Linkages between Arctic Sea Ice Loss and Mid-Latitude Weather Patterns

Session #1 – Big Picture Context: The Role of Arctic Sea Ice Loss vs. Other Forcing Factors

Roles of the Stratosphere and Seasonal Snow Cover

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The Role of the Stratosphere

- Extratropical stratospheric variability is controlled by composition (e.g. ozone & GHGs) and driving from planetary waves from the troposphere.

- *Stratospheric influence*: A realistic change to the stratosphere affects the tropospheric circulation.

- Robust example: Antarctic Ozone Hole and Southern Hemisphere climate (Thompson & Solomon 2003, Gillett & Thompson 2003).

- In the Northern Hemisphere, the stratosphere has a potentially important but less direct role.
  - The relatively small decreases of Arctic stratospheric ozone have a weaker effect than the Antarctic Ozone Hole (WMO 2010).
  - There is some evidence that the stratosphere affects the tropospheric response to greenhouse gas forcing (Shindell et al. 1999, Sigmond et al. 2008).
  - I will focus on stronger evidence of intraseasonal stratosphere-troposphere coupling.
Stratosphere-Troposphere Coupling

- Stratosphere-troposphere NAM events (Baldwin and Dunkerton): Strengthened polar vortex leads positive AO with 2-4 week lag.
- Behavior captured in range of GCMs and isolated in stratospheric perturbation experiments.
Two Dynamical Pathways

NAM/Wave mean-flow interaction pathway:
• Baldwin & Dunkerton 2001, Polvani & Waugh 2004
• Upward propagating wave activity anomaly drives polar vortex.
• Initiates downward propagating zonal flow anomaly from stratosphere to troposphere.
• The downward coupling involves synoptic eddy mean-flow interactions (Barnes’s talk).
• Extensively studied.

Wave reflection pathway:
• Perlwitz & Harnik 2004, Shaw & Perlwitz 2013
• Stratospheric polar vortex can create a reflecting surface for upward propagating planetary waves.
• The reflected signal in the troposphere shows up as regional circulation anomalies like the NAO.
• Less well studied, but promising.
Applications & Questions

- Vortex weakening/negative NAM events lead cold Arctic and Eurasia and warm North America.
- Through NAM we can infer a modulation of blocking involving the stratosphere (e.g. Woolings et al. 2010, Mitchell et al. 2013).
- There is evidence that stratospheric information can improve seasonal prediction, particularly over the Arctic (Baldwin et al. 2003, Newman and Sardeshmukh 2008).
- This is all good … but stratospheric influence remains ambiguous.

- There are often robust tropospheric predictors of stratospheric events (see following).
- Newman & Sardeshmukh argue that tropical heating provides the bulk of midlatitude predictability.
Role of Boundary Forcing

• The stratosphere is involved in the NAM response to tropospheric forcing: ENSO, snow, sea ice, tropospheric blocking events.
  – Ineson & Scaife 2009; Garfinkel et al. 2010; Fletcher & Kushner 2010, 2013; Smith et al. 2010, 2011; Peings & Magnusdottir pers. comm..

• The polar vortex weakens when planetary wave anomalies reinforce the climatological stationary wave: a linear interference effect that is easy to tune in models.

**Tropical Pacific Ocean Warming**

- Negative NAM
- Constructive interference
- Pacific warming reinforces stationary wave

**Tropical Indian Ocean Warming**

- Positive NAM
- Destructive interference
- Indian Ocean warming cancels stationary wave
The Role of Seasonal Snow Cover

We consider two linkages involving seasonal snow cover:

1. Eurasian snow cover and its linkage to wintertime NAM variability.
2. Arctic sea ice and its linkage to Eurasian snow cover.

• These linkages are themselves linked in Cohen et al. 2012. What drives them?
• And why is there an apparent disconnect between October Eurasian Snow Cover trends and CMIP5 models?

Figure 1. (a) The annual-mean area-averaged land temperature anomalies (°C; averaged poleward of 20°N) from 1988–2010 from CRUTEM3 (solid red) and the ensemble mean temperature anomaly from the historical scenario of the CMIP5 models (solid black). Also shown is the linear trend for the observations (dashed red) and the CMIP5 ensemble mean (dashed black), including ±1 standard deviation. A double asterisk (**) indicates trends significant at the p < 0.01 level. (b) As in (a) but for DJF-averaged observed temperature anomalies (red) and the CMIP5 ensemble mean DJF temperature anomalies (black). (c) The spatial pattern of linear trends in DJF surface temperature (°C/10 yr) from CRUTEM3. In (a) and (b), the plots of model-based anomalies are shifted vertically so that the anomaly in 1988 matches that from the observations.

Figure 2. (a) JAS area-averaged (poleward of 60°N) surface temperature anomalies (°C) from NASA MERRA. (b) September area-averaged (poleward of 65°N) Arctic Ocean sea ice coverage (fractional area). (c) September–October vertically integrated (700–1000 hPa) and area-averaged (poleward of 60°N) specific humidity (kg m⁻²). (d) October mean snow cover areal extent (10⁶ km²) over the Eurasian continent from observations (black) and the ensemble mean from the historical runs of the CMIP5 model output (brown line). (e) The DJF average AO index (standardized). Same-coloured dashed lines in (a)–(e) represent the linear trend in each index. A double asterisk (**) indicates trends that are significant at the p < 0.01 level.
Snow/NAM Linkage

- Eurasian snow cover in fall linked to AO/NAM in winter (Cohen and Entekhabi 1999, and lots of follow on work by Cohen and collaborators).
- The linkage is thought to be driven by a snow-forced planetary wave that induces stratosphere-troposphere coupling (Gong et al. 2002, Cohen et al. 2007, Smith et al. 2011).

Detrended October Eurasian Snow Index (OCTSNW, Rutgers)

Correlation of $Z_{p_{cap}}$ with OCTSNW

Snow/NAM Linkage

- The negative NAM event is associated with a linear interference effect. The EP flux increases when the wave anomaly coherent with October Eurasian snow locks phase with the planetary stationary wave in December (Smith et al. 2011).

- There is evidence that this linkage can improve seasonal predictability (Cohen and Fletcher 2007, Orsolini and Kvamsto 2009, Cohen and Jones 2011).

- But important questions remain.
  
  - Why are these linkages not reproduced in free running climate simulations (Hardiman et al. 2008, Smith et al. 2011)?
  
  - Peings et al. (2013) find that the snow-NAM linkage is not stationary over the 20th century. Does this linkage change over time?
Sea Ice/Snow Linkage

- Arctic Sea ice reductions in JAS have been linked to increases in Eurasian October snow cover extent in models and observations (Deser et al. 2010, Ghatak et al. 2010, 2012).

- Mechanism proposed: Enhanced equatorward moisture transport from open water over the Arctic Ocean increases SCE.

- Ghatak et al. 2010 show that these linkages are weak in interannual variability and really reflect simultaneous trends in Arctic sea ice and in snow cover extent.

- But recent work suggests these snow cover trends are uncertain.
Uncertainties in October Snow Trends

- The Rutgers/NOAA CDR exhibits Eurasian snow cover extent trends in October that disagree with four other independent datasets (Brown and Derksen 2013).
- Using adjustments provided by R. Brown, we found that in situ data over Siberia shows better agreement with simulated trends in snow cover in October in CCSM4 (Mudryk et al. 2013).
- It is thus important to revisit the issue of these trends to assess linkages between sea ice extent and snow cover extent.
Conclusions

1. Stratosphere-Troposphere Coupling and Midlatitude Weather
   • In NAM variability, it is challenging to distinguish independent role of different factors: stratospheric, tropical, snow, sea ice.
   • Wave reflection framework (Perlwitz, Harnik, Shaw) links stratospheric conditions and regional weather --- less well studied.
   • Ozone, greenhouse gas, and volcanic forcing of stratosphere are worth thinking about for understanding decadal variability.
   • For this workshop, keep in mind the seasonality of stratospheric influence: wintertime and early spring.

2. Snow cover extent / NAM / sea ice extent linkages.
   • The connection between high latitude snow cover and sea ice is physically plausible, and linked to stratospheric influence (Cohen et al. 2012).
   • Need to address issues raised by recent observational work: Snow/NAM linkages and October Eurasian snow extent trends are uncertain (Peings et al. 2013, Brown and Derksen 2013).
Additional Slides
Wave activity flux (EP flux) into stratosphere measured by $\nu^*T^*$.

Positive $\nu^*T^*$ events (1) drive stratospheric warming, negative NAM (2).

NAM anomalies propagate into troposphere (3).

- Given $\nu^*T^*$ anomaly (1), we can predict polar vortex strength (2).
  - These anomalies can come from internal stratospheric variability or boundary influences (tropical SSTs, Eurasian snow cover, sea ice variability).
- Step 3 is more complex and involves synoptic eddy/tropospheric jet feedbacks (Barnes).
21-day Lag Covariance in $p_s$ from Linear Inverse Model

LIM with stratosphere and tropical heating

LIM with no stratosphere

Newman & Sardeshmukh 2008
Consistent with Fig. 4b, the seasonal cycle of the terrestrial air temperature response follows that of the net surface energy flux response, with maximum warming in winter (November–December and January–February) and weaker warming in autumn (September–October) and spring (March–April). The terrestrial warming is largest in coastal regions adjacent to the Arctic Ocean, with the maximum temperature response over Siberia and northern Canada and Alaska, and penetrates approximately 1500 km inland.

The terrestrial surface air temperature responses in early (November–December) and mid-(January–February) winter are largely confined to regions with a mean boundary layer temperature inversion in the late twentieth century (marked by thick black contours on the bimonthly air temperature responses in Fig. 5; note that there is no inversion in the warm season May–June through September–October).

Indeed, the vertical structures of the December atmospheric temperature responses over the Arctic Ocean and high-latitude (65°–80°N) continents are confined to below 800 hPa, with the warming amplifying toward the surface (maximum values of 6.5°C over land and 16°C over the ocean; Fig. 6).

As a consequence of the vertical structure of the warming, the static stability of the boundary layer decreases from the late twentieth century to the late twenty-first century. Over the ocean, the 10°C inversion between 1000 and 900 hPa in the late twentieth century is completely eroded in the late twenty-first century. Over land, the capping inversion, while not completely gone in the twenty-first century, is only approximately 50% of that in the twentieth century (Fig. 6).

The geographical distributions of the strength of the December low-level inversion in the late twentieth and twenty-first centuries are shown in Fig. 7. The marine inversion, which exceeds 12°C over the central Arctic Ocean in the late twentieth century, disappears entirely in the late twenty-first century. The terrestrial inversion, while not completely gone in the twenty-first century, is only approximately 50% of that in the twentieth century (Fig. 6).

Deser et al. 2010
Figure 1. (a) 20CR snow detection performance: percentage of October days with snow/no snow in both 20CR snow cover and HSDSD data (threshold 5 cm) over 1881–1994. (b) Difference in % between the 20CR and NSIDC snow detection performance over 1972–1994. (c) Observed snow frequency in % of October days over 1972–1994, defined as the ratio of HSDSD data higher than 5 cm.

Figure 2. Time evolution of the snow detection performance for 20CR and NSIDC averaged over the available HSDSD stations. The monthly snow frequency averaged over available stations is indicated. The snow detection and frequency are expressed in % on the left axis and the number of HSDSD stations is indicated on the right axis.

Given the steadiness of the 20CR snow quality over the entire 20th century (section 3a), and the good agreement between SAI-20CR and SAI-NSIDC over recent decades, the study of the snow-AO relationship was extended back in time (until 1891). Figure 3b shows the correlation between two AO indices (AO-CPC and AO-20CR) and SAI-20CR, computed over a 21 year moving window (black lines). Over the common period, these sliding correlations are very close, depending on the use of the CPC or 20CR AO index. It gives us confidence in using 20CR to construct an AO index over the whole 20th century. The main result in Figure 3b is that the snow-AO relationship is not stationary. While the correlation significance is higher or close to the 95% confidence level over recent decades (in line with SAI-NSIDC, solid red line), it is not significant before the 1970s and even changes sign. The same conclusion is...