GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 23, 2190, doi:10.1029/2003GL018053, 2003

Eurasian snow cover, more skillful in predicting U.S. winter climate than the NAO/AO?

Judah L. Cohen
Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA

Kazuyuki Saito
Frontier Research System for Global Change, Yokohama-city, Japan

Received 26 June 2003; revised 4 September 2003; accepted 23 September 2003; published 4 December 2003.

[1] Successfully predicting the phase and strength of the dominant winter mode of variability for the Northern Hemisphere (NAO/AO) is considered the most important future breakthrough in winter climate prediction; however skillful prediction of the index has been elusive. In this Letter we present a snow index constructed from observed summer and fall anomalies that is more highly correlated than the observed value of the winter AO with winter surface temperatures in the eastern United States. Ease of use and the potential for greater predictive skill could potentially render forecasting the phase and strength of the NAO/AO irrelevant as a tool for prediction of U. S. winter surface temperatures. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Cohen, J. L., and K. Saito, Eurasian snow cover, more skillful in predicting U.S. winter climate than the NAO/AO?, *Geophys. Res. Lett.*, *30*(23), 2190, doi:10.1029/2003GL018053, 2003.

1. Introduction

[2] The most important advance in seasonal climate prediction has been the linkage of the dominant tropical atmosphere and ocean signal (El Niño/Southern Oscillation or ENSO) with surface temperatures and precipitation patterns across the globe; though predictive skill for temperature forecasts outside of the tropics, including the U.S., has been mixed [*Spencer and Slingo*, 2003]. Improving the skill of predicting the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO) is often recognized as the next most important anticipated advance in seasonal climate forecasting [*Cohen*, 2003] especially for the eastern U.S. and Europe, regions where forecasts based on ENSO have low or no skill.

[3] In a series of papers using both observational analyses and numerical models, Eurasian snow cover in the fall has been shown to be a skillful predictor of mean climate conditions, including surface temperatures, during the winter across the mid-to-high latitudes of the Northern Hemisphere [*Cohen and Entekhabi*, 1999; *Cohen et al.*, 2001; *Saito et al.*, 2001; *Gong et al.*, 2003]. More recently it has been shown that summer snow cover in Eurasia and in North America are also skillful predictors of winter climate conditions of equal or greater magnitude than that of autumn snow cover [*Bojariu and Gimeno*, 2003; *Saito and Cohen*, 2003; *Saunders et al.*, 2003]. Because summer and fall snow cover are not strongly correlated with each other (r = 0.15), the obvious question is how to reconcile the often-mixed signals provided by multi-seasonal snow cover as a predictor of winter climate?

[4] In a recent set of papers, we have advanced the idea that anomaly patterns associated with the winter NAO/AO evolve according to two basic paradigms, referred to as either Type A or Type N [*Cohen et al.*, 2002; *Cohen*, 2003]. We distinguish/forecast Type A and Type N winters based on the following three main criteria:

[5] 1. *The region of origin of surface anomalies.* In Type A years, sea-level pressure (SLP) and surface temperature (T_s) anomalies originate in Siberia and then grow and/or propagate into the NAO/AO pattern which dominates that particular winter. In Type N years, the SLP and T_s anomalies originate in the North Atlantic and western Eurasia.

[6] 2. *The spatial scale of the winter NAO/AO pattern of variability.* In Type A winters, the SLP anomaly associated with the NAO/AO is hemispheric in scale with a nearly symmetric response in both the North Atlantic and North Pacific ocean basins. In Type N winters, the associated SLP anomaly is more regional with the dipole anomaly signature confined to the North Atlantic basin, independent of anomalies in the North Pacific basin.

[7] 3. *Coupling between the troposphere and stratosphere.* In Type A years, strong Eliassen-Palm (EP) flux anomalies (vertically and horizontally propagating wave energy or activity associated with Rossby waves in the atmosphere) are observed originating in the lower troposphere but eventually propagate into the stratosphere. The strong anomalies in EP flux perturb the stratosphere. This is then followed by an apparent or real downward propagation of same-signed height and wind anomalies down to the surface, creating strong coupling between the stratosphere and the troposphere. Even though upward and downward propagation occur on timescales of days and weeks, their impact can persist much longer, and in case of this early-winter coupling its influence can last for most of the following winter. In contrast, in Type N winters, coupling between the troposphere and stratosphere is absent or weak. Tropospheric EP flux anomalies are disorganized and subsequent tropospheric height and wind anomalies evolve independently of anomalies in the stratosphere.

[8] Identifying winters as Type A or N can potentially be used to predict the phase and strength of the AO and even predict monthly and regional temperature anomalies with as

0094-8276/03/2003GL018053$05.00

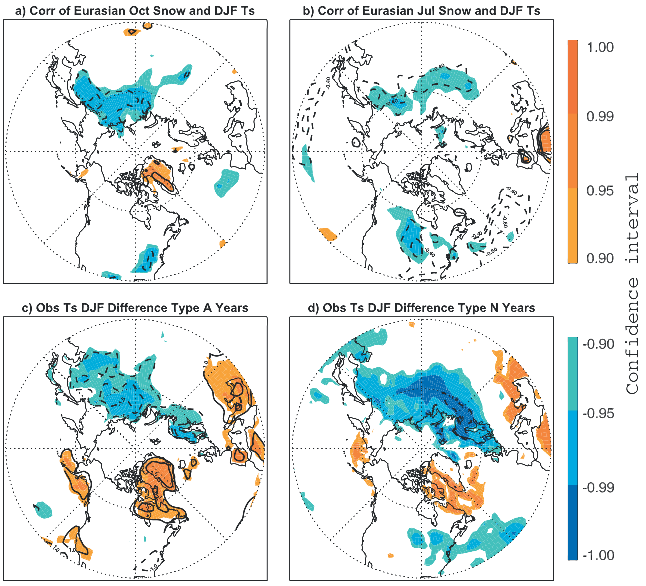

Figure 1. Regression of DJF surface temperatures with a) Eurasian October snow cover and b) Eurasian July snow cover. Maps of Northern Hemisphere gridded surface temperature differences between negative and positive c) Type A and d) Type N winters (DJF). Type A winters are (year listed according to December): 1949, 1951, 1957, 1959, 1960, 1969, 1972, 1975, 1976, 1979, 1984, 1988, 1991, 1992, 2000. Remainder of winters are Type N except for 1968 and 2002 which are considered hybrids of two types and not included in composites. Light, dark, darkest shading indicate 90%, 95% and 99% confidence limits. Statistical significance, for all correlation plots in Figures 1–3, has been adjusted for autocorrelations on a gridcell by gridcell basis [*Chelton*, 1983]. In panels c) and d) contouring intervals ±1., 1.5, 2., 2.5, 3. indicate normalized anomalies.

much as four months lead-time. In the rest of the Letter we will demonstrate that dividing winters into Type A and Type N can be used to harness the predictive potential of snow cover so much so as to reduce or even eliminate the need to forecast the AO for winter climate prediction.

2. Results

[9] In Panel 1a we correlate October Eurasian snow cover anomalies with gridded December, January and February (DJF) 2-meter T_s. All indices of snow cover represent total snow-covered area, averaged over the entire month. We use snow cover data from 1972–2002 [*Robinson et al.*, 1993] and gridded reanalysis data from 1949–2003 [*Kalnay et al.*, 1996]. October snow cover emerges as a skillful predictor of winter temperatures for two main regions—Asia, mostly east of 90°E and the eastern U.S. In Panel 1b we correlate July snow cover with gridded DJF T_s. July snow cover is shown to be a skillful predictor of winter temperatures for Eurasia, mostly west of 90°E, the eastern U.S and North Atlantic air temperatures. So even though the regions of significant correlations for the two monthly snow anomalies differ in Eurasia they coincide in North America. For comparison we show the regional pattern of anomalies associated with Type A and Type N winters in Panels 1c and 1d respectively. Though the regions of anomalies are similar in both types they differ in Eurasia with the anomalies mostly east of 90°E in Type A but west of 90°E in Type N. Another important difference is the observed strong signal in air temperatures over the North Atlantic Ocean in Type N winters, absent in Type A winters.

[10] Next we regress October snow cover with gridded DJF SLP in Panel 2a. The pattern of SLP anomalies associated with October snow cover resembles the AO with one signed anomaly over most of the Arctic and an opposite-signed anomaly in both major ocean basins. In Panel 2b we regress July snow cover with gridded DJF SLP. The pattern of SLP anomalies associated with July snow cover resembles the NAO with one signed anomaly at high latitudes mostly confined to the Atlantic side of the Arctic and an opposite-signed anomaly confined to the North Atlantic sector. For comparison we show the regional pattern of anomalies associated with Type A and Type N winters in Panels 2c and 2d respectively. SLP anomalies associated with Type A resemble the AO while SLP anomalies associated with Type N more closely resemble the NAO.

[11] We conclude that regression of October snow cover with DJF T_s and SLP resemble Type A winter anomalies and the regression of July snow cover with DJF T_s and SLP resemble Type N winter anomalies. To further support our claim, in Table 1 we have computed the pattern correlation among the four panels of Figures 1 and 2. The correlation values between Panels a/c and b/d are all statistically significant at greater than the 99% confidence interval. Furthermore the values for Panels a/c and b/d are higher than for panels a/d and b/c for both figures.

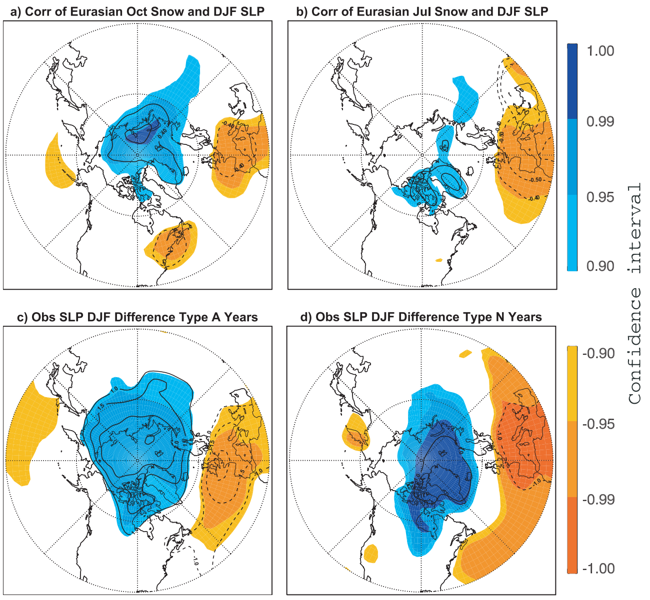

Figure 2. Regression of DJF sea level pressure with a) Eurasian October snow cover and b) Eurasian July snow cover. Maps of Northern Hemisphere gridded sea level pressure differences between negative and positive c) Type A and d) Type N winters (DJF). Shading and contouring same as in Figure 1.

[12] Winter T_s and SLP anomalies related to October and July snow cover and Type A and Type N differ in Eurasia but coincide in North America. We argue that this convergence in the eastern U.S. of anomalies related to two temporally different snow anomalies allows for a unique opportunity of skillful prediction greater than that associated with perfect knowledge of the winter NAO/AO and even perfect knowledge of the winter ENSO. We construct a snow index using observed Eurasian October normalized anomalies preceding Type A winters and Eurasian July normalized anomalies preceding Type N winters. The dilemma becomes which snow cover anomaly to choose when both types characterize a winter. During those fall/winters when a strong response is observed in the anomalous EP flux, October snow cover was chosen and during those winters when only a weak response is observed in the EP flux, July snow cover was chosen. Operationally, a prediction of whether a winter will be of either Type A or N can be issued as early as late October/early November.

[13] In Panel 3a we regress the observed DJF Niño 3.4 index with DJF T_s over the U.S.; Niño 3.4 shows little skill as a predictor of T_s for the period studied. In Panel 3b we regress the observed DJF AO index with DJF T_s over the U.S. The AO is statistically correlated with T_s for most of the eastern U.S. Finally in Panel 3c we correlate the constructed snow index with T_s. The region of statistical significance associated with the snow index exceeds both in magnitude and spatial domain those associated with the observed DJF AO index, the ENSO index or even the combination of both observed winter indices (not shown). This improvement occurs despite the snow index consisting of observed snow cover anomalies prior to the onset of winter while the AO and ENSO indices are concurrent with T_s. In Panel 3d we duplicate Panel 3c but with all temperature and snow data detrended. Though common trends do contribute to some of the skill, most of the predictive skill of snow cover is independent of trends.

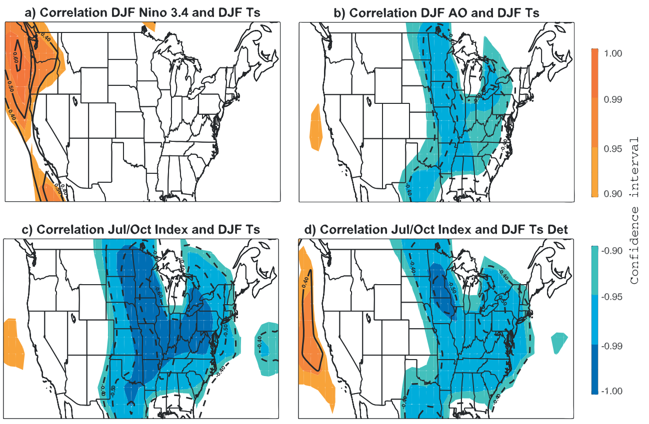

Figure 3. Regression of a) DJF Niño 3.4 index b) DJF AO index and c) snow cover index with gridded surface temperatures across the United States for winters 1972/73–2002/03. Eurasian October snow anomalies chosen from years 1972, 1975, 1976, 1979, 1984, 1988, 1991, 1992, 2000 and 2002 and July snow anomalies chosen from the remaining years. d) We also detrended the July snow cover, October snow cover and surface temperatures and recomputed the regression from c). Robust relationship between snow cover index and DJF T_s is not dependent on trends. Light, dark and darkest shading indicate 90%, 95% and 99% confidence limits. Contouring intervals ±.4, .5, .6, delineate isolines of the correlation coefficients.

Table 1. Pattern Correlations Among the Four Panels of Figures 1 and 2

	Raw-data	Detrended-data
Figure 1 a/c	0.78**	0.77**
a/d	0.51	0.49
b/c	0.49	0.66**
b/d	0.73**	0.73**
Figure 2 a/c	0.86**	0.86**
a/d	0.69	0.65*
b/c	0.77*	0.74*
b/d	0.89**	0.81**

We repeated computations for detrended data as well. Values of statistical significance greater than 95% (99%) confidence denoted by single (double) asterisk based on Monte Carlo simulations.

[14] Finally in Figure 4 we plot the constructed snow index with observed T_s for various cities in the eastern U.S. All station data used from 1972–2003 [*Peterson and Vose*, 1997]. Also shown in the plot is the correlation coefficient for the two series and in parenthesis is the correlation coefficient for the observed T_s and the observed winter AO index. The correlation coefficients between the snow index and observed T_s for all cities shown vary between .58 and .75; 0.6 being considered the minimum value required for a predictor to be useful [*Barnston and Ropelewski*, 1992]. All correlation values exceed those using only the observed winter AO.

3. Discussion and Conclusion

[15] Recent papers have demonstrated the predictive potential of October and July Eurasian snow cover, but how to effectively combine the two, often contradictory, signals has not been addressed. How a fall regional snow cover anomaly can influence remote T_s and SLP anomalies is relatively well understood. The diabatic cooling associated with snow cover anomalies in Siberia perturb local stationary wave energy forced by the high topography of East Asia. Increased upward energy flux first perturbs the stratosphere and eventually the troposphere, consistent with our knowledge of troposphere-stratosphere coupling [*Saito et al.*, 2001; *Cohen et al.*, 2002; *Zhou et al.*, 2002; *Gong et al.*, 2003]. When lower tropospheric T_s and height anomalies in Siberia are strong enough to alter the vertical and horizontal propagation of wave energy so that the troposphere and stratosphere are strongly coupled during the winter season, October snow cover is a good proxy for the ensuing mean winter state.

[16] On the other hand, why summer snow cover is an effective predictor of remote winter climate is not as well understood. *Saunders et al.* [2003] argue that summer snow cover variability is associated with subpolar zonal air temperature gradients and other circulation changes which force North Atlantic SST anomalies, which, if persisted through to winter, give the correct NAO-index signal. We offer an alternate link between summer snow and the winter NAO. We hypothesize that summer snow cover, unlike fall snow cover, does not directly force subsequent changes in the winter atmosphere, but rather merely acts as an indicator

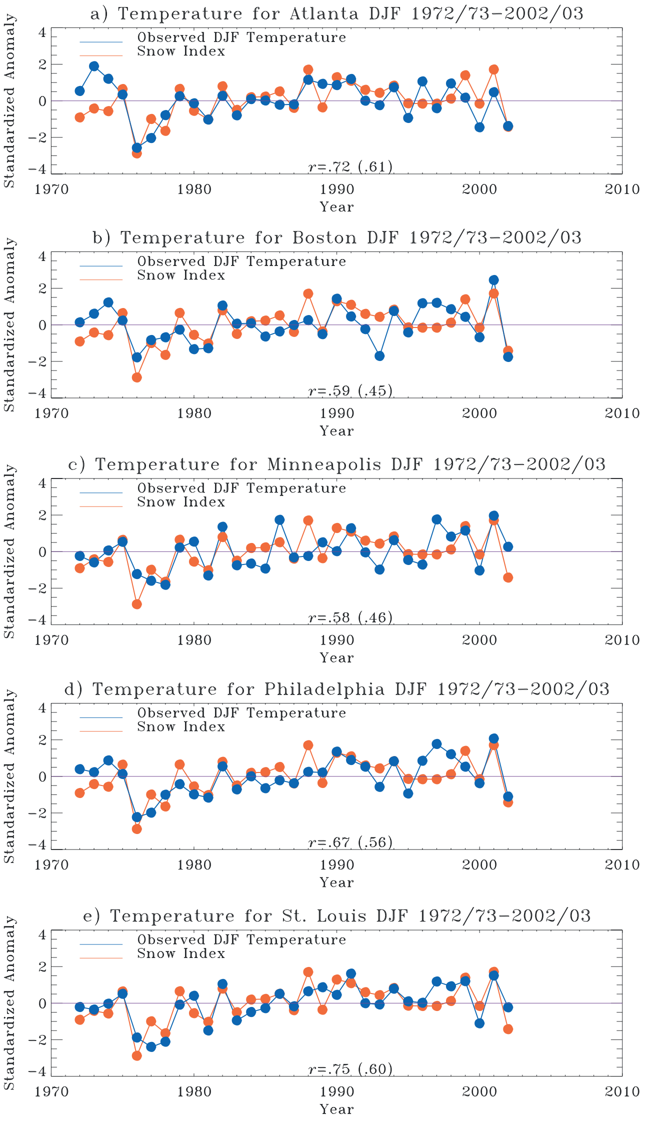

Figure 4. Plots of annual standardized anomalies of the snow index and observed anomalies of city DJF temperatures for a) Atlanta, b) Boston, c) Minneapolis, d) Philadelphia, and e) St. Louis. Also included is the correlation coefficient for the two time series and in parenthesis is the correlation coefficient for the observed DJF AO index and the respective observed city DJF temperatures.

of current climate conditions, which persist and expand during the ensuing cold season. More extensive summer snow cover is indicative of colder T_s, possibly more extensive sea ice and colder SSTs. Sparse snow cover reflects a warmer background state resulting in weaker and more transient cold air masses during the ensuing winter. If the climate system is in a colder (warmer) initial state with an expanded (contracted) cryosphere, the colder (warmer) summer conditions are more likely to persist through winter; therefore July snow cover is a good proxy for this natural cycle.

[17] Ability to predict the phase and strength of the NAO/AO is considered by forecasters the most important advance needed to improve seasonal climate prediction. Yet we demonstrate here that during the observational period of continental snow cover, a constructed leading snow cover index is more skillful in predicting T_s temperatures in eastern North America than the AO index, even if a perfect prediction of the phase and strength of the winter AO were feasible. The potential of such a predictive index is especially fortuitous given that the dynamics of the AO are not well understood and forecasts of the AO have demonstrated mix skill. By using snow cover anomalies for winter prediction the choice is reduced to a binary one, with the much easier task of identifying whether a winter will be of Type A or Type N.

[18] **Acknowledgments.** This investigation was supported by the National Science Foundation grant ATM-0124904. We would like to thank two anonymous reviewers for insightful comments. We would like to thank Drs. Richard Rosen and Mathew Barlow for beneficial discussions and suggestions.

References

Barnston, A. G., and C. F. Ropelewski, Prediction of ENSO episodes using canonical correlation analysis, *J. Clim.*, *5*, 1316–1345, 1992.

Bojariu, R., and L. Gimeno, The role of snow cover fluctuations in multiannual NAO persistence, *Geophys. Res. Lett.*, *30*, doi:10.1029/2002GL015651, 2003.

Chelton, D. B., Effects of sampling errors in statistical estimation, *Deep-sea Res.*, *30*, 1083–1101, 1983.

Cohen, J. L., Introducing sub-seasonal and temporal resolution to winter climate prediction, *Geophys. Res. Lett.*, *30*(4), 1191, doi:10.1029/2003GL016916, 2003.

Cohen, J. L., and D. Entekhabi, Eurasian snow cover variability and Northern Hemisphere climate predictability, *Geophys. Res. Lett.*, *26*, 345–348, 1999.

Cohen, J. L., K. Saito, and D. Entekhabi, The role of the Siberian High in Northern Hemisphere climate variability, *Geophys. Res. Lett.*, *28*, 299–302, 2001.

Cohen, J. L., D. Salstein, and K. Saito, A dynamical framework to understand and predict the major Northern Hemisphere mode, *Geophys. Res. Lett.*, *29*(10), doi:10.1029/2001GL014117, 2002.

Gong, G., D. Entekhabi, and J. Cohen, Modeled Northern Hemisphere Winter Climate Response to Realistic Siberian Snow Anomalies, *J. Clim.*, in press, 2003.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, *77*, 437–471, 1996.

Peterson, T. C., and R. S. Vose, An overview of the Global Historical Climatology Network temperature data base, *Bull. Amer. Meteor. Soc.*, *78*, 2837–2849, 1997.

Robinson, D. A., K. F. Dewey, and R. R. Heim Jr., Global snow cover monitoring, An update, *Bull. Amer. Meteor. Soc.*, *74*, 1689–1696, 1993.

Saito, K., J. Cohen, and D. Entekhabi, Evolution of atmospheric response to early-season Eurasian snow cover anomalies, *Mon. Wea. Rev.*, *129*, 2746–2760, 2001.

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*(6), 1302, doi:10.1029/2002GL016341, 2003.

Saunders, M. A., B. Qian, and B. Lloyd-Hughes, Summer Snow Extent Heralding of the Winter North Atlantic Oscillation, *Geophys. Res. Lett.*, *30*(7), 1378, doi:10.1029/2002GL016832, 2003.

Spencer, H., and J. M. Slingo, The simulation of peak and delayed ENSO teleconnections, *J. Clim.*, *16*, 1757–1774, 2003.

Zhou, S., A. J. Miller, J. Wang, and J. K. Angell, Downward-propagating temperature anomalies in the preconditioned polar stratosphere, *J. Clim.*, *15*, 781–792, 2002.

J. L. Cohen, Atmospheric and Environmental, Inc., 131 Hartwell Avenue, Lexington, MA 02421, USA. (jcohen@aer.com)

K. Saito, Frontier Research System for Global Change, Yokohama-city, Japan.