Hemispheric-scale climate response to Northern Eurasia land surface characteristics and snow anomalies

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Abstract

This paper presents a synopsis of recently published studies by the co-authors, which show that several land surface characteristics unique to Northern Eurasia are responsible for facilitating a causal relationship between autumn snow anomalies in this region and subsequent hemispheric winter climate patterns. The large size and extratropical location of the contiguous Eurasian land mass results in broad, continental-scale interannual snow cover extent and depth variations throughout autumn and winter, and corresponding diabatic heating anomalies. These surface anomalies occur in the presence of a large region of stationary wave activity, produced in part by the orographic barriers that separate northern/central Eurasia from southern/eastern Eurasia. This co-location of snow-forced anomalies and ambient wave energy is unique to Northern Eurasia, and initiates a teleconnection pathway involving stationary wave–mean flow interaction throughout the troposphere and stratosphere, ultimately resulting in a modulation of the winter Arctic Oscillation (AO). Complementary new results are also presented which show that partial snow cover extent or snow depth only anomalies in Northern Eurasia are insufficient to initiate the teleconnection pathway and produce a winter AO signal. This synopsis provides a useful interpretation of the earlier studies in the specific context of Northern Eurasia regional climate and environmental change.

Keywords: Eurasia; snow; climate; orography

1. Introduction

High latitude regions in the Northern Hemisphere are already understood to be highly responsive to natural and anthropogenic global climate change, especially during the winter season (Houghton, 2004). This sensitivity to climate is particularly strong in Northern Eurasia, due to factors such as the size of the contiguous land mass, large mountain ranges which separate high and low latitude regions, and relatively low magnitudes of surface water and energy fluxes. Conversely, these surface characteristics also enable regional perturbations to potentially impact broader scale climate. This study focuses on one aspect of the climate modulating capability of Northern Eurasia, namely the hemispheric-scale response to interannual snow anomalies over Northern Eurasia.
Anomalies originating in Eurasia have widespread effects on remote as well as local climate. Arid and semi-arid conditions in Central and East Asia lead to one of the world’s largest sources of aeolian mineral dust, and recent climate and land use changes only compound aridization and the occurrence of dust storms. Once in the atmosphere, these aerosols can be transported downwind as far as western North America, and can impact atmospheric chemistry, cloud cover, precipitation and radiation throughout the Pacific Basin (Darmenova and Sokolik, 2002). Anomalies in the thermal state of permafrost and the active layer can lead to changes in warm season microbial activity and terrestrial carbon dioxide exchange with the atmosphere (Oechel et al., 1993, 1995). Northern Eurasia watersheds contribute a substantial amount of freshwater inflow to the Arctic Ocean (Aagaard and Carmack, 1989; Barry et al., 1993), so variations in surface runoff can influence the density of water in the Arctic Ocean and hence global thermohaline circulation (Wang and Cho, 1997).

Seasonal snow cover is perhaps the largest and most influential Eurasian feature with regard to climate impact. One of the more widely studied phenomena is the relationship between the Indian summer monsoon and the preceding Eurasian snow cover (e.g., Douville and Royer, 1996; Bамзai and Shukla, 1999; Liu and Yanai, 2002; Robock et al., 2003). Eurasian winter snow has also been linked to subsequent summer monsoon rainfall over Korea (Kripalani et al., 2002), subsequent winter sea-surface temperatures in the eastern and central tropical Pacific Ocean (Ye and Bao, 2001), and concurrent geopotential heights over the North Pacific Ocean (Clark and Serreze, 2000). Snow extent over Eurasia during the warm season has been associated with the state of the following winter North Atlantic Oscillation (Bojariu and Gimeno, 2003; Saunders et al., 2003).

Recent studies by the co-authors have reported observed and modeled lead–lag relationships between autumn snow anomalies over Siberia and the subsequent winter Arctic Oscillation (e.g., Cohen and Entekhabi, 1999; Gong et al., 2003a, 2004a), and investigated the causal factors behind this association. These studies represent one of the few demonstrated linkages between precursive Northern Eurasia surface anomalies and subsequent climatic conditions over the entire extratropical Northern Hemisphere. This paper presents a synopsis of these previous studies (with some additional supporting results), and highlights the particular characteristics of the region which enable it to exhibit a pronounced modulating effect on large-scale climate. By focusing more on Northern Eurasia and less on general snow forcings, detailed physical mechanisms and teleconnection pathways, this synopsis provides a useful interpretation of the earlier studies in the specific context of Northern Eurasia regional climate and environmental change.

Several unique features of Eurasia are described in Section 2, which facilitate autumn snow–winter climate relationships as described in Section 3. Section 4 presents the results of modeling studies which demonstrate that these features are responsible for the large-scale climatic response to snow, and conclusions are presented in Section 5.

2. Northern Eurasia land surface features

Large, contiguous land masses comprise roughly half of the total surface area north of 30°N, and Eurasia is by far the largest of these land masses, spanning almost half of the extratropical Northern Hemisphere. The presence of this land mass produces large-scale diabatic heating gradients relative to oceans due to their different thermal capacities. The resulting land–ocean contrasts are largely responsible for the zonal asymmetries that characterize the general atmospheric circulation in the Northern Hemisphere.

Another feature is the large system of mountain ranges that isolates extratropical Northern Eurasia from tropical Southern Eurasia, and to a lesser extent Central Eurasia from Eastern Eurasia. These orographic barriers in conjunction with the land–ocean heating contrasts produce a large region of stationary wave energy over Eastern Eurasia (Plumb, 1985). Fig. 1 shows autumn and winter climatological average values of the three-dimensional wave activity flux (WAF), which describes the presence and transmission of this stationary wave energy. This climatology was produced from a twenty-year control integration of the ECHAM3 GCM (see Section 3.2), and compares favorably to observation-based values (Gong et al., 2004a). A large center of stationary wave activity is centered over far-east Asia throughout the troposphere, and propagates upward, eastward and primarily equatorward. It is strongest during winter but apparent during autumn as well.

In addition to these static features, temporally varying features and large-scale anomalies over Eurasia also have the potential to influence atmospheric circulation and climate variability on a broader scale than what has traditionally been investigated. One of the most significant land surface features in Eurasia is the seasonal snow cover extent, which ranges from roughly 2 million km² during the summer to 30 million km² during the winter (Robinson et al., 1993), compared to a total Eurasian
surface area of roughly 60 million km². The snow cover is basically confined to the extratropics, meaning that Northern Eurasia is essentially snow-free during the summer and fully snow-covered during the winter. Snow cover exerts a strong effect on the surface energy balance via the high albedo of snow and also snowpack insulative processes such as decreased thermal conductivity (Cohen, 1994; Gong et al., 2004b), and generally results in lower surface temperatures.

Snow cover extent over Northern Eurasia is subject to considerable interannual variability during the autumn accumulation season. NOAA provides weekly visible satellite observations of Northern Hemisphere snow cover over a roughly 30-yr period (Robinson and Frei, 2000). Fig. 2 shows weekly time series of autumn–winter Eurasian snow cover extent from this dataset, for the years with maximum and minimum autumn snow cover extent over Eurasia. A substantial difference is observed throughout October and part of November. For Northern Eurasia a clear difference occurs from late September through mid-December (Gong et al., 2003a). The largest difference occurs in mid-October, when the spatial snow cover extent over Northern Eurasia can range from virtually snow-free to essentially fully snow-covered in any given year, as shown in Fig. 3.

Likewise, snow depth over Northern Eurasia is subject to interannual variability, however the timing and magnitude of snow depth variations is not necessarily

![Fig. 1. Three-dimensional wave activity flux climatology over the extratropical Northern Hemisphere, from a twenty-year control simulation of the ECHAM3 GCM. Vectors denote horizontal fluxes (scale indicated on figure) and contours denote vertical fluxes. Dashed line denotes negative contour value. (a) Autumn, 500 hPa elevation. (b) Autumn, 150 hPa elevation. (c) Winter, 500 hPa elevation. (d) Winter, 150 hPa elevation. Contour intervals at 500 hPa elevation drawn at ±.03, .06, .15, .25 m² s⁻². Contour intervals at 150 hPa elevation drawn at ±.01, .02, .03, .04 m² s⁻². Solid black line indicates Siberia forcing region for GCM snow perturbation experiments (see Section 3.2). Reproduced in part from Gong et al. (2004a) Fig. 2.](image)

![Fig. 2. Weekly time series of NOAA satellite-observed snow cover extent over Eurasia, for the period September 1976–February 1977 (solid line) and September 1988–February 1989 (dashed line).](image)
consistent with snow extent or snow frequency variations. Fig. 4a,b shows the interannual distribution of monthly snow frequency and snow depth during the snow season (September–April), derived using Eastern Siberia station measurements available from the National Snow and Ice Data Center (NSIDC; Romanovsky, 2003). Twelve stations with a continuous 23-yr record (1968–1990) were averaged, and thrice-monthly snow depth measurements were averaged, so that each monthly box plot in the figure is consist of 23 annual values. All stations are located within approximately 115°E–135°E and 60°N–70°N.

Snow frequency (a point surrogate for spatial extent) exhibits considerable variability during the autumn accumulation season (consistent with Figs. 2 and 3) and spring ablation season, but exhibits almost no variability during the mid-season, since the entire region is essentially snow-covered. In contrast, snow depth exhibits steadily increasing variability throughout the snow season, peaking in late winter/early spring. Fig. 4c shows that frequency and depth anomalies are strongly correlated during autumn and spring, but not during winter. Hence snow frequency/extent and snow depth anomalies appear to be coupled during the accumulation and ablation seasons, but during the mid-season snow depth anomalies can occur in the absence of snow extent anomalies. By considering depth as well as frequency/extent, snow anomalies that initially occur during autumn accumulation may persist throughout the snow season.

3. Northern Eurasia–hemispheric climate relationships

The co-authors have recently published a series of papers, whose common theme has been the association of hemispheric-scale climate patterns with precursive land surface conditions. The primary climatic phenomenon of interest is the winter Arctic Oscillation (AO), sometimes referred to as the Northern Annular Mode (NAM). The land surface feature of interest is snow conditions over Siberia during the preceding autumn, which is found to modulate the subsequent winter AO. Both observational analyses and modeling experiments...
have been performed, and the results as they relate to Northern Eurasia are summarized below.

3.1. Observational analyses

Cohen and Entekhabi (1999) first suggested that the main impact of Eurasian snow cover variability is not downstream on the general circulation of the North Pacific but rather over the Arctic and North Atlantic, and therefore plays a potentially important role in the variability of the AO/NAO. Correlations between the observed snow cover and climate diagnostics, such as sea level pressure (SLP), 500 hPa and standard climate indices, all show a significant statistical relationship concentrated in the North Atlantic (Cohen and Entekhabi 1999; Cohen et al. 2001; Cohen and Saito, 2003). As an example, Fig. 5 shows that Eurasian October snow cover anomalies are correlated with DJF SLP and surface temperature anomalies, and that the resultant spatial anomaly patterns resemble the AO pattern of variability.

These and related papers hypothesize possible dynamical mechanisms linking Eurasian snow anomalies and hemispheric climate variability, e.g. through the strength and position of the Siberian high. Using a proxy index for the AO, Cohen et al. (2001) showed that the winter AO in the lower troposphere originates as a negative tropospheric height/surface temperature anomaly in Siberia during the fall. A second hypothesized mechanism is based on an observed stationary wave energy anomaly originating at the surface, in response to a Siberian snow anomaly (Saito et al., 2001; Cohen et al., 2002). This anomalous energy propagates up to the stratosphere, and is followed by a downward propagating AO signal. Section 3.2 summarizes a detailed investigation of this pathway utilizing numerical model simulations.

In an effort to better understand when the snow–climate mechanism is more influential to the winter climate and when it is less influential, Cohen et al. (2002) and Cohen (2003) have advanced the idea that anomaly patterns during winter evolve according to two basic paradigms, referred to as either Type A or Type N, depending on where the dominant sea level pressure anomalies originate. Both types of anomalies originate in autumn, and evolve over the course of the winter season into the NAO/AO pattern of variability. In Type A winters, surface temperature and circulation anomalies originate during the fall over Northern Eurasia; furthermore the troposphere and stratosphere are coupled. In Type N winters, surface temperature and circulation anomalies originate during the fall in the North Atlantic and Northern Europe; in this paradigm the troposphere and stratosphere remain uncoupled. The snow–climate relationship is generally stronger in Type A winters, where Northern Eurasia is the region of origin.

3.2. Modeling analyses

Gong et al. (2003a) performed a numerical modeling experiment which complements these observational analyses, by isolating the effect of Siberian autumn snow anomalies on winter climate in an effort to demonstrate a causal relationship. This work went beyond earlier exploratory modeling studies, by forcing the model with realistic, observation-based snow anomalies.
rather than idealized perturbations. In addition, the physical mechanisms involved in this remote teleconnection pathway were explicitly investigated.

The experiments basically consisted of a pair of 20-member ensemble simulations of September–February climate using the Max Planck Institute for Meteorology ECHAM3 atmospheric general circulation model (GCM) at T42 spectral truncation (roughly 2.8° grid cell resolution). The experiments were forced with large positive (negative) snow anomalies over a specified region in Siberia spanning 67.5°E–140.5°E and 36.5°N–90.0°N, based on NOAA visible satellite data from 1976 to 1977 (1988–1989), which represents the year with the most extensive (limited) snow cover extent in the available record. The difference between these two experiments (extensive snow–limited snow) was computed to analyze the climatic response to a positive Siberian autumn snow forcing. Please refer to Gong et al. (2003a) for experiment details.

Fig. 6 shows the autumn (SON average) surface temperature response and the winter (DJF average) sea level pressure (SLP) response to the snow forcing.
During autumn when the snow forcing is strongest, a strong negative temperature response is apparent, which is the expected climate response to snow. Note that this concurrent temperature response is restricted to the Siberian snow forcing region only. During the winter season, this localized diabatic heating response has evolved into a hemispheric-scale, dipole SLP response, reminiscent of a negative AO pattern. Thus an isolated and realistic snow forcing over Siberia has produced a clear negative AO signal, whose magnitude amounts to roughly 30% of the total AO mode variability. This result is consistent with observational studies that indicate a statistically significant correlation between autumn snow cover over Eurasia and the subsequent winter AO Index.

A suite of atmospheric diagnostics were analyzed in Gong et al. (2003a) to discern the physical mechanisms responsible for this modeled snow–AO relationship. Only a qualitative overview of the identified teleconnection pathway is presented here; more quantitative evidence is provided in Section 4, in the context of the features unique to Eurasia which initiate and enable this pathway. Fig. 7 (left panel; bracketed letters refer to text below) shows a sketch of the upward components of the pathway. The positive snow forcing over Siberia is colocated with one of the centers of stationary wave activity (see Fig. 1), so that the snow-forced local surface diabatic heating anomaly induces a strengthening of this wave energy center. This anomalously strong regional wave activity propagates up through the troposphere [a] and weakens the stratospheric polar vortex [b], transforming the regional signal into a hemispheric one.

The downward components of the pathway are sketched in Fig. 7 (right panel; bracketed letters refer to text below). The weakened vortex causes upper-tropospheric stationary waves throughout the Northern Hemisphere to refract poleward, towards the vortex anomaly [c]. As a result, the weakened zonal winds associated with the weakened vortex are drawn down into the high-latitude upper troposphere [d]. This in turn promotes additional stationary wave refraction, continued downward propagation of high-latitude negative zonal wind anomalies, and also the development of mid-latitude positive zonal wind anomalies [e]. These tropospheric signals are characteristic of the AO. A positive feedback is established, whereby the coupled mean flow and stationary wave anomalies both propagate downward over time [f], ultimately yielding a negative AO signal at the surface.

Note that this teleconnection pathway involves the interaction of dynamic wave and mean flow processes throughout the troposphere and also the stratosphere. It is consistent with both established wave–mean flow interaction theory (e.g., Charney and Drazin, 1961), and much of the recent literature on troposphere–stratosphere interaction and downward propagating AO signals (e.g., Baldwin and Dunkerton, 1999; Kodera and Kuroda, 2000; Zhou et al., 2002). The timing between the primary mid-autumn Siberian snow forcing and the initial early-winter hemispheric surface response

Fig. 7. Modeled remote teleconnection pathway in response to positive snow forcing over Siberia. Red (blue) denotes a positive anomaly. Refer to text for pathway components represented by [a] through [f]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
is also consistent with the multi-week timescale suggested in the literature for such wave–mean flow interactions (see Gong et al., 2003a).

### 4. The role of Northern Eurasia land surface characteristics

Both observational and modeling analyses consistently indicate a lead–lag relationship between autumn snow anomalies in Siberia and the subsequent winter AO mode. Subsequent papers by the co-authors describe a series of additional GCM experiments, which elucidate the role of Northern Eurasia land surface characteristics in facilitating this large-scale snow–climate teleconnection (Gong et al., 2003b, 2004a,b). The results from these papers are summarized below, along with some complementary, previously unpublished findings. All experiments followed the same format as for the original Siberian snow-forced experiment described in Section 3.2 above (hereafter designated SIB), but with modified surface boundary conditions. Table 1 lists the boundary modifications applied to each experiment.

Fig. 8 shows the response to a positive snow forcing for SIB, for three diagnostic parameters involved in the teleconnection pathway depicted in Fig. 7. The autumn vertical WAF at 850 hPa increases over central and eastern Eurasia (Fig. 8a), a direct local response to the Siberian snow forcing. Note that a large center of stationary wave activity is located in this region (Section 2), so that the snow forcing acts to amplify the pre-existing upward wave activity. The winter zonal wind at 50 hPa decreases at high latitudes (Fig. 8b), which is indicative of a weakened stratospheric polar vortex in response to the snow-forced upward stationary wave energy anomalies propagating through the troposphere. Fig. 8c shows the response of an unstandardized proxy AO index metric, computed simply as the difference between mid-latitude and high-latitude zonal average geopotential heights (see Gong et al., 2003a). Such a metric enables the evaluation of the AO response to snow as it evolves both spatially and temporally. A negative AO signal first appears in the stratosphere in November, and propagates downward to the surface over the course of the autumn–winter season.

Fig. 9 shows the same set of diagnostics for the ORO experiment, in which the surface boundary in central and eastern Siberia (north of the Tibetan plateau) is restricted to a maximum elevation of 400 m (see Gong et al., 2004a). This modification effectively removes the roughly 1000 m Northern Eurasia mountain ridge (i.e., the Altay Shan Sayan, Yablonovyy and Cherski Mountains) extending northeast from Mongolia to the Arctic Ocean, which is instrumental in producing the

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**Table 1**

| Snow-forced GCM experiments subject to varying land surface boundary conditions |
|-----------------|---------------------------------------------------------------------------|
| **Experiment designator** | **Land surface boundary condition** |
| SIB | Realistic, observation-based snow forcing over Siberia |
| ORO | SIB snow forcing with Northern Eurasia mountains removed |
| NA | Realistic, observation-based snow forcing over North America |
| COV | Partial snow cover extent only forcing over Siberia |
| INS | SIB snow forcing with albedo effect suppressed |

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Fig. 8. Climatic response to a positive snow forcing, for the SIB experiment. (a) Vertical WAF at 850 hPa elevation during autumn (SON). (b) Zonal wind at 50 hPa elevation during winter (DJF). (c) Weekly evolution over the atmospheric column of normalized 42-day running mean hemispheric proxy AO index. Reproduced in part from Gong et al. (2003a) Figs. 5 and 9.
Eastern Eurasia center of stationary wave activity depicted in Fig. 1. Indeed, the climatological upward wave activity for ORO is notably damped over East Asia and the Pacific Ocean (not shown), and the response to the same snow forcing as for SIB is also substantially reduced. Without this amplified upward wave activity, the polar vortex does not weaken, and the downward AO propagation from the stratosphere to the surface does not materialize. Thus the orography of Northern Eurasia is critical for producing the stationary wave activity that initiates the teleconnection pathway response to Siberian snow anomalies.

Fig. 10 shows the pathway diagnostics for the NA experiment, in which anomalous autumn snow forcings are applied to North America instead of Siberia (see Gong et al., 2003b). In this experiment, the snow forcing is not co-located within a center of stationary wave activity, hence there is little pre-existing wave energy for the snow-forced diabatic heating anomalies to amplify. Since the teleconnection pathway is not initiated, the subsequent polar vortex and AO index diagnostics correspondingly show little response to snow for this experiment. Thus the large-scale winter climate response to autumn snow anomalies is unique to Northern Eurasia, again due to the existence of stationary wave activity in this region.

Fig. 11 shows the pathway diagnostics for the COV experiment, in which the Siberian snow forcing consists of snow cover extent anomalies but not snow depth anomalies (see Gong et al., 2004b). This results in transient snow forcings restricted to the autumn season (Figs. 2, 4a), where the high albedo of snow-covered relative to snow-free land is expected to be the dominant thermodynamic mechanism. The diminished snow forcing reduces the magnitude of the upward WAF response over Siberia, however this boundary modification
has no effect on the wave energy climatology (not shown). Thus the modest snow-forced upward WAF can nevertheless propagate through the troposphere and weaken the polar vortex somewhat. However, the mild vortex anomaly is not sufficient to produce the subsequent tropospheric wave refraction, positive feedback, and downward AO propagation as seen for SIB. When only snow cover extent over Northern Eurasia is considered, the teleconnection pathway is still in place, but the diminished snow forcings are insufficient to propagate through the entire pathway.

Finally, Fig. 12 shows the pathway diagnostics for the INS experiment, in which the albedo for both snow-covered and snow-free land is set at the background, snow-free value (see Gong et al., 2004b). By suppressing the albedo effect, only the insulative processes associated with the snowpack are considered, so that the snow forcing is greatly reduced during the mid-autumn accumulation season when snow extent anomalies dominate, but largely maintained during late autumn and winter when depth anomalies are more influential (Fig. 4b). This diminished/delayed snow forcing mitigates the autumn upward WAF response, however a positive anomaly occurs during the winter months (not shown), so that a weakened winter vortex is still produced. A negative AO mode response occurs in the stratosphere roughly one month later than with a full snow forcing; it propagates downward but has yet to appreciably reach the surface by February when the simulation period ends. In the absence of albedo-related snow forcing effects over Northern Eurasia, the snow–AO teleconnection pathway still occurs, but is diminished to a degree and also delayed, since the albedo effect is mainly associated with snow cover extent anomalies that are strongest in mid-autumn.
5. Conclusions

Recent papers by the co-authors have focused on establishing regional-scale land surface anomalies as a viable modulator of hemispheric-scale winter climate, using both observational analyses and numerical modeling experiments. An overall synopsis of this body of research has been presented in this paper, within the context of Northern Eurasia as the critical land surface region for producing coherent climate variations. Specifically, a physically-based, remote teleconnection pathway has been identified linking positive autumn snow anomalies over Northern Eurasia with the negative phase of the winter Arctic Oscillation (AO) pattern. This summary is complemented by new results regarding the distinction between interannual snow cover extent vs. snow depth anomalies in Northern Eurasia (Section 2), and the relative effect of these partial snow forcings on the teleconnection pathway and winter AO signal (Section 4).

The lead–lag relationship between anomalous snow and climate is enabled by several land surface characteristics unique to Northern Eurasia. The size of the contiguous Eurasian land mass, and its location in the extratropics, produces extensive seasonal snow cover which also exhibits considerable interannual variability during the autumn snow accumulation season. Due to the thermodynamic effects of snow on the surface energy balance, these broad snow anomalies produce a strong and widespread diabatic heating anomaly over Northern Eurasia, which in turn generates related anomalies that propagate to remote regions.

A second unique feature of Northern Eurasia is the presence of a large center of stationary wave activity centered over far-east Asia, arising in part from the tall mountain ranges that separate northern/central Eurasia from southern/eastern Eurasia. This co-location of ambient stationary wave energy with snow-forced diabatic heating anomalies is crucial for generating upward wave activity flux anomalies which initiate the snow–climate teleconnection pathway. The importance of this co-location was confirmed by simulating the climatic response to Northern Eurasia snow forcings in the absence of mountains, and also to North America snow forcings where stationary wave activity is minimal. Neither experiment yielded an appreciable AO signal, since the lack of prevailing stationary wave energy inhibits the snow-forced diabatic heating anomaly from propagating away from the surface.

The specific characteristics of the Northern Eurasia snow anomalies are also important for producing a winter AO response. Snow extent anomalies are generally limited to a brief period within the autumn accumulation season, while snow depth anomalies can persist throughout the autumn and winter. Furthermore, snow extent and snow depth anomalies primarily affect the surface energy balance via different thermodynamic mechanisms. When these partial snow forcings are considered individually, the climate response is notably mitigated. When they are considered in conjunction, extent anomalies provide a strong initial autumn forcing while depth anomalies provide a persistent autumn–winter forcing, and this total forcing results in a clear teleconnection pathway response and modulation of the winter AO signal.

While Northern Eurasia is already known to be a sensitive responder to global climate variability and change, this region is being increasingly recognized as an active modulator of global climate. Thus a comprehensive understanding of the dynamical processes and feedbacks between Northern Eurasia and the global Earth system is crucial to understanding and predicting the ultimate impacts of anthropogenic climate change. This paper contributes to this effort by highlighting a causal relationship between autumn snow anomalies in Northern Eurasia and the subsequent winter AO pattern. Anthropogenic climate change is likely to have a strong impact on seasonal snow cover over Northern Eurasia, which may in turn have climatic consequences throughout the Northern Hemisphere.

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References


