THE ANOMALOUS ARCTIC LOWER STRATOSPHERIC POLAR VORTEX OF 1992-1993

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Abstract

The strength of the Arctic lower stratospheric polar vortex is examined for the last 16 Arctic winters. Potential vorticity (PV) gradients, calculated from area-integrals of PV, defining the vortex during the 1992-1993 winter were anomalously strong and persistent. For nearly 3 months PV gradients were closer to typical southern hemisphere values than to most northern hemisphere values. The 1992-1993 Arctic lower stratospheric vortex is thus expected to be substantially more isolated than is typical in the northern hemisphere; this is supported by air motion diagnostics computed for 3-dimensional air parcel trajectories. Such isolation will delay and perhaps reduce the export of the higher ozone concentrations typical of the winter lower stratospheric vortex to mid-latitudes, This may have contributed to the record-low total ozone amounts observed in northern mid-latitudes in 1993.

Introduction

Considerable attention has been focused on the 1992-1993 Arctic winter lower stratosphere, both in the polar regions and in mid-latitudes. Manney et al [1994a] analyzed Upper Atmosphere Research Satellite (UARS) data to show strong evidence for substantial chemical ozone depletion in the polar vortex during that winter. Gleason et al. [1993] and Herman and Larko [1994] reported anomalously low northern mid-latitude column ozone observed throughout 1993 and in late 1992 by the Total Ozone Mapping Spectrometer (TOMS). Manney et al. [1994b, submitted to *J. Geophys. Res.*] showed meteorological and UARS Microwave Limb Sounder (MLS) ozone observations indicating that the lower stratospheric vortex in 1992-1993 was stronger than in 1991-1992 or 1993-1994, and that smaller areas of high ozone (values typical of the vortex) were seen outside the vortex in 1992-1993. Relatively large areas of higher ozone outside the vortex were seen in LIMS data in the 1978-1979 winter, during which the lower stratospheric vortex was weak [Manney et al. 1994a]. The strength of the polar vortex during northern winter can affect lower stratospheric ozone at polar and mid-latitudes in two ways. First, temperatures remain lower within a stronger, more isolated vortex, favoring more polar stratospheric cloud (PSC) formation. Heterogeneous processes on the surface of PSCS both liberate reactive chlorine from reservoir species, and inhibit re-formation of chlorine reservoirs by sequestering reactive nitrogen. These effects enhance concentrations of reactive chlorine species and the corresponding chemical loss of ozone [Waters et al. 1993]. When vortex air is finally mixed into mid-latitudes, perhaps as late as the final warming, ozone mixing ratios are not as high as they would otherwise be because of this photochemical loss. Second, with a stronger vortex, the ozone-rich air in the lower stratosphere remains largely confined inside the vortex. The chemical ozone loss in the Arctic is highly variable, and the wintertime variation of high-latitude ozone still tends to be dominated by transport. Thus, the second effect is potentially the more important one. Here, we examine the strength of the Arctic lower stratospheric vortex during the last 16 winters and show that the lower stratospheric vortex was anomalously strong during the 1992-1993 winter. Implications for the evolution of lower stratospheric ozone are discussed.

Data and Analysis

The data are 16 years of geopotential height and temperature data from the US National Meteorological Center (NMC); these data and changes in NMC's analysis procedures over the years are described by Finger et al. [1993] and references therein. The Rossby-Ertel potential vorticity (PV) calculated from these [Manney and Zurek 1993] displayed on isentropic surfaces is used to describe the evolution of the lower stratospheric vortex. PV is displayed in "vorticity units" [Dunkerton and Delisi 1986] by dividing the values by a standard atmosphere value of the static stability; it thus has units of s^{-1}. The analysis is based on area-integrals of PV [Butchart and Remsberg 1986] which show the overall time evolution of the polar vortex. We examine 1 December through 30 April, for the 1978-1979 through 1993-1994 Arctic winters.

Some diagnostics of air motion are shown for the 1991-1992, 1992-1993, and 1993-1994 winters, calculated from the 3-d trajectory simulations described by Manney et al. [1994b]. Winds from the United Kingdom Meteorological Office (UKMO) data assimilation system [Swinbank and O'Neil] 1994] were used for these. Comparisons of UKMO and NMC fields show very small differences in PV gradients calculated from each in the lower stratosphere [Manney et al., in preparation]; Manney et al. [submitted to *J. Geophys. Res.*] showed area integrals of PV calculated from UKMO data, which strongly resemble those shown here calculated from NMC data.

Results

Figure 1 shows area-integrals of PV on the 465 K (≈50-60 hPa in high latitudes) isentropic surface, for the 1978-1979 through 1993-1994 Arctic winters. The position of the bold contour (a scaled PV value of 1.4 x 10^{-4} s^{-1}) indicates the relative size (areal extent) of the polar vortex in each year, while the spacing of the contours indicates the strength of the vortex. The Fig. 1 panels are arranged to correspond to a three-year pattern in minimum polar lower stratospheric temperatures noted by Zurek et al. [submitted to *J. Geophys. Res.]* for 1978 through 1994. As described there, a relatively cold year is followed by a relatively warm year, followed by one which is in between. Those years identified as "warm" are in the left column in Figure 1, and the correspondence of higher minimum temperatures to a weaker lower stratospheric vortex is generally seen in weaker PV gradients (especially 1987-1988) and/or a smaller polar vortex (especially 1984- 1985). The "cold" years in the right column of Figure 1 include most of the years when PV gradients are strongest or most persistently strong, the most dramatic example being 1992-1993.

Major stratospheric warmings occur during a number of years, including events in February 1979, February 1981, January 1985 [Andrews et al. 1987], December 1987 [Baldwin and Dunkerton 1989], and February 1989 [Fairlie et al. 1990]. Although the strongest effects of warmings are in the middle and upper stratosphere, most events also produce an abrupt decrease in vortex size at 465 K, followed by a weakening of the PV gradients. The most dramatic example is in 1988-1989, when the February major warming led directly to a very early final warming. In 1991-1992, effects are seen of a nearly major warming in late January [e.g., Manney and Zurek 1993]. A virtually major warming at the beginning of January 1994 had a profound effect on the mid-stratospheric circulation [Manney et al 1994b], but its effect on the lower stratospheric vortex was transitory,

In 1992-1993, strong stratospheric warmings in late February and early March raised lower stratospheric temperatures above the PSC formation threshold [Manney et al. 1994a,c]. The lower stratospheric vortex, however, remained strong through earl y April 1993. Although several other years, including 1989-1990, 1991-1992 and 1993-1994 show relatively strong PV gradients and large vortex areas as late in the season as in 1992-1993, the PV gradients in 1992-1993 appear stronger throughout January and

February than any shown in the other panels. To quantify this, Figure 2 shows time series for the same periods of the maximum average daily PV gradient, calculated from the values shown in Figure 1 (i.e., $\Delta PV/\Delta\phi_{eq}$, where ϕ_{eq} is the equivalent latitude in degrees), but examining only those contours with PV $\geq 1.2 \times 10^{-4}$ s^{-1}, and at equivalent latutudes less than 80°. This restriction insures that spurious strong PV gradients caused by noise at high PV values are excluded. It also serves as an indication of when the polar vortex can reasonably be defined. We assume that if the 1.4×10^{-4} S-l PV contour is at greater than 80° equivalent latitude, the polar vortex is not well defined, and we set the PV gradient for that day equal to zero. The horizontal solid (dashed) line on each Figure 2 panel shows the average of the daily maximum PV gradients for the December through April period, calculated including (excluding) those days with zero gradients where the vortex was not defined by the criterion given above. The solid line thus folds the length of the winter into the calculation. Figure 3 summarizes these average values for each winter, and also gives the maximum value of this gradient reached during each winter. For reference, values calculated for the Antarctic winter of 1992 (June through October) are also indicated in Figure 3. There is much less interannual variability in the southern hemisphere (SH), so these represent typical SH values,

As was apparent in Figure 1, the maximum PV gradients in 1992-1993 are considerably stronger than in any other year, and strong for a longer period, Maximum average daily PV gradients in 1992-1993 are greater than 6 x 10-6 $(\text{deg s})^{-1}$ for ≈110 days, while in 1989-1990 this period is ≈75 days, and in 1988-1989, ≈ 45 days. Periods with PV gradients greater than 6 x 10-6 $(\text{deg s})^{-1}$ are much shorter in all other years, with some of the warmer years never reaching this value. Although the maximum values shown in Figure 3 for 1992-1993 are still considerable y lower than those for the SH in 1992, they are closer to the SH values than to most of the NH values. 1989-1990 stands out as the previous year in the NH which most resembles 1992-1993 in the strength and persistence of its lower stratospheric vortex, By the criterion used here of when the lower stratospheric vortex is defined, the 1989-1990 and 1991-1992 winters are slightly longer than that of 1992-1993, while 1983-1984, 1989-1990 and 1992-1993 have the strongest PV gradients. The correspondence to the three-year pattern described by Zurek et al. [submitted to *J. Geophys. Res.]* is again apparent in Figure 3, with the strongest PV gradients in years with lowest minimum temperatures.

Discussion

We have shown that the Arctic lower stratospheric vortex in 1992-1993 was substantially stronger than that in any other of the last 16 Arctic winters. Manney et al. [submitted to *J. Geophys. Res.]* examined UARS MLS ozone in the lower stratospheric vortex during the 1991-1992, 1992-1993 and 1993-1994 Arctic winters. They found that the areal extent of higher ozone mixing ratios (values typical of the vortex) at mid-latitudes (≈40-60^{o}N) at 465 K was considerably less in 1992-1993 than in either 1991-1992 or 1993- 1994; it was also less than in 1978-1979 [Manney et al. 1994a]. Largest regions of higher ozone at mid-latitudes were seen in 1978-1979 and 1993-1994. Higher ozone values outside the vortex may result from horizontal transport, as filaments of material are pulled off the vortex edge region, and/or downward transport. Air motion calculations [Manney et al. 1994b] for January 1993 and January 1994 suggest that: 1) the lower stratospheric vortex in 1993 presented a much stronger barrier to horizontal transport than in 1994, and 2) due to stronger wave activity in early 1994, strong diabatic descent in the lower stratosphere occurred throughout the vortex, and outside the vortex edge, whereas in early 1993 it was confined well within the vortex.

Figure 4 shows some diagnostics of air motion at the end of runs described by Manney et al. [1994b] started on 1 Dec 1992 and 1 Dec 1993, and from a similar run started 1 Dec 1991. For parcels started at 465 K, Figure 4a shows the latitude dispersion of parcels binned by their initial PV, Fig. 4b shows the average change in potential temperature of the parcels; Fig. 4c shows the number of parcels from each bin that have crossed into another bin while decreasing their PV value; Fig. 4d shows the number of parcels from each PV bin that have crossed the 1.3 x 10^{-4} s^{-1} PV contour while decreasing PV, and (on the low PV side of this contour), the number that ended up in each bin. The diagnostics shown in Fig. 4a-4c are described in more detail by Manney et al. [1994b]. Fig. 4d gives a measure of the number of parcels getting out of the vortex. The 1.3 x 10^{-4} s^{-1} PV contour is used to define the vortex edge since it is near where dispersion drops abruptly in Fig. 4a, and near where there is a minimum in the number of parcels decreasing in PV in Fig, 4c. The dispersion in 1993 is lower overall than in the other two years, indicating less mixing, and drops more abruptly near the vortex edge in 1992 and 1993 than in 1994. While the overall amount of descent is similar in the three years, the region of strongest descent extends to lower PV values in 1992 and 1994 than in 1993. The maximum number of parcels decreasing in PV is not only less in 1993 than in the other two years, but drops abruptly along the vortex edge, and shows no secondary maximum inside the vortex like those seen in the 1992 and 1994. The narrowness of the region where parcels are decreasing in PV and its position outside the vortex edge mean that fewer of the parcels that experience strong descent are moving toward lower PV in 1993 than in 1992 or 1994. Figure 4d shows many fewer parcels moving out of the vortex in 1993 than in either 1992 or 1994, and those parcels mainly originate just inside the vortex edge as defined here, as opposed to a large number farther in for the other two years. These results suggest that differences in transport related to the strength of the lower stratospheric vortex are partially responsible for observations of lower ozone at mid-latitudes in the lower stratosphere in the 1992-1993 Arctic winter.

Some correspondences are seen between the PV gradients shown in Fig. 2, and isentropic entrainment/ejection fluxes calculated by Dalberg and Bowman [1994] for 1978-1979 through 1991-1992. Most notably, weakest entrainment/ejection fluxes in March were in 1990 and 1992, the years in which PV gradients were strong latest, Also, the ejection flux is unusually low in January and February 1989, when strongest PV gradients (before 1992-1993) were seen. Similar isentropic calculations for 1992-1993 show better than average vortex isolation in December 1992, February 1993, and particularly in March 1993 [S. Dahlberg, personal communication]. Closer correspondences may result when calculations that include diabatic effects are done. Stronger wave activity, which results in strong descent near or outside the vortex edge, is associated with a weaker lower stratospheric vortex. More detailed air motion calculations are in progress, with the goal of quantifying the relationship between the strength of the lower stratospheric vortex as defined here, and transport of vortex, or vortex-edge air into mid-latitudes.

Froidevaux et al. [1994] showed that the anomalously low NH mid-latitude column ozone observed by TOMS [Gleason et al. 1993, Herman and Larko 1994] during late 1992 and throughout 1993 results mainly from low ozone in the layer from 100 to 50 hPa, near the level discussed here. Herman and Larko [1994, their Figure 4] showed TOMS ozone for 1979 through mid- 1993 averaged in 10 degree latitude bands. In the 50-60°N latitude band, in January through April 1993 column ozone is much lower than in any other year. Excluding 1992-1993, wintertime values for 1991-1992 and 1989-1990 stand out as being lower than typical, with 1991-1992 values being lower early in the year and 1989-1990 values being lower in March. They are also among the lowest years in the 40-50°N latitude band. As noted above, 1989-1990 was the year in which the strength of the Arctic lower stratospheric vortex most resembled that in 1992-1993. Although the vortex in 1991-1992 was not on the average unusually strong, very strong PV gradients were present early in the year, and the vortex was among the most persistent.

Although the observed anomalously low NH mid-latitude ozone during 1992 and 1993 is thought to be related to chemical effects of the Mt. Pinatubo eruption [see for example, discussion by Froidevaux et al. 1994], it is clear that a complete explanation of the anomalously low ozone in northern mid-latitudes during the winter of 1992-1993 must also take into account the effects of the anomalously strong lower stratospheric vortex during that winter.

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Figure Captions

Figure 1. Time series of area integrals of PV for 16 Arctic winters, on the 465 K isentropic surface, running from 1 December through 29 April, Area is expressed in terms of equivalent latitude. PV is scaled in "vorticity units" as described in the text. In these units, the contours run from 0.8 to 3,0 x 10^{-4} s^{-1}, with a contour interval of 0.2 x 10^{-4} s^{-1}; the bold contour is 1.4 x 10^{-4} s^{-1}.

Figure 2. Time series of maximum daily average PV gradients (10-6 [deg s]$^{-1}$) calculated from Fig. 1, for the 16 winters for 1 December through 29 April. The maximum gradients is searched for among PV contours ≥ 1.2 x 10^{-4} s^{-1} which are at equivalent latitudes ≤80^{o}, as described in text. The solid (dashed) line shows the average for all days, including (excluding) those with zero values where the vortex is not defined (see text).

Figure 3. Summary of PV gradients for the 16 winters; open squares show average maximum PV gradient for each year excluding days with zero values; solid dots show average maximum PV gradient calculated including zero values; open circles show the maximum PV gradient reached at any time during each winter, The large open rectangle and large open diamond at the 1992 position show the average and maximum PV gradients for the SH 1992 winter. Units are 10-6 [deg s]$^{-1}$.

Figure 4. Diagnostics of air motion for parcels initialized at 465 K on 1 Dec 1991 (thin solid line), 1 Dec 1992 (thick solid line) and 1 Dec 1993 (dashed line), on 5

February 1992, 1993 and 1994, respectively. Diagnostics are displayed for parcels binned by their initial PV, in bins $0.2 \times 10^{-4}\ s^{-1}$ wide, centered on the tick marks. (a) shows latitude dispersion (deg^2), (b) average change in potential temperature of the parcels started in each bin, (c) the number of parcels initialized in each bin that decrease in PV enough to move into another bin, and (d) for PV > $1.3 \times 10^{-4}\ s^{-1}$, the number of parcels from each bin that crossed the $1.3 \times 10^{-4}\ s^{-1}$ contour moving toward lower PV, and for PV < $1.3 \times 10^{-4}\ s^{-1}$ the number of parcels that ended up in each bin after crossing the $1.3 \times 10^{-4}\ s^{-1}$ contour moving toward lower PV.

465 K AREA INTEGRALS OF SCALED PV

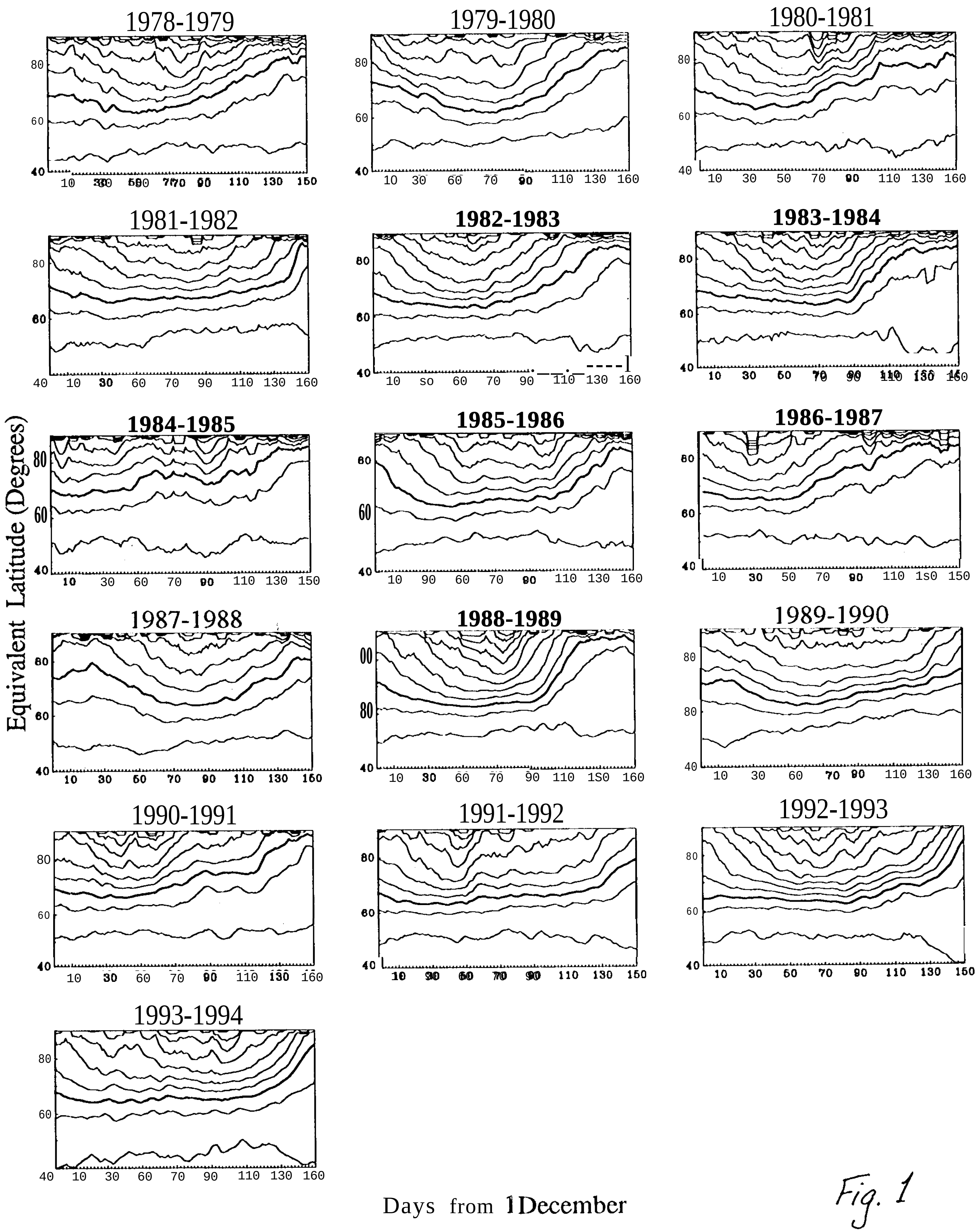

Fig. 1

465 K SCALED PV GRADIENTS

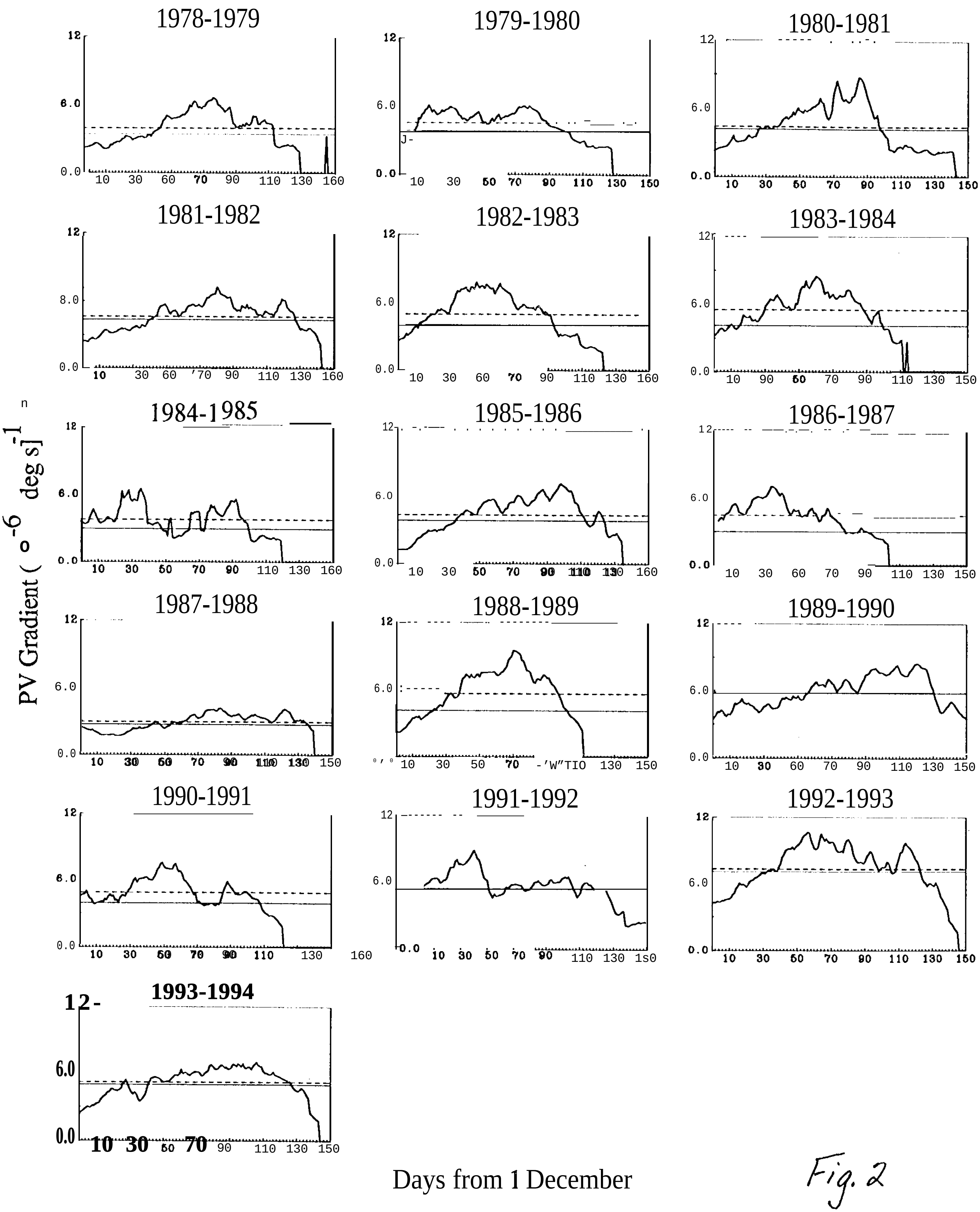

Fig. 2

NORTHERN WINTERS: 1978 - 1994

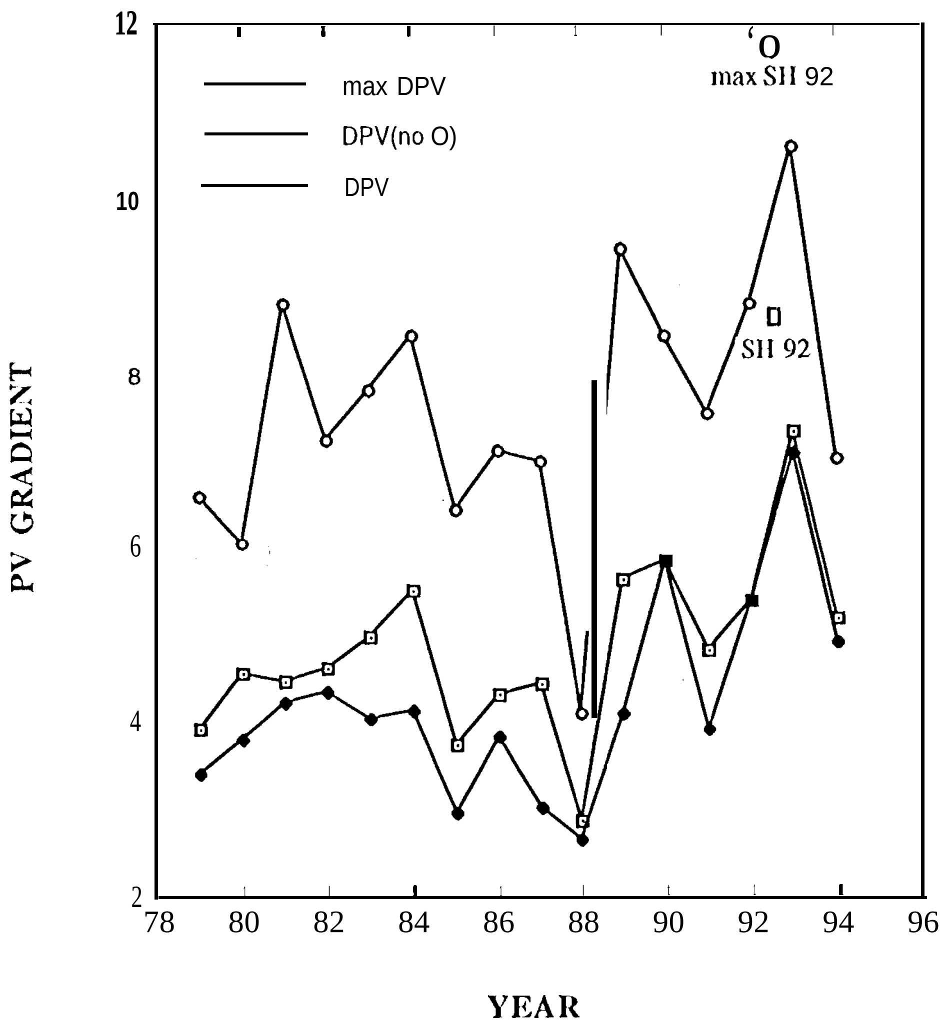

Fig. 3

MIXING DIAGNOSTICS ON 5 FEBRUARY

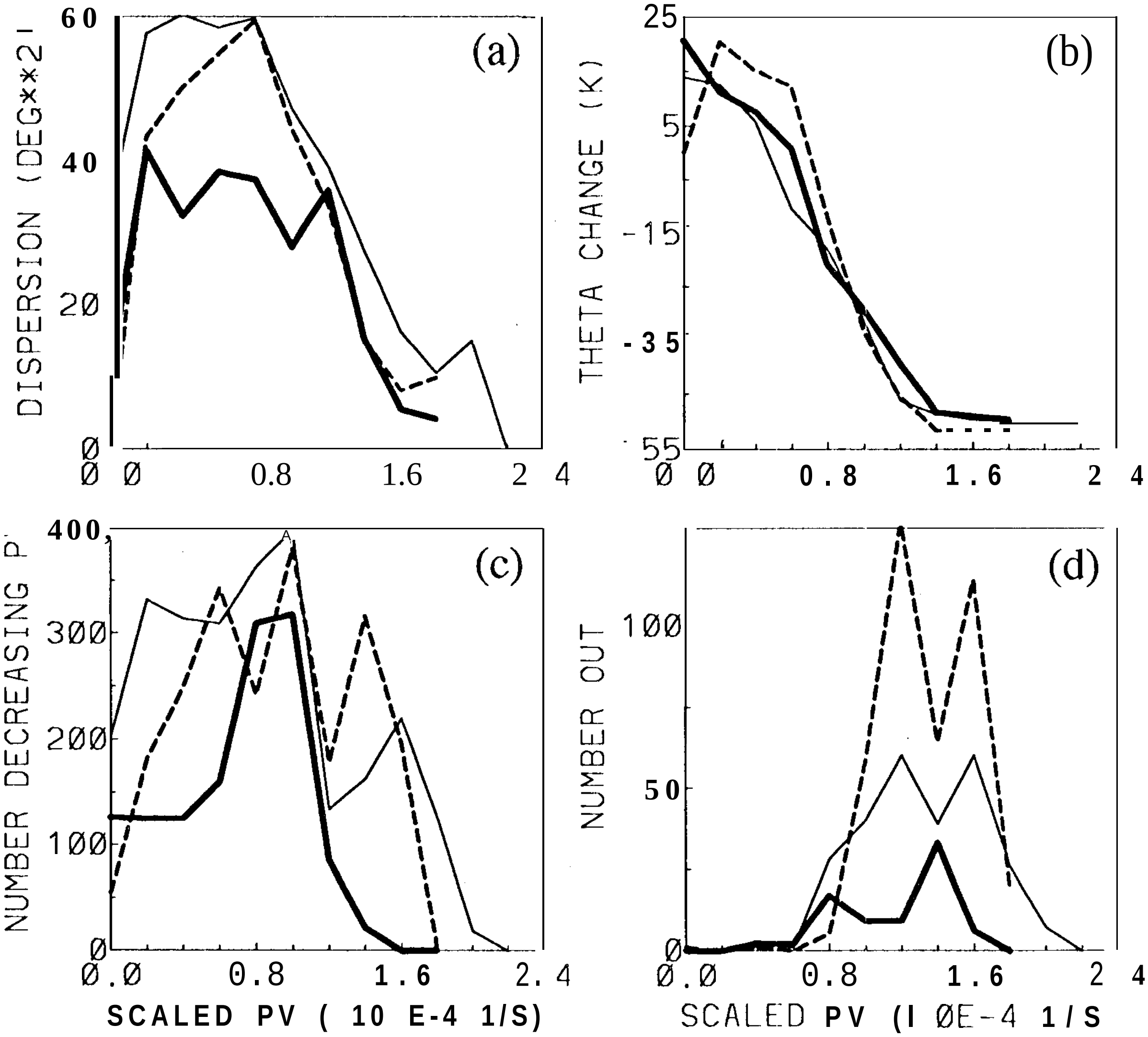

Fig. 4