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Eurasian Snow Cover Variability and Links with Stratosphere-Troposphere Coupling and Their Potential Use in Seasonal to Decadal Climate Predictions

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ABSTRACT

Over a decade of research has allowed us to understand how variability in Siberian snow cover, mostly in October, can influence the weather in remote regions including the Eastern US and Europe months later. Below we describe the six-step model with a timeline that begins with the advance of Siberian snow cover in October and ends with more (less) frequent Arctic outbreaks during the winter in the Eastern US, Europe and East Asia associated with the negative (positive) phase of the large-scale telconnection pattern the Arctic Oscillation (AO). This link has been demonstrated for year-to-year variability and used to improve seasonal-timescale winter forecasts; however this coupling can also be shown to have influenced recent decadal-scale temperature trends.

1. Introduction

Snow cover exhibits the greatest temporal and spatial variability of any other land surface condition (Cohen 1994). Correlations between observed snow cover with sea level pressure (SLP), 500 hPa and standard climate indices all show a significant snow-climate statistical relationship concentrated in the North Atlantic. In Figure 1, Eurasian October snow cover anomalies are correlated with December, January, February (DJF) surface temperature anomalies. The resultant anomaly pattern resembles the Arctic Oscillation (AO) pattern of variability. The AO is an index that measures the pressure gradient between high- and mid-latitudes and is linked to the frequency of Arctic outbreaks in the mid-latitudes. Cohen and Entekhabi (1999) hypothesize that a possible dynamical mechanism linking Eurasian snow anomalies and North Atlantic climate variability is 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 lower tropospheric height anomaly in

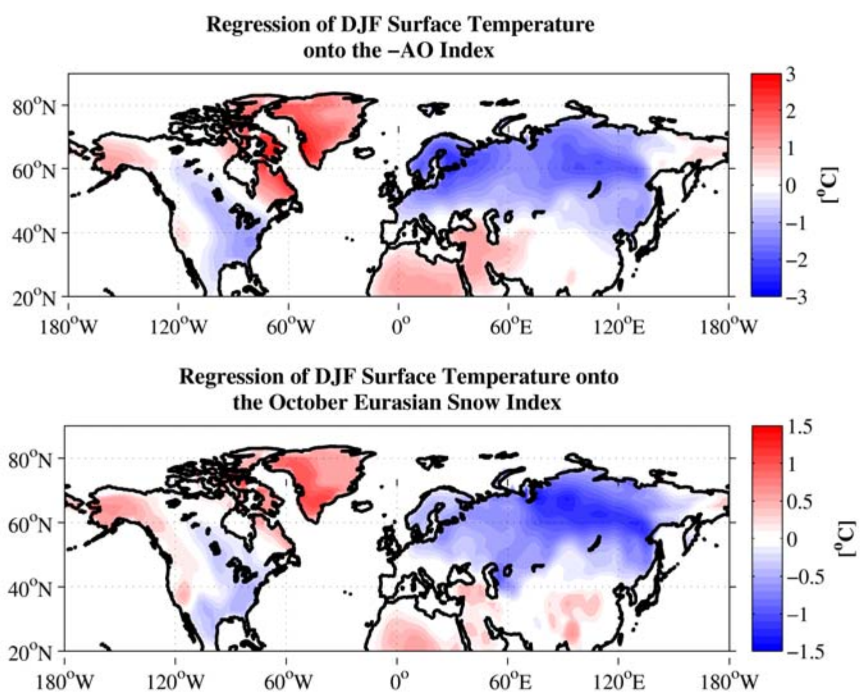

Fig. 1 a) Regression of DJF land surface temperatures from NCEP/NCAR reanalysis onto the standardized inverted DJF AO index (top). b) As in a) but for regression onto the standardized October Eurasian snow cover index (bottom). Units are in °C.

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Siberia during the fall. Persistent positive SLP anomalies and negative surface temperature anomalies in the region of Siberia, as early as October, were found to precede a negative winter AO. This provided a further link of the hemispheric scale AO to origins with the inception of the Siberian high in the fall.

We have operationally produced real-time winter forecasts for the extratropical Northern Hemisphere based on fall Eurasian snow cover and atmospheric anomalies for over a decade. The operational forecasts continue to demonstrate skill, up through the most recent winter season. These snow-based forecasts and hindcasts appear to provide considerable additional information beyond the standard-ENSO based forecasts and even the most sophisticated dynamical models (Cohen and Fletcher 2007).

2. Conceptual model

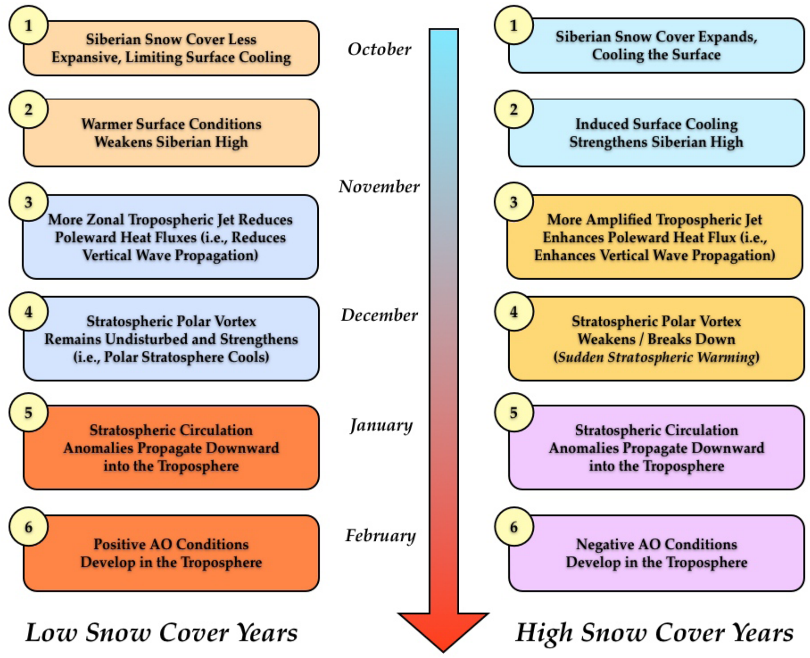

Fig. 2 Conceptual model for how fall snow cover modifies winter circulation in both the stratosphere and the troposphere. Case for extensive snow cover on right: 1. Snow cover increases rapidly in the fall across Siberia, when snow cover is above normal diabatic cooling helps. 2. to strengthen the Siberian high and leads to below normal temperatures. 3. Snow forced diabatic cooling in proximity to high topography of Asia increases upward flux of energy in the troposphere, which is absorbed in the stratosphere. 4. Strong convergence of WAF indicates higher geopotential heights, a weakened polar vortex and warmer down from the stratosphere into the troposphere all the way to the surface. 6. Dynamic pathway culminates with strong negative phase of the Arctic Oscillation at the surface. Also shown is case for low snow cover on left.

We outline a conceptual model of the dynamical pathway demonstrated by the statistically significant relationship between snow and the winter AO discussed above (Figure 2). October is the month snow cover makes its greatest advance, mostly across Siberia. October is also the month that the Siberian high, one of the three dominant centers of action across the Northern Hemisphere (NH), forms. In years when snow cover is above normal this leads to a strengthened Siberian high and colder surface temperatures across Northern Eurasia in the fall. We suggest that the intensification of the Siberian high, along with the thermal impacts of enhanced snow cover and topographic forcing, corresponds to a positive wave activity flux anomaly in the late fall and early winter, leading to stratospheric warming and to the January tropospheric negative winter AO response we have mentioned above.

a) Snow cover advance

The month when snow cover extent makes its greatest advance is in October. The variability in October snow cover extent from year to year can be very large, with the highest years having a snow cover extent twice or even three times as great as the lowest years. Snow cover has the highest reflectivity or albedo of all naturally occurring surfaces. The presence of snow cover can increase the amount of sunlight reflected back into space from 20 to 80% (Cohen and Rind 1991). Also snow cover is a good insulator or a thermal blanket, preventing heat form the ground escaping into the atmosphere. These radiative properties of snow cover cool the atmosphere above the earth’s surface. The presence of snow cover can lead to much colder temperatures than the absence of snow cover.

b) Formation of the Siberian high

The presence or absence of snow cover can lead to colder or warmer air masses. When snow cover extent is above normal this cools the overlying atmosphere. Cold-dense air above the snow cover promotes high pressure while warm more buoyant air above a snow free surface promotes low pressure.

During the fall when snow cover rapidly advances across Siberia, the Siberian high starts to form. If snow cover extent is above normal this favors a stronger and more expansive Siberian high. During those falls when snow cover is more extensive, anomalous high pressure is more common stretched across Northern Eurasia. Then during the winter the high-pressure anomalies first limited to northern Eurasia spread across the Arctic Ocean. Simultaneously, high-pressure anomalies dominate the mid-latitude ocean basins. This pattern of sea level pressure variability is recognizable to climatologists as the negative phase of the AO. During the negative phase, high pressure is increased at high latitudes while low pressure is strengthened at mid-latitudes decreasing the pressure gradient between these two regions. Once again a regional perturbation in the fall across Northern Eurasia grows into a hemispheric pattern of variability in the winter.

However when snow cover is below normal across Siberia, this favors the occurrence of predominately low-pressure anomalies across Northern Eurasia during the fall. Then during the winter the low pressure anomalies first limited to northern Eurasia spread across the Arctic Ocean. Simultaneously, low-pressure anomalies dominate the midlatitude ocean basins. This pattern of sea level pressure variability is recognizable to climatologists as the positive phase of the AO. During the positive phase, low pressure is strengthened at high latitudes while high pressure is increased at mid-latitudes increasing the pressure gradient between these two regions. A regional perturbation in the fall across Northern Eurasia grows into a hemispheric pattern of variability in the winter.

The fall sea level pressure precursors not only affect the weather near the earth’s surface but they also impact the weather in the stratosphere, the layer of atmosphere between 10 and 50 km above the earth’s surface. These fall tropospheric precursors, as we refer to them, initiate anomalous energy transfer from the troposphere to the stratosphere that impacts the winter polar vortex, which we are now discovering plays an important role in the sensible winter weather across the Eastern US, Europe and East Asia.

c) Vertical transfer of energy

The vertical transfer of energy in the atmosphere can have important impacts on the weather across the entire Northern Hemisphere. We have shown an important connection between snow cover extent in Siberia, the strength of the Siberian high and energy transfer in the atmosphere.

During the fall a rapid advance in snow cover favors a strengthened and a more expansive Siberian high. We have shown that a stronger Siberian high can increase the amount of energy transfer from the troposphere or the lower atmosphere to the stratosphere or upper atmosphere. Less snow cover and a weakened Siberian high can lead to a decreased amount of energy transfer from the troposphere to the stratosphere.

Often when the transfer of energy from the troposphere to the stratosphere is increased that excess energy is absorbed in the polar stratosphere. That increase in energy absorption leads to a warming of the polar stratosphere and a weakening of the polar vortex. Warming of the polar stratosphere is often very dramatic and is referred to as a sudden stratospheric warming (SSW). The polar vortex is a fast stream of air that flows west to east around the Pole and it derives its energy from the strong temperature gradient between the equator and the Pole in the stratosphere. During a SSW, the pole to equator temperature gradient is weakened and consequently the polar vortex also weakens. Alternatively, if the transfer of energy from the troposphere to the stratosphere is less, the polar stratosphere cools and the stronger pole to equator temperature gradient strengthen the polar vortex.

d) Changes in the polar vortex

Often when the polar vortex is strong, temperatures are mild in the mid-latitudes across the Eastern US and Northern Eurasia; and when the vortex is weak, temperatures tend to be cold across the Eastern US and northern Europe and Asia.

Strong is the more common state of the polar vortex. When the polar vortex is strong, this creates strong low pressure in the Arctic region. Because of the pressure difference between the Arctic and mid-latitudes, air flows into low pressure and this confines the cold air to high latitudes closer to the Arctic. Therefore it is often mild across the Eastern US, Europe and East Asia during winters when the polar vortex is strong. When there is less transfer of energy from the troposphere to the stratosphere the polar vortex remains strong. During strong polar vortex, the airflow is fast and in a direction from west to east. Low pressure in the Arctic region is referred to as the positive phase of the AO.

When there is more transfer of energy from the troposphere to the stratosphere the polar vortex becomes perturbed. When the polar vortex is weak or "perturbed," the flow of air is weaker and meanders north and south (rather than west to east). This allows a redistribution of air masses where cold air from the Arctic spills into the mid-latitudes and warm air from the subtropics is carried into the Arctic. This mixing of air masses also favors more storms and snow in the mid-latitudes. During a weak polar vortex, high pressure occurs in the Arctic region and is referred to as the negative phase of the AO. Air flows away from the high pressure Arctic. The north to south direction of the polar vortex carries cold Arctic air into the mid-latitudes of Eastern US, Europe and East Asia. Therefore it is cold across the Eastern US, Europe and East Asia during winters when the polar vortex is weak.

e) Downward propagation

When the stratospheric polar vortex is strong this leads to lower heights/pressures in the stratospheric Arctic. These same circulation anomalies then occur in the troposphere all the way down to the surface. With low pressure dominating the Arctic and the Jet Stream poleward of its climatological position, this results in the positive phase of the AO and less frequent Arctic outbreaks into the mid-latitudes and a warmer than normal winter in the Eastern US, Europe and East Asia.

Instead when the stratospheric polar vortex is weak this leads to higher heights/pressures in the stratospheric Arctic. These same circulation anomalies then occur in the troposphere all the way down to the surface. With high pressure dominating the Arctic and the Jet Stream equatorward of its climatological position, this results in the negative phase of the AO and more frequent Arctic outbreaks into the mid-latitudes and a colder than normal winter in the Eastern US, Europe and East Asia.

f) Winter Arctic Oscillation

The forced changes by above (below) normal Siberian snow cover in the atmosphere culminates with an extended period of cold (warm) temperatures across the Eastern United States and Northern Eurasia that dominate the winter mean temperatures.

During the fall a rapid advance in snow cover favors a strengthened and a more expansive Siberian high, which leads to increased energy transfer from the lower to the upper atmosphere and a weakened polar vortex. The cycle ends with the negative phase of the AO. During the negative phase of the AO high pressure dominates the Arctic and the Jet stream shifts southward. Also meridional or north-south flow of air increases. This allows for Arctic air masses to penetrate further south than usual into the midlatitudes while warm subtropical air can reach the Arctic.

In contrast, a slower advance in snow cover favors a weaker and a more contracted Siberian high, which leads to decreased energy transfer from the lower to the upper atmosphere and a strengthened polar vortex. The cycle ends with the positive phase of the AO. During the positive phase of the AO, low pressure dominates the Arctic and the Jet stream shifts northward. Also the meridional or north-south flow of air weakens. This keeps the air masses at different latitudes separated so that cold air remains confined to the Arctic and mild air sweeps across the mid-latitudes.

3. Decadal variability

This snow-AO relationship has been demonstrated for year-to-year variability and is used to improve seasonal-timescale winter forecasts; however, this coupling may be modulating the winter warming trend, with implications for decadal-scale temperature projections.

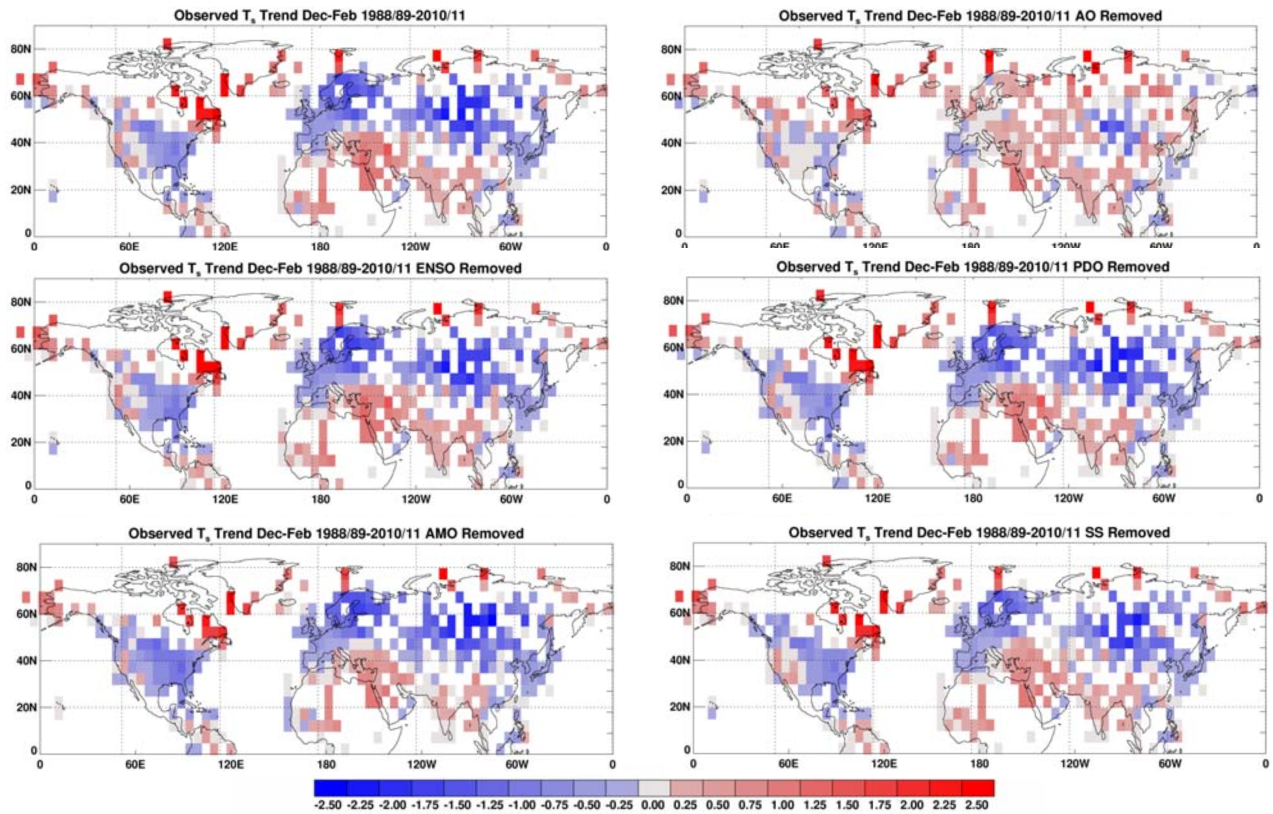

Fig. 3 a) The decadal trend in December, January, February and March land-surface temperatures 1988/89-2010-11 (top left). b) The decadal trend in December, January, February and March land-surface temperatures 1988/89-2010/11 after the regressed values of temperature with the concomitant AO have been removed (top right). c) Same as b but with ENSO removed (middle left), d) same as b but with the Pacific Decadal Oscillation removed (middle right), e) same as b but with the Atlantic Multi-Decadal Oscillation removed (bottom left) and f) same as b but with solar variability represented by sunspot number removed (bottom right). Colored shading in degrees Celsius; values between –0.25 and 0.25 are shown in grey and missing and ocean values are shown in white.

Over the past four decades, the globe has experienced continued warming. Over the past two decades this warming has continued unabated for three of the four seasons – spring, summer and fall. However, during the winter season the warming trend has all but disappeared for the extratropical NH landmasses. Large regions of the extratropical Northern Hemisphere landmasses have experienced a cooling trend, and the hemispheric temperature trend pattern closely resembles the temperature anomaly pattern associated with the negative phase of the AO.

Over the past two decades, Eurasian snow cover in October has been increasing. We argue that the positive trend in snow cover has contributed a significant fraction of the observed cooling in eastern North America and Northern Eurasia where snow cover is significantly correlated with winter temperatures (Cohen *et al.* 2009). Therefore, much of the recent observed late winter cooling across the NH is a response to increased October Siberian snow cover, increased Wave Activity Flux (WAF) mainly over Eurasia and increased stratosphere-troposphere coupling forcing a dynamical response in the hemispheric circulation. This dynamical forcing has resulted in both stratospheric polar warming and lower tropospheric cooling over the NH landmasses and has largely masked the global warming trend much more apparent earlier in the spring, summer and fall. The surface temperature trend pattern is most closely associated with the negative polarity of the AO, which has been linked with leading stratospheric circulation anomalies. We also computed how much of the winter cooling trend can be explained by the following other large-scale climate modes: the El Niño/Southern Oscillation, the Pacific Decadal Oscillation, the Atlantic Multidecadal

Oscillation and solar variability. Only the AO explains a large fraction of the observed winter cooling trend; the other climate modes explain essentially none of the observed winter cooling trend (Figure 3).

4. Conclusions

Over a decade of research has demonstrated the statistical link between October Eurasian snow cover and the phase and magnitude of the winter AO. Above we outlined a dynamical pathway beginning with the advance of snow cover in the fall and culminating with the phase of the AO and the frequency of Arctic outbreaks in the mid-latitudes. October snow cover has been used to produce skilful real-time operational winter forecasts for the extratropical NH (Cohen and Fletcher 2007).

This same pathway may also be modulating winter temperatures on a decadal scale. Though temperatures continue to rise throughout most of the year consistent with global warming, large regions of the extratropical NH have experienced winter cooling over the past two decades. An observed increasing trend in Eurasian snow cover is the most likely boundary condition for partially forcing winter hemispheric trends over the past two decades that has heretofore been identified.

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