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Relative impacts of Siberian and North American snow anomalies on the winter Arctic Oscillation

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[1] Numerical model mean climatic response to realistic land surface snow forcings is evaluated for two different forcing regions, Siberia and North America. The atmospheric teleconnection pathway and negative winter AO mode response produced by the Siberia forcing, described by the authors in previous studies, is not produced by the comparable-extent North America forcing. It is shown that the combination of a large snow-forced local diabatic heating anomaly over a region of substantial stationary wave activity is required to produce strong upward wave activity flux anomalies which initiate the teleconnection pathway. These features are unique to Siberia, making it a critical region for reproducing the snow - winter AO statistical relationship evident in the observational record. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Gong, G., D. Entekhabi, and J. Cohen, Relative impacts of Siberian and North American snow anomalies on the winter Arctic Oscillation, *Geophys. Res. Lett.*, *30*(16), 1848, doi:10.1029/2003GL017749, 2003.

1. Introduction

[2] An emerging body of literature recognizes the role of land surface snow anomalies in modulating Northern Hemisphere climate. Most of these studies focus on snow anomalies in Eurasia, and specifically Siberia, since it is a large, contiguous land surface region characterized by extensive and variable snow conditions. The magnitude and extent of local surface diabatic heating anomalies that arise from Siberian snow anomalies can potentially affect regional and remote climatic conditions via atmospheric dynamic and thermodynamic pathways [*Cohen*, 1994].

[3] Long-standing work in this field involves an inverse relationship between winter Eurasian snow cover and subsequent Indian summer monsoon rainfall [*Bamzai and Shukla*, 1999]. A more recent avenue of snow-climate research relates Eurasian snow anomalies with the dominant mode of Northern Hemisphere extratropical winter climate variability, as represented by the Arctic Oscillation (AO, also referred to in the literature as the North Atlantic Oscillation, NAO, and the Northern Annular Mode, NAM). Observational analyses have revealed significant statistical relationships between the winter AO mode and Eurasian snow anomalies in various prior seasons [*Cohen and Entekhabi*, 1999, 2001; *Bojariu and Gimeno*, 2003; *Saito and Cohen*, 2003; *Saunders et al.*, 2003]. Exploratory General Circulation Model (GCM) studies have suggested traceable linkages between autumn Siberian snow anomalies and the subsequent winter AO mode [*Watanabe and Nitta*, 1998; *Gong et al.*, 2002].

[4] *Gong et al.* [2003; hereafter GEC03] identify a distinct and physically-based teleconnection pathway linking realistic, observation-based early season Siberian snow perturbations to a modulation of the winter AO. This pathway draws on established wave-mean flow interaction theory, and is consistent with recent literature on stratosphere-troposphere coupling of the AO signal. The pathway is enabled by the presence of a major stationary wave activity center over Siberia, and thereby provides a physical basis by which Siberia acts as a critical region for snow-forced winter AO variability on interannual timescales.

[5] This letter contributes to the investigation of Siberia as a key snow-forcing region by comparing the modeled climatic response between comparable snow perturbations in Siberia and North America. North America is also a sizable land mass with extensive and variable snow conditions. However stationary wave activity is relatively suppressed over this region, therefore an analogous hemispheric-scale dynamical response may not occur. This explicit comparison of snow forcing over the two major land masses in the extratropical Northern Hemisphere will provide additional insight to the physical mechanisms behind the apparent snow - AO relationship.

2. GCM Experiments

[6] The fundamental design of the snow-forced GCM experiments has been fully documented (please refer to GEC03 for details). In this letter we present four ensemble experiments using the Max-Planck Institute for Meteorology ECHAM3 GCM [*Roeckner et al.*, 1992] with monthly-varying sea surface temperature climatology. Each experiment consists of twenty independent realizations of a six-month (September–February) model integration period, where ensemble member initial conditions are drawn from the September 1 prognostics of a twenty-year control integration. One pair of experiments specifies a snow forcing region in Siberia, and a second pair of experiments specifies an equivalent size snow forcing region in North America. Figure 1 shows the regions in which snow perturbations are prescribed, outside of which snow-pack dynamics are free to respond to the simulated climate. In this way, each

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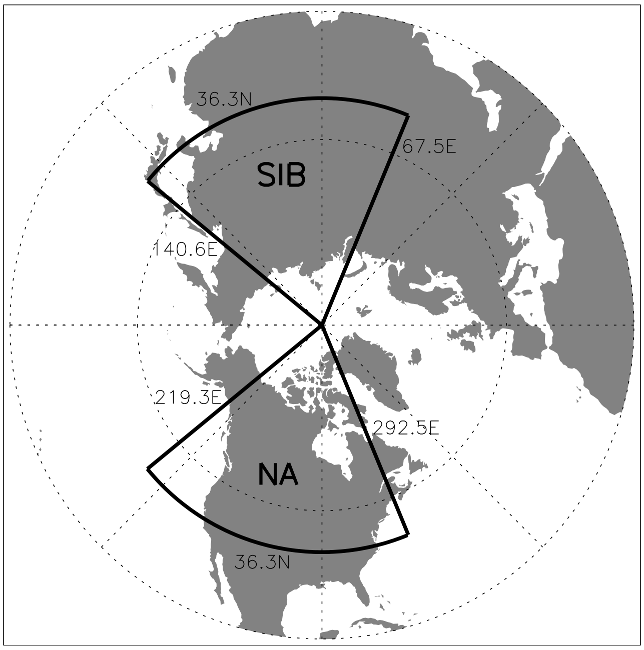

Figure 1. Snow forcing regions applied for the Siberia (SIB) and North America (NA) GCM experiments.

experiment explicitly isolates the climatic response to a clearly defined regional snow perturbation, and the relative impacts of the two regions can be effectively compared.

[7] For the Siberia region, the extensive (limited) snow experiment prescribes snow based on Sept 1976–Feb 1977 (Sept 1988–Feb 1989) NOAA visible satellite snow cover observations [*Robinson et al.*, 1993], which correspond to the most (least) extensive autumn snow cover recorded over Eurasia. For each experiment, snow depth is specified at each timestep using an approximate adjustment, which consistently associates deeper (shallower) snow depths with more (less) extensive snow cover, throughout the temporal integration period and geographical forcing region. Although the resulting snow forcings do not precisely depict year-specific observed snow depths, they do represent a reasonable upper (lower) bound on observed Siberian snow anomalies [GEC03]. Ensemble mean differences between the two experiments are computed (extensive snow - limited snow), and statistical significance is evaluated using the standard t-test. The ensemble mean response to Siberia snow forcing has been extensively documented in GEC03; for this letter it will be denoted as SIB.

[8] The same approach is applied for the two snow-forced experiments over North America. The only difference is that the snow forcing is prescribed based on September 1996–February 1997 (September 1987–February 1988) observations, corresponding to the most (least) extensive autumn snow cover recorded over North America. The ensemble mean climatic response to these extreme but realistic snow perturbations over North America will be denoted as NA.

3. Results

[9] Figure 2 shows the vertical wave activity flux (WAF; see *Plumb* [1985]) response to a positive snow perturbation, at 850 hPa elevation, during autumn (SON), for SIB (repeated from GEC03 Figure 5) and NA. While an upward anomaly over southern Siberia is apparent for SIB, a comparable anomaly does not occur over North America for NA. GEC03 asserts that the regional co-location of the Siberia snow forcing and a major stationary wave activity center over East Asia serves to amplify this pre-existing wave activity center, producing the strong upward WAF anomaly seen in Figure 2a over southern Siberia. For NA, the snow forcing occurs in a region of reduced stationary wave activity; because there is no pre-existing wave activity center to amplify, an appreciable local upward WAF anomaly fails to develop.

[10] Note in Figure 2b that weak areas of upward WAF anomalies do occur over western Europe and Siberia, well removed from the North America snow forcing region. These regions roughly coincide with the two major stationary wave activity centers that exist in the Northern Hemisphere, centered over East Asia and the North Atlantic.

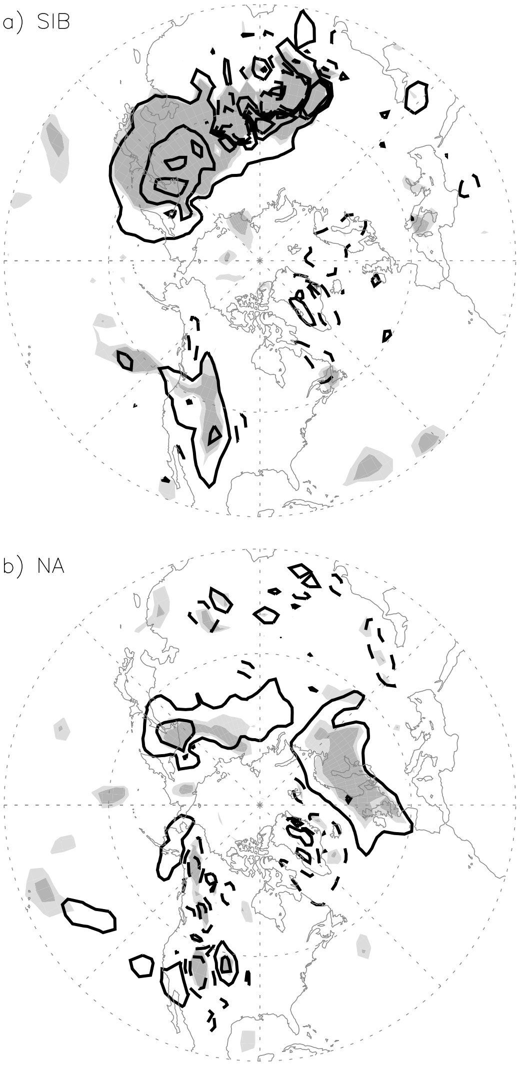

Figure 2. Vertical wave activity flux response to a positive snow perturbation at 850 hPa over the extratropical Northern Hemisphere, for autumn (SON). Contours drawn at ±0.01, 0.04, 0.08 $m^2 s^{-2}$. Dashed line denotes negative contour value. Light (dark) shading indicates 90% (95%) statistical significance. (a) SIB. (b) NA.

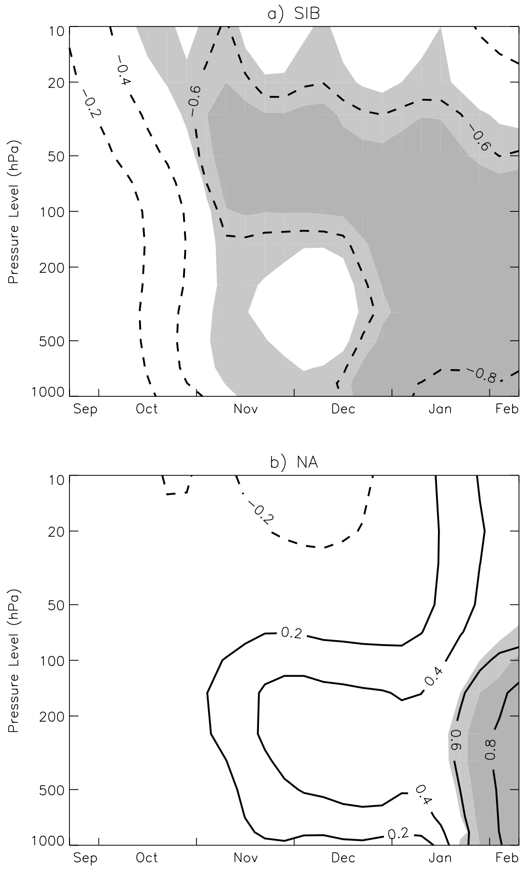

Figure 3. Weekly evolution over the atmospheric column of 42-day moving average hemispheric AO index response to a positive snow perturbation. Contours drawn at ±.2, .4, .6, .8 standard deviations (geopotential height normalized over the atmospheric column). Light (dark) shading indicates 90% (95%) statistical significance. (a) SIB. (b) NA.

Thus rather than producing a strong localized upward wave anomaly, the snow forcing over North America appears to modestly enhance the prevailing stationary wave fluxes throughout the Northern Hemisphere. The reasons for this unexpected response and a detailed analysis of their significance are beyond the scope of this concise letter. A hypothesized mechanism is nonetheless put forward for consideration at the end of this section.

[11] For SIB, the resulting strong upward WAF anomaly over southern Siberia propagates up through the troposphere and into the stratosphere, and weakens the polar vortex. The subsequent downward component of the teleconnection pathway involves the propagation of poleward stationary wave refraction and dipole mean-flow anomalies associated with the weakened vortex, from the stratosphere down to the surface. It can be summarized by evaluating the snow-forced change in a proxy AO index metric, computed as the difference in geopotential height between mid and high latitude hemispheric zonal bands, normalized over the atmospheric column (see GEC03). The weekly evolution of this AO index response to snow is presented for SIB in Figure 3a (repeated from GEC03 Figure 9). A negative AO index anomaly first appears in the late autumn stratosphere, indicative of the weakened polar vortex. The anomaly then gradually propagates downward, culminating in a strong negative AO index response at the surface by mid-winter.

[12] The corresponding AO index evolution for NA is presented in Figure 3b. In the absence of a strong upward WAF anomaly (Figure 2b), the polar vortex exhibits no apparent weakening in response to North American snow forcing. Consequently, the subsequent downward propagation of negative AO index anomalies also fails to materialize (Figure 3b). Thus the AO mode modulation that occurs in response to a Siberian snow forcing is not reproduced for a comparable North American snow forcing. This modeling result provides additional confirmation that Siberia is a critical region for producing the fall snow-winter AO mode statistical relationship found in the observational record.

[13] Figure 4 shows the winter sea level pressure (SLP) response to snow for SIB and NA. The response to Siberian snow (Figure 4a, repeated from GEC03 Figure 4f)

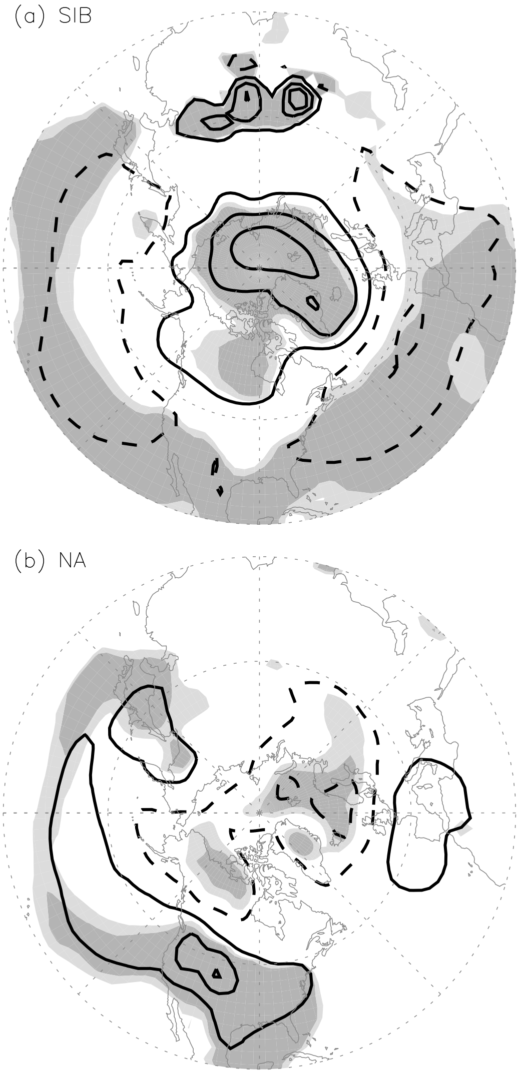

Figure 4. Winter (DJF) sea level pressure response to a positive snow perturbation over the extratropical Northern Hemisphere. Contours drawn at ±1, 3, 5 hPa. Dashed line denotes negative contour value. Light (dark) shading indicates 90% (95%) statistical significance. (a) SIB. (b) NA.

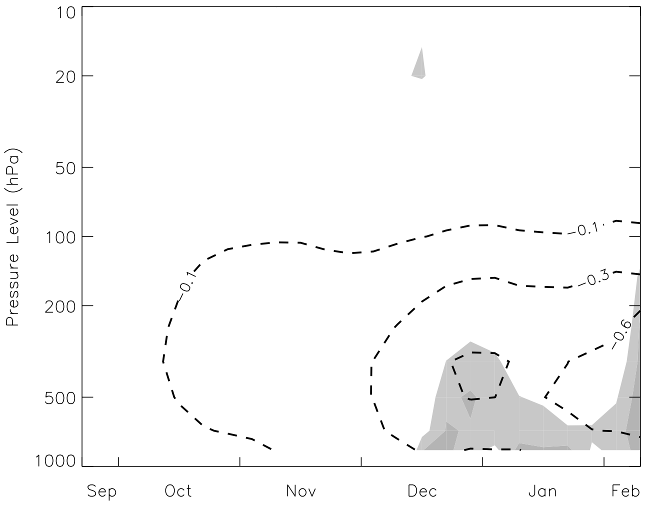

Figure 5. Weekly evolution (horizontal axis) over the atmospheric column (vertical axis) of meridional wave activity flux response to positive North American snow forcing (NA). Contours represent 42-day moving average, over extratropical (36.5N–81N) Northern Hemisphere, drawn at ±.1, .3, .6, .9 m2s-2. Dashed line denotes negative (equatorward) contour value. Light (dark) shading indicates 90% (95%) statistical significance.

clearly resembles a negative AO pattern. The response for NA (Figure 4b) is somewhat reminiscent of a positive AO pattern, though the high-latitude anomaly is much weaker and the mid-latitude anomalies are not as broad. Note that the positive SLP anomaly over North America is a direct local response to the snow forcing, which generally occurs later in the season for NA than for SIB. Similarly, Figure 3b shows a weak positive AO index anomaly appearing in the late autumn troposphere and gradually intensifying over time. This positive AO mode response for NA is counter to the physically-based pathway described for SIB.

[14] A possible interpretation of this unexpected result is as follows. The snow-forced diabatic heating anomaly over North America translates into a modest enhancement of the two prevailing Northern Hemisphere stationary wave activity centers during autumn, as indicated previously in Figure 2b. These WAF anomalies are insufficient to propagate into the stratosphere and weaken the polar vortex. Rather, they remain in the troposphere, producing an enhancement of the prevailing equatorward tropospheric stationary wave activity [*Plumb*, 1985]. As indicated in Figure 5, equatorward wave refraction occurs throughout the troposphere for NA, beginning in mid-autumn and continuing through the winter season. This equatorward wave flux produces a poleward momentum flux, which results in dipole mean flow anomalies indicative of a positive AO mode response. Additional research efforts are required to confirm or refute this hypothesis for the apparent and unexpected positive winter AO mode response to North American snow forcing.

4. Conclusions

[15] The modeled snow-AO relationship for SIB is facilitated by the co-location of the local snow anomaly within a region of strong prevailing stationary wave activity. Resulting local diabatic heating anomalies amplify this pre-existing wave activity, producing upward WAF anomalies over southern Siberia that initiate a physically-based teleconnection pathway. For NA, the snow-forcing region is not co-located with a significant wave activity center, so there is no mechanism by which local WAF anomalies can develop and propagate upwards.

[16] This result supports the assertion that Siberia is the critical region for snow-forced winter AO variability.

[17] It is important to bear in mind that the results presented here are based on the output from one GCM. Another question which naturally arises involves the symmetry of the climate response to positive vs. negative snow anomalies. These issues are outside the scope of this concise letter, however ongoing research involving long-term snow-forced GCM experiments is aimed at addressing these and other important issues.

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