Winter Northern Hemisphere surface air temperature variability associated with the Arctic Oscillation and North Atlantic Oscillation

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[1] The interannual variability of winter surface air temperature (SAT) in the Northern Hemisphere (NH) associated with the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) is studied. The AO and the NAO show different impacts on winter NH SAT variations. The AO affects the SAT over the Euro-Asian and African continents, whereas the NAO is more regional with the major effect on the SAT in the western North Africa. This discrepancy can be reflected in other atmospheric variables such as sea level pressure and geopotential height fields as well. The analyses in this paper also suggest that the AO-related signal can penetrate deeply into the stratosphere while the NAO one is largely a tropospheric phenomenon. **Citation:** Wang, D., C. Wang, X. Yang, and J. Lu (2005), Winter Northern Hemisphere surface air temperature variability associated with the Arctic Oscillation and North Atlantic Oscillation, *Geophys. Res. Lett.*, *32*, L16706, doi:10.1029/2005GL022952.

1. Introduction

[2] The Northern Hemisphere (NH) atmospheric variability in the winter has been extensively studied during the past decades. Two related modes have been identified in the high- and mid-latitudes: The Northern Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). The NAO is a regional phenomenon associated with meridional displacement of atmospheric mass over the North Atlantic [*Wallace and Gutzler*, 1981], whereas the AO is a hemispheric seesaw mode characterized with zonally symmetric and equivalent barotropic structure [*Thompson and Wallace*, 1998]. Some researchers advocated the inseparability of the two modes, especially in the boreal winter when the stratospheric and tropospheric anomalies couple [*Rogers and McHugh*, 2002]. Following the study by *Deser* [2000] who found the weak correlations between the Atlantic and Pacific centers of the AO paradigm, *Ambaum et al.* [2001] suggested that the NAO paradigm may be more physically relevant and robust for NH climate variability than the AO paradigm. These results gave rise to a heated dispute on the physical reality of the AO [e.g., *Itoh*, 2002; *Christiansen*, 2002a].

[3] Many studies have been performed to distinguish the two mode patterns recently [e.g., *Monahan et al.*, 2000; *Kodera*, 2002]. By the non-linear analysis of regime transitions, *Christiansen* [2002b] demonstrated the strong connection between the AO and stratospheric variability, thereby partitioning the AO mode and the primarily troposphere-confined NAO mode. This result has been further confirmed by model simulations [*Boer et al.*, 2001; *Tanaka and Tokinaga*, 2002]. More recently, *Kodera and Kuroda* [2003] succeeded in distinguishing the NAO- and AO-related variations as regional and hemispheric features respectively and proposed a physical mechanism for the AO. They suggested that the AO is produced through changes in vertical motion in the polar region driven by waves in the troposphere and lower stratosphere. Subsequently, *Kodera and Kuroda* [2004] further showed that the NAO and the AO represent two independent teleconnection patterns in the sea level pressure: One is a sea level pressure (SLP) seesaw between the Azores and Iceland (AI) and the other one is between the Polar and Mediterranean (PM) region. The differences in the NAO and AO indices mainly arise from the inclusion of different portions of the AI and PM. *Wang and Ikeda* [2000] identified the leading Sea-Ice Area (SIA) mode as AO-related and the second SIA mode as NAO-related, which served to differentiate the AO and NAO by the atmosphere-ice interaction mechanism.

[4] In previous studies, the impacts of the AO and the NAO on NH surface air temperature (SAT) are collectively examined by a linear correlation or regression with one of these two indices (see the recent NAO book by *Hurrell et al.* [2003]). The purpose of the present paper is in attempt to distinguish variability of winter NH SAT associated with the NAO and the AO. The paper shows that the NAO and the AO have different impacts on winter NH SAT. The variability of other atmospheric variables related to the AO and the NAO is discussed.

2. Data

[5] *Hurrell* [1996] defines the NAO index as the difference of normalized SLP anomalies between Lisbon, Portugal and Stykkisholmur, Iceland. *Wanner et al.* [2001] point out that the station-based NAO index does not capture well the NAO pattern. *Lu and Greatbatch* [2002] show that the SLP pattern associated with the NAO exhibits an eastward shift since the late 1970s. Moreover, individual-station pressures are significantly affected by small-scale and transient meteorological phenomena not related to the NAO and, thus, contain noise. Here we use the NAO definition by *Barnston and Livezey* [1987]—the leading rotated principal component of monthly mean 700 hPa height anomalies. The AO index is determined by projec-

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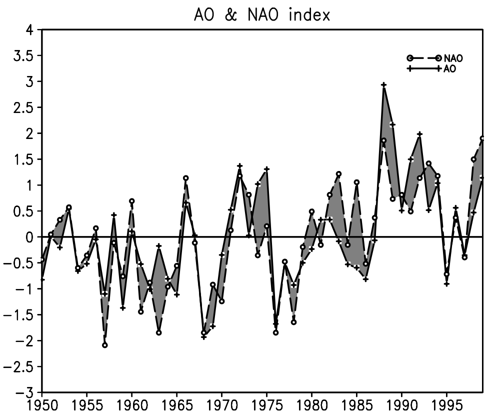

Figure 1. Time series of the normalized AO index (solid) and NAO index (dashed with open circle). The trend coefficients are 0.0256 yr^{-1} for the AO index and 0.0197 yr^{-1} for the NAO index.

ting the monthly mean 1000 hPa height poleward of 20°N onto its first leading EOF mode [*Thompson and Wallace*, 1998]. The seasonal cycle has been removed.

[6] The monthly-mean SAT data over land is from *Willmott and Matsuura* [1995], with a spatial resolution of 1° × 1° grid. All the other monthly atmospheric variables are based on the NCEP/NCAR reanalysis dataset [*Kalnay et al.*, 1996] with a 2.5° × 2.5° grid. The months of December–March (DJFM) are averaged to denote the boreal winter-averaged data. The period of analysis is chosen from January 1950 to March 2000, with the exception of the surface air temperature that spans from January 1950 to March 1999.

3. Results

3.1. The NAO and AO Indices

[7] The normalized winter mean AO and NAO time series are shown in Figure 1 with the shaded areas denoting their differences. Both indices display a tendency of shift from negative to positive phase around the 1970s. The trend coefficients are calculated by linear regression of the indices on time, being 0.0256 yr^{-1} for the AO and 0.0197 yr^{-1} for the NAO. The previous studies indicate that this upward trend can explain much of variance for the NH warming of the past 30 years [*Thompson et al.*, 2000; *Ostermeier and Wallace*, 2003]. As this paper primarily focuses on interannual variability, the secular trend is subtracted from the original indices. Interannually, the NAO and AO indices are similar, with a correlation of 0.74. However, differences remain quite notable for some periods as the year of 1974, 1980, 1981, 1983 and 1985 during which the two indices are nearly out-of-phase.

[8] Spatial structures of SLP associated with the NAO and the AO can be examined by performing a linear regression of SLP field onto the two indices. The NAO and the AO display a similar SLP distribution over the Atlantic-Europe region (not shown). For both the NAO and the AO, the north-south seesaw patterns of SLP emerge between the mid-latitude and polar region with the phase-shift node around 50°N. However, the southern SLP center of the AO elongates closer to Euro-Asian continent, which, combined with its much stronger Pacific center, gives the prominent annular structure of the AO [also see *Thompson and Wallace*, 1998, 2000; *Wallace and Thompson*, 2002].

3.2. Surface Air Temperature Variability

[9] The correlation distributions of NH surface air temperature (SAT) over land with the AO and NAO indices are shown in Figures 2a and 2b, respectively. Both the AO and NAO show positive correlations over the mid- and high-latitude Euro-Asian continent and the east/southeast of the United States, whereas negative correlations are located over Greenland, eastern Canada and the entire North African continent. Nevertheless, discrepancies of the two modes can be found over Northeast Asia, Middle East and tropical North Africa where the correlations between the AO and SAT are above 95% significant level, but not true for the NAO.

[10] To isolate the impacts of the AO and the NAO on SAT, we perform partial correlation analysis. For three variables of y, x_1, and x_2, the partial correlation is:

$$R_{y,x_1,x_2} = \frac{R_{y,x_1} - R_{x_1,x_2} \times R_{y,x_2}}{\sqrt{\left(1 - R^2_{y,x_2}\right) \times \left(1 - R^2_{x_1,x_2}\right)}}$$

where R_{y,x_1,x_2} denotes the partial correlation of y and x_1 with the contribution of x_2 being extracted from both, while R_{y,x_1} the original correlation of the two variables. The partial correlation is calculated by regressing y on x_2 and regressing x_1 on x_2, respectively, then performing the linear correlation for residuals of y and that of x_1. In this sense, it is similar to the analysis of subtracting a "linear congruent part" [*Thompson*

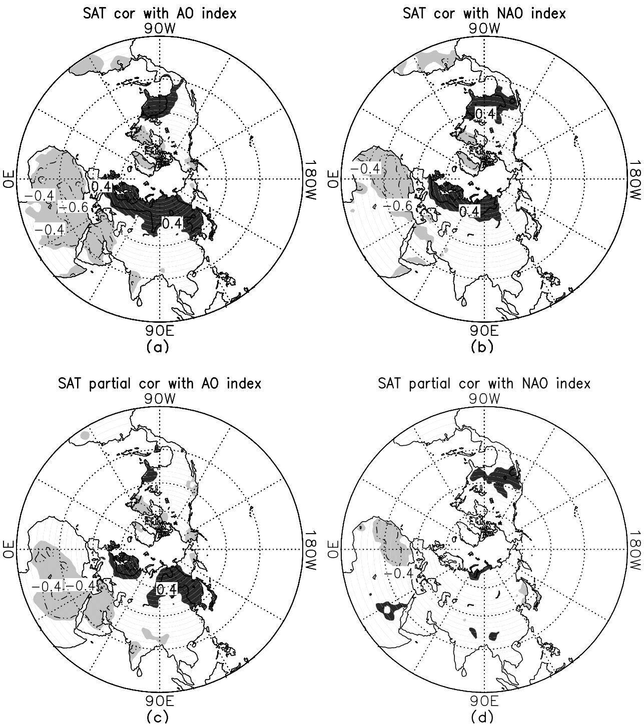

Figure 2. Correlations of surface air temperature over land with detrended (a) the AO index, and (b) the NAO index; The contour interval is −0.6, −0.4, 0.4, 0.6; The shaded areas denote correlations exceed 95% confidence level t-test; (c), (d), the same as (a), (b) but for the partial correlations.

Table 1. Correlation Coefficients of AO and NAO With Three SAT Indices,[a] as Well as Their Corresponding Partial Correlation Coefficients When Removing the Influence of the Other Mode[b]

	Correlation Coefficients			Partial Correlation Coefficients		
	ENAME	WNA	NEA	ENAME	WNA	NEA
AO	**−0.598**	**−0.564**	**0.513**	**−0.556**	−0.237	**0.40**
NAO	**−0.308**	**−0.636**	**0.351**	0.162	**−0.419**	0.007

[a]Eastern North Africa and Middle-East (ENAME), 15°∼60°E, 5°∼45°N; western North Africa (WNA), 15°W∼15°E, 20°∼40°N; Northeast Asia (NEA), 90°∼150°E, 40°∼70°N.

[b]The bold items are the coefficients above the 95% significant level.

et al., 2000]. If the original correlation is significant but the case is not for partial correlation, the original correlation is assumed as spurious—no direct causal link exists between y and x_1. In this way, the independent contribution of x_1 to y can be singled out. Since the partial correlation still requires meeting all the usual assumption of Pearsonian correlation, the significance test of partial correlation used here is the same as that of common linear correlation—Student's t-test. The partial correlation between the AO and SAT removing the NAO in Figure 2c shows a similar pattern with Figure 2a except for the northernmost Africa. When the influence of the AO is removed, the area of partial correlation between the NAO and SAT above the 95% significant level is largely shrunken (Figure 2d).

[11] The relationships can be more clearly seen by focusing on three regions: eastern North Africa and Middle-East (ENAME) (15°∼60°E, 5°∼45°N), western North Africa (WNA) (15°W∼15°E, 20°∼40°N), and Northeast Asia (NEA) (90°∼150°E, 40°∼70°N). The correlations and the partial correlations of the AO and the NAO with SAT in these three regions are listed in Table 1. Table 1 shows that the AO and the NAO are significantly correlated with the SAT over these three regions (all above the 95% significant level based on the Student's t-test). However, the partial correlations between the AO and SAT after removing the NAO are significant over the ENAME and NEA, whereas the partial correlations between the NAO and SAT after removing the AO are significant only in the WNA region. These suggest that the SAT over the ENAME and NEA is mostly related to the AO and the SAT in the WNA region is more associated with the NAO.

3.3. Atmospheric Circulation Associated With the AO and NAO

[12] To examine individual effects of the AO and the NAO on NH atmospheric circulation, we extend the partial correlation analysis to other atmospheric variables. Figure 3 shows the partial correlation maps of the AO and the NAO with SLP, 500 hPa and 50 hPa geopotential height. Two points can be made from Figure 3. First, the AO can affect the whole NH atmosphere (Figures 3a, 3c, and 3e), whereas the main influence of the NAO is on the region of the Atlantic (Figures 3b, 3d, and 3e). Second, the effects of the AO can reach deeply into the stratosphere (Figure 3e) and it displays coherent pattern throughout the whole atmospheric level—an equivalent barotropic structure as mentioned in previous works [e.g., *Thompson and Wallace*, 1998]; however, the NAO is confined only in the troposphere (Figure 3f).

[13] The partial correlations of the AO and the NAO with the zonal wind anomalies over Euro-Asia (0°E–150°E) and the Atlantic (90°W–0°E) are shown in Figure 4. Again, the AO affects both the troposphere and stratosphere and exhibits greater zonal symmetry in the stratosphere (Figures 4a and 4c) and the impacts of the NAO are only confined in the troposphere (Figures 4b and 4d). Comparison of Figures 4a and 4b shows that the correlation amplitudes are largely reduced when the AO is removed from the correlation map between the zonal wind and the NAO, suggesting that the NAO is a regional phenomenon.

4. Summary

[14] Some of previous studies treat the AO and the NAO as similar phenomena, if not identical [e.g., *Wallace*, 2000]. Therefore, their impacts on winter NH variability are

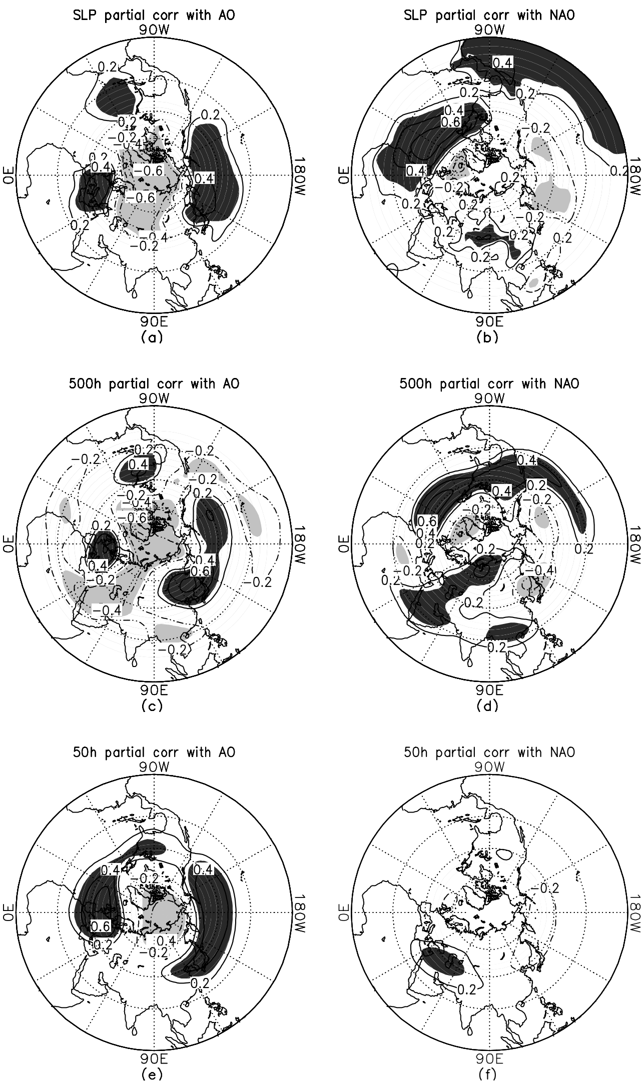

Figure 3. Partial correlation of sea level pressure with (a) the AO index (removing NAO), and (b) the NAO index (removing AO). The contour interval is −0.6, −0.4, −0.2, 0.2, 0.4, 0.6; The shaded areas denote correlations exceed 95% confidence level t-test. (c), (d), the same as (a), (b), but for 500 hPa geopotential height; (e), (f), the same as (a), (b), but for 50 hPa geopotential height.

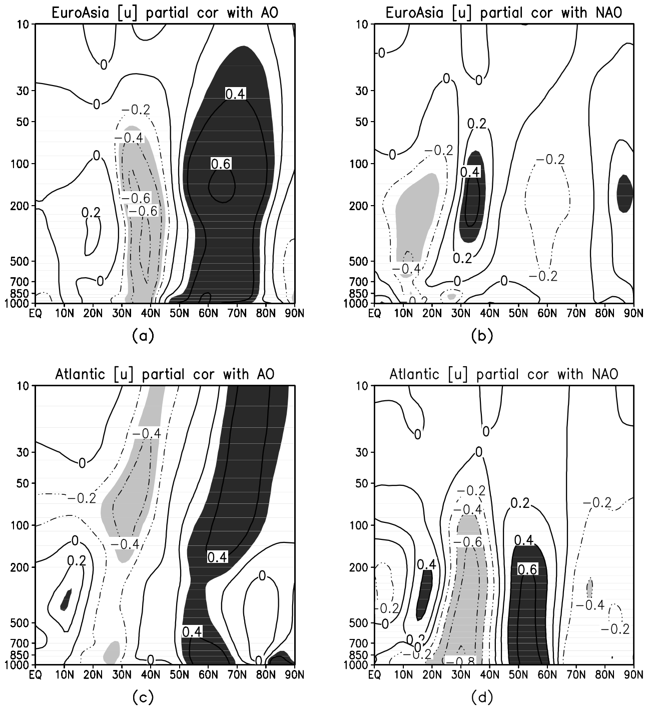

Figure 4. Latitude-altitude section of the partial correlation between Euro-Asian continent zonal mean (0∼150° E) zonal wind and (a) the AO index (removing NAO), (b) the NAO index (removing AO); (c), (d) the same as (a), (b), but for Atlantic zonal mean (90°W∼0°E) zonal wind. The contour interval is 0.2. The shaded areas denote the correlations exceed 95% confidence level t-test.

usually estimated by a linear correlation or regression with either the AO or NAO index [*Hurrell et al.*, 2003]. This note uses the partial correlation analysis to distinguish different influences of the AO and the NAO on winter NH SAT and other atmospheric variables. The correlations after removing the NAO show that the positive (negative) AO phase corresponds to the warm (cold) weather conditions in the northern part of Euro-Asian continent and cold (warm) weather conditions in most of Africa and Middle-East. When the AO is removed, it is shown that the NAO can only significantly affect the SAT in the western North Africa. Our analyses also suggest that the AO is a hemispheric phenomenon that can affect variability of the whole Northern Hemisphere and the NAO is a regional one that mainly influences the variations in the region surrounding the Atlantic. This study shows that the AO can reach deeply into the stratosphere, whereas the NAO is only confined in the troposphere, consistent with previous studies.

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