The role of snow cover fluctuations in multiannual NAO persistence

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Received 11 June 2002; revised 24 July 2002; accepted 12 August 2002; published 19 February 2003.

[1] In this article authors explore the relation in the observed data between the Eurasian snow cover anomalies and the NAO variability on interannual to decadal time scales. Results reached in this study suggest that in winter and early spring, NAO type atmospheric circulation influences the extent of snow cover and the snow cover affects the atmosphere in the late spring, summer and early autumn leading to a mechanism that seems to be responsible for the multiannual NAO persistence in the last half century. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1863 Hydrology: Snow and ice (1827); 3319 Meteorology and Atmospheric Dynamics: General circulation; 1620 Global Change: Climate dynamics (3309). **Citation:** Bojariu, R., and L. Gimeno, The role of snow cover fluctuations in multiannual NAO persistence, *Geophys. Res. Lett.*, *30*(4), 1156, doi:10.1029/2002GL015651, 2003.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is the regional manifestation of Arctic Oscillation (AO), a hemispheric mode of variability defined by expansion and contraction of the polar vortex [*Thompson and Wallace*, 1998; *Hurrell*, 1995; *Ting et al.*, 1996]. The positive (negative) NAO phases are associated with enhanced (diminished) Icelandic Low and Azores High [*van Loon and Rogers*, 1978]. It has been long recognized that the NAO is a preferred internal mode of the extratropical atmosphere [e.g. *Robinson*, 1996]. However, the statistics of the atmospheric flow over the North Atlantic seem to be sensitive to slowly varying boundary conditions and to external factors.

[3] The ocean is favored as the most likely cause for forcing atmospheric variability on time scales greater than one year, given the time scales of ocean circulation and its large heat capacity. The atmosphere land-interaction over the large Northern Hemisphere landmass in the extratropics is another candidate for, at least, amplifying climate fluctuations. *Watanabe and Nitta* [1999] found in a CGM experiment that decreasing Eurasian snow cover during autumn raised surface temperatures over Eurasia and produced a dipole pattern in 500-hPa heights resembling that associated to the NAO during the winter of 1988/89. *Cohen and Entekhabi* [1999] based on observations (satellite data for snow cover and reanalysis for the atmosphere) over a period of 25 years have presented some evidence that the Eurasian snow anomalies in autumn may have a role in the atmospheric fluctuations of the following winter. Most of the recent observational analysis and the modeling experiments are consistent in showing that positive-anomalous snow cover is associated with a diminished polar vortex. *Randall et al.* [1994], who examined snow feedbacks in 14 GCMs as part of Atmospheric Modeling Intercomparison Programe (AMIP), reported that the impacts of snow anomalies on the atmosphere largely depend on the GCMs used, varying from strong positive feedback to even weak negative feedback. The variable strength of snow feedback is attributed not only to different snow responses to the boundary forcing (i.e., SSTs) but also to the indirect effects, such as changes in water vapor, surface radiation, and cloudiness.

[4] Thus, there may remain some ambiguities in the results of the GCM experiments with snow anomaly forcing. As in the case of other boundary conditions, it is still unclear to what extent the snow cover is coupled with the atmosphere and which are the mechanisms responsible for local as well as large-scale responses to regional snow cover anomalies. The main goal of this paper is to investigate the relations in observed data between the snow cover anomalies over Eurasia and NAO variability.

2. Data and Methodology Analysis

[5] The primary dataset used here consists of monthly NCEP/NCAR reanalysis of sea level pressure (SLP) over the Northern Hemisphere poleward of 20°N and air temperature at 1000 hPa over Eurasia (from 11°W to 150°E and from 10°N to 70°N) from 1961–2000 [*Kalnay et al.*, 1996]. Output variables of NCEP/NCAR reanalysis experiment are classified into four classes, depending on the degree to which they are influenced by the observations and/or the model. Both SLP and air temperature at 1000 hPa are in the most reliable class (A), which is mainly determined using observed data.

[6] Monthly values of Eurasian snow cover area are obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/snow/). The primary weekly snow data consists of ones and zeros, where one signifies that snow cover exists in a grid box and zero means no snow cover. The entire archive covers the interval from 1973 to present but in this study only the data from the homogeneous period 1973–1998 will be used. Monthly snow cover frequencies and frequency anomalies are also computed merging weekly data in monthly values, on a $2° \times 2°$ grid. In addition we use the Hurrell's NAO index defined as the difference of normalized SLP between Lisbon, Portugal and Stykkisholmur, Iceland [*Hurrell*, 1995].

[7] Mapping the correlation coefficients between Eurasian snow cover area and SLP over the Northern Hemisphere identifies the linkage between NAO variability and snow cover extent over Eurasia. Knowing the NAO is strongest in the cold season, November, December, January, February and March values have been used. Another perspective of the relation between snow cover area and

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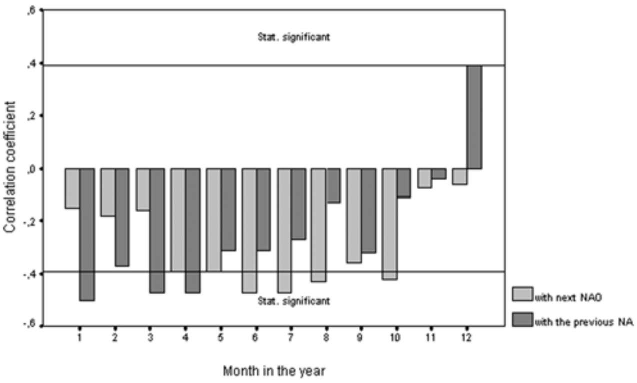

Figure 1. Correlation coefficients between monthly Eurasian snow cover extent and Hurrell's NAO index for the previous and next winter (1973–1998).

NAO type circulation patterns is investigated using the canonical correlation analysis (CCA) [*von Storch*, 1995] applied to the Northern Hemisphere SLP from December to March and temperature over Eurasia from the previous April–October interval.

3. Results

[8] Knowing that the NAO mode accounts for the largest part of variability in the Northern Hemisphere winter, our analysis is focused on patterns related to its canonical manifestation. The correlation coefficients linking monthly values of Eurasian snow cover area and Hurrell's NAO index [1995] in the next/previous winter were computed for the interval 1973–1998 (see Figure 1). The winter and spring snow anomalies from January to April are better correlated simultaneously to the NAO while the snow fluctuation from May to October are better correlated with the NAO index of the following winter. Among the other months, November and December are different from the standpoint of snow extent/atmosphere relationship. These results support the idea that in midwinter and early spring, NAO type atmospheric circulation influences the extent of snow cover. Also the correlation analysis suggests the existence of a lagged snow-atmosphere mechanism linking the two successive winters through snow cover anomalies in late spring, summer and early autumn. The annual mean of snow cover area over the Eurasia is significantly correlated with the NAO index for both next and previous winter, but surprisingly, the correlation is stronger ($r = -0.50$) when snow anomalies lead the NAO than in the case of NAO leading the snow fluctuations ($r = -0.42$).

[9] Although the sign is consistent with our findings, the correlation found by *Cohen and Entekhabi* [2001] between September to November (SON) snow extent over Eurasia and the next December to February (DJF) NAO index is rather small ($r = -0.31$), for the interval 1972–1996. Instead, they identified a higher positive correlation coefficient of 0.56 with the DJF Scandinavian or Eurasia-1 Pattern (SCA) index. However, the SCA mode accounts for lessvariability in the Northern Hemisphere winter then the NAO.

[10] Using April-to-October (AMJJASO) mean of snow cover extent instead of SON values, a stronger relation with the Hurrell's NAO index is found for the interval 1973–1998. In this case, the correlation coefficient associated with the two time series is $r = -0.56$ (statistically significant at 99% confidence level). The correlation remains highly significant ($r = -0.55$) even when the two time series are detrended. Mapping the correlation coefficients between Eurasian snow cover area for AMJJASO interval and Northern Hemisphere SLP for the next December to March (DJFM) interval reveals a NAO type pattern with positive values over Arctic and Iceland regions and negative values over a latitudinal belt stretching from eastern seaboard of North America to the Central and Southern Europe (see Figure 2a). The correlation between Eurasian snow cover area for AMJJASO interval and Northern Hemisphere SLP for the previous December to March (DJFM) interval shows a quite different picture with significant correlation coefficients displayed in a latitudinal belt from 20°N to 40°N (see Figure 2b).

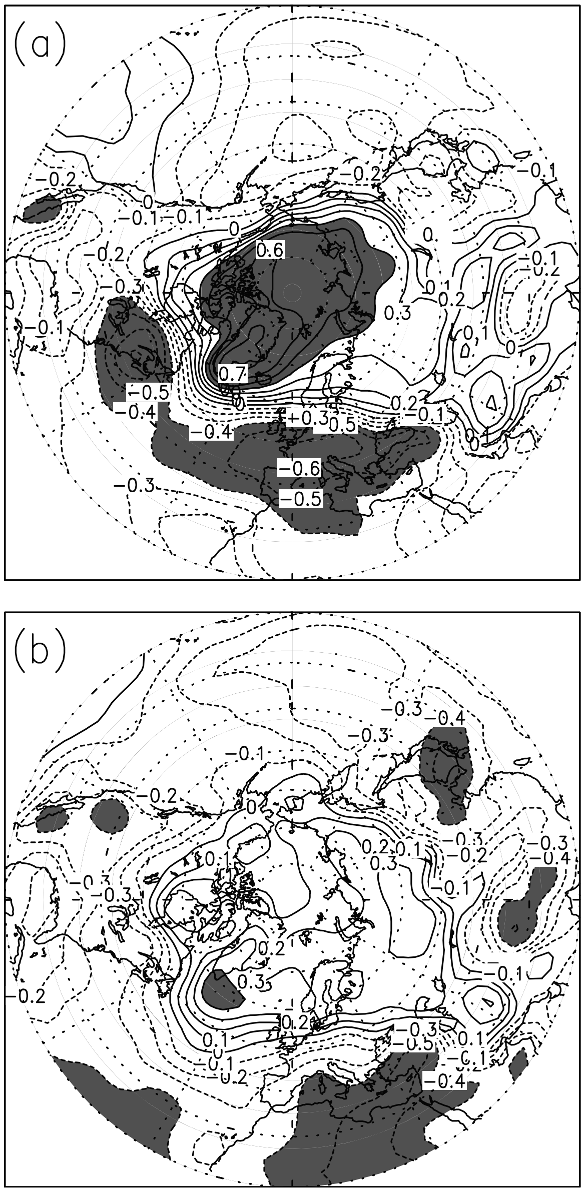

Figure 2. Correlation coefficients between the mean extent of Eurasian snow cover from April to October and following (a) and previous (b) December to March NCEP-NCAR SLP anomalies (1973–1998). Shaded areas are statistically significant at 95% level.

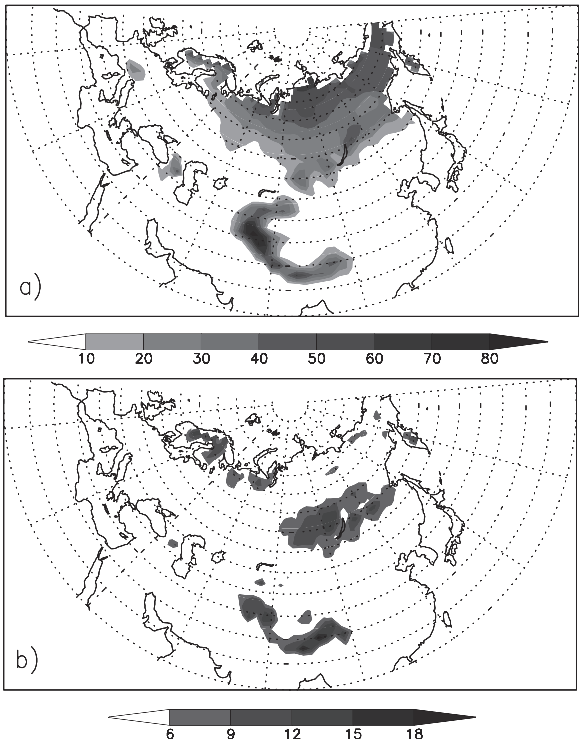

Figure 3. Composite maps with frequency of AMJJASO Eurasian snow cover occurrence (in %) before 5 NAO− events (a) and the difference map for NAO− minus NAO+ (b). The selected years preceding high NAO index are 1982, 1988,1989,1993,1994. The selected year preceding low NAO index are 1976, 1978, 1984, 1986 and 1995.

[11] The composite map using mean frequency of snow cover occurrence from April to October interval that precedes 5 NAO− winters is presented in Figure 3a. In Figure 3b, the map displays the difference between the mean frequencies preceding the 5 NAO− and 5 NAO+ winters from the interval 1973–1998. In the difference map there is a region over Eastern Siberia with positive (negative) values for the AMJJASO interval preceding NAO− (NAO+) winters supporting the hypothesis of *Cohen and Entekhabi* [2001] and the findings of *Watanabe and Nitta* [1999]. However, the results presented here show that the relationship between snow cover extent and NAO type circulation is stronger if late spring and summer values of snow cover area are added to early autumn values. This characteristic cannot be solely explained by the Siberian High influences. In order to identify a mechanism responsible for the lagged relationship between AMJJASO snow anomalies and DJFM NAO index, a CCA has been applied to the air temperature at 1000 hPa over Eurasia and Northern Hemisphere SLP in the interval from 1961 to 2001. The CCA spatial pattern suggests a relation linking AMJJASO centers of thermal variability in Northern Africa, Western and Central Asia with DJFM centers of SLP variability resembling NAO pattern (Figure 4). Preliminary CCA test with different number of EOFs [*Kharin*, 1994] suggested that the best choice from the standpoint of both correlation and associated variance is to retain the first 5 EOFs of air temperature at 1000 hPa and the first 5 EOFs of SLP. This canonical correlation mode accounts for 17% and 25% of the total variance of air temperature and SLP data, respectively, and has an associated correlation coefficient of 0.63. The correlation between the time coefficient, which modulates the thermal pattern of the CCA, and the NAO index of the next winter is −0.61. Also, the correlation coefficient between the time evolution of AMJJASO thermal pattern and the AMJJASO snow extent anomalies is 0.50, for the common interval 1973–1998, suggesting a link between snow anomalies and thermal conditions over Eurasia in the warm season. The link involving the variability centers from Western and Central Asia (Figure 4) may be a non-local response produced by anomalous diabatic heating due to snow cover anomalies in the Eastern Eurasia (Figure 3). Tropical processes could be also involved. We tried to see if the summer monsoon precipitation is related to these modes of variability. The correlation coefficient between all India monsoon precipitation and the CCA time evolution is not statistically significant.

4. Discussions and Conclusions

[12] How local surface heating anomalies generate lagged and remote dynamical changes it is still unclear. For the fall/winter signal several hypothesis have been proposed. The physical rationale used by *Cohen and Entekhabi* [1999] to explain their results is that extensive Eurasian snow cover in SON interval excites the dominant modes of Northern Hemisphere variability by its effects on the extension of Siberian high and on the latitudinal thermal gradient. *Cohen et al.* [2002] further develop the hypothesis of a AO mechanism originating in the lower troposphere, in eastern Siberia, during late fall, when vertical wave activity flux due to the snow cover anomaly propagates vertically into the stratosphere and returns as zonal wind anomalies in

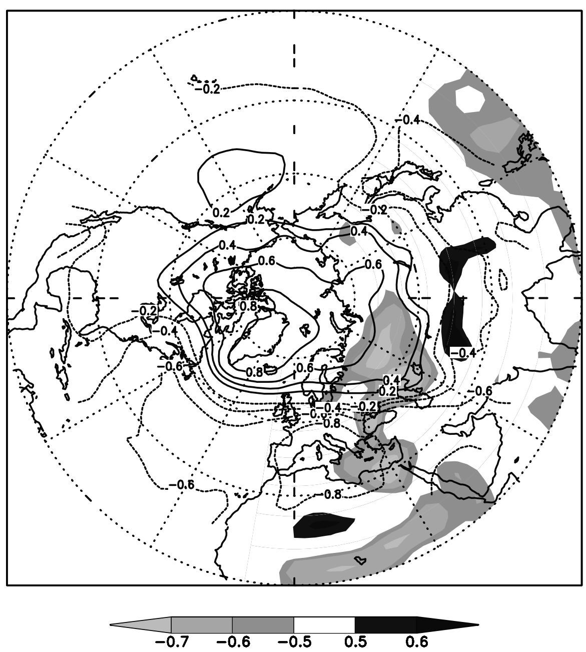

Figure 4. The first CCA spatial pattern of NCEP-NCAR air temperature at 1000 hPa from April to October (standardized anomalies, shaded) and NCEP-NCAR SLP from next December to March (standardized anomalies, contour) in the interval 1961–2001.

early winter. *Watanabe and Nitta* [1998] hypothesis that snow cover anomalies interact with zonal asymmetries and transient eddies to produce height changes observed in the atmosphere and in their GCM experiment.

[13] The results presented here suggest that the snow-atmosphere interaction in the cold season is only a part of a mechanism, which seems to be responsible for the multi-annual persistence shown by the NAO in the last half century. The full mechanism has to take into account the lagged relationship between snow cover extent from late spring to early autumn and atmospheric circulation in the next winter. The interplay of two basic mechanisms may explain the snow-atmosphere interaction on continental scale: the albedo feedback [*Yasunari et al.*, 1991] playing a role in spring and autumn and the hydrological feedback of snow-cover during summer [*Yeh et al.*, 1983; *Yasunari et al.*, 1991]. The hydrological feedback determining the negative anomalies of surface temperature is preceded and followed by the albedo feedback in spring, and autumn, respectively. The high albedo of the snow, which reduces the total incoming solar radiation and hence surface temperature, plays a role especially in the lower latitudes, where the incoming radiation is extremely strong. The responses of the Northern Hemisphere atmosphere to these continental processes seem to be partly non-local, leading to the excitation of AO/NAO circulation patterns.

[14] Plausible candidates for the key factors in relating regional processes to hemispheric modes of variability are sea-ice extent over Arctic and tropical SSTs, both variables showing changes consistent with the modified behavior of NAO in the last half century [e.g. *Deser et al.*, 2000; *Hoerling et al.*, 2001]. Our results suggest that the snow cover extent over Eurasia may be another key factor linking tropical and high latitude processes.

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