Sub-Monthly Polar Vortex Variability and Stratosphere-Troposphere Coupling in the Arctic

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July 2008
Submitted to Journal of Climate.

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**ABSTRACT**

A principle component analysis is performed to characterize intraseasonal variability in the boreal stratospheric polar vortex. Compared to previous studies, the current analysis examines daily zonal-mean variability within a limited spatial domain encompassing the stratospheric polar vortex. The leading EOFs are vertically coherent north-south dipoles in zonal-mean zonal wind extending through the lower stratosphere. The first mode (denoted SNAM) represents variability in polar vortex strength and is highly correlated with the stratospheric NAM. The second mode, denoted the Polar Annular Mode (PAM), represents variability in the latitudinal position of the polar vortex and possesses a poleward-retracted dipole anomaly structure. Composite analyses indicate that large amplitude PAM events are relatively short-lived (1-2 weeks) compared to SNAM events (1 month or longer). Trend analyses further reveal that recent decadal trends in the boreal polar vortex project more strongly onto PAM than SNAM.

Composite analyses illustrate that the time evolution of sudden stratospheric warming events is dominated by SNAM whereas SNAM and PAM play approximately equal roles in final warming events. Linear regression analyses reveal that SNAM and PAM result in circumpolar circulation and temperature anomalies of similar magnitudes within the high latitude troposphere. It is concluded that PAM represents a previously unrecognized annular mode that strongly couples the stratosphere and troposphere on submonthly time scales at mid to high latitudes. It is further suggested that the SNAM/PAM framework provides a means for isolating the proximate tropospheric response to respective variations in the strength and position of the stratospheric polar vortex.
1. Introduction

It is now well-established that robust stratosphere-troposphere coupling occurs during boreal winter in connection with intraseasonal variations in the Northern Annular Mode (NAM - Thompson and Wallace 1998; Baldwin and Dunkerton 2001; McDaniel and Black 2005). This coupling is associated with a vertically coherent zonal wind anomaly pattern extending from the Earth’s surface upward into the middle stratosphere. At stratospheric altitudes the NAM is manifested by variations in the strength of the stratospheric polar vortex (“pulsing”) while at tropospheric altitudes the NAM is interpreted as a north-south “wobble” in the position of the midlatitude jet stream (Wittman et al. 2005). The NAM is linked to important large-scale circulation anomalies in the extratropical troposphere impacting regional weather conditions (Thompson and Wallace 2001).

Although midwinter weakenings of the polar vortex, known as sudden stratospheric warming (SSW) events, are linked to intraseasonal NAM variability (Limpasuvan et al. 2004) this relationship is not one-to-one (Charlton and Polvani 2007). Furthermore, there are distinctions among SSW events in their respective impact the stratospheric polar vortex. Charlton and Polvani (2007) find that just under 50% of SSW events result in a “splitting” of the polar vortex (wavenumber 2) while the remainder lead to polar vortex “displacement” (wavenumber 1). Vortex splitting events are typically preceded by a period of stratospheric “preconditioning” during which time the polar vortex strengthens and retracts poleward. Interestingly, the net tropospheric impact of SSW events is nonetheless found to be similar for splitting and displacement events (Charlton and Polvani 2007).

In addition to midwinter polar vortex weakenings, each winter season concludes with a rather abrupt transition from circumpolar stratospheric westerly winds to easterlies. This
annual breakdown of the polar vortex is known as the stratospheric final warming (SFW). A recent observational study of SFW events found that these events strongly organize the large-scale circulation of the stratosphere and troposphere (Black et al. 2006; hereafter BMR). Specifically, SFW events are associated with a vertically coherent north-south dipole pattern in the zonal wind anomaly field at mid to high latitudes. However, this pattern is distinct from the canonical NAM structure as the primary centers in the north-south anomaly dipole are retracted northward compared to the NAM.

SFW events exhibit a robust bi-directional dynamical coupling of the stratosphere and troposphere (Black and McDaniel 2007). The evolution is characterized by an anomalous upward Eliassen-Palm (E-P) signature at high latitudes extending from the surface to the middle stratosphere. This is followed by direct and indirect feedbacks, respectively, of the stratospheric annular circulation upon the high latitude troposphere (Black and McDaniel 2007). As for SSW splitting events, SFW events are preceded by a preconditioning of the stratospheric zonal-mean flow. Conversely, the zonally-asymmetric (wave) evolution of SFW events (characterized by a strong wavenumber 1 component) more closely resembles SSW displacement events. Thus, SFW events have notable structural and dynamical distinctions from both SSW events and subseasonal NAM variability.

Studies of long-term variability in Arctic climate have revealed a paradox in which there has been an apparent decoupling between the Arctic Oscillation (AO - the near-surface manifestation of NAM) and high latitude climate (Overland and Wang 2005), which were previously considered to be intrinsically linked (e.g., Thompson et al. 2000). This leaves residual high latitude climate variability that is unaccounted for by the primary extratropical modes of climate variability such as the AO/NAM and Pacific-North American pattern (e.g.,
Recent studies of highlatitude tropospheric climate variability reveal the existence of higher-order annular modes (e.g., the “central Arctic” pattern of Maslanik et al. 2007; Arctic mode RPC2 of Bromwich and Wang 2008) that provide important impacts upon Arctic climate. Similar to SFW events, these modes are more circumpolar and northward retracted in comparison to the canonical AO/NAM signatures.

The results discussed above indicate that SFW (and some SSW) events may be linked to distinct and previously unrecognized annular modes of variability at high latitudes, with potential implications for Arctic climate. Here we explore this idea more rigorously by characterizing the primary modes of intraseasonal variability in the wintertime stratospheric polar vortex. In contrast to previous studies (Nigam 1990; Lorenz and Hartmann 2003; Itoh and Harada 2004; Song et al. 2006), the current analysis concentrates on zonal-mean variability on short (daily) time scales within a limited spatial domain (the lower stratosphere at high latitudes) encompassing the stratospheric polar vortex. This analysis leads to the identification of a previously unrecognized intraseasonal annular mode that is orthogonal to the stratospheric NAM and strongly couples the stratosphere and troposphere on submonthly time scales at mid to high latitudes. Regression analyses reveal that this mode induces circumpolar circulation and temperature anomalies within the high latitude troposphere. Our paper follow the following structure: Section 2 outlines the details of our methodological approach, the fundamental structures and vertical connections are presented in Section 3, the statistical robustness of our fundamental results is tested in Section 4, while variability on intraseasonal and interannual time scales is examined in Sections 5 and 6, respectively. Finally, a summary and concluding remarks are provided in Section 7.
2. Data and Methods

The basic dataset employed consists of 49 years (1958-2006) of NCEP-NCAR daily-average reanalyses (Kalnay et al. 1996) archived on 17 pressure levels extending from 1000 hPa to 10 hPa. Daily anomalies in the field variables are taken as deviations from a smoothed climatological trend (itself defined as the sum of the first 6 Fourier harmonics of a seasonal cycle derived from a calendar time-series of long-term daily means). Daily variability in the polar vortex is characterized by performing a principle component (PC) analysis of daily anomalies in zonal wind and geopotential height. We first consider anomalies in the zonal-mean zonal wind field in the lower stratosphere at high latitudes. More specifically, we perform the PC analysis over a domain (illustrated graphically in Fig. 1c) encompassing the polar vortex in the lower stratosphere (from 45°N to 90°N and 100-10 hPa). The analysis considers the months of January through April, during which time the polar vortex is highly variable and most SFW events typically occur (BMR). The input zonal wind anomalies are weighted latitudinally (by square root of the cosine of latitude) and normalized in the vertical (by the long-term and areal average standard deviation at each level, following Baldwin and Dunkerton 1999). A principle component analysis is then performed to identify the dominant empirical orthogonal functions (EOFs) and PC time series.

The resulting PC time series for each EOF is normalized for the same time period (January through April) and then used as a basis for performing composite, linear regression, power spectrum and trend analyses. In pursuing the composite analyses, discrete events are identified using running 5-day means of the respective PC time series. Otherwise, all of the analyses presented and discussed employ unfiltered daily anomalies in the field variables considered. The statistical significance of linear regression analyses are assessed using a 2-
sided t-test (e.g., Robinson et al. 2006). The robustness of the basic PC results are tested by performing a series of sensitivity analyses that examine the dependence upon (a) the spatial domain specification (with respect to latitude and pressure), (b) the field variable analyzed (zonal wind versus geopotential height) and (c) the use of zonal-mean versus zonally-varying quantities. To facilitate direct comparisons with canonical NAM variability, we also derive a separate daily NAM index for each vertical level (as in Baldwin and Dunkerton 2001). This involves first identifying EOFs from the low frequency intraseasonal height anomaly field and then projecting the daily height anomalies upon the leading EOF (NAM).

3. Fundamental structures and tropospheric connections

The leading eigenvectors of the EOF analysis of daily zonal-mean zonal wind account for 71% and 15% of the respective variance in the high latitude stratosphere. EOF2 is well-separated from the EOF3 which explains 5% of the total variance. The representative zonal-mean zonal-wind anomaly structures for the first two EOFs are obtained by regressing the daily zonal wind anomaly field against the respective normalized PC time series for JFMA (Fig. 1). EOF1 is a prominent north-south anomaly dipole in the stratospheric zonal wind field with a nodal line in midlatitudes. Both anomaly features have significant extensions down into the troposphere. The pattern in the high latitude stratosphere strongly resembles the NAM (especially at upper levels), and primarily acts to modify the polar vortex strength (contrast Figs. 1a and 1c). Further, the PC time series for EOF1 is highly correlated with the stratospheric NAM (e.g., correlation of 0.97 with 50 hPa NAM). However, the tropospheric zonal wind anomaly pattern corresponds less well to the canonical NAM structure (e.g., Fig. 7d of Thompson and Wallace 2000). Given the strong correspondence with the canonical stratospheric NAM, here we refer to EOF1 as the
stratospheric NAM pattern (or SNAM).

The structure of EOF2 exhibits strong parallels with EOF1 except that the north-south anomaly dipole pattern is retracted substantially northward. The northern pole achieves maximum amplitude between 70°N and 80°N, whereas the southern pole is concentrated in midlatitudes. Interestingly, these latitude bands overlap the key latitude bands in which BMR observed strong zonal wind changes during SFW events. We note prominent and statistically significant downward extensions of the dipole pattern into tropospheric altitudes, especially for the northern pole. In fact, it is interesting to note that the zonal wind signature in the high latitude troposphere is actually larger in amplitude than its EOF1 counterpart (compare Figs. 1a & 1b), in stark contrast to the respective stratospheric signatures. The nodal line for EOF2 is approximately aligned along the axis of the polar vortex. Thus, in contrast to EOF1, EOF2 represents north-south excursions in the polar vortex position as might occur in association with stratospheric “preconditioning” (Andrews et al. 1987). This behavior is illustrated in Fig. 2 which shows the typical net impact of the two opposing phases of EOF2 upon the total zonal wind field. We note there is a 10° latitudinal shift in the polar vortex position between the positive and negative phases of EOF2. An analysis of the respective time series reveals, as anticipated, that EOF2 is effectively uncorrelated with the canonical stratospheric NAM (correlation of less than 0.05). Consequently, EOF2 is a newly identified annular mode that (a) extends over stratospheric and tropospheric altitudes, (b) is distinct from the stratospheric NAM, and (c) exhibits a robust circumpolar circulation with a downward extension in the high latitude troposphere. Here we will refer to EOF2 as the Polar Annular Mode (PAM).

As discussed above we ascribe the respective behavior of the SNAM and PAM
patterns as representing variability in the strength (pulsing) and position (wobbling) of the stratospheric polar vortex. We earlier noted that the interpretation of the canonical NAM’s role in the stratosphere is different from its tropospheric impact, where it is considered to modulate the position of the midlatitude (eddy driven) tropospheric jet. Thus, the respective roles of SNAM and PAM in polar vortex variability represent a reordering of the canonical paradigm for the impact of leading annular modes upon the extratropical troposphere (Lorenz and Hartmann 2003; Wittman et al. 2005). The fact that the canonical tropospheric NAM pattern is distinct from the SNAM pattern exhibited in Fig. 1a is consistent with the idea that, during periods of stratosphere-troposphere NAM coupling, the tropospheric NAM represents, at least in part, an internal tropospheric response to stratospheric NAM variability. As such, the tropospheric portion of the EOF1 pattern likely more closely represents the direct impact of the stratospheric NAM upon the troposphere (e.g., McDaniel and Black 2005).

The statistical relationship between the stratospheric and tropospheric NAM is further explored in Fig. 3, which displays vertical profiles of the daily temporal correlation between different stratospheric-based NAM measures (including SNAM) and the canonical NAM time series for each vertical level. For example, the red line is the correlation between the 10 hPa canonical NAM time series and the canonical NAM time series at all other vertical levels (resulting in a value of 1.0 at 10 hPa with a monotonic decrease below). Other stratospheric NAM measures considered are the 50 hPa canonical NAM time series (blue), a vertical average of the canonical NAM time series (gold) over the lower stratosphere (from 10 - 100 hPa) and the SNAM time series (purple). We first note that the respective vertical profiles for SNAM, the vertically averaged NAM, and the 50 hPa time series are
very close to one another (with the latter two virtually identical), achieving peak correlations near 50 hPa. Except for 10 hPa curve, all the correlation profiles exceed 0.85 above 150 hPa, suggesting a strong linkage between each time series and the canonical NAM in the lower stratosphere. All the correlation profiles then drop precipitously (by 0.4 or more) between 100 hPa and 300 hPa, which encompasses the tropopause layer. Below 300 hPa all the correlation profiles are less than 0.5 but are relatively uniform. The 10 hPa profile nears 0.2 while the other three curves fall in between 0.4 and 0.5. Considering the 10 hPa NAM time series as representing mid-stratospheric NAM behavior, our correlation results indicate the following behavior for day-to-day variability in the NAM:

1) Strong vertical coherence in the lower stratosphere
2) Substantial decoupling across the tropopause
3) Vertically uniform impact of SNAM upon tropospheric NAM
4) Mid-stratospheric NAM poorly correlated with tropospheric NAM
5) SNAM accounts for less than 25% of daily tropospheric NAM variability

A key result is that daily stratospheric and tropospheric NAM variability is largely decoupled, consistent with the above idea that the proximate tropospheric manifestation of SNAM (as revealed in Fig. 1a) differs from the canonical tropospheric NAM pattern.

We next consider the impact of PAM upon the zonal-mean tropospheric circulation. In addition to directly impacting the latitudinal position of the stratospheric polar vortex, Fig. 2 reveals that the opposing phases of PAM provide substantial alterations to the zonal-wind structure in the vicinity of the tropopause at mid to high latitudes. In particular, the positive (negative) PAM phase is characterized by a relatively weak (strong) meridional gradient in zonal wind along the tropopause north of 50°N. This difference is quite dramatic and is very
likely to impact both the forcing and propagation of tropospheric Rossby wave activity.

We next isolate the regional (zonally varying) manifestations of SNAM and PAM by performing linear regression analyses of the SNAM and PAM indices against geopotential height and near-surface temperature fields (Fig. 4). The analysis of the 50 hPa height field reveals largely zonally symmetric anomaly structures for both SNAM and PAM. For each EOF, the positive phase is associated with circumpolar negative height anomalies that are surrounded by positive height anomalies at lower latitudes. The main structural difference is that the PAM anomaly pattern is retracted poleward relative to the SNAM pattern, as would be expected from a consideration of Fig. 1 (in association with geostrophic balance). Also, the SNAM anomaly magnitudes are much larger than those for PAM. The parallel analysis for 500 hPa geopotential height shows qualitatively similar patterns with (a) less zonal symmetry than at 50 hPa and (b) comparable magnitudes. Again, the latter feature is consistent with the results presented in Fig. 1. A comparison of the tropospheric expression of SNAM with the canonical tropospheric NAM (e.g., Fig. 1 of Baldwin and Dunkerton 1999) reveals that the main structural difference is in the relative strength of the North Atlantic anomaly centers, which are less prominent (versus the polar center) in the current analysis. Although the respective Arctic anomaly centers have similar magnitudes in the two analyses, the local height anomaly minimum over southern Greenland is ~65% larger in magnitude in the canonical pattern. This is consistent with the idea that the tropospheric adjustment to stratospheric NAM events is concentrated over the North Atlantic region.

The regression analysis for near-surface temperature field (third row in Fig. 4) shows that positive SNAM and PAM events result in polar cooling and Northern Siberian warming
of similar magnitudes. For PAM the polar cooling is relatively axisymmetric over the Arctic while for SNAM the cooling is shifted westward with a prominent extension to the west of Greenland. Although relatively weak, the two modes are associated with oppositely signed temperature anomalies over the eastern continental US. Finally, we note that the SNAM pattern found here is qualitatively consistent with the canonical tropospheric NAM result (Fig. 1 of Thompson and Wallace 1998). The main difference is the relative weakness in magnitude of the temperature anomaly pattern in the current analysis. The analyses presented here reveal that the SNAM and PAM events induce large-scale tropospheric circulation anomaly patterns having (a) distinct spatial patterns and (b) similar amplitudes. This suggests that, in terms of direct impacts, first order variations in both the strength and position of the stratospheric polar vortex provide comparable alterations to the tropospheric circulation. However, these impacts have differing spatial patterns and time scales. Further, it is apparent that the net tropospheric response to the stratospheric NAM includes an indirect response that is concentrated over the North Atlantic region.

4. Sensitivity analyses

We next examine the robustness of our fundamental results by performing sensitivity tests for the principle component analysis. We first test the dependence upon spatial domain specification by separately (a) extending the lower latitude boundary to 20°N (from 45°N) and (b) limiting our analysis to a single vertical level (50 hPa) within the domain of interest (but keeping the lower latitude boundary fixed at 45°N). The PC analysis is then repeated for the daily zonal-mean zonal wind anomaly field. A third test uses the original spatial domain (Fig. 1c) but applies the PC analysis to the daily zonal-mean geopotential height anomaly field. In all three cases we then repeat the linear regression calculations presented
in Fig. 1a and 1b for the first two EOFs. The resulting zonal-mean zonal wind patterns are presented in Fig. 5 (where SNAM and PAM are still used to indicate the first and second EOFs, respectively). In each of the three test cases the patterns associated with the leading EOFs are remarkably similar in both structure and magnitude to those identified in our baseline case (presented in Fig. 1). The primary difference is that the PAM pattern emerging from the third sensitivity analysis (based upon geopotential height) exhibits somewhat less poleward retraction. We conclude that our zonal-mean PC analyses are not sensitive to the details of either our spatial domain specification or the input field variable considered.

It is of further interest to study whether or not we can reproduce our results from a consideration of zonally-varying stratospheric anomaly fields on a single vertical level. To test this we perform an additional sensitivity test in which we perform a PC analysis of the zonally-varying height anomaly field at 50 hPa (with latitudinal boundaries as in our baseline case). Since, in this case, we are permitting zonal asymmetry we expect to obtain prominent modes having wavelike structure with respect to longitude. These are required in order to fully describe spatial variability associated with the vertical propagation of planetary waves through the lower stratosphere. Indeed, we obtain 6 statistically distinct EOFs in this analysis (North et al. 1982) and several of the leading modes are characterized by either planetary wavenumber 1 (EOF modes 2 and 3) or 2 (EOF modes 4 and 5). Nonetheless, both EOF 1 and 6 exhibit strongly zonally symmetric anomaly structures at 50 hPa. Linear regression results are presented for these two modes in Fig. 6. Although there are certainly differences in regional detail, the regression results bear a striking resemblance to the parallel baseline analyses of the zonal-mean flow presented in Figs. 1 and 4. In particular, the zonal mean manifestation of EOF 6 (Fig. 6: third row, right panel) closely resembles the
PAM anomaly structures identified in the 4 other EOF analyses (Figs. 1b, 5d, 5e and 5f). Furthermore, the PC time series for EOF 6 has a correlation of 0.8 with the baseline PAM PC time series. We conclude that PAM-like anomaly structure emerge from a consideration of zonally-varying stratospheric anomaly fields in addition to zonal-mean anomaly fields.

5. Intraseasonal variability and role in stratospheric warming events

We next examine the characteristic temporal variability of the SNAM and PAM. To identify the characteristic subseasonal times scales, we first perform a spectral decomposition (via a fast fourier transform analysis) of the unfiltered PC time series for both SNAM and PAM (Fig. 7). Although no significant spectral peaks are identified, it is nonetheless evident that PAM (SNAM) has more power at shorter (longer) intraannual time scales. PAM is dominant at periods less than 50 days while SNAM dominates at periods greater than 100 days. The two modes exhibit more equitable power in between these two bounds.

A similar dichotomy exists in the respective behavior of discrete SNAM and PAM episodes which is studied via composite analyses of the PC time series. We first study events for which SNAM and PAM occur independently. To do this, we identify times (onset or lag 0) when the 5-day running mean of either index first exceeds (falls below) $+1\sigma$ ($-1\sigma$) without a corresponding threshold crossing in the other index within an ensuing 10 day period. We further require events within each of the four classes to be separated by 30 days. This result in 47 (48) positive (negative) SNAM events and 77 (69) positive (negative) PAM events.

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Although, strictly speaking, such an analysis includes information about SNAM and PAM outside of JFMA, the spectrum is dominated by variability within JFMA.
Respective lag composite analyses of the PC time series for each event category are shown in Fig. 8a-b. Positive SNAM events are characterized by a relatively gradual development and decay with index values remaining above $+0.5\sigma$ for a period of $\sim$60 days. Although negative SNAM events develop more rapidly, they remain below $-0.5\sigma$ until 30 days after onset. In contrast to SNAM events, PAM events develop and decay relatively quickly, with index magnitudes remaining above $0.5\sigma$ for less than two weeks. Thus, a key result is that the characteristic time scale for discrete PAM events is on the order of 1-2 weeks, which is considerably shorter than that of the SNAM. As such, PAM variability is not only inherently intraseasonal but also includes a substantial submonthly component. Consequently, PAM-type variability is likely to be less evident (or even absent) in similar analyses of monthly mean anomalies (this issue was anticipated by Nigam 1990).

We also identify episodes for which like-signed SNAM and PAM events occur at the same time. These are selected to be times when both PC time series first exceed (fall below) $+1\sigma$ ($-1\sigma$). As above, we also require like-signed events to be separated by 30 days leading to 22 (30) positive (negative) events. The respective lag composite analyses are shown in Fig. 8c-d. Interestingly, the simultaneous occurrence of positive PAM and SNAM events strongly accelerates SNAM decay relative to its occurrence in isolation (Fig. 8a). This juxtaposition of stratospheric zonal circulation anomalies represents a strengthening and poleward shift of the stratospheric polar vortex. This corresponds to the behavior associated with stratospheric preconditioning (which is thought to predispose the stratosphere to SSW events, Andrews et al. 1987). Although less pronounced, similar behavior is observed during simultaneous occurrences of negative SNAM and PAM events (Fig. 8d).

We next investigate the relative roles of SNAM and PAM patterns in the evolution
of SSW and SFW events. This is done by simply compositing the SNAM and PAM PC time series with respect to SFW and SSW onset (Fig. 8e-f). We use the 27 SSW events identified in Charlton and Polvani (2007) and 47 SFW events considered by BMR. The lag composite analyses reveal that the development and onset of SSW events is dominated by SNAM variability, with the SNAM index dropping below -1.5σ during SSW onset. Both the SNAM and PAM indices exhibit positive tendencies after SSW onset, during which time the polar vortex recovers in strength. We note that PAM appears to lead in this process, indicating that the stratospheric polar vortex recovers more quickly at higher latitudes after SSW events.

In contrast to SSW events, both SNAM and PAM play approximately equal roles in the development, onset, and decay of SFW events. In particular, we note that SFW events have a precursor evolution qualitatively mimicking the behavior of the simultaneous positive SNAM and PAM events in Fig. 8c. It is evident that the newly identified PAM pattern plays a first order role in SFW events, consistent with the observation by BMR that SFW events have important distinctions from the (stratospheric or tropospheric) NAM. Last we separate our SSW composite time series analysis into SSW split events (12) and displacement events (15), following the designations of Charlton and Polvani (2007). These results (Figs. 8g-h) indicate that PAM appears to play a larger role in the early stages of split-type SSW events compared to the displacement events. This is consistent with Charlton and Polvani’s finding that SSW splitting events are associated with a pronounced preconditioning of the stratospheric polar vortex.
6. Interannual variability and long-term trends

It is also of scientific interest to study the respective roles of SNAM and PAM in the modulation of the polar vortex on longer time scales. This is motivated partly in response to the Arctic climate paradox discussed in the Introduction. There is increasing interest in the potential role of the stratospheric circulation in modulating long-term climate variability (e.g., Son et al. 2008). In the Northern Hemisphere, the polar vortex-climate connection is anticipated to be strongest during the cool season, when stratosphere-troposphere dynamical coupling is most active (Baldwin et al. 2003). As such, interannual variability in the boreal winter polar vortex has the potential to impact Arctic climate on interannual and longer time scales. In response to the above issues, we perform an exploratory analysis of the long-term variability in the stratospheric polar vortex, phrased in terms of the leading EOFs obtained from our PC analysis. Fig. 9 shows the respective interannual anomalies in the SNAM and PAM PC time series (where each data point represents the JFMA average anomaly for the calendar year). For comparison, the SNAM PC time series is directly contrasted with the analogous time series for the canonical 50 hPa NAM (Baldwin and Dunkerton 2001). There are several points to note regarding the year-to-year variability in SNAM/NAM:

1) SNAM and the canonical 50 hPa NAM track each other very well
2) Both series reveal a long-term NAM trend between ~1970 and ~1995 (as discovered by Thompson et al. 2000)
3) There is a dramatic reversal in this trend in more recent years
4) Over the 49 year time period considered, neither SNAM or the canonical 50 hPa NAM has a statistically significant trend

In contrast to SNAM, the year-to-year variability in the PAM index includes a
statistically significant (at the 99% confidence level) trend in which PAM has shifted from a positive phase toward a more predominantly negative phase (Fig. 9b). This trend is consistent with a long-term southward shift in (and high latitude weakening of) the polar vortex (recall Fig. 2b) over the past 50 years. To further explore the role of SNAM and PAM structures in the long-term trend of the stratospheric polar vortex, we next decompose existing trends in the zonal-mean zonal wind into parts linearly congruent with either SNAM or PAM (following the methods of Thompson et al. 2000). The linear trend and interannual standard deviation in zonal-mean zonal wind are displayed in the top panels of Fig. 10. Although the trend pattern at sub-tropical latitudes is rather noisy (and associated with a large standard deviation), at higher latitudes within the stratosphere there is a coherent north-south dipole pattern of zonal accelerations (decelerations) at middle (high) latitudes. Again, this zonal wind anomaly pattern is consistent with a southward shift in the stratospheric polar vortex. To explore this further, we use the results of our PC analysis in order to determine the respective contributions of SNAM and PAM to the long-term trend pattern (in the parlance of Thompson et al. we assess the trend components that are “linearly congruent” with SNAM and PAM, respectively). These results are displayed in the bottom frames of Fig. 10. Although SNAM appears to provide a weak long-term strengthening of the polar vortex, the long-term trend pattern has more strong associations with the negative phase of the PAM pattern. We conclude that PAM plays a major role in describing the long-term trend in the boreal stratospheric polar vortex, which is characterized by a modest southward shift in the polar vortex location. Thus, PAM (and/or the latitudinal position of the boreal polar vortex) may be an important stratospheric signature to look for in climate change “fingerprinting” (as most studies focus on long-term variability in the behavior of NAM).
7. Conclusions

Intraseasonal variability in the boreal stratospheric polar vortex is characterized using an principle component (PC) analysis of daily anomalies in the zonal-mean zonal wind field within the high latitude lower stratosphere. The leading modes are found to be associated with vertically coherent north-south dipoles in the zonal wind field extending from the mid-stratosphere downward to Earth’s surface. The first mode, referred to as SNAM, represents intraseasonal variability in polar vortex strength and is highly correlated with the canonical stratospheric NAM. The second mode, referred to as the Polar Annular Mode (or PAM), represents intraseasonal variability in the latitudinal position of the polar vortex and is structurally and statistically distinct from SNAM. In its positive (negative) phase the PAM pattern is associated with a northward (southward) shift in the polar vortex position with below (above) normal heights over the pole. PAM also provides important alterations to the zonal-mean zonal wind structure along the tropopause at middle to high latitudes. Sensitivity analyses indicate that the main results of our PC analysis are robust to (a) the spatial domain specification, (b) the input field variable considered and (c) the use of zonal-mean or zonally-varying anomaly fields.

Linear regression analyses show that, at both stratospheric and tropospheric altitudes, the PAM anomaly pattern is retracted substantially northward in comparison to the SNAM. Nonetheless, PAM events are associated with circumpolar circulation anomaly patterns in the high latitude troposphere with magnitudes comparable to (and even exceeding) SNAM. In addition, the positive phase of PAM leads to colder (warmer) surface air temperatures over the Arctic (Northern Siberia). Composite analyses of the respective PC time series indicate that PAM events are relatively short-lived (1-2 weeks) compared to SNAM.
However, when SNAM and PAM events of the same sign occur simultaneously they synergistically interact in such a way as to hasten the demise of SNAM. For positive phases, the concomitant strengthening and tightening of the polar vortex may predispose the vortex to an abrupt decay via the stratospheric preconditioning process (Andrews et al. 1987). We also find that the evolution of sudden stratospheric warming events is dominated by SNAM variability whereas SNAM and PAM play approximately equal roles in stratospheric final warmings.

An important new result of our study is the finding that stratospheric and tropospheric NAM variability is largely decoupled on daily time scales, with SNAM accounting for less than 25% of the daily tropospheric NAM variability. Consistent with this result, we also find that the direct tropospheric manifestation of SNAM (as determined via linear regression analysis) has only a modest correspondence to the canonical tropospheric NAM pattern (Thompson and Wallace 2000). The tropospheric anomaly patterns obtained in our study are more strongly annular with relatively weak amplitudes over the North Atlantic sector. Taken together, the two above results are consistent with the idea that the proximate tropospheric manifestation of SNAM differs from the canonical tropospheric NAM pattern. This suggests that, during periods of stratosphere-troposphere NAM coupling, the ultimate net tropospheric response has a substantial component representing an internal tropospheric adjustment to the SNAM variability (e.g., the indirect tropospheric response discussed by McDaniel and Black 2005). As such, the current analysis may provide a useful dynamical model for delineating stratospheric and tropospheric NAM variability and their coupling. This separation also serves to isolate the direct impact of the polar vortex variability upon the troposphere. Since SNAM and PAM induce large-scale tropospheric
circulation anomaly patterns with similar amplitudes, our results suggest that first order variations in the strength and position of the stratospheric polar vortex each provide significant direct alterations to the tropospheric circulation of comparable strength. However, these tropospheric impacts have different spatial patterns and time scales. Finally, our results also reveal that recent decadal trends in the boreal stratospheric polar vortex project more strongly onto PAM than SNAM.

In summary, we conclude that Polar Annular Mode represents a newly recognized annular mode that (a) strongly couples the troposphere and stratosphere on submonthly time scales, (b) provides a robust circumpolar circulation in the high latitude troposphere, and (c) plays a essential role in stratospheric final warming events as well as long-term trends in the boreal stratospheric polar vortex. Our future research efforts will use the current paradigm as a dynamical framework for exploring stratosphere-troposphere coupling on submonthly time scales.

Acknowledgments

This research was supported by the NSF Climate and Large-Scale Dynamics Program under Grant ATM-0456157 (under the U.S. CLIVAR Program). The NCEP-NCAR reanalyses come from the NOAA Climate Diagnostics Center from their web site at http://www.cdc.noaa.gov/.
References


Figure Legends

Figure 1. Zonally-averaged zonal windfield (units: m s\(^{-1}\)). Frames (a) and (b) display regressions of boreal winter (JFMA) wind anomalies against the daily SNAM and PAM indices, respectively. The 95% confidence level is also plotted in green. For reference, the climatological winter mean is shown in (c) with the region used in the EOF calculation bounded in black.

Figure 2. Zonally-averaged zonal windfield (units: m s\(^{-1}\)) illustrating the effect of PAM on the climatological winter mean. Frames (a) and (b) display the winter mean plus and minus the one-sigma PAM field, respectively.

Figure 3. Multi-level correlations for daily wintertime (JFMA) NAM indices. Each contour represents the correlation of a given index with the canonical NAM index at various levels. See text for details on how the indices were calculated. For reference, the green contour represents perfect correlation.

Figure 4. Linear regressions of boreal winter (JFMA) 50 hPa geopotential height anomalies (first row; units: m), 500 hPa height anomalies (second row; units: m) and 1000 hPa temperature anomalies (third row; units: K) against the daily SNAM index (left column) and PAM index (right column). The 95% confidence level contour is plotted in green.

Figure 5. Sensitivity study displaying the zonally-averaged zonal windfield (units: m s\(^{-1}\)). Frames (a), (b), and (c) display regressions of boreal winter (JFMA) wind anomalies against the daily SNAM indices calculated using the zonally averaged zonal wind field from 20N to 90N, the zonally averaged windfield at 50hPa, and the zonally averaged height anomaly field, respectively. Frames (d), (e) and (f) are the same as above but for the PAM patterns.
Figure 6. Linear regressions of boreal winter (JFMA) 50 hPa geopotential height anomalies (first row; units: m), 500 hPa height anomalies (second row; units: m) and zonal-mean zonal wind anomalies (third row; units: m/s) against the first PC time series (ZLV1; left column) and sixth PC time series (ZLV6; right column) of the 50 hPa EOF analysis of geopotential height (see text for further details).

Figure 7. Characteristic timescale for the boreal wintertime (JFMA) SNAM (blue) and PAM (pink).

Figure 8. The composite time evolution of daily unfiltered and normalized SNAM and PAM indices (red and blue respectively). Frames (a) and (b) display composites of discrete SNAM and PAM events occurring in isolation while frames (c) and (d) display composites for simultaneous, like-signed SNAM and PAM events. In (a-d) solid (dashed) lines represent positive (negative) events. Frames (e) and (f) are composites with respect to the onset of SFW and SSW events, respectively. Frames (g) and (h) are composites of SSW events stratified by type (split and displacement, respectively). In all cases lag 0 represents the time of event onset (see text for further details).

Figure 9. Long-term trends in the wintertime averaged (JFMA) NAM and PAM. The upper panel shows the SNAM (blue) and the NAM index at 50mb. The bottom panel shows the long-trend in the PAM. All data plotted has been lightly smoothed using a 5-point running mean.

Figure 10. Long-term trends in the zonally-averaged zonal windfield (units: m s⁻¹ per 48 years). The top panels display the long-term trend in the JFMA-averaged zonal wind field (left) as well as the long-term variability represented by the standard deviation. The bottom panels illustrate the contribution to the overall trend due to the trends in PAM and SNAM (left and right, respectively).
Zonally-averaged zonal windfield (units: m s\(^{-1}\)). Frames (a) and (b) display regressions of boreal winter (JFMA) wind anomalies against the daily SNAM and PAM indices, respectively. The 95% confidence level is also plotted in green. For reference, the climatological winter mean is shown in (c) with the region used in the EOF calculation bounded in black.

**Figure 1**
Figure 2

Zonally-averaged zonal windfield (units: m s$^{-1}$) illustrating the effect of PAM on the climatological winter mean. Frames (a) and (b) display the winter mean plus and minus the one-sigma PAM field, respectively.
Figure 3

Multi-level correlations for daily wintertime (JFMA) NAM indices. Each contour represents the correlation of a given index with the canonical NAM index at various levels. See text for details on how the indices were calculated. For reference, the green contour represents perfect correlation.
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Linear regressions of boreal winter (JFMA) 50 hPa geopotential height anomalies (first row; units: m), 500 hPa height anomalies (second row; units: m) and 1000 hPa temperature anomalies (third row; units: K) against the daily SNAM index (left column) and PAM index (right column). The 95% confidence level contour is plotted in green.
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Sensitivity study displaying the zonally-averaged zonal windfield (units: m s\(^{-1}\)). Frames (a), (b), and (c) display regressions of boreal winter (JFMA) wind anomalies against the daily SNAM indices calculated using the zonally averaged zonal wind field from 20N to 90N, the zonally averaged wind field at 50hPa, and the zonally averaged height anomaly field, respectively. Frames (d), (e) and (f) are the same as above but for the PAM patterns.
Figure 6

Linear regressions of boreal winter (JFMA) 50 hPa geopotential height anomalies (first row; units: m), 500 hPa height anomalies (second row; units: m) and zonal-mean zonal wind anomalies (third row; units: m/s) against the first PC time series (ZLV1; left column) and sixth PC time series (ZLV6; right column) of the 50 hPa EOF analysis of geopotential height (see text for further details).
Figure 6 (Continued)
Figure 7

Characteristic timescale for the boreal wintertime (JFMA) SNAM (blue) and PAM (pink).
The composite time evolution of daily unfiltered and normalized SNAM and PAM indices (red and blue respectively). Frames (a) and (b) display composites of discrete SNAM and PAM events occurring in isolation while frames (c) and (d) display composites for simultaneous, like-signed SNAM and PAM events. In (a-d) solid (dashed) lines represent positive (negative) events. Frames (e) and (f) are composites with respect to the onset of SFW and SSW events, respectively. Frames (g) and (h) are composites of SSW events stratified by type (split and displacement, respectively). In all cases lag 0 represents the time of event onset (see text for further details.)
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Long-term trends in the zonally-averaged zonal windfield (units: m s$^{-1}$ per 48 years). The top panels display the long-term trend in the JFMA-averaged zonal wind field (left) as well as the long-term variability represented by the standard deviation. The bottom panels illustrate the contribution to the overall trend due to the trends in PAM and SNAM (left and right, respectively).