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Interannual Variability of the North Polar Vortex in the Lower Stratosphere during the UARS Mission

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Abstract. Three of the four northern winters since the launch of the Upper Atmosphere Research Satellite had daily NMC minimum temperatures in the lower stratosphere that approached or fell below the lowest values experienced during the previous 13 years. Northern temperature minima on the 465 K isentrope were unseasonably low during December 1994 and during a late winter cold spell of an otherwise average 1993-94 winter. Both the 1992-93 and 1994-95 winters were somewhat reminiscent of the winter Antarctic lower stratosphere in that, compared to other northern winters since 1978, they had prolonged spells with low minimum temperatures, their polar vortices were relatively isolated by very strong PV gradients, and these vortices persisted in the lower stratosphere into spring. Meteorological conditions in both these years were more conducive than in most northern winters since 1978 to formation of polar stratospheric clouds and thus to chlorine activation and associated chemical loss of ozone in the lower stratosphere. In the near future the amount of Arctic ozone loss due to chlorine chemistry should continue to reflect interannual and possibly decadal variations in lower stratospheric temperatures.

Introduction

The phenomenon of polar stratospheric cloud (PSC) formation and associated conversion of stratospheric chlorine into a form which chemically destroys stratospheric ozone is most pervasive over Antarctica where it produces the well-known “ozone hole” during late winter and spring (Solomon, 1990 and references therein). Aircraft data indicate that this phenomenon also occurs to a lesser extent at high northern latitudes during the coldest winter periods (Anderson and Toon, 1993 and references therein). Regionally, satellite data have confirmed the association of northern vortex temperatures low enough for PSC formation, stratospheric chlorine activation and ozone chemical loss in the lower stratosphere. Manney et al. (1994a, 1995) compared minimum temperatures in the polar vortex with vortex-averaged concentrations of the chlorine monoxide radical (C1O) and of ozone retrieved (Waters et al., 1993; 1995) in the lower stratosphere by the Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS). Elevated concentrations of C1O were observed in sunlit regions of the polar vortex near the 46 hPa level whenever temperatures somewhere within the vortex remained below ≈ 195 K, a typical threshold value for PSC formation.

Quantitative descriptions of chlorine activation and associated ozone loss are limited by intricacies of PSC microphysical processes and by the motion of vortex air. These are particularly important in the north polar vortex, where temperatures often hover near the PSC threshold values and where ozone chemical loss during winter in the Arctic lower stratosphere competes against a large seasonal transport of ozone-rich air poleward and downward. However, it is clear that the duration of temperatures low enough to produce PSCS currently affects the amount of ozone chemical loss in the lower stratosphere, as it will continue to do as long as stratospheric chlorine amounts remain high.

In this paper, National Meteorological Center (NMC) daily minimum temperatures in the lower stratosphere and within the wintertime north polar vortex are compared for the period of UARS observations to those observed since 1978. We emphasize this measure rather than zonal averages or area integrals, as even relatively small regions of PSC may chemically process significant amounts of vortex air. A similar comparison against climatology was done by Nagatani et al. (1990) for the 1988-1989 Airborne Arctic Stratospheric Expedition. We also examine briefly the daily maximum potential vorticity (PV) gradients in the region of strong gradients that define the polar vortex itself, as these give a measure of the relative confinement of vortex air in the lower stratosphere.

Data and Analysis

We use standard NMC Climate Analysis Center daily global stratospheric analyses of geopotential height and temperature from October 1978 to the present, with analyses since September 1991 provided as correlative UARS data (Gelman et al., 1994), Horizontal winds and Rossby-Ertel potential vorticity (PV) are calculated for each day as described in Manney and Zurek (1993). The daily calculated PV fields are derived on nine isentropic levels close to standard NMC pressure levels in the stratosphere.

In this paper we concentrate on the 465 K isentropic surface (≈ 50 hPa) where ClO concentrations at high northern latitudes are observed to be large during winter (Waters et al. 1993, 1995; Manney et al., 1995), and thus the potential is greatest for chemical loss of Arctic ozone. Near this level (Type I) Arctic PSCS typically form when temperatures are below ≈ 195 K (Poole and Pitts, 1994), suggesting compositions involving various nitric acid hydrates (e.g., Hanson and Mauersberger, 1988). The formation of water-ice (Type II) PSCS, which can lead to dehydration and denitrification of vortex air through particle sedimentation, may occur when air at this level cools below ≈ 188 K.

Daily Minimum Temperatures at 465 K

Figure 1 shows the daily minimum temperatures within the polar vortex and its maximum PV gradients on the 465 K isentrope. These have been smoothed with a 5-day running average, in part to emphasize events which are sufficiently persistent to affect ozone chemistry. Curves for the four winters since the UARS launch are shown against the envelope, and its average, of similarly smoothed daily minimum temperature or maximum PV gradient values for the prior 13 year period.

From mid-December through January the average temperature minima for 1978/79-1990/91 is below the nominal Type I PSC threshold. In 1991, minimum temperatures also fell below 195 K in mid-December, but were lower than average in early January 1992. In mid-January, a stratospheric warming quickly raised the minimum temperatures above the Type 1 threshold and well above the average until March.

From mid-December 1992 to early January 1993, daily minimum temperatures fluctuated somewhat, but fell overall as in 1991-1992. However, minimum temperatures continued to fall in 1993, reaching a lower limit in late January attained in years prior to the UARS launch. Minimum temperatures rose in February, but remained well below the average for the rest of the winter. From late January to late February, the 1993 temperature minima were the lowest of the four winters with UARS observations; in the full record since 1978, only 1984 and 1990 had noticeably lower values sometime in this period.

In December 1993 through mid-February 1994, minimum temperatures at 465 K were near or above the 1978/79 - 1990/91 average. Temperature minima were above 195 K during a stratospheric warming at the beginning of January 1994. In late February, vortex temperatures at 465K plummeted from near 195 K to new lows for this period and remained below the envelope through the first week of March. This was the latest that such low temperatures occurred in the full seventeen-year data set.

In 1994-1995, daily minimum temperatures again fell to new lows, this time in early winter and again in late March. Minimum temperatures, already near 195 K on December 1, 1994, fell at a rate reminiscent of their counterparts in the southern winter polar vortex (e.g., Manney and Zurek, 1993; Gelman et al., 1994). From mid-December until mid-January minimum temperatures were near the 188 K (Type II) threshold. The 17 days during this winter with minima ≤ 188 K is comparable to the two coldest winters since 1978, namely 1984 and 1990 (Fig. 2), but the occurrence in 1994 of such temperatures in December is unprecedented (Fig. 1a), as is the= 80 days in 1994-1995 that Arctic minimum temperatures were ≤ 195 K (Fig. 2).

The early 1994-1995 cold spell ended in a series of stratospheric warming events in late January and in early February. However, daily minimum temperatures again fell below 195 K near the end of February. By mid-March, minimum temperatures hovered near 195 K, but were confined to a very small area. This eclipsed 1986 as the Arctic winter having the latest occurrence of NMC temperatures < 195 K at 465 K and made the 1994-1995 PSC season the longest in the 1978-1995 period (Fig. 3).

Potential Vorticity Gradients at 465 K

Manney et al. (1994b) computed maximum PV gradients from area integrals of PV for each winter from 1978-1979 to 1992-1993; they showed that 1992-1993 had exceptionally strong gradients and these were associated with relatively weak mixing across the strong PV gradients which mark the vortex edge. The PV area integrals for the last four winters are shown in Fig. 4, and their maximum PV gradients were shown in Fig. 1b against the background climatology and average for the years 1978/79 - 1990/91.

Since 1978, the 1994-1995 winter had the strongest PV gradients at 465 K from early December to mid-January and had PV gradient maxima second only to 1992-1993 until early February 1995, a week or so after the temperature minima at 465 K increased. The decrease in minimum temperatures at 465 K in early March 1995 was followed by a sharp increase in PV gradients, although these gradients surrounded a smaller vortex (Fig. 4). The PV gradients at 465 K show that a well-defined vortex persisted and remained exceptionally isolated late in March of both 1993 and 1995.

Discussion and Summary

In recent years polar vortex temperature minima fell below the 1978/79 - 1990/91 envelope by a few degrees in December 1994, in late February and early March 1994, and in March 1995. In 1993 minima after mid-January were well below the envelope average, and minima in early January 1995 were at the envelope's lower edge. Given the large interannual variability at high latitudes, it is uncertain whether these low temperature minima in recent years reflect longer term stratospheric temperature trends.

Angell (1988) found no significant trend (at the 95% confidence level) in Arctic 100-50 hPa average temperatures for the period 1973-1987 in any season, though winter values were possibly becoming warmer. Using 50 hPa data from 1964-1985, Karoly (1989) found negative trends in high-latitude temperatures mostly over western North America; as these longitudes are frequently dominated by the Aleutian anticyclone, this suggests a decrease in warmer temperatures outside the polar vortex. Elsewhere, negative 50-hPa temperature trends in middle and lower latitudes may reflect observed decreases in extratropical stratospheric ozone (Miller et al., 1992). Such ozone feedback may significantly amplify radiative cooling effects in the lower stratosphere of increasing greenhouse gases such as C02 (e.g., Austin et al., 1992).

Stratospheric aerosols can affect high-latitude temperatures by radiative effects in the polar twilight and, perhaps more substantively, by the indirect influence of radiative effects at lower latitudes on planetary wave activity and the diabatic circulation (Pitari, 1993). Possibly, the "near-average" wintertime vortex temperature minima of 1993-1994 reflects a delayed effect of the Mt. Pinatubo induced aerosols. This would not explain the late cold spell that year.

Holton and Tan (1980, 1982) found that during the westerl y phase of the equatorial Quasi-Biennial Oscillation (QBO) winds, temperatures and geopotential heights at 50 hPa and poleward of 60°N were lower than during the easterly phase. However, Christy and Drouilhet (1994) found that zonally averaged Microwave Sounding Unit brightness temperatures for the 40-120 hPa layer were warmer near the pole for northern winters in the years 1979-1992 during the QBO westerly phase.

In the years since the UARS launch equatorial zonal-mean easterly winds prevailed through most of 1992, finally changing near 50 hPa to weak westerlies in December (Swinbank and O'Neill, 1994). Zonal-mean easterlies had descended to ≈ 30 hPa by late summer 1993, where their descent stalled, eventually reaching the 50-hPa level in early 1994, where they persisted until late fall 1994 (R. Swinbank, private communication). Thus, the period of near-record or record low temperature minima and strong PV gradients in January-February 1993 and in December 1994 -January 1995 did correspond to periods of westerly wind maxima over the equator near 30 hPa.

Including the late cold spell in 1994, three of the four northern winters with UARS observations had, for significant periods, lower NMC temperature minima near 50 hPa, as compared to winters since 1978. Including the first half of the 1991-1992 winter, three of the four years also had unusually strong PV gradients. UARS observations and trajectory calculations indicate that Arctic ozone loss due to chlorine chemistry was largest in 1992-1993 and 1994-1995 (Manney et al., 1994a; 1995), which were the two UARS years with the most persistently low temperature minima and the strongest PV gradients.

The 1994-1995 northern winter was exceptional in its early, rapid temperature decrease and persistence of unusually low temperature minima in the lower stratosphere during December. The Aleutian anticyclone was late in developing and remained weak throughout the 1994-1995 winter, while the polar vortex at 46S K appeared remarkably robust and isolated, with relatively strong PV gradients developing in early winter.

The 1992-1993 and 1994-1995 northern winters are reminiscent of the wintertime lower stratosphere over Antarctica in that they both had prolonged spells with low minimum temperatures, vortices marked by very strong PV gradients, and vortices which persisted in the lower stratosphere until spring. The greater dynamical activity of the northern winter is still able, however, to limit periods of PSC formation as compared to the southern hemisphere, and presently northern temperatures infrequently drop below the Type 11 PSC threshold. Even so, recent wintertime temperature observations show that extended cold spells can occur in the Arctic lower stratosphere during the coming decade, with associated ozone loss due to chlorine chemistry.

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FIGURE LEGENDS

Figure 1: a) NMC daily minimum temperatures within the north polar vortex as defined by the 0.25 x 10^{-4} K $m^2kg^{-1}s^{-1}$ contour of PV, and b) the maximum daily PV gradients computed from area integrals (i e., the area enclosed within a chosen PV contour differentiated with respect to equivalent latitude). All on the 465K isentropic surface (≈ 50 hPa). Daily values have been smoothed with a five-day running mean. Curves are shown for the four northern winters with UARS observations. Shaded region indicates the range of (smoothed) daily temperature minima as determined by wintertime NMC data for 1978/79 to 1990/91. White curve indicates the average minima for that period. Straight lines in (a) at 195 K and 188 K indicate approximate threshold temperatures for Type I and Type 11 PSC formation, respectively.

Figure 2: The number of days during northern winter that the NMC daily minimum temperatures were ≤ 195 K (Type 1 PSC threshold) and 188 K (Type II PSC threshold) on the 465 K isentrope (in the polar vortex). Computed for the years 1978/79 - 1994/95. The UARS launch date is indicated.

Figure 3: The first and last days of each northern winter for which the NMC daily minimum temperature was ≤195 K (Type I PSC threshold) on the 465 K isentrope. The difference between these dates is denoted the PSC season (shaded area). Computed for the years 1978/79 - 1994/95. The UARS launch date is indicated.

Figure 4: PV area integrals expressed as equivalent latitude of scaled PV contours (in "vorticity units" of 10-4 s^{-1}; Manney et al., 1994b) on the 465 K isentropic surface for the four northern winters since the UARS launch. Contour intervals are 0.2, with the 1.4 (x 10^{-4} s^{-1}) contour in bold.

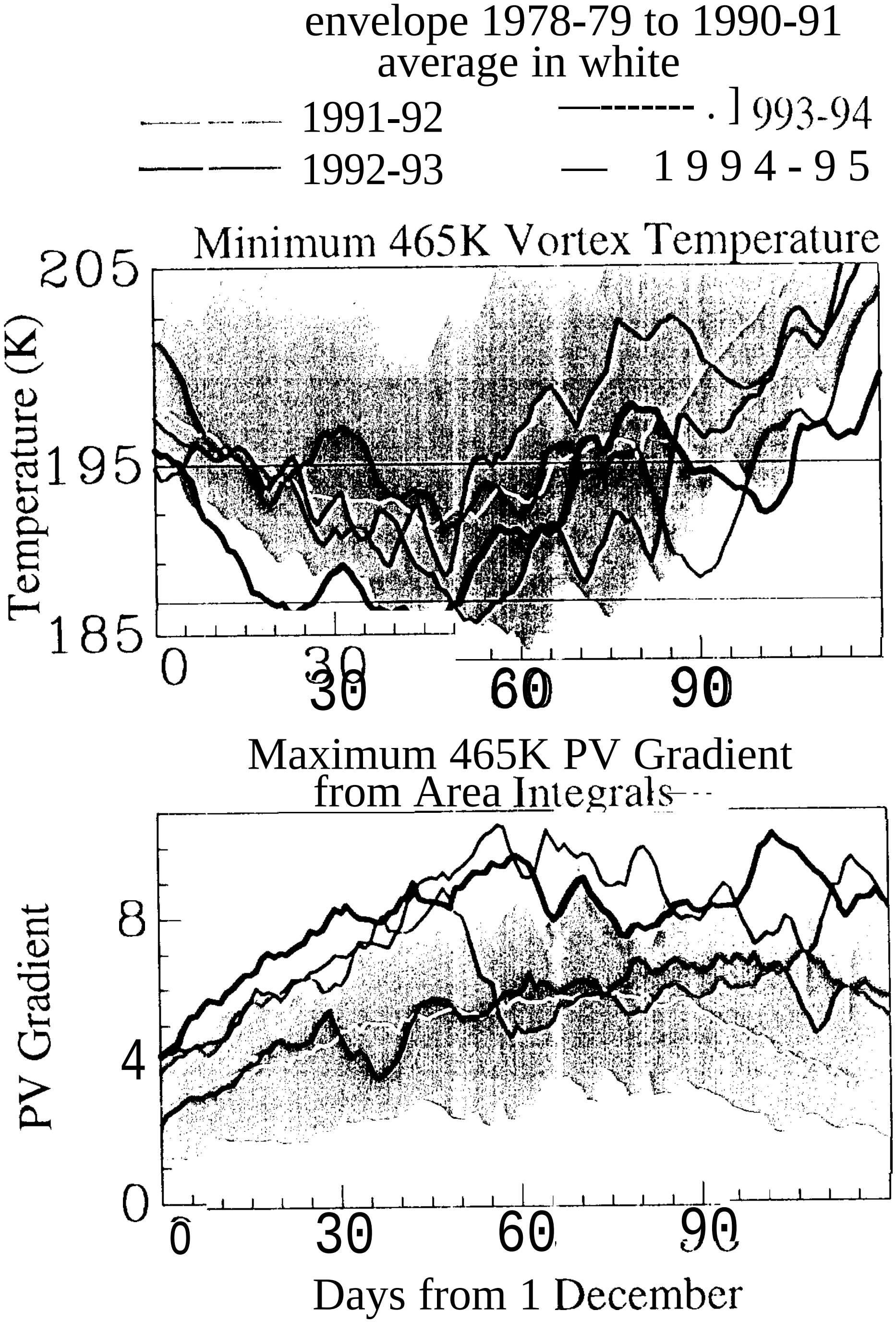

envelope 1978-79 to 1990-91
average in white
1991-92
1992-93
1993-94
1994-95
Minimum 465K Vortex Temperature
Temperature (K)
205
195
185
0
30
60
90
Maximum 465K PV Gradient
from Area Integrals
PV Gradient
8
4
0
0
30
60
90
Days from 1 December

Figure 1

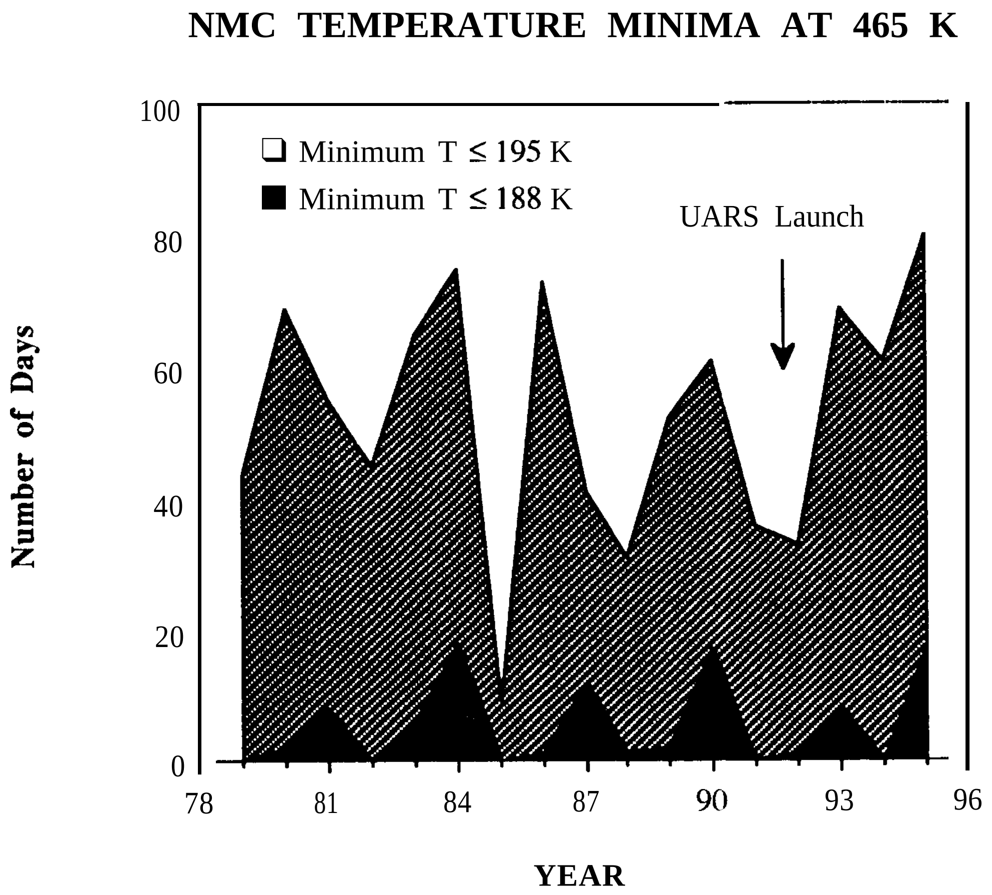
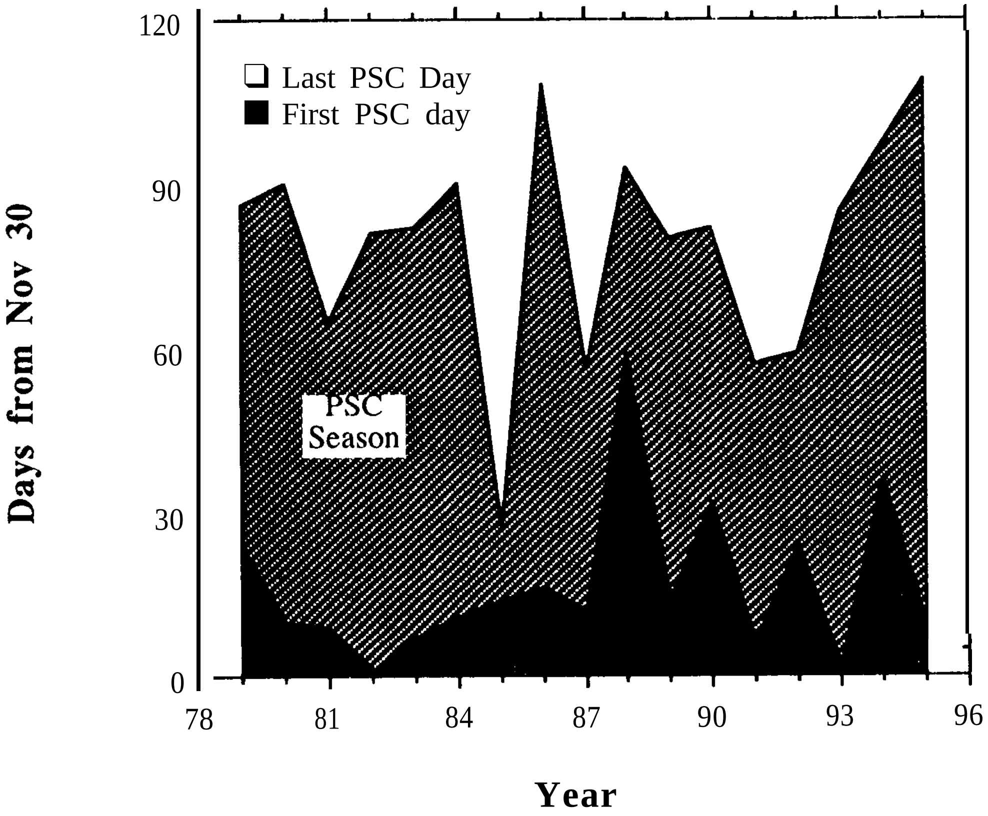

NMC TEMPERATURE MINIMA AT 465 K
☐ Minimum T ≤ 195 K
■ Minimum T ≤ 188 K
UARS Launch
Number of Days
100
80
60
40
20
0
78
81
84
87
90
93
96
YEAR

FIGURE 2



Days of First and Last Occurrence at 465K of NMC Vortex Temperatures < 195 K

FIGURE 3

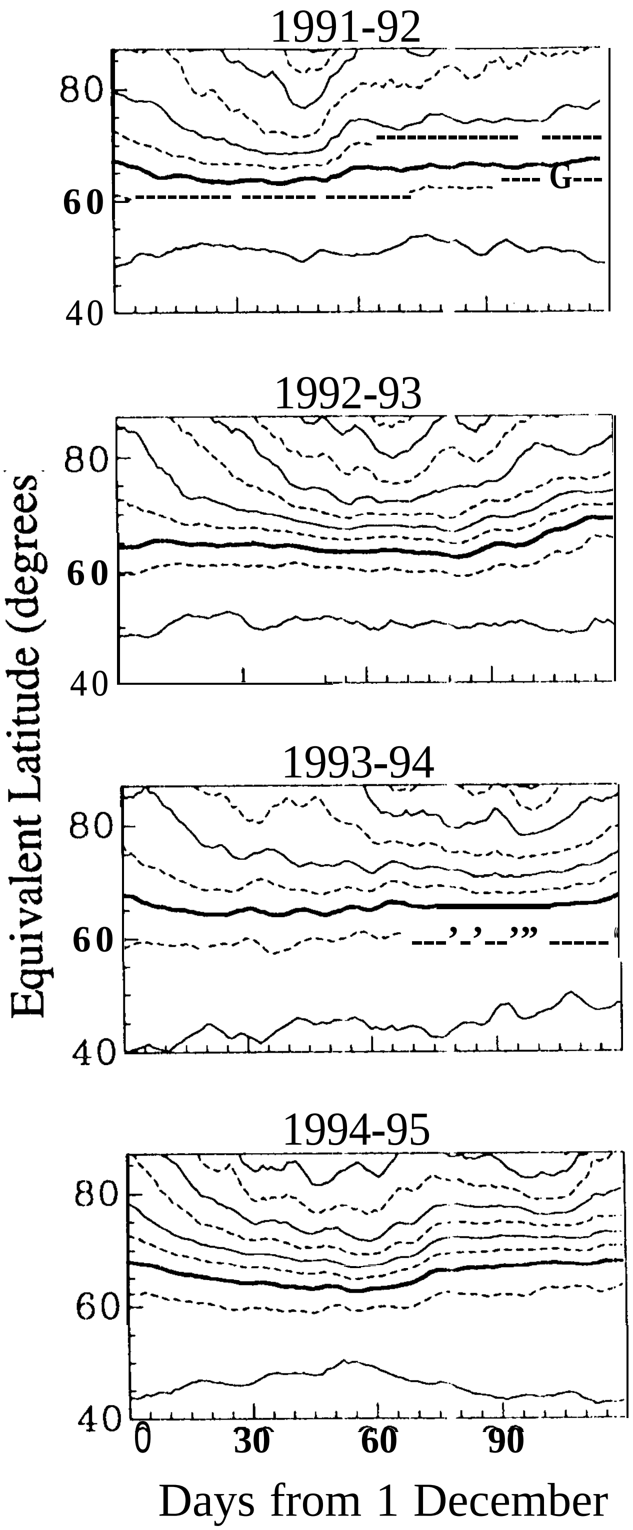

1991-92
1992-93
1993-94
1994-95
80
60
40
Equivalent Latitude (degrees
0
30
60
90
Days from 1 December

FIGURE 4