The potential role of snow cover in forcing interannual variability of the major Northern Hemisphere mode

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[1] Decadal trends have been noted in the leading mode of boreal winter variability. Given that this mode is thought to be an internal mode of the atmosphere it remains unclear as to what is responsible for interannual to interdecadal oscillations of this mode. We demonstrate that continental-scale snow cover varies at the same multi-year time periods as the atmosphere but leads the atmosphere by several months through their mutual oscillations. Therefore we propose snow cover as a potential contributor to the interannual variability of the leading boreal winter mode of the atmosphere. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3319 Meteorology and Atmospheric Dynamics: General circulation; 1863 Hydrology: Snow and ice (1827); 1899 Hydrology: General or miscellaneous. **Citation:** Saito, K., and J. Cohen, The potential role of snow cover in forcing interannual variability of the major Northern Hemisphere mode, *Geophys. Res. Lett.*, *30*(0), XXXX, doi:10.1029/2002GL016341, 2003.

1. Introduction

[2] The dominant mode of winter variability (though it is observed throughout the year) is known as the North Atlantic oscillation (NAO) or Arctic oscillation (AO). The mode is characterized by a strong oscillation in a pressure/height center anomaly over the Arctic basin, extending from the surface well into the stratosphere. At mid-latitudes an opposite pressure height anomaly stretches mostly across the two major ocean basins [*Barnston and Livezey*, 1987; *Thompson and Wallace*, 1998]. The AO/NAO mode of variability is considered as an internal mode of variability of the atmosphere [*Feldstein*, 2002], whose variability is not dependent on external boundary forcings [*Gong et al.*, 2002]. As an internal atmospheric mode, the variance of the AO/NAO mode on interannual time scales should be described as white or climate noise, yet the AO/NAO is slightly red [*Marshall et al.*, 2001] and over the past thirty years has exhibited an upward trend well in excess of that expected from a random time series of internal atmospheric variability [*Feldstein*, 2002].

[3] Coupling of the atmosphere to boundary conditions can either produce spectral [*Robertson*, 2001] or enhance low frequency variability or in effect "redden" the spectrum of atmospheric variability [*Barsugli and Battisti*, 1998]. The time series of the AO/NAO has been shown to exhibit spectral peaks at the quasi-biennial period (2–3 years) [*Stephenson et al.*, 2000; *Marshall et al.*, 2001] and at quasi-decadal periods (8–9 years) [*Robertson*, 2001]. Eurasian snow cover has also been shown to exhibit enhanced variability on quasi-biennial and quasi-decadal time [*Ye*, 2001].

[4] *Dickinson* [2000] and *Feldstein* [2002] argue that changes in the variance of atmospheric modes such as the AO/NAO can be due to either coupling of the atmosphere to boundary forcings (e.g. oceans, soil moisture) or external forcings (secular changes to greenhouse gases). Sea surface temperatures (SSTs) [*Kushnir*, 1994; *Marshall et al.*, 2001], the stratosphere [*Baldwin and Dunkerton*, 1999; *Shindell et al.*, 1999] and sea ice [*Mysak and Venegas*, 1998] all have been suggested as boundary conditions, which contribute to or influence interannual variability of the AO/NAO. We suggest that snow cover should also be considered as potentially influencing the interannual variability of the AO/NAO.

[5] Eurasian snow cover during both the cold [*Cohen and Entekhabi*, 1999] and the warm [*Bojariu and Gimeno*, 2002] seasons have been suggested to at least partially modulate the winter AO/NAO. Furthermore it has been suggested that the winter AO/NAO influences Eurasian winter [*Clark et al.*, 1999] and spring snow cover extent[*Bojariu and Gimeno*, 2002; *Bamzai*, 2002]. Identifying statistically significant relationships, up to fourteen months lead time, between Eurasian snow cover and North American snow cover, and between Eurasian snow cover and the NAO [*Iwasaki*, 1991; *Walland and Simmonds*, 1997; *Bamzai*, 2002] has led some scientists to propose the importance of snow cover on interannual variability [*Iwasaki*, 1991; *Bojariu and Gimeno*, 2002]. In the remainder of the Letter, we will explore the lead-lag snow-atmosphere relationship in greater detail.

2. Results

[6] We begin by presenting in Figure 1 correlation plots of snow cover [*Robinson et al.*, 1993] and the AO/NAO for up to 36 months lead-lag. NCEP/NCAR reanalysis is the source for all atmospheric [*Kalnay et al.*, 1996]. The AO is defined as the time series of the first empirical orthogonal function (EOF) of Northern Hemisphere (NH, north of 20°N) sea level pressure (SLP; *Thompson and Wallace*, 1998) and the NAO as the difference of normalized sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland [*Hurrell*, 1995]. All time series have been linearly detrended. Included in each plot is a diagonal

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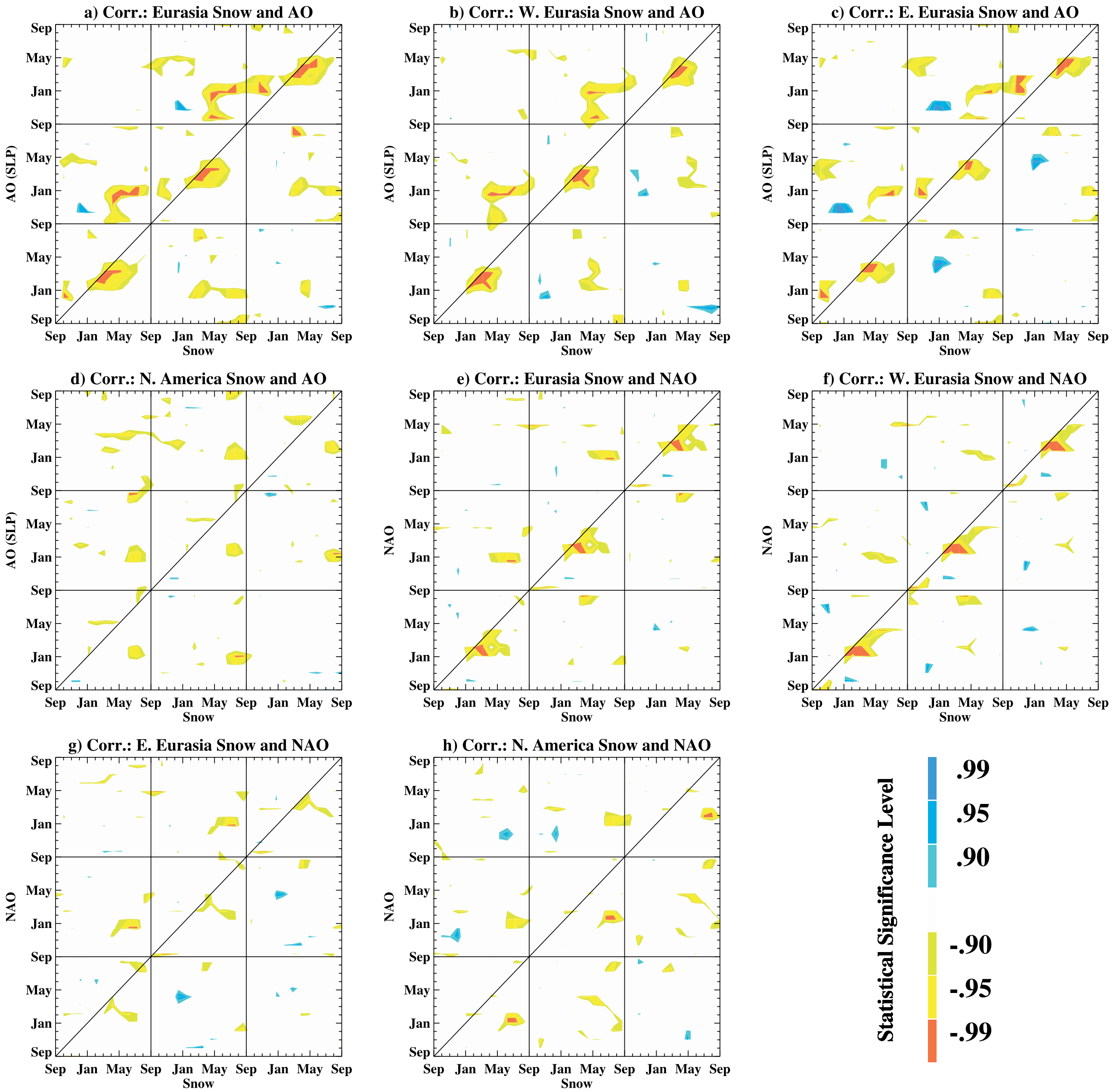

Figure 1. Lead-lag correlation plot between 27-year monthly AO index and snow cover extent in (a) Eurasia, (b) West Eurasia, (c) East Eurasia, and (d) North America for a span of 36 months. Dataset in each column is shifted one year later from previous column. Diagonal line denotes contemporaneous correlation. Positive (negative) correlations at 90%, 95% and 99% confidence are shaded yellow-red (blue). (e) to (h) are same as (a) to (d) except for the NAO.

line delineating simultaneous correlations; to the left of the diagonal snow leads and to the right the AO/NAO leads. We show correlations for Eurasian, West Eurasian only, East Eurasian only and North American snow cover.

[7] In the correlation plot of Eurasian snow and the AO (Panel 1a) there are two prominent shaded regions of significant correlations, one where late winter/spring AO leads spring/summer snow and a second where spring/summer snow leads the following fall/early winter AO. This result can also be seen for the NAO, though the region of significant correlations consists of fewer months (Panel 1e). The first region is consistent with the findings of *Bamzai* [2002] that the late winter AO is a leading indicator of spring snow and the second region is consistent with the findings of *Bojariu and Gimeno* [2002] that late spring/summer snow is significantly correlated with the following winter NAO. These two lead-lag correlations can be seen for both West and East Eurasian snow cover, at least for the AO. In the correlation plot of Eurasian snow and the AO a third shaded region is noted where October snow leads the winter AO. This shaded region is not apparent in the plot of West Eurasian snow and is most prominent in the plot of East Eurasian snow (it also does not appear in any of the NAO plots). This result confirms the findings that the

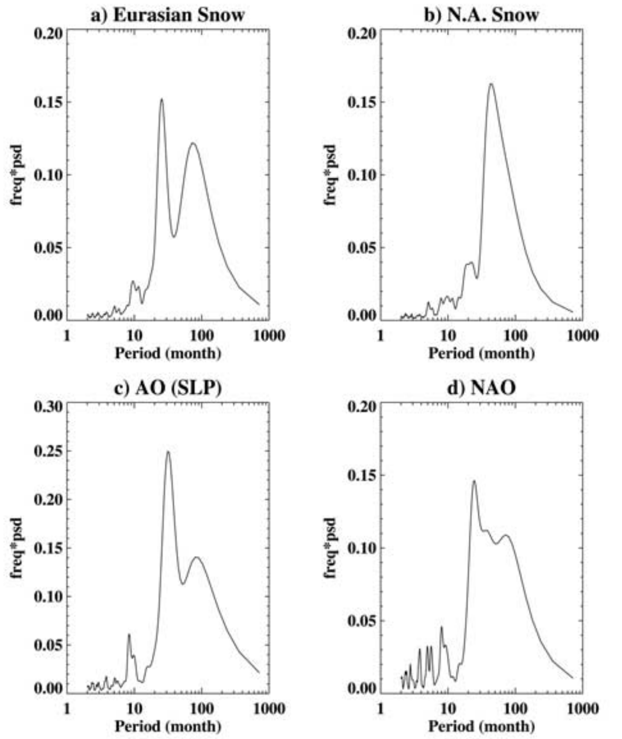

Figure 2. Power spectrum of monthly (a) Eurasian and (b) North American snow cover extent, (c) AO and (d) NAO indices for 1971–99 in variance-preserving plot against the period. The time series are filtered to remove annual and shorter cycles and then normalized.

winter AO is influenced by October snow anomalies in Siberia [*Cohen et al.*, 2001; *Saito et al.*, 2001; *Cohen et al.*, 2002; *Gong et al.*, 2002]. Finally we show similar plots for North American snow cover. The relationship of summer snow leading the winter AO is found but the region is smaller than that shown for Eurasia. There is also a second noted region unique to North America where the winter AO/NAO leads summer snow cover. Correlation plots between the AO and snow cover for the whole Northern Hemisphere strongly resemble those for Eurasia only (not shown), so even though summer North American snow cover exhibits a significant relationship with the winter AO, it is not large enough to appreciably improve the stronger correlations for Eurasia only.

[8] We next explore the preferred time scale of variability for continental snow cover and the AO/NAO. In Figure 2 we present the power spectrum for these variables. Consistent with previous studies, we find that the AO and Eurasian snow cover have preferred periods of oscillation on the order of quasi-biennial and quasi-decadal time scales (somewhat similar results were found for North American snow and the NAO). In Figure 3 we present the cross spectrum for snow cover and the AO or NAO. Eurasian snow cover and the AO are found to co-vary at the quasi-biennial and quasi-decadal time scale, however only the oscillation at the longer (period of 70 months or greater) time scales were found to be significant. The phase also shows that snow cover leads the AO at the longer time scales. These results further suggest the potential influence of large-scale snow cover on the interannual to decadal variability of the AO and/or NAO.

3. Discussion and Conclusion

[9] Correlation lead-lag plots and spectral analysis have been used to demonstrate the statistically robust relationship between continental-scale snow cover and the dominant mode of NH climate variability, in particular - winter. The results further suggest that snow is partially forcing the atmosphere on interannual to decadal time scales. But what mechanisms exist for warm season snow cover to influence winter climate variability. A mechanism has been proposed linking October snow cover to the winter AO through a vertical pathway involving the stratosphere [*Saito et al.*, 2001; *Cohen et al.*, 2002] however this is not applicable to the spring and summer seasons during which the stratosphere is decoupled from the troposphere.

[10] Another possibility is that the snow cover is passive in regards to the atmosphere and simply acts as to record or mirror current atmospheric conditions. In other words the winter atmosphere retains some residual from the summer atmosphere and this is reflected in the summer snow cover. Interestingly, summer North Atlantic SSTs also explain a

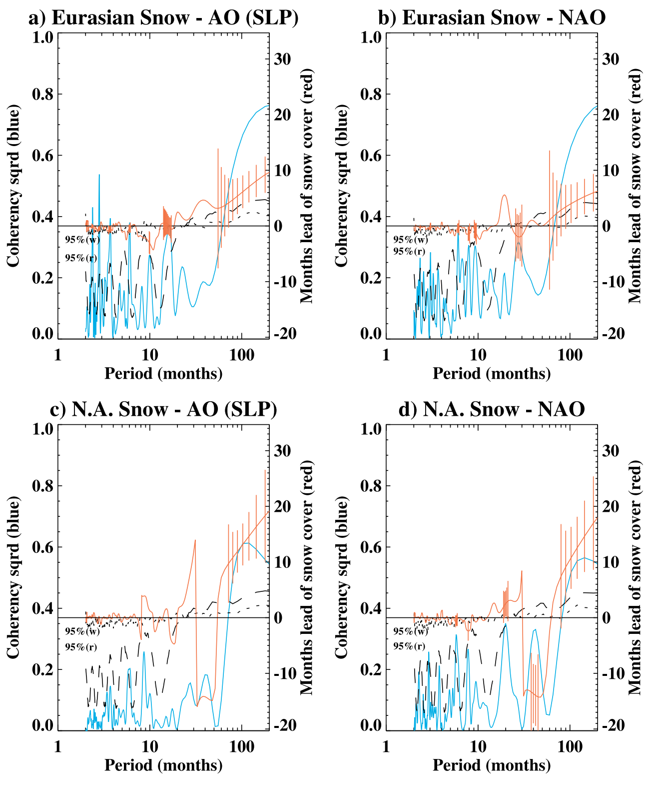

Figure 3. (a) Coherency squared (blue; scale on left) and month-lead (for snow cover in red; scale on right) between the low-pass filtered and normalized monthly Eurasian snow cover extent and the AO index. Dotted (dashed) denotes 95% confidence level for white (red) noise of the coherency squared derived from Monte Carlo simulations and red bars denote 95% confidence level for month-lead. (b) same as (a) but for NAO instead of AO. (c) and (d) are same as (a) and (b) but for North America instead of Eurasia.

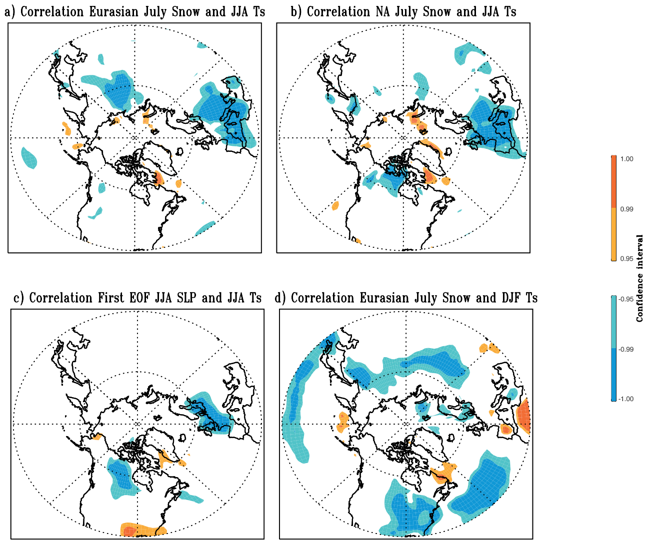

Figure 4. (a) Map of Eurasian July snow cover regressed on to JJA surface air temperatures (b) Map of North American July snow cover regressed on to JJA surface air temperatures (c) Map of first EOF of JJA SLP regressed on to JJA surface air temperatures (d) Map of Eurasian July snow cover regressed on to DJF surface air temperatures. Region of light shading for correlations greater than 95% confidence and dark for correlations greater than 99% confidence.

greater percentage of the variance of the winter NAO than SSTs from other leading seasons [*Czaja and Frankignoul*, 1999]. In Figure 4 we present surface temperature (Ts) regressed with July snow cover and the JJA AO. In Panel 4a Eurasian snow cover is regressed with JJA Ts which shows that July snow cover anomalies are associated with temperature anomalies in East and West Eurasia. Regression instead with North American snow cover (Panel 4b) shows that July snow cover anomalies are associated with temperature anomalies in Northern Canada and West Eurasia. Regression with the JJA AO gives similar results that the JJA AO is associated with temperature anomalies in Northern Canada and Northern Europe but none in East Eurasia. A similar regression map of JJA 500 hPa heights does not suggest any organized large-scale atmospheric dynamics (not shown).

[11] In Panel 4d we regress Eurasian July snow with the following DJF Ts, the resultant pattern is reminiscent of the AO Ts pattern of variability; regression with snow cover from other summer months show similar but weaker results (not shown). Substituting the JJA AO instead of snow cover shows no organized pattern of temperature anomalies (not shown). Finally, in contrast to summer snow cover, the JJA AO is not significantly correlated with the DJF AO. All these results practically eliminate the possibility that the relationship between warm season snow and cold season AO is a proxy of some residual atmospheric memory.

[12] Another possible linkage, discussed in the literature, involves soil moisture [*Yeh et al.*, 1983; *Yasunari et al.*, 1991; *Iwasaki*, 1991]. The argument is that increased spring/summer snow cover leads to increased summer and late fall soil moisture which then results in increased fall snow cover and a negative winter AO. A negative winter AO further results in increased spring snow and the cycle continues to produce interannual persistence; though a recent study found a carry over of the same-signed anomaly from snow to soil moisture to be quite limited in region [*Shinoda*, 2001]. Another potential linkage, given that significant anomalies exist both for Eurasian and North American snow cover, is sea ice. Sea ice extent has also been in a downward trend over the past thirty years (summer sea ice especially) and has been shown to influence SLP independent of NAO forcing [*Deser et al.*, 2000]. Finally, the contemporaneous peak correlation for both snow cover and North Atlantic SSTs in the warm season and the winter AO/NAO is suggestive of a linkage. However, these hypotheses will require well organized GCM simulations for validation.

[13] In this paper we attempt to contribute to the debate of what influences the observed interannual variability of the AO/NAO. Here we present statistical analysis of snow cover and indices representative of the dominant mode of NH atmospheric variability that suggests snow cover plays a role in the interannual to decadal variability of the dominant mode. Though the winter AO may affect spring snow cover, spring/summer and fall snow cover may potentially influence the winter AO. Contrary to the little or no trend observed in fall and winter snow cover, a strong downward trend has been observed in spring and summer snow cover over the recent thirty-year record of reliable remotely-sensed snow cover. However, further research is needed on whether the warm-season trend may partially explain the strong upward trend, which has been observed in the winter AO/NAO and/or NH Ts over the past three decades [*Feldstein*, 2002].

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