The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s

Gloria L. Manney,1,2 Kirstin Krüger,3,4 Joseph L. Sabutis,5 Sara Amina Sena,6 and Steven Pawson7

Received 19 August 2004; revised 24 November 2004; accepted 3 December 2004; published 25 February 2005.

The 2003–2004 Arctic winter was remarkable in the ~50-year record of meteorological analyses. A major warming beginning in early January 2004 led to nearly 2 months of vortex disruption with high-latitude easterlies in the middle to lower stratosphere. The upper stratospheric vortex broke up in late December, but began to recover by early January, and in February and March was the strongest since regular observations began in 1979. The lower stratospheric vortex broke up in late January. Comparison with 2 previous years, 1984–1985 and 1986–1987, with prolonged midwinter warming periods shows unique characteristics of the 2003–2004 warming period: The length of the vortex disruption, the strong and rapid recovery in the upper stratosphere, and the slow progression of the warming from upper to lower stratosphere. January 2004 zonal mean winds in the middle and lower stratosphere were over 2 standard deviations below average. Examination of past variability shows that the recent frequency of major stratospheric warmings (7 in the past 6 years) is unprecedented. Lower stratospheric temperatures were unusually high during 6 of the past 7 years, with 5 having much lower than usual potential for polar stratospheric cloud (PSC) formation and ozone loss (nearly none in 1998–1999, 2001–2002, and 2003–2004, and very little in 1997–1998 and 2000–2001). Middle and upper stratospheric temperatures, however, were unusually low during and after February. The pattern of 5 of the last 7 years with very low PSC potential would be expected to occur randomly once every ~850 years. This cluster of warm winters, immediately following a period of unusually cold winters, may have important implications for possible changes in interannual variability and for determination and attribution of trends in stratospheric temperatures and ozone.


1. Introduction

[2] The detection and attribution of trends in the Arctic winter stratosphere are among the most complex and important issues in furthering our understanding of climate change and ozone recovery. The Arctic winter stratosphere is thought to be at a threshold where cooler and wetter conditions could lead to severe ozone loss becoming common [Chipperfield and Pyle, 1998; Waibel et al., 1999; Ramaswamy et al., 2001; WMO, 2003, and references therein]; several indications of decreasing temperature trends have been noted [WMO, 1999, 2003; Ramaswamy et al., 2001, and references therein]. However, large interannual and intraseasonal variability in Arctic winter makes detection and attribution of trends extremely challenging. Pawson and Naujokat [1999, and references therein], hereinafter referred to as PN99, reported on the unusually cold winters in the mid-1990s, their relationship to past variability, and their consistency with the expected cooling of the lower stratosphere. They noted that the clustering of cold winters may be related to year-to-year randomness, an idea supported by apparent randomness of warm and cold winters in long-term climate model simulations [e.g., Hamilton, 1995; Taguchi and Yoden, 2002], but noted that the cold years seemed to be getting colder. Consistent with this, Rex et al. [2004] concluded that in the cold years the potential for polar stratospheric cloud (PSC) existence throughout the winter has increased in the past ~30 years in a manner consistent with ozone loss estimates. Several studies suggest increased persistence of the spring Arctic vortex [Waugh et al., 1999; Offermann et al., 2004], but there is no evidence of a clear
relationship between midwinter (January–February) vortex strength/coldness and spring persistence [Waugh et al., 1999]. Several studies suggest the existence of weaker/warmer and stronger/colder vortex regimes in the Arctic stratosphere [Perlwitz and Graf, 2001; Perlwitz and Harnik, 2003, and references therein]. Others suggest that anthropogenically caused changes may project on natural modes of atmospheric variability, and thus might be manifested in a change in occurrence frequency of such regimes [e.g., Corti et al., 1999]. Such changes might be consistent with stepwise temperature changes [e.g., Pawson et al., 1998], or with evidence for a shift from weaker/warmer to stronger/colder vortex regimes in the late 1970s [e.g., Christiansen, 2003]. In addition to large uncertainties in observed temperature trends in the Northern Hemisphere (NH) lower stratosphere, climate model simulations tend to underestimate these trends, and suggest that observed changes in ozone and greenhouse gases (GHGs) may be insufficient to explain the trends [Austin et al., 2003; Shine et al., 2003; WMO, 2003, and references therein].

[1] Studies showing substantial cooling trends in the Arctic lower stratosphere have not included the most recent NH winters, which have been unusually warm and dynamically active. The cold, more quiescent winters studied by Rex et al. [2004] were characterized, among other things, by having no “major” (defined as events where both the zonal mean temperature gradient and zonal mean winds at 10 hPa reverse sign poleward of 60°) stratospheric warmings [e.g., PN99]. Before 1990, major warmings occurred about once every two years [Labitzke, 1982; Naujokat and Labitzke, 1993; Labitzke et al., 2002, and references therein]. No major warmings occurred in nine consecutive winters from 1989–1990 through 1997–1998 (a strong warming in early February 1990 has sometimes been classified as major, but the 10 hPa zonal mean wind did not reverse sign at 60°N) [e.g., PN99; Manney et al., 1999; Labitzke et al., 2002]. In contrast to this previous behavior, we show below that there have been seven major warmings in five of the past six years. The 2003–2004 winter was particularly remarkable, with an extended period from early January through mid-February with high-latitude easterlies. The 1999–2000 winter was unusually cold [e.g., Manney and Sabatis, 2000; Rex et al., 2004], but each other winter beginning with 1998–1999 had at least one major warming, with two each in 1998–1999 and 2001–2002 [Manney et al., 1999; Naujokat et al., 2002].

[2] The occurrence of major warmings, especially early in winter, is associated with warmer conditions and hence reduced PSC formation potential following the vortex disruption, as shown in Figure 1. Following the cold winters in the mid-1990s [PN99], only in 1999–2000 and 2002–2003 was there significant ozone loss [and references therein Rex et al., 2004] in the past seven years. The 2002–2003 early winter was unusually cold, but a major warming in late January was followed by two nearly major warmings in mid-February and early March, so potential for ozone loss was cut off by late January [after which largest ozone loss typically occurs, [e.g., WMO, 2003, and references therein]. The 1997–1998 winter was also warm, although no major warmings occurred [e.g., PN99]. We examine here the unusual behavior of the stratosphere in recent winters, focusing on 2003–2004, in the context of the previous record of interannual variability in Arctic polar vortex conditions, and with an eye to the consequences of this behavior for deducing and attributing trends. Several gridded meteorological data sets have been examined and are used herein, depending on their appropriateness for the specific application, as described in Appendix A and discussed further there. We focus on the “satellite era” since 1978–1979 when operational satellite data have been routinely used to constrain stratospheric temperatures in the analyses. We show interannual variability in vortex evolution and stratospheric warming activity using zonal mean winds. While this view does not fully capture the three-dimensional evolution of the vortex, it does provide a succinct, objective overview that can be compared with many previous studies [e.g., PN99, and references therein]. Further, the conventional definition of a major warming, which is cast in a zonal mean framework, while somewhat arbitrary, provides a useful objective measure for which no viable alternative has been developed. However, other ways of viewing polar vortex evolution and stratospheric warming activity [e.g., Waugh and Randel, 1999; Harvey et al., 2002, and references therein] will undoubtedly provide further insight in future studies.

Figure 1. Time series of area (percent of Northern Hemisphere) at 50 hPa with temperatures less than \( T_{\text{NAT}} \) for 1 December through 31 March in 1991–1992 through 2003–2004 from NCEP/CPC analyses. Dates of major warmings (first day of wind reversal at 60°) are marked with “W”s.
In section 2 we detail the synoptic evolution during the 2003–2004 NH winter in comparison with two winters with some similar characteristics. The recent winters are shown in the context of interannual variability in section 3. Section 4 provides a summary and discussion. This work extends that of PN99, documents the recent warm Arctic winters (focusing on 2003–2004), and characterizes interannual variability including these years, providing background for future studies of variability and trends in Arctic vortex characteristics and ozone loss.


Examination of the meteorological analyses and studies thereof in the past 50 years, [e.g., Labitzke, 1982; Naujokat and Labitzke, 1993] shows only two winters since 1978–1979 with prolonged midwinter warming periods that may be comparable to that in 2003–2004: 1984–1985 (also described by Randel and Boville [1987]) and 1986–1987. We compare the evolution of the polar vortex in 2003–2004 with that in these two winters to highlight the remarkable behavior in 2003–2004.

Figure 2 shows 10 hPa zonal mean winds and wave 1 and wave 2 in geopotential height for these three winters. High-latitude easterlies in 2004 lasted nearly two months, from the beginning of January through late February. High-latitude easterlies lasted approximately one month in the other years shown, from late December through January in 1984–1985 and from late January through late February in 1987 (but with a larger region of easterlies during that period). After the return to westerlies in 2004, the vortex recovered to become unusually strong for late winter; similar behavior was seen in 1985 when the warming period was also early, though the final warming was much earlier (at a more typical time); in 1987, the midstratospheric vortex never recovered to a typical midwinter character. The major warming that began in late December 2003 was preceded by a very large wave 1 amplification. In mid-January 2004 a wave 2 amplification (more prominent at lower altitudes, not shown) led almost immediately to another prolonged wind reversal (though not quite a major warming) and the splitting of the lower stratospheric vortex (see below). A similar pattern was seen in 1987, but with a stronger wave 2 pulse in late January following the wave 1 pulse, and the major warming criteria fulfilled throughout the period. The 1984–1985 major warming, in contrast, was initially a “wave 2” type warming, with the second warming pulse triggered by wave 1 amplification.

Figure 3 shows the accompanying evolution of north pole temperatures. In 2004, low temperatures were quickly re-established at high altitudes after mid-January, and by early February (while winds were still easterly) midstratospheric temperatures were comparable to those before the warming. This is in contrast to the previous years with prolonged warmings: In 1985, low temperatures were quickly re-established at high altitudes after mid-January, and by early February (while winds were still easterly) midstratospheric temperatures were comparable to those before the warming. In 1987, when the warming period was later, prewarming temperatures were never re-established in the middle stratosphere. Lower stratospheric temperatures after the warming remained unusually high for the remainder of the winter in all three years. Thus, as will
North Pole Temperature (K)

Figure 3. Time series for 1 December through 30 April of 90°N temperatures (K) as a function of pressure in (top) 1984–1985, (middle) 1986–1987, and (bottom) 2003–2004. The 1980s fields are from ERA-40 data; 2003–2004 are from operational ECMWF. Contour interval is 5 K with light shading above 240 K and dark shading below 210 K. be seen below, while the character of these three prolonged warming periods was quite different in detail, the effect on lower stratospheric temperatures was similar.

[9] Maps of sPV (potential vorticity scaled in “vorticity units”, e.g., Dunkerton and Delisi [1986] and Manney et al. [1994b]) (Figure 4) show the synoptic evolution of the vortex and temperatures during the 2003–2004 winter in the upper (1700 K, ~50 km), middle (850 K, ~30 km) and lower (520 K, ~20 km) stratosphere. The vortex began to shrink and shift off the pole by 11 December in the upper stratosphere, and by 19 December (not shown) in the middle stratosphere; by 27 December (Figure 4), the vortex had broken down and easterlies appeared (see below) in the upper stratosphere, while it had shrunk appreciably but not decreased in depth or strength in the middle stratosphere; in the lower stratosphere the vortex shifted off the pole, but continued to gradually strengthen through this date. 10 hPa 60°N winds became easterly on ~2 January (Figure 2), and by 8 January (Figure 4), the middle stratospheric vortex was a weak crescent near 40°N, with a large region of high temperatures near the pole, very similar to the pattern at the peak of the December 1998 major warming [Manney et al., 1999]. The vortex had weakened slightly and shifted further off the pole in the lower stratosphere, while in the upper stratosphere it began recover. By 18 January, the vortex in the upper stratosphere had recovered to a strength, size and pole-centered position typical of a strong NH midwinter vortex, and did not begin to weaken again until mid-March. In contrast, the vortex weakened even further in the middle stratosphere and split into two fragments (consistent with the wave 2 amplification seen in Figure 2) and continued to weaken gradually in the lower stratosphere. On 1 February, the lower stratospheric vortex split, with the easternmost fragment rapidly weakening and then coalescing again with the western fragment by 17 February. During this period, the vortex also reformed in the middle stratosphere, but remained extremely weak, only beginning to strengthen substantially after ~23 February (not shown); lowest temperatures at 850 K moved back near the pole by 1 February, and by 17 February (although the vortex was still disrupted) were lower than before the warming. By 20 March, the vortex had recovered to a size, strength and coldness greater than usual for March in the middle stratosphere, while it strengthened only slightly and remained very small and weak for the rest of the winter in the lower stratosphere; the upper stratospheric vortex by 20 March had begun to weaken prior to the final warming. The long period when the vortex was strong in the upper stratosphere but very small and weak in the lower to middle stratosphere was quite uncommon. The final warming was late, with 10 hPa zonal mean easterlies appearing only at the end of April, as discussed further in section 3.

[10] Figure 5 shows cross sections of zonal mean winds on the same days as in Figure 4, illustrating the relatively brief appearance of easterlies recovering to a strong westerly jet by mid-January in the upper stratosphere, and the very prolonged period of high-latitude easterlies in the middle and lower stratosphere. High-latitude zonal mean winds returned to westerly at 10 hPa in mid-February, and to very weak westerlies in the lower stratosphere only at the end of February.

[11] The 1700, 850 and 520 K sPV maps similar to those in Figure 4 are shown in Figure 6 during the 1984–1985 and 1986–1987 winters, a few days after the major warming condition was fulfilled (comparable to 8 January 2004), and well into the recovery, but when the vortex was still weak in the middle stratosphere (comparable to 17 February 2004). Figure 7 shows cross sections of zonal mean winds on the same days. In contrast to 2004, when the vortex already showed signs of recovery in the upper stratosphere when the major warming condition was fulfilled in the middle stratosphere, the recovery was not as rapid in the upper stratosphere in either 1985 or 1987. The vortex in the lower stratosphere shortly after the peak of the warming (3 January 1985, 26 January 1987, compared to 8 January 2004) was more disrupted in 1985 and 1987 than in 2004, with strong easterlies extending further into the lower stratosphere (especially during the wave 2 warming in 1985). The behavior seen in these earlier years is more typical of that during major warmings [e.g., Naujokat and Labitzke, 1993; Manney et al., 1994a, 1999; Naujokat et al., 2002, and references therein]. During the recovery, the patterns were more similar between the years, but the vortex did not recover as strongly in the upper stratosphere, especially in 1987 when the warming period was later. Also, the vortex in 1985 recovered much more substantially
in the lower stratosphere than in either 2004 or 1987; this (as well as the very strong easterlies extending through the lower stratosphere before the recovery) may be more characteristic of a wave 2 warming, as weak recovery in the lower stratospheric has also been reported after other early wave 1 warmings [e.g., Baldwin and Dunkerton, 1989; Manney et al., 1999; Naujokat et al., 2002, and references therein]. Overall, the synoptic behavior during the prolonged 2003–2004 warming period was remarkable, even compared to the most similar previous events.

3. Interannual Variability and the Historical Context

[12] We now examine 2003–2004 and the other recent warm NH winters in the context of previous patterns of

Figure 4. The (top row) 1700 K, (middle row) 850 K, and (bottom row) 520 K sPV (10^{-4} s^{-1}) maps with overlaid temperature contours on 27 December 2003, 8 and 18 January, 1 and 17 February, and 20 March 2004. Temperature contours are 220–280 K by 10 K at 1700 K, 200–260 K by 10 K at 850 K, and 195–225 K by 5 K at 520 K. Fields are from GEOS-4 analyses. Domain is from equator to pole with dashed circles at 30° and 60°N; 0° longitude is at the bottom and 90°E to the right.

Figure 5. Latitude-pressure cross sections of zonal mean wind on 27 December 2003, 8 and 18 January, 1 and 17 February, and 20 March 2004 from GEOS-4 analyses. Contour interval is 5 m/s, with values less than zero shaded.
interannual variability, focusing on the past 26 years, when operational satellite data have been included in the meteorological analyses.

An overview of 10 hPa high-latitude zonal mean winds for 1978–1979 through 2003–2004 is given in Figure 8, along with an indication of the occurrence of major warmings. For this purpose, the “standard” WMO criteria are used, that is, both the temperature gradient and the zonal mean winds north of 60° change sign; the major warmings in March 1980, February 1984, March 1986, and February 1988 have been classified as “major final” warmings [e.g., Naujokat and Labitzke, 1993; Labitzke et al., 2002; Naujokat and Labitzke [1993] also classified the warming in early February 1991 as major, but the zonal wind did not change sign at 60°N. Besides 2004, 1985 was the only other year in the record with a prolonged period of easterly or near-zero winds in January, and 1987 the only other year with a comparably prolonged midwinter period of easterly winds. In recent years, major warmings occurred in December 1998, February 1999, February 2001, December 2001, February 2002, January 2003, and January 2004, a total of seven in five of the past six winters. There is no other period since 1978–1979 with as much warming activity; the most similar period is 1983–1984 through 1988–1989 when there were five major warmings in six years, and several of those were early (e.g., December 1987) or late (e.g., late February 1984) in winters with otherwise strong, cold vortices. Examination of the long-term reanalyses (ERA-40 to 1957 and REAN to 1948, not shown) and FUB data set indicate one other period with five major warmings in six years (1967–1968 through 1972–1973) and one other prolonged warming period in January (a “wave 1” warming in January 1970). As noted by Naujokat et al. [2002], many of the recent stratospheric warmings have been atypically early (three in December/early January and one in mid-January), in contrast to the more typical occurrence in February before the 1990s [e.g., Naujokat and Labitzke, 1993; Labitzke et al., 2002]. However, the unusual frequency of major warmings in recent years has not resulted in earlier final warmings; in fact, the earliest spring vortex breakup (seen in Figure 8 in the final reversal to easterlies) in the past six years was in 2000, the one cold

Figure 6. The (top row) 1700 K, (middle row) 850 K, and (bottom row) 520 K sPV maps (10^{-4} s^{-1}) with overlaid temperature contours on 3 January and 17 February 1985 and 26 January and 11 March 1987. Data are from ERA-40 analyses; blank regions at 1700 K are where that level is above 1 hPa, the top level provided in the ERA-40 fields. Layout is as in Figure 4.

Figure 7. Latitude-pressure cross sections of zonal mean wind on (top row) 3 January and 17 February 1985 and (bottom row) 26 January and 11 March 1987 from ERA-40 analyses. Contour interval is 5 m/s, with values less than zero shaded.
The uniqueness of 2003–2004 even among the recent warm winters is underscored in the time series of January and February average monthly mean 60–80°N winds in the upper, middle and lower stratosphere and their frequency distribution in the middle stratosphere (Figure 9). January 2004 10 hPa winds were the lowest in the record, and 50 hPa winds were similarly low only in 1984–1985, with both being over two standard deviations below the 1979–2004 average. Easterlies were present in a large region throughout the middle and lower stratosphere in January and February.
The dynamical activity shown above is reflected in temperatures, though not in a simple one-to-one manner. Figure 10 shows the number of days in each year with temperatures low enough for NAT or ice PSC formation at 50 hPa, and the average area over the season (December through March) where temperatures were low enough for NAT PSC formation (note that the latter is essentially the same diagnostic as \( PN99 \)'s \( A_t \), except scaled by the fixed number of days in the season). Though they did not have major warming according to the criteria used here, 1981–1982, 1990–1991, and 1997–1998 were all very warm winters with low PSC potential, which underscores the complexity of the relationship between winds, vortex evolution and temperatures, and the necessity of considering the full synoptic evolution in characterizing a winter. The recent winters stand out in Figure 10, with three of the last seven (1998–1999, 2001–2002 and 2003–2004, those with the earliest major warmings) having only a few days conducive to PSC formation; the average area where PSCs could form in these years is near zero, and over one standard deviation below the 1978/1979–2003/2004 average. The only other year in the satellite era comparable to these three was 1984–1985, in which there was also an early major warming (1987–1988, the only other year with a major warming before mid-January, also having well below average PSC potential). Two other years in the last seven, 1997–1998 and 2000–2001, also had unusually low (near one standard deviation below average) integrated areas where PSCs could form. A Monte Carlo simulation of these data suggests that the pattern seen between 1997–1998 and 2003–2004 would occur randomly once every 853 years. (Although the observed time series is not random (because the minimum number of days is limited to zero), it was assumed to be normally distributed with mean and variance estimated from the data. The estimate was obtained by tallying in each simulation the number of years until five out of seven consecutive years occurred that deviated from the mean with a value lower than the average of the lowest five of the last seven points in Figure 10. 50,000 simulations were performed and averaged. Because of the zero-day lower bound on the data, this estimate should be taken as a lower limit.) In the long-term reanalyses and in the historical FUB data (see Appendix A), a similarly warm period is apparent in 1965–1966 through 1970–1971, coinciding approximately with the previous cluster of frequent major warmings.

As noted by \( PN99 \), 1992–1993 and 1994–1995 through 1996–1997 stand out as unusually cold, as does 1999–2000. Exceptions 1999–2000, the past seven years had remarkably little potential for PSC formation and hence ozone loss. The average potential for PSC formation in the individual months of January and February is highlighted in Figure 11. The high PSC formation potentials in 1992 through 1997 stand out in both months. Also striking is the recent cluster of warm years and how different the expectation for PSC formation potential in January and February appears (background histograms) when the past seven years are included in the series; the recent years more than double the frequency of lowest PSC potentials in January and nearly double it in February. While these patterns would appear somewhat less extreme in the full 50-year record (which includes the warm years in the late
1960s), the recent pattern is nevertheless quite extraordinary. A Monte Carlo simulation of the detrended February data suggests that the pattern of three extremely warm years in succession between 2001–2002 and 2003–2004 would occur randomly once every 556 years, while the pattern of six extremely warm years during the seven years 1997–1998 through 2003–2004 would occur randomly once every 12,908 years. (The time series were detrended and verified to be random; these random series were assumed to be normally distributed, with mean and variance calculated from the data. 50,000 simulations were performed and averaged in both cases.)

To give an overview of the temperatures throughout the stratosphere, Figure 12 shows time series of monthly average north pole temperatures for January and February at 50, 10 and 2 hPa; other diagnostics, such as minimum and 60–90°N average temperatures, exhibit similar patterns. High-latitude 50 hPa temperatures were unusually high in the past three years and 1998–1999 in January, and the past four years and 1998–1999 in February, with January 2004 temperatures matching the previous highest in 1985. 50 hPa north pole temperatures in January and February 2004 were over a standard deviation above average. In the middle stratosphere, 2004 temperatures were unusually high only during January, consistent with the synoptic evolution shown in section 2. In keeping with the brief disruption and rapid recovery of the vortex in the upper stratosphere, 2 hPa temperatures were lower than usual in both January and February 2004 (February the lowest in the 26-year record, over three standard deviations below average). Similar behavior, albeit less extreme, was seen in January/February 1985 and in February 1987 following those prolonged warming periods, and in the other recent years with early warmings (1998–1999 and 2001–2002). This pattern of strong redevelopment of the upper stratospheric vortex has been seen in previous studies of stratospheric warmings [e.g., Labitzke, 1972; Naujokat and Labitzke, 1993; Labitzke and van Loon, 1999, and references therein]. Over the full winter (not shown), 2003–2004 lower stratospheric high-latitude temperatures were anomalously high, and upper and middle stratospheric temperatures atypically low. High temperatures in March are consistent with the relationship found by Newman et al. [2001] between temperatures...
January-February wave activity (very high during strong stratospheric warmings) and March lower stratospheric temperatures, though they do not, as shown above, indicate a shorter winter.

4. Summary and Implications

[21] The years 1998–1999, 2001–2002 and 2003–2004 each had only a few days with temperatures below PSC formation thresholds; six of the last seven years had much lower than usual PSC formation potential; such a pattern might be expected to occur randomly approximately every 850 years.

[24] In the past seven years, the frequency of occurrence in the past 26 years of winters with extremely low PSC potential nearly doubled.

[25] The 50 hPa north pole temperatures in January and February 2004 were among the highest on record, with atypically high lower stratospheric temperatures during six of the past seven years.

[26] Upper stratospheric temperatures after January, and averaged over the 2003–2004 winter, were the lowest on record; middle stratospheric average winter temperatures were also atypically low.

[27] Four of the seven major warmings in the past six years were unusually early, in December or early January.

[28] The frequency of major warmings and cluster of warm Arctic winters is unprecedented, with only one previous period (1965–1966 through 1970–1971) with similarly high temperatures, but fewer major warmings.

[29] The series of several very cold and then several very warm Arctic winters may have important implications for diagnosis and attribution of trends and changes in the Arctic circulation. Because the determination of trends depends most strongly on the deviations in the beginning and ending years of the record [e.g., Weatherhead et al., 2004], the previous cold years may have biased calculated temperature trends toward larger decreases, while the recent warm winters would bias them toward much less negative trends. Since ozone loss in the lower stratospheric vortex (which depends critically on temperature, and may also be strongly influenced by the structure and evolution of the vortex [e.g., Degorska and Rajewksa-Wiech, 1996; Manney et al., 2003a]), is a large influence on NH extratropical ozone trends and variability [e.g., Andersen and Knudsen, 2002; Rex et al., 2004, and references therein], and ozone variations are also closely coupled with temperature variations by dynamical processes [e.g., Salby et al., 2002; Salby and Callaghan, 2002], the high temperatures and limited ozone loss in six of the past seven years are expected to significantly influence apparent NH ozone trends. Recent studies have suggested a slowdown in ozone decline or beginning of an increase in ozone (both in column and in the upper stratosphere) in some regions starting in the 1996–1998 time frame [e.g., Fioletov et al., 2002; Newchurch et al., 2003; Steinbrecht et al., 2004a, 2004b; Cunnold et al., 2004]. Such changes appear to be consistent with changes in chlorine loading, and are not limited to the Arctic winter. However, this period does mark a transition between periods of cold/quiescent and warm/active winters; influences of lower stratospheric winter temperature and ozone changes can be global and extend beyond the winter season and throughout the stratosphere [e.g., Fioletov and Shepherd, 2003; Salby and Callaghan, 2004]. Thus additional care should be taken in the attribution of changing trends during this period.

[30] The cluster of very warm winters following several very cold winters raises the interesting question of whether we may be experiencing a change in the patterns or
magnitude of interannual variability in the Arctic stratosphere. While PN99 and Rex et al. [2004] showed evidence that the cold years are becoming more conducive to ozone loss, there has certainly overall been much less ozone loss potential in the past seven years. Pawson et al. [1998] showed apparently discontinuous changes in temperature through the mid-1990s, and Labitzke and Kunze [2005] noted the overall warmer winters in the 1960s relative to the 1990s (also noted in Appendix A), and changes in monthly winter temperature trends in the late 1970s. Christiansen [2003] showed evidence for a shift to a stronger, colder vortex regime in the late 1970s; the recent warm winters raise the possibility of a shift back to a more active regime. Corti et al. [1999] noted that the response to anthropogenic forcing may project largely on modes of natural variability, thus such changes could be related to anthropogenic effects. On the other hand, millennial integrations of simple climate models with no anthropogenic forcing do show random distributions of warm winters [e.g., Taguchi and Yoden, 2002], which could result in similar clustering.

[31] Changes in interannual variability, or "regime shift"-type changes in dynamical activity, may reflect changes in the patterns of wave activity forcing the stratospheric circulation. It has been suggested that such changes may accompany increasing GHGs [Austin et al., 2003; Shine et al., 2003; WMO, 2003, and references therein] and may be an important factor in lower stratospheric temperature trends and the timing of ozone recovery. Some studies indicate that cooling of the polar stratosphere in winter has been enhanced by changes in dynamical activity; both early ozone recovery related to an increase in dynamical activity, and delayed recovery due to decreased wave activity have been reported in climate model simulations [Austin et al., 2003; Shine et al., 2003; WMO, 2003, and references therein]. Given the large uncertainties in and inconsistent results of current studies, both characterizing and understanding the reasons for recent variability will be important to improving climate models and thus predicting future changes.

[32] Regime shifts or changes in variability also have important implications for trend detection, since the time required to confidently detect a trend depends on both the variance (year-to-year variability) and the autocorrelation (degree of dependence of one point in the time series on the previous one) [e.g., Weatherhead et al., 1998, 2000; Reinsel et al., 2002], both of which may be affected by changing amounts or patterns of variability. Both larger variance (if interannual variability were greater) and higher autocorrelation (as might be indicated by groups of years with similar characteristics) would increase the time needed to detect a trend. In addition, discontinuous changes may affect the appropriateness of linear or other models for characterizing trends [e.g., Seidel and Lanzante, 2004].

[33] The recent cluster of warm Arctic winters, with 2003–2004 standing out as the extreme example, raises many provocative questions regarding our understanding of and ability to characterize trends and variability in the NH winter. By studying in detail the origins and life cycles of stratospheric warmings, the full three-dimensional evolution of the polar vortex, how trace gases such as ozone are transported, and the patterns of tropospheric variability underlying the stratospheric flow, we can use this recent unusual behavior of the stratosphere as a laboratory to test and expand our knowledge of the processes underlying variability in the NH winter stratosphere and possible relations between that variability and changes in climate.

Appendix A: Meteorological Data Sets and the Presatellite Record

[34] Several meteorological analyses are available that extend back at least through the 1978–1979 Arctic winter, when operational satellite observations began to be used routinely in these analyses (referred to as “the satellite era”), as well as several more for shorter periods. No single data set is ideal for all purposes, so we use several of them here for different applications. We show the synoptic evolution during the 2003–2004 winter using NASA’s Global Modeling and Assimilation Office’s Goddard Earth Observation System-4 (GEOS-4) analyses [e.g., Lin, 2004; Manney et al., 2005; S. Li et al., Sensitivity of middle atmospheric analysis to the representation of gravity wave drag, submitted to Journal of Atmospheric Science, 2004], which provide a high-resolution (1 × 1.25° latitude × longitude) state-of-the-art assimilation product. For 1978–1979 to the present, we have examined NCEP (National Centers for Environmental Prediction)CPC (Climate Prediction Center) objective analyses, NCEP/NCAR (National Center for Atmospheric Research) Reanalyses (for the lower stratosphere, hereinafter REAN), ECMWF’s (European Centre for Medium-Range Weather Forecasts) ERA-40 reanalysis through 2001–2002, augmented by operational ECMWF data for the past two winters, and Freie Universität Berlin (FUB) subjective analyses through 2000–2001; in addition, the record from 1991–1992 through the present has been compared with UK Met Office analyses. Though we focus on the satellite era, since 1978, the ERA-40, REAN, and FUB data sets were also used to examine general characteristics of the flow in earlier years. A more detailed description of these data sets and the consequences of some differences between them to studies of the winter stratosphere is given by Manney et al. [2003b, 2005] and Labitzke and Kunze [2005]; PN99 also discuss the use of the FUB data in interannual variability studies.

[35] The REAN data set, because of the poor vertical resolution in the stratosphere and outdated assimilation model, is not generally recommended for stratospheric studies, and does not extend into the upper stratosphere. While the ERA-40 reanalyses show unrealistic vertical temperature structure in the Antarctic lower stratosphere in recent years [Simmons et al., 2005; Manney et al., 2005], such behavior in the Arctic is much less pronounced and limited to the upper stratosphere and the last few years; however, the ERA-40 reanalysis does not cover the past two NH winters. Since the FUB data only cover through the 2000–2001 winter, the NCEP/CPC objective analysis is the only continuing data set that covers the entire stratosphere and is available for the whole period from 1978–1979; we typically show results from NCEP/CPC for historical records involving this period.

[36] Comparisons of NCEP/CPC analyses with ERA-40/operational ECMWF, REAN, and FUB indicate that the most sensitive diagnostics, such as minimum temperatures and the area below PSC formation thresholds, agree very
well for monthly or seasonal averages between NCEP/CPC, REAN, and FUB analyses (e.g., Figure A1); the ERA-40 lower stratospheric temperatures often appear to be biased low (larger area in Figure A1) with respect to the others, with higher average PSC areas over both the years overlapping the NCEP/CPC record and the complete record. However, the patterns of interannual variability are very similar in ERA-40 to those in the other analyses, despite the relative cold bias. Labitzke and Kunze [2005] found significant differences in 30 hPa temperatures during October through January, but much smaller differences in February and March, as well as smaller differences at 50 hPa. Our findings also indicate that most of the differences in Figure A1 (and other temperature diagnostics) arise from differences in December and, to a smaller degree, January. During February, when temperatures in recent years were most unusual (section 3), agreement between the analyses is quite good.

Differences are much less between NCEP/CPC, ERA-40 and REAN in the diagnostics based on the wind fields; monthly mean 60–80°N winds at 50 and 10 hPa are nearly identical, while at 2 hPa, ERA-40 winds are often slightly higher (up to about 5–6 m/s, but usually much less) than NCEP/CPC winds; this probably results partially from the use of a balanced wind calculation [e.g., Randel, 1987] for the NCEP/CPC data. The NCEP/CPC objective analysis fields in the upper stratosphere are inferior to the assimilated products for examining detailed synoptic evolution [e.g., Manney et al., 2005], so synoptic fields and detailed day-to-day evolution in earlier years are shown using the ERA-40 reanlyses.

We have chosen to focus on the satellite era because of the better constraints on stratospheric temperatures in the analyses during this period; interannual variability including the earlier period was discussed by PN99. That the presatellite period from the late 1950s through the late 1970s was overall warmer has been previously noted [Christiansen, 2003; Labitzke and Kunze, 2005, and references therein], and is apparent in Figure A1, as is the previous cluster of warm winters in the late 1960s discussed in the text.

There are numerous caveats in using any of these analyses for interannual comparisons, due to changes in inputs to the assimilation systems (e.g., different satellite observing systems for the stratosphere) and in some cases changes in the analyses [e.g., PN99]. All the diagnostics shown or discussed here have been compared between the NCEP/CPC, ERA-40, REAN, and FUB data sets (the latter two excepting the upper stratosphere), and the particular data set chosen does not significantly affect any of our conclusions. The data set shown in each figure is specified in the figure captions.

Acknowledgments. Thanks to the UK Met Office and the British Atmospheric Data Centre for MetO data, the GSFC ACD Science Data System (Eric Nash and Paul Newman) for NCEP/CPC Data, the German Weather Service (Deutscher Wetterdienst, DWD) and ECMWF for ECMWF and ERA-40 and NASA’s GMAO for GEOS-4 data; NCEP/NCAR Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their web site at http://www.cdc.noaa.gov/. We thank the JPL MLS team, especially Brian Knopf and Robert Thurstans, for technical assistance, data management and computer support, Paul Newman for original routines used to calculate PV, and Crystal Montoya for bibliography database maintenance. Work at the Jet Propulsion Laboratory, California Institute of Technology, was done under contract with the National Aeronautics and Space Administration.

References


K. Krüger, Alfred Wegener Institute for Polar and Marine Research, P.O. Box 60 01 49, Telegrafenberg A43, D-14401 Potsdam, Germany.

G. L. Manney and S. A. Sena, Department of Natural Sciences, New Mexico Highlands University, Las Vegas, NM 87701, USA. (manney@mls.jpl.nasa.gov)

S. Pawson, Global Modeling and Assimilation Office, Code 900.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771-0001, USA.

J. L. Sabutis, School of Education, Department of Mathematical Sciences, New Mexico Highlands University, Las Vegas, NM 87701, USA.