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Reconstructing Summer North Atlantic Oscillation (SNAO) variability over the last five centuries

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Introduction

The North Atlantic Oscillation

The climate over the North Atlantic region exhibits considerable variability on a wide range of timescales, manifested as coherent fluctuations in ocean and land temperature, rainfall and surface pressure (Hurrell et al. 2002). Without doubt, the North Atlantic Oscillation (NAO) is the most widely known example of such variability. The NAO is a major source of interannual variability in the atmospheric circulation, and is associated with changes in the westerlies across the North Atlantic Sector (Hurrell 1995). The NAO can be described as an oscillation of atmospheric mass between the Arctic and the subtropical parts of the Atlantic, usually defined through changes in surface pressure. These oscillations produce changes in wind speed (and direction) over the North Atlantic, which affects heat and moisture transport over land adjacent to the ocean, as well as frequency and intensity of storms (Hurrell et al. 2003). Furthermore, the NAO strongly affects the heat and freshwater exchange at the ocean surface of the Atlantic Ocean itself by inducing changes in surface wind patterns (Hurrell et al. 2001). Such changes affect the strength and character of the overturning in the North Atlantic and could thus have influence on the thermohaline circulation (Delworth & Dixon 2000). Perhaps the main reason for the recent focus on the NAO is the strong positive trend in the index of the winter NAO from the 1980s and onwards. Hurrell & van Loon (1997) noted that the recent cooling over the northwest Atlantic and the warming across Europe since the early 1980s was related to the decadal variability of the NAO. Furthermore, they showed that since the early 1980s, circulation changes over the Atlantic was linked to coherent large-scale anomalies in precipitation (e.g. dry conditions over southern Europe and the Mediterranean and wetter-than-normal conditions over northern Europe and parts of Scandinavia). Also, Hurrell et al. (2001) suggested a link between the Northern Hemisphere warming and the positive trend in the NAO. In addition to the direct effects of the NAO on, mainly winter-time, climate, a vast number of papers have shown a correspondence between the NAO and a number of ecological features, such as phenology, terrestrial and marine ecosystems, agriculture etc. (see Drinkwater et al. 2003, Mysterud et al. 2003).

Defining the NAO

NAO indices can be derived in different fashions; either from the simple difference in surface pressure anomalies between various northern and southern locations (e.g. Iceland and Azores/Portugal/Gibraltar), or from the principal component (PC) time series of the leading empirical orthogonal function (EOF) of sea level pressure (SLP). In the past, the former approach has been most widely used (e.g. Hurrell 1995, Jones et al. 1997, Visbeck et al. 2001). However, a disadvantage of station-based indices is that they are fixed in space. As shown by e.g. Barnston & Livezey (1987), the NAO centers of action shifts throughout the year, and consequently, such indices can only adequately capture the NAO variability for parts of the year (Hurrell et al. 2003, Allan & Ansell 2006). The advantage of using PC analysis on SLP is that such indices provide more optimal representations of the NAO spatial pattern, but since they are based on gridded SLP data, they usually provide shorter time series than those based on station data (Hurrell et al. 2003). However, recently Allan & Ansell (2006) provided an upgraded version of the Hadley Centre's

monthly historical hemispheric mean SLP (MSLP) data set and Ansell et al. (2006) a daily MSLP reconstruction for the European-North Atlantic region, both going back to 1850.

The summer NAO (SNAO)

Because the winter months are dynamically the most active, the largest amplitude anomalies in SLP occur during the cold season. Consequently, most focus has been on winter-time NAO. However, Barnston & Livezey (1987) noted that the NAO pattern was found throughout the year, but that it showed pronounced seasonal variation in location. In winter, they found a Greenland center near 70°N and an Atlantic center at 30°-35°N. In summer, the action centers had moved further to the north: a Greenland center near 70°-75° N and an Atlantic center at 40°-50°N. Although the NAO is most pronounced in the cold season, strong climate anomalies can be detected outside winter. This is especially true for summer, when variability is particularly important from the perspective of droughts and heat waves (Hurrell et al. 2002). Taking the leading eigenvector of SLP during July-August, over a large domain centered over the North Atlantic, Hurrell & Folland (2002) found a dipole pattern much like that of Barnston & Livezey, where the southern center extending over the northeast Atlantic across western Europe into Scandinavia. Their SNAO time series revealed strong variations on interannual to multi-decadal time scales (see Fig. 1 in Hurrell & Folland 2002). The most significant characteristic of this time series is the transition from an extended period of below average SLP anomalies since about 1967 to above average SLP anomalies, indicating a change toward persistent anticyclonic flow during high summer in recent decades. The SNAO index increase corresponded to an increase in mean central England temperatures (CET), and Greatbatch & Rong (2006) found that a strong correlation between SNAO and CET holds for much of the twentieth century. Also, this increase in SNAO corresponds to a lowering of precipitation over much of Northern Europe. In fact, some of the driest summers over the UK in recorded history have occurred during this most recent period (Hurrell et al., 2002). Strong associations between SNAO and temperature/precipitation are found over large parts of Europe, but also elsewhere in the northern hemisphere, e.g. over the Sahel in Africa (Hurrell & Folland 2002, Folland et al. submitted).

NAO and tree rings

Previous reconstructions of the NAO, using different kinds of proxies including tree rings, have focused on the winter NAO (e.g. Appenzeller et al. 1998, Cook et al. 1998, Cullen at al. 2001, Glueck & Stockton, 2001, Cook et al. 2002). From a tree-ring point of view, it means that trees respond to conditions of the winter prior to the year of growth. This is certainly true for trees sensitive to precipitation variability, e.g. in arid/semi-arid regions. But also tree growth at higher latitudes seems to be influenced by the winter NAO (see e.g. D'Arrigo et al. 1993, Linderholm et al. 2003). Trees growing in regions surrounding the North Atlantic Ocean could be useful for SNAO reconstruction, considering the links between SNAO and climate in these regions and the strength of tree growth/climate relationships in the growing season. In a first attempt, tree-ring data (tree-ring widths (TRW) as well as maximum latewood density (MXD)) from Great Britain and western Scandinavia were used to reconstruct the SNAO back to 1706, showing promising results (Folland et al. submitted). Here an extension of that reconstruction, based on tree-ring data from a wider geographical area is presented.

Material and Methods

Reconstructing the SNAO

The definition of the SNAO used here is a covariance eigenvector analysis of July-August MSLP anomalies for 25°N-70°N, 70°W-50°E, for 1850-2003. The data derive from the new daily MSLP analysis by Ansell et al. (2006) where EOF1 is defined as the summer NAO (Fig. 1).

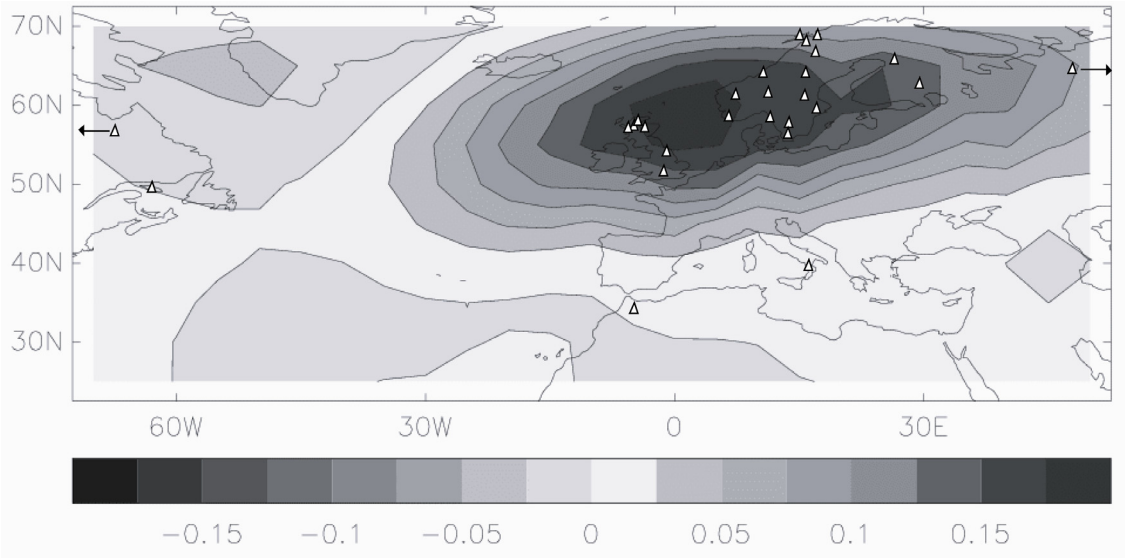

Figure 1: The definition of the SNAO used here is first area weighted covariance EOF of daily pressure at mean sea level over the region 70W-50 °E, 25N-70°N for July-August, 1850-2003, based on the new daily EMSLP data set by Ansell et al. (2006). Shown in this figure is the pattern of the SNAO, with its southern action centre located over the British Isles and southern Scandinavia. White triangles indicate locations of the tree-ring chronologies used in the reconstruction (Note: some sites provided both TRW and MXD).

Folland et al. (submitted), show that SNAO is positively correlated to temperatures over north western Europe and eastern North America, and negative over the eastern Mediterranean/Middle East. Strong negative correlations between SNAO and precipitation are found over north western Europe and moderate positive correlations over the Mediterranean. Consequently, although it is likely that the strongest SNAO signal is found in trees close to the southern node, tree-ring data from all around the North Atlantic sector may be suitable as SNAO predictors. In order to extend the reconstruction as far back in time as possible, we concentrated on chronologies approaching (or exceeding) 500 years, but shorter records from areas with strong SNAO/climate relationships (mainly north-western Europe) were also chosen. Most tree-ring data were obtained from the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html), while the remaining data (mainly for Sweden) was provided by Keith Briffa and the first author. All available long tree-ring chronologies (TRW and MXD) from different species from the area within the 25ºN-70ºN; 70ºW-50ºE boundary were extracted, as well as some long chronologies further east and west in the higher latitudes (western North America and eastern Siberia). The chronologies were standardized, using negative exponential or lines of zero or negative slope on individual tree-ring series to remove the age effect and to strengthen the common climate signel. This process results in loss of century scale variability in the data, but since we were mainly interested in the interannual to interdecadal variability, the standardization method was sufficient. Initially, 168 tree-ring chronologies were screened. To select chronologies suitable for reconstructing SNAO, we chose those showing significant ($p<0.05$, two-tailed test) moderate to strong correlations ($r >0.2$ or <-0.2) over the 1850-2000 period (with the end date of the correlations depending on the length of the individual chronology lengths) with observed SNAO index. Thirty seven chronologies passed that criterion. Since start years varied among the accepted chronologies, the number of available chronologies decreases back in time. In addition, a large number of the chronologies end in the late 1970s or early 1980s. Using only the common overlapping period would give a very time-restricted reconstruction, so instead we used the method previously used to reconstruct Fennoscandian summer temperatures (Gouriand et al. 2007). The thirty seven chronologies were divided into five subsets, where each subset consisted of those chronologies going back to (at least) some specific year. The first subset contained all thirty seven chronologies (1850-1976), the

second subset included those chronologies covering the period 1706-1976 (17 chronologies), etc. (Tab. 1).

Table 1: Correlations (annual/decadal) between the subgroup SNAO reconstructions and observed SNAO in the period 1850-1976 (1978-1995 for subgroup 5). In the final reconstruction, each subgroup represents the time given in the first column, but all reconstructions were calibrated over the same period (except subgroup 5). Number of PCs indicates the number of predictors used in the regression models to reconstruct SNAO.

Subgroups	Corr recon vs obs (1850-1995)	Number of PCs	Number of tree-ring chronologies
1: 1441-1499	0.46/0.73	1	8
2: 1500-1705	0.50/0.68	3	10
3: 1706-1849	0.69/0.90	4	17
4: 1850-1976	0.72/0.93	6	37
5: 1977-1995	0.42/0.66	3	9

Subsequently, SNAO was reconstructed for each subset. EOF/PC decomposition was performed on the tree-ring chronologies in each of the five subsets and the PCs with eigenvalues >1 were regressed against observed SNAO and significant (0.05 level) PCs retained for further analysis. To make the five separate reconstructions, the significant PCs were set as predictors into a multiple linear regression analysis, where the SNAO was the predictand. The models were initially calibrated using half of the data (e.g. 1915-1978), and then verified over the other half (e.g. 1850-1914). The procedure was then reversed to assess the stability in time of the relationship between observed SNAO and tree-ring PCs. The final model for each subset was calibrated using the full common period. The full reconstruction of SNAO was obtained by combining the six individual reconstructions into one single reconstruction. This combined reconstruction is constructed by using the reconstruction based on subgroup one for the period AD 1441-1499, subgroup two for AD 1500-1705, etc., and subgroup five for the period 1978-1995 (Tab. 1).

Results

SNAO evolution over the last 550 years

The reconstruction is quite skilful in reproducing the interannual variability in observed SNAO and very skilful on decadal timescales. However, it fails to provide the full high-frequency variability evident in the observed data (Fig. 2).

The lack of correlation between observed and reconstructed SNAO in the early twentieth century corresponds to a period of zero correlation between SNAO and CET noted by Greatbatch & Rong (2006), a feature that has yet to be explained. The highest correlations between observed and reconstructed SNAO were found in the subgroup four reconstruction (1850-1978), which includes the maximum number of tree-ring chronologies, although the subgroup three reconstruction (1706-1849) is similar in strength of correlation. Quite naturally, the correlation weakens with lower number of chronologies (PCs) in the other subgroups (especially subgroup five, see table 1). This is due to the lack of long tree-ring chronologies in the immediate area of the southern action centre of the SNAO. Consequently, there is a large increase in the uncertainty of the reconstructions back in time. On decadal timescales, there is better agreement, suggesting that tree-rings are useful in capturing the SNAO variability on those timescales. Throughout the last 550 years the SNAO has been, in general, in a negative phase, with occasional short term excursions into positive phases (Fig. 3). Only a handful of positive phases are found beyond 1850, but no coherent positive phases exceed 20 years (decadally smoothed data, see Fig. 3).

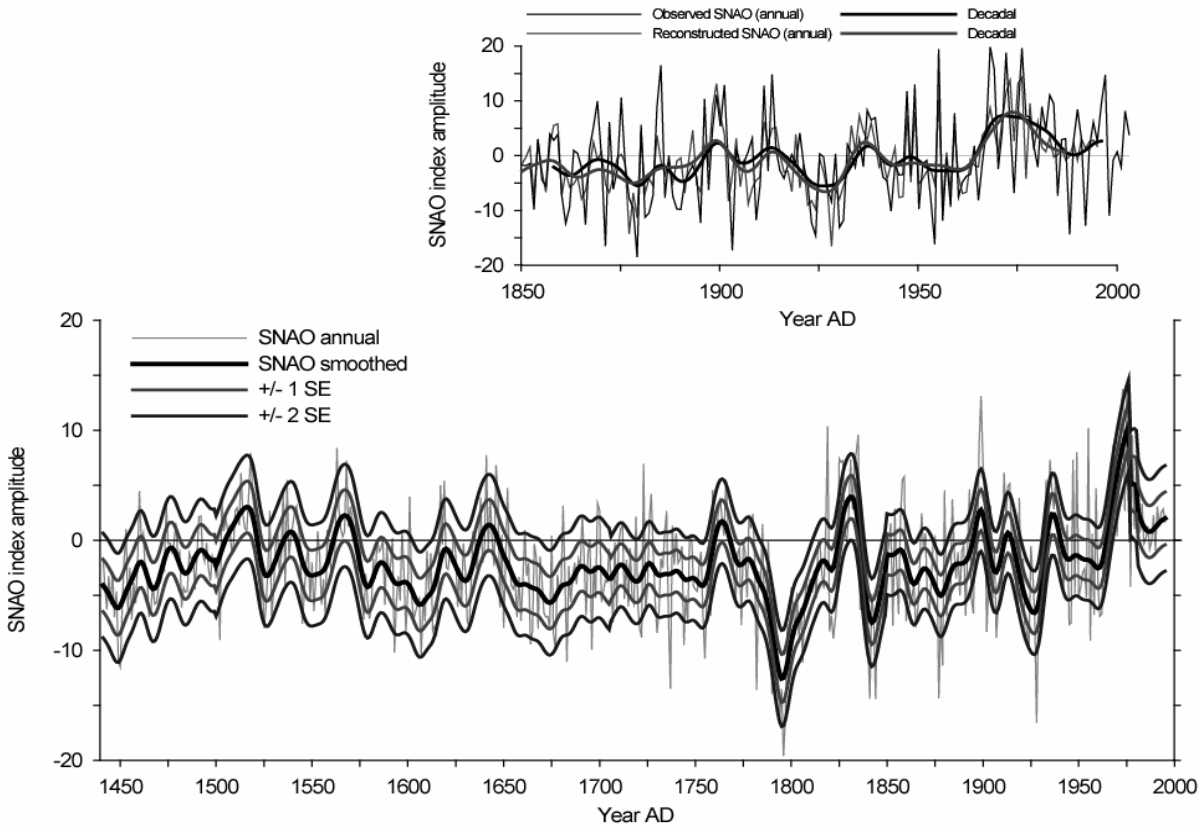

Figure 2: Reconstruction of the SNAO. Upper figure shows reconstructed vs. observed SNAO 1850-1995. Lower figure shows the full reconstruction, with 1 and 2 standard errors (SE). Note that SE is based on the decadal values. Thick black lines represents smoothed (Gaussian filtered, σ=3) values, highlighting variability on timescales longer than 10 years.

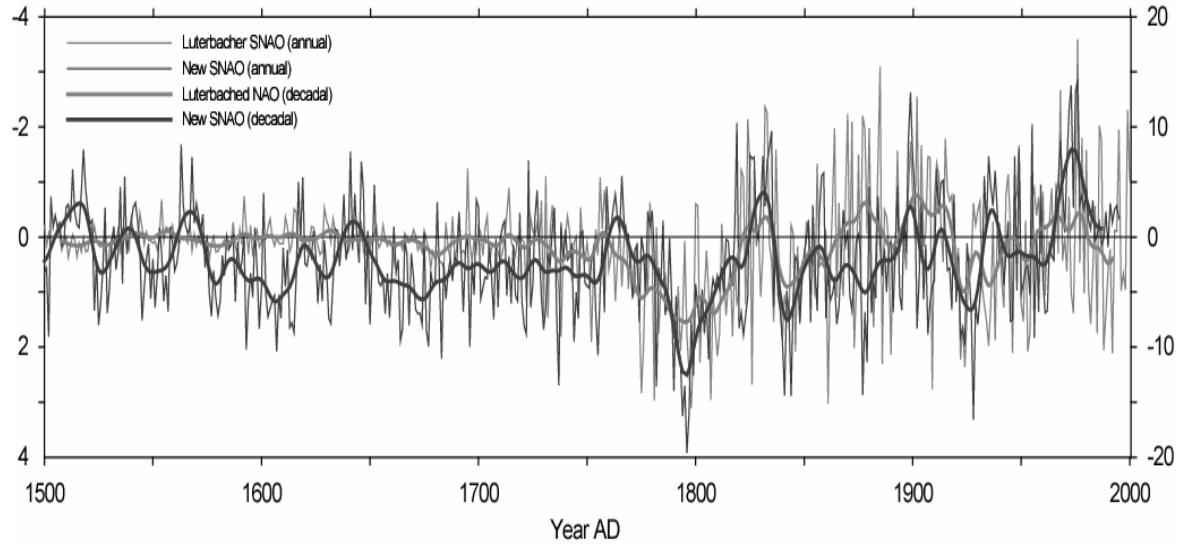

Figure 3: The new SNAO reconstruction compared to average July-August NAO reconstructed by Luterbacher et al. (2002b). Note that before 1659, the Luterbacher reconstruction gives seasonal values (June-August).

On the contrary, the longest coherent period of negative SNAO lasts for a century between ca 1650 and 1750, a period which is also characterized by low interannual and decadal variability. The strongest negative phase was found in the late eighteenth century, while the high positive values in the late 1960s to early 1980s seems anomalous within the 550 years. Overall, there is a slight positive trend in the SNAO over the reconstructed period.

Discussion

Since previous studies have mostly focused on reconstructing past winter NAO variability, only few SNAO records are available for comparison with our reconstruction. However, Luterbacher et al. (2002a) reconstructed the NAO back to AD 1500, with monthly resolution from 1659 and seasonal estimates 1500–1658. This reconstruction was developed using principal component regression analysis based on the combination of early instrumental station series (pressure, temperature and precipitation) and documentary proxy data from Eurasian sites, but no tree-ring data (Luterbacher et al., 2002a, 2002b). The NAO index was defined as the standardized (1901–1980) difference between SLP average of four grid points on a 5×5 longitude-latitude grid over the Azores and over Iceland. In the comparison (Fig. 3), the Luterbacher SNAO is based on July-August averages from 1659 and June-August averages prior to that. In general there is quite good agreement between the two reconstructions, although disagreements are found in the last halves of the nineteenth and twentieth centuries. The low SNAO values just before 1800 are found in both records, as well as low values in the period between 1650 and 1750. The lack of correspondence prior to 1650 is mainly caused by the significant drop in proxies used to reconstruct the Luterbacher SNAO. Despite the obvious differences (which in part are due to the Luterbacher record being "station based"), the similarities of the two records between approximately 1650 and 1850, suggests that our new reconstruction captures some of the "true" variability in SNAO back in time.

Since the relationship between NAO and climate using the traditional definition (see above) is much weaker in summer than in winter, previous attempts to reconstruct NAO with tree-ring data have focused on the winter season (Cook et al. 1998, Cullen at al. 2001, Glueck & Stockton, 2001, Cook et al. 2002). Additionally, the relationship between tree growth and station-based NAO during summer in Scandinavia was previously found to be quite weak (e.g. Linderholm et al. 2003). However, here we show that tree-ring data are indeed useful for inferring past SNAO variability, especially on decadal timescales. Furthermore, the spatial distribution of the tree-ring chronologies we used in our reconstruction suggests that SNAO is more than a feature influencing the immediate surroundings of the North Atlantic Ocean. The tree-ring data indicate that it also affects climate down to the Mediterranean as well as further west and east over North America and Eurasia.

Conclusion

We have shown that using tree-ring data from a large geographical region, the SNAO can be reconstructed with some skill on interannual to interdecadal timescales. Extending the SNAO record back in time will be of importance for increasing the understanding of the influence of summer atmospheric circulation on climate, ocean-atmosphere coupling, as well as global teleconnections and their role in climate variability and change.

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