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Winter 2009–2010: A case study of an extreme Arctic Oscillation event

Judah Cohen,[1] James Foster,[2] Mathew Barlow,[3] Kazuyuki Saito,[4,5] and Justin Jones[1]

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[1] Winter 2009–2010 made headlines for extreme cold and snow in most of the major population centers of the industrialized countries of the Northern Hemisphere (NH). The major teleconnection patterns of the Northern Hemisphere, El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation (AO) were of moderate to strong amplitude, making both potentially key players during the winter of 2009–2010. The dominant NH winter circulation pattern can be shown to have originated with a two-way stratosphere-troposphere interaction forced by Eurasian land surface and lower tropospheric atmospheric conditions during autumn. This cycle occurred twice in relatively quick succession contributing to the record low values of the AO observed. Using a skillful winter temperature forecast, it is shown that the AO explained a greater variance of the observed temperature pattern across the extratropical landmasses of the NH than did ENSO.

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1. Introduction

[2] Record cold snaps and record snowfalls were numerous across the industrialized population centers of the United States, Europe and East Asia during boreal winter 2009–2010. Most notable were a series of U.S. East Coast snowstorms that buried the Middle Atlantic region. Snowfalls in a number of locations exceeded 135 cm (54 inches) during the 17-day period from January 29–February 15 (see Figure S1 in the auxiliary material).[1] Many Mid-Atlantic observing stations easily broke their prior seasonal snowfall records. Relatively frequent southern and East Coast snowstorms contributed to making North American snow cover in winter (DJF) 2009–2010 the most extensive on record (Robinson, personal communication).

[3] Though observed global temperature trends continue to warm with no observed reversals (according to NOAA, globally it was the fifth warmest December–February (DJF) period), public perceptions were clearly influenced increasing skepticism towards global warming (e.g., New York Times Feb 10, 2010; Wall Street Journal Feb 16, 2010). Therefore, we would argue that attribution of the harsh winter weather is critical to the debate of anthropogenic climate change.

[4] ENSO is the dominant mode of tropical climate variability [*Rasmusson and Wallace*, 1983] and the AO, also referred to as the Northern Annular Mode (NAM), is the dominant mode of NH extratropical climate variability [*Thompson and Wallace*, 2000]. Both of these two climate modes were of moderate to strong amplitude throughout the winter of 2009–2010, making both potentially important contributors to the winter weather experienced regionally across the NH. We will demonstrate that the strong negative winter AO of 2009–2010 originated as a regional perturbation across Northern Eurasia and that some unique conditions across Eurasia contributed to its exceptional amplitude.

[5] One of the earliest studies linking autumn snow cover with winter climate was that of *Foster et al.* [1983], who found that Eurasian autumn snow cover extent (SCE) explained as much as 52% of the variability of ensuing winter temperatures locally. Cohen and colleagues then demonstrated that a statistically significant relationship exists between snow cover extent and lower tropospheric anomalies across Northern Eurasia in the fall and the winter AO [*Cohen and Entekhabi*, 1999; *Saito et al.*, 2001; *Cohen et al.*, 2001]; numerical modeling experiments have confirmed the snow-atmospheric circulation linkage [*Orsolini and Kvamtso*, 2009, and references therein].

[6] *Cohen et al.* [2007] put forth a conceptual model of a dynamical pathway consisting of a six-step process starting with a rapid advance in Eurasian snow cover and culminating in a negative surface AO. The six steps in sequential order are: 1) rapid advance of Siberian snow cover in October, 2) a strengthened Siberian high with colder than normal temperatures and higher sea level pressure (SLP) anomalies, 3) increased upward Eliassen Palm (EP) flux or the three dimensional wave activity flux (WAF [*Plumb*, 1985]), 4) a stratospheric warming, 5) downward propagation of the associated height and wind anomalies from the stratosphere down to the surface and finally 6) a negative surface AO (Figure S2). Typically the cycle begins with the advance in snow cover in October and concludes with a lower tropospheric AO response beginning in mid to late January. As we will demonstrate in this Letter, winter 2009–2010 was unusual and even unique in that the six steps outlined by *Cohen et al.* [2007] occurred consecutively, in rapid succession and the entire process occurred twice in the same amount of time that typically one full cycle occurs; this

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[1] Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA.
[2] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3] Environmental, Earth, and Atmospheric Sciences, University of Massachusetts, Lowell, Massachusetts, USA.
[4] Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan.
[5] International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA.

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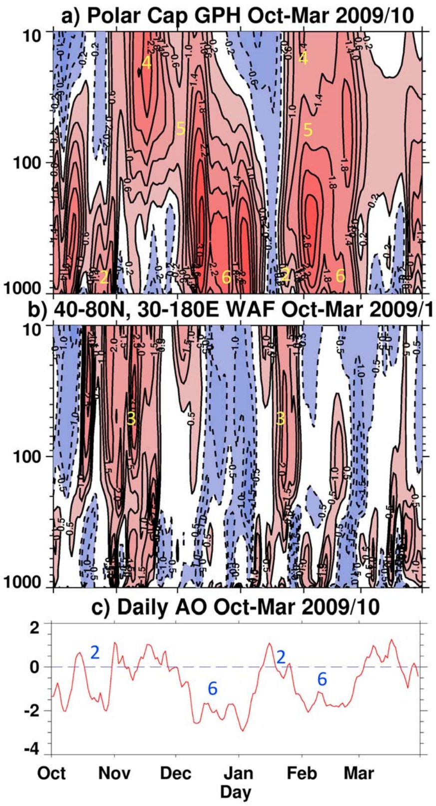

a) Polar Cap GPH Oct-Mar 2009/10

b) 40-80N, 30-180E WAF Oct-Mar 2009/10

c) Daily AO Oct-Mar 2009/10

Figure 1. (a) The daily geopotential height normalized anomaly area averaged around the polar cap poleward of 60°N from 1000 to 10 hPa, (b) the daily wave activity flux (WAF) area averaged between 40–80°N latitude and 30–180°E longitude from the 1000 to 10 hPa, (c) the daily polar cap index at 1000 hPa. Plots are all October 2009–March 2010. Numbers 2–6 in Figures 1a–1c correspond to the six steps of the conceptual model described in the text.

directly contributed to the record low AO values observed in 2009–2010.

2. Results and Discussion

[7] The winter (DJF) AO of 2009–2010 was the lowest observed since at least 1950, accelerating the downward trend in the winter AO observed over the past two decades [*Cohen et al.*, 2009]. Empirical orthogonal function analysis of SLP poleward of 20°N (standard definition of the AO) gives a value of −2.5 standard deviations.

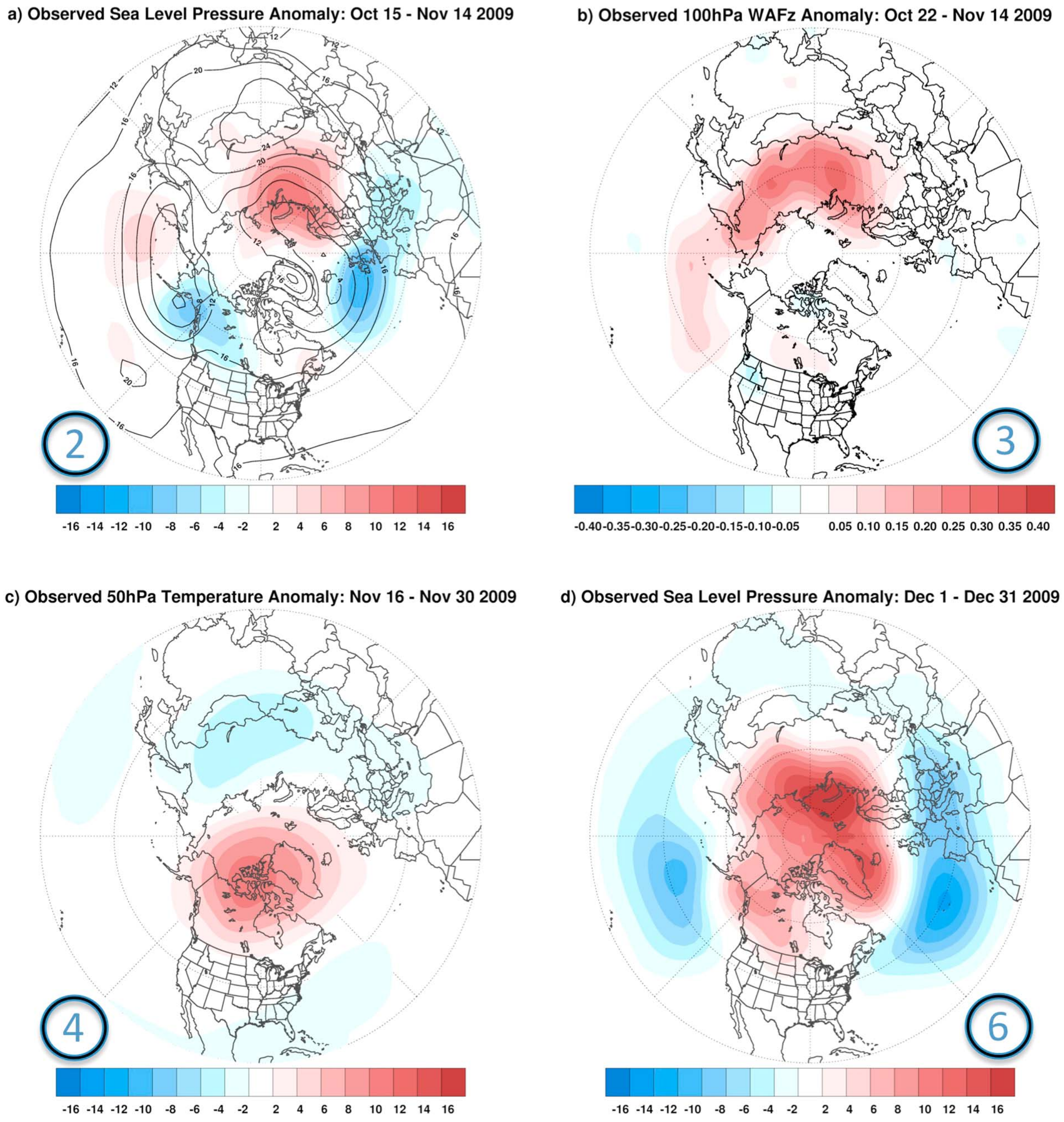
[8] The negative AO observed during winter 2009–2010 was not confined to the lower troposphere but was similarly observed throughout the troposphere and the stratosphere. *Baldwin and Dunkerton* [2001] demonstrated that the AO is often of coherent phase throughout the atmospheric column and that the AO originates in the middle stratosphere and propagates through the lower stratosphere and then through the entire troposphere on a time scale of one to two weeks. *Wang and Chen* [2010] argue that the strong negative surface AO observed in December 2009 originated in the stratosphere in November.

[9] *Cohen et al.* [2002] developed a polar cap geopotential height diagnostic of the daily area averaged geopotential height anomaly poleward of 60°N at all pressure levels. The diagnostic is an excellent proxy for the AO index since during robust AO events the height anomalies poleward of 60°N are often of the same sign.

[10] In Figure 1a we present the polar cap diagnostic from October 1, 2009 through March 31, 2010 (red shading represents above normal heights around the polar cap; all atmospheric data is taken from NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996]). In Figure 1c we plot the daily polar cap index at 1000 hPa as a proxy for the daily AO for the same period where two distinct and strong negative surface AO events are seen, one in December and a second in February (labeled “6” in Figure 1). But as argued by *Cohen et al.* [2002], not only can the negative AO events be traced back in time up into the stratosphere (labeled “4” and “5”) as demonstrated by *Baldwin and Dunkerton* [2001], they can be traced even further back in time to two distinctive upward WAF events (labeled “3” and Figure S3). Furthermore, the stratospheric warming and the upward WAF events were preceded still by strong tropospheric events associated with positive geopotential heights (labeled “2”). Note that the polar cap diagnostic clearly shows that two major events of high heights originated or commenced in the troposphere and not in the stratosphere. As will shortly be demonstrated, both strong negative AO events can be shown to originate as regional perturbations across Northern Eurasia. The first tropospheric precursor that initiated the mid-November minor stratospheric warming we estimate existed from the second half of October until mid-November. The second tropospheric precursor that initiated a major stratospheric warming existed at the end of January. *Cohen et al.* [2002] argued that tropospheric precursors preceded both the stratospheric warming that often-lead strong surface AO events, which was more easily highlighted in the polar cap diagnostic. These tropospheric precursors force anomalous WAF that drives stratospheric variability.

[11] Snow cover extent was well below normal across Eurasia the first week of October 2009. But during the last three weeks of October the SCE rapidly advanced by over 15×10^6 km^2 to 18×10^6 km^2 (SCE was derived from NOAA’s satellite-sensed observations [*Robinson et al.*, 1993]). So even though SCE was well below normal after the first week of October, by the end of the month Eurasian SCE was the greatest since 1976. Furthermore, monthly Eurasian SCE remained in the top quartile for the months October–February (winter 2009–2010 Eurasian SCE was the second greatest on record for DJF). And though we are unsure how much influence the extensive snow cover after October had on the second AO event, it supported cold temperatures and high pressure across northern Eurasia through the cold season, which was critical to initiating the second AO event as discussed below.

[12] Soon after the rapid advance in SCE began, temperatures responded by reversing from above normal to below normal. For the period from late October and the first half of November the only meaningful region with below normal surface temperatures (T_S) across the entire extratropical NH was Siberia (Figure S4). The cold dense air also helped to build high pressure in the region. The largest positive SLP anomalies in the extratropical NH are centered across Northern Eurasia to the northwest of the climatological center of the Siberian high (Figure 2a). The SLP and T_s anomalies across Northern Eurasia are similar in location and orientation as the tropospheric precursor to stratospheric warming and


a) Observed Sea Level Pressure Anomaly: Oct 15 - Nov 14 2009

b) Observed 100hPa WAFz Anomaly: Oct 22 - Nov 14 2009

c) Observed 50hPa Temperature Anomaly: Nov 16 - Nov 30 2009

d) Observed Sea Level Pressure Anomaly: Dec 1 - Dec 31 2009

Figure 2. (a) 30-year (1971–2000) mean SLP-1000 (contours) and observed SLP anomalies (shading) in hPa October 15, 2009 – November 14, 2009, (b) vertical WAF anomalies in m^2s^2 at 100 hPa October 15 – November 14, 2009, (c) observed temperature anomalies at 50 hPa in °C November 16 – 30, 2009 and (d) observed SLP anomalies in hPa December 1–31, 2009.

negative surface AO events, identified previously [*Cohen et al.*, 2001, Figures 1 and 2; *Cohen et al.*, 2002, Figure 1b; *Cohen*, 2003, Figures 1d and 2d]. The tropospheric precursor forces an increase in upward WAF (Figure 2b) focused across Northern Eurasia in general and Siberia in particular, which is then absorbed in the stratosphere leading to warming over the pole (Figure 2c). Finally, the hemispheric circulation anomalies propagate from the stratosphere down through the troposphere (as seen in Figure 1a) culminating in a negative AO. The negative AO is characterized by positive SLP anomalies across the Arctic, negative SLP anomalies in the mid-latitude ocean basins (Figure 2d) and an expansion of cold T_s into Europe and North America (Figure S4).

[13] From the polar cap heights and the daily AO presented in Figure 1, the strong negative AO event that was observed during the month of December weakened and ended during the first couple of weeks of January. In Figure 3a we plot the SLP anomaly for the second half of January 2010. Clearly the AO pattern is gone; however, similar to late October and early November 2009, a strong positive SLP anomaly is observed across Northern Eurasia northwest of the climatological center of the Siberian high. Furthermore, the negative T_s anomalies

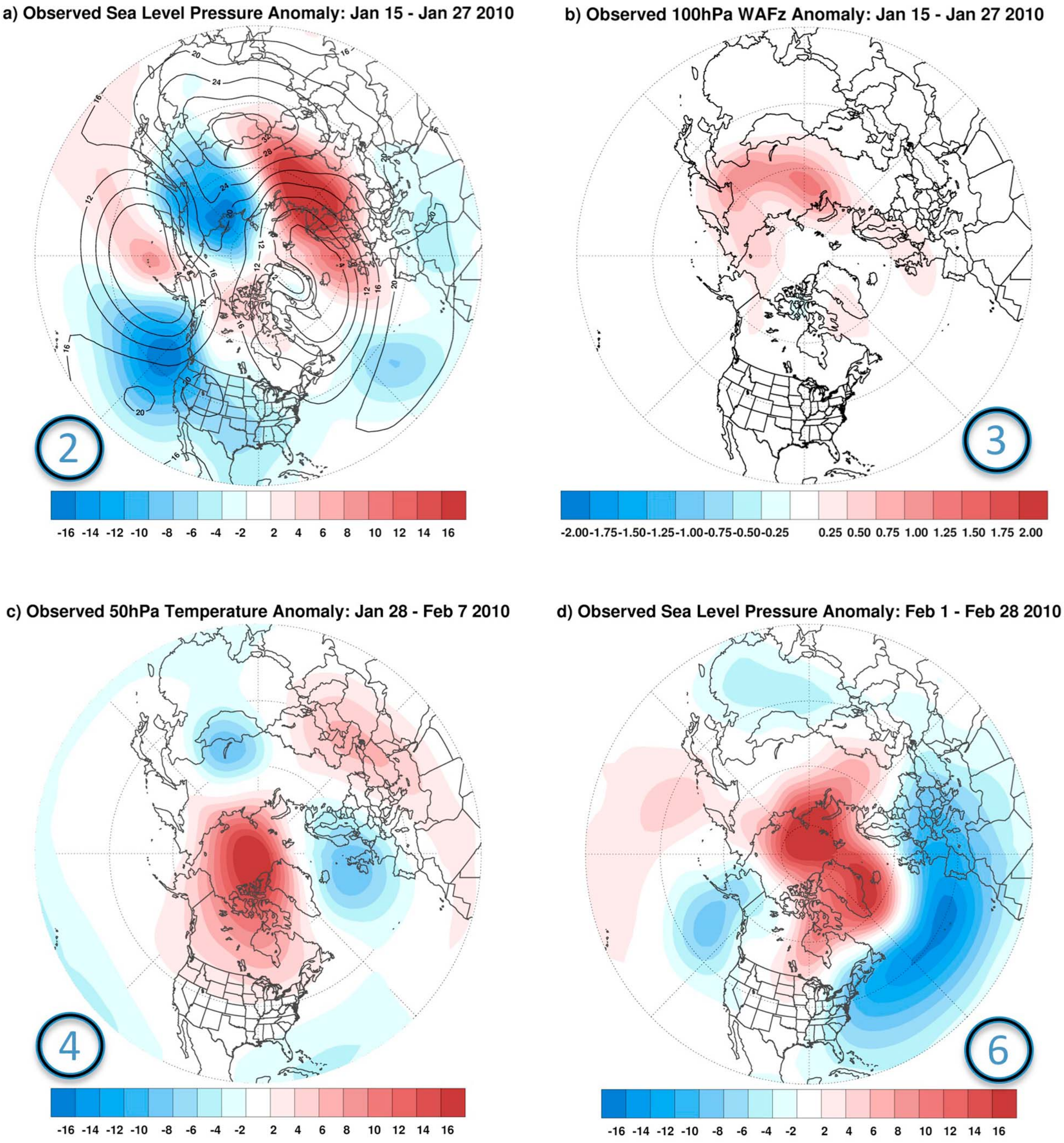


Figure 3. (a) Thirty-year (1971–2000) mean SLP-1000 (contours) and observed SLP anomalies (shading) in hPa January 15 – 27, 2010, (b) vertical WAF anomalies in m^2s^2 at 100 hPa January 15 – 27, 2010, (c) observed temperature anomalies at 50 hPa in °C January 28 – February 7, 2010 and (d) observed SLP anomalies in hPa February 1 – 28, 2010.

receded into Northern Eurasia (Figure S4). This is synoptically similar to the tropospheric precursor present at the end of October and early November; the re-establishment of the tropospheric precursor once again initiated a strong upward WAF and subsequent stratospheric warming. In Figure 3b we show the anomalous WAF for late January at 100 hPa, which is focused across Siberia. The convergence of WAF in the stratosphere forces a second warming in the polar vortex of the stratosphere (Figure 3c). Finally, February 2010 is characterized by strong positive SLP anomalies across the Arctic, negative SLP anomalies across the ocean basins of the midlatitudes, especially the North Atlantic (Figure 3d) and the expansion of below normal T_s across Northern Eurasia and the Eastern U.S. (Figure S4). These patterns of SLP and T_s anomalies are consistent with the strong negative daily AO values observed during February (Figure 1c).

[14] *Cohen and Fletcher* [2007] describe and provide verification statistics for an operational seasonal statistical forecast model where the main inputs for predicting winter T_s are October Eurasian SCE and SLP anomalies. This model

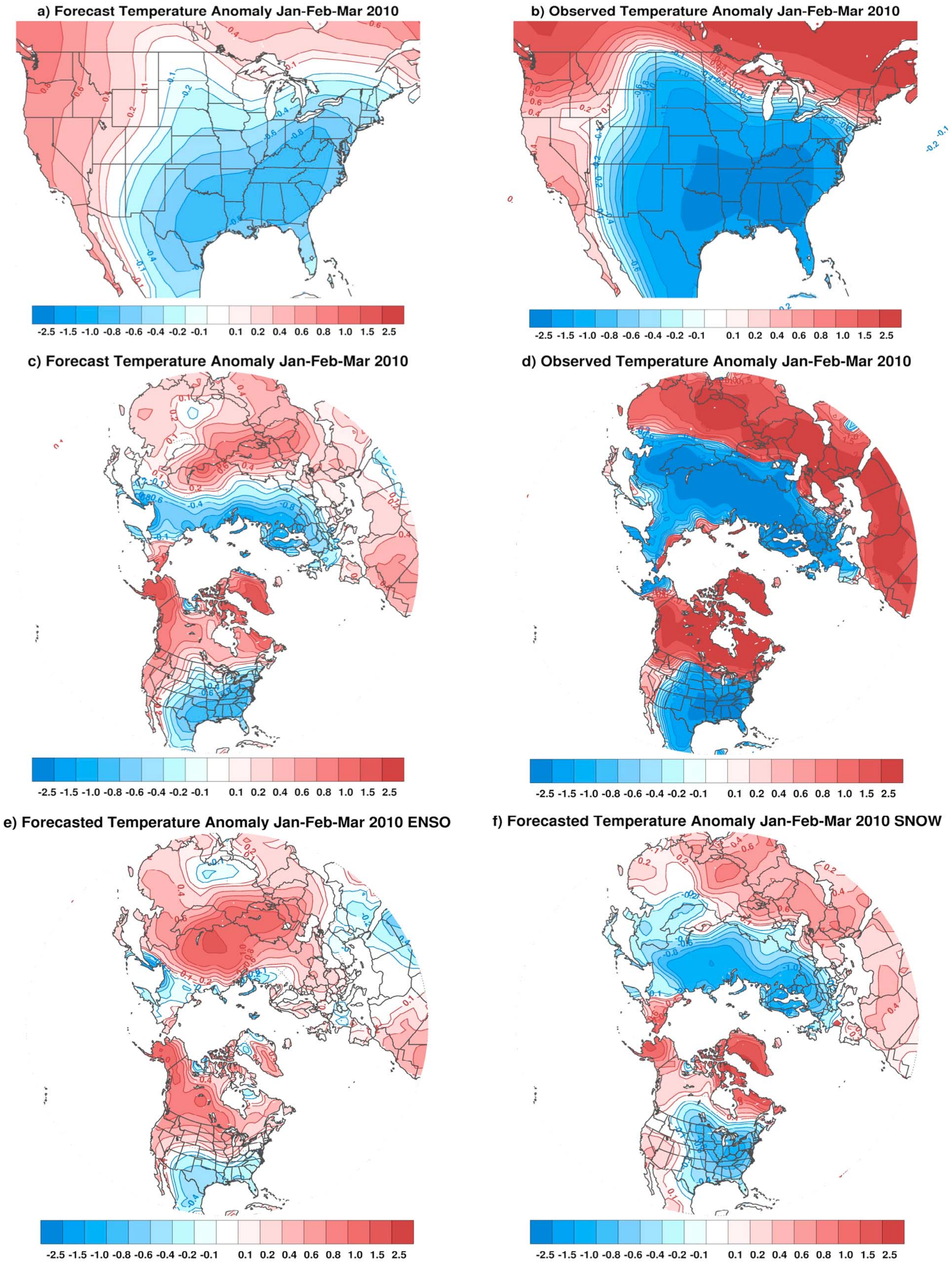


Figure 4. (a) Surface temperature anomalies forecast for the U.S. in °C January–March 2010, (b) observed surface temperature anomalies for the U.S. in °C January–March 2010, (c) surface temperature anomalies forecast for the extratropical NH in °C January–March 2010, (d) observed surface temperature anomalies for the extratropical NH in °C January–March 2010, (e) surface temperature anomalies forecast for the extratropical NH with only ENSO as a predictor in °C January–March 2010 and (f) surface temperature anomalies forecast for the extratropical NH with only October Eurasian snow and SLP anomalies as predictors in °C January–March 2010.

was shown to have positive skill for many regions of the extratropical NH landmasses and higher inherent skill than the dynamical models that strongly rely on ENSO. A winter forecast for JFM 2010 was posted prior to the season on the National Science Foundation website (http://www.nsf.gov/news/special_reports/autumnwinter/predicts.jsp). The model used three predictors in the forecast for winter 2009–2010: Eurasian SCE and SLP anomalies for October and the predicted winter value of Niño 3.4. In Figures 4a and 4b we show the JFM 2010 temperature anomaly forecast and observations for the U.S. Though the magnitude of the anomalies was underpredicted, the predicted temperature anomaly pattern is strikingly similar to the observed pattern. In Figures 4c and 4d we show forecast and observed NH T_s anomalies. The pattern of variability across the NH was well predicted by the model, though it incorrectly predicted above normal temperatures across southeastern Russia and especially in Mongolia. Because it is a linear statistical model we can separate the contribution of ENSO and the snow forcing, which is a proxy for the AO, to the T_s pattern. In Figure 4e we show the NH T_s anomaly pattern forecast using ENSO only, and in Figure 4f we show the T_s anomaly pattern using Eurasian snow and SLP anomalies only. From Figure 4, it is clear that the snow forcing, which is a proxy for the AO, explains most of the observed temperature variability in the NH extratropics. In fact, the model with snow forcing only is the best match with the observed extratropical NH T_s pattern. On the other hand, the predicted pattern associated with ENSO across Eurasia shows little resemblance to the observed pattern. And though the inclusion of ENSO seemed to have degraded the real-time forecast for Eurasia, this may be more a function of the snow and SLP anomalies used as input into the model underpredicting the amplitude of the observed winter AO; substitution of a value closer to the observed AO in the model produced a temperature pattern closer to the observed pattern (Figure S5).

3. Conclusions

[15] The winter of 2009–2010 was particularly severe for many of the industrialized population centers of the NH midlatitudes of the U.S., Europe and East Asia. One of the biggest contributing factors to the severe winter weather was a redistribution of mass across the NH with anomalously high pressure at high latitudes and low pressure at mid-latitudes. This seesaw pressure pattern is most closely associated with the AO index. We argue that the record low AO values observed in the winter of 2009–2010 was a result of an unusual occurrence of two troposphere-stratosphere coupling events that occurred more rapidly than usual and in quick succession during the winter of 2009–2010. During a normal winter, none or possibly just one event would typically occur [*Cohen et al.*, 2007]. We also argue that these two events were forced by a rapid advance in Eurasian SCE and persistently extensive snow cover that supported below normal temperatures and a strengthened Siberian high. No better proof of concept exists than a correct forecast. Using Eurasian October SCE and SLP anomalies as input into a prediction model resulted in a highly skillful forecast of temperature anomalies across the extratropical landmasses of the NH. Inclusion of ENSO in the model further improved skill of the model but across North America only. Further, and somewhat counterintuitively, the severe *cold* winter weather may be attributed to boundary forcing changes consistent with an overall *warming* planet. A warmer atmosphere can hold more moisture and as the interior of the NH continents cool in fall, this can lead to increased snowfall. And as argued here, more extensive fall snow cover contributed to the extreme negative AO observed during the winter of 2009–2010. This hypothesis is being further investigated.

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M. Barlow, Environmental, Earth, and Atmospheric Sciences, University of Massachusetts, One University Ave., Lowell, MA 01854, USA.

J. Cohen and J. Jones, Atmospheric and Environmental Research, Inc., 131 Hartwell Ave., Lexington, MA 02421, USA. (jcohen@aer.com)

J. Foster, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

K. Saito, International Arctic Research Center, University of Alaska Fairbanks, 930 Koyukuk Dr., Fairbanks, AK 99775, USA.