A unique stratospheric warming event in November 2000

Gloria L. Manney,[1,2] Joseph L. Sabutis,[2] and Richard Swinbank[3]

Abstract. Stratospheric sudden warmings frequently influence temperatures and circulation in the Arctic winter stratosphere. A unique stratospheric warming in Nov 2000 was characterized by wave 1 amplification with little phase tilt with height, a large displacement of the vortex off the pole, a warm pool at high latitudes, and a modest polar temperature increase, all of which are characteristic of early winter "Canadian" warmings. Unlike most Canadian warmings, the Nov 2000 event led to a strong zonal mean wind reversal for ~9 days in the mid and lower stratosphere. Wind reversals during Canadian warmings occurred only three times before in the last 23 years. Midstratospheric minimum temperatures continued to decrease during the warming, but lower stratospheric temperatures increased substantially. The Nov 2000 warming was unique in its timing, intensity and duration, and in its impact on the development of the polar vortex, especially in the lower stratosphere.

The Nov 2000 Canadian Warming

Sudden warmings play an important role in the evolution of the Northern Hemisphere (NH) winter stratosphere; major warmings [e.g., *Andrews et al.*, 1987] are characterized by reversals of zonal mean temperature gradients and winds north of 60°N in the midstratosphere (at and above 10 hPa), and usually occur in Jan or Feb. Minor warmings are common in NH early winter [e.g., *Labitzke*, 1977, 1982] and have been reported as early as late Oct-early Nov [e.g., *Rosier et al.*, 1994; *Manney et al.*, 2000, and references therein]. Many early winter warmings are "Canadian warmings" [e.g., *Labitzke*, 1977, 1982], characterized by strong wave 1 amplification in the midstratosphere resulting in a shift of the vortex off the pole along 0° longitude, less disturbance in the upper stratosphere, and little phase tilt with height [e.g. *Labitzke*, 1982; *Clough et al.*, 1985; *Juckes and O'Neill*, 1988]. Unlike major warmings, Canadian warmings rarely lead to a zonal mean wind reversal.

Here we describe, using Met Office (UKMO) data, a unique Canadian warming in Nov 2000. On 14 Nov 2000, the Met Office switched to a new 40-level 3-D variational data assimilation system [*Lorenc et al.*, 2000] that assimilates satellite radiances rather than retrieved temperature profiles. Time series of temperatures show large discontinuities in the upper stratosphere when the switch is made, mainly due to a correction to the ozone climatology, but also due to changes in model configuration and assimilation of satellite data. However, no obvious discontinuity is seen in wind or eddy geopotential height fields, or in temperature fields at and below 10 hPa. Fields shown here agree well with US National Center for Environmental Prediction (NCEP) and NCAR/NCEP reanalysis (REAN) data.

Fig. 1 shows potential vorticity (PV) maps on the potential temperature (θ) = 840 K (~10 hPa) surface, with temperature contours overlaid; maximum windspeeds along the vortex edge approximately follow the $1.6 \times 10^{-4} s^{-1}$ scaled PV contour. Fig. 2 shows zonal mean winds on a pressure-latitude grid on the same four days, near the beginning of the warming (18 Nov), immediately after the initial wind reversal (21 Nov), at the peak of the wind reversal (24 Nov), and the first day after westerlies are reestablished throughout the stratosphere (30 Nov). The vortex does not weaken during the warming, but is strongly distorted and pushed off the pole along the Greenwich meridian. PV area diagnostics (not shown) indicate slightly strengthening PV gradients along the vortex edge during the warming and nearly constant vortex size through ~8 Dec (after which the vortex shrinks during a wave 2 warming). On 18 Nov, the south side of the vortex is near 40°N and the portion of the north side where winds are still westerly near 70°N (Fig. 1), resulting in the double-jet pattern seen in Fig. 2; a similar pattern appears on 30 Nov. On 21 and 24 Nov, the vortex is so

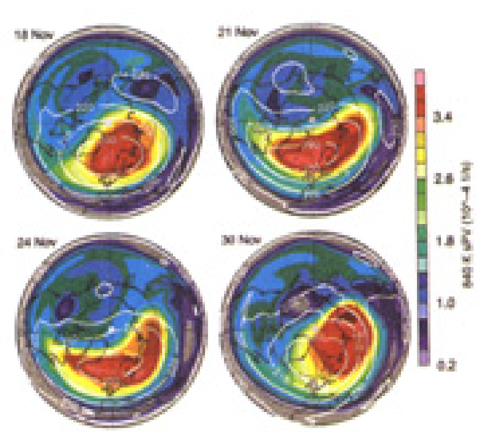

Figure 1. UKMO 840 K sPV ($10^{-4} s^{-1}$, colors) maps on 18, 21, 24, and 30 Nov 2000. Temperatures at 10 K intervals are overlaid in white. Projection is orthographic, 0°E at bottom, 90°E at right; domain is 0-90°N, dashed lines 30 and 60°N.

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

[2]Department of Physics, New Mexico Highlands University, Las Vegas, New Mexico, USA.

[3]Met Office, Bracknell, Berkshire, UK.

Paper number 2001GL012973.
0094-8276/01/2001GL012973$05.00

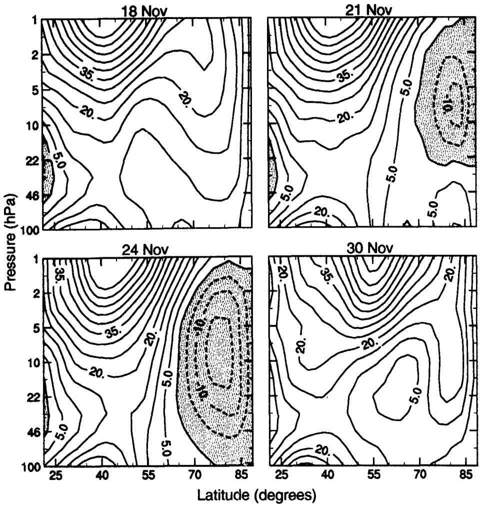

Figure 2. Zonal mean wind (m/s) on 18, 21, 24, and 30 Nov 2000 as a function of pressure and latitude. Contour interval is 5 m/s, values less than zero are shaded.

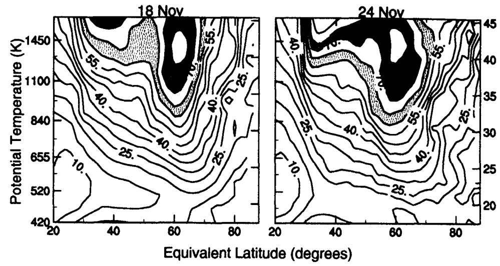

Figure 4. UKMO windspeed (m/s) as a function of equivalent latitude and θ, on 18 and 24 Nov 2000. Contour interval is 5 m/s, light shading, 60-65 m/s, dark shading, 70-75 m/s.

far displaced off the pole, and distorted into a crescent, that winds are easterly along much of its poleward side, as well as in the anticyclone, resulting in the strong (up to $\sim$17 m/s) easterlies seen in Fig. 2. Easterlies peak near 10 hPa and are not significant at 1 hPa. Westerlies near 40°N remain relatively strong above $\sim$10 hPa through the warming. Easterlies decay first above 10 hPa, lingering longest (until 29 Nov) below $\sim$40 hPa.

A closed anticyclonic circulation is apparent in Fig. 1 each day, with tongues drawn off the vortex and evidence of high PV air being drawn into and coiled up with low-PV air in the anticyclone (e.g., 21 Nov). Such filamentation is typical of early winter warmings [e.g., *Manney et al.*, 2000] and resultant enhanced mixing in midlatitudes is associated with development of the main vortex/surf zone structure [e.g., *Juckes and O'Neill*, 1988]. The size of the 200 K temperature contour in Fig. 1 suggests little or no minimum temperature increase during the warming. A warm pool of air (>230 K) is drawn into high latitudes (near 60° on 18-24 Nov), which, when averaged with the minimum temperatures at approximately the same latitude, results in a modest zonal mean temperature increase during the warming. Thus, as for many early winter warmings [*Harvey and Hitchman*, 1996], this event appears as an unusually strong, temporary intensification of the Aleutian high.

Fig. 3 shows 60°N eddy geopotential heights before (14 Nov), during (22 Nov, 26 Nov) and after (2 Dec). the warming. The Nov 2000 warming is characterized by a decrease in the tilt of the vortex with height, with very little phase tilt on 22 Nov, just before the peak of the warming. A larger phase tilt is seen before the warming (e.g., 14 Nov), and again after the warming (e.g., 2 Dec). Before and after the warming, a more typical early winter Aleutian high pattern prevails; *Harvey and Hitchman* [1996] showed that a westward tilt similar to that seen on 2 Dec is typical of the Aleutian high. This contrasts with the behavior during major warmings (even those in Dec), when a very strong westward tilt with height develops near the beginning, and persists until after the peak, of the warming [e.g., *Manney et al.*, 1999, and references therein]. A nearly barotropic structure (little tilt with height) is characteristic of Canadian warmings [e.g., *Clough et al.*, 1985; *Juckes and O'Neill*, 1988].

Fig. 4 shows windspeed in equivalent latitude (the latitude that would enclose the same area as a given PV contour)/θ space, similar to figures shown by *Manney and Sabutis* [2000], near the beginning and at the peak of the warming. The windspeed continues to increase during the warming in the mid and upper stratosphere. A double-peak in the upper stratosphere is seen throughout Nov, becoming more pronounced during the warming. The double peak is associated with tongues drawn off the upper stratospheric vortex such that an anticyclone is cutoff in a large region of cyclonic material; this structure is common in early winter [*Manney and Sabutis*, 2000]. Comparison with other years indicates that the double-peak structure is stronger and more persistent in 2000 than in more quiescent early winters. Windspeeds in the mid and upper stratosphere are similar to or stronger than in more quiescent years [e.g., *Manney and Sabutis*, 2000]. In contrast, in the lower stratosphere (near 520 K), the windspeed does not increase much during the warming, whereas in quieter years more strengthening of the lower stratospheric vortex occurs over this time period. Examination of PV gradients indicates that the midstratospheric vortex was stronger than usual after the Nov 2000

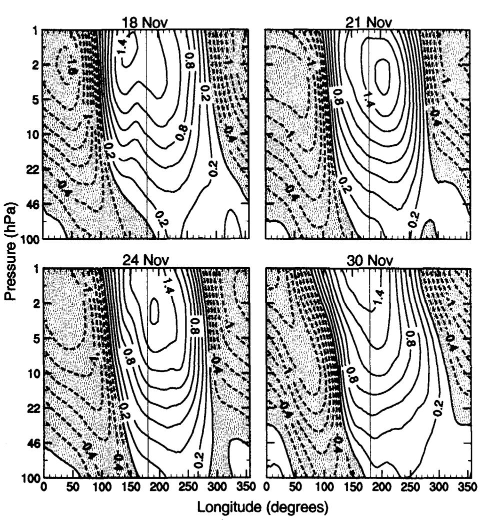

Figure 3. Eddy UKMO geopotential heights (km) at 60°N on 14, 22, 26 Nov, and 2 Dec 2000. Negative regions are shaded with dashed lines; contour interval is 0.2 km.

warming, while the lower stratospheric vortex was considerably weaker than average.

Canadian warmings in early winter are associated with much smaller temperature increases than strong midwinter warmings [*Labitzke*, 1977, 1982; *Clough et al.*, 1985]. North Pole temperatures in the midstratosphere increased by ~15 K during the Nov 2000 warming (Fig. 5). However, Fig. 5 shows no significant increase in minimum 10 hPa temperatures; a small increase from ~19-28 Nov is not seen in NCEP data, and the amount of the increase is comparable to day-to-day variability and differences between datasets. The midstratospheric polar and zonal mean temperature increase resulted from the distortion and displacement of the temperature field (Fig. 1). Polar temperatures in the lower stratosphere also increased by ~15 K. However, in the lower stratosphere, minimum temperatures increased substantially after ~22 Nov and continued to rise until after the recovery of westerlies. Examination of the temperature evolution during previous weaker Canadian warmings indicates similar behavior, i.e., an increase in lower stratospheric minimum temperatures persisting after the warming, and no obvious increase in the midstratosphere. The lower stratospheric temperature increase in Nov 2000 resulted in above average temperatures until mid-Dec 2000, after which a strong wave 2 warming led to temperature increases throughout the stratosphere. While the mid-Dec wave 2 warming had a stronger influence on midstratospheric temperatures, the Nov warming had a much more profound effect on the lower stratosphere, in changes of both polar and minimum temperatures. A plot like Fig. 5 using NCEP data shows similar features; 10-hPa NCEP minimum temperatures are typically 1-2 K lower than UKMO after the 14 Nov change in assimilation systems, and comparable before. UKMO lower stratospheric temperatures run ~1 K higher than NCEP. Slightly lower midstratospheric and higher lower stratospheric temperatures in UKMO than NCEP data were typical of earlier NH winters [*Manney et al.*, 1996].

Comparison with Previous Years

Fig. 6 shows 10 hPa UKMO zonal mean winds for 10 Nov-20 Dec in 2000-1991. The interannual variability shown is typical of that during Nov-Dec in the NH. Fig. 6 shows that zonal wind reversals are rare during early winter minor warmings (seen as reductions in zonal winds, e.g., in late Nov 99, 97, 95, 91, early-mid Dec 2000, 97, 93, 92). The mid-Dec 2000 wave 2 warming seen in temperatures

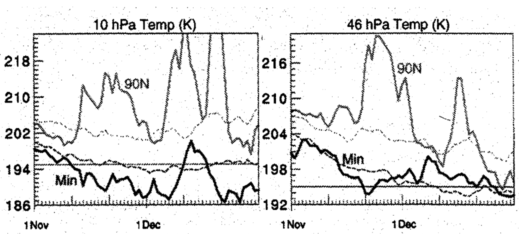

Figure 5. Minimum (black) and 90°N (grey) UKMO temperatures at (left) 10 hPa and (right) 46 hPa for 1 Nov-31 Dec 2000. Dashed lines show corresponding averages for 1991-1999.

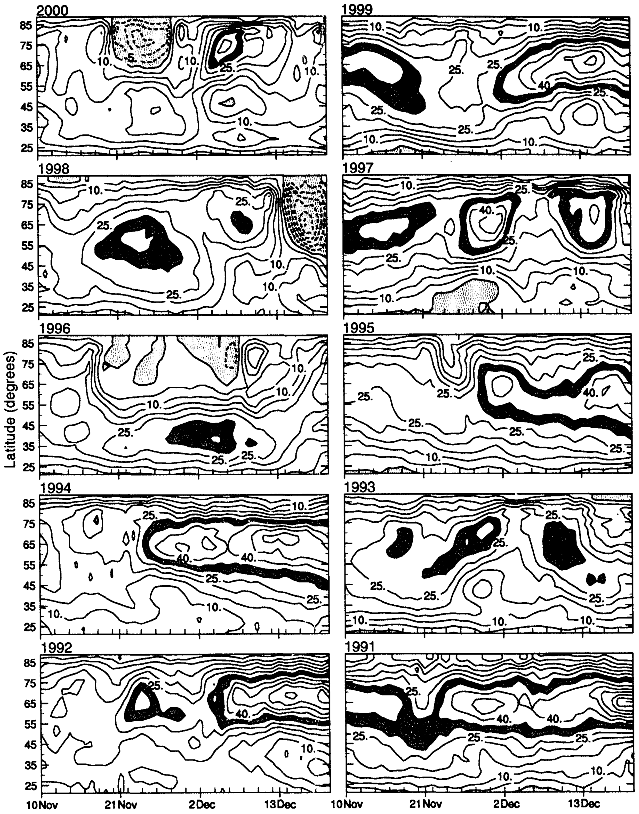

Figure 6. 10 Nov-20 Dec 10 hPa UKMO zonal mean zonal winds for 2000-1991. Contour interval is 5 m/s, light shading less than zero, dark shading 30-35 m/s.

(Fig. 5) produced a prolonged decrease in, but no reversal of, the zonal wind. The strong easterlies in mid-Dec 1998 are the signature of a rare Dec major warming [*Manney et al.*, 1999] when winds reversed for ~6 days. Only in 1996 do high-latitude easterlies occur in conjunction with early winter minor warmings.

Examination of the 23 years of NCEP data indicates similar interannual variability. Early winter minor warmings accompanied by significant wind reversals were seen only in 1979 and 1981. In mid-Dec 1979, and early Dec 1981, winds reversed for ~3-5 days, and maximum easterly speeds were $\lesssim$10 m/s. During the Dec 1987 major warming [*Baldwin and Dunkerton*, 1989] winds reversed for ~10 days. REAN data for 1951-1979 show two brief wind reversals in mid-Dec 1977 and 1978 and one in mid-Nov 1952 associated with Canadian warmings; these data, however, are not directly comparable with NCEP or UKMO data, and not as reliable in the stratosphere, since satellite data were not available to incorporate into these assimilations.

Fig. 7 shows 10 hPa maximum wave 1 and wave 2 geopotential height amplitudes and 90°N temperatures for 2000-1991. The Nov 2000 warming is associated with a persistent wave 1 amplification, negligible and non-amplifying wave 2 (Fig. 7), and weak zonal mean winds before the warming (Fig. 6). The warming in 1996 responsible for the wind reversal around 5 Dec was similar in character. Other minor warmings that were qualitatively similar, in these characteristics and those discussed above, to the Nov 2000 event were around 25 Nov 1999 (discussed by *Manney and*

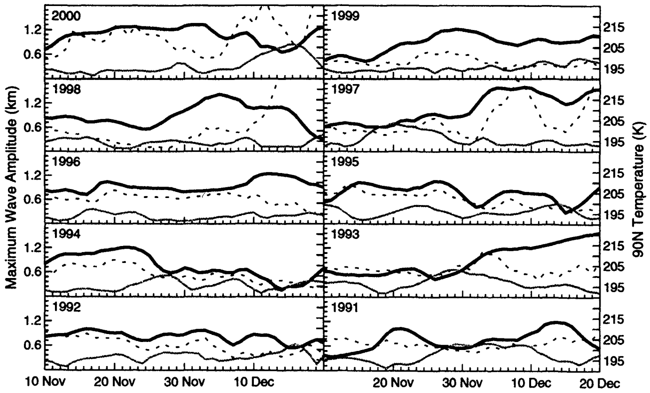

Figure 7. Maximum UKMO geopotential height wave 1 (black) and wave 2 (grey) amplitudes (km), and 90°N temperatures (K, dashed), for 10 Nov-20 Dec, 2000-1991.

Sabutis [2000] and *Sabutis and Manney* [2000]), 6 Dec 1997, 12 Nov 1994 (shown in *Manney et al.* [2000]), 14 Dec 1993, and 20 Nov 1991 (discussed by *Rosier et al.* [1994]). During each event, a large wave 1 amplifies, wave 2 is negligible, and a modest polar temperature increase is associated with a warm pool at high latitudes. The Nov 2000 warming stands out amongst these and previous events as an unusually early wind reversal, and the strongest, most prolonged wind reversal associated with an early winter minor warming.

Summary

A unique Canadian minor warming in Nov 2000 led to a zonal mean wind reversal from ~65°N to the pole for ~9 days. Wind reversals were associated with Canadian warmings only three times before in the last 23 years; these reversals were shorter, weaker, and all occurred in early to mid-Dec. Data prior to 1979, although not directly comparable, suggest wind reversals associated with Canadian warmings only six times (including Nov 2000) in the past 50 years. The warming in Nov 2000 was characterized by wave 1 amplification and strong easterlies in the mid and lower stratosphere, barotropic structure, and a modest polar temperature increase. In the midstratosphere there was a very large displacement and distortion, but no weakening or significant warming, of the vortex - i.e., a strong, temporary intensification of the Aleutian high. Midstratospheric minimum temperatures did not increase during the event, but a warm pool moved up near 60°N resulting in the modest polar temperature increase. In contrast, major warmings are characterized by large phase tilts, strongest easterlies in the upper stratosphere, weakening and shrinkage of the vortex, and large temperature increases in the midstratosphere. A substantial increase in lower stratospheric temperatures was associated with the Nov 2000 minor warming, along with a pause in the strengthening of the lower stratospheric vortex. The common early-winter double jet in the upper stratosphere was more pronounced than in quieter years. These qualitative characteristics of the Nov 2000 warming are common during early winter warmings. However, the Nov 2000 warming was unique in its timing, intensity and duration - the strongest Canadian warming in at least 23 - very likely 50 - years. The intensity of stratospheric warmings in early winter when the vortex is developing has profound implications for temperatures, vortex strength and transport, especially in the mid and lower stratosphere, during the entire winter following. The Nov 2000 Canadian warming had a substantial impact on minimum temperatures and vortex development in the lower stratosphere.

Acknowledgments. We thank the Met Office, NCEP and the NCAR/NCEP Reanalysis Project for meteorological data. Work at the Jet Propulsion Laboratory, California Institute of Technology, was done under contract with the National Aeronautics and Space Administration.

References

Andrews, D. G., J. R. Holton, and C. B. Leovy, *Middle Atmosphere Dynamics*, 1st ed., Academic Press, San Diego, Calif., 1987.

Baldwin, M. P., and T. J. Dunkerton, The stratospheric major warming of early December 1987, *J. Atmos. Sci.*, *46*, 2863–2884, 1989.

Clough, S. A., N. S. Grahame, and A. O'Neill, Potential vorticity in the stratosphere derived using data from satellites, *Q. J. R. Meteorol. Soc.*, *111*, 335–358, 1985.

Harvey, V. L., and M. H. Hitchman, A climatology of the Aleutian high, *J. Atmos. Sci.*, *53*, 2088–2101, 1996.

Juckes, M. N., and A. O'Neill, Early winter in the Northern Hemisphere, *Q. J. R. Meteorol. Soc.*, *114*, 1111–1125, 1988.

Labitzke, K., Interannual variability of the winter stratosphere in the Northern Hemisphere, *Mon. Weather Rev.*, *105*, 762–770, 1977.

Labitzke, K., On the interannual variability of the middle stratosphere during the Northern winters, *J. Met. Soc. Japan*, *60*, 124–139, 1982.

Lorenc, A. C., et al., The Met. Office global three-dimensional variational data assimilation scheme, *Q. J. R. Meteorol. Soc.*, *126*, 2991–3012, 2000.

Manney, G. L., and J. L. Sabutis, Development of the polar vortex in the 1999-2000 Arctic winter stratosphere, *Geophys. Res. Lett.*, *27*, 2589–2592, 2000.

Manney, G. L., et al., Comparison of U. K. Meteorological Office and U. S. National Meteorological Center stratospheric analyses during northern and southern winter, *J. Geophys. Res.*, *101*, 10,311–10,334, 1996.

Manney, G. L., et al., Simulation of the December 1998 stratospheric major warming, *Geophys. Res. Lett.*, *26*, 2733–2736, 1999.

Manney, G. L., et al., Lamination and polar vortex development in fall from ATMOS long-lived trace gases observed during November 1994, *J. Geophys. Res.*, *105*, 29,023–29,038, 2000.

Rosier, S. M., B. N. Lawrence, D. G. Andrews, and F. W. Taylor, Dynamical evolution of the northern stratosphere in early winter 1991/92, as observed by the Improved Stratospheric and Mesospheric Sounder, *J. Atmos. Sci.*, *51*, 2783–2799, 1994.

Sabutis, J. L., and G. L. Manney, Wave propagation in the 1999-2000 Arctic early winter stratosphere, *Geophys. Res. Lett.*, *27*, 3205–3208, 2000.

Gloria L. Manney, Joseph L. Sabutis, Department of Physics, New Mexico Highlands University, Las Vegas, NM 87701 (manney@mls.jpl.nasa.gov, jsabutis@physics.nmhu.edu).

Richard Swinbank, Met Office, London Road, Bracknell, Berkshire RG12 2SZ, UK (richard.swinbank@metoffice.com).

(Received February 6, 2001; revised April 18, 2001; accepted April 30 2001.)