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# Enhancement of the Summer North Atlantic Oscillation Influence on Northern Hemisphere Air Temperature

YUAN Wei*[1] (袁 薇) and SUN Jianqi[2] (孙建奇)

[1] *China Meteorological Administration Training Centre, Beijing* 100081

[2] *Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

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**ABSTRACT**

This study investigates the relationship between the summer North Atlantic Oscillation (SNAO) and the simultaneous Northern Hemisphere (NH) land surface air temperature (SAT) by using the Climate Research Unit (CRU) data. The results show that the SNAO is related to NH land SAT, but this linkage has varied on decadal timescales over the last 52 years, with a strong connection appearing after the late 1970s, but a weak connection before. The mechanism governing the relationship between the SNAO and NH land SAT is discussed based on the NCEP/NCAR reanalysis data. The results indicate that such a variable relationship may result from changes of the SNAO mode around the late 1970s. The SNAO pattern was centered mainly over the North Atlantic before the late 1970s, and thus had a weak influence on the NH land SAT. But after the late 1970s, the SNAO pattern shifted eastward and its southern center was enhanced in magnitude and extent, which transported the SNAO signal to the North Atlantic surrounding continents and even to central East Asia via an upper level wave train along the Asian jet.

**Key words**: Summer North Atlantic Oscillation, surface air temperature, wave train

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## 1. Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of natural climate variability in the North Atlantic and for the surrounding continents (Wallace and Gutzler, 1981; Hurrell et al., 2003). It features primarily a large-scale seesaw in atmospheric mass between the subtropical high and the polar low. The NAO has been extensively studied in the past century. It is found that the NAO has a profound influence on the precipitation and temperature over the North Atlantic and the surrounding regions of North America, Europe (Hurrell, 1995; Pekarova and Pekar, 2007), and North Africa (Li et al., 2003). In addition, the NAO even has far-reaching impacts on the Asian winter (Wu and Huang, 1999) and summer (Yang et al., 2004; Lu et al., 2006) monsoon systems, Eurasian snow cover (Bojariu and Gimeno, 2003), temperature east of the Tibetan Plateau in March (Yu and Zhou, 2004), and the winter circulation over the Ural Mountains (Li, 2004).

Given the importance of the NAO, its variability and causes have also been the focus of intense research. Some previous studies have revealed that the NAO exhibits a strong interannual and decadal variability (e.g., Hurrell et al., 2003). The primary sources of this variability are interactions between and within climate sub-systems, such as the atmosphere (Robinson, 1996), ocean (Li et al., 2007), and land surfaces (Bojariu and Gimeno, 2003; Saito and Cohen, 2003; Saunders et al., 2003). Bojariu et al. (2008) further addressed that the land-atmosphere interaction over the huge continental mass of Eurasia produces a persistence of the Arctic Oscillation (AO)/NAO-like pattern throughout the annual cycle.

Recently, Hilmer and Jung (2000) have noticed one new feature of NAO variability in winter: an eastward shift of the NAO pattern occurred in 1978–1997 as compared to 1958–1977. Following this decadal shift of the NAO pattern, its relationships with many

*Corresponding author: YUAN Wei, yuanwei@cma.gov.cn

variables, such as sea ice export through the Fram Strait, Siberian wintertime temperatures, North Atlantic storm activity, and the Eurasian cryosphere have all become correlated significantly (Lu and Greatbatch, 2002; Bojariu et al., 2008). Further analyses indicate that such spatial shift of the NAO pattern may be related to trend towards higher NAO index during the last several decades of the 20th century (Peterson et al., 2003), storm activity over the North Atlantic (Lu and Greatbatch, 2002), and anthropogenic climate change (Ulbrich and Christoph, 1999).

The NAO is also one of the teleconnection patterns that have a year-round presence, although it is most active during winter as mentioned in the above studies. It has been claimed that the summer NAO (SNAO) also explains a large portion of the total variance in the atmospheric circulation over the North Atlantic region (Hurrell et al., 2003). Hurrell and Folland (2002) examined the variation of the southern center of the SNAO, and studied its climatic influence, finding that the southern center of the SNAO shows strong interannual to multi-decadal variations and impacts summer climate over the North Atlantic and surrounding regions. More recently, Sun et al. (2008) investigated the decadal variation of the SNAO, and found that the SNAO pattern experienced a shift along with the globally abrupt climate change around the late 1970s. The motivation of this study is to investigate if and how decadal changes of the SNAO alter its relationship with climate over the Northern Hemisphere (NH).

## 2. Data

The atmospheric circulation data utilized are from the reanalysis produced by the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996). The variables analyzed include winds, geopotential heights, and thickness. According to the classification proposed by NCEP/NCAR, all the variables involved in this study are strongly influenced by observed data (class A), indicating that the results concluded from these data analysis are reliable.

The monthly land SAT data are extracted from the Climate Research Unit (CRU, Norwich, U.K., dataset: CRU TS 2.1) (Mitchell and Jones, 2005), which cover the global land surface at 0.5° resolution. The NAO index used is the difference between the normalized sea level pressures (SLPs) over Gibraltar and Reykjavik, Iceland. Considering there is a decadal scale change of the SNAO variability around the late 1970s (Fig. 1), the following analysis is performed within two subperiods of equal length: 1951–1975 and 1978–2002.

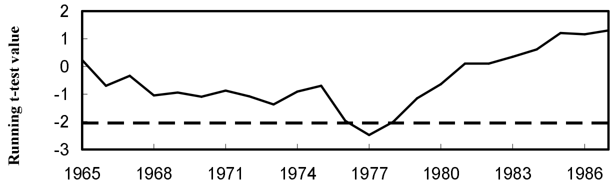


**Fig. 1.** Running $t$-test values for the SNAO index with a 15-year window width for the period of 1951–2002. Dashed line indicates the 5% significance level.

## 3. Relationship between the SNAO and NH land SAT

Figure 2a shows the correlation map between the SNAO and NH land SAT in summer (July–September) during the period 1951–1975. It suggests that the correlations during this period are weak in general. Except for a significant negative correlation region over northern Africa and several other small significant positive correlation regions sparsely spread over Eurasia and northern Africa, most of the NH continental areas

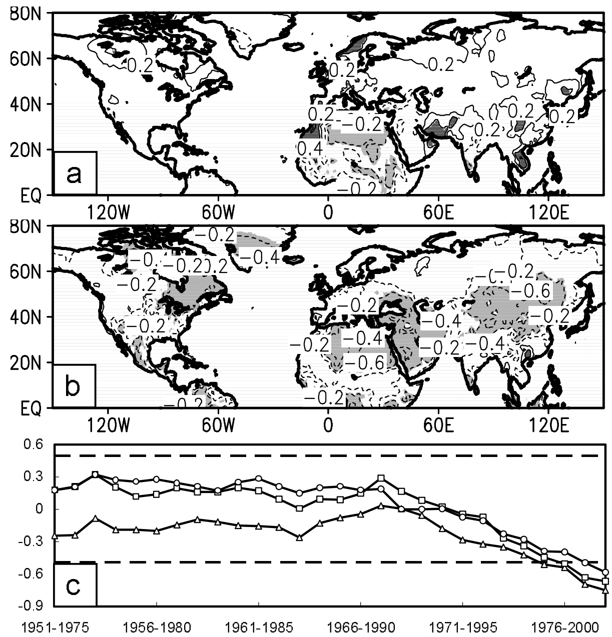


**Fig. 2.** Geographical distribution of the correlation coefficients between the SNAO and CRU land SAT in summer over the periods of (a) 1951–1975 and (b) 1978–2002, as well as (c) running correlations between the SNAO index and SAT indices for north Africa-Mediterranean sea region (curve with triangle), northeastern North American (curve with circle), and central East Asia (curve with square) with a 25-year window width for the period of 1951–2002. Dark (light) shading in (a) and (b) shows areas where SAT significantly correlates positively (negatively) with the SNAO index at the 5% significance level, and dashed line in (c) indicates the 1% significance level.

have quite weak correlation during this period, indicating the connection between the SNAO and NH land SAT was tenuous at this time. However, this situation is changed after the late 1970s (1978–2002). As shown in Fig. 2b, the significant correlation regions are enlarged as compared to the period 1951–1975. There are three major significant correlation regions over the NH continent. The aforementioned significant negative correlation over northern Africa now extends to cover not only northern Africa but also most of the Mediterranean region, forming the largest significant negative correlation center. Another significant correlation center is located over northeastern North America. In addition, there is a significant negative correlation center over central East Asia as well, which is consistent with the results of Sun et al. (2008) based on 160 stations of temperature data in China.

A similar result is found from an additional index analysis. The SATs for the northern Africa-Mediterranean Sea region, northeastern North America and central East Asia are measured respectively by indices defined as the mean SATs over the regions, (20°–50°N, 0°–60°E), (40°–60°N, 90°–60°W), and (35°–60°N, 70°–120°W). Figure 2c shows the running correlations between the SNAO index and these three SAT indices with a 25-year window width for the period of 1951–2002. It demonstrates that the running correlations become more negative with the time, and the significant correlations only appear for the period after the mid-1970s.

This decadal change of the correlation between the SNAO and NH land SAT may to some extent result from the decadal change of these two climatic systems' variability. Figure 3 displays the normalized indices of the SNAO and the mean NH land SAT for the whole period from 1951 to 2002. It displays that these two indices exhibit an abrupt decadal scale change around the late 1970s. During the period 1951–1975, the mean NH land SAT displays a significant decreasing trend, while the SNAO does not have much trend. Thus, in

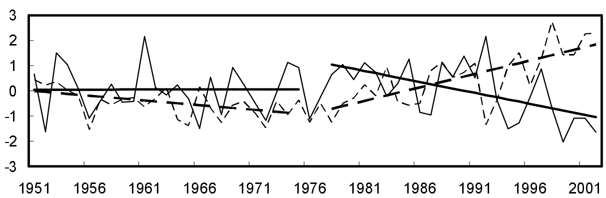


**Fig. 3.** Normalized indices of the SNAO (solid curve) and mean NH land SAT (dashed curve) over the period of 1951–2002. The mean NH land SAT is defined as the averaged SAT from the CRU data over the whole NH. The solid (dashed) line indicates the linear trend for the SNAO (the mean NH land SAT) over the periods of 1951–1975 and 1978–2002.

this period, the variabilities of the SNAO and the mean NH land SAT are inconsistent, and consequently the correlation between the two is low. On the contrary, during 1978–2002 the SNAO has a significant decreasing trend, while the mean NH land SAT shows a strongly accelerated warming trend. The variabilities of these two indices are highly consistent and out of phase, so their correlation becomes now significantly negative.

## 4. Mechanism for the variable relationship between the SNAO and NH land SAT

The variability of SAT is closely related to the fluctuations and changes in atmospheric circulations. Thus, the SNAO-related atmospheric circulations are now analyzed in order to explore the mechanism for the variable relationship between the SNAO and NH land SAT. Also, the SNAO-related atmospheric circulation is investigated in two sub-periods: 1951–1975 and 1978–2002.

Figures 4a and 4b show, respectively, the linear regression patterns of 1000 hPa geopotential height and horizontal wind against the SNAO index during these two sub-periods. There is a significant difference between the two sub-periods' circulations. Over the period before the late 1970s, the anomalous circulations associated with the SNAO are mainly located over the North Atlantic. The northern center of SNAO is to the south of Greenland, and the southern center is over the middle Atlantic extending to coastal Europe. However, during the period after the late 1970s the centers of the SNAO shift eastward. In particular, the southern center of the SNAO moves to dominate the Mediterranean Sea region, and the anomalous magnitude and extent of the SNAO southern center are both remarkably strengthened. The central value is doubled compared to the former period. The SNAO-related significant circulation now dominates most of the middle North Atlantic and surrounding continents. Additionally, the influence of the SNAO extends eastward at this time, with a strong positive anomalous center over northern Russia. The eastward extension of the SNAO influence is more clearly exhibited at the upper levels. As shown in Fig. 4d, over the latter sub-period, there is a significant zonal wave train along the Asian upper level jet. Meanwhile, over the former sub-period there is no such zonal wave train (Fig. 4c). Thus, in the latter sub-period, the SNAO can influence the SAT over the downstream region via the impact on the wave train pattern trapped in the Asian upper level jet.

Branstator (2002) pointed out that the wave train teleconnection trapped in the upper level jet stream

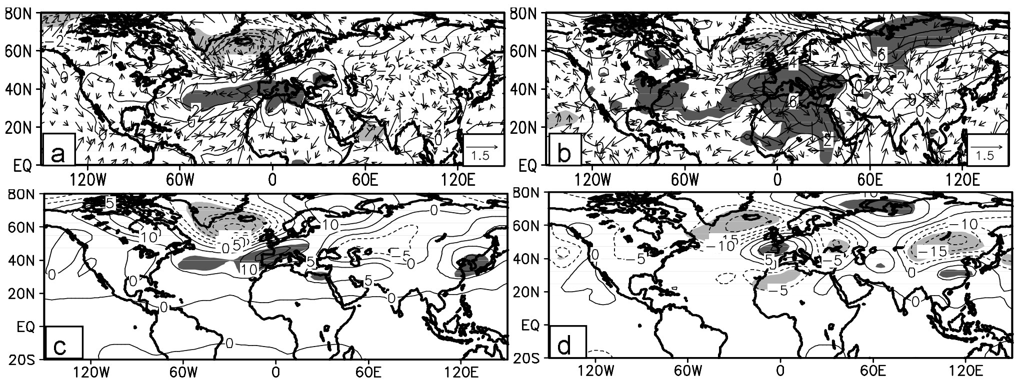

**Fig. 4.** Patterns obtained by regressing the summer geopotential heights and horizontal wind against the SNAO index at 1000 hPa (a, b) and 250 hPa (c, d) in 1951–1975/1978–2002. Dark (light) shading shows areas where the correlation between the geopotential height and SNAO index is positively (negatively) significant at the 5% significance level.

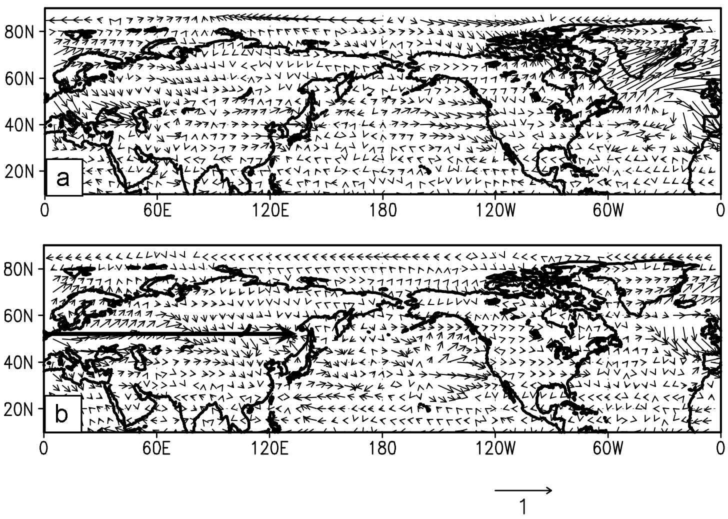

**Fig. 5.** Horizontal stationary wave activity flux (units: $m^2$ $s^{-2}$) at 500 hPa associated with the SNAO pattern in (a) 1951–1975 and (b) 1978–2002.

can also make a contribution to the variability of the NAO in wintertime. Under the influence of the circumglobal waveguide pattern, the NAO exhibits more hemispheric distribution. This motivates us to believe that the wave train teleconnection revealed in this study might to some extent also contribute to the extension and intensification of the southern center of the SNAO in the latter sub-period. There could be a positive feedback between the SNAO and the upper level wave train pattern, which results in the persistence of the impact of the SNAO on the downstream SAT. Of course, this hypothesis needs to be confirmed by further analysis in a future study.

At the upper level, the SNAO-related atmospheric circulations over the North Atlantic region have remarkable differences, as well, between these two sub-periods. For the former sub-period, the SNAO-related anomalous circulation features a meridional dipole pattern mainly over the North Atlantic. But for the latter sub-period, the SNAO-related anomalous circulation shows a tripole pattern with a northwest-southeast tilt. The latter sub-period circulation dominates more land areas relative to the former sub-period, which is consistent with the SNAO-related lower level circulation and land SAT anomalies.

The wave activity in the atmosphere is used to describe the atmospheric motions and variability. Here, the SNAO-related wave activity fluxes are analyzed to understand why there is a significant difference of the SNAO-related circulation patterns and their impact on the NH land SAT between these two sub-periods. Figure 5 shows the wave activity flux for the anomalous stationary waves from the height anomalies obtained from the regression of the summer heights against the

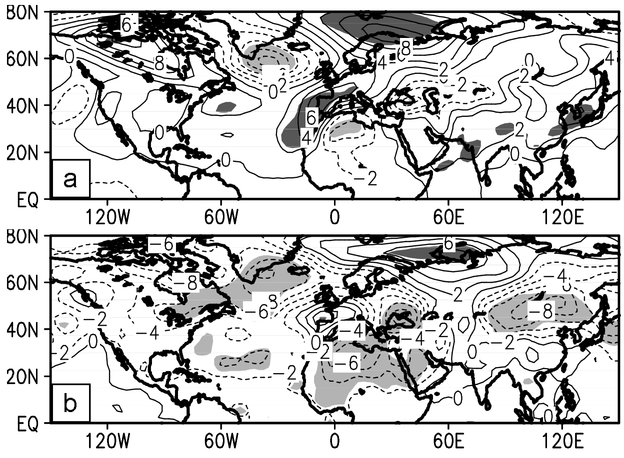


**Fig. 6.** As in Fig. 4, except for the summer 500–1000 hPa thickness.

SNAO index. This method is similar to what Karoly et al. (1989) did for several cases including the Pacific-North America (PNA) pattern. It suggests that in the former sub-period, the SNAO-related anomalous wave activities are strong in the North Atlantic, but are relatively weak in other regions. On the contrary, in the latter sub-period the SNAO-related anomalous wave activities extend more significantly. These cover most of middle-latitudes of the NH during that time. An eastward wave propagation occurs over the Eurasian Continent-North Pacific region which is exported from the North Atlantic. The enhanced wave activity over the latter sub-period thus significantly extends the influence of the SNAO to more land regions.

The aforementioned different circulation consequences of the SNAO in the two sub-periods result in different tropospheric air temperature responses over the NH. As shown in Fig. 6a, similar to the SNAO-related atmospheric circulation distributions in the former sub-period, significant 500–1000 hPa thickness anomalies are mainly located over the North Atlantic region. Over the NH continents, there are several small significant anomalies sparsely distributed. However, for the latter sub-period, there exist four large-scale significant negative anomalous regions. They are located, respectively, over the northern Africa-Mediterranean Sea region, central East Asia, the eastern North America-southern Greenland-northern North Atlantic region, and the central North Atlantic region. Additionally, there is a significant positive anomaly over the Arctic Sea around Nova Island. In addition, the regions of significant cold/warm tropospheric air in Fig. 6 are consistent with those of cold/warm land SAT in Fig. 2, which further confirms the changing relationship between the SNAO and the NH land SAT with time.

## 5. Conclusions and discussions

This study explores the relationship between the SNAO and the simultaneous NH land SAT. It is found that this relationship is different over the periods before and after the late 1970s when a globally abrupt climate change occurred. Over the former sub-period, the only SNAO-related large-scale land SAT anomaly is over northern Africa. In contrast, over the latter sub-period, the situation is changed. The variability of the SNAO is related to the SAT over the northern Africa-Mediterranean Sea region, central East Asia, and northeastern North America. Such a different relationship between the SNAO and NH land SAT over these two sub-periods could result from the changes of the NAO mode observed around the late 1970s. Before the late 1970s, the SNAO centers are located mainly over the North Atlantic. Thus, the SNAO's dominant influence is over the North Atlantic. At that time SNAO influence on the land areas is quite weak. But after the late 1970s, the SNAO pattern and its related circulations shift eastward. In addition, the SNAO's southern center is also enhanced in magnitude and extent. Such changes of the SNAO-related atmospheric circulations extend its impact, consequently resulting in anomalous SAT over more land regions. Of course, the strong statistical link between the SNAO and NH SAT after the late 1970s revealed here is merely based on observational data. In a future study, the response of the NH SAT to the prescribed wind anomalies associated with the SNAO pattern should be evaluated based on climate models, to further confirm the mechanism and impact of the SNAO on the NH land SAT.

In addition, it is well known that since the mid-late 1970s, the global SAT shows an accelerated warming, which is quite similar to the NH land SAT variability shown in Fig. 3. Under this background, many climatic systems exhibit a decadal change. One of the interesting aspects of this study is that the spatial shift of the SNAO and the strong correlation between the SNAO and NH land SAT occur over the period after the middle 1970s when the global warming is remarkably accelerated. So this implies that anthropogenic climate change may play a role in the SNAO pattern shift and its related enhancement of the relationship with the NH land SAT. Nevertheless, it is still possible that the eastward shift of the SNAO pattern and the changing relationship between the SNAO and the NH land SAT may simply be part of the natural variability of the climate system. Further work, especially using coupled climate models with and without the forcing of the increasing greenhouse gas concentrations, is needed to resolve the above issues.

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## REFERENCES


Bojariu, R., and L. Gimeno, 2003: The influence of snow cover fluctuations on multiannual NAO persistence. *Geophys. Res. Lett.*, **30**, 1156, doi: 10.1029/2002GL015651a.

Bojariu, R., R. Garcia-Herrera, L. Gimeno, T. Zhang, and O. W. Frauenfeld, 2008: Cryosphere-atmosphere interaction related to variability and change of Northern Hemisphere annular mode. *Trends and Directions in Climate Research: Annals of the New York Academy of Sciences*, **1146**, Gimeno et al., Eds., Wiley-Blackwell, 50–59.

Branstator, G., 2002: Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation. *J. Climate*, **15**, 1893–1910.

Hilmer, M., and T. Jung, 2000: Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. *Geophys. Res. Lett.*, **27**, 989–992.

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

Hurrell, J. W., and C. K. Folland, 2002: A change in the summer atmospheric circulation over the North Atlantic. *Exchanges*, **25**, 1–3.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeckand Eds., 2003: *The North Atlantic Oscillation: Climatic Significance and Environmental Impact. Geophysical Monograph Series*, No. 134, American Geophys. Union., Washington D. C., 279pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteorol. Soc.*, **77**, 437–471.

Karoly, D. J., R. A. Plumb, and M. Ting, 1989: Examples of the horizontal propagation of quasi-stationary waves. *J. Atmos. Sci.*, **46**, 2802–2811.

Li, S. L., 2004: Impact of the Northwest Atlantic SST anomaly on the circulation over the Ural Mountains. *J. Meteor. Soc. Japan.*, **82**(4), 971–988.

Li, S. L., W. A. Robinson, and S. Peng, 2003: Influence of the North Atlantic SST tripole on northwest African rainfall. *J. Geophys. Res.*, **108**(D19), 4594–4610.

Li, S. L., W. A. Robinson, M. P. Hoerling, and K. M. Weickmann, 2007: Dynamics of the extratropical response to a tropical Atlantic SST anomaly. *J. Climate*, **20**(3), 560–574.

Lu, J., and R. J. Greatbatch, 2002: The changing relationship between the AO/NAO and northern hemisphere climate variability. *Geophys. Res. Lett.*, **29**, 1148, doi: 10.1029/2001GL014052.

Lu, R., B. Dong, and H. Ding, 2006: Impact of the Atlantic multidecadal oscillation on the Asian summer monsoon. *Geophys. Res. Lett.*, **33**, L24701, doi: 10.1029/2006GL027655.

Mitchell, T. D., and P. D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, **25**, 693–712.

Pekarova, P., and J. Pekar, 2007: Teleconnection of interannual streamflow fluctuation in Slovakia with Arctic Oscillation, North Atlantic Oscillation, Southern Oscillation, and Quasi-biennial Oscillation phenomena. *Adv. Atmos. Sci.*, **24**(4), 655–663, doi: 10.1007/s00376-007-0655-z.

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

Robinson, W. A., 1996: Does eddy feedback sustain variability in the zonal index? *J. Atmos. Sci.*, **53**, 3556–3569.

Saito, K., and J. Cohen, 2003: The potential role of snow cover in forcing interannual variability of the major Northern Hemisphere mode. *Geophys. Res. Lett.*, **30**, 1302, doi: 10.1029/2002GL016341.

Saunders, M. A., B. Qian, and B. Lloyd-Hughes, 2003: Summer snow extent heralding of the winter North Atlantic Oscillation. *Geophys. Res. Lett.*, **30**, 1378, doi: 10.1029/2002GL016832.

Sun, J. Q., H. J. Wang, and W. Yuan, 2008: Decadal variations of the relationship between the summer North Atlantic Oscillation and middle East Asian air temperature. *J. Geophys. Res.*, **113**, D15107, doi: 10.1029/2007JD009626.

Ulbrich, U., and M. Christoph, 1999: A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dyn.*, **15**, 551–559.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.*, **109**, 784–812.

Wu, B. Y., and R. H. Huang, 1999: Effects of the extremes in the North Atlantic Oscillation on East Asia winter monsoon. *Chinese. J. Atmos. Sci.*, **23**, 641–651. (in Chinese)

Yang, S., K. M. Lau, S. H. Yoo, J. L. Kinter, K. Miyakoda, and C. H. Ho, 2004: Upstream subtropical signals preceding the Asian summer monsoon circulation. *J. Climate*, **17**, 4213–4229.

Yu, R. C., and T. J. Zhou, 2004: Impacts of winter-NAO on March cooling trends over subtropical Eurasia continent in the recent half century. *Geophys. Res. Lett.*, **31**, L12204, doi: 10.1029/2004GL019814.