Impact of Eurasian snow cover on the northern hemisphere winter circulation

Yvan J. Orsolini[(1)] and Nils G. Kvamstø[(2)]

(1) Norwegian Institute for Air Research (NILU), Kjeller, Norway
(orsolini@nilu.no)
(2) Geophysical Institute and Bjerknes Centre for Climate Research,
University of Bergen, Norway

1. Introduction

Landmasses cover a large portion of the northern hemisphere, and nearly one-half of Eurasia and North America are extensively covered with snow in the cold season (Dery and Brown, 2007). Snow-covered land plays a key role in the climate system, owing to the snow radiative and thermodynamical properties, such as high albedo, high emissivity and low thermal conductivity, and its effect on surface fluxes of moisture and heat. Snow covered land can hence impact climate in a variety of ways. The snow-albedo feedback plays an important role in the spring (e.g. Schlosser and Mocko, 2003) when an early seasonal retreat of the snow cover acts as a positive feedback on spring temperatures. However, the climate response to high-latitude snow cover could also involve thermodynamical feedbacks in the surface energy balance, as well as large-scale dynamical feedbacks. Eastern Eurasia for example, is a region where the Asian jet establishes a near-zonal waveguide for propagating Rossby waves arising from thermal anomalies, and transient propagating eddies could also be influenced by the meridional extent of the snow cover (Corti et al., 1999). At high northern latitudes, the snow cover seasonal variability is also important for greenhouse gases emissions (e.g. methane), the carbon cycle as well as the river run-off.

There are also indications from model and observational studies that snow cover also affects large-scale atmospheric variability. The snow cover obviously depends strongly on the atmospheric circulation. Hence the weak, indirect feedback of snow cover on the atmospheric circulation is not easily derived from observational correlative studies, or from standard model studies. Dedicated model studies are more amenable to test such a weak coupling, as is the case for soil moisture feedback on precipitation and temperature (Koster et al., 2006).

However, it is not obvious to design experiments to test the snow cover impact on circulation and especially on atmospheric predictability. Long simulations are needed to establish beyond doubt a skill increment resulting from improved representation of the snow variables. On the observational side, a reliable satellite record of snow cover extent from visible and infrared imagery dates only from the early seventies, and the retrieval of snow depth (or snow water equivalent) from satellite microwave passive measurements is even shorter (Grippa et al., 2004). Despite these limitations, there is increased interest in tapping into the memory effect of surface conditions, such as soil moisture and snow, as a possible source of improved seasonal-to-decadal predictability.

Several links between Eurasian snow cover and the atmospheric general circulation have been studied. A linkage between the spring Eurasian snow cover and the summer Indian monsoon has been proposed but its stationarity is being revisited in light of more recent data (see Douville, this issue). On the other hand, there is a robust track of observational studies and modelling experiments indicating an Eurasian snow cover impact over the North Pacific, with extensive snow cover leading to a deeper than normal Aleutian low (Wash and Ross, 1988; Yasunari et al.,1991; Clark and Serreze, 2000). In addition, a series of papers (Cohen et al., 2002; Gong et al., 2003; Saito et al., 2001; Fletcher et al., 2007;2009) provided evidence that the autumn Eurasian snow cover correlates with the North Atlantic Oscillation (NAO) during the following winter. The authors proposed that, through the albedo feedback, extensive Eurasian snow cover anomalies in early autumn induce diabatic cooling, amplify the Siberian High and augment the upward stationary wave activity flux above Siberia. In their view, the response to snow anomalies, far from being shallow, involves the propagation of stationary waves into the stratosphere.

While there is a NAO / autumn Eurasian snow cover link in observations, many GCM simulations fail to reproduce this linkage, and Hardiman et al. (2008) indicated several possible cause for this deficiency. One first issue is that the inter-annual variability in many models is lesser than in the satellite observations during transition seasons. Another might be the longitudinal structure of the response to snow forcing, and Hardiman et al. (2008) showed the example of the GFDL model having a too zonally confined response, which hampers vertical propagation into the stratosphere.

To correct model deficiencies, one approach consists of prescribing idealised or observed snow cover, and possibly depth, through nudging. In this category are the large-ensemble, nudging experiments using satellite observations (Cohen and Entekhabi, 1999; Gong et al., 2002), but these were often restricted to extreme winters. Also, Flechter et al. (2008) and Gong et al. (2004) used prescribed, idealized snow forcings in their studies, applying a constant depth throughout Eurasia. Most of the previous studies were either observational or else model studies for specific seasons, and it remains to be evaluated if inter-annual circulation anomalies could be attributed to the snow cover variability in climate model simulations spanning several decades, with realistically varying, satellite-derived snow cover. Kumar and Yang (2003) performed decadal simulations, comparing prognostic and prescribed climatological snow variables, but not satellite-derived varying snow cover.

2. Simulation with the “Arpege Climat” model using prescribed snow cover

To this end, we performed a suite of dedicated model ensemble simulations, spanning two decades (1979-2000). We did not perform rigorous data assimilation, but rather forced the observed snow cover extent from satellite observations onto the model, akin to a “data insertion” approach. Our ensemble simulations with the “Arpege Climat” AGCM (V3.0) (Deque et al., 1994) were made at horizontal resolution T63, with 31 vertical levels, a top at 10 hPa and with prescribed SSTs and sea-ice conditions. After a 5-year spin-up, simulations were analysed over the years 1979 to 2000.

The “Arpege Climat” model comprises a land-surface scheme and a physically based snow hydrology model, as described by, e.g., Douville et al. (1995a,b). Snow observations consists of observed, gridded, 24-square-kms snow cover fraction, from the EASE dataset provided by the US National Snow and Ice Data Centre (NSIDC, Boulder, Colorado). The remotely sensed data is based on visible and infrared satellite imagery. In our main prescribed snow simulation, labelled SNS, the model snow cover is overwritten using year-round satellite snow cover fraction observations every 5 days. Snow cover is not a prognostic model variable, and the snow mass is adjusted using a model climatological value; more information about the treatment of snow variables is given in Orsolini and Kvamstø (2009). The control simulation is labelled PCL. Our analysis so far has focused on winter months (DJF). ECMWF ERA-40 re-analyses are used for verification.

In Figure 1, the climatological annual cycle of the fractional snow cover area and its inter-annual variance are shown over Eastern Eurasia (80E-155E; 35-70N) in the forced and prognostic simulations, and in the satellite observations. The snow cover extent in SNS is more extensive than in PCL throughout the cold season (November to March), when it closely matches the satellite-derived extent. The inter-annual variance is enhanced in the two transition seasons: in the autumn-early winter, marking the beginning of the cold season snow build-up, and in the spring. These two seasonal maxima are better reproduced in SNS than in PCL simulation, albeit still weaker than in the observations. Figure 2 shows the mean October-November-December (OND) fractional snow cover over Eastern Eurasia from 1979 to 2000. The year-to-year variability is much weaker in PCL than in the observations, but is augmented in the forced simulation, as could be inferred from Figure 1 as well. In SNS, the snow cover closely follows, but is not identical to, the observations. The mean snow cover is slightly more extensive than in the observations, and autumns with reduced snow cover are overestimated, due to imperfect nudging.

The winter high-latitude circulation is characterised by two semi-permanent oceanic lows, the Aleutian Low (AL) and the Icelandic Low (IL). The two Lows fluctuate in unison in a seesaw, with a peak period in late winter, in a teleconnection termed the Aleutian Low-Icelandic Low Seesaw (AIS) (Honda et al., 2001). The AIS originates from early winter Pacific anomalies, which propagate downstream into the Atlantic sector over a time scale of 1-2 months, through the eastward extension of a PNA-like pattern. In the positive phase of the seesaw, the AL is weaker than normal. We now demonstrate that their year-to-year variability is more realistic in the ensemble-mean forced than in the control simulations. Variability of the AL and IL is examined using monthly AL and IL indices, obtained from averaging SLP over the regions where the SLP inter-annual variability is maximal. The AIS index is defined as the difference between the standardized AL and IL (Honda et al., 2001a,b). In our forced simulation (SNS), the AL/IL anti-correlation is 0.32 while it is –0.43 in ERA-40 re-analyses. The AIS has been shown to be strongly influenced by the ENSO phenomenon, and to extend into the stratosphere (Nakamura and Honda, 2002; Orsolini et al., 2008).

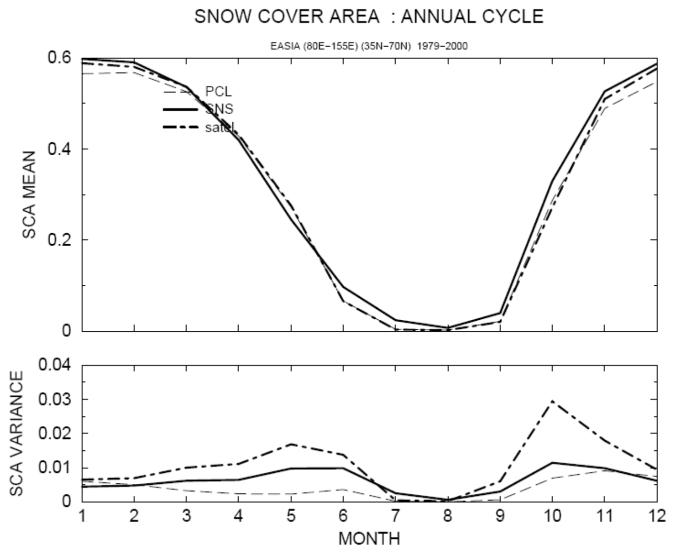

Figure 1. Climatological annual cycle of the fractional snow cover area over Eastern Eurasia (80E-155E; 35N-70N). The three curves refer to the forced (SNS, thick line) and prognostic (PCL, long dash thin line) simulations, and satellite observations (dot-dash line). Also shown is the inter-annual variance of the same quantity.

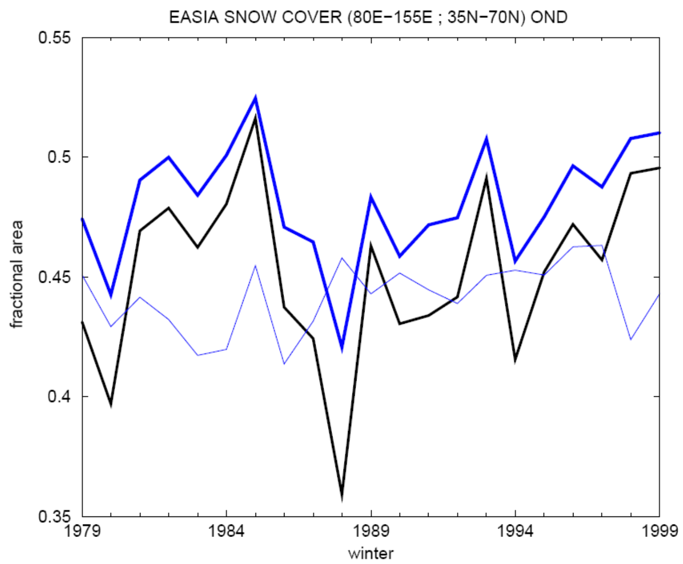

Figure 2. Fractional snow cover area of Eastern Eurasia (80E-155E; 35N-70N) in autumn-early winter (October-November-December, labelled as winter on x-axis), for the satellite observations (black line), the prognostic snow (PCL, thin blue line) and the forced snow (SNS, thick blue line) simulations.

The February ensemble-means of these 3 indices are shown in Fig. 3 over the period 1979-1999, for both simulations and for ERA-40 re-analyses. The (deterministic) skill score is defined as the correlation of the ensemble-mean index with the corresponding observed index, derived from ERA-40 re-analyses. In the forced simulation, the ensemble-mean skill for the AIS is higher (0.66) than in the control simulation (0.38), hinting that the snow cover is indeed modulating the AIS in late winter.

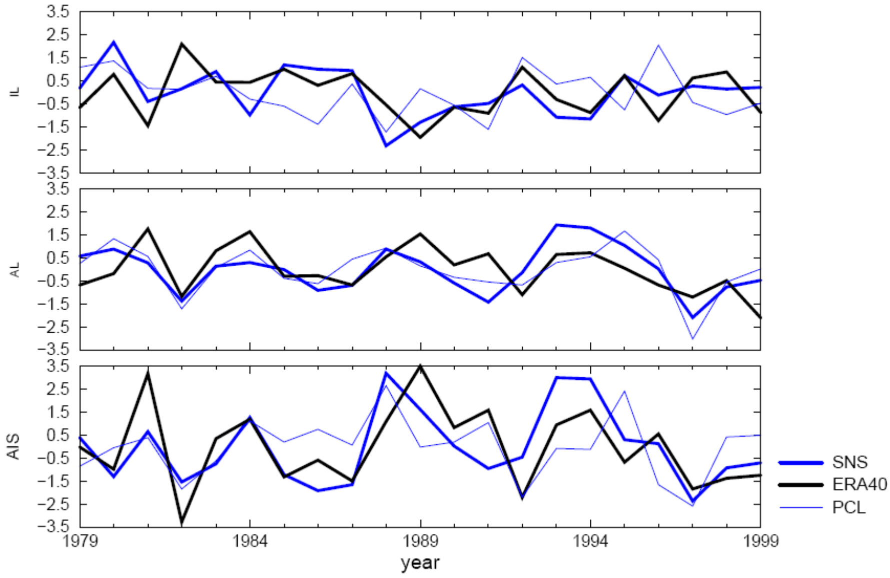

Figure 3. Ensemble-mean normalised indices for the Icelandic Low (IL), Aleutian Low (AL) and the Aleutian-Icelandic Low Seesaw (AIS, or AL minus IL) in February. Indices are shown for ERA40 re-analyses (black line), the forced (SNS, thick blue line) and prognostic (PCL, thin blue line). Although the AIS is calculated in February, the x-axis refers December in order to ease comparison with Figure 2. (e.g. 1989 refers to winter 1989/90, and AIS index in February 1990).

3. Discussion of the results

Several findings of Cohen and Entekhabi (1999), Saito et al. (2001), Gong et al. (2004), and Hardiman et al. (2008), are consistent with our study: with extensive (lessened) Eurasian autumn snow cover, the late-winter AIS negative (positive) phase is indeed associated with enhanced upward wave activity flux across Eurasia in mid-latitudes. On the other hand, we did not find an anti-correlation between autumn Eurasian snow indices and the winter NAO in our simulations, while such an anti-correlation exists between the satellite-derived Eurasian snow cover index and the ERA-40 based NAO index (-0.51). One possible explanation is that, while Eurasian snow cover exerts an influence upon the North Pacific and the North Atlantic, the models might not capture the mid-latitude component of the NAO, that is, the Atlantic High variability. This issue needs further investigation.

The stratospheric pathway proposed by these authors would in fact be consistent with the quasi-horizontal propagation associated to the AIS discussed here: in the negative phase of the AIS, enhanced wave propagation into the stratosphere (Nakamura and Honda, 2002) would lead to a more disturbed polar vortex, and the downward propagation of stratospheric anomalies would reinforce the negative phase of the AIS, as well as the NAO, and increase heights over the Arctic. The ability of our model to demonstrate the occurrence of a stratospheric downward-propagating influence is limited by the fact that only monthly-mean fields have been retained, and that the model lid is at 10 hPa.

While other model or observational studies (cited in Introduction) had found a seasonal influence of the Eurasian snow cover onto the North Pacific circulation, our analysis of decadal simulations demonstrate that the autumn-early winter Eastern Eurasian snow cover distinctly influences the year-to-year variability over the North Pacific from the surface to the stratosphere (extensive snow cover leading to a deepened Aleutian Low), even impacting the North Atlantic in late winter. This improves the hindcast of the Aleutian and Icelandic lows, and the Aleutian-Icelandic Low Seesaw teleconnection. The snow cover influences the stationary planetary waves and their upward propagation, as demonstrated in previous studies (eg. Saito et al., 2001), reinforcing the trough over Eastern Eurasia and the North Pacific.

4. Future prospects

In order to investigate the influence of snow conditions onto the surface and upper-air circulation, and especially the actual impact on predictive skill brought by improved snow initialisation, newer dedicated simulations are needed. One potential promising approach would be to follow the GLACE-2 (see Koster, this issue) methodology used to investigate the local soil moisture impact on surface temperature and precipitation during the warm season. Simulations with most realistic snow initial conditions would be compared with simulations with randomised snow initialisation, but the two set of ensemble simulations would be identical in their initialisation of atmospheric conditions or of other surface variables. In such an approach, local “cool spots” of snow-atmosphere coupling would be better identified. Potential remote effects induced by the snow-induced cooling would also of great interest for seasonal forecasting. A sufficient number of years would have to be simulated to establish the skill increment resulting from a better initialisation of snow variables.

Acknowledgements. This study was financed by the Norwegian Research Council under projects MACESIZ and NORCLIM. We acknowledge the US National Snow and Ice Data Center (NSIDC) in Boulder, for snow cover data provision. Snow-related GLACE2-type of simulations were suggested by G.-P. Balsamo and F. Doblas-Reyes (ECMWF).

References

Clark, M.P. and M.C. Serreze, Effects of variations in East Asian snow cover on modulating atmospheric circulation over the North Pacific ocean, *J. Clim*., **13**, 3700-3710, 2000.

Cohen J. and D. Entekhabi, Eurasian snow cover variability and North Hemisphere climate variability, *Geophys. Res. Lett.*, **26**(3), 345-348, 1999.

Cohen J., D. Salstein and K. Saito, A dynamical framework to understand and predict the major Norther Hemisphere mode, *Geophys. Res. Lett.*, **29**(10), 1412, 2002.

Cohen J., M. Barlow, P.J. Kushner and K. Saito, Stratosphere-Troposphere coupling and link with Eurasian Land-Surface variability, *J. Clim*., **20**, 5335-5343, 2007.

Corti, S., F. Molteni, and C. Brankovic, Predictability of snow-depth anomalies over Eurasia and associated circulation patterns, *Q. J. R. Meteorol. Soc*., **126**, 241-262, 2000.

Dery, S.J. and R.D. Brown, 2007: Recent northern hemisphere snow cover extent trends and implications for the snow-albedo feedback, *Geophys. Res. Lett.,* **34**, L22504, doi:1.1029/2007GL031474.

Deque, M., C. Dreveton, A. Braun and D. Cariolle, 1994, The climate version of the Arpege/IFS: a contribution to the French community climate modelling, *Clim. Dyn*., **10**, 249-266.

Douville H., J., F. Royer, and J. F. Mahfouf, 1995a: A new snow parameterization for the Météo-France climate model. Part I: validation in stand-alone experiment. *Clim. Dyn*., **12**, 21-35.

Douville H., J., F. Royer, and J. F. Mahfouf, 1995b: A new snow parameterization for the Météo-France climate model. Part II: validation in a 3-D GCM experiment. *Clim. Dyn*., **12**, 37-52.

Fletcher C.G., P.J. Kushner, and J. Cohen, Strastopheric control of the extratropical circulation response to surface forcing, *Geophys. Res. Lett*., **34**, L21802, doi:1.1029/2007GL031626, 2007.

Fletcher C.G., S. C. Hardiman and P.J. Kushner, The dynamical response to snow cover perturbations in a large ensemble of atmospheric GCM integrations, *J. Clim*., **22**(5), 1208-1222, doi:10.1175/2008CLI2505, 2009.

Gong G., D. Entekhabi, and J. Cohen, A large-ensemble model study of the wintertime AO-NAO and the role of interannual snow perturbations, *J. Clim*., **16**, 3917-3931, 2002.

Gong G., D. Entekhabi, and J. Cohen, Modeled Northern Hemisphere winter climate response to realistic Siberian snow amomalies, *J. Clim*., **16**, 3917-3931, 2003.

Gong G., D. Entekhabi, and J. Cohen, 2004: Sensitivity of atmospheric response to modeled snow anomaly characteristics. *J. Geophys. Res.*, **109**, D06107.

Grippa et al., 2004: Siberia snow depth climatology derived from SSM/I data using a combined dynamic and static algorithm, Remote Sensing of Environment, **93**, 30-41.

Hardiman, S., P.J. Kushner, and J. Cohen, Investigating the ability of general circulation models to capture the effects of Eurasian snow cover on winter climate, *J. Geophys. Res*., **113**, D21123, doi:10.1029/2008JD010623, 2008.

Honda, M., H. Nakamura, J. Ukita, I. Kousaka and K. Takeuchi, 2001, Interannual seesaw between the Aleutian and Icelandic Lows. Part I : Seasonal dependence and life cycle, *J. Climate*, **14**, 1029-1042.

Honda, M. and H. Nakamura, 2001, Interannual seesaw between the Aleutian and Icelandic Lows. Part II: Its significance in the interannual variability over the wintertime northern hemisphere, *J. Climate*, **14**, 4512-4529.

Koster, R.D. et al., GLACE: The Global Land-Atmosphere Coupling Experiment. PART I: Overview, *J. Hydrometeor*., **7**, 590-610, 2006.

Kumar A. and F. Yang, Comparative influence of snow and SST variability on extratropical climate in Northern winter, *J. Clim.*, **16**, 2248-2261, 2003.

Nakamura, H. and M. Honda, 2002, Interannual seesaw between the Aleutian and Icelandic Lows. Part III : Its influence upon the stratospheric variability, *J. Meteor. Soc. of Japan*, **80**, 1051-1067.

Orsolini, Y., N. Kvamstø, I. Kindem, M. Honda and H. Nakamura, Influence of the Aleutian-Icelandic low seesaw and ENSO onto the stratosphere in ensemble winter hindcasts, *J. Met. Soc. Japan*, **86**, 817-825, 2008.

Orsolini, Y. J., and N. Kvamstø, The role of the Eurasian snow cover upon the wintertime circulation: decadal simulations forced with satellite observations, *J. Geophys. Res*., **114**, D19108,, doi:10.1029/2009JD012253, 2009.

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.

Schlosser C. A. and D. M. Mocko, 2003: Impact of snow conditions in spring dynamical seasonal predictions. *J. Geophy. Res*., **108**, D16, 8616.

Walsh, J. E. and B. Ross, Sensitivity of 30-day dynamical forecasts to continental snow cover, *J. Climate,* **1**, 739-754, 1988.

Yasunari, T., A. Kitoh, and T. Tokioka, Local and remote responses to excessive snow mass of Eurasia appearing in the northern spring and summer climate: a study with the MRI GCM, *J. Met. Soc. Japan*, **69**, 473-487, 1991.