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Evolution of microwave limb sounder ozone and the polar vortex during winter

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Abstract. The evolution of polar ozone observed by the Upper Atmosphere Research Satellite Microwave Limb Sounder is described for the northern hemisphere (NH) winters of 1991/1992, 1992/1993, and 1993/1994 and the southern hemisphere (SH) winters of 1992 and 1993. Interannual and interhemispheric variability in polar ozone evolution are closely related to differences in the polar vortex and to the frequency, duration and strength of stratospheric sudden warmings. Ozone in the midstratospheric vortices increases during the winter, with largest increases associated with stratospheric warmings and a much larger increase in the NH than in the SH. A smaller NH increase was observed in 1993/1994, when the middle stratospheric vortex was stronger. During strong stratospheric warmings in the NH, the upper stratospheric vortex may be so much eroded that it presents little barrier to poleward transport; in contrast, the SH vortex remains strong throughout the stratosphere during wintertime warmings, and ozone increases only below the mixing ratio peak, due to enhanced diabatic descent. Ozone mixing ratios decrease rapidly in the lower stratosphere in both SH late winters, as expected from chemical destruction due to enhanced reactive chlorine. The interplay between dynamics and chemistry is more complex in the NH lower stratosphere and interannual variability is greater. Evidence has previously been shown for chemical ozone destruction in the 1991/1992 and 1992/1993 winters. We show here evidence suggesting some chemical destruction in late February and early March 1994. In the NH late winter lower stratosphere the pattern of high-ozone values (typical of the vortex) seen in mid-latitudes is related to the strength of the lower-stratospheric vortex, with the largest areal extent of high ozone outside the vortex in 1994, when the lower stratospheric vortex is relatively weak, and the least extent in 1993 when the lower stratospheric vortex is strongest.

1. Introduction

Knowledge of the evolution of ozone in the stratospheric polar vortex is crucial to understanding the chemical and dynamical mechanisms in that region as well as diagnosing the influence of the polar regions on global ozone. Previously available ozone data are limited in vertical, latitudinal, and temporal coverage, with few data available in the polar night or in the lower stratosphere.

The Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) has now measured concentrations of several species of interest in the middle atmosphere, including ozone, through three northern hemisphere (NH) and two southern hemisphere (SH) winters. MLS measurements extend throughout the stratosphere and include the polar night. They provide unprecedented coverage of the winter polar regions, including the vertical distribution of ozone and both northern and southern polar regions. The only similar data are from LIMS, but they cover only one NH winter and do not extend below 60°S. *Froidevaux et al.* [1994] describe the general features of MLS ozone, focusing on the zonal mean; *Elson et al.* [1994] show corresponding observations of planetary scale waves in ozone. *Waters et al.* [1993a] show the evolution of vortex-averaged ozone in the Arctic lower stratosphere during the 1991/1992 winter, and *Manney et al.* [1993] and *Waters et al.* [1993b] report on some aspects of ozone evolution in the 1992 Antarctic late winter. *Manney et al.* [1994a] show the evolution of ozone in the NH lower stratosphere in late winter 1993.

In the following we describe the distribution and evolution of ozone during winter (December through March in the NH and June through September in the SH) in relation to the structure and evolution of the stratospheric polar vortex, for each of the winters with MLS observations. We focus on the vertical distribution of and interannual and interhemispheric variations in ozone and their relation to polar vortex structure.

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2. Data and Analysis

The MLS ozone data are from the 205-GHz radiometer; they have horizontal resolution of ≈400 km and intrinsic vertical resolution of ≈4 km; however, current retrievals are performed on a vertical grid with ≈5.5-km spacing [*Froidevaux et al.,* 1994]. The measurement technique is described by [*Waters* [1993] and the UARS MLS instrument by [*Barath et al.* [1993]. Retrieval methods are summarized by [*Froidevaux et al.* [1994]. Precisions (rms) of individual ozone measurements from 50 to 1 hPa are ≈0.2-0.3 part per million by volume (ppmv), with absolute accuracies of ≈5-10% in the middle and upper stratosphere, and 10-30% in the lower stratosphere [*Froidevaux et al.,* 1994]. The ozone data used here are gridded using Fourier transform techniques that separate time and longitude variations [*Elson and Froidevaux,* 1993].

The Rossby-Ertel potential vorticity (PV) is used to describe the polar vortex. The meteorological data used in conjunction with the MLS data are analyses from the United Kingdom Meteorological Office (UKMO) assimilation system [*Swinbank and O'Neill,* 1994]. The UKMO analyses are currently based on NOAA operational sounders and do not as yet include assimilation of UARS data. Winds and temperatures are used to calculate PV employing the algorithm described by *Manney and Zurek* [1993]. Since MLS temperatures are currently available only for pressures $\leq$22 hPa, UKMO temperatures are used to interpolate gridded MLS ozone to isentropic (potential temperature, θ) surfaces. PV is scaled in "vorticity units," where it is divided by a standard atmosphere value of the static stability [*Dunkerton and Delisi,* 1986; *Manney and Zurek,* 1993; *Manney et al.,* 1994d], for examination of vertical sections. With this scaling, PV on isentropic surfaces throughout the stratosphere has a similar range of values.

MLS data are available for the 1991/1992, 1992/1993, and 1993/1994 winters in the NH and 1992 and 1993 winters in the SH. The UARS platform orientation causes the MLS instrument to switch between viewing ≈34°S to 80°N and ≈80°S to 34°N approximately every 36 days. This observational pattern provides north-looking observations during December and early January and mid-February to mid-March and south-looking observations during June and early July and mid-August to mid-September. A summary of the observational coverage for winter high latitudes is given in Table 1, with dates noted when MLS data are missing or incomplete. Days when sufficient data were missing that the Fourier transform gridding procedure was not reliable can be seen as blank spaces in the time series shown in Figure 4.

3. Time Evolution of Ozone and the Polar Vortex

3.1. Time Mean Ozone in Early and Late Winter

Figure 1 shows time-mean, zonal-mean plots of ozone as a function of latitude and pressure for each of the early and late winter periods examined, and Figure 2 shows plots of the difference between the corresponding early and late winter time mean fields. Each time average is for 30 consecutive days, so those for June/July 1992, December 1993 and February/March 1994, when there are missing data, include less than 30 days of data (Table 1). A number of features are apparent in the middle- and high-latitude ozone distributions that are similar to climatological ozone from the Solar Backscatter Ultraviolet (SBUV) instrument shown by *Nagatani et al.* [1988] (although SBUV data do not cover the polar night or the lower stratosphere). In early winter the level of maximum ozone mixing ratio tilts up-

Table 1. UARS MLS High-Latitude Winter Coverage

Hemisphere	Nominal High-Latitude Coverage Dates	Days of Missing or Incomplete Data
	Early Winter	
NH	Dec. 5, 1991 to Jan. 13, 1991	...
NH	Nov. 30, 1992 to Jan. 8, 1993	...
NH	Nov. 26, 1993 to Jan. 4, 1994	Dec. 3-4, 24-25, 1993
SH	Jun. 1, 1992 to Jul. 12, 1992	Jun. 1-14, 18-19, 23-26; Jul. 8-9, 1992
SH	May 29, 1993 to Jul. 7, 1993	...
	Late Winter	
NH	Feb. 15, 1992 to Mar. 22, 1992	...
NH	Feb. 10, 1993 to Mar. 19, 1993	Mar. 15, 1993
NH	Feb. 5, 1994 to Mar. 14, 1994	Feb. 28-Mar. 1, 1994
SH	Aug. 14, 1992 to Sep. 21, 1992	...
SH	Aug. 9, 1993 to Sep. 16, 1993	...

MLS, Microwave Limb Sounder; NH, northern hemisphere; SH, southern hemisphere.

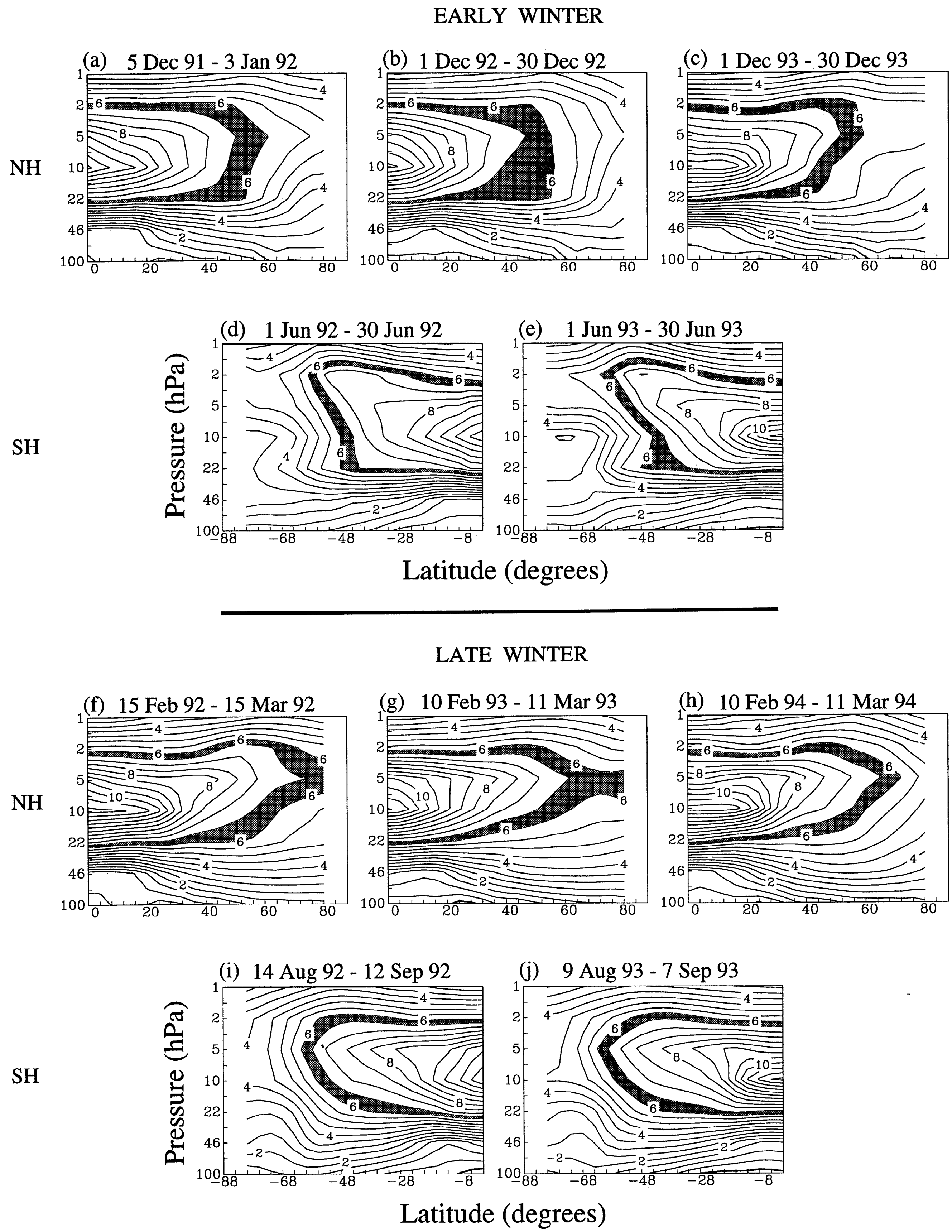

Figure 1. Thirty-day averages of zonal mean ozone mixing ratio (parts per million by volume, ppmv) as a function of latitude and pressure: (a) to (e) early winter and (f) to (j) late winter. The labeled pressure levels correspond to those at which Microwave Limb Sounder (MLS) ozone is currently retrieved.

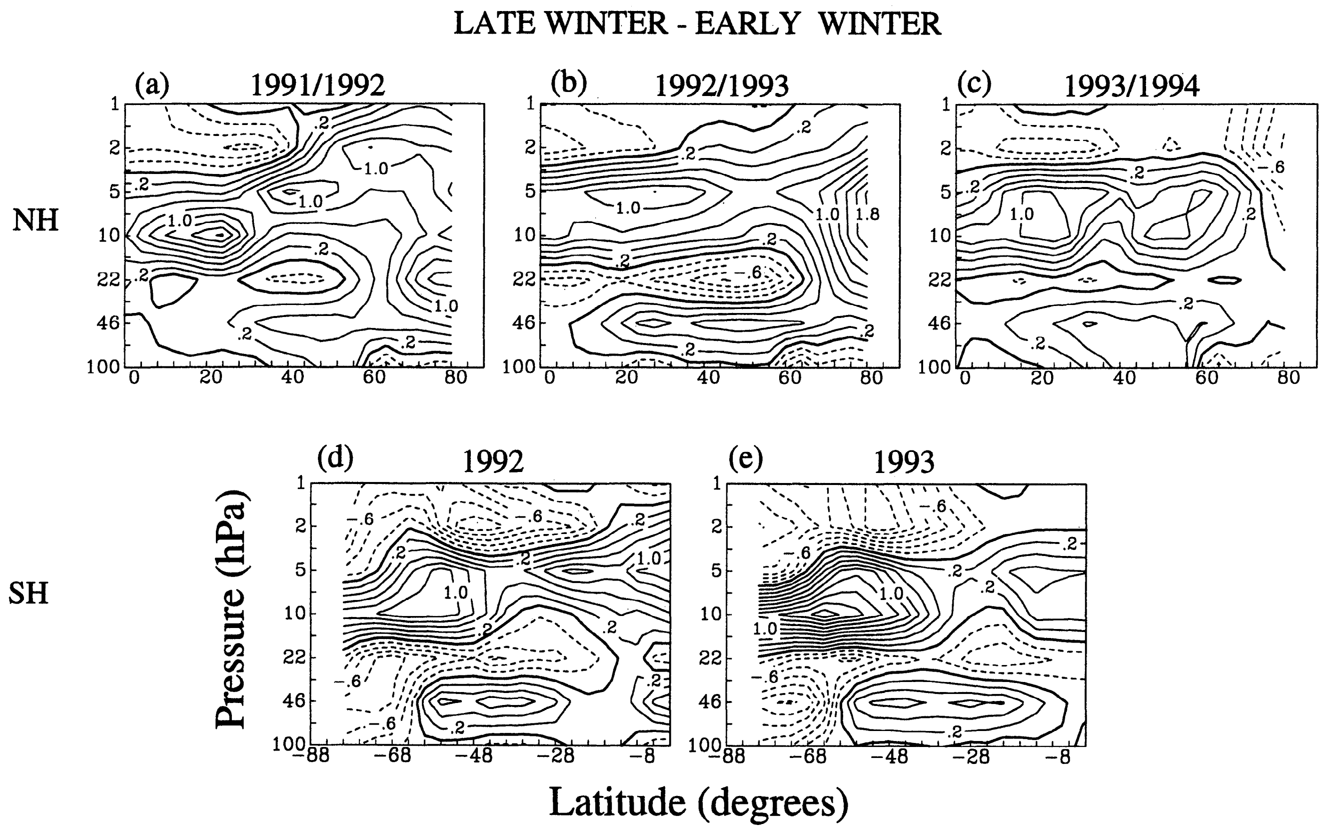

Figure 2. The difference (ppmv) between late winter and early winter plots shown in Figure 1 for each winter, with dashed contours indicating less ozone in late winter.

ward toward the pole, an effect which is much more pronounced in the SH than in the NH. This feature has previously been noted in other ozone data [e.g., *Dutsch*, 1974; *Wu et al.*, 1985]. In the data shown here and in the SBUV climatology the ozone mixing ratio at high latitudes peaks at ≈5 hPa in the NH (slightly higher in December 1993) and ≈2 hPa in the SH. In December 1991 and December 1992, this upward shift with latitude of the ozone maximum is less pronounced than in December 1993 and in the SBUV climatology. The upward tilt with latitude, which is reproduced in two-dimensional model simulations, is attributed to a combination of photochemical and vertical transport processes [*Ko et al.*, 1984; *Tung and Yang*, 1988; *Yang et al.*, 1991; *Perliski and London*, 1989]. In the SH, during early winter, there is a shoulder apparent in the MLS data below 10 hPa near 50°-60° latitude, with nearly constant mixing ratios between 50 and 10 hPa. This shoulder also appears but is not as pronounced in the NH in December 1993 and in the SH in the SBUV climatology. A shoulderlike feature has been reproduced in some two-dimensional model simulations [e.g., *Tung and Yang*, 1988], although the mechanisms involved in its formation were not discussed in detail.

During late winter the upward altitude shift with latitude of the ozone peak is less pronounced than during early winter, particularly in the SH. For each period the high-latitude ozone peak in late winter is between 5 and 3 hPa. In the NH in 1991/1992 and in 1992/1993 (Figures 2a and 2b), ozone at high latitudes is greater in late winter than in December at all altitudes above the ≈50-hPa pressure level. In contrast, in the NH in 1993/1994 and in the SH (Figures 2c, 2d and 2e), mid-stratospheric ozone is greater in late winter below the altitude of the ozone mixing ratio peak and smaller in late winter above; this pattern results from the lack of strong midwinter warming events, with their associated increase in upper stratospheric ozone. In these important respects the NH middle and upper stratosphere in 1993/1994 resembles the SH winters more strongly than it does the previous two NH winters. The decrease above the ozone peak in the NH in 1993/1994 and in the SH winters indicates that downward transport (which reduces ozone above the peak) dominates poleward transport (which enhances high-latitude ozone) in the upper stratosphere for these winters.

In the SH lower stratosphere the formation of the "ozone hole" is apparent in the large high-latitude ozone decrease between early and late winter (Figures 2d and 2e); this decrease continues into early spring. Although chemical depletion occurred in the NH lower stratosphere in February/March 1993 [*Manney et al.*, 1994a], only a very slight decrease is seen below ≈50 hPa between early and late winter (Figure 2b). The use of time averages underestimates the total decrease by about half in the SH (where it is fairly linear) and by a greater amount in the NH (where most of the decrease occurs between mid-February and early March). The NH decrease is also slower than the SH decrease [*Manney et al.*, 1994a].

Figures 1 and 2 show much more variation between years in the NH than in the SH, consistent with the greater interannual variability in NH dynamics [e.g., *Andrews*, 1989]. We examine below the relationship between the evolution of the stratospheric polar vortex and the seasonal changes in ozone shown above.

3.2. Evolution of the Polar Vortex

Figure 3 gives an overview of the evolution of the polar vortex throughout each winter. Area integrals of PV [*Butchart and Remsberg*, 1986] derived from the UKMO analyses are shown for December (June) through March (September) in the NH (SH), at 840 K (near 10 hPa, in the middle stratosphere) and 465 K (near 50 hPa, in the lower stratosphere). Strong stratospheric warmings are common in the NH winter [e.g., *Andrews et al.*, 1987]. In 1992 there was a nearly-major warming in mid-January [*Rosier et al.*, 1994]. In 1993 two strong warmings occurred in mid-February and early March [*Manney et al.*, 1994b]. In 1994 there was a virtually major warming at the beginning of January 1994 [*Manney et al.*, 1994d]. These events are evident in the 840 K plots, when the area within contours of PV in the region of strong gradients (indicating the edge of the vortex) shrinks and they subsequently begin to spread out; the approximate times of the peaks of significant warming events are marked in Figure 3. In addition, during the strongest warmings and during the NH final warming, the region of strong PV gradients may shift so that PV contours that were toward the low PV side of this region move outside of it (e.g., late February and March 1992, Figure 3a and late March 1994, Figure 3c).

After the warming in late January 1992, the midstratospheric vortex remains weaker through the remainder of that winter, until the final warming in late March. In 1993 the late warmings in February and early March lead directly into the final warming. In contrast, the midstratospheric vortex in 1994 recovers after the strong warming in early January, and no more strong warmings occur until the beginning of the final warming in late March; midstratospheric PV gradients remain strong much later than in 1992 or 1993, reminiscent of the SH.

The midstratospheric vortex in the SH (Figures 3d and 3e) is considerably larger and stronger than the NH vortex, and there is little impact of strong wave activity before the end of August. In 1992 there are several minor warmings in late August/early September [*Fishbein et al.*, 1993; *Manney et al.*, 1993], and strong wave activity continues to erode the vortex after this time. In 1993 the vortex remains strong throughout the period shown, with one warming event noticeable in late August.

Minor warmings in early winter (i.e., November/December (May/June) in the NH (SH)) are common in both hemispheres [*Farrara et al.*, 1992], although they have little impact on the development of the SH polar vortex. Because the NH polar vortex is weaker, their effect is more apparent there, as seen in Fig. 3a through 3c.

In the lower stratosphere at 465 K the effect of stratospheric warmings on the vortex evolution in the NH can again be seen in a weakening of the strong PV gradients and decrease in the area enclosed by the contours. This occurs later than the corresponding change in the midstratosphere. The virtually major stratospheric warming in early January 1994 had a stronger and more lasting effect on the lower stratosphere (Figure 3h) than the strong warmings in late January 1992 (Figure 3f) or late February 1993 (Figure 3g). While the 1994 midstratospheric vortex recovered (Figure 3c), the lower stratospheric vortex remained weak until late February. This pattern of recovery in the midstratosphere but not in the lower stratosphere occurs in previous years with strong early winter warmings that affect the entire stratosphere. For early winter warmings, short radiative time constants in the middle and upper stratosphere facilitate recovery, while in the lower stratosphere, radiative time constants are sufficiently long that recovery after a strong disturbance may be delayed or not take place at all. The lower-stratospheric vortex is larger and stronger in the SH than in the NH; stratospheric warmings there are weaker and generally confined to higher altitudes [e.g., *Fishbein et al.*, 1993], so their effect is not readily apparent at 465 K (Figures 3i and 3j).

Strong warmings in midwinter and late winter in the NH are usually sufficient to raise lower-stratospheric temperatures above the polar stratospheric cloud (PSC) formation threshold, while SH lower-stratospheric temperatures remain well below this threshold throughout the winter [e.g., *Manney and Zurek*, 1993]. Overall, NH lower-stratospheric temperatures were lowest and most persistently low in 1993 and highest in 1994 until late February [*Waters et al.*, 1995] Consistent with this, the lower-stratospheric vortex in 1993/1994 is slightly weaker than in 1991/1992, and much weaker than in 1992/1993 (Figure 3). In late February 1994 the lower-stratospheric vortex strengthens, and temperatures decrease below the PSC formation threshold for approximately a 2-week period.

3.3. Polar Ozone Time Evolution

Figure 4 shows a view of the time evolution of MLS ozone as a function of height in each early and late winter high-latitude viewing period. An area-weighted average of ozone at locations with scaled PV greater than $1.4 \times 10^{-4} s^{-1}$ (bold PV contour in Fig. 3) is shown. Plots of zonal mean MLS ozone as a function of time and latitude throughout the stratosphere are shown by *Froidevaux et al.* [1994]. The PV contour chosen is always in the region of strong PV gradients for these periods, although in the NH midstratosphere it is nearer the outside of this region (Fig. 3). It thus serves as a guide for averaging over ozone that is generally within the polar vortex. The general features of the average

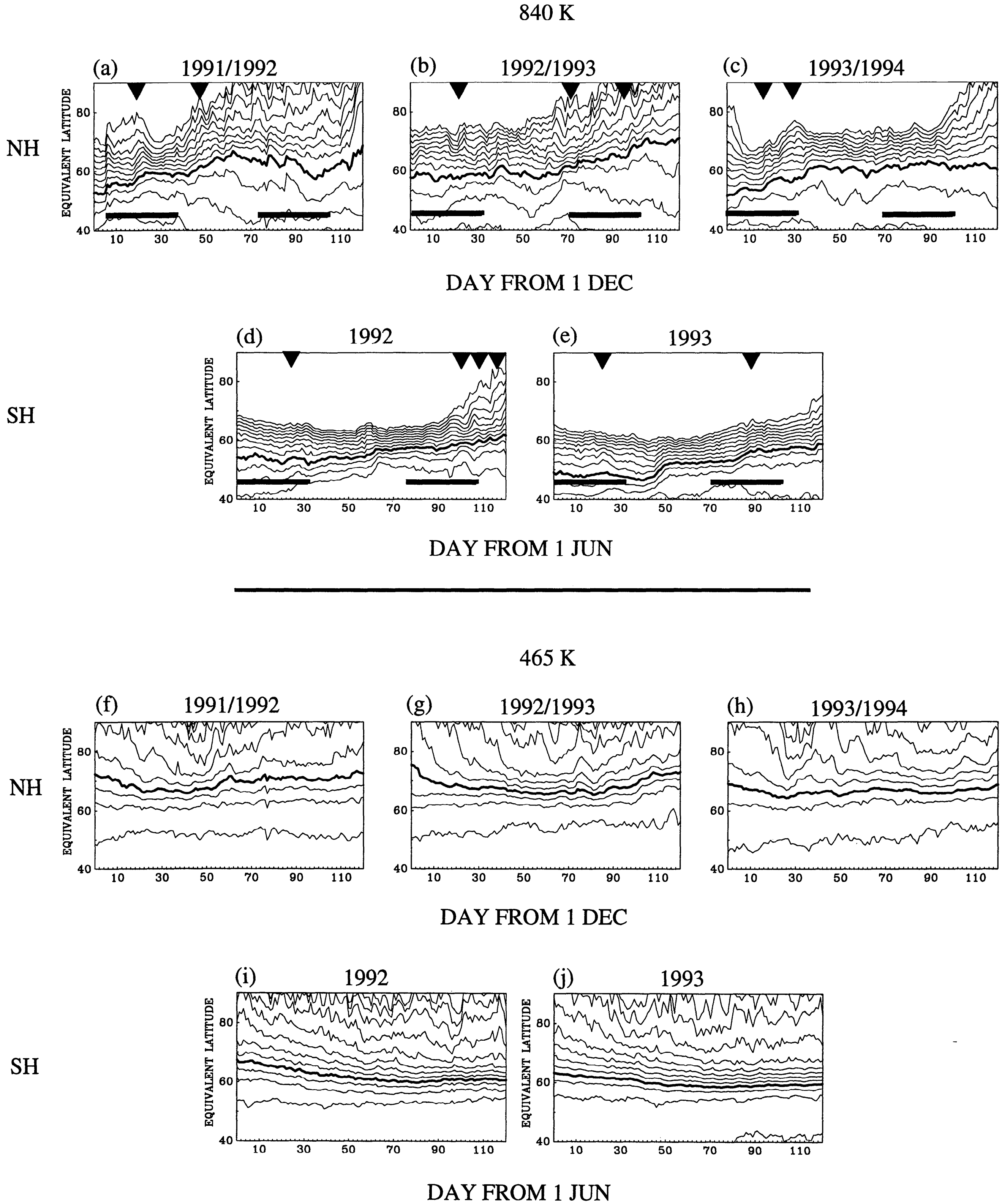

Figure 3. Area integrals of potential vorticity (PV) for 120 days starting December 1 in the northern hemisphere (NH) and June 1 in the southern hemisphere (SH): (a) to (e) 840 K in the midstratosphere and (f) to (j) 465 K in the lower-stratosphere. The contours are scaled PV, from 0.8 to $3.0 \times 10^{-4}\text{s}^{-1}$, with a contour interval of $0.2 \times 10^{-4}\text{s}^{-1}$; the bold contour is $1.4 \times 10^{-4}\text{s}^{-1}$. Thick horizontal bars near the bottom of the 840 K plots show the averaging periods used in Figs. 1 and 2. Arrowheads indicate approximate times of the peaks of significant stratospheric warmings discussed in the text. The discontinuity on approximately December 5, 1991 in the 840 K contours is due to changes in the United Kingdom Meteorological Office (UKMO) analyses at this time [*Swinbank and O'Neill,* 1994].

shown in Fig. 4 are not highly sensitive to the exact PV contour used for the average, as long as it is in the region of strong PV gradients. In the following discussion, for conciseness, we refer to levels below 690 K as "lower stratosphere" and levels above 690 K as "upper stratosphere."

3.3.1. Upper stratosphere (θ > 690K). In the upper stratosphere, especially near the level of the ozone mixing ratio peak, the trend is for vortex ozone to decrease slightly in early winter in the NH and in early to midwinter in the SH. This decrease is terminated by an overall but episodic increase in middle to late winter which, by the final warming in the NH, produces the highest ozone mixing ratios for the year in the polar regions. In the SH the final warming is much later (mid-November in both 1992 and 1993); by the end of the period shown here, peak ozone mixing ratios are comparable to the values at the beginning of the early winter period. The timing, intensity, and persistence of the warming events previously discussed are critical to the detailed features seen in individual years.

The NH early winter 1992/1993 upper stratospheric vortex was relatively strong and not much disrupted by warmings, and the decrease in area-averaged ozone in the upper stratosphere was apparent in early December and persisted through the early winter period (Fig. 4c). Early winter ozone decreases in 1991/1992 (Fig. 4a)

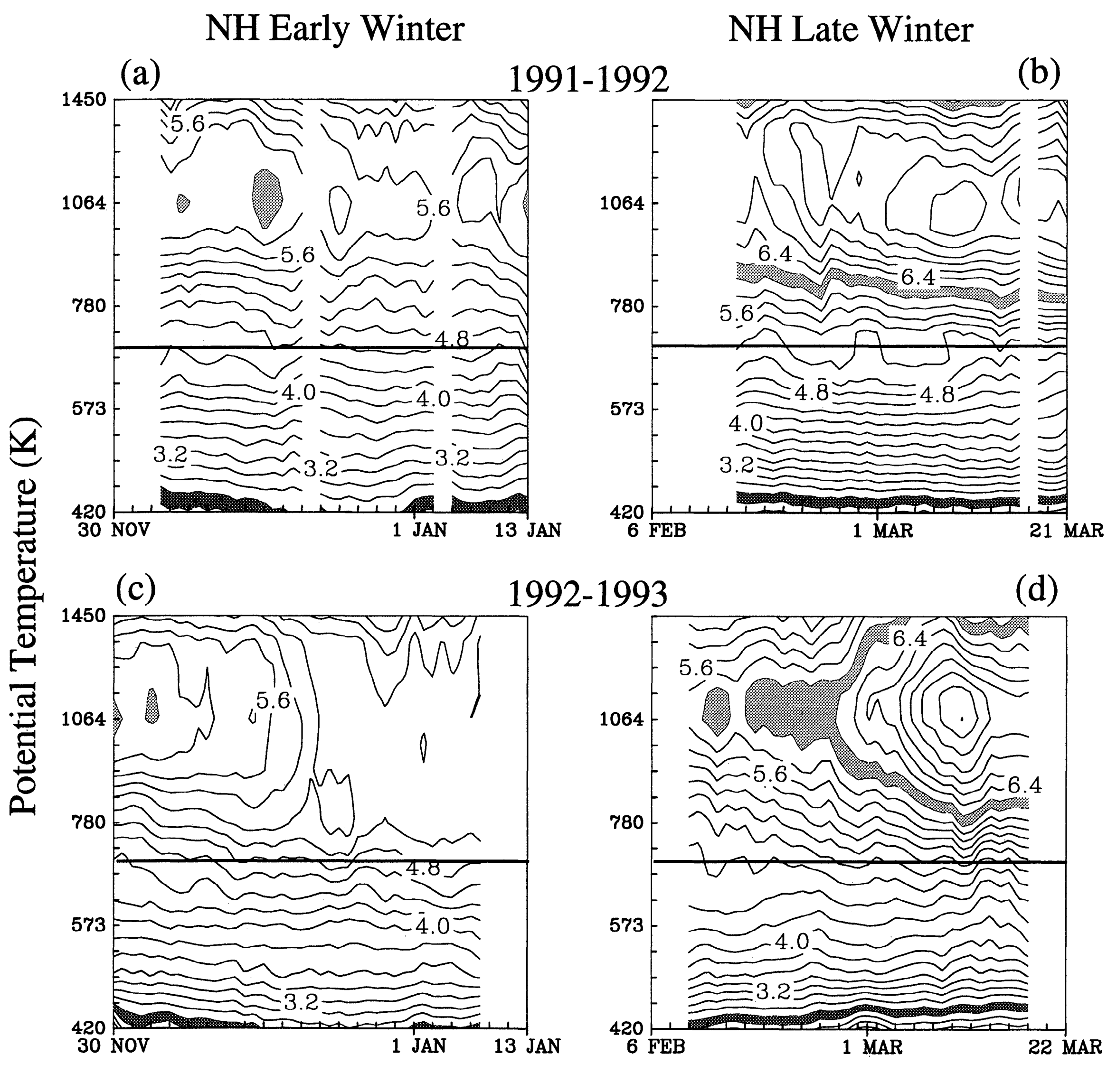

Figure 4. Time series for early and late winter MLS high-latitude observing periods of ozone mixing ratio (ppmv) averaged over the area where the scaled PV is greater than $1.4 \times 10^{-4}s^{-1}$, as a function of θ. The contour interval is 0.2 ppmv, with dark shading between 2.4 and 2.6 ppmv, and light shading between 6.0 and 6.2 ppmv. Blank spaces in the interior of individual series are either days when sufficient data were missing that the gridding procedure could not be applied or days when there are known data problems in high latitudes. Horizontal line at 690 K indicates division between what is referred to as "upper stratosphere" and "lower stratosphere."

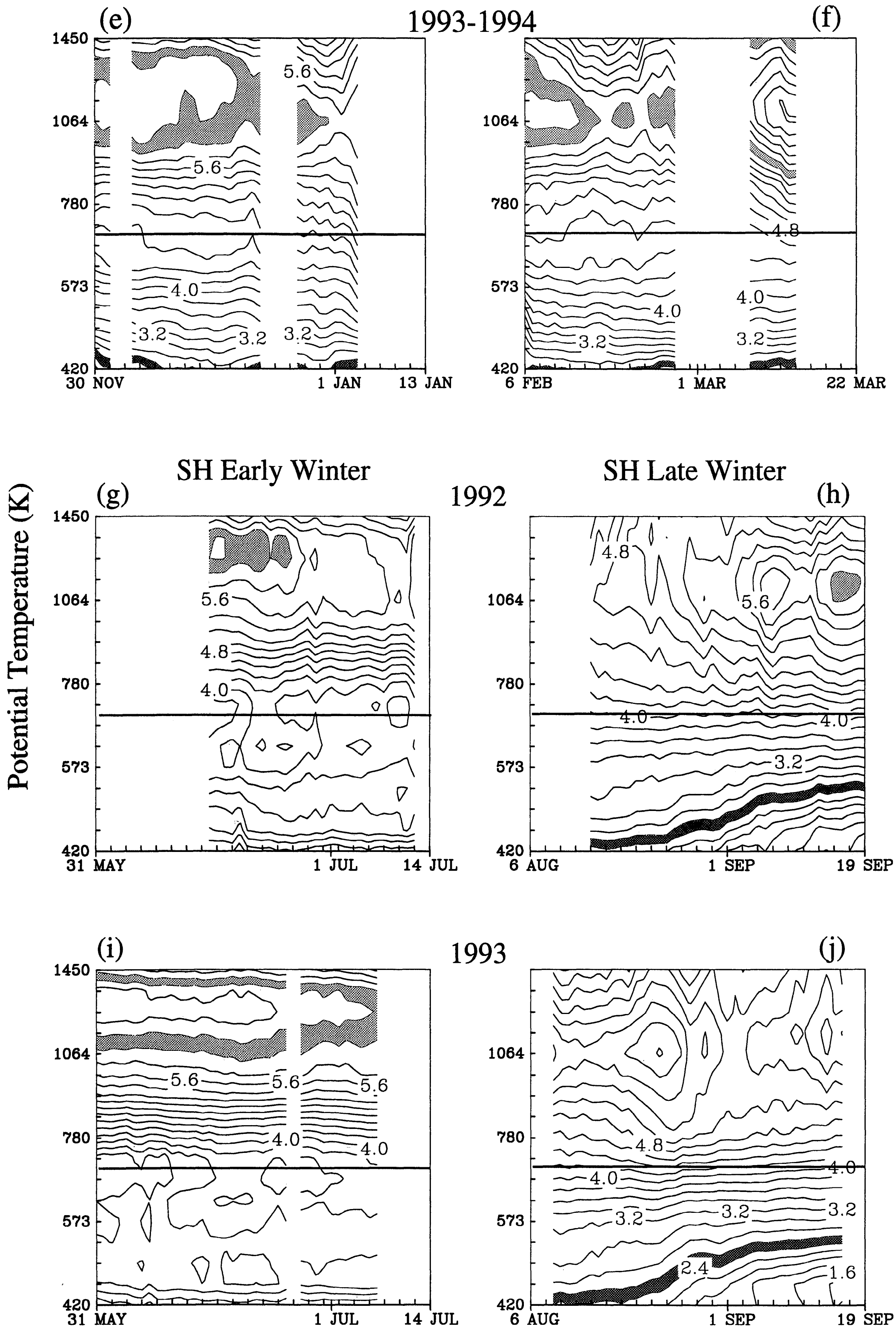

Figure 4. (continued)

and 1993/1994 (Fig. 4e) are apparently temporarily reversed by minor warmings in December. The beginning of the increase in NH ozone in 1991/1992 was coincident with the strong warming in early to mid-January 1992 that significantly eroded the vortex. Ozone in early February 1994, when MLS resumed looking north in that year, is much higher than it was in early January 1994. This suggests that the virtually major warming at the beginning of January 1994 may have led to a significant increase in vortex ozone.

In the NH late winter upper stratosphere, strong warming events are accompanied by sharp increases in the area-averaged (vortex) ozone mixing ratios. In March 1992 the vortex is already weak as the final warming begins, and ozone increases gradually (Fig. 4b). Rapid ozone increases are seen at the time of stratospheric warmings in February and early March 1993 (Fig. 4d). In 1994 no strong warmings occur after early January, and upper stratospheric vortex ozone does not increase substantially until the beginning of the final warming in mid-March (Fig. 4f).

In the SH the decrease in vortex ozone near the mixing ratio peak in early winter 1992 (Fig. 4g) resembles that in the NH in December 1992. The major decrease in 1993 SH vortex ozone was in midwinter, when MLS was looking north (note the decrease between Fig. 4i and Fig. 4j). The increase in SH upper stratospheric vortex ozone is smaller and occurs much later than in the NH, consistent with the presence of a strong PV barrier throughout the winter. Ozone increases begin in early September, when minor warmings begin to significantly weaken the polar vortex. An ozone increase in the upper stratosphere in late August 1993 is transient, associated with a single, short-lived warming at that time, which weakens the vortex only temporarily. The weakening of the 1992 SH vortex in early September (Fig. 3d) suggests that more poleward transport is likely in the 1992 SH late winter than in 1993. This is consistent with calculations of air motion for these two winters [*Manney et al.,* 1994d]. Time-series of zonal-mean ozone [*Froidevaux et al.,* 1994] indicate similar increases in high-latitude upper stratospheric ozone.

The above picture is consistent with the early decline in vortex ozone in the middle and upper stratosphere being due to seasonally developing downwelling [e.g., *Rood and Schoeberl,* 1983; *Andrews et al.,* 1987; *Fisher et al.,* 1993; *Manney et al.,* 1994d] and differences in the effects of diabatic cooling on the distributions of PV and ozone and with the increases being due to horizontal transport of ozone during stratospheric warmings [e.g., *Wu et al.,* 1987]. The effect of downwelling is to lower the level of the ozone peak and reduce peak vortex average mixing ratios by changing the relationship between ozone mixing ratio and PV [e.g. *Butchart and Remsberg,* 1986; *Haynes and McIntyre,* 1987]. Warming events which significantly perturb the zone of strong PV gradients are much more frequent and persistent in the NH than in the SH, and the strongest events are usually in the NH late winter. While the early winter ozone mixing ratio peak is at higher θ in the SH and in December 1993 in the NH, by late winter the peak moves down to comparable levels (near 1100 K) in all five winters. This descent is particularly rapid during early January 1994, consistent with enhanced diabatic descent during a stratospheric warming at that time which is stronger than events in early winter in other years [*Manney et al.,* 1994d].

3.3.2. Lower stratosphere (θ < 690K). Ozone in the lower stratosphere shows little trend in the NH vortex over the December/early January time periods. In the SH early winter, in late June 1992, ozone decreases slightly between ≈550 and 600 K. This may be due to chemical loss, as it appears inconsistent with the results of transport calculations [G. L. Manney et al., Lagrangian transport calculations using UARS data. Part II: Ozone, submitted to *Journal of the Atmospheric Sciences,* 1995]. A similar but even smaller decrease is seen near these levels in 1993.

Between early July and mid-August in the SH (when MLS was looking north (compare right-hand side of Figure 4g (Figure 4i) with left-hand side of Figure 4h (Figure 4j))), ozone throughout the lower stratosphere decreases substantially; *Waters et al.* [1993b] show that enhanced chlorine monoxide was seen throughout the sunlit part of the vortex by early July 1992, so chemical depletion of ozone would be expected. In the NH in 1992 (between Figures 4a and 4b) and 1993 (between Figures 4c and 4d), ozone is seen to decrease slightly between early January and mid-February below ≈500 K, during the time when MLS is looking south; a slight increase occurs between early January and mid-February 1994 (between Figures 4e and 4f). Enhanced ClO was seen in the NH in early January 1992 [*Waters et al.,* 1993a] and from middle to late February 1993 [*Manney et al.,* 1994a]; in 1994, little enhancement of ClO was seen in either early January or mid-February, consistent with warmer lower stratospheric temperatures at this time [*Waters et al.,* 1995]. Since dynamical effects would generally be expected to increase ozone in the lower stratosphere at this time, especially in late January 1992 when there was a strong stratospheric warming [e.g., *Manney et al.,* 1994a], the slight decreases that occurred in 1992 and 1993 during the time when MLS was viewing the SH are suggestive of chemical loss.

By mid-February 1992, MLS observed a significant decrease in enhanced Arctic ClO from values observed in January 1992, and lower stratospheric ClO continued to decrease through the late winter [*Waters et al.,* 1993a]. NH lower-stratospheric vortex ozone increases slightly in February and March, consistent with dynamical effects [*Manney et al.,* 1994a]. *Manney et al.* [1994a] showed that the decrease in NH vortex-averaged lower-stratospheric ozone between mid February and mid-March 1993 was not consistent with dynamical effects, and elevated ClO values at this time indicate chemical depletion.

Lower-stratospheric ozone in the SH late winter decreases rapidly from mid-August to mid-September. At 465 K in the SH in both 1992 and in 1993, MLS observed enhanced ClO persisting through at least the end of its south-looking period [*Waters et al.,* 1993a, b; J. W. Waters et al., paper in preparation, 1995]. The steep decrease in lower stratospheric ozone during August and September is consistent with chemical destruction being the dominant mechanism for changing ozone at this time. The vortex-averaged ozone at ≈465 K is higher during early winter in 1993 than in 1992 but lower during late winter. During late winter the rate of ozone decrease is nearly identical in the two winters. Vortex-averaged ClO at 465 K was slightly higher at the beginning of the August/September period in 1993 than in 1992, and decreased somewhat more slowly over the time period [J. W. Waters et al., paper in preparation, 1995].

3.3.3. Contrasts between NH and SH. One striking difference between the NH and SH is the vertical variation of vortex ozone in early winter at levels below the ozone peak. Below about 690 K the vertical gradient of ozone in the SH vortex is small in early winter, particularly in 1993. In the NH, vertical gradients of vortex ozone are remarkably similar in the three years below about 690 K in early winter and are much stronger than those in the SH. Early winter SH vertical ozone gradients are stronger than in the NH between about 700 K and 900 K.

The contrast in the evolving distribution of ozone in the northern and southern hemispheres is striking. Because there is much stronger wave activity in the NH, and the vortex is weaker, ozone in the NH upper stratospheric vortex increases much more rapidly in late winter. In the 1993/1994 NH winter, there was considerably less wave activity in the upper stratosphere during middle and late winter than in the other two NH winters. As a result of this and of an early winter ozone distribution already more similar to the SH, the upper stratospheric ozone distribution during the 1993/1994 NH winter bears a stronger resemblance to that in the SH winters, as was seen in Figs. 1 and 2. In the lower stratosphere the more disturbed NH conditions give rise to higher temperatures and thus considerably less time when conditions are such that PSCs can form and lead to ozone destruction via chlorine chemistry. The behavior of ozone in the NH lower stratosphere is thus usually controlled by dynamics, while in late winter that in the colder SH is controlled by chemistry.

3.4. Evolution of the Vertical Distribution of Ozone

In Plate 1, we examine the distribution of ozone mass in the polar vortex in the two hemispheres. The mass of ozone in the polar vortex is calculated for layers throughout the stratosphere, as described by *Manney et al.* [1993], and these layers are summed over upper and lower stratosphere (separated by the 690 K isentrope, as discussed in the previous section) to estimate the mass of ozone in the polar vortex. The mass of air in the vortex has been estimated in the same manner. In early winter, changes in ozone mass within the vortex follow the changes in the mass of air in the vortex, and the distributions are similar in the two hemispheres (not shown). Plate 1 shows, for the late winter periods in each hemisphere, the vortex ozone mass for 400-1570 K (essentially the entire stratosphere) and for the upper (690-1570 K) and lower (400-690 K) stratosphere separately. In the SH the areal extent of the vortex is significantly larger, but colder temperatures raise the isentropes to lower pressure, so the total masses are similar at the beginning of the late winter periods in each hemisphere. The total stratospheric ozone mass in the NH vortex shows different trends in each year (Plate 1a). In the SH, ozone mass in the vortex decreases rapidly (Plate 1b).

In late winter the ozone mass increases rapidly in the upper stratosphere in the NH (Plate 1c), and only slightly in the SH (Plate 1d), so that near the end of these time series there may be up to twice as much ozone mass in the NH upper stratospheric vortex as in the SH. Lower SH temperatures result in less mass in a given area and isentropic layer, since the layer is at lower pressure; this, as well as weaker poleward transport, contributes to smaller SH ozone mass in the upper stratospheric vortex. The high-ozone mass in the NH upper stratosphere in late winter 1992 (Plate 1c) is due in part to the fact that the chosen PV contour lies farther on the outer edge of the region of strong PV gradients (Figure 3a), where ozone mixing ratios are larger. The NH ozone mass for late winter 1992 may thus be somewhat overestimated but is still expected to be larger than for 1993 and 1994 in late winter.

The fact that the ozone mass is frequently larger in the lower stratosphere in the SH late winter than in the NH despite the large SH chemical ozone loss (Plates 1e and 1f) is due to the greater size of the SH lower-stratospheric vortex. Ozone mass in the lower-stratospheric vortex decreases rapidly in the SH late winter. Late winter decreases are seen in the NH lower stratosphere in 1993 and 1994, and a slight increase occurs in 1992. The abrupt decrease in the last ≈10 days of the 1993 period (Plates 1a, 1c and 1e, blue line) is due mainly to the decrease in vortex size (as indicated by a decrease in the air mass in the vortex) during the strong stratospheric warming at this time. The weak decreases in the NH lower stratosphere, and strong increases in the NH upper stratosphere lead to a vortex ozone mass which may show a relatively small decrease (1993, 1994) or increase (1992) in late winter. In contrast, the SH lower-stratospheric decrease is so large and the upper-stratospheric trend so small that a strong decrease is seen in the total mass of ozone in each year. A similar effect is seen in zonal-mean column ozone [*Froidevaux et al.,* 1994], where the column above the 22-hPa pressure level (near 650 K) contributes considerably more to the total column at high latitudes in the NH than in the SH.

4. Synoptic Evolution in Late Winter

We examine here some details of the synoptic evolution of ozone during late winter, when there is considerable dynamical variability in both hemispheres.

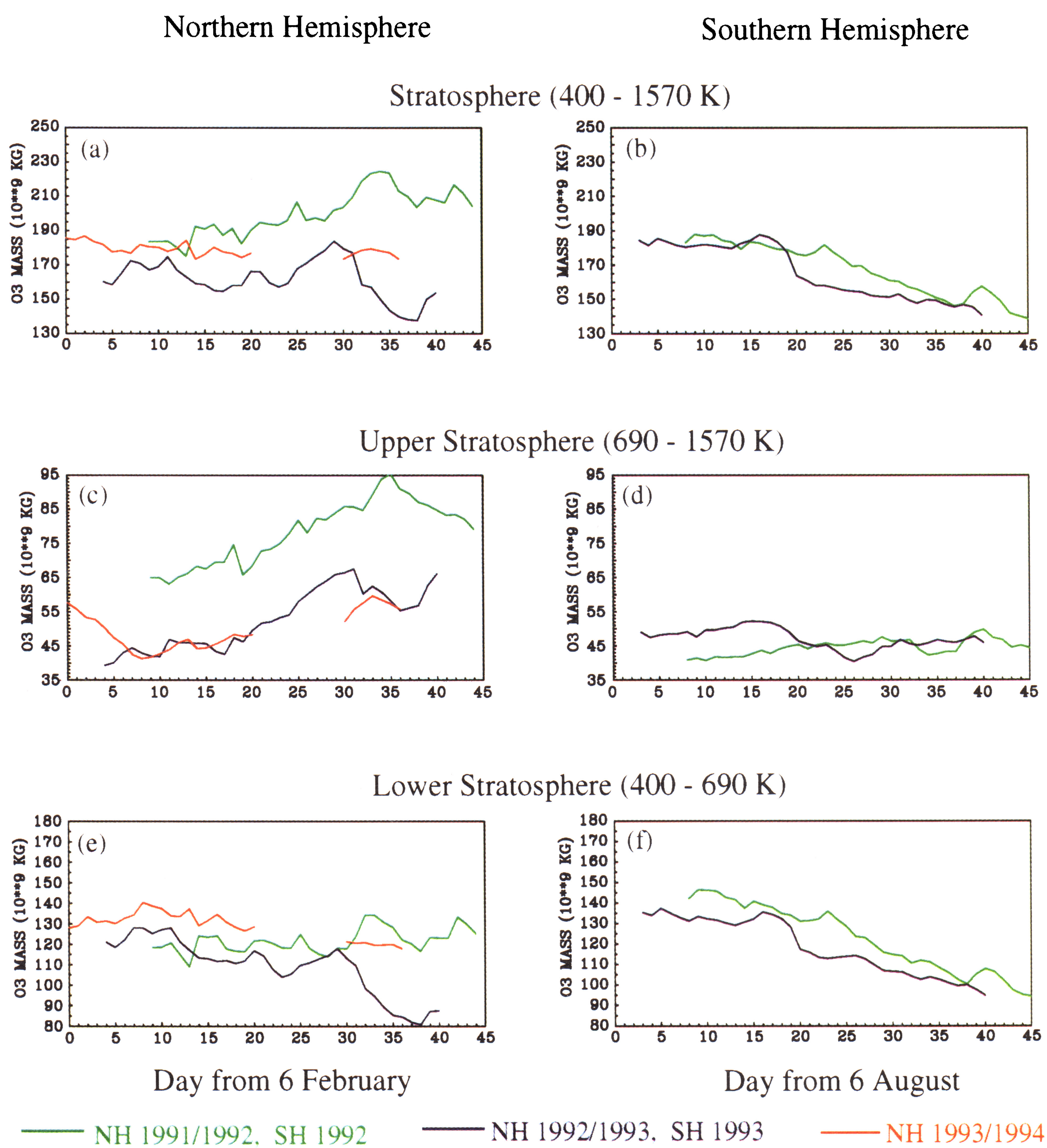

Plate 1. Estimates of ozone mass in the stratospheric polar vortex for late winter: (a) and (b) entire stratosphere from 400 to 1570 K, (c) and (d) upper stratosphere, 690 to 1570 K, and (e) and (f) lower stratosphere, 400 to 690 K. Green line shows 1991/1992, blue line 1992/1993, red line 1993/1994 in the NH; green line shows 1992 in the SH and blue line shows 1993. See text for details of calculation.

4.1. The Lower Stratosphere

Plate 2 shows synoptic maps of NH ozone and several PV contours at 465 K in mid-February and mid-March 1992 and 1993. At 465 K, ozone increases in the polar vortex between February 16 and March 15, 1992; this is expected, as diabatic descent brings in higher ozone [*Manney et al.,* 1994a]. In 1992 the late January warming resulted in temperatures rising well above those necessary for the formation of PSCs, and since ClO had decreased considerably by February 16 [*Waters et al.,* 1993a], any chemical loss is too small to modify the expected dynamical effect. The vigorous wave activity that is typical of the NH winter is obvious

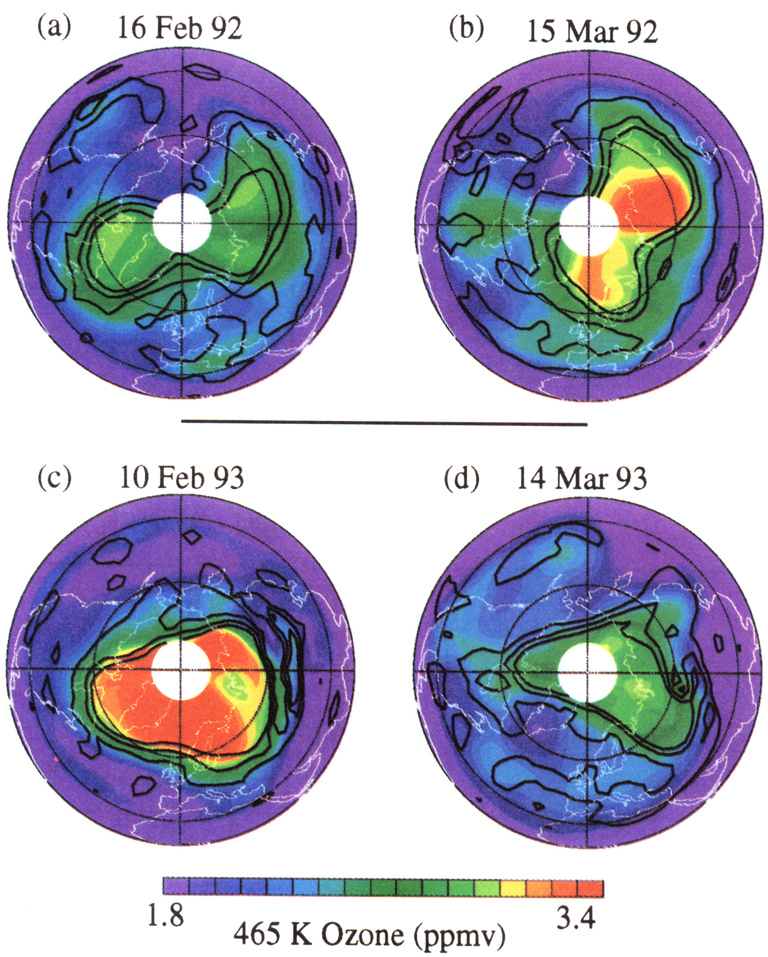

Plate 2. Synoptic maps of ozone mixing ratios (ppmv) with overlaid PV contours at 465 K, on February 16, 1992, Mar 15, 1992, February 10, 1993, and March 14, 1993 in the NH. Overlaid PV contours are from 0.25 to 0.35 × 10^{-4}Km^{2}kg^{-1}s^{-1}, with a contour interval of 0.05 × 10^{-4}Km^{2}kg^{-1}s^{-1}. Projection is orthographic, with 0°longitude at the bottom of the plot, and 30°and 60°latitude circles shown as thin dashed lines.

in the distorted shape of the polar vortex at 465 K, and on February 16, 1992, tongues of high ozone appear to have been stripped off the edge of the vortex at 465 K.

During mid-February to mid-March 1993, the vortex remains strong and highly distorted. The most obvious difference difference between 1993 and other years for which ozone has been observed in the NH is that, between February 10 and March 14, the ozone mixing ratio decreases significantly in the polar vortex, with the sharpest decrease during late February, due to chemical ozone depletion [*Manney et al.,* 1994a].

Plate 3 shows 465 K ozone during February and March 1994. Ozone in the vortex increases between February 7 and 23, as expected from diabatic descent. However, a decrease is seen between February 23 and March 12, 1994. At this time, the lower stratosphere cools below the threshold for PSC formation for approximately 2 weeks, and the lower stratospheric vortex strengthens (Figure 3h); MLS observed enhanced ClO in the vortex [*Waters et al.,* 1995], indicating the possibility of chemical loss of ozone.

We note that in 1994 there are considerably larger areas of relatively high ozone outside the vortex at 465 K than in either 1992 or 1993 and larger areas in 1992 than in 1993 (particularly, compare Plates 2a, 2c, and 3a). Figure 3 shows that throughout the winter (before mid-February) the lower stratospheric polar vortex was weakest in 1994 and strongest in 1993 in the NH. The patterns of high ozone seen at mid-latitudes confirm that ozone is significantly more confined within the vortex in 1993 than in 1994, consistent with the relative strength of the lower stratospheric vortex in those years. Because the vortex is stronger in the lower stratosphere when temperatures are colder, those years in which there is most potential for the activation of chlorine and the associated chemical destruction of ozone will also generally be those in which the air in the lower-stratospheric vortex is most confined during winter.

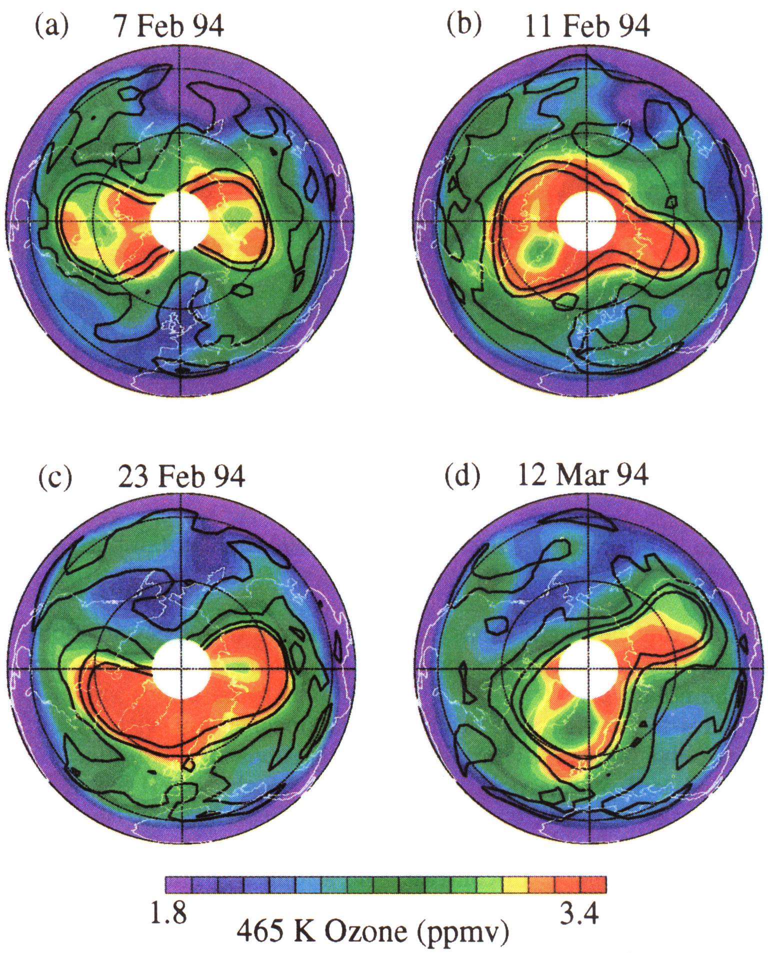

Plate 3. As in Plate 2, but for February 7, 11, and 23, 1994, and Mar 12, 1994.

Downward transport supplies higher ozone from above throughout the vortex and near the vortex edge, since significant diabatic descent is confined to those regions [e.g., *Schoeberl et al.*, 1992; *Manney et al.*, 1994d]. In years when the vortex is weaker, this downward transport is concentrated along or outside the vortex edge, while in less active years, it is well within the vortex [*Manney et al.*, 1994a, d]. Thus higher-ozone values outside the vortex can originate from the vortex or the region near the vortex edge; examination of synoptic maps throughout the observed part of the winter shows that high ozone being drawn out into midlatitudes from the vicinity of the vortex edge is a regular occurrence, but larger tongues are drawn off more frequently in 1994 than in 1992 or 1993. In addition, there was more downward transport along the vortex edge in 1994 than in 1993 [*Manney et al.*, 1994d]. Calculations comparing transport in the lower stratosphere for early 1993 and early 1994 confirm that the lower stratospheric vortex is a considerably weaker barrier to tranport into midlatitudes from the vortex edge region in 1994 than in 1993 [*Manney et al.*, 1994d].

Synoptic maps for the SH 1992 winter lower stratosphere were shown by *Manney et al.* [1993] and *Waters et al.* [1993b]. These showed the effects of chemical destruction on ozone in the lower stratosphere. Plate 4 shows SH ozone at 465 K in mid-August and mid-September 1993. As in 1992 [*Waters et al.*, 1993a, b], the SH 465 K ozone fields for 1993 show marked effects of chemical destruction of ozone. As can be seen in the time series shown in the previous sections (Figure 4 and Plate 1), lower-stratospheric ozone is lower during August and September 1993 than in 1992. Although some tongues of higher ozone are seen being drawn off the vortex edge at 465 K, the extent of regions of higher ozone outside the vortex is less than in any of the NH winters, consistent with the stronger and less disturbed lower-stratospheric vortex in the SH.

4.2. Stratospheric Warmings and Vertical Structure

Stratospheric warmings are most apparent in the middle and upper stratosphere. Plate 5 shows synoptic maps of NH 840 K ozone and PV in mid-February and mid-March 1992. This is after the warming event in late January, and the polar vortex remains relatively weak in the midstratosphere. Although no major warming occurs during this time period, the vortex at 840 K is

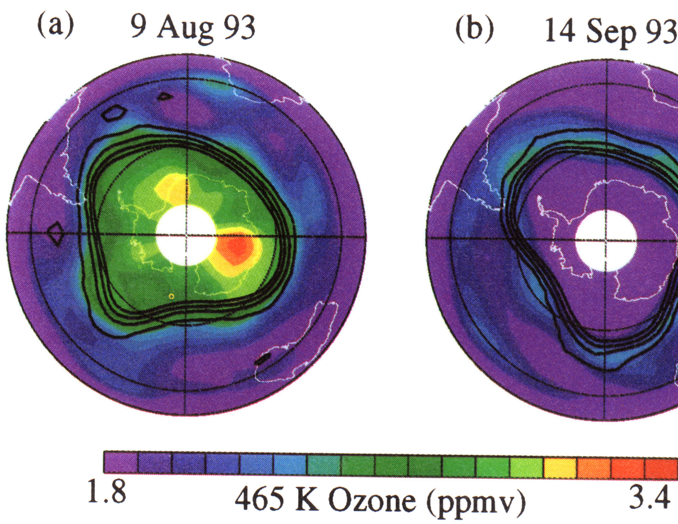

Plate 4. As in Plate 2, but for the SH on August 9, 1993 and September 14, 1993; 0°longitude is at the top of the plots.

distorted and variable, and in this case high ozone can be seen being drawn from low latitudes into the polar regions along the edge of the polar vortex.

Plate 6 shows similar figures for several days in February and March 1993. The polar vortex was strong on February 10, although shifted well off the pole. February 24 and March 6 are in the midst of two strong stratospheric warmings. The later warming leads into the final warming [*Manney et al.,* 1994b]. In contrast to the lower stratosphere, large tongues or blobs of high ozone are drawn from low latitudes into the polar regions around the edge of the polar vortex. During the later warming (Plates 6c and 6d) material from the vortex edge is drawn out into low latitudes. This behavior of ozone is similar to that of nitrous oxide shown by *Manney et al.* [1994b]. The blob of low ozone that appears in the anticyclone on March 6 and 14 is a common feature in the NH winter, and chemical effects are thought to be important in its origin, since its behavior is inconsistent with that of passive tracers and with calculations of air motion [*Manney et al.,* 1995].

Plate 7 shows NH 840 K ozone in mid-February and mid-March 1994. At this time, the vortex is relatively strong in the middle stratosphere. Although there are no strong warmings at this time, we again see tongues of high ozone being drawn around the vortex from low latitudes and some evidence (e.g., February 7) of low ozone being drawn off the vortex.

Synoptic maps for the 1992 SH midstratosphere were shown by *Manney et al.* [1993]. Evidence of poleward transport of ozone was apparent during the minor warmings in late August and September, as tongues

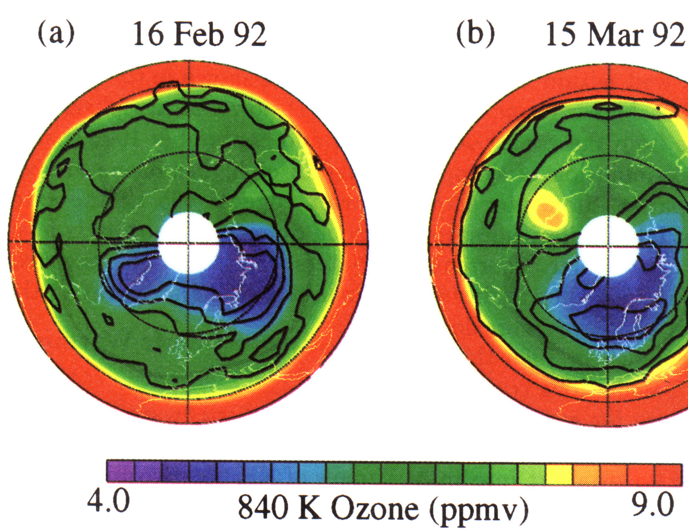

Plate 5. As in Plate 2, but at 840 K, for February 16, 1992 and March 15, 1992; Overlaid PV contours are from 4.0 to 6.0$\times 10^{-4}$K$m^2kg^{-1}s^{-1}$, with a contour interval of 1.0$\times 10^{-4}$K$m^2kg^{-1}s^{-1}$.

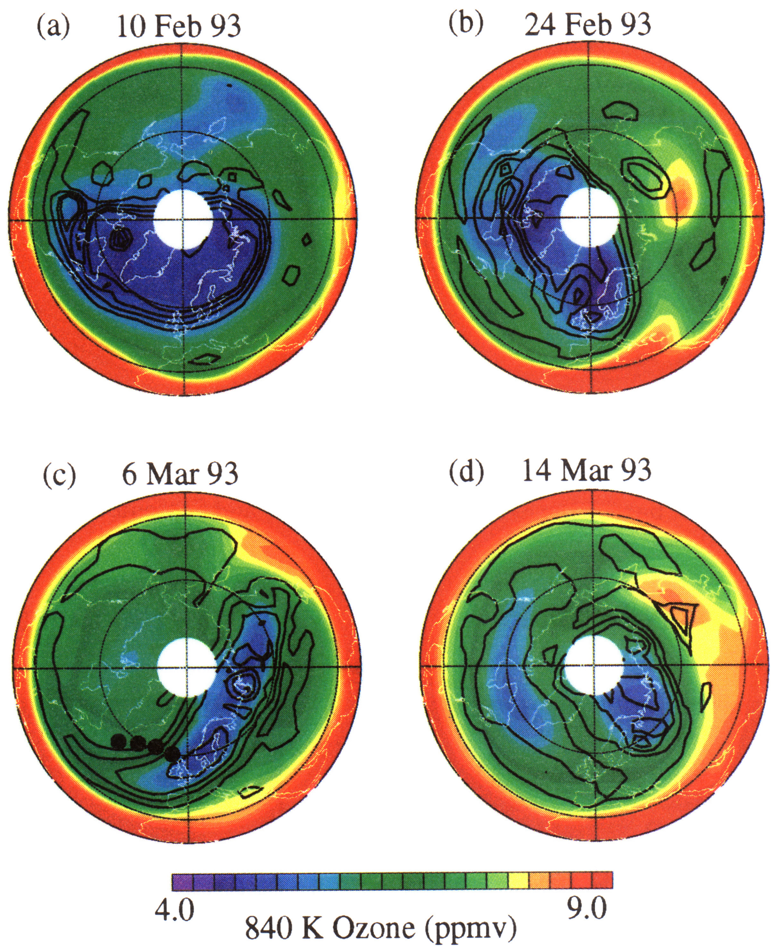

Plate 6. As in Plate 5, but for February 10 and 24, 1993, and March 6 and 14, 1993.

of ozone were drawn up around the edge of the vortex. Plate 8 shows SH ozone in late August 1993, near the peak of a relatively strong minor warming and mid-September 1993, at the beginning of another. Although the strongest perturbations of the SH are considerably weaker than those that commonly occur in the NH, many similar features are noted in the behavior of the polar vortex and the ozone in the midstratosphere dur-

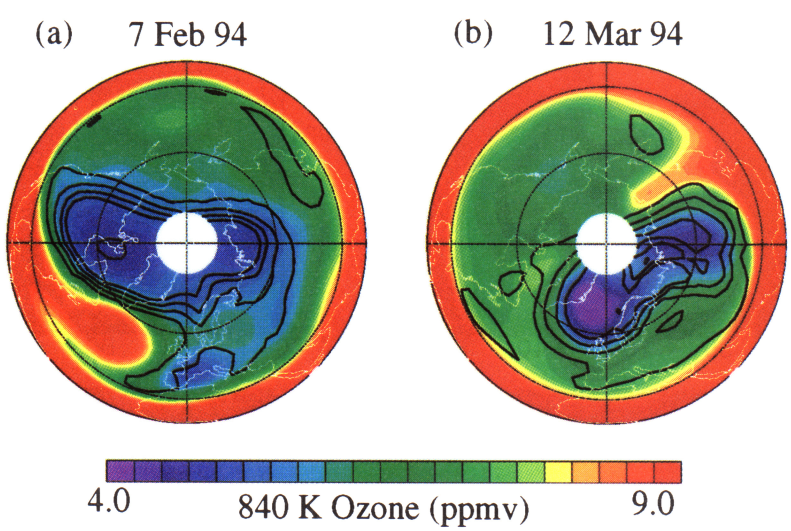

Plate 7. As in Plate 5, but for February 7, 1994, and March 12, 1994.

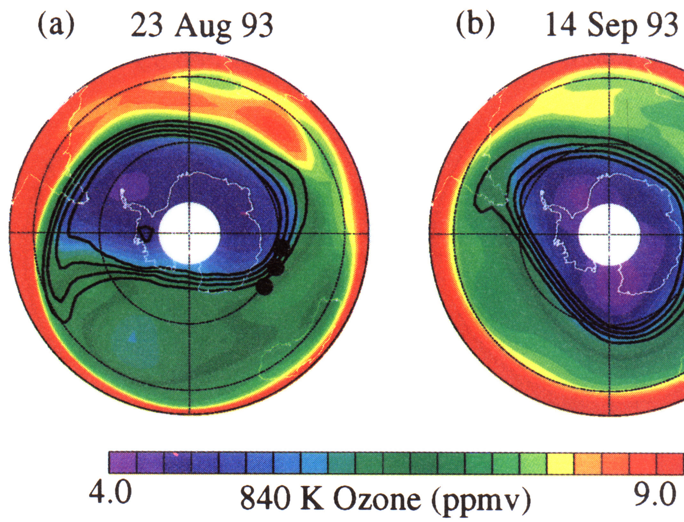

Plate 8. As in Plate 5, but for the SH on August 23, 1993, and September 14, 1993; 0°longitude is at the top of the plots.

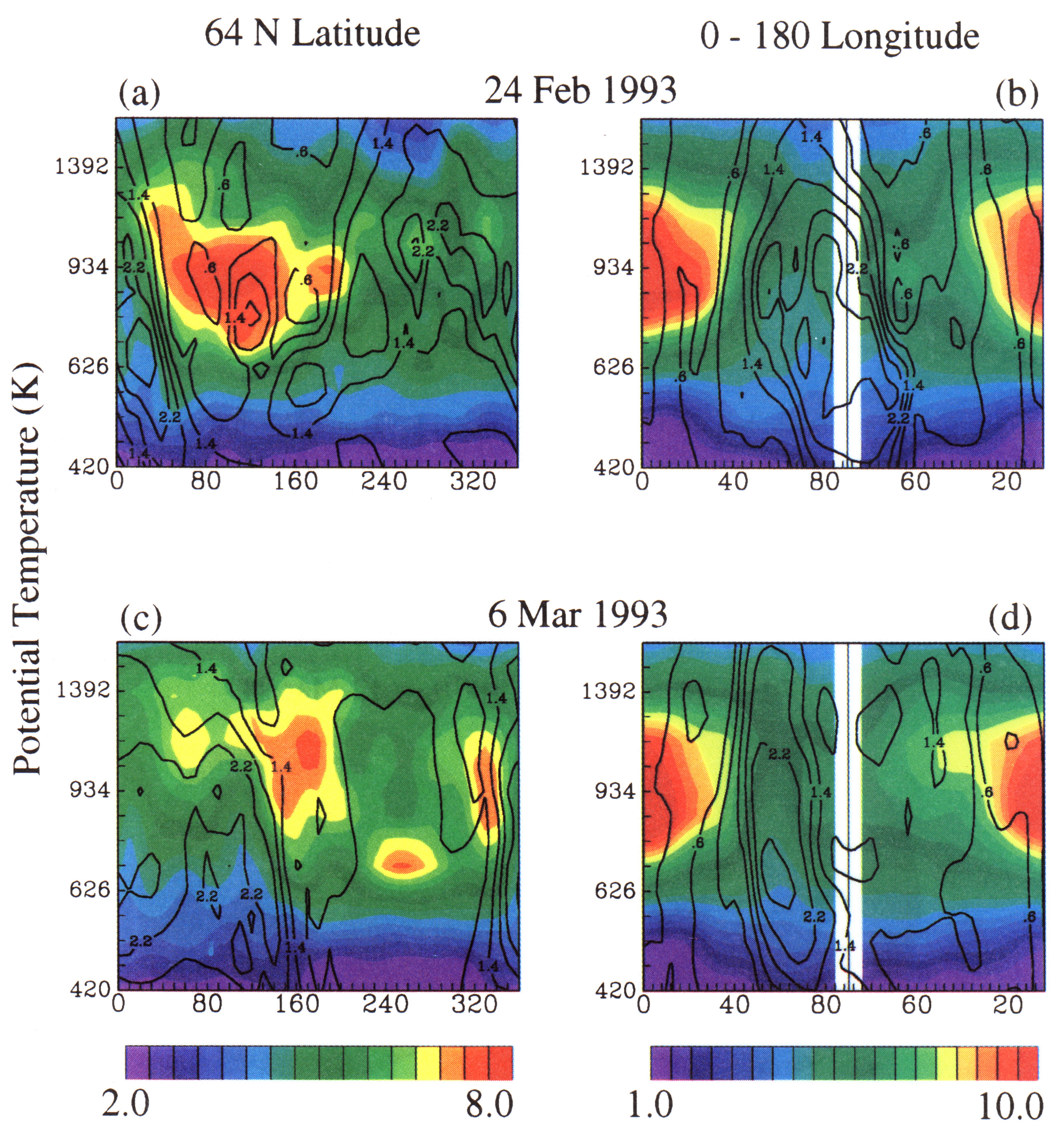

Plate 9. Vertical sections of ozone mixing ratios and scaled PV contours on February 24, 1993, and March 6, 1993 in the NH: (a) and (c) longitude/θ sections at 64°N; (b) and (d) latitude/θ section across the pole along 0°to 180°longitude. Units of scaled PV are $10^{-4}s^{-1}$.

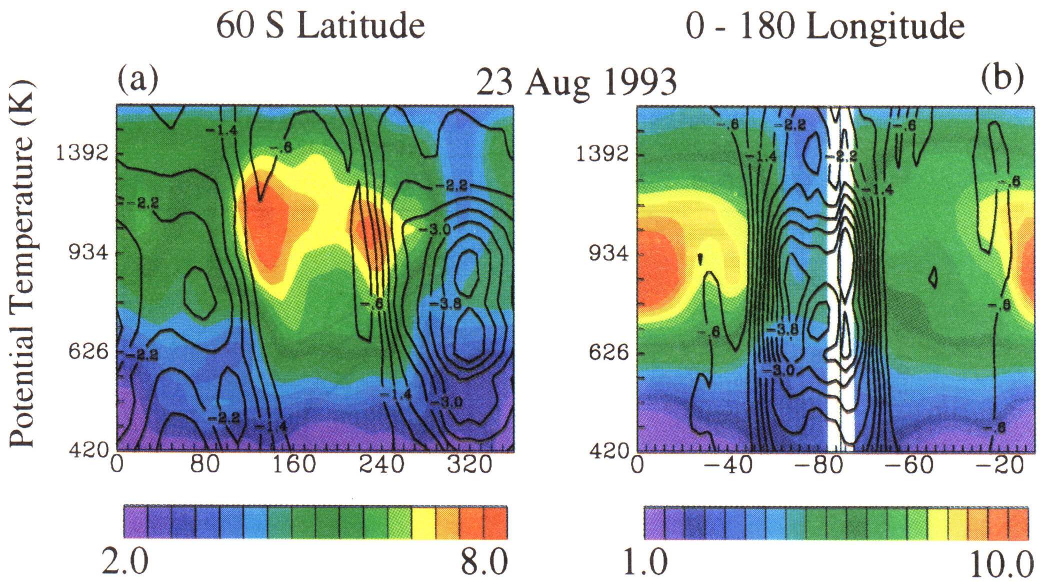

Plate 10. As in Plate 9, but for the SH on August 23, 1993; Plate 10a is at 60°S latitude.

ing these events. These include tongues of high ozone being drawn from low latitudes into the polar regions and evidence for tongues of low ozone being drawn off the vortex (Plate 8a). The pattern of high ozone being drawn up around the vortex from low latitudes is common to all times when planetary wave activity is strong. Except when the vortex is seriously weakened, this material generally remains outside the vortex. The increase in ozone near 50°latitude between early and late winter seen in Figure 2 results from events such as these. The increase is most pronounced and localized in the SH and in the 1993/1994 NH winter, since the midstratospheric vortex is stronger, providing more of a barrier to transporting ozone to higher latitudes and less mixing in mid-latitudes with low ozone from inside the vortex. The zonal mean shown in Figure 2 also comes closer to separating "inside" and "outside" the vortex during these less active periods.

Plate 9 shows the vertical distribution of ozone and the vertical structure of the NH polar vortex on February 24 and March 6 1993. Plates 9a and 9b are cross sections showing ozone and scaled PV as a function of longitude and θ, at 64°N; Plates 9c and 9d are cross sections showing ozone and scaled PV as a function of latitude and θ, along 0 to 180°longitude. These figures show that the polar vortex tilts westward and equatorward with increasing altitude during the intensification of stratospheric warmings, as noted by *Manney et al.* [1994c]. The abrupt decrease in ozone going into the polar vortex is apparent, coincident with the region of strong PV gradients. An increase in ozone in the vortex between February 24 and March 6 is apparent between ≈800-1400 K (blue to green colors in Plates 9b and 9d). This is consistent with enhanced diabatic descent during the warmings and enhanced poleward transport of ozone. The vortex above ≈1000 K is very weak by March 6, suggesting a greatly reduced barrier to transport into the vortex. This is the origin of the rapid increase seen in vortex-averaged ozone in Figure 4d.

Plate 10 shows vertical cross sections of ozone and scaled PV in the SH similar to those shown in Plate 9 for the NH, on August 23, 1993. A westward and equatorward tilt of the polar vortex and the ozone field with height is apparent, as is typical during stratospheric warmings. Because of the larger role that chemical destruction plays in the lower stratosphere in the SH, there is a drop in ozone mixing ratios apparent in crossing from outside to inside the vortex at the lowest levels. A similar drop was not obvious in the NH (Plate 9) because although lower stratospheric vortex ozone had been chemically depleted, this was not enough to make vortex ozone less than extravortex ozone (e.g., Plate 2). The vortex remains strong throughout the stratosphere during this SH minor warming; examination of similar cross sections on later days (not shown) indicates only a small increase in ozone in the middle and upper stratospheric vortex, consistent with the transient effect of this warming seen in Figure 4j.

The westward and equatorward tilt of the vortex with height during warmings results in individual profile measurements near the vortex edge which frequently show complex and rapidly varying vertical structures. Plate 11 shows four individual ozone profiles from MLS along the edge of the NH vortex on March 6, 1993 (the locations are indicated in Plate 6c) and three profiles along the edge of the SH vortex on August 23, 1993 (the locations are indicated in Plate 8a). The westernmost (red and brown) profiles in Plate 11a have ozone mixing ratios characteristic of the vortex edge or exterior at all levels; the easternmost (green) one has ozone characteristic of the vortex interior at all levels. The ozone values in the blue profile suggest that it sampled air inside the vortex at 4.6 hPa and outside at 10 hPa and below. Similarly, in the SH, although the western-

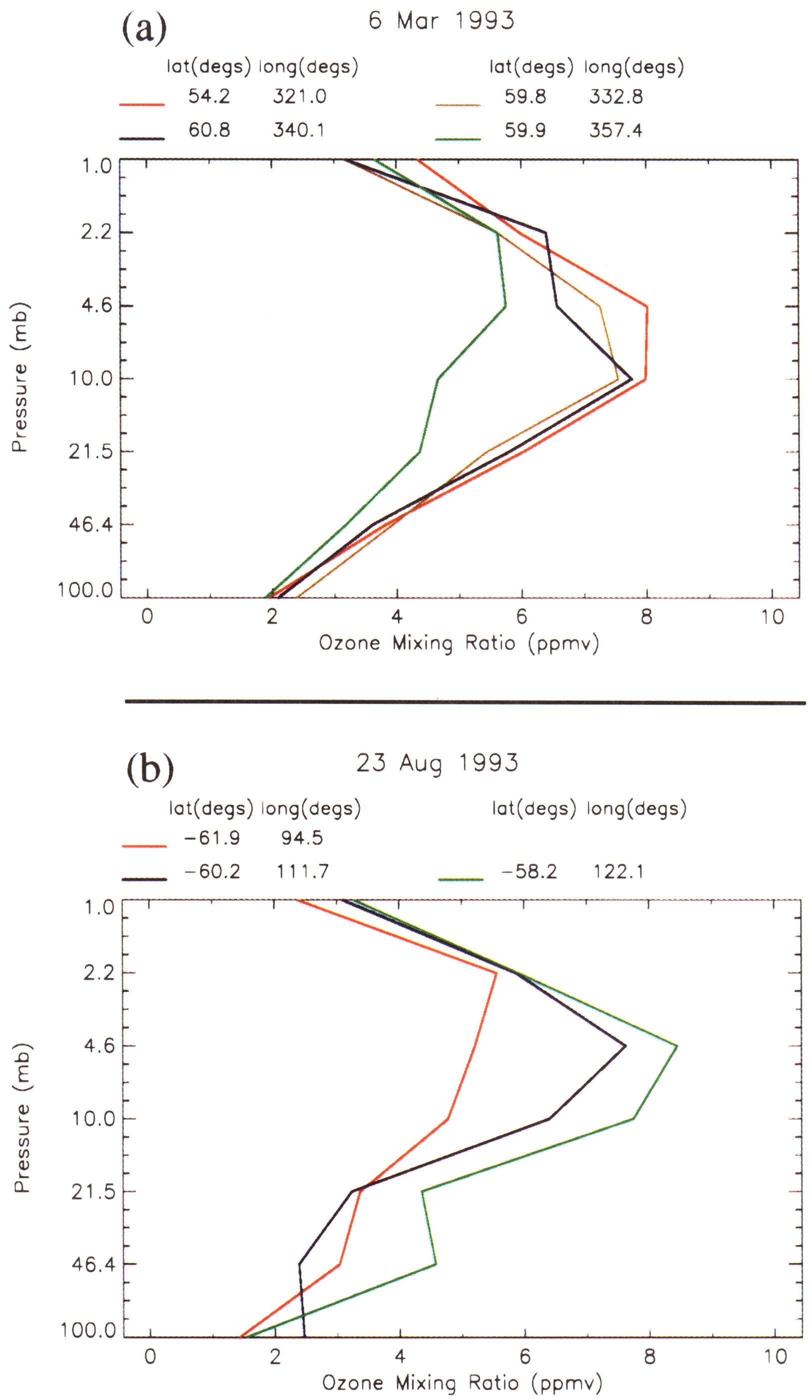

Plate 11. Individual ozone profiles on (a) March 6, 1993 (NH) and (b) August 23, 1993 (SH), crossing the vortex edge. Approximate profile locations for Plate 11a are indicated in Plate 6c, and for Plate 11b in Plate 8a.

most (red) profile sampled air from within the vortex at all levels, the blue and green profiles sampled air from outside the vortex above 22 hPa; at 46 hPa the green profile sampled air characteristic of the vortex edge or exterior, while the blue one sampled air characteristic of the interior.

5. Summary and Conclusions

The time evolution of UARS MLS ozone throughout the stratosphere during winter is shown in relation to the evolution of the stratospheric polar vortex for three NH and two SH winters. The general results show poleward and downward transport of ozone in the middle and upper stratosphere during December through March in the NH and June through September in the SH, consistent with previous theoretical [e.g., *Rood and Schoeberl,* 1983; *Andrews et al.,* 1987; *Fisher et al.,* 1993; *Manney et al.,* 1994d] and observational [e.g., *Wu et al.,* 1985, 1987; *Manney et al.,* 1993] studies. Overall increases in high-latitude ozone in the middle and upper stratosphere between early and late winter were seen in the NH in 1991/1992 and 1992/1993, even at levels above the ozone mixing ratio peak, indicative of strong poleward transport at these levels. In the 1993/1994 NH and the 1992 and 1993 SH late winters, ozone is still less than the early winter values above the mixing ratio peak but greater below, reflecting the dominant effects of downwelling.

Interannual and interhemispheric differences in polar ozone are related to the timing, spatial structure, and intensity of stratospheric warmings. Rapid increases are seen in vortex ozone in the middle and upper stratosphere during strong warmings, due to enhanced diabatic descent resulting from greater departures from radiative equilibrium and enhanced horizontal transport into the vortex when the mixing barrier becomes sufficiently weak. Stratospheric warmings are more frequent and stronger in late winter than in early winter in both hemispheres. Warmings are stronger, more frequent, and more persistent in the NH than in the SH, resulting in a smaller, weaker, and more distorted NH vortex. The polar vortex in the NH upper stratosphere is so eroded during strong warmings that it presents little barrier to mixing; in contrast, during SH warmings the vortex, although distorted, remains strong throughout the stratosphere. Much less increase in NH middle and upper stratospheric ozone is seen in late winter 1994, when the NH midstratospheric vortex remains relatively strong, than in 1992 or 1993. In this regard, the 1993/1994 NH winter resembles those in the SH. Large NH increases in vortex ozone mean than the middle and upper stratosphere contribute more to the total mass of vortex ozone in the NH than in the SH.

Ozone decreases during late winter in the SH lower stratosphere are attributed to chemical destruction; similar late winter ozone decreases were observed in the SH 1992 and 1993 winters. The behavior in the NH is more ambiguous and variable. Evidence was previously presented suggesting chemical destruction of ozone in the lower stratospheric vortex during the 1991/1992 [*Waters et al.,* 1993a] and 1992/1993 [*Manney et al.,* 1994a] NH winters. In late February and early March 1994, a decrease is seen in lower stratospheric ozone, concurrent with a decrease in temperatures and enhancement of ClO. This suggests chemical ozone depletion at this time; further analysis is under way to determine whether dynamical processes could have caused ozone to decrease.

The synoptic evolution of ozone and the polar vortex is compared for late winters in the NH and SH. The midstratospheric vortex in both hemispheres shows strong effects of stratospheric warmings. High ozone from low latitudes is drawn up along the edge of the polar vortex, into the region of the anticyclone. Tongues of low ozone are drawn off the vortex around the low-latitude side of the anticyclone. NH planetary wave activity is sufficiently strong and persistent that this type of behavior is seen nearly continuously; in contrast, in the SH, high ozone being drawn around the vortex and low ozone coming off the vortex are seen only at the peaks of the stronger warmings.

Synoptic maps of ozone in the NH lower stratosphere demonstrate a relationship between the extent of higher-ozone values seen at middle latitudes, outside the vortex, and the strength of the lower stratospheric vortex, as indicated by the 465 K PV gradients. In 1994 the lower stratospheric vortex was considerably weaker during most of the NH winter than in 1992 or 1993, and much larger areas of higher ozone are seen outside the vortex in 1994. *Manney et al.* [1994a] showed that in February 1979, during a NH winter when the lower stratospheric vortex was even weaker than in 1994, even larger areas of relatively high ozone (from Limb Infrared Monitor of the Stratosphere measurements) are seen outside the vortex. The degree of isolation in the NH winter is thus quite variable. Lower-stratospheric ozone is expected to be much more confined in the vortex during winter in the coldest years; since less of the higher vortex ozone is tranported to lower latitudes, this effect favors lower midlatitude ozone during colder NH winters.

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References

Andrews, D. G., Some comparisons between the middle atmosphere dynamics of the southern and northern hemispheres, *Pure Appl. Geophys., 130,* 213-232, 1989.

Andrews, D. G., J. R. Holton, and C. B. Leovy, *Middle Atmosphere Dynamics,* 489 pp. Academic, San Diego, Calif., 1987.

Barath, F. T., et al., The Upper Atmosphere Research Satellite Microwave Limb Sounder instrument, *J. Geophys. Res., 98,* 10,751-10,762, 1993.

Butchart, N., and E. E. Remsberg, The area of the stratospheric polar vortex as a diagnostic for tracer transport on an isentropic surface, *J. Atmos. Sci., 43,* 1319-1339, 1986.

Dunkerton, T. J., and D. P. Delisi, Evolution of potential vorticity in the winter stratosphere of January-February 1979, *J. Geophys. Res., 91,* 1199-1208, 1986.

Dutsch, H. U., The ozone distribution in the atmosphere, *Can. J. Chem., 52,* 1491-1504, 1974.

Elson, L. S., and L. Froidevaux, The use of Fourier transforms for asynoptic mapping: Early results from the Upper Atmosphere Research Satellite Microwave Limb Sounder, *J. Geophys. Res.*, *98*, 23,039-23,049, 1993.

Elson, L. S., G. L. Manney, L. Froidevaux, and J. W. Waters, Large-scale variations in ozone from the first two years of UARS MLS data, *J. Atmos. Sci.*, *51*, 2867-2876, 1994.

Farrara, J. D., M. Fisher, C. R. Mechoso, and A. O'Neill, Planetary-scale disturbances in the southern stratosphere during early winter, *J. Atmos. Sci.*, *49*, 1757-1775, 1992.

Fishbein, E. F., L. S. Elson. L. Froidevaux, G. L. Manney, W. G. Read, J. W. Waters, and R. W. Zurek, MLS observations of stratospheric waves in temperature and ozone during the 1992 southern winter, *Geophys. Res. Lett.*, *20*, 1255-1258, 1993.

Fisher, M., A. O'Neill, and R. Sutton, Rapid descent of mesospheric air in the stratospheric polar vortex, *Geophys. Res. Lett.*, *20*, 1267-1270, 1993.

Froidevaux, L., J. W. Waters, W. G. Read, L. S. Elson, D. A. Flower, and R. F. Jarnot, Global ozone observations from UARS MLS: An overview of zonal mean results, *J. Atmos. Sci.*, *51*, 2846-2866, 1994.

Haynes , P. H., and M. E. McIntyre, On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces, *J. Atmos. Sci.*, *44*, 828-841, 1987.

Ko, M. K., N. D. Sze, M. Livshits, M. B. McElroy, and J. A. Pyle, The seasonal and latitudinal behavior of trace gases and O_3 as simulated by a two-dimensional model of the atmosphere, *J. Atmos. Sci.*, *41*, 2381-2408, 1984.

Manney, G. L., and R. W. Zurek, Interhemispheric comparison of the development of the stratospheric polar vortex during fall: A 3-dimensional perspective for 1991-1992, *Geophys. Res. Lett.*, *20*, 1275-1278, 1993.

Manney, G. L., L. Froidevaux, J. W. Waters, L. S. Elson, E. F. Fishbein, R. W. Zurek, R. S. Harwood, and W. A. Lahoz, The evolution of ozone observed by UARS MLS in the 1992 late winter southern polar vortex, *Geophys. Res. Lett.*, *20*, 1279-1282, 1993.

Manney, G.L., et al., Chemical depletion of lower stratospheric ozone in the 1992-1993 northern winter vortex, *Nature*, *370*, 429-434, 1994a.

Manney, G. L., R. W. Zurek, A. O'Neill, R. Swinbank, J. B. Kumer, J. L. Mergenthaler, and A. E. Roche, Stratospheric warmings during February and March 1993, *Geophys. Res. Lett.*, *21*, 813-816, 1994b.

Manney, G. L., J. D. Farrara, and C. R. Mechoso, Simulations of the February 1979 stratospheric sudden warming: Model comparisons and three-dimensional evolution, *Mon. Weather Rev.*, *122*, 1115-1140, 1994c.

Manney, G. L., R. W. Zurek, A. O'Neill, and R. Swinbank, On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, *51*, 2973-2994, 1994d.

Manney, G. L., L. Froidevaux, J. W. Waters, R. W. Zurek, J. C. Gille, J. B. Kumer, J. L. Mergenthaler, A. E. Roche, A. O'Neill, and R. Swinbank, Formation of low ozone pockets in the middle stratospheric anticyclone during winter, *J. Geophys. Res.*, in press, 1995.

Nagatani, R. M., A. J. Miller, K. W. Johnson, and M. E. Gelman, An eight-year climatology of meteorological and SBUV ozone data, *NOAA Tech. Rep. NWS 40*, 1988.

Perliski, L. M., and J. London, Satellite-observed long-term averaged seasonal and spatial ozone variations in the stratosphere, *Planet. Space Sci.*, *37*, 1509-1525, 1989.

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.

Rood, R. B., and M. R. Schoeberl, Ozone transport by diabatic and planetary wave circulations on a beta plane, *J. Geophys. Res.*, *88*, 8491-8504, 1983.

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield, The structure of the polar vortex, *J. Geophys. Res.*, *97*, 7859-7882, 1992.

Swinbank, R., and A. O'Neill, A Stratosphere-troposphere data assimilation system, *Mon. Weather Rev.*, *122*, 686-702, 1994.

Tung, K. K., and H. Yang, Dynamical component of seasonal and year-to-year changes in Antarctic and global ozone, *J. Geophys. Res.*, *93*, 12,537-12,559, 1988.

Waters, J. W., Microwave limb sounding, in *Atmospheric Remote Sensing by Microwave Radiometry*, Edited by M. A. Janssen, pp. 383-496, 1993.

Waters, J. W., L. Froidevaux, W. G. Read, G. L. Manney, L. S. Elson, D. A. Flower, R. F. Jarnot, and R. S. Harwood, Stratospheric ClO and ozone from the Microwave Limb Sounder on the Upper Atmosphere Research Satellite, *Nature*, *362*, 597-602, 1993a.

Waters, J. W., L. Froidevaux, G. L. Manney, W. G. Read, and L. S. Elson, MLS observations of lower stratospheric ClO and ozone in the 1992 southern hemisphere winter, *Geophys. Res. Lett.*, *20*, 1219-1222, 1993b.

Waters, J. W., G. L. Manney, W. G. Read, L. Froidevaux, D. A. Flower, and R. F. Jarnot, UARS MLS observations of lower stratospheric ClO in the 1992-93 and 1993-94 Arctic winter vortices, *Geophys. Res. Lett.*, in press, 1995.

Wu, M.-F., M. A. Geller, J. G. Olson, A. J. Miller, and R. M. Nagatani, Computations of ozone transport using Nimbus 7 Solar Backscatter Ultraviolet and NOAA/National Meteorological Center Data, *J. Geophys. Res.*, *90*, 5745-5755, 1985.

Wu, M.-F., M. A. Geller, J. G. Olson, and E. M. Larson, A study of global ozone transport and the role of planetary waves using satellite data, *J. Geophys. Res.*, *92*, 3081-3097, 1987.

Yang, H., E. Olaguer, and K. K. Tung, Simulation of the present-day atmospheric ozone, odd nitrogen, chlorine and other species using a coupled 2-D model in isentropic coordinates, *J. Atmos. Sci.*, *48*, 442-471, 1991.

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