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Observed correlations between winter-mean tropospheric and stratospheric circulation anomalies

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Abstract. It is shown that interannual variability of the northern winter stratospheric flow in 1964-1993 was closely linked to large-scale circulation anomalies in the middle troposphere. Of the known tropospheric teleconnection patterns, the one having the strongest relation to the DJF zonal-mean stratospheric flow was the North Atlantic Oscillation (NAO). Singular value decomposition between the 500 and 50-hPa geopotential heights produced a 500-hPa structure containing elements of the NAO pattern, but including an anomaly in eastern Siberia. During this time period, the correlation of NAO-related modes to the polar lower stratosphere exceeded that of the equatorial quasi-biennial oscillation.

Introduction

On interannual timescales, the wintertime stratospheric circulation is influenced in several ways. One of the strongest influences is the quasi-biennial oscillation of the equatorial lower stratosphere (QBO), with variable period averaging about 28 months [*Holton and Tan,* 1980; *Holton and Tan,* 1982; *Baldwin and Dunkerton,* 1991; *Dunkerton and Baldwin,* 1991]. There is a stronger polar vortex during the west 40-hPa QBO phase, and a weaker vortex (and greater likelihood of sudden warmings) during the east phase. The mechanism involves a modulation of the waveguide for upward propagating planetary-scale waves. The QBO's influence has been confirmed in modeling studies [e.g. *O'Sullivan and Young,* 1992; *O'Sullivan and Dunkerton,* 1994].

Since planetary waves are essential to stratospheric variability, interannual variations of tropospheric forcing are potentially important; e.g., those associated with the El Niño/Southern Oscillation (ENSO). Stratospheric effects of ENSO were investigated by several authors. Due to a coincidence of ENSO and QBO phases, *Wallace and Chang* [1982] and *van Loon and Labitzke* [1987] found that the influence of the QBO and ENSO were apparently similar, with warm ENSO events resulting in a weaker, more disturbed polar vortex. Using several partitioning schemes to minimize overlap with the QBO, *Hamilton* [1993] found however that ENSO's influence was moderate compared to that of the QBO, and not statistically significant.

In a related study, *Baldwin and O'Sullivan* [1994] examined the stratosphere's observed relationship with three tropospheric modes of variability that are influenced, in part, by ENSO. Using principal-component time series corresponding to the Pacific/North American (PNA), Western Pacific Oscillation (WPO), and the Tropical/Northern Hemisphere (TNH) patterns, Baldwin and O'Sullivan found no significant effect on the strength of the polar vortex, although waves 1 and 2 were modulated at the 50-hPa level.

In this paper we investigate the possibility that interannual variability of other tropospheric circulation patterns (beside PNA, WPO, and TNH) unrelated to either ENSO or the QBO may modulate the strength of the stratospheric polar vortex. In particular, we examine the North Atlantic Oscillation (NAO) and related patterns and use singular-value decomposition (SVD) to find the strongest association between height field and mean zonal wind anomalies in the troposphere and lower stratosphere.

Data Analysis

Our dataset consisted of daily (12Z) National Meteorological Center (NMC) height fields for the period 1/1/64–5/8/93. These data were available north of 18°N at the standard levels 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 10 hPa. EOFs were calculated from 30 years of December–February (DJF) average 500-hPa geopotential using the covariance matrix. The leading modes were obtained with varimax rotation using a 317-point, polar stereographic grid which corresponds approximately to 6° latitude horizontal resolution. SVD analysis was carried out between the 500 and 50-hPa height fields using a similar polar stereographic grid or, alternatively, using 500 hPa geopotential and 1000-10 hPa mean zonal wind as input.

Results

Applying varimax rotation to EOFs of the temporal covariance matrix of the DJF 500-hPa height field gave structures corresponding closely to the PNA, NAO, and WPO patterns of *Wallace and Gutzler* [1981] and *Kushnir and Wallace* (1989). Figure 1 shows the second mode, which resembled the NAO and accounted for 14.3% of the variance in the 30-year dataset. This mode

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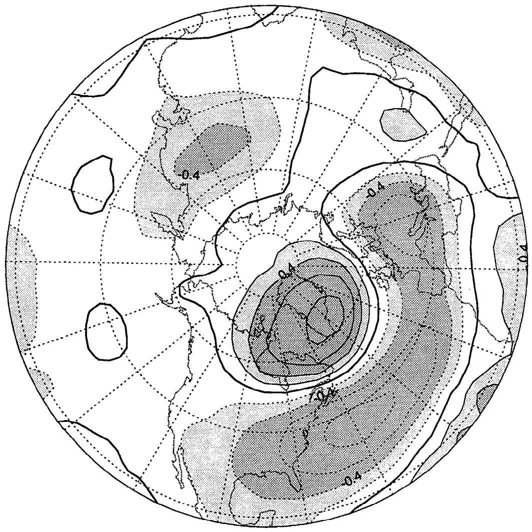

Figure 1. The second rotated EOF of the temporal covariance matrix of 500 hPa geopotential based on winter (DJF-average) data for the years 1964-93. 10 modes were included in the varimax rotation. The value at each grid point is the correlation between the principal-component time series and the geopotential anomalies at that point. Contour interval 0.2; negative values dashed.

was characterized by a north-south dipole in the North Atlantic, with a center near Greenland and a longitudinally broad anomaly stretching from Europe to the West Atlantic near 40°N. A third feature over eastern Siberia was somewhat weaker. The Siberian center was less prominent in a longer dataset (1946-93) than in the 30-year dataset used here. This mode does not appear to influenced by ENSO. The correlation between its principal component and winter-mean Tahiti-Darwin sea level pressure anomalies is .07.

When we correlated the principal-component time series of the NAO-like mode of Figure 1 with the mean zonal wind, the result was a strong north-south dipole extending at least through 10 hPa (Figure 2). Near 50-60°N, correlations greater than 0.6 extended up through 70 hPa, but values decreased to less than 0.4 by 10 hPa.

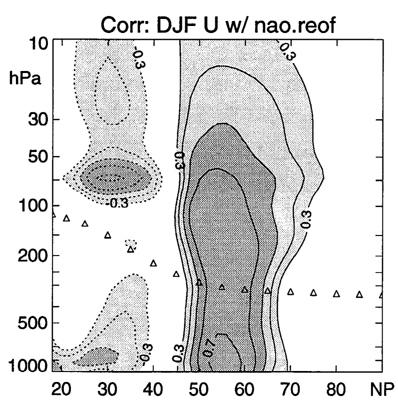

Figure 2. Correlation between the principal component of the NAO-like EOF (Figure 1) and the DJF mean zonal wind. Triangles represent the approximate wintertime tropopause. Contour interval 0.1, beginning at ±0.3.

The stratospheric dipole was a fundamental mode of variability, appearing as the leading mode (accounting for 70% of the interannual variance) in an EOF analysis of the mean zonal wind [*Dunkerton and Baldwin,* 1992].

A more direct approach to investigate tropospheric links with the stratosphere employs SVD analysis, e.g., of the covariance matrix between 500 and 50-hPa geopotential height [*Cheng,* 1993]. This method identifies pairs of spatial patterns that most efficiently explain the temporal covariance between two fields [*Bretherton et al.,* 1992]. The 500-hPa height pattern of the leading SVD mode is shown in Figure 3a. Features of this pattern were broadly similar to the NAO-like mode, but differed in several ways. 1) The South Atlantic anomaly was longitudinally more confined, with a single center near the Atlantic coast of Europe. 2) The Siberian center was more prominent. 3) The Greenland center was located farther west, north of Labrador, and extended farther over the polar cap. 4) Circular symmetry, about a vortex center displaced toward Greenland, was more

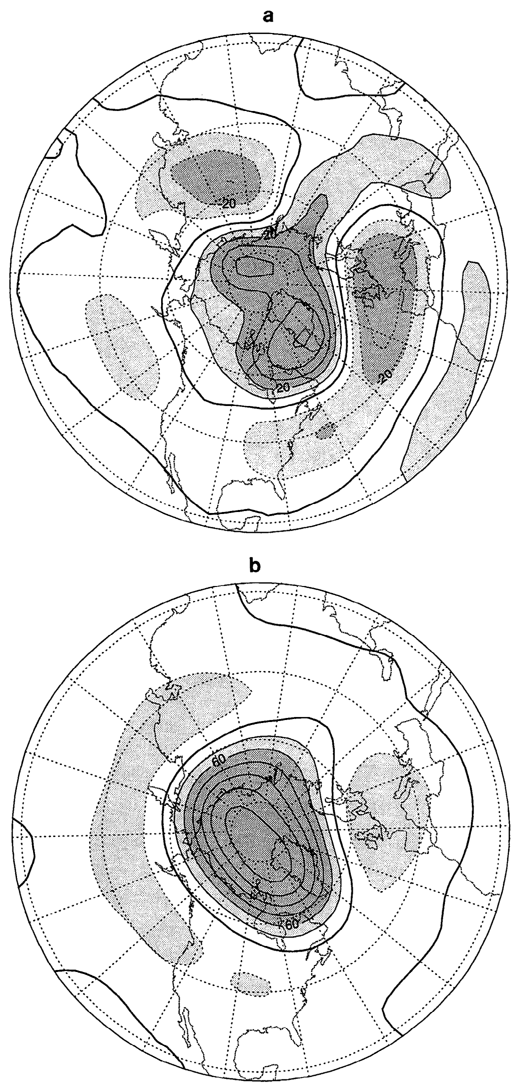

Figure 3. The leading mode (heterogeneous regression map) from SVD analysis between DJF 500 and 50-hPa height fields. (a) 500 hPa (contour interval 10 m); (b) 50 hPa (contour interval 30 m).

pronounced. The corresponding stratospheric anomaly (Figure 3b) was centered near the pole. When we performed SVD between the 500-hPa height field and the mean zonal wind, the resulting pattern (Figure 4) was similar to that of Figure 2, but with higher correlations exceeding 0.9 in the lower stratosphere and 0.6 at 10 hPa. The 500-hPa structure (not shown) was similar to Figure 3a.

The 500-hPa SVD pattern indicates that the troposphere-stratosphere link was not just a simple manifestation of the NAO pattern with its north-south 'seesaw' over the North Atlantic, but also involved an anomaly over eastern Siberia. In order to highlight these regional aspects, time series were constructed based on pairs of grid points, in a manner similar to *Wallace and Gutzler's* [1981] definitions of the WPO and other patterns. We defined a North Atlantic index (NA) as the difference between normalized geopotential anomalies at 62°N, 80°W and 46°N, 20°W. A cross-polar index (XP) was defined similarly, using 62°N, 80°W and 58°N, 100°E. Although the correlation between the indices was 0.86, they appeared to represent two distinct aspects of a troposphere-stratosphere link. Figure 5a illustrates the correlation between the NA index and the mean zonal wind. Correlations in the northern half of the stratospheric dipole far exceeded those using the principal component of the NAO-like mode (Figure 1) and nearly matched those of the leading SVD mode (Figure 4). Correlations with the NA index at 60°N exceeded 0.6 from the surface through 10 hPa.

Correlations between the XP index and the mean zonal wind (Figure 5b) were slightly higher than correlations using the NA index, and exceeded those of the 500-hPa SVD mode above 50 hPa. Overall, the correlations using gridpoint-based indices were similar, as expected from the high correlation between the two indices. By comparison a QBO index, defined as the 40-hPa Singapore wind, was not as highly correlated with the mean zonal wind as the NA index, the XP index, or the leading SVD mode (Figure 5c). Correlations did not exceed 0.6 anywhere in the diagram, and

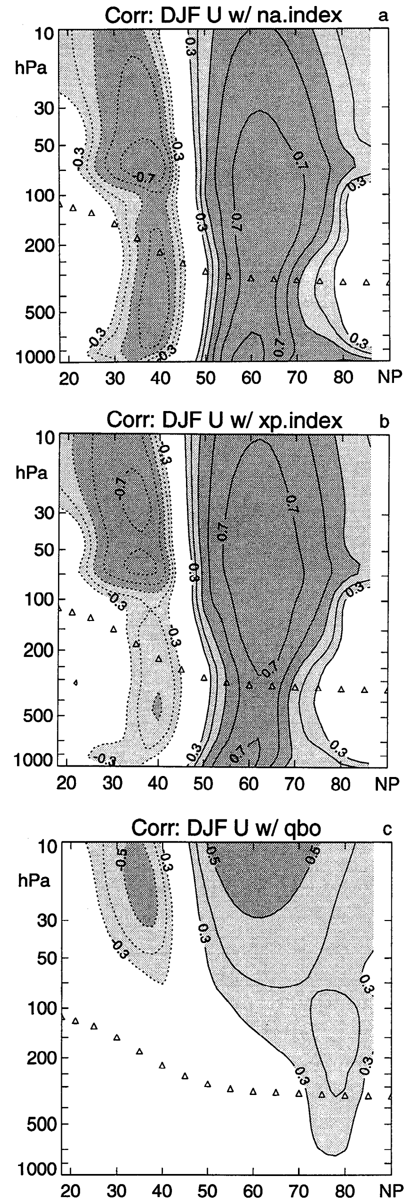

Figure 5. Correlation of mean zonal wind with (a) NA index, b) XP index, and c) the 40 hPa Singapore QBO. See text for definition of indices.

diminished greatly upon entering the troposphere. Unlike the tropospheric indices, however, the effect of the QBO increased with height in the stratosphere.

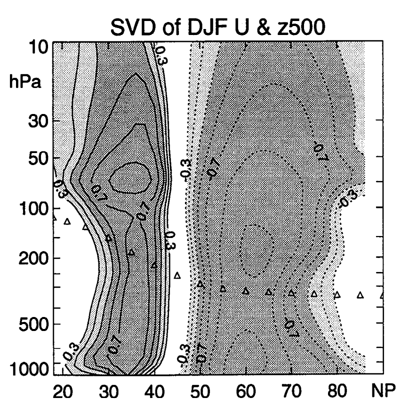

Figure 4. Heterogeneous correlation between 500 hPa principal component and mean zonal wind, from SVD analysis using 500 hPa geopotential and 1000-10 hPa mean zonal wind as input.

Conclusion

A pattern resembling the North Atlantic Oscillation (NAO) was strongly correlated with the zonal-mean stratospheric polar vortex in 1964-1993. This structure, best represented as the 500-hPa SVD mode in Figure 3a, had prominent anomalies in eastern Siberia and eastern Atlantic, opposing a main center north of Labrador. The pattern displayed a large degree of ci3-cular symmetry about a central point displaced toward Greenland. This displacement off the pole seems important, as it may result in a wave-1 anomaly which could act to force the stratosphere from below. Interestingly there were two parts of the tropospheric pattern (NA, XP). Either by itself was sufficient to generate high correlations with the stratosphere, yet both appeared as a single mode in SVD analysis. This suggests that combinations of tropospheric teleconnection patterns are essential to stratospheric interannual variability; e.g., cross-polar excitation of wave 1 combined with blocking over Greenland. Alternatively, part of the tropospheric pattern may represent downward influence from the stratosphere. Analysis of daily data (to be reported elsewhere) indicates however that the strongest lag correlations within most SVD patterns occur when the troposphere leads the stratosphere by a few days – suggesting that the direction of cause-and-effect is for the most part upward.

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