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Unusual extremes in the negative phase of the Arctic Oscillation during 2009

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[1] During 2009, the Arctic Oscillation (AO) index was exceptionally negative during four months, which was unprecedented in a 60-year record extending back to 1950. The negative phase of the AO corresponded to a nearly zonally symmetric anomaly of temperature and pressure over the middle-to-high latitudes of the Northern Hemisphere. Consistent with the strong negative phase of the AO, below-average temperatures were also observed over North America and parts of Eurasia during June, July, October, and December 2009. Although the impact of the AO on 2-meter temperatures was near zero when averaged over the entire hemisphere (20°–90°N), positive anomalies were evident in the residual pattern of observed temperature. The residual, along with observed below-average stratospheric temperatures, are consistent with anthropogenic climate projections. The possible implication of the recent negative values on the long-term AO trend is also discussed. **Citation:** L'Heureux, M., A. Butler, B. Jha, A. Kumar, and W. Wang (2010), Unusual extremes in the negative phase of the Arctic Oscillation during 2009, *Geophys. Res. Lett.*, *37*, L10704, doi:10.1029/2010GL043338.

1. Introduction

[2] The Arctic Oscillation (AO), or the Northern Annular Mode (NAM), is the leading pattern of variability in the Northern Hemisphere atmospheric circulation [*Thompson and Wallace*, 2000; *Quadrelli and Wallace*, 2004]. The AO is characterized by a large-scale zonally symmetric structure featuring a nearly concentric ring of anomalous pressure over the Arctic and surrounding anomalies of opposite sign within the middle latitudes of the Northern Hemisphere. The time series of the AO is highly correlated with the North Atlantic Oscillation (NAO) index, but implies impacts over much of the Northern Hemisphere and not just the North Atlantic sector. The AO and its analogous Southern Hemisphere counterpart, the Southern Annular Mode, are driven by dynamical processes that are internal to the atmosphere and are maintained by a positive feedback between eddies and the zonal mean flow [*Robinson*, 2000; *Lorenz and Hartmann*, 2003]. During certain seasons, the influence of the Annular Modes extends beyond the troposphere and coupling with the stratosphere occurs [*Baldwin and Dunkerton*, 2001, *Thompson et al.*, 2002].

[3] The AO accounts for a large fraction of temperature variability, and trends in the AO have been associated with long-term surface trends [*Hurrell*, 1995]. During boreal winter from 1970–2000, positive trends in the AO described ~50% of the warming over Europe and Asia, ~30% of the warming over the entire Northern Hemisphere, ~40% of stratospheric cooling, and ~40% of March ozone depletion [*Thompson et al.*, 2000]. Changes in the AO have been linked to changes in the frequency of blocking and incidence of cold air outbreaks over the entire hemisphere [*Thompson and Wallace*, 2001; *Higgins et al.*, 2002].

[4] During several months of 2009, large regions of the contiguous United States experienced below-average temperatures, although the long-term temperature trend is positive over most of the United States. The NOAA National Climatic Data Center (NCDC) noted that June–August 2009 was the 42nd coolest summer since 1895 with below-average temperatures prevalent through the Central and Northern Plains, Midwest, and Great Lakes regions. NCDC also documented unusually cool conditions over much of the United States during October 2009 (third coolest October) with Florida as the only state with above-average temperatures. Finally, during December 2009, a series of cold air outbreaks resulted in temperatures that were nearly 3.2°F (1.6°C) below the long-term average for the contiguous United States.

[5] Here we show that one- third of the months in 2009 were accompanied by extreme negative values of the AO index, which coincided with the relative (to the long-term mean) minimum in temperatures observed over the United States. We will also show evidence that the temperature and circulation anomalies spanned the entire Northern Hemisphere and closely corresponded to the negative phase of the AO.

2. Data and Methods

[6] Geopotential height, 2-meter temperature, and zonal wind data from this study are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis [*Kalnay et al.*, 1996]. Anomalies were formed by removing the 1979–2000 monthly averages. To assess the influence of observed sea surface temperatures (SST) anomalies, an ensemble average is created from several atmospheric model simulations that use prescribed sea surface temperatures from June, July, October, and December 2009. These models include the NCEP Global Forecast System (GFS), the Seasonal Forecast Model (SFM), and European Centre Hamburg Model (ECHAM4.5).

[7] The AO index is calculated from the first leading mode of an Empirical Orthogonal Function (EOF) analysis of monthly mean 1000-hPa height anomalies from the NCEP/NCAR Reanalysis for 1950–2009. The gridded anomalies are cosine weighted prior to the EOF procedure in

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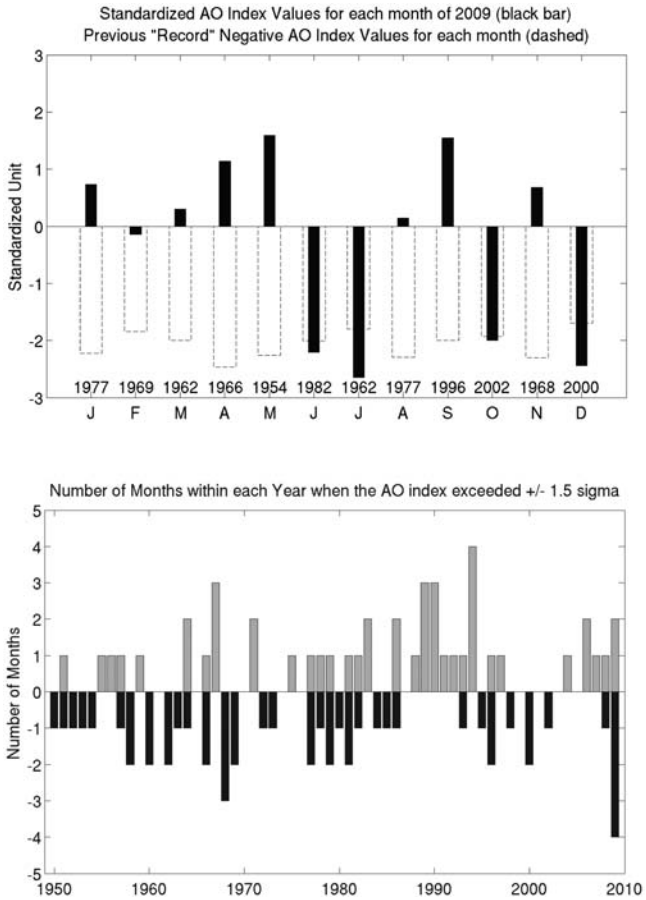

Figure 1. (top) Standardized monthly AO index values for each calendar month of 2009 (black bars) and previous minimum AO index value for each month (dashed bars). The year in which the previous minimum AO occurred for each month is listed just above the x-axis. (bottom) Number of months within each year when the AO index exceeded +1.5 (gray shading) or −1.5 (black shading) standard deviations. Standardized monthly values are calculated based on the 1950–2009 period.

order to ensure equal area weighting for the covariance matrix. Year-round monthly mean data was used to obtain the loading pattern and therefore favor wintertime patterns (with the largest variance). After the EOF procedure, the AO index values are standardized for each individual calendar month (e.g. January is standardized on the basis of all Januarys), so that each month's AO index has a mean of zero and a standard deviation of one for 1950–2009. Because the variability of the AO is larger during winter months, this standardization procedure facilitates comparison among different months.

[8] "AO reconstruction" maps are used as a diagnostic tool, and are created by (1) regressing the anomaly field (temperature or height) onto the standardized monthly AO index, and then (2) multiplying the regression map by that month's standardized value. For example, the October 2009 AO value is −2 standardized units, and so the October regression map is multiplied by a factor of −2.

[9] In this paper, June and July (JJ) 2009 and October and December (OD) 2009 anomalies are averaged together reflecting the seasonality and spatial similarity of the individual monthly means (October and December are shown individually in the auxiliary material).[1] November 2009 was not characterized by a negative AO pattern and is therefore not included in the analysis.

3. Results

[10] Figure 1 (top) shows the AO index values for each month of 2009 (black bar) and the previous "record" minimum (since 1950) AO (dashed bar). The years of the previous record negative AO value for each month are shown along the x-axis. During 2009, the AO index value for the months of June, July, October, and December represented the lowest negative values in 60 years. Figure 1 (bottom) shows the number of months in each year when the AO index was in excess of ± 1.5 standard deviations. 2009 was exceptional in the 60-year record with 4 months reaching such large negative amplitudes. After randomly sampling from a normal distribution, the odds of 4 months out of the year (in a 60-year record) exceeding a threshold of −2 standard deviations is 0.7% (or 99.3% significant).

[11] The negative phase of the AO is associated with positive (negative) 1000-hPa geopotential height anomalies over the Arctic (middle latitudes), which reflects the zonally symmetric seesaw in atmospheric mass between the higher and lower latitudes. This historical AO pattern is displayed in Figure 2 (top) depicting the AO reconstruction for June and July (JJ) 2009 and October and December (OD) 2009 using the NCEP/NCAR Reanalysis. Figure 2 also illustrates the correspondence of the negative phase of the AO with above-average temperatures over the Arctic and cooling in the middle latitudes, particularly over North America and sections of Eurasia. The AO pattern is more pronounced during Northern Hemisphere winter, and this is reflected in the relative strength of the JJ and OD anomalies.

[12] Figure 2 (middle) shows the observed JJ 2009 and OD 2009 anomalies of 2-meter temperature (shaded) and 1000-hPa geopotential height (contour) using the NCEP/NCAR Reanalysis. The spatial-scale of the negative temperature anomalies over the United States corresponds well with the NCDC summaries that documents cool conditions during these months. A visual comparison of Figures 2 (top) and 2 (middle) shows that a substantial fraction of the AO pattern is mirrored in the observed anomalies, not just over the United States, but across the entire Northern Hemisphere. The spatial correlation coefficients between Figures 2 (top) and 2 (middle) for JJ 2009 are 0.54 and 0.75 for temperature and 1000-hPa height, respectively. For OD 2009, the correlation coefficients increase to 0.64 (temperature) and 0.85 (height).

[13] Figure 2 (bottom) shows the zonal average of 2-meter temperature presented in Figures 2 (top) and 2 (middle) for JJ2009 (Figure 2, left) and OD 2009 (Figure 2, right). The solid dark line represents the observed anomalies during 2009, the solid dark line with open circles shows the AO reconstruction, and the dashed line indicates the "residual," which is, by construction, uncorrelated with the AO reconstruction. During both JJ and OD, the observed 2009 temperature anomalies are positive poleward of 50°–55°N

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043338.

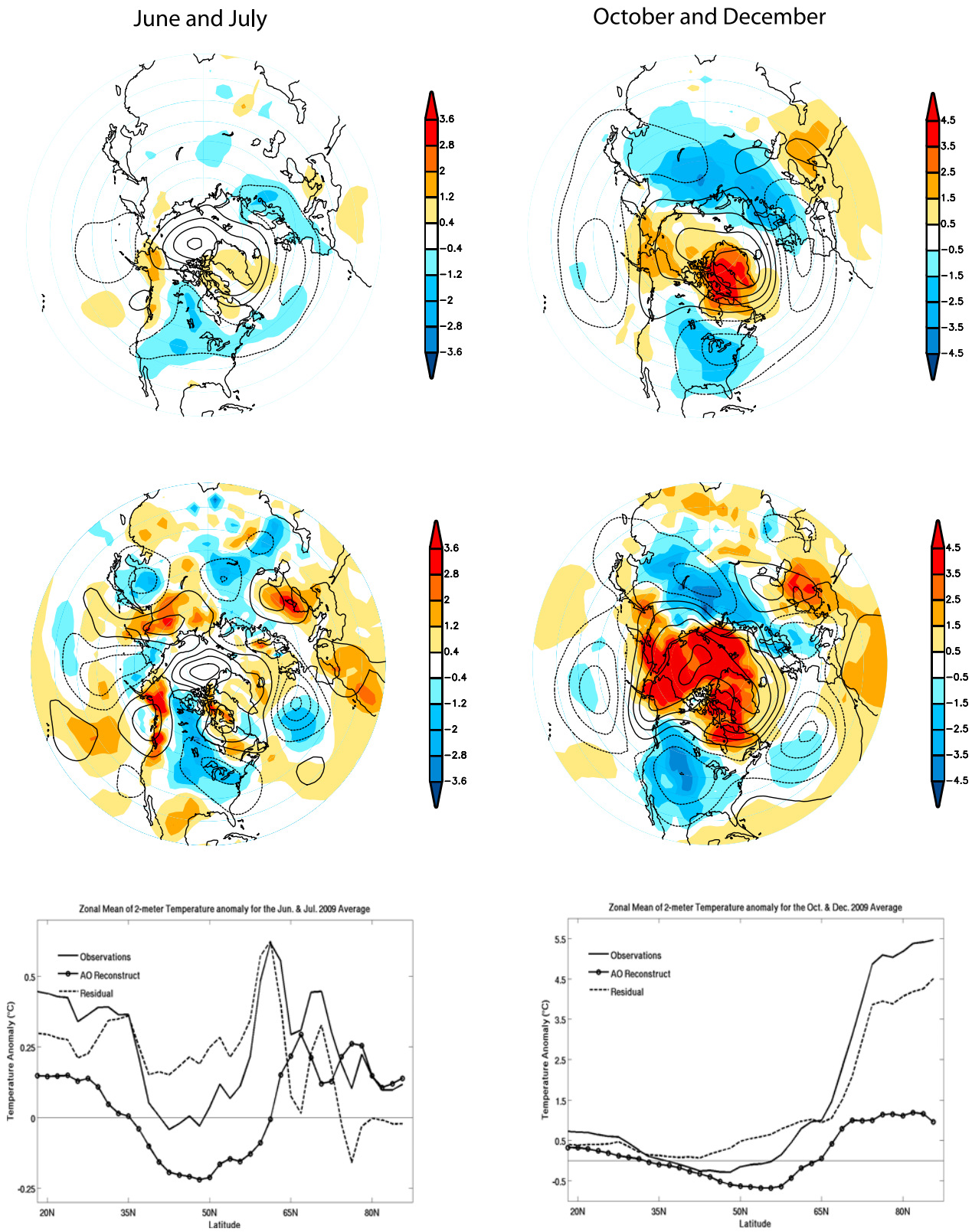

Figure 2. (top) The AO reconstruction of 2-meter temperature (shading, units are in degree Celsius) and 500-hPa geopotential height anomalies (contour interval is 30 meters) for (left) June/July 2009 and (right) October/December 2009. (middle) Same variables as in Figure 2 (top), except showing the observations for June/July 2009 and October/December 2009. (bottom) Zonally averaged 2-meter temperature anomalies for the AO reconstruction shown in Figure 2 (top) (solid line with open circles), the observed data in Figure 2 (middle) (solid line), and for the residual (dashed line). Anomalies are the departure from the 1979–2000 period mean.

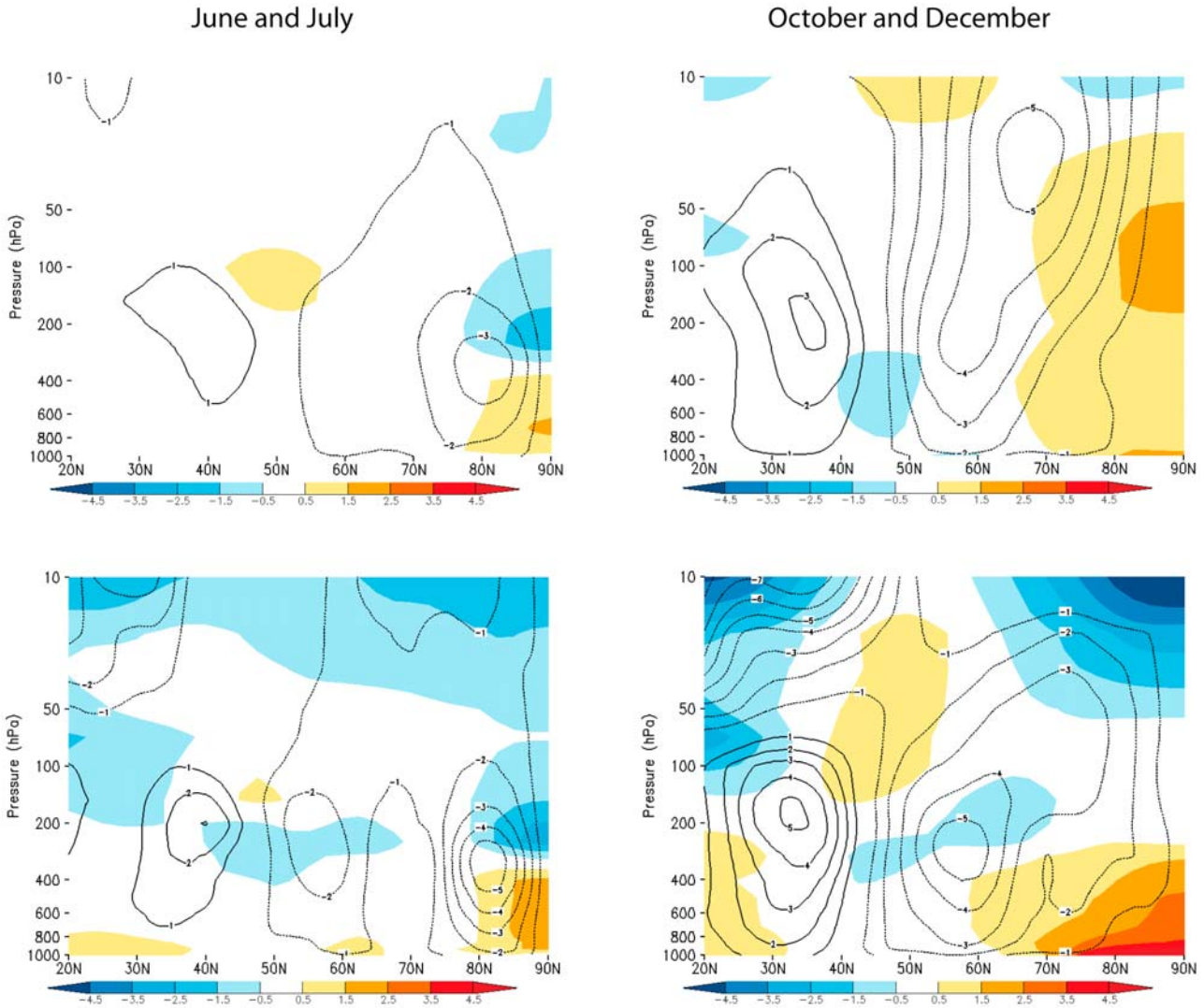

Figure 3. (top) The AO reconstruction of zonal mean temperature (shading, units are in degree Celsius) and zonal wind anomalies (contour interval is 1 meter per second) for (left) June/July 2009 and (right) October/December 2009. (bottom) Same variables as in Figure 3 (top), except showing the observations for June/July 2009 and October/December 2009. Anomalies are shown as the departure from the 1979–2000 base period mean.

and either near zero or slightly negative between these latitudes and 35°–40°N. This dipole of negative anomalies in the middle latitudes and positive anomalies in the higher latitudes is also part of the AO reconstruction. Interestingly, the average of the AO reconstructed temperature anomalies from 20°–90°N is nearly zero for JJ and OD. This neutral impact of the AO on Northern Hemisphere temperature reinforces the role of the AO as a dynamical process intrinsic to the atmosphere [e.g., *Baldwin*, 2001]. Once the linear portion of the AO signal is removed from the observed temperature anomalies, the leftover zonal-mean "residual" is positive nearly throughout the hemisphere. The temperature anomalies are especially positive north of 65°N during OD 2009 indicating that a large degree of warmth experienced at higher latitudes was linearly uncorrelated with the AO reconstruction. The positive temperature residual at higher latitudes is consistent with the expected anthropogenic warming modulated by the ice-albedo feedback mechanism [*Intergovernmental Panel on Climate Change*, 2007].

[14] Figure 3 illustrates the vertical structure during JJ and OD 2009, with the zonal-mean temperature anomalies (shaded) and zonal wind anomalies (contour) for the AO reconstruction (Figure 3, top) and for the observed data (Figure 3, bottom). During JJ 2009, the observed zonal wind and temperature anomalies corresponded well with the AO pattern of tropospherically confined anomalous easterlies and anomalous warm temperatures at higher latitudes, with cooling extending into the polar stratosphere. During OD, the AO pattern of tropospheric zonal-mean zonal wind anomalies represents a shift in the position of the mid-latitude jet. The zonal wind anomalies at higher latitudes have an equivalent barotropic structure, with zonal wind increasing with height into the stratosphere and reflecting the strength of the stratospheric polar night jet. This upward amplification is evidence of stronger linkages between the troposphere and stratosphere and is most prevalent during the winter [*Thompson and Wallace*, 2000]. However, during OD 2009, the maximum amplitude in the high latitude easterly zonal-mean zonal wind anomaly was located in the

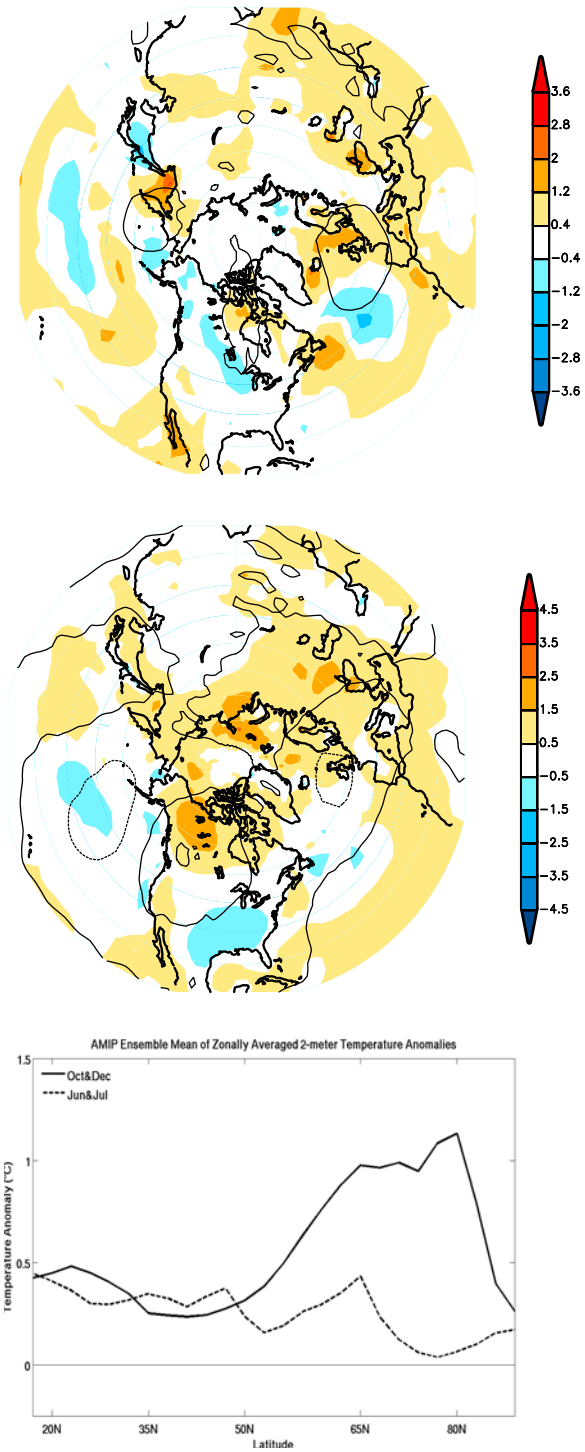

Figure 4. The average of 3 different atmospheric models forced with observed global sea surface temperatures for (top) June/July 2009 (middle) October/December 2009. Shading shows 2-meter temperature anomalies (units are in degree Celsius) and contour shows the 500-hPa geopotential height anomalies (interval is 30 meters). (bottom) Zonally average 2-meter temperature anomalies in Figures 4 (top) and 4 (middle) for June/July 2009 (dashed line) and October/December 2009 (solid line). Anomalies are shown as the departure from the 1950–2000 base period mean.

troposphere (300-hPa) indicating that the stratospheric jet was only weakly anomalous. Interestingly, the corresponding OD 2009 zonal-mean temperature anomalies at high latitudes are more reminiscent of the JJ 2009 pattern with positive anomalies in most of the troposphere and negative anomalies in the stratosphere.

[15] An El Niño episode formed during June 2009 and became strong in December 2009 (D. S. Arndt and M. O. Baringer, State of the climate in 2009, submitted to *Bulletin of the American Meteorological Society*, 2010). Figure 4 examines the possible influence of global SSTs on the observed temperature pattern using an ensemble of several atmospheric model simulations. A comparison between Figures 4 (top) and 4 (middle) (JJ and OD 2009) with Figure 2 (middle) indicates that the observed pattern of temperature and height anomalies in the middle and higher latitudes are not well replicated as a response to SSTs. In particular, the below-average temperature anomalies across North America and Eurasia are only weakly suggested, with a prevailing pattern of above-average temperatures across most of the hemisphere (also indicated by the zonal-mean temperature profiles shown in Figure 4 (bottom)). For OD 2009, below-average temperature anomalies in the southeastern United States are consistent with historical El Niño episodes [*Ropelewski and Halpert*, 1986]. While there is no known linear relationship between the AO and ENSO [*L'Heureux and Thompson*, 2006], work by *Quadrelli and Wallace* [2002] indicates the Arctic center of the AO extends further into Siberia during El Niño. This hints that, during OD 2009, the non-linear combination of the AO and ENSO may have contributed to the large amount of Arctic warmth observed near Siberia.

4. Discussion and Conclusions

[16] The four months in 2009 with exceptionally negative AO index values represent a frequency and magnitude (of negative AO values) that is unprecedented within the 60-year record. It is uncertain from this analysis how the recent negative AO values fit into the context of longer-term trends in the AO index; though we note that even with 2009 included, the 60-year linear trend of the AO index remains positive in the annual-mean and wintertime (JFM) averaged index values (not shown). Some have noted that positive trends in the wintertime AO index have diminished since the mid-1990s [*Overland and Wang*, 2005], but it is questionable whether these short-term trends rise to the level of statistical significance [*Wunsch*, 1999].

[17] Arguments have been made that the long-term positive trend in the AO index, associated with the cooling and strengthening of the stratospheric polar vortex, is evidence of external forcing by anthropogenic greenhouse gases [*Shindell et. al.*, 1999, *Miller et al.*, 2006, *Lu et al.*, 2008]. The negative temperature anomalies shown at high latitudes in Figure 3 (bottom right) are consistent with the longer-term stratospheric trends, although the cooling does not extend to the surface as would be consistent with longer-term positive trends in the surface AO index. However, other studies have suggested that additional external forcings (e.g., the melting of Arctic sea ice [*Deser et al.*, 2010; *Seierstad and Bader*, 2009], increases in snow cover [*Cohen et al.*, 2007; *Fletcher et al.*, 2007], etc.) could, paradoxically, force AO trends toward negative values. Further

attribution studies are needed to understand the relative importance of these various external forcings, their role in recent negative AO events, and their potential influence on the long-term AO trend.

[18] What is clear from the results herein is that large month-to-month swings in the AO can exert a considerable impact across the Northern Hemisphere, and at times can easily overshadow projected climate trends. In particular, during 2009, the negative phase of the AO largely contributed to below-average temperature anomalies observed over the middle latitudes and the above-average temperatures over the Arctic. However, irrespective of the deeply negative phases of the AO, the residual hemispheric temperature pattern was characterized by anomalous warmth that is consistent with the signal due to anthropogenic climate forcing.

[19] At the time of this submission, the February 2010 value of the AO represented a 61-year minimum (−2.4 standardized units).

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