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Northern Hemisphere winter climate variability: Response to North American snow cover anomalies and orography

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[1] Links between autumn-winter snow anomalies over North America and winter climate parameters throughout the Northern Hemisphere are examined. GCM integrations are performed from September through February, with prescribed snow forcings over North America (NA) reflecting realistic, observed high/low autumn snow conditions. Forty-member ensemble differences reveal robust responses in surface air temperature and sea level pressure (SLP) fields. Over NA a negative temperature/positive SLP response occurs while over Europe a positive temperature/negative SLP response emerges. Additionally, a dynamic wave response occurs in the troposphere, across NA and extending downgradient into Eurasia. The contribution of North American (NA) orography is evaluated via an additional pair of experiments in which mountains are removed. The resulting climatic response is mitigated considerably, which suggests a nonlinear coupling of thermal and mechanical forcings. Finally, possible physical pathways for the remote response are hypothesized, involving dynamical mechanisms consistent with previous studies. **Citation:** Sobolowski, S., G. Gong, and M. Ting (2007), Northern Hemisphere winter climate variability: Response to North American snow cover anomalies and orography, *Geophys. Res. Lett.*, *34*, L16825, doi:10.1029/2007GL030573.

1. Introduction

[2] A number of complex interacting processes can influence Northern Hemisphere wintertime climate variability. Research has typically focused on the oceans as the main drivers of large-scale climate variability, since their thermal inertia accentuates land-ocean heating contrasts. However, regional-hemispheric climate may also respond to the land surface state, via mechanical (e.g. orography, land-ocean contrast) and/or low-level thermal (e.g. snow cover, soil-moisture) forcings. Here we focus on the specific effects of North American (NA) snow cover and orography on Northern Hemisphere winter climate.

[3] The ability of surface orographic features to produce stationary wave trains which influence downstream climate is well documented [*Hoskins and Karoly*, 1981; *Chen and Trenberth*, 1988]. On local to regional scales this forcing has a mechanical component (mountains physically alter the flow), and a thermal component (air cools, then warms while traversing a mountain). Model studies generally indicate that the linear sum of individual mechanical and thermal forcings is not equal to the total forcing when all components are included [*Chen and Trenberth*, 1988; *Ringler and Cook*, 1999; *Ting et al.*, 2001]. Additionally, both thermal and mechanical forcings may be altered by the land-surface state. For example, *Ringler and Cook* [1999] demonstrate that low-level heating (cooling) tends to reduce (amplify) mechanical forcing, producing both near and far-field changes in the circulation response.

[4] Snow cover anomalies can be conceptualized as a surface thermal forcing, since the presence of snow is known to exert a local diabatic cooling effect, via various surface thermodynamic mechanisms (see *Cohen* [1994] for a review). Studies examining the remote effects of snow cover on climate have focused primarily on Eurasia, and report diverse continental to hemispheric scale responses to snow and also orography. An apparent inverse relationship between Eurasian snow cover and the Indian Monsoon, which itself relies on orographic forcing and land-ocean heating contrasts, has been extensively studied [*Bamzai and Shukla*, 1999; *Robock et al.*, 2003]. *Gong et al.* [2004] describe an orographically constrained pathway by which autumn Eurasian snow cover modulates the wintertime Arctic Oscillation.

[5] Given the size and extent of the Rocky Mountains and the prevalence of seasonal snow cover, it is reasonable to hypothesize that NA snow cover and orography may also influence local and remote climate. Early studies examining the remote effects of NA snow cover on climate find that positive snow anomalies increase baroclinicity at the land-ocean boundary, resulting in a shift of the North Atlantic storm tracks with implications for European climate [*Walland and Simmonds*, 1996; *Dickson and Namias*, 1976]. In contrast, *Gong et al.* [2003] found that climate response to NA snow was ambiguous compared to a clear signal generated by Siberian snow anomalies. None of these studies considered orography, while conversely *Ting and Wang* [2006] find that nonlinear orographic forcings are largely responsible for the observed Great Plains low-level jet, but do not consider snow cover.

[6] The current study represents a follow-up analysis to *Gong et al.* [2003], focusing explicitly on NA snow cover and orography. We examine the wintertime atmospheric circulation response to realistic NA snow anomalies both with and without the presence of orography. Mean climatic responses of surface parameters and the dynamic response of the atmosphere are analyzed.

2. Methodology

[7] A suite of snow-forced experiments are conducted using the Max Planck Institute for Meteorology's ECHAM3

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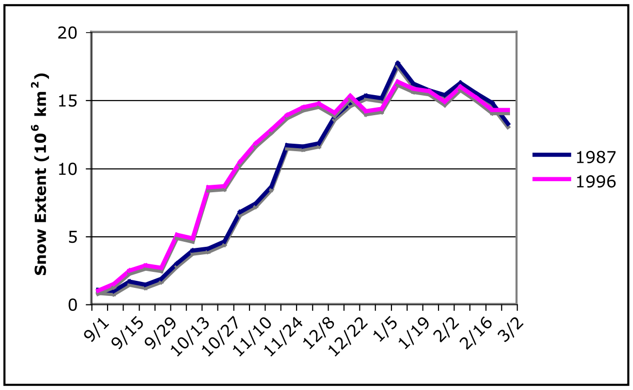

Figure 1. Weekly time-series (month/day) of satellite-observed snow extent for years with high (1996–1997, pink/solid) and low (1987–1988, blue/dashed) snow.

GCM at T42 spectral truncation (~2.8° grid cell resolution). The experimental design follows those of *Gong et al.* [2003, 2004] for Siberia, so only a brief overview is provided here. One important exception is that the number of realizations is extended to 40 from 20, due to the modest magnitude of NA snow anomalies relative to those over Siberia (see Discussion).

[8] All experiments are integrated from September through February using climatological sea surface temperatures (CSST), with initial conditions for each realization obtained from a different year within a forty-year CSST control simulation. The model control run reproduces the general structure of the mean stationary wave streamfunction fields obtained from NCEP/NCAR reanalyses (not shown). An initial pair of experiments representing high and low snow conditions over NA is conducted by prescribing satellite-observed snow cover data from representative years (Figure 1), and snow depths scaled from model climatology in proportion to the snow cover anomaly magnitude. A second pair of experiments is conducted with identical high and low snow forcings, but with the surface elevation boundary condition reduced to a maximum of 300m over a broad region spanning 197°E–276°E and 0°N–90°N. Final elevations are spectrally fitted to the T42 model resolution used, and the global mean surface pressure adjusted to accommodate the additional air mass that results. Ensemble mean monthly and seasonal differences (high-snow minus low-snow) are calculated for surface climate and atmospheric dynamic parameters, and evaluated for statistical significance using the student's t-test, for both the with-mountains and without-mountains cases.

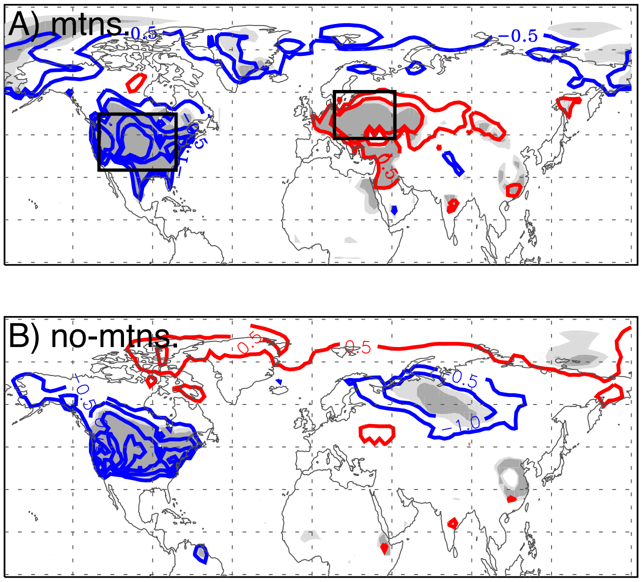

Figure 2. Winter surface temperature response to positive snow forcing (a) with and (b) without mountains. Contours at ±0.5, 1, 2, 3 °C. Red (blue/dashed) denotes positive (negative) response. Shading indicates statistical significance (light gray, 90%; dark gray, 95%). Regions chosen for spatial averaging (Figure 3) outlined in Figure 2a.

3. Results

[9] Realistic, observation-based autumn NA snow forcings applied to the GCM experiments result in a robust set of thermodynamic and dynamic responses, spanning the surface and the troposphere, both locally over the forcing region and over remote downgradient regions. All of the following results describe the response to a positive prescribed snow forcing (high-snow minus low-snow experiments), which was designed to emphasize snow anomalies during autumn (SON).

[10] Figure 2a shows that winter (DJF) surface temperatures decrease significantly over the NA forcing region, which is a direct thermodynamic response to increased snow cover. Figure 3 shows that this response persists throughout most of the autumn-winter integration period, evolving gradually and peaking in November, consistent with the monthly snow forcing shown in Figure 1. The regions over which the area-weighted spatial averages shown in Figure 3 are taken appear in 2a and 4a. This response evolves spatially from north to south during the integration (not shown). Figure 2a also shows that over Europe a significant positive winter temperature response

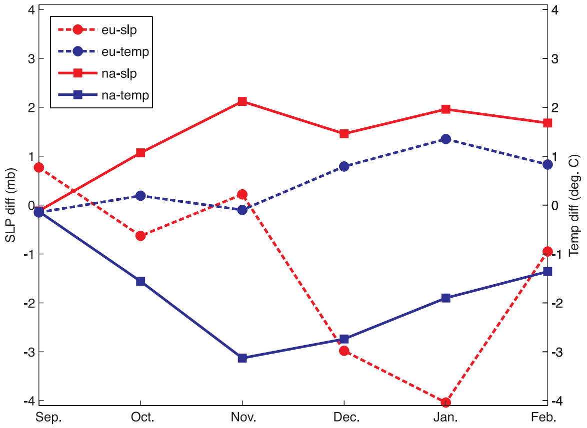

Figure 3. Area-weighted, spatially averaged monthly NA (solid lines) and European (dashed lines) SLP and TEMP responses to positive snow forcing. Averaging regions are shown in Figures 2a and 4a.

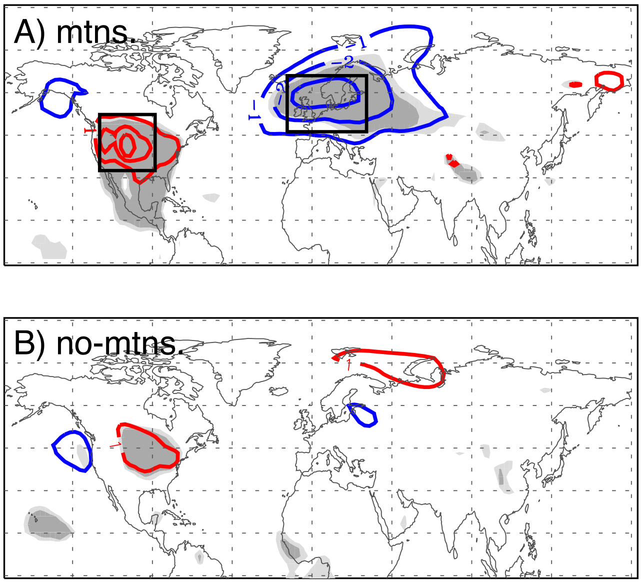

Figure 4. Wintertime sea level pressure response to positive snow forcing with (a) and (b) without mountains. Contours at ±1, 2, 3, 5 hPa. Red/Solid (blue/dashed) denotes positive (negative) response. Shading indicates statistical significance (light gray, 90%; dark gray, 95%). Regions chosen for spatial averaging (Figure 3) outlined in Figure 4a.

emerges; it evolves from west to east through the winter months (not shown), and its magnitude peaks in January two months later than the NA response (Figure 3). The physical pathway leading to positive winter temperature anomalies over Europe is not immediately apparent (see Discussion); however, the persistence of the European response over multiple winter months gives us confidence that this modeled response is genuine. Furthermore, vertical profiles of the temperature response (not shown) indicate that the NA response is constrained to near-surface elevations due to the surface snow forcing, while the European response is equivalent barotropic throughout the troposphere, suggesting an atmospheric driver.

[11] In the no-mountains case, a local NA temperature response is still evident but it shifts north slightly (Figure 2b). However, the persistent positive European winter temperature response disappears in the absence of NA mountains. Other regions of anomalous temperatures at higher latitudes are evident in both Figures 2a and 2b, but they do not exhibit spatial or temporal consistency over the winter season. Hence the orography of NA appears to be critical for facilitating a remote European response to NA snow cover anomalies.

[12] Sea level pressure (SLP) exhibits an analogous winter response over both NA and Europe, as shown in Figure 4. With mountains (Figure 4a), SLP increases over NA as a consequence of the local snow forcing and temperature response, but decreases over Europe. The time evolution of the NA and European SLP responses follows that of the temperature response (Figure 3). A similar north-south geographic evolution occurs over NA, but the winter west-east evolution over Europe is not as clear as for temperature (not shown). Without mountains (Figure 4b), a local SLP increase over the snow forcing region is still apparent but diminished considerably, while the remote European SLP decrease disappears entirely. Hence surface air temperature and SLP fields consistently indicate a remote teleconnection linking NA snow anomalies and orography with subsequent winter European climate.

[13] The apparent contribution of NA orography suggests that dynamical processes may be involved. The winter 850 hPa low-snow ensemble-average stationary wave streamfunction field and response to snow forcing, shown in Figure 5, shows a response concentrated within the forcing region and further downstream, i.e. mid-latitude North Atlantic and Eurasia. Centers of positive and negative circulation appear to strengthen and also shift eastward in response to a positive snow forcing. For the no-mountains case, the dynamic stationary wave response to snow is largely absent throughout the Northern Hemisphere (not shown), which once again indicates the importance of NA orography, and furthermore suggests a nonlinear relationship between thermal and mechanical forcings (see Discussion).

[14] Our modeled stationary wave response is generally consistent with previous research on the combined effects of diabatic heating/cooling and orography on atmospheric circulation [*Ringler and Cook*, 1999; *Hoskins and Karoly*, 1981; *Ting et al.*, 2001]. These earlier studies are not precisely equivalent, since they generally prescribe a direct diabatic heating anomaly whereas ours occurs via snow anomalies. However the experiments and results are conceptually similar in that heating/cooling in the presence of mountains yields downgradient near and far field dynamic circulation responses. In addition, snow cover is noted as a

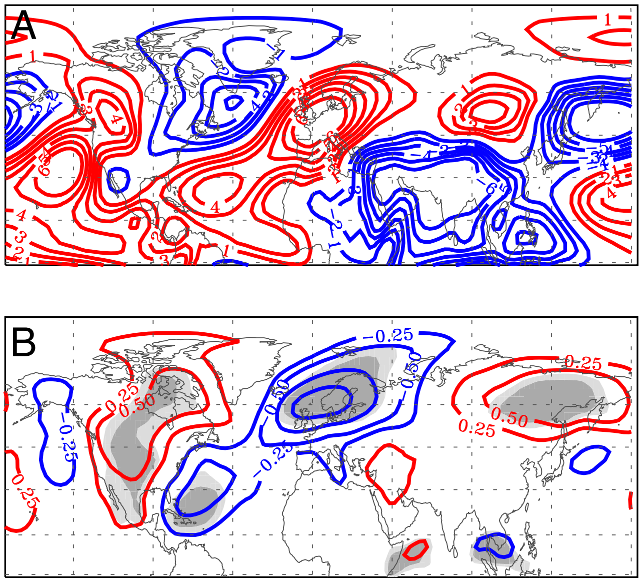

Figure 5. (a) 850 hPa winter stationary wave streamfunction with mountains for ensemble-average low-snow field and (b) response to positive snow forcing. Contours at ±1 × 10^6 m^2 s^{-1} and ±.25, 0.5, 1, 1.5 × 10^6 m^2 s^{-1}, respectively. Red/Solid (blue/dashed) denotes positive (negative) response. Shading indicates statistical significance (light gray, 90%; dark gray, 95%).

viable mechanism for inducing the idealized low-level heating perturbations used in these studies.

4. Discussion

[15] While snow-forced remote teleconnections have been reported involving Eurasian snow and the Indian monsoon [*Bamzai and Shukla*, 1999], and Siberian snow and the AO [*Gong et al.*, 2003], this report is to our knowledge, the first instance of a possible snow-forced teleconnection involving NA snow and European climate. The occurrence of a significant winter stationary wave response in addition to tropospheric temperature and SLP responses over Europe suggests that atmospheric dynamical mechanisms may be responsible for this modeled teleconnection.

[16] One hypothesized mechanism involves an enhancement and an eastward shift of the low-level wintertime stationary wave patterns in response to a positive snow forcing. An immediate response to the surface snow cover is a cold high over continental US (Figure 3). This high enhances the climatological ridge over the western NA (Figure 5a) and extends it further to the east. Through interaction with the NA topography, a downstream stationary wave response can be induced in a similar way as in the forcing of the climatological stationary waves illustrated by *Ting et al.* [2001]. A detailed stationary wave diagnosis is not possible with the current model data due to the lack of detailed model output on stationary wave forcing.

[17] A major consequence of this hypothesized lateral wave perturbation is an eastward displacement of the Icelandic Low into Western Europe. This is manifested as the negative winter SLP response over Europe shown in Figure 4a. The European temperature anomaly in Figure 2a arises when warm Atlantic air carried between the displaced Icelandic Low and the Azores High is sent deep into Europe. *Seager et al.* [2002] note that NA orography plays an important role in ameliorating Western European climate and their proposed mechanism for atmospheric heat transport across the North Atlantic is consistent with that described above. By late winter the snow forcing dissipates, the stationary wave field returns to normal, and both the NA and European surface responses subside (Figure 3).

[18] Another possible mechanism for the observed remote response involves the location and strength of North Atlantic storm tracks. Snow-forced cooling of the NA continent causes the region of strongest winter temperature gradient to shift southward, displacing and weakening the polar front across NA which serves as an entry point for North Atlantic cyclone activity. Hence the North Atlantic storm track shifts southwards, resulting in positive temperature and negative SLP anomalies over the European continent. Under this hypothesis, stationary wave anomalies over both NA and Europe are a consequence of local surface climate anomalies, and cyclone activity across the Atlantic is the mechanism linking NA snow forcings to European climate. Such a mechanism would be consistent with previous research on remote responses to NA snow anomalies [*Walland and Simmonds*, 1996; *Dickson and Namias*, 1976].

[19] Our results implicate NA orography as an important factor for producing the snow-forced climate response. The positive SLP response over NA likely results from a coupled response to the snow anomaly and orography. Orography induces anticyclonic flow east of the mountains [*Ringler and Cook*, 1999], while snow cover and associated diabatic cooling augments this flow by inducing sinking of the cool air and hence higher SLP [*Cohen*, 1994]. While these individual effects are generally well known, the noticeably reduced SLP response to snow in the absence of mountains emphasizes the importance of orography in modifying the total flow in the atmosphere.

[20] The results also suggest that snow and orography represent a coupled nonlinear forcing whose combined effect is greater than the linear sum of the individual forcings (see *Chen and Trenberth* [1988] for a review of mechanical and thermal forcing). The snow-driven thermal forcing is identical for the cases with and without the orographically-derived mechanical (and associated thermal) forcing. However, the magnitude of the climatic response to the same snow forcing is dramatically mitigated when it is decoupled from orographic forcing. Such nonlinearities may arise from the ability of thermal forcing directly over mountains to alter mechanical forcing [*Ringler and Cook*, 1999]. It should be noted that while the snow forcing is identical in both cases, the removal of the mountains impacts both mechanical and thermal forcing (by eliminating adiabatic heating/cooling). Thus the absolute thermal forcings will differ in the absence of orography, but the relative thermal forcing due to snow will be the same.

[21] Prior experiments with 20 realizations [*Gong et al.*, 2003] did not reveal a coherent remote climate response to NA snow anomalies. For this follow-up study the ensemble size is doubled to 40 realizations, in part because a relatively modest observation-based snow forcing is applied over NA (Figure 1), using an approach that was originally designed to replicate observed maximum October snow extent differences over Siberia. Snow forcings in the presence and absence of NA mountains are also considered. What emerges is a clear remote response over Europe for various surface climatic and dynamical parameters, and also the importance of NA orography for producing this snow-forced response. Two mechanisms have been hypothesized for producing this remote teleconnection, consistent with our results and the prevailing literature. Detailed investigation of these mechanisms is the subject of ongoing study; here we report for the first time evidence of a remote climatic response to NA snow anomalies.

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