Changing relationship between the North Atlantic Oscillation and key North Atlantic climate parameters

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[1] The North Atlantic Oscillation (NAO) is the key indicator of long-term variability in the North Atlantic. Numerous studies have accepted as a paradigm a steady relationship between the NAO and key North Atlantic climate parameters like the sea surface temperature (SST), surface air temperature (SAT), and sea level pressure (SLP). However, some studies suggest that this relationship is not always steady. For example, the recent decline of the Arctic ice cap is accompanied by a neutral or negative NAO index, whereas the ice decline observed over the last decades is associated with the positive NAO phase and with high atmospheric cyclonicity. In this study, we point to a lack of steadiness in the relationship between the NAO and SAT, SST, and SLP over the North Atlantic region when observed over long (decadal) time intervals. This suggests that the relationship is more complex than previously thought and may require further investigation. **Citation:** Polyakova, E. I., A. G. Journel, I. V. Polyakov, and U. S. Bhatt (2006), Changing relationship between the North Atlantic Oscillation and key North Atlantic climate parameters, *Geophys. Res. Lett.*, *33*, L03711, doi:10.1029/2005GL024573.

1. Introduction

[2] According to the common NAO/climate paradigm, a NAO positive (negative) phase is associated with a stronger (weaker) north-south pressure gradient between the subtropical high and the Icelandic low. Two of the most important cycles for the North Atlantic climate are decadal with a period of approximately 10–15 years [e.g., *Deser and Blackmon*, 1993] and multi-decadal with a period of 50–80 years [e.g., *Delworth and Mann*, 2000]. Understanding the mechanisms affecting long-term variability is not trivial due to the complex nature of the North Atlantic Oscillation (NAO), defined as the north-south oriented dipole in sea-level pressure over the Atlantic (see *Hurrell et al.* [2002] for an in-depth discussion of the role of the NAO in long-term North Atlantic variability). On Multi-decadal time scales the atmospheric circulation associated with a positive (negative) NAO phase displays stronger (weaker) than normal westerly winds and enhanced (suppressed) poleward heat transport by the ocean through the Gulf Stream system resulting in generally warmer (cooler) temperatures (SATs and SSTs) north of 45°N [*Visbeck et al.*, 2002]. Note, that on decadal and shorter time scales there is a spatial dipole structure in climate anomalies associated with the NAO [*Hurrell*, 1995]. There are, however, some studies hinting that the NAO paradigm may not always hold. For example, *Slonosky et al.* [2001] applied a running correlation analysis to several long-term temperature records from Europe and found significant non-stationarities between surface temperature and atmospheric circulation [NAO] on decadal time scales. *Schmith and Hansen* [2003] found that the (1830–1994) reconstructed Fram Strait ice export is only weakly correlated with the NAO index (R = 0.18) – much weaker than estimates based on shorter time records. Mechanisms for the changing Fram Strait/NAO relationship are presented by *Peterson et al.* [2003] and *Rogers et al.* [2004]. In a recent study, *Overland and Wang* [2005] presented evidence that, despite the recent decrease of the Arctic Oscillation (AO) index (which encompasses many of the features of the NAO [*Thompson and Wallace*, 1998]), many physical and biological Arctic parameters continue their nearly linear trends that began in earlier decades.

[3] In this paper, using long-term observational data we present evidence that the relationship between the NAO and SAT, SST, and SLP vary over time and these changes generally occur in conjunction with low-frequency (decadal to multi-decadal) climate variability in the North Atlantic.

2. Data

[4] Our study area comprises the North Atlantic Ocean region limited by 0–80°N and 80°W–20°E. The data consist of the mobile North Atlantic Oscillation (NAOm) index time series of *Portis et al.* [2001] for the period 1873–2001. These authors showed that during non-winter months the traditionally defined NAO index [e.g., *Hurrell*, 1995] has a lower correlation with the intensity of westerly winds than the NAOm index. The NAOm index is therefore retained in our study to investigate its relation with key climatic parameters such as the North Atlantic SST, SAT, and SLP. These data are available from the web at http://ingrid.ldeo.columbia.edu/sources/.kaplan/.extended/.ssta/, http://cru.uea.ac.uk/cru/data/temperature.htm, and http://www.cru.uea.ac.uk/cru/data/pressure.htm. The SST and SAT data sets provide spatial anomalies, while the original SLP data provide the gridded monthly values. These data were reduced to anomalies by subtracting corresponding same-month means taken over the entire available SLP record (128 years). The SST and SAT data sets cover the period 1856–2002 and the SLP data set covers 1873–2000. The SST and SAT data have a 5° × 5° spatial resolution, while the SLP data set is limited to the Northern Hemisphere above 15°N latitude with a 5° × 10° resolution.

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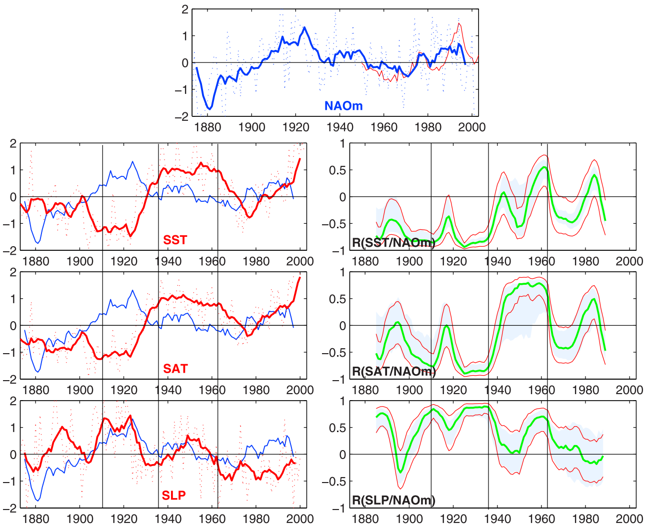

Figure 1. Standardized time series and running correlations between NAOm and SST, SAT and SLP. (top) The annual (dashed blue line) and the 7-yr running mean (solid blue line) NAOm index time series. For comparison purposes, the smoothed 7-yr running mean AO index time series is also shown in red. (left) The annual (dashed red line) and the 7-yr running mean (solid red line) SST, SAT, and SLP time series. The NAOm index time series is shown as a solid blue line. (right) The running correlations between the NAOm time series and SST, SAT, and SLP time series are shown as the green lines. Upper and lower 95% confidence intervals based on Fisher's method, are shown as red lines; correlations based on the randomization procedure described in Appendix A are shown by blue shading. These running correlations are based on 25-year overlapping windows.

Before 1981, uncertainty associated with SST anomalies is ±0.3°C; after 1981, this uncertainty is reduced to ±0.1°C [*Kaplan et al.*, 1998]. The SAT uncertainty is ±0.2°C during the 1850s; it decreases gradually in time to ±0.05°C remaining constant since 1951. Uncertainty associated with the SLP data set is ±1 hPa [*Jones*, 1987].

[5] For this study, we use the spatial fields of SST, SAT, the SLP anomalies, and the composite time series obtained by averaging these data over the North Atlantic Ocean for each year of the time domain. Our SAT time series is nearly indistinguishable from the Atlantic Multidecadal Oscillation (AMO) index [*Enfield et al.*, 2001]. The annual composite time series (Figure 1) are obtained by averaging the gridded data, using weights to account for different grid box areas. In order to remove the high frequency "noise" from these composite time series (as well as from the NAOm time series), we applied a 7-year running linear average. These smoothed composite time series form the basis of our analyses (unless otherwise specified).

3. Changing Relationship Between the NAO and SST, SAT, and SLP

[6] Here we show that the relationship between the NAO and SST, SAT, and SLP experiences long-term (decadal and longer) modulation. A comparison of the NAOm and SST time series based on visual inspection (Figure 1) shows a relatively good correspondence between these two parameters over the last 70 years of the 20th century (except for a few years in the late 1990s). Many observational and modeling studies using the NAO index are limited to this time period [e.g., *Visbeck et al.*, 2002]. Note, however, the striking negative correlation between the NAOm and SST anomalies in the earlier part of the 20th century. The other period of negative correlation seems to be developing in the late 1990s. *Overland and Wang* [2005] observed a similar "irregularity" in the relationship between the AO index (Figure 1) and thickness of the Arctic ice cap and several other Arctic physical and biological quantities during the last few years of the 20th century. Note, that since our SST time series is nearly indistinguishable from the AMO index [*Enfield et al.*, 2001], all above results are applicable to the AMO climate index as well. The strongly correlated (R = 0.90) SST and SAT time series allow us to apply the above observations to the relationship between NAOm and SAT time series. The time intervals when the NAOm and SAT records experience negative (positive) correlations coincide with the periods of negative (positive) correlations of the NAOm and SST time series. The comparison of the SLP and NAOm time series shows that, in general, these two curves closely follow each other except at the end of the 19th century (1878–95s) and possibly in the 1970–90s.

[7] The running correlation method is widely used in climate research for analyses of possible variations in the relationships between two climate time series [e.g., *Slonosky et al.*, 2001; *Gershunov et al.*, 2001]. The basic idea is to compute the correlations over a sliding window moving over the full time records. The results of applying this method to the NAOm and SST, SAT, and SLP time series are shown in Figure 1, and support our previous conclusion based on visual inspection of the time series. For the SST/NAOm, the maximum negative correlation ($R \cong -0.8$) observed in the late 1920s persists relatively stably until the 1930s. The correlations become more positive with decadal fluctuations during the 1940–1960s (with a maximum reached in 1959 at $R \cong 0.55$). Because the SST and SAT time series are so much alike, the NAOm/SAT running correlations reflect the NAOm/SST relationship with prolonged periods of substantially different levels of correlations. The SLP/NAOm correlations are all significantly positive and stable in the 1900–39s ($R \cong 0.8$). This prolonged stable period gave way to a steep decline after 1960 toward minimum negative correlations of $R \cong -0.2$ in the early 1980s. Note that the correlation fluctuations seen in Figure 1 are deemed significant based on two different statistical tests (see Appendix A for details).

[8] Fluctuations in the correlations between NAOm and SST, SAT, and SLP occur not only in time, but also in space. Correlations maps (Figure 2) between NAOm and SST, SAT, and SLP time series were drawn for the two time periods (1910–36 and 1937–63). These time periods were chosen for their two different levels of correlations previously observed in Figure 1. These maps were obtained by computing the correlations between the NAOm index and the SST, SAT and SLP time series at each node of the gridded North Atlantic data. The correlation difference maps were calculated based on two methods, the simple

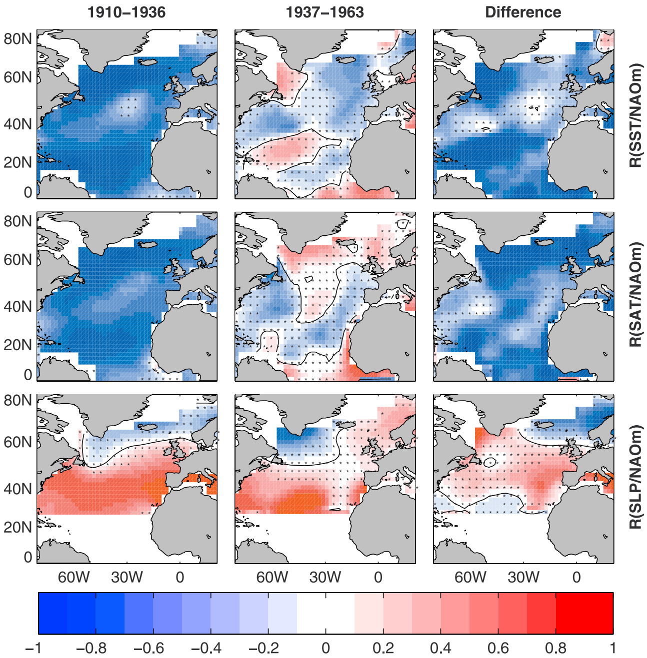

Figure 2. Correlation maps between the NAOm index and the (top) SST (°C), (middle) SAT (°C), and (bottom) SLP (hPa) for two time periods with marked different levels of correlations. The differences between the two periods are shown in the right column. Areas with statistical confidence less than 95% are stippled (Fisher's transform is used for these computations).

difference and the Fisher's z-transform, both of which produced nearly indistinguishable spatial structures. For this study, the simple difference was used. As expected, the SST/NAOm and SAT/NAOm correlation maps display similar spatial patterns: strongly negative correlations dominate the earlier period with maxima of $R \cong -0.9$ at ~(20°N, 50W) and (60°N, 55W); then in the latter period 1937–63, the spatial pattern becomes more variable with areas of positive and negative correlations all weaker than during the earlier period. This is reflected in the maps of correlation differences dominated by negative values. For both time periods, the spatial SLP/NAOm correlations are generally strong with negative (positive) correlations in the northern (southern) part of the sector. Note, the change of correlation sign (from negative to positive) in the northeastern part of the domain from 1910–36 to 1937–63. The map of correlation differences is dominated by positive values in the central part and negative values in the northeastern part of the North Atlantic.

[9] The spatial distributions of the North Atlantic climate parameters allow us to further demonstrate the lack of steadiness in the NAO paradigm. Figure 3 shows maps of the SST and SAT anomalies, their difference (i.e., SAT–SST), and the SLP and wind anomalies corresponding to the periods with very different correlations as shown in Figure 1. Again, as with correlation maps (Figure 2), the SST and SAT anomalies have very similar spatial structures. Generally, the SST and SAT anomalies are negative (except for the central part of the North Atlantic at ~50°N) in 1910–36; they become positive in 1937–63. This is consistent with the general trends displayed by the composite time series shown in Figure 1. As a result, the anomaly differences are strongly negative (right column of Figure 3). These anomalies are as large as anomalies associated with multi-decadal variability [*Kushnir*, 1994]. For a rough measure of air–ocean thermal interactions we calculated the difference between SST and SAT anomalies (third row of Figure 3). Negative differences (up to −0.2/−0.3°C) dominated both periods with similar spatial patterns. The largest difference is located in the northern North Atlantic: the maximum SST–SAT difference extends from the US eastern coast to northern Europe following a pattern roughly similar to that of Gulf Stream [*Deser and Blackmon*, 1993]. The SLP and wind anomalies (last row of Figure 3) are generally weaker in 1937–63 than in 1910–36 resulting in a difference map dominated by anomalies from the earlier period. Note that the striking negative correlation between the SST (SAT) and NAOm variations observed in 1910–36 is related to strong negative temperature anomalies and strong positive NAOm index values associated with amplified north-south pressure gradient between the subtropical high and the Icelandic low (Figure 3).

4. Discussion and Concluding Remarks

[10] We have examined the relationship between the NAOm index and key North Atlantic climate parameters using long-term records of North Atlantic SAT, SST, and SLP and show that decades of strong correlations alternate

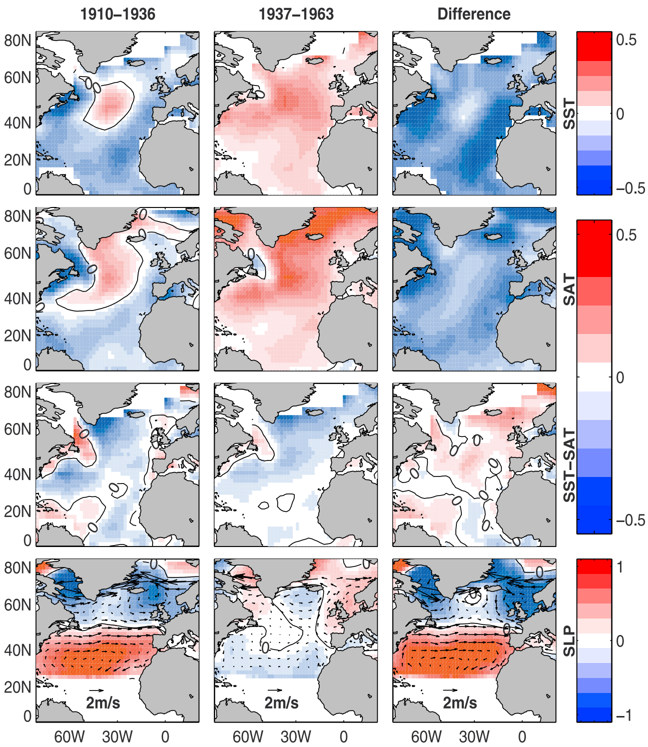

Figure 3. The SST, SAT, SAT-SST, and SLP maps for two periods with different correlation between the NAOm and the other climatic parameters. (top) SST (°C) anomalies, (second from top) SAT anomalies (°C), (second from bottom) SST–SAT (°C) anomalies, and (bottom) SLP (hPa) and geostrophic wind (m/s) anomalies. The right column shows the difference between the two periods.

with decades of insignificant or even of opposite sign correlations. Our analysis shows that these changes cannot be attributed to purely random processes (see Appendix A) and should be attributable to physical mechanisms. A clue to understanding such exceptions to the NAO paradigm may be found in the correlation level between the NAO and key climate parameters which appear to fluctuate in conjunction with phases of multi-decadal variability seen in the SST/SAT time series [*Enfield et al.*, 2001]. For example, the running SST/NAOm correlations are generally positive when SST is in its warm multi-decadal phase, it is negative otherwise. *Slonosky et al.* [2001] and *Schmith and Hansen* [2003] also found low-frequency modulation of the correlation time series between the NAO index and several regional parameters. We expect that the physics behind the changing relationship of NAO and the circulation/temperature in the North Atlantic could be tied to multi-decadal variability in the Arctic–North Atlantic region.

[11] Due to the short length of the available records (only one century), climate models and proxy records are needed for a better understanding of the physical processes associated with this changing relationship between climate variables. Our investigation of the NCAR CCSM3 multi-century control simulation indicates variations of the relationship at multi-decadal time scales similar to what we observe in this study. Further work is needed to investigate the possible physical mechanisms for such non-stationarities in the fundamental relationship between the NAO, the major mode of the North Atlantic variability, and key climate parameters.

Appendix A

[12] The low-frequency modulation of the relationship between the NAO and key North Atlantic parameters cannot be solely explained by random noise. To verify this, we added Gaussian noise to the time series of SST, SAT and SLP. This random noise was calculated using means and variances based on the entire time records of the corresponding parameters. The resulting noisy time series were used to calculate the running correlations with the NAOm time series; this process was repeated 1000 times. The blue shaded area (Figure 1, right) shows the range of the resulting correlations. For all parameters, this area is generally bounded by the Fisher's 95% confidence intervals shown by the red lines. However, for example, in the 1940–60s the uncertainty in the SAT/NAOm correlations estimated by the randomization method was higher compared to that based on Fishers confidence method. These two estimates suggest the observed change of relationship between the NAOm index and SST, SAT, and SLP time series should not be solely attributed to the random noise.

[13] A sensitivity analysis of our running correlation to the running window length (Figure 1) and time intervals (Figure 2) demonstrates the robustness of our conclusions. For example, the running correlations were computed with different sliding windows ranging from 15 to 30 years. These correlations are well correlated with the times series based on the "standard" 25 year window used in Figure 1 with $R = 0.70$ (0.93) for the 15 (30) year sliding window. Varying the period length for the correlation map analysis of Figure 2 also showed the robustness of the regional correlation estimates. Increasing the length of time period did not change the overall spatial structure of the correlation maps and correlation differences.

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References

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–6762.

Deser, C., and M. L. Blackmon (1993), Surface climate variations over the North Atlantic Ocean during winter: 1900–1989, *J. Clim.*, *6*, 1743–1753.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080.

Gershunov, A., N. Schneider, and T. Barnett (2001), Low-frequency modulation of the ENSO–Indian monsoon rainfall relationship: Signal or noise?, *J. Clim.*, *14*, 2486–2492.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (Eds.) (2002), *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, 279 pp., AGU, Washington, D. C.

Jones, P. D. (1987), The early twentieth century Arctic High—Fact or fiction?, *Clim. Dyn.*, *1*, 63–75.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan (1998), Analysis of global sea surface temperature 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589.

Kushnir, Y. (1994), Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions, *J. Clim.*, *7*, 141–156.

Overland, J. E., and M. Wang (2005), The Arctic climate paradox: The recent decrease of the Arctic Oscillation, *Geophys. Res. Lett.*, *32*, L06701, doi:10.1029/2004GL021752.

Peterson, K. A., J. Lu, and R. J. Greatbatch (2003), Evidence of nonlinear dynamics in the eastward shift of the NAO, *Geophys. Res. Lett.*, *30*(2), 1030, doi:10.1029/2002GL015585.

Portis, D. H., J. E. Walsh, M. E. Hamly, and P. J. Lamb (2001), Seasonality of the North Atlantic Oscillation, *J. Clim.*, *14*, 2069–2078.

Rogers, J. C., S. Wang, and D. H. Bromwich (2004), On the role of the NAO in the recent northeastern Atlantic Arctic Warming, *Geophys. Res. Lett.*, *31*, L02201, doi:10.1029/2003GL018728.

Schmith, T., and C. Hansen (2003), Fram Strait ice export during the Nineteenth and twentieth centuries reconstructed from a multiyear sea ice index from southwestern Greenland, *J. Clim.*, *16*, 2782–2791.

Slonosky, V. C., P. D. Jones, and T. D. Davies (2001), Atmospheric circulation and surface temperature in Europe from the 18th century to 1995, *Int. J. Climatol.*, *21*, 63–75.

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

Visbeck, M., E. P. Chassignet, R. Curry, T. Delworth, B. Dickson, and G. Krahmann (2002), The ocean's response to North Atlantic Oscillation variability, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, pp. 113–145, AGU, Washington, D. C.

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