A dynamical framework to understand and predict the major Northern Hemisphere mode

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[1] The dynamics of the leading mode of boreal winter and its excitation by varying boundary conditions remain mostly unclear. A novel framework is presented to explain the evolution of this dominant winter mode. It is shown that there exists a dichotomy of pathways with the characteristics of the dominant mode dependent upon the pathway taken. All winters examined fall into one of the two different dynamic evolutions presented, the knowledge of which clarifies prior uncertainties associated with the dominant mode and provides excellent potential for the successful prediction of subsequent winter mean climate states. *INDEX TERMS:* 3319 Meteorology and Atmospheric Dynamics: General circulation; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions

1. Introduction

[2] The arctic oscillation (AO) is characterized by a strong oscillation in a pressure/height center anomaly covering the entire Arctic basin, extending from the surface well into the stratosphere. At mid-latitudes an opposite pressure height anomaly stretches mostly across the two major ocean basins [*Thompson and Wallace*, 1998]. This dominant mode of winter Northern Hemisphere (NH) atmospheric pressure variability has been linked with variability in sea surface temperatures, snow cover, sea ice, stratospheric forcing and aerosols [*Kushnir*, 1994; *Rodwell et al.*, 1999; *Cohen and Entekhabi*, 1999; *Mysak and Venegas*, 1998; *Baldwin and Dunkerton*, 1999; *Shindell et al.*, 1999]. Furthermore this mode has been shown to originate in the lower troposphere in eastern Eurasia in October [*Cohen et al.*, 2001], in contrast with the demonstrated downward propagation of the mode from the stratosphere sometime after the beginning of November [*Baldwin and Dunkerton*, 1999]. We analyze daily data [*Kalnay et al.*, 1996] from two winters where strong negative AO signals were observed (about one standard deviation below normal). To emphasize dynamical characteristics rather than statistical ones, we will present results from two paradigm winters (1978/79, 2000/01) and list other years that bear resemblance to these two paradigm years. We will then conclude with a composite analysis, which will demonstrate the generality of these two winters.

2. Results

[3] We analyze pressure/height anomaly fields for horizontal and vertical propagation of anomalies influential in characterizing the dominant NH winter mode. We begin our analysis with multi-day averaged sea level pressure (SLP) anomalies starting with September 22, 2000 in Figure 1. The propagation and growth of the SLP anomaly is similar to a composited analysis for 1972–1998 [*Cohen et al.*, 2001] and consistent with the hypothesis that the winter AO signal originates in the lower troposphere in eastern Siberia during fall and is forced by snow cover variations (fall 2000, Siberian snow cover was above normal [*Robinson et al.*, 1993]). The original SLP anomaly first propagates to the west and then northward across the Arctic where at its peak it closely resembles the canonical AO pattern. From calculation of the daily AO with height [*Baldwin and Dunkerton*, 1999], the AO pattern appears to originate in the stratosphere and propagate down into the troposphere on a time scale of about two weeks during December (not shown). Therefore the winter of 2000/01 is a good example of the contradiction posed earlier, i.e., how could the AO both originate in the lower troposphere and mid-upper stratosphere?

[4] We substitute the AO diagnostic with one that is designed to capture both the hemispheric scale AO pattern of the stratosphere and troposphere, and the more regional precursor height anomaly, which originates near the surface. Because the most prominent feature of the AO pattern is a coherent and same-signed height anomaly of all regions north of 60°N [*Thompson and Wallace*, 1998], we plot the area averaged normalized height anomaly summed over every grid box of that polar cap (Figure 2a). The diagnostic is an excellent proxy for the AO, yet by eliminating all areas south of 60°N it also captures the dominant regional height anomaly at high latitudes. The downward propagation of the height anomaly corresponds well with the one shown by computing the AO. But it also clearly shows that the downward propagating anomaly indeed originated even earlier near the surface. The diagnostic nicely shows that the winter AO originated in the troposphere propagated upwards into the stratosphere and was then reflected back into the troposphere. These results are consistent for all strong AO events examined since 1968 that also show a downward propagating AO signal from the stratosphere into the troposphere.

[5] Siberia is the major source of vertical wave activity flux (WAF) for the Northern Hemisphere [*Plumb*, 1985]. The most important contribution to the variation in interannual WAF is diabatic heating, with radiational cooling enhancing the upward WAF and heating reducing the upward WAF [*Ringler and Cook*, 1999]. It has already been shown that preceding the downward propagation of the zonal wind anomalies from the stratosphere to the troposphere, associated with the winter AO, is anomalous upward WAF in the fall over Siberia [*Kuroda and Kodera*, 1999; *Saito et al.*, 2001]. Vertical propagation of anomalous wave energy is associated with planetary-scale Rossby waves [*Plumb*, 1985]. Consistent with this result, calculations of WAF anomalies [*Plumb*, 1985] for October and November 2000, shown in Panels 2b and 2c, show strong upward flux of energy originating in the lower troposphere and eventually propagating throughout the troposphere and much of the stratosphere. While in December the WAF reverses and is downward in the lower stratosphere and

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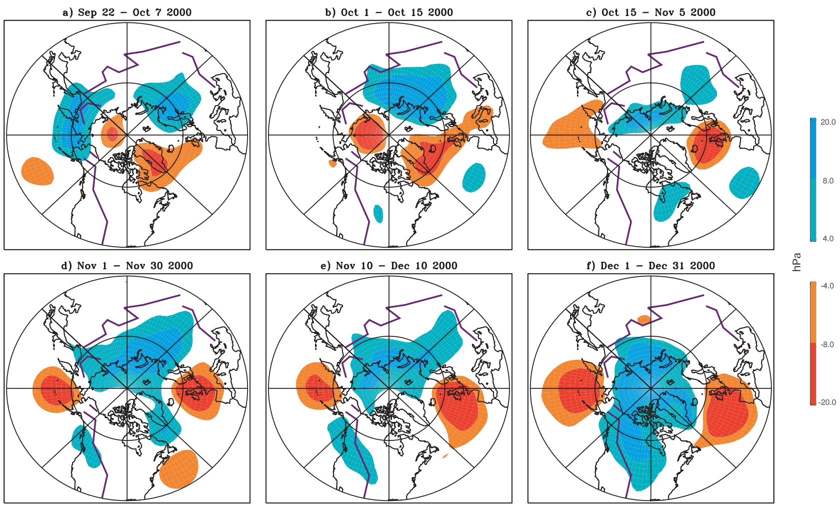

Figure 1. Maps of NH gridded SLP anomalies for (a) September 22–October 7, 2000 (b) October 1–October 15, 2000 (c) October 15–November 5, 2000 (d) November 1–November 30, 2000 (e) November 10–December 10, 2000 (f) December 1–December 31, 2000. Solid purple lines in a–e are 1000 meter isopleth. Light blue shading for anomalies ≥4 hPa and dark blue for anomalies ≥8 hPa. Orange shading for anomalies ≤−4 hPa and red for anomalies ≤−8 hPa. In supplemental data we have included an animation of the SLP anomalies from September 15, 2000–January 31, 2001.

troposphere (Panel 2d). The zonal component of the WAF shows the center of greatest flux to emanate from the region of the large SLP anomaly in Eurasia (not shown). Greater absorption of WAF in the stratosphere results in negative zonal wind anomalies, which then propagate downward as occurred in December 2000 (not shown). Positive fall SLP and lower tropospheric height anomalies supported or maintained by positive snow anomalies, are the precursors of the downward propagation of the negative winter AO signal observed. In autumns of large negative height anomalies and reduced snow cover, the upwards WAF is decreased, zonal winds in the stratosphere accelerate and downward propagation of positive zonal wind anomalies commence in the early winter.

[6] The troposphere has many more degrees of freedom than the stratosphere [*Perlwitz and Graf*, 2001]. Lower tropospheric boundaries are constrained by the existing boundary conditions and mostly remain regionalized. On the other hand, these boundaries do not exist in the stratosphere where anomalies can spread quickly and become hemispheric in scale. We propose that, in winters similar to 2000/01, the winter AO originates regionally in Eurasia and that energy from this regional anomaly propagates vertically into the stratosphere where it spreads out. Since the pattern of

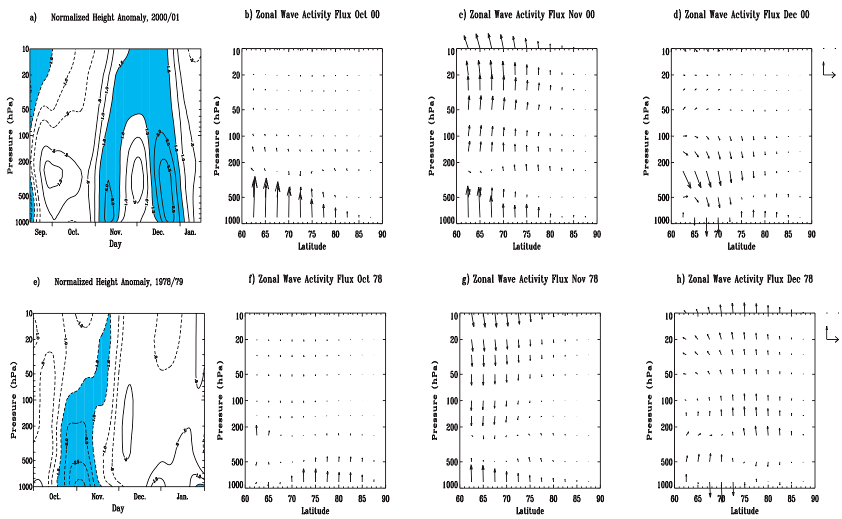

Figure 2. (a) Daily value of area-averaged normalized height anomaly for all grid points north of 60°N from September 15, 2000–January 15, 2001 (28-day filter was applied). Values greater than 1.5 and less than −1.5 are shaded blue. Note strong positive anomaly first propagates upward beginning of November and then downward from stratosphere beginning in December. (b) Zonal mean of WAF anomaly for October 2000. (c) same as (b) except for November 2000. (d) same as (b) except for December 2000. In (b) (c) and (d) value of reference arrows to right are 3.0 (meridional component) and 9.0×10^{-2} (vertical component) m^2/s^2, all values are scaled by $(pressure/150)^{1/2}$. Note strong upward flux of energy beginning in the lower troposphere in October which extends into the stratosphere in November and is then downward in December. (e) Same as (a) except for October 1, 1978–January 31, 1979. (f) same as (b) except for October 1978. (g) same as (c) except for November 1978. h) same as d) except for December 1978. Note in (e)–(h) no organized upward propagation of height anomalies or wave activity flux is observed from the troposphere into the stratosphere or vice versa.

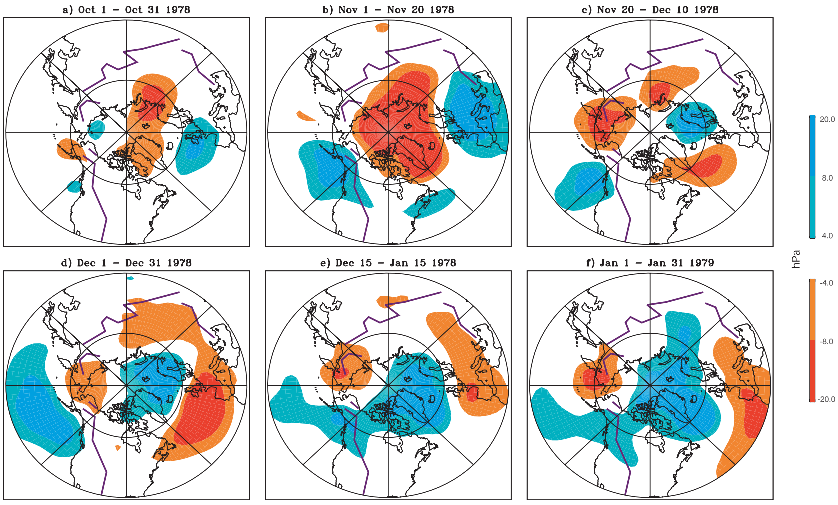

Figure 3. Maps of 20–31 daily averaged NH gridded SLP anomalies for (a) October 1–October 31, 1978 (b) November 1–November 20, 1978 (c) November 20–December 10, 1978 (d) December 1–December 31, 1978 (e) December 15–January 15, 1978/79 (f) January 1–January 31 1979. Solid purple thick lines in a–e are 1000 meter isopleth. In supplemental data we have included an animation of the SLP anomalies from October 1, 1995 to January 31, 1996 as another example of the eastward propagation of SLP anomalies which eventually grows into the observed NAO pattern for the winter of 1995/96.

variability tends to be annular in the stratosphere [*Cohen and Saito*, in Press], the descending signal from the stratotosphere to the troposphere is most likely to be annular. However as it turns out the annular mechanism is the exception rather than the rule for the formation of the winter AO.

[7] In Figure 2 we also plot the same vertical anomaly propagation diagnostics for the fall/winter of 1978/79. This time both the AO diagnostic (not shown) and the normalized height anomalies (Panel 2e), both demonstrate that the tropospheric AO anomaly is decoupled from the stratosphere. Calculations of WAF (Panels 2f–2h) and zonal wind anomalies (not shown) show little in the way of enhanced vertical propagation. In Figure 3 we plot the multi-day averaged SLP anomalies from October 1, 1978–January 31, 1979. The SLP anomaly that eventually resulted in the dominant SLP pattern for the winter propagated eastward from the North Atlantic Ocean into Eurasia. Since the SLP anomaly, which eventually formed the dominant winter AO pattern, was located in the North Atlantic region during the fall remote from Siberia, it is therefore unlikely to influence significantly the vertical WAF. Once winter begins the troposphere and stratosphere are decoupled [*Charney and Drazin*, 1961; *Kodera and Kuroda*, 2000], the AO anomaly is trapped in the troposphere and cannot communicate with the stratosphere. This isolation leads to a slower evolution and a more regional anomaly pattern. The resultant anomaly pattern rather than being annular, more closely resembles the pattern of variability associated with the North Atlantic Oscillation (NAO).

3. Discussion and Conclusion

[8] We analyzed the evolution of SLP/height anomalies of every winter since 1972/1973 and also included the two strong AO winters of 1965/66 and 1968/69. Winters were then categorized (N or A) according to similarity with the paradigm winters of 1978/79 and 2000/01. In the more common type, the SLP anomaly propagates upstream from the North Atlantic or North America into Eurasia, and because the antecedent anomaly originates remote from Siberia it does not influence the stratosphere, is therefore trapped in the troposphere during the winter months, evolution is slower, and the pattern is more regionalized. The resultant pattern is more likely to resemble the NAO pattern of variability (Type N), and the associated climate anomalies are more likely to be focused in western Eurasia and the North Atlantic. In the second type, the SLP anomaly propagates downstream from eastern Siberia into central Eurasia (in some years this anomaly combines with an already existing anomaly to the west, as happened in the fall of 2000). Because the anomaly forms in Siberia it is most likely to propagate vertically from the troposphere into the stratosphere, which results in a downward propagation of energy from the stratosphere. As the anomaly descends from the stratosphere to the troposphere the SLP anomaly is quickly pulled across the polar cap into North America. This AO or annular pattern of variability (Type A), and the associated climate anomalies are more likely to be focused in eastern Eurasia and eastern North America.

[9] In Table 1 we list all winters analyzed according to type and highlight strong positive and negative phases in each category with a plus or minus sign accordingly. From Table 1 it is apparent that Type N occurs in greater frequency. Yet since 1972 the stronger events have been overwhelmingly Type A. Also there has been a definite trend of less Type N and more Type A strong events since 1960; there has not been a strong Type N event since 1985. We calculate in Figure 4 the first EOF of

Table 1. List of Type N and Type A Events of AO DJFs During 1972/73–2000/01

Dynamic Type of AO	Years
Type N events:	1965–, 1968–, 1972+, 1973, 1974, 1977, 1978–, 1980, 1981, 1982, 1983*, 1985–, 1986, 1987*, 1989*, 1990*, 1993, 1994*, 1995*, 1996*, 1997*, 1998*, 1999
Type A events:	1975+, 1976–, 1979, 1984–, 1988+, 1991+, 1992+, 2000–

Also included are two strong events from the 1960's–1965/66 and 1968/69. DJF listed under same year as December (e.g., DJF 1972/73 listed under calendar year 1972). Type N and Type A events are described in text. Strong events (± one standard deviation) are denoted by ± depending on phase. Some events which displayed elements of both type of events are denoted with an asterisk.

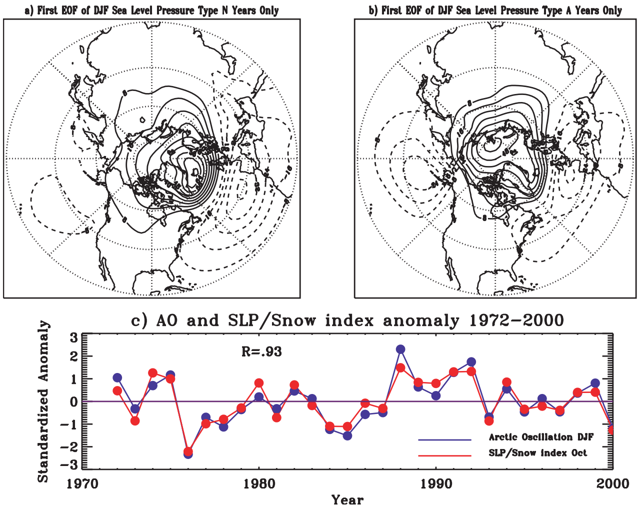

Figure 4. The leading mode of DJF monthly SLP variability for (a) all winter months from the years listed in Table 1 as Type N (including all winter months from December 1960 thru February 1972) and (b) all winter months from the years listed in Table 1 as Type A. (c) Standardized DJF time series of the principal component of the leading mode of SLP variability for all winters since 1972/73 (DJF AO, in blue) and a SLP/snow index derived from the linear combination of October SLP anomalies and snow cover area anomalies (Oct SLP/Snow index in red). Correlation between two time series is also shown.

monthly SLP since 1960 grouped solely by Type N (Panel 4a) and Type A (Panel 4b), with no other manipulation of the data. The pattern of variability in Type N years is most closely associated with that of the NAO; involving signals in the North Atlantic and western Eurasia with little in the Pacific or annularity. The pattern of variability for Type A years is most closely associated with that of the AO, where the variability in the North Pacific closely resembles the one in the North Atlantic, giving the appearance of zonal symmetry or annularity.

[10] Finally in Figure 4c we create an index using Siberian snow cover and NH SLP anomalies from October [*Cohen et al.*, 2001] and correlate it with the following December, January and February (DJF) AO. SLP anomalies were chosen from eastern Eurasia preceding a Type A event and from the North Atlantic and North America preceding a Type N event. The correlation between the two indices is 0.93. Forecasting a Type N or Type A appears relatively simple. The default is the more common Type N. Type A events require an organized SLP anomaly in eastern Siberia, which propagates westward. Figure 4c suggests that forecasting mean NH winter conditions may be no more difficult than short-range weather forecasting, with comparable skill.

[11] Until now predictability of the NAO/AO has been poor due to the blending of two different dynamical evolutions. Recognizing their distinctive dynamical frameworks will lead to better understanding of past and forecasts of future winter states.

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References

Baldwin, M. P., and T. J. Dunkerton, Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, *104*, 30,937–30,946, 1999.

Charney, J. G., and P. G. Drazin, Propagation of planetary-scale disturbances from the lower into the upper atmosphere, *J. Geophys. Res.*, *66*, 83–109, 1961.

Cohen, J., and D. Entekhabi, Eurasian snow cover variability and Northern Hemisphere climate predictability, *Geophys. Res. Let.*, *26*, 345–348, 1999.

Cohen, J., K. Saito, and D. Entekhabi, The role of the Siberian high in Northern Hemisphere climate variability, *Geophys. Res. Let.*, *28*, 299–302, 2001.

Cohen, J., and K. Saito. A test for annular modes. *J. Climate*, in Press.

Kalnay, E., et al., The NCEP/NCAR 40-Year reanalysis project, *Bull. Amer. Meteor. Soc.*, *77*, 437–471, 1996.

Kodera, K., and Y. Kuroda, Tropospheric and stratospheric aspects of the Arctic Oscillation, *Geophys. Res. Let.*, *27*, 3349–3352, 2000.

Kuroda, Y., and K. Kodera, Role of planetary waves in the stratosphere-troposphere coupled variability in the Northern Hemisphere winter, *Geophys. Res. Let.*, *26*, 2375–2378, 1999.

Kushnir, Y., Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions, *J. Climate*, *7*, 141–157, 1994.

Mysak, L. A., and S. A. Venegas, Decadal climate oscillations in the Arctic: A new feedback loop for atmosphere-ice-ocean interactions, *Geophys. Res. Let.*, *25*, 3607–3610, 1998.

Perlwitz, J. and H.-F. Graf, The variability of the horizontal circulation in the troposphere and stratosphere—a comparison, *Theor. Appl. Climat.*, *69*, 149–161, 2001.

Plumb, R. A., On the three-dimensional propagation of stationary waves, *J. Atmos. Sci.*, *42*, 217–229, 1985.

Ringler, T. D., and K. H. Cook, Understanding the seasonality of orographically forced stationary waves: Interaction between mechanical and thermal forcing, *J. Atmos. Sci.*, *56*, 1154–1174, 1999.

Robinson, D. A., F. Dewey, and R. Heim, Jr., Northern Hemispheric snow cover: An update, *Bull. Amer. Meteor. Soc.*, *74*, 1689–1696, 1993.

Rodwell, M. J., D. P. Rowell, and C. K. Folland, Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature*, *398*, 320–323, 1999.

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.

Shindell, D. T., R. L. Miller, G. A. Schmidt, and L. Pandolfo, Simulation of recent northern winter climate trends by greenhouse-gas forcing, *Nature*, *399*, 452–455, 1999.

Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Let.*, *25*, 1297–1300, 1998.

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