacent gridpoints on a 5°x5° longitude-latitude grid in order to account for the (moderate) shift of the pressure centers throughout the year, and to facilitate comparison with gridded output by climate models. The individual indices were: NAO1: average of four gridpoints over the Azores minus average over Iceland; NAO2: station data from Ponta Delgada (Azores) minus Reykjavik (Iceland); EU1 and EU2: average of four gridpoints over Great Britain minus average close to the Black Sea and the Caspian Sea, respectively. The gridded monthly mean SLP data were obtained from the National Center for Atmospheric Research (NCAR) [*Trenberth and Paolino*, 1980]. The station data were taken from the NAO data web site of the Climatic Research Unit, Norwich.

The predictors were given by a large, time-varying data base[2] (Figs 1a and 1b), which included mostly instrumental station pressure, temperature and precipitation records pro-

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[2] Supporting data [tables] are available on diskette or via Anonymous FTP from agu.org, directory APEND (Username=anonymous, Password-guest). Diskette may be ordered by mail from AGU, 2000 Florida Ave., NW, Washington, DC 20009 or by phone at (800) 966-2481; $15.00. Payment must accompany order.

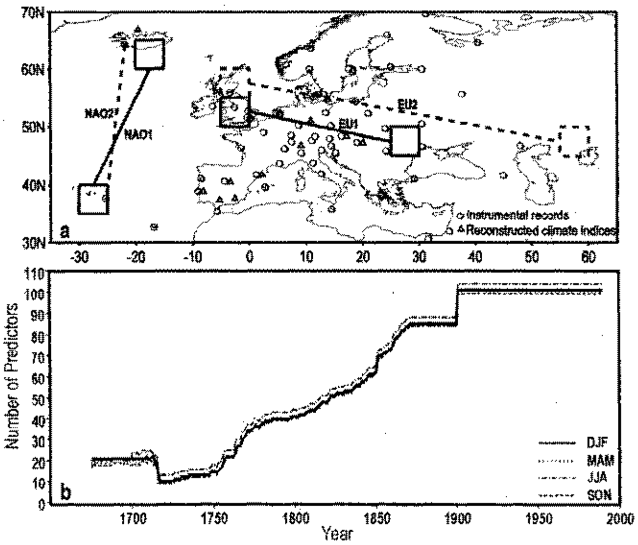

Figure 1. Shown in (a) is the geographical distribution of the data locations (predictors) and location of the four reconstructed circulation indices (predictands). In (b) we show the development over time of the number of predictors used for the reconstructions.

vided by *Vose et al.* [1992] and *Jones et al.* [1999]. For the pre-instrumental period (i.e. AD 1780), a few ordinal monthly temperature, precipitation and other paleoenvironmental indices were used. They are estimations from very high-resolution documentary proxy data such as observations of ice, snow, phenological and biological features and tree-ring data. Most of these indices were the outcome of the European project ADVICE (*Annual to Decadal Variability In Climate in Europe*) [*Jones et al.*, 1999; *Luterbacher et al.*, 1999].

The reconstruction was based on a canonical correlation analysis (CCA) [*Barnett and Preisendorfer*, 1987; *von Storch and Zwiers*, 1999] between the predictors and the four circulation indices (predictands). CCA identifies pairs of patterns and associated new, optimally correlated variables, from two multivariate data sets. The new variables are obtained by projecting the original data onto the respective patterns. CCA accounts for correlations in the predictors and/or predictands. The established relationships can be used in a linear regression model to simultaneously estimate all predictands from the predictors [*von Storch and Zwiers*, 1999]. In order to reconstruct the four index values for a given month, we first identified all predictors for which data were available for that month and all other months from the same season. This resulted in a total of 264 different cases (cf. Fig. 1b). Second, we selected a period for fitting of the CCA models: P_1 (1901-1960) or P_2 (1931-1990) for model testing, and P_3 (1901-1990) for the actual reconstruction. Third, the predictor and predictand variables were standardized separately for each month using the means and standard deviations from the respective period. Finally, CCA was performed, and all four resulting pairs of CCA-patterns were used to estimate the predictands for the target month. The quality of our reconstructions was tested by applying each of the 264 CCA-models fitted during periods P_1 and P_2 to independent data from the verification periods 1961-1990 (VP_1) and 1901-1930 (VP_2), respectively. Model performance was assessed by the coefficient of determination (r^2) and the reduction of error (RE) [*Lorenz*, 1956]. RE ranges from +1 to -∞ with RE = 0 no better than climatology, and RE = -1 no better than a random process. The r^2 and RE values were plotted against the time period for which a given CCA model was used, thus yielding for each index a time series for the quality of our reconstructions.

In order to test whether the reconstructed index time series show significant periodic oscillations we used a local wavelet spectrum analysis with a Morlet wavelet base [*Torrence and Compo*, 1998]. The analysis was restricted to the period 1760-1990, for which the most reliable reconstructions were obtained. The statistical significance of a given global wavelet power spectrum was tested against the null hypothesis that the respective index stems from a white noise process.

Results

The reconstructed NAO1 and NAO2 index time series showed a high correlation, such that here results mainly for the NAO1 index are presented. Further we will focus on the EU1 index and the winter and autumn seasons, for which the most reliable reconstructions were obtained (see also Fig. 3).

Figure 2 presents the winter and autumn mean NAO1 and EU1 indices back to 1675, as derived from the monthly reconstructions. All time series exhibit strong decadal to interdecadal variations. Sub-periods of enhanced and reduced variability can be discerned.

Figure 3 summarizes the performance of the CCA models that were fitted in P_1 and tested in VP_1. The quality of the reconstructions degraded successively prior to 1870 and, for autumn and winter only, reached a minimum in the period 1716-1750. For all seasons, generally better results were obtained for the EU1 as compared to the NAO1 index. Very similar results were obtained for P_2 and VP_2 (not shown).

The wavelet analysis showed that the dominant frequencies of the NAO1 and EU1 time series vary strongly with index and season. For the seasonal mean NAO1 index time-series significant (α=95%) power was found for spring at 19-23 and 50-68 years, and for summer at 54-88 and above 128 years. For the seasonal mean EU1 time series, significant (α=95%) power was only obtained in spring for 16-22 years and in summer for 6-7 years and 22-28 years. The annually (April to

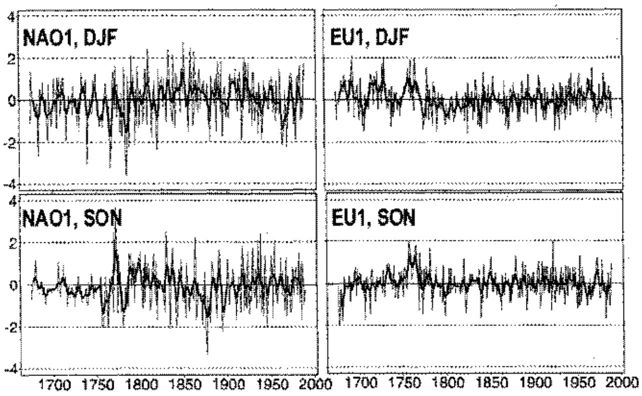

Figure 2. Normalized time series of the reconstructed NAO1 and EU1 indices. Data are winter and autumn means. Thick lines are 7 point low-pass filtered time series.

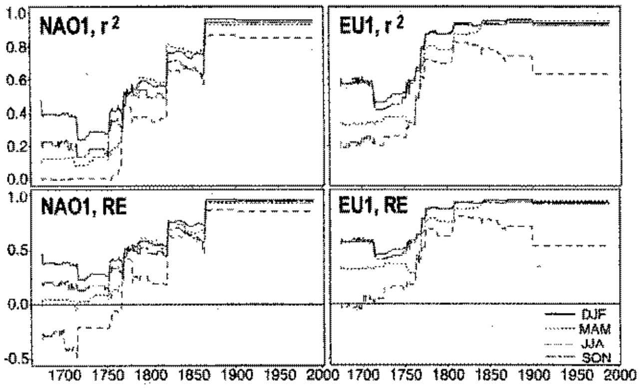

Figure 3. Seasonal CCA model performance (r^2 and RE) for the reconstructed NAO1 and EU1 indices from 1675 to 1990.

March) averaged NAO1 time series showed highly (α=99%) significant power for period lengths between 54 and 68 years.

The running 30-year correlation between the winter and autumn mean NAO1 and EU1 indices is presented in Figure 4. In both seasons, the correlations were mostly positive, suggesting that strong (weak) westerlies over the North Atlantic tend to go along with strong (weak) northerly flow over central Europe. The correlations varied strongly, however, throughout the entire 315 year period. In particular, during the years 1840-1860, the mean correlation for winter becomes slightly negative, though does not differ significantly from zero.

Discussion

The quality of our reconstructions depended on the season, and the number, quality, and spatial distribution of the predictors (cf. Figs 1 and 3). For all indices, the best results were obtained for winter, which is consistent with the greater spatial coherence of the atmospheric circulation and climate variables during the cold season. Pressure station series were found to be the most important predictors. The earliest such series was available for Paris from 1675 to 1713. Afterwards, the reconstructions became less reliable, until the next pressure series (1755, Basel; Switzerland) was included. The generally better performance for the EU1 index as compared to the NAO and EU2 indices is due to better data availability in the vicinity of the locations used to define this index (cf. Fig. 1a). Accordingly, from 1770 onwards 40 stations were sufficient to obtain excellent results (Fig. 3).

Our index is highly correlated with the instrumentally based indices provided by *Hurrell* [1995] and *Jones et al.* [1997] (not shown). However, no significant correlations were found with the NAO indices reconstructed by *Cook et al.* [1998], *Appenzeller et al.* [1998] and *Stockton and Glueck* [1999]. The reconstructions by *Cook et al.* [1998] and *Stockton and Glueck* [1999] captured 41% and 31% of the predictand variance in the calibration period, respectively. The index by *Appenzeller et al.* [1998] was developed independently from measurements of the NAO and explained 32% and 27%, respectively, of the interannual variability of the annual and winter mean observed NAO indices. Our tests using independent data yielded for winter in the worst case (1716-1725) r^2 = 25%, and otherwise r^2 > 40% (Fig. 3). The better quality of our reconstructions probably reflects the use of an extensive database (Fig. 1), whereas the above studies relied upon a relatively small number of predictors with a poor spatial coverage and/or temporal resolution and precision. At present, only paleoenvironmental data are available prior to 1675, enabling only the reconstruction of low-frequent variations of the atmospheric circulation.

Our results from the wavelet analysis of the reconstructed winter mean NAO1 index are roughly consistent with earlier findings by *Rogers* [1984], *Hurrell and van Loon* [1997], *Cook et al.* [1998] and *Stockton and Glueck* [1999]. With regard to the annual mean NAO index, our analysis suggested significant spectral power between 54 and 68 years. In contrast, the index time series of *Appenzeller et al.* [1998] does not show any significant peaks in the global wavelet spectrum (analyses not shown). Further studies are needed to understand this discrepancy and also to clarify whether our results are affected by shortcomings of our data base and/or reconstruction method.

The same applies to some extent to the strong fluctuations found in the co-variability between the two indices. However, the quality of our reconstructions for autumn and winter was good, such that the found drop in the correlations in the nineteenth century is probably real. Possibly, it reflects systematic shifts in the dominant planetary wave number and/or the location of planetary waves. Further analysis based on reconstructions of the entire SLP [*Jones et al.*, 1999; *Luterbacher et al.*, 1999] and geopotential height fields could help to clarify this issue.

Conclusions

Based on long-term instrumental and proxy time series it is possible to reconstruct temporally highly resolved (monthly

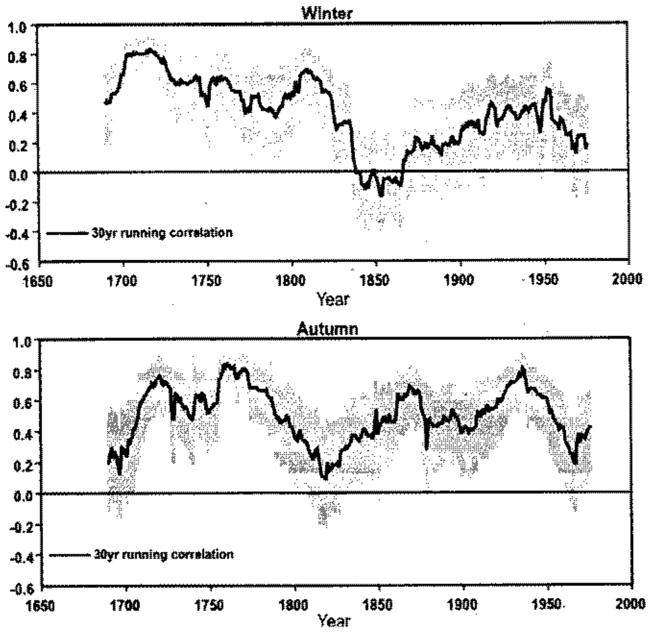

Figure 4. 30-year running correlation between the reconstructed winter (top) and autumn (bottom) NAO1 and EU1 indices. The bars indicate the 90% confidence intervals for the correlation coefficients.

to seasonal) indices of the atmospheric circulation for the North Atlantic and Eurasian sectors as far back as to AD 1675. The quality of the reconstructions depends strongly on data availability and thus varies for different time intervals. Nevertheless, comparison with other studies suggests that the derived indices present the most reliable reconstructions prior to the early nineteenth century available to date.

For the annual, spring and summer mean reconstructions, significant power at different period lengths was found for the NAO1 and the EU1 indices. Further studies are needed to confirm and explain the reconstructed low-frequency variability. Our analysis confirmed the results by earlier studies that there are weak indications for regular oscillatory behavior of the winter NAO index.

The breakdown of the running correlations between winter NAO1 and EU1 indices in the middle of the nineteenth century suggests that the circulation over the eastern North Atlantic at sea level is temporally decoupled from the continental flow, hence the NAO is not always the dominant mode for the European climate.

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