GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 17, PAGES 2589-2592, SEPTEMBER 1, 2000

Development of the polar vortex in the 1999-2000 Arctic winter stratosphere

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Abstract. The 1999-2000 Arctic stratospheric vortex was unusually cold, especially in the early winter lower stratosphere, with a larger area near polar stratospheric cloud formation temperatures in Dec and Jan, and much lower temperatures averaged over Nov-Jan, than any previously observed Arctic winter. In Nov and early Dec, there was a double jet in the upper stratosphere, with the anticyclone cutoff in a region of cyclonic material. By late Dec, there was a discontinuous vortex, large in the upper stratosphere, small in the lower stratosphere; evolving to a strong, continuous, relatively upright vortex by mid-Jan. This vortex evolution in 1999-2000 is typical of that in other cold early winters. Despite unusually low temperatures, the lower stratospheric vortex developed more slowly than in previous unusually cold early winters, and was weaker than average until late Dec.

The cold early winter of 1999-2000

During winter, the northern hemisphere (NH) stratosphere exhibits large interannual variability in temperatures, and in the strength of the stratospheric polar vortex. Several recent winters, 1994-95, 1995-96 and 1996-97, had periods of ~1.5-2.5 months with unusually low temperatures [*Pawson and Naujokat*, 1999], and substantial ozone depletion has been reported in the lower stratosphere [e.g., *Manney et al.*, 1996b, 1997; *Rex et al.*, 1997, and references therein]. Although lower temperatures are frequently associated with a stronger polar vortex, vortex strength depends on both horizontal and vertical wind and temperature gradients, and the relationship is by no means monotonic [e.g., *Manney et al.*, 1994; *Zurek et al.*, 1996].

Fig. 1 shows minimum temperatures and maximum potential vorticity (PV) gradients in the lower stratosphere during 1999-2000, compared to ranges in the previous 21 winters, from U.S. National Center for Environmental Prediction (NCEP) data. NH lower stratospheric temperatures were unusually low in mid to late Nov, and during mid-Dec–mid-Mar. While The Met Office (UKMO) temperatures in previous NH winters have often been slightly higher than NCEP temperatures [*Manney et al.*, 1996a] (*Sabutis and Manney* [2000] show a plot similar to Fig. 1 for UKMO temperatures), UKMO temperatures were ~1-3 K lower than NCEP temperatures during mid-Dec 1999–mid-Jan 2000 (dashed line in Fig. 1). Maximum PV gradients rose to about average only after early Jan; thus, a weak vortex was associated with the unusually low temperatures.

Fig. 2 compares the area with UKMO temperatures less than 195 K in 1999-2000 to the three unusually cold winters mentioned above. During 1999-2000, NH lower stratospheric vortex temperatures were less than 195 K longer and over a larger area at levels between ~46 and 14 hPa than in any of the previous 21 winters. NCEP data show maximum 1999-2000 areas comparable to those in 1995-96, but NCAR/NCEP Reanalysis data show a similar difference between 1995-96 and 1999-2000 areas as the UKMO data.

Fig. 3 shows average temperatures and the number of days with minimum temperatures below 195 K as a function of equivalent latitude (EqL) and potential temperature (θ) over Nov-Jan for 1995-96 (the coldest previously observed NH winter). Nov 1999-Jan 2000 had more days with temperatures less than 195 K over a large part of the vortex than any previously observed NH winter, and substantially lower temperatures when averaged with respect to the vortex. Although the low temperature region in Jan 1996 was centered on one side of the vortex [e.g., *Manney et al.*, 1996b], so the 1995-96 average may reflect more averaging of higher with lower temperatures, other analyses (e.g., hemispheric maps of monthly average temperatures and cold days) confirm dramatically lower average temperatures in 1999-2000. NCEP data also show lower average temperatures and more cold days in Nov-Jan 1999-2000 than in 1995-96.

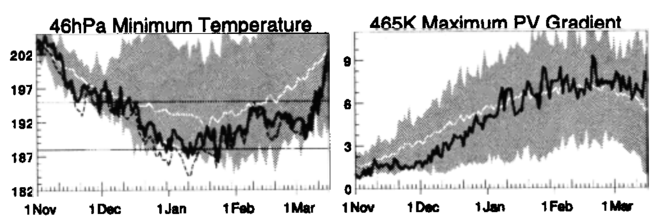

Figure 1. (Left) Minimum 46 hPa temperatures (K) north of 40°N and (right) maximum 465 K sPV (PV in "vorticity units" [e.g., *Manney et al.*, 1994]) gradients with respect to equivalent latitude ($10^{-6}deg^{-1}s^{-1}$, a measure of vortex strength), from NCEP data. Shading shows the range for 1978-79 to 1998-99, thin white line the 21-year average. Thick black line (dashed line) shows 1999-2000 NCEP (UKMO) temperatures.

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Paper number 2000GL011703.
0094-8276/00/2000GL011703$05.00

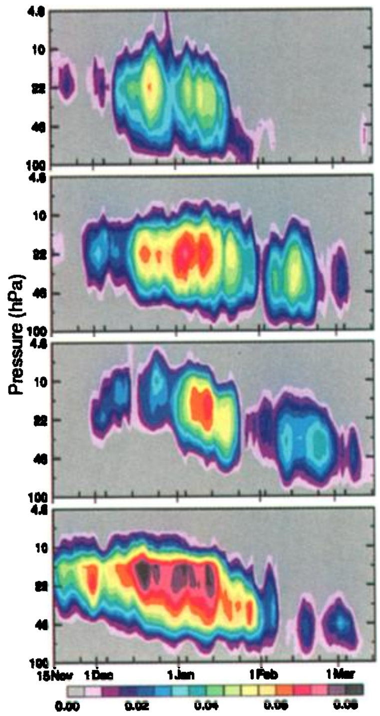

Figure 2. Area (fraction of a hemisphere) north of 30°N with minimum UKMO temperatures less than 195 K for 1994-95, 1995-96, 1996-97 and 1999-2000.

The above diagnostics show unprecedentedly low temperatures during the 1999-2000 early winter. However, Fig. 1 shows an associated weak to average lower stratosphere vortex, underscoring the complexity of the relationship between vortex strength and temperature. Below, we describe in detail the development of the polar vortex in 1999-2000, compared to other recent cold winters.

Development of the 1999-2000 Polar Vortex

Fig. 4 shows PV maps from UKMO data during NH fall/early winter 1999-2000. In the upper stratosphere, the vortex was strong by 1 Nov, and thereafter strengthened slightly. In the mid-stratosphere, although the vortex was apparent as a region of strong PV gradients on 1 Nov, it strengthened and grew considerably during Nov; PV gradients approached their maximum by mid-Dec. In the lower stratosphere, the Nov vortex was not well defined (no coherent region of strong PV gradients), but strengthened rapidly in Dec. Lower stratospheric temperatures fell below 190 K by about 23 Dec; Dec temperatures this low were seen before only in 1994-95 [*Zurek et al.*, 1996].

The 25 Nov, 11 Dec, and 23 Dec maps illustrate minor warming or wave amplification events (i.e., displacement of the vortex off the pole and an accompanying temperature increase) that typically perturb the early winter vortex; the 16 Jan maps show a minor warming event, dominated by wave 2, more typical of midwinter. The early winter events were dominated by wave 1, with the polar vortex shifted towards western Europe and large tongues of low-latitude air drawn into the Aleutian high region. Similar events have previously been reported by, e.g., *Juckes and O'Neill* [1988] and *Rosier et al.* [1994]. These wave 1 events in late 1999, which were the most disturbed conditions of that early winter, were small compared to previously described early winter minor warmings [e.g., *Rosier et al.*, 1994, and references therein]. In the upper stratosphere during these wave 1 events, there was less displacement of the vortex from the pole than in the mid-stratosphere, but longer tongues with higher PV were drawn off the vortex around the developing anticyclone(s); in some cases (e.g., 25 Nov, 11 Dec), a weak cutoff anticyclone was embedded in a large region of cyclonic flow. By Jan, the upper stratospheric flow resembled that in the mid-stratosphere, with a single region of strong PV gradients defining the vortex, and narrow tongues of vortex air pulled off and coiled up with air drawn in from low latitudes.

Fig. 5 shows UKMO windspeeds and PV gradients (normalized by the average PV gradient at each level) in EqL/θ space for the same days as Fig. 4. In the upper stratosphere on 25 Nov and 11 Dec, windspeeds and PV gradients showed a distinct double peak. This can be associated with material drawn off the main vortex, such that the developing anticyclone was cutoff, or nearly cutoff, in a large cyclonic region (Fig. 4). On 23 Dec, the upper stratospheric jet was very broad (windspeed >55 m s^{-1} from ~35-60°EqL), with the strong PV gradient region near 40°EqL indicating a large vortex. In contrast, the mid and lower stratospheric vortex was small (strong PV gradient region poleward of 60°EqL) with a narrow jet; a well-defined transition region was apparent near 900 K.

Fig. 6 compares the average normalized (as above) PV gradients for Nov, Dec and Jan 1999-2000 to those in 1994-95, 1995-96 and 1996-97. A double jet in the upper stratosphere in Nov in each year indicates that the patterns seen in Figs. 4 and 5 are common and persistent during Nov. This

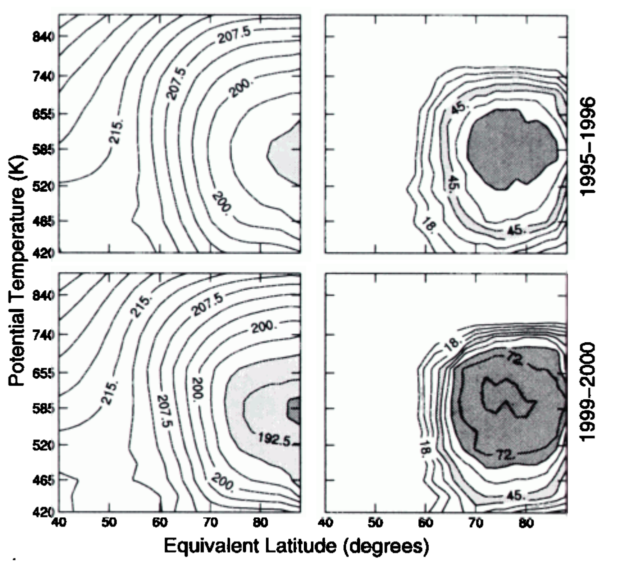

Figure 3. (Left) Average temperatures as a function of EqL and θ for Nov–Jan 1995-96 and 1999-2000; contour interval is 2.5 K, with light shading below 195 K, dark shading below 190 K. (Right) Number of days in Nov–Jan with minimum temperatures at a given EqL and θ less than 195 K; contour interval is 9 days; light shading 36-45 days, dark shading over 63 days.

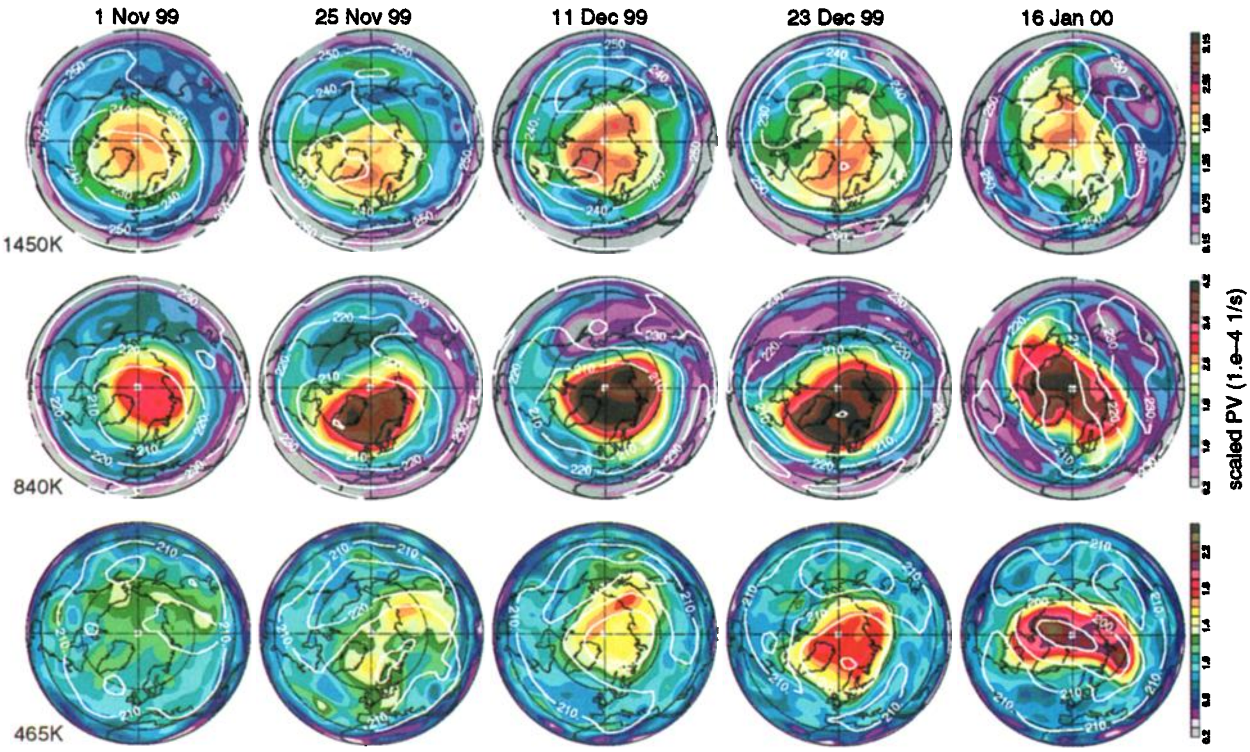

Figure 4. sPV (10^{-4} s^{-1}, colors) maps from UKMO data in early winter 1999-2000, at 1450 K (top, ~2 hPa), 840 K (center, ~10 hPa) and 465 K (bottom, ~50 hPa). Temperatures at 10 K intervals are overlaid in white. Projection is orthographic, 0°E at bottom, 90°E at right; domain is 0° to 90°N, with dashed lines at 30° and 60°N.

double-jet pattern was weaker in 1994-95, the coldest and least disturbed Nov and early Dec on record [*Zurek et al.*, 1996]. In Dec (except in 1996-97 when the vortex was very weak in Nov and Dec), the monthly averaged pattern is similar to that on 23 Dec 1999, with a large upper stratospheric/small mid and lower stratospheric vortex. By Jan, the polar vortex is continuous throughout the stratosphere, somewhat larger at the top in 1996-97 and 1999-2000. Similar averages for the past 21 NH winters show that the pattern of a double jet in Nov, a discontinuous large upper/small lower stratospheric vortex in Dec, and a continuous, upright vortex in Jan is common, apparent in ~15 of 22 winters in the NCEP data examined.

Although temperatures in Nov 1999 were lower than in Nov 1994 and 1995, the lower stratospheric vortex had not developed in Nov 1999 as it had in Nov 1994 and 1995. The 1996-97 lower stratospheric vortex was unusually warm and weak in Nov and Dec, but became unusually cold [*Coy et al.*, 1997] and fairly strong in Jan. In Dec 1999, the lower stratospheric vortex strengthened rapidly and was comparable to those in Dec 1994 and 1995; in Jan 2000, the vortex was stronger than in the three previous years shown.

Summary and Conclusions

In fall/early winter (Nov-Jan) 1999-2000, temperatures in the NH lower stratospheric polar vortex were unusually low. While different meteorological analyses show variations of several K, all data studied show larger areas of temperatures near or below polar stratospheric cloud formation thresholds

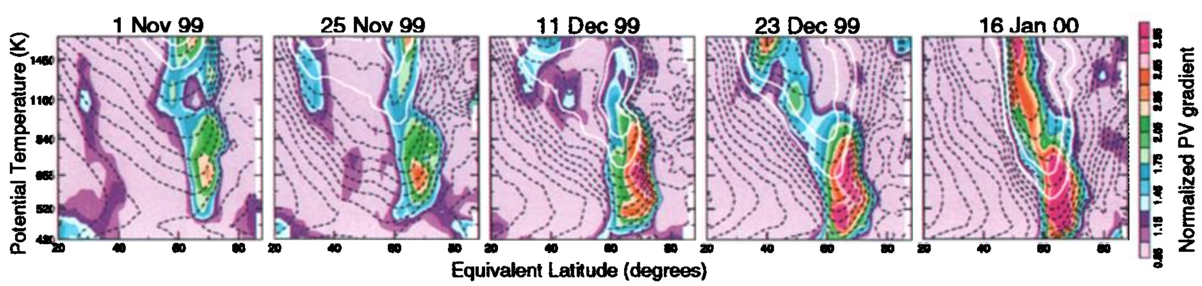

Figure 5. Normalized sPV gradients (colors) and windspeed (m s^{-1}, contours) from UKMO data as a function of EqL and θ, for the early winter 1999-2000 days shown in Fig. 4. Colors above lavender indicate stronger than average sPV gradients. Windspeed contour interval is 5 m s^{-1}, with white contours at 55 and 65 m s^{-1}.

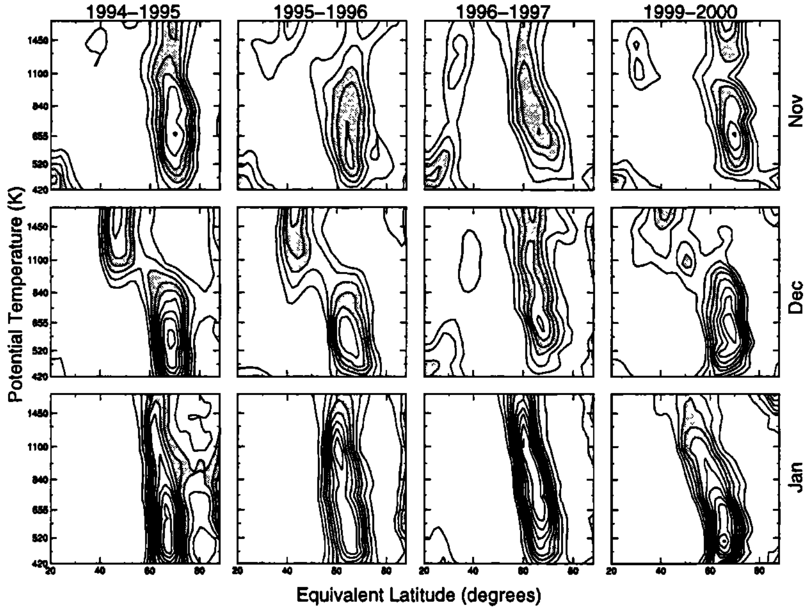

Figure 6. Average normalized sPV gradients in EqL/θ space for Nov, Dec and Jan in 1994-95, 1995-96, 1996-97 and 1999-2000, from UKMO data. Contour interval is 0.25, with shading from 1.5 to 2.0; contours start at 1.0, showing only above average sPV gradients.

in Dec and Jan than in any previously observed NH winter. Temperatures averaged with respect to the vortex for Nov–Jan were significantly lower than in 1995-96, the previous coldest NH winter. *Sabutis and Manney* [2000] show evidence that less wave energy entering the stratosphere in 1999-2000, as well as differences in propagation characteristics of the background stratospheric flow, was related to the unusually cold 1999-2000 early winter.

The development and evolution of the polar vortex in 1999-2000 included a double jet, with the anticyclone(s) embedded in a region of cyclonic flow, in the upper stratosphere in Nov/early Dec; a discontinuous vortex, large in the upper stratosphere and small in the lower stratosphere, in late Dec; and a strong, continuous, and relatively upright vortex by mid-Jan. Comparison with other cold winters shows that these structures are typical in Nov, Dec and Jan monthly averages. This complexity of early winter vortex structure may have important implications for the transport of trace gases in the developing vortex and for mixing between vortex and extra-vortex air. The development of the vortex in the 1999-2000 mid and upper stratosphere was very similar to that in 1994-95 and 1995-96, also years with unusually cold early winters. The lower stratospheric vortex, in contrast, developed much more slowly than in previous cold early winters, and was weaker than average until late Dec, despite unusually low temperatures. Although less wave propagation into the stratosphere, such as seen in early winter 1999-2000 [*Sabutis and Manney*, 2000], is associated with a colder vortex, it can still occur in conjunction with a weak vortex if mid to high latitude temperature gradients are weak. The complex relationship between wave activity, temperature and vortex strength is currently being investigated in more detail.

Acknowledgments. We thank the NCEP/CAC and The Met Office for meteorological data, M. E. Gelman and R. Swinbank for advice and expertise on those data, the MLS team for data management, and H. A. Michelsen, M. L. Santee, and an anonymous reviewer for helpful comments. Work at the Jet Propulsion Laboratory, California Institute of Technology, was done under contract with the National Aeronautics and Space Administration.

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(Received April 13, 2000; accepted July 5, 2000.)