Abstract. The Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE) was conducted in the spring of 1993 from Moffett Field, California (NASA Ames Research Center), utilizing the NASA high-altitude ER-2 aircraft. These northern midlatitude aircraft flights showed laminae containing high ozone concentrations, traceable to the April 1993 polar vortex breakup and corroborated by laminae of other trace gases such as CFCs, CH₄, N₂O, and CO₂. These laminae are clearly traceable as polar vortex breakup fragments using Rossby-Ertel’s potential vorticity and isentropic trajectory calculations. Laminae in stratospheric ozone profiles are commonly observed in the northern hemisphere from fall to spring, and are hypothesized to originate from very low frequency transverse waves, and/or via Rossby wave breaking. On the basis of these results, the ozone laminae observed during SPADE were a result of Rossby wave breaking during the breakdown of the polar vortex. In addition, it is shown that conventional once-per-day meteorological analyses were adequate for representing the transport of this material into the lower stratosphere midlatitudes over the course of the spring vortex breakup.

1. Introduction

Laminae in ozone vertical profiles have been commonly observed since the first launchings of routine high-quality vertical ozonesondes [Hering and Dutsch, 1963]. Pittock [1966] described a series of vertical ozone profiles taken at Boulder, Colorado, in March 1964 which displayed laminae in the 200 to 40 hPa range. Ozone laminae are generally characterized by anomalous values of ozone when compared to a relatively smooth vertical profile. Dobson [1973] summarized results of ozonesonde observations of these laminae, noting that they were most frequently observed in spring and at high latitudes, and were generally found in the 14- to 18-km region. Reid and Vaughan [1991] used a more comprehensive set of ozonesondes to refine the observations of Dobson [1973], noting that the laminae were most common in the 9.5- to 21.5-km region (peak near 14 km). Reid and Vaughan [1993] used NASA DC-8 lidar observations taken during the first Airbus Arctic Stratospheric Expedition (AASE 1) to further analyze such laminae, and concluded that they were most common in the 370-430 K potential temperature range at lower latitudes, and they occurred up to 520 K in March and April at latitudes northward of 75°N. Reid et al. [1994] used ozonesondes from the European Arctic Stratospheric Ozone Experiment (EASOE) to further delineate laminae near the polar vortex.

The explanation of the ozone laminae involves two hypotheses: (1) differential transport by a very low frequency transverse wave augmented by higher-frequency, shear gravity waves [Danielsen et al., 1991], and/or (2) transport of ozone-rich air from the polar vortex to midlatitudes via Rossby wave breaking [McIntyre and Palmer, 1983; McIntyre and Palmer, 1984; McIntyre and Palmer, 1985]. The first hypothesis [i.e., Danielsen et al., 1991] was based upon aircraft observations made in April 1984 in the southwestern United States. These April 1984 observations revealed laminae in the ozone, water vapor, and condensation nuclei profiles. The laminae had short vertical scales (1.7 km), and relatively long horizontal scales (350–600 km). Danielsen et al. [1991] used filtering techniques to estimate these scales of motion, and linear perturbation theory to calculate that the laminae were consistent with ultra low frequency waves.
The wave breaking hypothesis was first formulated as a source for these laminae via an analysis of Rossby-Ertel's potential vorticity (PV) maps in the middle stratosphere [McIntyre and Palmer, 1983]. Wave breaking processes have been observed in the lower stratosphere by the NASA ER-2 high-altitude aircraft and the NASA DC-8 long-range aircraft during the second Airborne Arctic Stratospheric Exchange Project (AASE 2) during the winter of 1991-1992 [Waugh et al., 1994; Plumb et al., 1994]. A low-ozone lamina was also observed in the southern hemisphere as a result of wave breaking following the breakup of the ozone hole and the vortex in December 1987 [Atkinson et al., 1989]. Support for the wave breaking hypothesis was provided by Newman and Schoeberl [1995], who reanalyzed the results from the Danielsen et al. [1991] paper and concluded that differential transport via Rossby wave breaking could explain the 1984 Stratosphere-Troposphere Exchange Project (STEP) midlatitude observations. In addition, Reid et al. [1994] used mesosphere-stratosphere-troposphere (MST) radar observations to conclude that the wind values associated with inertia-gravity waves were too small to account for the large degree of laminations in the EASOE observations. Orsolini et al. [1995] used the European Centre for Medium Range Weather Forecast (ECMWF) winds in an off-line transport model to show that layering of idealized tracers in the 1991-1992 midwinter period was a result of large-scale transport.

The Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE) was designed to investigate the photochemistry and dynamics of the lower stratosphere [Wofsy et al., 1984]. The SPADE campaign was staged from the NASA Ames Research Center at Moffett Filed, California, from April 19 to May 18, 1993. Including the April test flights, and excluding the November 1992 test flights, the SPADE campaign involved a total of 12 flights. In this paper we use these northern hemisphere springtime SPADE observations to investigate ozone and other trace gas laminae observed during the campaign. These laminae apparently originated from the lower stratospheric polar vortex, based on the trace gas measurements from the ER-2. In section 2, we will describe the various meteorological data sources used in SPADE, and section 3 will show some of the ER-2 measured trace gas measurements of the laminae. Section 4 will contain a detailed determination of the origins of the ozone laminae using both potential vorticity analyses, and high-resolution trajectory model results, while section 5 will look at the vertical structure of the laminae. In section 6, the results will be discussed and summarized.

2. Meteorological Data

Four types of meteorological analyses were utilized for the study of these ozone laminae: (1) Goddard Space Flight Center (GSFC) Data Assimilation Office (DAO) stratospheric data assimilation analyses with 4° latitude by 5° longitude resolution (STRATAN), (2) GSFC DAO stratospheric data assimilation analyses with 2° latitude by 2.5° longitude resolution (GEOS 1), (3) National Meteorological Center (NMC) Climate Analysis Center (CAC) analyses, and (4) United Kingdom Meteorological Office (UKMO) data assimilation analyses. These analyses were used in conjunction with a trajectory model, for the purpose of assessing the movement of stratospheric air.

The GSFC DAO has developed GEOS 1 for the production of global analyses. Key elements of GEOS 1 are a general circulation model (GCM) and a method of inserting or blending the observations with the GCM. The GEOS 1 GCM is a finite difference model [Suarez and Takacs, 1994], with relaxed Arakawa-Schubert convective parameterization [Moorhi and Suarez, 1992; Sud and Molod, 1988], radiation [Harshvardhan et al., 1987], and boundary layer parameterization [Helfand and Labraga, 1988; Helfand et al., 1991]. For the analysis scheme, data are grouped into 6-hour bins and a statistical interpolation is done using a 3-hour forecast as a first-guess field. The analysis-forecast difference of each prognostic variable is gradually inserted into the assimilation as forcing terms in the prognostic equations beginning 3 hours before the analysis time, and ending 3 hours after the analysis time. GEOS 1 is a continuous running GCM with forcing terms determined from the observations that change every 6 hours. This insertion scheme, called incremental analysis update (IAU), is designed to prevent data insertion from generating large transient adjustments to the GCM [Bloom et al., 1991].

An overview of the data assimilation system can be found in work by Schubert et al. [1993]. The GCM is most often run at 2.5° longitude by 2° latitude resolution with 20 levels in the vertical. However, for stratospheric studies the number of vertical level is increased to 46 and the horizontal resolution often decreased to 5 by 4° longitude latitude resolution (STRATAN)[Rood et al., 1990].

The NMC CAC stratospheric analysis system for 70 to 10 hPa in the northern hemisphere is a successive corrections method [Cressman, 1959; Finger et al., 1965]. The analysis for levels above 10 hPa and the southern hemisphere stratosphere (70 to 0.4 hPa) uses a similar successive corrections method [Yanai, 1964], but the successive scans are around the data rather than the grid points. The net result is a map that essentially uses the same analysis system for the whole stratosphere. The first guess for all maps is the previous day's map. Satellite data are then injected into the analysis for the current map. The satellite maps are then further used as a first guess field for the northern hemisphere radiosonde analysis from 70 to 10 hPa, while all other fields use the satellite maps as a final field. NMC Data quality is generally quite good in the lower stratosphere [Getman et al., 1986; Nagatani et al., 1988; Nagatani et al., 1990; Treberth and Olson, 1988]. Winds and PV are derived from the geopotential heights using a balanced wind approximation [Randel, 1987; Newman et al., 1988; Newman et al., 1989].
The UKMO analyses are also based on a data assimilation system [Swinbank and O’Neill, 1994; Lorenc et al., 1991]. In the UKMO “analysis correction” assimilation scheme, observations are treated asymptotically. The GCM is gradually adjusted toward the observations over a period centered on the observation time. The GCM is the UKMO “unified model”, which uses a split-explicit finite difference scheme [Cullen, 1993]. For these analyses, the UKMO GCM is run with a horizontal resolution of 2.5° of latitude by 3.75° of longitude, and with 42 levels in the vertical. The analyzed fields are interpolated from the hybrid coordinate levels to a set of pressure levels for output. The output levels are equally spaced in log pressure coordinates, with six levels per factor of 10 in pressure. As with the GEOS 1, STRATAN, and the NMC data, the UKMO assimilation is based on standard operational meteorological observations.

In addition to the four analyses, a trajectory model is used to analyze air parcel motion. Descriptions of the trajectory model used in this analysis can be found in Schoeberl et al. [1993b]. Excellent agreement has been found between the trajectory calculations of the advection of the Cerro Hudson volcanic cloud using NMC winds and the satellite observations of the cloud [Schoeberl et al., 1993a]. Furthermore, trajectories in general have been found to yield excellent agreement with lower stratospheric filaments observed in midwinter during AASE 2 [Waugh et al., 1994; Plumb et al., 1994], and with lower stratospheric temperatures and chlorine observations [Newman et al., 1993; Schoeberl et al., 1993a, b, c].

3. Trace Gas Observations

For the flights studied in this analysis, trace gas measurements of O₃, N₂O, CH₄, HCl, CFC-11, CFC-113, and CO₂ were collected by the ER-2 aircraft, although the full SPADE payload included additional gas and particle measurements [Wofsy et al., 1994]. Ozone measurements were made every second by a dual beam UV absorption ozone photometer, with an accuracy of 3%, and a precision of about 10⁻⁶ mol/cm³ [Proffitt and McLaughlin, 1983]. The N₂O measurements were obtained from the Airborne Tunable Laser Absorption Spectrometer (ATLAS) [Loewenstein et al., 1989] with an estimated accuracy of ±3%(1σ) and a time resolution of 1 s. The Aircraft Laser Infrared Absorption Spectrometer (ALIAS) provided CH₄ every 3 s, and HCl every 30 s, in addition to N₂O measurements every 3 s to complement the ATLAS N₂O data [Webster et al., 1994]. CFC-11 and CFC-113 were measured every 2 min. using gas chromatography [Woodbridge et al., 1995]. Carbon dioxide measurements were obtained with 2 s resolution by a nondispersive infrared CO₂ analyzer with a long-term precision of ±0.04(1) ppmv (SPADE CD rom) [Boering et al., 1994].

Figure 1 displays ozone measurements versus potential temperature from a flight on April 30, 1993. The profile has an obvious lamina of high ozone near approximately 460 K. The solid line is the second-order fit of all of the ozone profile data taken during SPADE. The ozone deviations from this fit are illustrated on the right-hand side, and clearly show an ozone anomaly of about 0.8 ppm at the 460 K potential temperature level (67 hPa or about 18 km).

Nitrous oxide (N₂O) is a more useful alternate to ozone for diagnosing air of polar origin. N₂O provides this alternate for ozone since they are generally anticorrelated in the lower stratosphere over the range of N₂O values sampled by the aircraft [Proffitt et al., 1990]. This anticorrelation primarily arises from the background circulation and its relationship to the sources and sinks of both N₂O and ozone [Plumb, 1995]. Slow vertical lifting in the tropics carries high values of N₂O and low values of ozone from the upper troposphere into the lower stratosphere [Rosenlof and Holton 1993; Avallone and Prather, 1995]. Similarly, the midwinter downward circulation in the polar vortex brings low...
values of N₂O and high values of ozone downward from the mid and upper stratosphere [Rosenfield et al., 1987; Rosenlof and Holton 1993]. Since both N₂O and ozone have long lifetimes in the lower stratosphere (greater than 30 years [Demore et al., 1994] and greater than 4 months [Wennberg et al., 1994], respectively), and since diabatic heating in the lower stratosphere is small [Rosenfield et al., 1987], lower stratospheric polar air in the midlatitudes would be characterized by low values of N₂O and high values of ozone. Midwinter profiles in the lower stratospheric polar vortex measured by the NASA ER-2 during both the AASE 1 and AASE 2 campaigns [Strahan et al., 1994] display extremely low N₂O values with relatively high ozone [Proffitt et al., 1990]. Hence N₂O provides a better diagnostic for polar air than ozone.

Figure 2 displays nitrous oxide (N₂O) measurements versus potential temperature for the same April 30 flight shown in Figure 1. The N₂O falls to values below 100 ppbv at about 460 K over a layer less than 20 K in depth (0.5 km). Superimposed on Figure 2 are four average N₂O profiles: (1) interior vortex values (dotted line on left panel) [Strahan et al., 1994], (2) midlatitude 1988-1989 values (dashed line, from AASE 1 [Strahan et al., 1994]), (3) a subtropical profile (solid line, from AASE 2 20°–30°N [Strahan et al., 1994]), and (4) the average SPADE N₂O profile (triple dot-dash line). Comparison of the average SPADE profile, and the AASE 1 inner vortex profile indicates that the lamina of low N₂O near 460 K has the characteristic values of polar vortex air.

The magnitudes of the low N₂O laminae were calculated for each SPADE flight by differencing the N₂O values with the averaged SPADE vertical profile (i.e., the triple dot-dash line on left panel) of Figure 2. The right panel of Figure 2 displays the N₂O difference (dots) for the April 30, 1993 flight. Air for each SPADE flight was judged to originate in the polar vortex if the N₂O values were less than an averaged vortex edge profile (solid line on the right panel of Figure 2). This edge profile was produced by averaging the inner vortex profile (dotted line, left panel) with the AASE 2 subtropical profile of

<table>
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<tr>
<th>Date</th>
<th>Time, seconds</th>
<th>Theta, K</th>
<th>Latitude, deg.</th>
<th>Longitude, deg.</th>
</tr>
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<tr>
<td>April 23, 1993</td>
<td>67984.9</td>
<td>456</td>
<td>36.7</td>
<td>-123.0</td>
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<tr>
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<td>83823.8</td>
<td>518</td>
<td>38.5</td>
<td>-112.0</td>
</tr>
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<td>-124.4</td>
</tr>
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<td>425</td>
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Figure 3. (top, left) CFC-11 (parts per trillion by volume), (top, right) methane (parts per billion by volume), (bottom, left) carbon dioxide (parts per million by volume), and (bottom right) CFC-113 (parts per trillion by volume) versus potential temperature (K) for the SPADE ER-2 flight of May 7, 1993.

Strahan et al. [1994]. This average profile provided a reasonably conservative estimate of a vortex edge profile. The SPADE low N2O laminae (i.e., polar air intercepts) are listed in Table 1. The ER-2 intercepted very low N2O air on eight of the 12 flights in April and May. Laminations were apparent in all of the profiles on other days, but were relatively weaker and did not fit the objective criteria outlined here.

Associated with the high ozone and low N2O lamina observed between 450 and 470 K on May 7, 1993, flight are low values of the tropospheric source gases CFC-11, CH4, CO2, and CFC-113 (Figure 3). High values of HCl, NOy, water vapor are also found in association with this feature. The behavior of the tropospheric source gases in the laminae is consistent with polar air. Table 2 displays a listing of trace gas deviations from averaged profiles for each lamina listed in Table 1. The averaged vertical profiles are compiled from all of the SPADE observations during April and May 1993, and the deviations are the differences of the individual profiles from this average at the lamina position. This air was entrained into the stratosphere in the tropics some time in the past, as indicated by the low values of CO2 observed, for example [Boering et al., 1994]; the Brewer-Dobson circulation then lifted this air in the tropics to higher altitudes where N2O, CFC-11, CFC-113, and CH4 could be photolyzed and ozone and HCl could be produced. This circulation then carried the air poleward and downward to lower altitudes and higher latitudes. All of the laminae containing high

Table 2. Trace Gas Polar Vortex Fragment Deviations From SPADE Averaged Profiles

<table>
<thead>
<tr>
<th>Date</th>
<th>ALIAS CH4</th>
<th>CO2, ppmv</th>
<th>NOAA F11, pptv</th>
<th>NOAA F11, ppbv</th>
<th>NOAA HCl</th>
<th>NOAA N2O, ppbv</th>
<th>NOAA O3, ppmv</th>
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</thead>
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<td>April 23, 1993</td>
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<td>-3.44</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-122.2A</td>
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</tr>
<tr>
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<td>-1.61</td>
<td>-5.9</td>
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<td>0.27</td>
<td>-85.5</td>
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<tr>
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<td>-1.7</td>
<td>0.41</td>
<td>-85.1</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>May 7, 1993</td>
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<td>-2.31</td>
<td>-26.9</td>
<td>-90.6</td>
<td>0.41</td>
<td>-107.4</td>
<td>0.50</td>
</tr>
<tr>
<td>May 12, 1993</td>
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<td>x</td>
<td>x</td>
<td>-66.6</td>
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</tr>
<tr>
<td>May 14, 1993</td>
<td>-0.05</td>
<td>-2.90</td>
<td>-12.8</td>
<td>-85.1</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An x indicates no measurement in the fragment, because of missing data. ALIAS N2O is substituted for ATLAS N2O on April 23, 1993, Harvard H2O is substituted for NOAA H2O on April 26, 1993, and NOAA CH4 is substituted for ALIAS methane on May 14, 1993.
ozone and low \(N_2O\) displayed the polar characteristics in these other trace gas measurements (i.e., low \(CO_2\), low \(CH_4\), low CFCs, high HCl, high water, and high \(NO_y\)).

4. Tracing of Air Motion

On the basis of these trace gas measurements, it is plausible that the sampled laminae originated in the polar vortex. If these high ozone and low \(N_2O\) air masses came from the polar vortex, then they should have relatively high values of PV. PV is well conserved during this period, with a calculated loss term for this period having a timescale of a few months. As discussed in Nash et al. [1996] and Manney et al. [1994b], the breakup of the polar vortex occurred in mid-April 1993. This breakup is illustrated in Plate 1 by a sequence of PV images on the 460 K isentropic surface. Inner vortex values are denoted by the reds, oranges, and yellows of the spectrum color scale, while tropical PV values are indicated by purples and violets. In late-February, the polar vortex covered most of the northern hemisphere polar latitudes (Feb. 23), and polar PV values were quite high. By early April, the maximum polar vortex PV values were much reduced (April 6), and the vortex was somewhat reduced in size, and displaced off of the pole into the eastern hemisphere. By mid-April, the vortex began to split apart (April 16), and has completely fragmented and virtually disappeared by the first week of May [Nash et al., 1996].

The tracing back of the sampled polar air to the polar vortex is performed using four techniques. The first technique involves the forward tracing in time of synoptic scale PV maxima to the ER-2 interception point. The second technique uses direct back trajectories to calculate the history of an air mass. The third technique utilizes high-resolution contour advection of a line initialized to the edge of the polar vortex (i.e., the PV value associated with the maximum PV gradient on an isentropic surface) to trace the movement of the polar vortex, and air masses that break off the polar vortex. Finally, the fourth technique involves high-resolution mapping of PV using back trajectories.

In the first technique, potential vorticity analyses can be used to trace the transport of polar material [Clough et al., 1985]. This technique has been widely utilized to diagnose wave breaking events, whereby material is irreversibly stripped off of the vortex into the midlatitudes [e.g., McIntyre and Palmer, 1983; McIntyre and Palmer, 1984]. As an example of this tracing, Plate 2 displays PV derived from the STRATAN data assimilation from April 16 to April 23 on the 460 K isentropic surface. The ER-2 observed an ozone lamina on April 23 over California (bottom right panel of Plate 2). While the PV values are relatively weak, a PV high is located almost directly at the point where the ER-2 intercepted the polar air. This air can be traced back using the PV to its direct connection to the elongated vortex over Siberia on April 17. A piece of the vortex broke off between April 17 and 19, drifted across the Pacific, and was intercepted on April 23. Generally, the major PV features are very consistent between STRATAN and the UKMO, NMC, and GEOS 1 analyses. For example, on April 21, a high PV filament extends southeast from Alaska, and is also evident in the NMC, UKMO, and GEOS 1 data analyses. However, on days following April 21, this feature becomes much less distinct as it moves toward the west coast of North America. Hence tracing of PV is difficult at best, and is confounded by the following: (1) the 24-hour temporal resolution, since the precise movement of features is difficult under various evolving synoptic situations, (2) aliasing (i.e., the movement of waves having a similar periodicity to the 24-hour analysis sampling rate), (3) spurious analysis features which inhibit the accurate identification of real features, and (4) the gradual evanescence of features as they move away from the polar vortex either via PV loss terms or via features being sheared down to scales below the analysis resolution.

The second technique for tracing air masses is performed using back trajectories to determine the movement of the air directly. Superimposed on Plate 2 are parcel trajectories that indicate the movement of the air in time. The technique utilizes 15-day back trajectories for a set of 72 parcels initialized in a 400-km circle around the point where the ER-2 intercepted the polar air. A 400-km circle of parcels is used as a sensitivity estimate of the trajectory calculations. The large scatter in the positions of the back trajectories on April 16 (top left panel of Plate 2) indicates that during this vortex breakup phase, the trajectories near the vortex edge are fairly sensitive to the detailed evolution and structure of synoptic-scale features in the lower stratosphere. The trajectories correlate with the PV feature, and easily track back to the elongated vortex on April 17.

The third technique uses a contour advection technique with the trajectory model to follow the evolution of the vortex boundary [e.g., McIntyre and Plumb, 1984]. NMC winds and temperatures are employed with a trajectory model based contour advection scheme to analyze the breakup of the polar vortex between April 10 and April 23. The results of this contour advection are displayed in Plate 3, with the initial vortex boundary marked by the solid white line in the left panel. The solid white line in the middle panel (April 23) shows the vortex edge after 10 days of integration. This boundary has evolved into a convoluted structure that reflects the breakup of the polar vortex. The boundary of the vortex has maintained coherence with three pieces of high PV air that comprised the original vortex. This tracking by the vortex boundary of the polar vortex fragments is an indicator of the consistency of the trajectory calculations with the PV fields, at least for the larger-scale vortex fragments. Contour advection for all of the analyses shows good agreement with the major pieces of the polar vortex during over the breakup period. Furthermore, this tracking of the PV by the contour advection provides confidence in the quality of the trajectory calculations.
During this vortex breakup, a small air mass was transported from one of the main vortex fragments to the California region. The right-hand panel of Plate 3 shows a zoomed in view of the center panel, with the interior of the vortex boundary shaded in red. As shown from the STRATAN PV tracing of Plate 2, this piece of the polar vortex broke off, was advected into the California region, and was sampled during the flight of April 23. In contrast to this contour advection using the NMC and PV tracing from the STRATAN analyses, both the GEOS 1 and UKMO assimilation winds fail to advect a piece of the vortex into the California region on April 23. The difference seems to involve the advection following the breaking off of the material on April 17.
Plate 3. Rossby-Ertel's potential vorticity from NMC analyses for the northern hemisphere on (left) April 12, 1993 and (middle) April 23, 1993, and also zoomed in on the California region for (right) April 23, 1993. High values of PV (i.e., the polar vortex) are denoted by the white, reds, oranges, and yellows of the spectrum color scale, while tropical PV values are denoted by violets and purples. The solid white line displays the contour advection of the vortex boundary initialized on April 12, and run forward to April 23. The interior of the contour advection is shaded in red for the right panel. Note that the color scale has different limits than the two previous plates.

In the case of NMC and STRATAN, the trajectories track with a high PV feature that came off of the vortex on about April 17, while in the case of the GEOS 1 and UKMO data, the trajectories start too far south of this high PV feature, but eventually track with this PV feature by April 20 to arrive over California by April 23.

The fourth technique again uses back trajectories to trace air mass motion, but utilizes the conservation of PV to determine PV values of the air around the point where the ER-2 intercepted the polar air. This reverse domain filling (RDF) technique is used to derive "high-resolution" representations of conservative tracers such as $N_2O$ [Sutton et al., 1994] and PV [Newman and Schoeberl, 1995; Schoeberl and Newman, 1995]. In RDF, parcels are initialized on a regular global grid on May 7, 1993, at 2400 UT (i.e., May 8, 1993 0000 UT, approximately the midpoint time of the flight) and are run backward in time for 12 days. The right panel of Plate 4 displays the positions of parcels (white dots) that are within 400 km of the polar air intercept on May 7, 1993, at 2400 UT. The left panel of Plate 4 shows the positions of those same parcels 12 days earlier on April 26, 1993. Most of these parcels were located inside the major vortex fragment over the east coast of Asia. The PV values at the parcel positions for April 26 are conserved over the 12 day trajectory period to May 7, and are mapped forward in time to the par-

Plate 4. Rossby-Ertel's potential vorticity (PV) images for (left) 1200 UT on April 26, 1993, and (middle and right) 0000 UT on May 8, 1993, on the 460 K isentropic surface as derived from the UKMO stratospheric analyses using a reverse domain filling (RDF) technique. High values of PV (i.e., the polar vortex) are denoted by the reds, oranges, and yellows of the spectrum color scale, while tropical PV values are denoted by violets and purples. The white dots on the images indicate 12-day parcel back trajectory positions initialized on May 8, 1993 (0000 UT). Note that the color scale has different limits than the previous plate.
Plate 5. Modified Rossby-Ertel’s potential vorticity latitude-potential temperature cross sections for May 7, 1993. These cross sections are derived from the (top, left) GEOS 1, (top, right) STRATAN, (bottom, left) NMC, and (bottom, right) UKMO stratospheric analyses using a reverse domain filling (RDF) technique. High values of PV (inner vortex) are denoted by the reds, oranges, and yellows of the spectrum color scale, while tropical PV values are denoted by violets and purples. The white line on the images indicates the ER-2 flight path, while the black dots on this line indicate the positions of low N₂O observations.

The air masses sampled on April 23 and May 7 were of polar origin, and broke off of the polar vortex on or about April 17 and April 27, respectively. The four techniques used herein were also employed on each of the polar fragments listed in Table 1 using the four analyses: STRATAN, GEOS 1, NMC, and UKMO. The success of each technique is summarized in Table 3 (with Y being a successful identification, N being a failed identification, and I being indeterminate). The tracing back of polar material is based on some relatively objective criteria: (1) was vortex air (i.e., air with high potential values) advected to within a reasonable distance from the ER-2 sample position (nominally, 400 km), and (2) can the PV be reasonably traced back to the vortex? The PV and trajectory evidence suggests that the air sampled during SPADE originated in the polar vortex.

5. Laminae Vertical Structure

The vertical structure of the polar vortex fragments...
tend to be extremely shallow. In order to display the lamina nature of these filaments, we use modified potential vorticity (hereafter referred to as Mpv) [Latt, 1994]. Mpv has the properties of conventional PV, but removes the exponential growth with height for an isothermal atmosphere. The Mpv values are utilized in combination with a multiple isentropic level RDF to build high-resolution images of the Mpv field. Plate 5 displays these vertical RDF cross sections of Mpv on May 7, 1993, oriented north-south along the longitude of the flight. These cross sections are constructed utilizing a regular grid of points in latitude and potential temperature (0.2° x 2.0 K) in the same manner as the high-resolution images of Plate 4 which utilizes a regular grid in latitude and longitude [see Newman and Schoeberl, 1995]. The four analyses (GEOS 1, STRATAN, NMC, and UKMO) all reveal similar broad-scale characteristics. A filament of high Mpv (orange colored) tilts upward with latitude from about 430 K at 30°N to 480 K at about 50°N. As is evident from the figure, the flight passed through this narrow high Mpv lamina in all four cross sections. For this flight we estimate from these analyses that the lamina was approximately 20 K in depth (i.e., approximately 1 km), in good agreement with the observations (see Figure 3). In addition, the ER-2 observations below 430 K indicate trace gas measurements that are more characteristic of tropical values confirming the low values of Mpv that are characteristic of tropical air.

In all four RDF cross sections in Plate 5, both the polar filament and the tropical air below 430 K are well represented. Differences in structure primarily result from differences in trajectories, not the Mpv initialization, as demonstrated by initializing each set of trajectories with the other analyses. The speckled appearance of certain features in these Mpv RDF fields results from the 2.0 K (approximately 100 m) potential temperature grid spacing (i.e., smaller grid spacing eliminates the speckling with more continuous appearing filament structures). While the highest-resolution analysis (GEOS 1) is more highly structured than the other data sets (as observed in all of the other days), it is not clear that the observations are more faithfully represented. All of the analyses performed similarly in representing the ER-2 observations for both this date (May 7, 1993), and for the other flights during SPADE (see Table 1).

Both Plates 3 and 4 display a high degree of filamentation as PV features are sheared down to small horizontal scales. The same case is true for the vertical scales illustrated in Plate 5. Extremely fine vertical scales (less than 2 K isentropically and 100 m in height) are modeled after only 10 days of integration. The horizontal wind shear acts concurrently with vertical shear to rapidly reduce features that have vertical scales of more than 6-8 km to features with vertical scales on the order of hundreds of meters.

6. Discussion

On the basis of clear observations of ozone laminae from the ER-2, specifically ozone maxima, and N2O minima, it is highly likely that the observed air was of polar origin. This polar identification is primarily based on the aircraft observations, but is firmly backed up by the tracing of PV fragments and trajectory calculations.

Air that had been depleted of ozone during the polar winter of 1992–1993 would have been transported to the midlatitudes during this breakup. Atkinson et al. [1989] showed that Antarctic ozone hole fragments during 1987 were transported into the southern mid-latitudes following the breakup of the ozone hole. The result presented here parallel those of Atkinson et al. [1989], and reveal that ozone poor air is transported into the northern midlatitudes during the vortex breakup.

Assessment of the degree of the polar ozone loss in these vortex fragments is confounded by the extended period between the disappearance of polar stratospheric clouds (PSCs) on February 23, 1993, and the first SPADE polar fragment observation on April 23, 1993 (59 days). Furthermore, this 59 day post-PSC period and the lack of C1ONOa measurements aboard the ER-2 makes the quantitative determination of whether the air had been processed by PSCs difficult. While this study has established that the air observed by the ER-2 originated in the polar vortex, it has not established that the air was processed by PSCs. However, based on vortex processing rate calculations for 1993 (not shown here, and Manney et al. [1994b]), and Microwave Limb Sounder (MLS) observations of ClO [Manney et al., 1994a], it is clear that all of the material contained in the vortex had been processed by PSCs prior to February 23, 1993, and had undergone a 20 % ozone loss rates on the 465 K isentropic surfaces by March 17, 1993 [Manney et al., 1994a]. High-resolution trajectory calculations show that the majority of this material remained confined to the polar vortex prior to the breakup in mid-April. Thus it seems likely that the polar vortex air sampled by the ER-2 had undergone PSC processing and some ozone loss.

We have found a number of cases when PV tracing, contour advection, and trajectory techniques have shown polar filaments that are close to those sampled.

Table 3. Parcel Identification With Polar Air

<table>
<thead>
<tr>
<th>Date</th>
<th>Trajectory</th>
<th>Tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 23, 1993</td>
<td>Y I Y N</td>
<td>Y I Y Y</td>
</tr>
<tr>
<td>April 26, 1993</td>
<td>I I Y N</td>
<td>I I Y Y</td>
</tr>
<tr>
<td>April 30, 1993</td>
<td>Y I Y I</td>
<td>I I I I</td>
</tr>
<tr>
<td>May 1, 1993</td>
<td>Y Y Y Y</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>May 3, 1993</td>
<td>Y Y I Y</td>
<td>I I Y Y</td>
</tr>
<tr>
<td>May 7, 1993</td>
<td>Y I Y I</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>May 12, 1993</td>
<td>Y Y Y Y</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>May 14, 1993</td>
<td>Y Y Y Y</td>
<td>Y Y Y Y</td>
</tr>
</tbody>
</table>

Y indicates a positive identification with the polar vortex, N indicates a negative identification, and I is an inconclusive result.
S is the STRATAN assimilation data, G is the GEOS 1 assimilation data, N is the NMC stratospheric analyses, and U is the UKMO assimilation data.
by the ER-2 during SPADE. However, it is unrealistic to expect a 100% success rate. Analyzed winds from the UKMO, NMC, GEOS 1, and STRATAN give a good indication of the regions where filamentation occurs, but small errors in the analysis winds can lead to significant errors in trajectories, and thus in the precise placement of filaments. Comparisons of the winds between the various analyses are quite good, yet the absolute positioning of polar filaments by these analyses may differ by as much as 1000 km horizontally, and 20 K in potential temperature. All of the analyses were reasonably adequate for analyzing these features, with no particular analysis showing clear superiority.

These vortex fragments are sometimes quite shallow and have small horizontal scales (in most cases significantly finer than the grid spacing of the analyses). The depth and horizontal scales are sensitive to the vertical and horizontal wind shear. Extreme care needs to be exercised in the identification of such filaments, and the variability between analysis techniques should be used as cross-checks on polar fragment identification. Furthermore, since the variability of the fields around a single point can be quite large (e.g., Plate 3), studies which rely on single point trajectories may be seriously flawed. This conclusion is in agreement with the more general results of Morris et al. [1995]. In addition, the shallow vertical scales and small horizontal scales of these fragments make it difficult for satellites to adequately monitor the details of the vortex breakup.

As discussed in the introduction, ozone laminae are expected to originate from either very low frequency transverse waves, or via Rossby wave breaking. On the basis of these results, the major ozone laminae observed during the April–May 1993 SPADE campaign were primarily a result of Rossby wave breaking. The Mpvs RDF fields of Plate 5 are based on trajectories and analyses which do not include gravity waves. Hence the modeled laminae seen in Plate 5 are generated by Rossby waves. The polar fragments observed during SPADE were generally due to the highly nonlinear flow resulting from the polar vortex breakup. Dobson [1973] showed high levels of ozone profile lamination over Colorado predominating in winter and spring, and near-zero lamination in summer, and this is consistent with Rossby wave breaking during the fall, winter, and spring and the absence of any significant Rossby wave breaking in summer.

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