Are temperature-sensitive proxies adequate for North Atlantic Oscillation reconstructions?

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Received 30 April 2002; revised 14 June 2002; accepted 18 June 2002; published 31 July 2002.

[1] Reconstructions of the North Atlantic Oscillation Index (NAOI) for the last centuries are mostly based on statistical models linking this index with proxy records. The underlying assumption is that the relationship between the NAO and the proxy records is stable in time and independent of time scale. This assumption might not be physically substantiated, since at time scales of centuries, other processes, such as solar variability, might disturb the link between the NAOI and temperature-sensitive indicators. The statistical approach for NAOI reconstructions was tested using a climate simulation with a climate model driven by the external forcing of the last 490 years, as a surrogate climate. Two kinds of indicators were tested, air temperature and precipitation. It was found that the NAOI reconstructions based on precipitation are more reliable than the reconstructions based on temperature. Furthermore, the choice of geographical box has a non-negligible influence on the reconstructed NAOI. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3319 Meteorology and Atmospheric Dynamics: General circulation

1. Introduction

[2] The North Atlantic Oscillation is the leading pattern of wintertime atmospheric variability in the extratropical Northern Hemisphere at interannual time scales [*Hurrell*, 1995]. Since it is associated with important temperature and precipitation anomalies in the Northern Hemisphere, there has been a considerable interest in reconstructing its intensity in the last few centuries. Reconstructions of the North Atlantic Oscillation index (NAOI) in the last centuries are based on long instrumental records [*Jones et al.*, 1997], historical evidence [*Luterbacher et al.*, 2000] and on proxy data, such as tree-ring [*Cook et al.*, 1998], or ice-cores [*Appenzeller et al.*, 1998]. In general, although not always, proxies are sensitive to local climate conditions, mostly temperature or precipitation. In the typical approach, a statistical regression model linking the available proxy records and the NAOI is calibrated using data of the last decades, and subsequently, the longer proxy records are used to estimate past variations of the NAOI. The underlying assumption is that the empirical relationship between, for example, local temperatures and the NAOI, remains unchanged.

[3] However, this assumption might not be physically substantiated. It is generally accepted that the relationship between the NAOI and wintertime anomalous European and North American temperatures is caused, in the present climate, by advection of air masses perpendicular to the climatological isoterms, e.g. milder Atlantic air into the colder Eurasian continent. Also, the link between the NAOI and West European precipitation anomalies is associated to a meridional shift of the North Atlantic storm tracks [*Hurrell*, 1995]. However, in the past centuries, changes in local temperatures may have been partially caused by other external factors, such as solar irradiance variations, that related or not to NAOI changes. Also, changes in the atmospheric humidity might have had some influence on the precipitation rates, independently of variations in the location of storm tracks. If this were the case, the NAOI reconstructions based on proxy data would be contaminated by these other signals, possibly differing, depending on the nature of proxy data used. This potential problem could be at the core of the disagreement of available reconstructions of the NAO, which is still an unsolved issue [*Schmutz et al.*, 1999].

[4] We test the suitability of temperature-sensitive or precipitation-sensitive proxies for NAOI reconstructions, using, as a surrogate, a climate simulation of the last 490 years with a climate model. For this purpose we use the monthly mean temperature or monthly precipitation directly simulated by the climate model as surrogates of the real proxy records. The reconstructed NAOI can then be directly compared with the simulated NAOI.

2. Climate Model and Statistical Model

[5] The global climate model ECHO-G consists of the spectral atmospheric model ECHAM4 and the ocean model HOPE-G, both developed at the Max-Planck-Institut of Meteorology in Hamburg [*Legutke and Voss*, 1999]. The model ECHAM4 has, in this simulation, a horizontal resolution of T30 (approx. 3.75° × 3.75°). The horizontal resolution of the ocean model HOPE-G is about 2.8° × 2.8° with a grid refinement in the tropical regions. A constant in time flux adjustment was applied to avoid climate drift. Two simulations have been analyzed. In one (hereafter FORCED), the model was driven by estimations of three past external forcing factors: solar variability, atmospheric greenhouse gas concentrations, and radiative effects of stratospheric volcanic aerosols, in the period 1500–1990 AD, essentially as provided by *Crowley* [2000]. A more

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thorough description of this simulation is in preparation. A second 1000 year long simulation served as control (hereafter CONT), where the external forcing factors were kept constant at their present values.

[6] The NAOI is defined in the following as the leading Principal Component of an Empirical Orthogonal Function Analysis (EOF, *von Storch and Zwiers*, 1999) of sea-level-pressure field in the winter months (December–February) over the North Atlantic. For this analysis the covariance matrix, suitably weighted by latitude, was diagonalized. For the design of the statistical model, a similar regressional approach as in *Luterbacher et al.* [2002] was used. A regression equation between the detrended monthly NAOI, as predictand, and the principal components of the detrended monthly proxy indicators using data in the simulation period used for calibration 1900–1990 AD, as predictors, is prescribed. The principal components are also the result of an EOF analysis of the temperature or precipitation field over land in the North Atlantic sector in wintertime. The statistical model can be written down as:

$$naoi(t) = \sum_{k=1}^{N_{eof}} a_k pc_k(t) + \epsilon(t) \qquad (1)$$

where pc_k are the principal components of temperature or precipitation and a_k are the regression coefficients. These are estimated by minimizing the variance of the residuals ϵ in the calibration period. The number of principal components retained in equation (1), N_{eof}, was limited to those adding a statistically significant amount of explained variance of the NAOI in the calibration period: 3 for temperature and 6 for precipitation.

[7] The value of principal components in the verification period (1800–1900 AD) was found by projecting the proxy fields onto the corresponding EOF patterns:

$$pc_k(t) = \sum_{i=1}^{N_{grid}} w_i f_i(t) eof_i^k \qquad (2)$$

where i is the grid-point index, eof^k are the EOF patterns of the temperature or precipitation, $f_i(t)$ are the temperature or precipitation anomalies with respect to the calibration period, and w_i is the latitudinal weighting factor. Finally, the reconstructed NAOI was found by inserting the values of the principal components $pc_k(t)$ into equation (1).

[8] As this study is focused on the adequacy of the proxies, no detailed attempt was made to mimic the location of proxies in the real world. Instead, we used the simulated field, temperature or precipitation, over all land grid-points in the North Atlantic sector (i.e. the area shown in Figure 1), thereby ensuring that quality of the reconstructions was not affected by a different spatial relationship between the NAOI and the proxies as in the real world. However, some analysis of the influence of the geographical box was performed. The precipitation-reconstructed NAOI showed a small sensitivity to changes in this box, whereas the temperature-reconstructed NAOI varied more strongly (see section 4).

[9] The reason for limiting the model proxies to land grid-points is two-fold: first, most of the proxy data used to date are located over land. Second, to avoid potential complications in the interpretation of the results if sea-surface temperature data were included: although still a matter of debate, it is possible that sea-surface-temperature may exert an influence on atmospheric circulation anomalies at decadal time scales [*Rodwell et al.*, 1999]. This influence would introduce a statistical relationship between temperature and the NAO that is, in principle, not directly related to the causal link between the NAO and the proxy records.

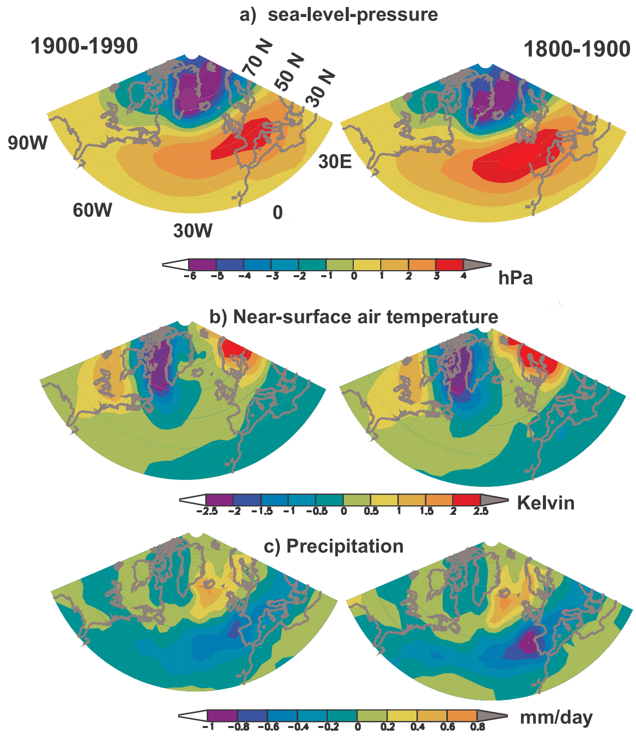

Figure 1. Regression patterns between the NAOI and sea-level-pressure, near-surface temperature and precipitation, from the ECHO-G simulation in the periods 1900–1990 and 1800–1900 AD, using detrended December–February data.

[10] The quality of the reconstructions in the model is an overestimation of the the real world, since, first, the complete spatial information is used, and second, no information is lost between the (model) proxy indicator and the local climate conditions. The possible divergences in the reconstructions caused by the use of annual or monthly means are not considered here [*Appenzeller et al.*, 1998; *Cook et al.*, 1998; *Luterbacher et al.*, 1999].

3. North Atlantic Oscillation in the Model ECHO-G

[11] Figure 1 shows the North Atlantic Oscillation pattern resulting from the EOF analysis of the DJF sea-level pressure field in the simulation FORCED in the calibration period. It displays the well known centers of action located over the subtropical North Atlantic and Greenland [*Hurrell*, 1995]. The model NAOI is the principal component associated to this EOF. Figure 1 also shows the regression patterns between the standardized NAOI and the local air-temperature and precipitation anomalies simulated by the model in the calibration period 1900–1990. The regression patterns also agree with the well known pattern of the real

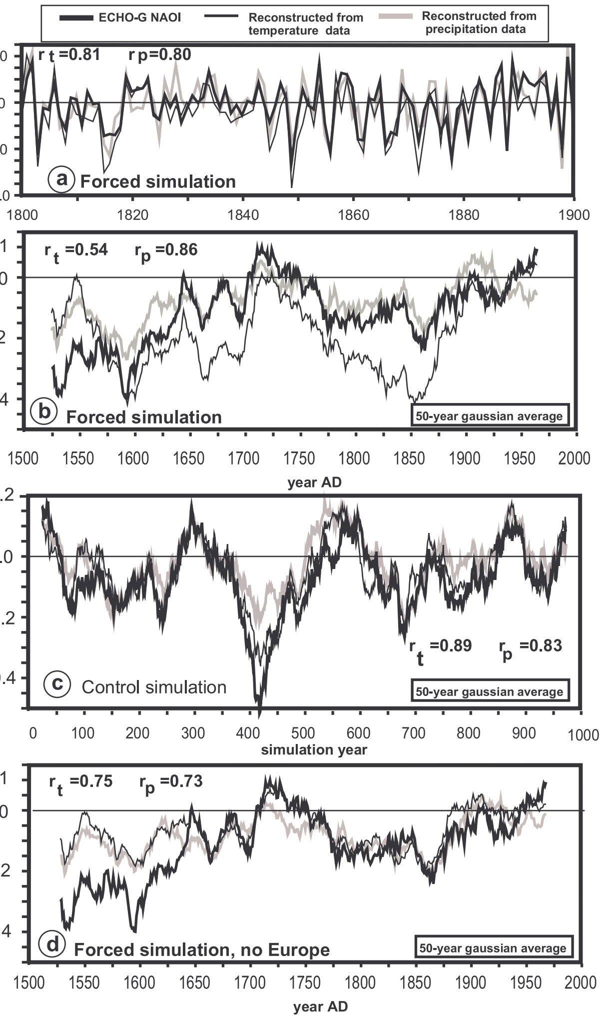

Figure 2. (a) NAOI in the forced climate simulation, simulated by the ECHO-G model, and reconstructed from the simulated air-temperature field and the precipitation field in the North Atlantic sector over land grid points. (b) as (a) with a 50-year gaussian filter. (c) NAOI as in (b) but in the control simulation. (d) as in a) but using a geographical box limited to east by 360°. In all subfigures the correlations between the simulated NAOI and the reconstructed NAO indices are indicated.

world [*Hurrell*, 1995] and in other climate simulations [e.g. *Shindell et al*, 1999; *Fyfe et al.*, 1999; *Zorita and Gonzalez-Rouco*, 2000]. For positive phases of the NAOI, the temperature anomalies show a see-saw structure between Greenland and Northern Europe, with slightly colder than normal temperatures over the Mediterranean and North Africa. This pattern can be explained by anomalous advection of air masses by the geostrophic wind. The precipitation pattern displays marked negative anomalies over Southern Europe and the Mediterranean, with positive rainfall anomalies in Scandinavia, matching also the pattern derived from observations and metereological reanalysis [*Hastenrath and Greischar*, 2001]. Physically this pattern is related to the meridional displacements of the North Atlantic storm track. To test if the relationship between the NAO on one side and temperature and precipitation, on the other side, at interannual time scales critically depends on the selected calibration period, a similar analysis (calculation of the SLP EOFs and of the regression between NAOI and temperature and precipitation) has been performed for the century 1800–1900 AD. The results are also displayed in Figure 1. The patterns obtained in this period are very similar to those of period 1900–1990 AD. We conclude that the spatial pattern of the NAO and its relationships at interannual time scales with the temperature and precipitation fields are stable in time.

4. NAOI Reconstructions in the Surrogate Climate

[12] The statistical model for NAOI reconstruction has been applied separately to the model temperature field and the precipitation field over land. Figure 2 illustrates the evolution of the reconstructed NAO indices at different time scales: the winter seasonal values in the period validation 1800–1900 (independent of the calibration) in Figure 2a, and in the whole period, after a 50-year gaussian filtering, to illustrate the low-frequency behavior of the reconstruction (Figure 2b). From Figure 2a it can be concluded that, in the verification period and at interannual time scales, both NAOI reconstructions are quite good. They are correlated with the simulated NAOI with r = 0.81 and r = 0.80 for temperature and precipitation, respectively. The situation is, however, different at longer time scales (Figure 2b). Whereas the precipitation-reconstructed NAOI reasonably follows the simulated NAOI, the temperature-based NAOI deviates from the modeled NAOI, especially at centennial time scales. Some broad qualitative similarities still persist, for instance, the maximum value of the index around 1730 AD, the minimum around 1850 AD and the subsequent positive trends towards the end of the simulation. This latter positive trend agrees with the positive trend simulated in future scenario simulations with several models [*Fyfe et al.*, 1999; *Shindell et al.*, 1999; *Zorita and Gonzalez-Rouco*, 2000]. At large, the reconstructed NAO indices are still relatively well correlated with the simulated NAOI (r = 0.82 and r = 0.54 for precipitation and temperature, respectively), but whereas the correlation for the precipitation-based NAOI has remained stable, the correlation for the temperature-based NAOI has clearly dropped.

[13] A possible explanation for this behavior may lie in the variable external forcing in the climate simulation. This

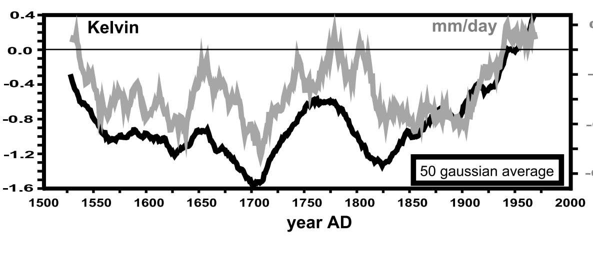

Figure 3. December–February average temperature and precipitation simulated by the ECHO-G model in the forced simulation over land-grid points in the North Atlantic sector shown in Figure 1.

Table 1. Standard Deviations of Winter Temperature (T) and Precipitation (P) Over Land Within the Geographical Window in Figure 1 in the FORCED Simulation and in the NCEP Reanalysis at Interannual Time Scales in the Present Climate, Compared to the Simulated Typical Centennial Scale Anomalies Shown in Figure 3

	T (K)	P (mm day^{-1})
FORCED (1940–1990 AD)	0.6	0.9
NCEP (1948–2000 AD)	0.4	1.0
FORCED cenntenial changes	1	0.05

hypothesis has been checked by performing the same reconstruction exercise in the 1000-year long CONT simulation with the ECHO-G model, where the forcing factors have been kept constant. The results are shown in Figure 2c. Here, the statistical model has been calibrated in the model years 900–1000. In this control simulation both reconstructed NAO indices closely follow the simulated NAOI and the correlation of the low-pass filtered time series are high (r = 0.89 and r = 0.83 for temperature and precipitation, respectively).

[14] The choice of geographical box to reconstruct the NAOI has influence on the reconstructions in the simulation FORCED. The largest differences are found when the European region is excluded, for instance, using a geographical window limited to the east by 360° W (Figure 2d), thus excluding the European area. In this case, both NAOI reconstructions resemble more closely the simulated NAOI. In our analysis it turned out that the deviation between the temperature-reconstructed NAOI and the simulated NAOI is mostly caused by the Northwestern European center of action in Figure 1b. It seems, therefore, that it is in this region where the centennial temperature variations are more NAO-independent, and perhaps more directly caused by the radiation forcing. Precipitation variations seem to be mostly related to the Nao, independently of time scale.

[15] Further insight in the differences between precipitation and temperature as possible proxies can be gained by looking at the winter temperature and precipitation over land grid-points averaged over the whole region in the simulation FORCED (Figure 3). The typical anomalies at centennial time scales relative to the present climate can be compared with the interannual standard deviation of the corresponding quantities in the simulation FORCED in the period 1940–1990 AD (Table 1). As illustration, the standard deviations calculated from the NCEP reanalysis [*Kalnay et al.*, 1996] in the period 1948–2000 are also included. The centennial-scale temperature variations in the forced climate simulation are larger than the typical observed and modeled interannual variations, whereas the centennial precipitation variability is much smaller than their interannual counterpart. This could be an indication that a statistical model based on precipitation data calibrated with interannual data can cover the range of centennial variability, whereas this does not seem to be the case for temperature.

5. Conclusions

[16] The climate model simulation is not representative of the real climate in all aspects, but it is a sufficiently complex system, so that the results from this study may have an implication for the real world. In the surrogate climate, precipitation proved to be superior to air temperature for NAOI reconstructions. In the real world, where the available information is much more limited, this situation could be exacerbated. Furthermore, it was found that in the model simulation, Greenland and European temperatures behave differently in their very-low frequency link to the NAO. This could imply that European temperature-sensitive proxies are not adequate for NAOI reconstructions. We suggest that this might be one of the reasons for the disagreement among the different NAOI reconstructions put forward in the literature to date [*Schmutz et al.*, 1999].

[17] **Acknowledgments.** We thank Dennis Bray for his editorial assistance. This work was partially funded by the project "Climate Variations in Historical Times" of the Helmholz Society. F.G-R. was partially supported by the Spanish CICYT (REN-2000-0786).

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