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Layering in stratospheric profiles of long-lived trace species: Balloon-borne observations and modeling

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Abstract. A series of balloon flights conducted in March 1993 from Aire-sur-Adour, in southern France, aimed at making in situ measurements of a variety of trace gases in the polar vortex during a dynamically active period. Meteorological analyses indicate that the balloons were launched when the vortex edge was passing aloft. These mid latitude balloon flights revealed coincident layering in long-lived tropospheric source gases such as nitrous oxide, methane and halocarbons as well as in ozone and water vapor. At low altitudes, well-resolved laminations appeared clearly in all these gases. A layer of mid latitude air, enriched in trace gases, was detected at the highest sampled level, near 15 mbar, inducing a pronounced reversal in the profiles of tropospheric source gases. Using global meteorological analyses, trace constituent data derived from the UARS observations and high-resolution advection models, fine-scale distributions of ozone, nitrous oxide, methane, and halocarbons have been constructed. The calculations show qualitatively how such profile reversal arises near 15 mbar, when a filament of air enriched in trace gases is drawn into the outer portion of the vortex. Very high resolution calculations furthermore provide reasonable quantitative agreement between predicted tracer mixing ratios and in situ balloon-borne measurements.

1. Introduction

There is a great interest today in high-resolution modeling of chemical species distributions for interpretation and even forecast of campaign observations. The TRAVERSE (Tracking Vortex Elements Reaching Southern Europe) campaign took place in southern France in March 1993 and consisted of a series of instrumented balloon launches. It aimed at measuring various stratospheric trace species concentrations within the winter polar vortex, at a time when it extended substantially over southern Europe.

On March 7, 1993, the meteorological forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) indicated that the upper level vortex was unusually elongated. Two balloons were launched from Aire-sur-Adour (44°N, 0°E) carrying respectively a light weight whole air sampler developed by the KFA Julich allowing for the measurement of methane, nitrous oxide, and several halocarbon concentrations [*Bauer et al.*, 1994; *Engel et al.*, 1996] and a hygrometer developed by the Laboratoire de Météorologie Dynamique (LMD) [*Ovarlez and Ovarlez*, 1994]. An electrochemical cell measuring ozone concentration was also attached to the former payload. All these gases are long-lived and can be considered as being transported passively in the extratropics below 30 km on timescales characteristic of synoptic and planetary waves. The tropospheric source gases (all of the above except for water vapor and ozone) decay with height, enter the stratosphere in the tropics, and are less abundant within the winter polar vortex. In the absence of heterogenous processing, ozone is more abundant inside of the vortex than in mid latitudes below about 600 K, while the reverse is true aloft.

The measured profiles of all these gases will be shown to exhibit pronounced layering. *Petzoldt et al.* [1990] had observed layering in long-lived trace species profiles also measured with the KFA grab sampler at Aire-sur-Adour in late March 1985. By calculating backward trajectories originating from Aire-sur-Adour at several levels, they noted that because of the vertical wind shear, air sampled at adjacent levels by the instrument would have been transported from very different parts of the globe.

Since then there has been considerable work on the observation and modeling of trace species' filamentation and layering in the stratosphere. Laminae, thin layering with a characteristic scale of 1-1.5 km, have been commonly observed in lower stratospheric ozonesonde profiles during winter and spring as well as in aerosol

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content profiles [*Reid and Vaughan*, 1991; *Reid et al.*, 1998; *Orsolini*, 1995; *Orsolini et al.*, 1997]. They appear most prominently near the vortex edge. *Reid and Vaughan* [1991] hypothesised that they originate through differential advection in strong shearing zones. High-resolution numerical simulations of the interleaving of tracer sheets of different latitudinal origins in the vortex edge region are given by *Orsolini* [1995] and *Schoerberl and Newman* [1995]. Only when such tracer sheets slope with height, do they appear as fine-scale vertical layering, or laminae, in vertical profiles. Gravity waves may contribute to some additional ozone lamination [*Teitelbaum et al.*, 1996].

Extensions of these studies would consist of investigating ozone laminations at heights not reached by conventional ozonesondes, as well as laminations in constituents other than ozone and aerosols. Scant attention has been paid to these topics. Recently, *Newman et al.* [1996] showed coincident laminae in a series of profiles of trace gases measured from the NASA ER-2 aircraft in the spring of 1993, and modeled their formation using a passive tracer initialized as potential vorticity. Because of the limited vertical extent of their data, their study was restricted to heights below about 20 km. Statistical studies of ozonesonde records [*Reid and Vaughan*, 1991; *Mlch and Lastovicka*, 1996] carried the same height limitation.

Bird et al. [1997] calculated the frequency of occurrence of ozone laminae up to 30 km, using recent lidar observations in the Canadian Arctic. Although the occurrence of laminae in ozone partial pressure peaks at about 16 km, it extends up to near 28 km. When viewed in ozone mixing ratio, the retrieved profiles, extending up to the stratopause, also show large dents above 30 km, which tend to be thicker at higher altitude.

Appenzeller and Holton [1997] determined regions in the middle atmosphere where the abundance of ozone laminae, or laminae in a tracer distributed as potential vorticity (PV), is expected to be high. They estimated where vertical wind shears coexist with tracer horizontal gradients, that is where the laminae generation is likely to be efficient. They based their calculations on the size of the thermal wind shears derived from satellite temperature observations, and the size of tracer horizontal gradients derived from the U.K. Meteorological Office (UKMO) stratospheric analyses or from Upper Atmosphere Research Satellite (UARS) observations. They showed that the production rate of laminae in a PV tracer increases steadily with height at winter high latitudes, reaching a maximum near 5 mbar. For ozone, however, the laminae production rate has a dip between 30 and 10 mbar, likely because of the reversal of the ozone latitudinal gradient, and it then maximizes near 5 mbar. On the basis of these estimations, long-lived tracer lamination by large-scale winds is arguably an important process in the extratropical middle stratosphere.

The aim of this paper is to examine fine-scale spatial structures in long-lived trace species, both modeled and observed, and in particular their vertical layering, in relation with the vertical structure of the polar vortex during TRAVERSE. The originality of the balloon-borne data examined in this study lies in providing of near-simultaneous profiles of several constituents up to near 10 mbar, some with high vertical resolution.

To examine fine-scale three-dimensional tracer structures during TRAVERSE, we performed very high resolution passive tracer transport simulations on isentropic surfaces using analyzed winds, hence providing realistic meteorological conditions. High horizontal resolution is needed to resolve the filamentary imprints of tracer sheets on isentropic surfaces. Two models have been used : the transport model used in *Orsolini et al.* [1995], which is global, and the reverse trajectory model of *Manney et al.* [1996] which allows computation of a dense ensemble of trajectories on a local domain.

2. Observations of Long-Lived Species' Vertical Distribution

Thirteen stratospheric air samples were collected in the morning of March 7 during the rapid descent phase of a grab sampler developed by the KFA, between 0720 and 0730 UT. It covered altitudes between 750 K and 320 K [*Engel et al.*, 1996]. The vertical resolution of these measurements depends on the parachuted payload speed but ranges from 400 m near 750 K to 150 m near 320 K. Ozone concentration was also measured during the balloon ascent between 0524 and 0656 UT, up to a height of 723 K. Figure 1 shows the profiles of halocarbons F12 and F113, methane (CH_4) and nitrous oxide (N_2O) along with measurement errors (thick lines with triangles). Figure 1 also shows some reference profiles for F12 and N_2O constructed from balloon-borne observations (thick dashed lines). These are derived from a series of multi-year observations in October and November at a mid latitude site (44°N) [see *Schmidt et al.*, 1994]. Figure 1 also shows the ozone sounding taken during the ascent phase. In addition, the stratospheric water vapor (H_2O) mixing ratio was measured in situ during the night of March 7, during the 30-min-long descent of a balloon-borne payload starting at 2315 UT and covering altitudes between 580 K (near 24 km) to 360 K (near 14 km) with a resolution of about 5 K (near 200 m). It is also shown in Figure 1; the measured accuracy is of 10 %. The balloon-borne reference profile for H_2O is the average of four profiles measured at Kiruna (67°N) in the winter of 1991/1992, while Kiruna was outside of the polar vortex, and it is hence representative of subpolar latitudes.

Two features are noteworthy in these sets of profiles.

A) A pronounced kink above 700 K : A most peculiar point raised by these observations is that at 750 K the N_2O and F12 profiles show values close to the reference mid latitude profile. Between 500 K and 700 K however, mixing ratios of these tropospheric source gases are much lower than the reference mid latitude values (Figure 1), and are representative of polar vortex air. In that 500 to 700 K layer the mixing ratios of H_2O are also

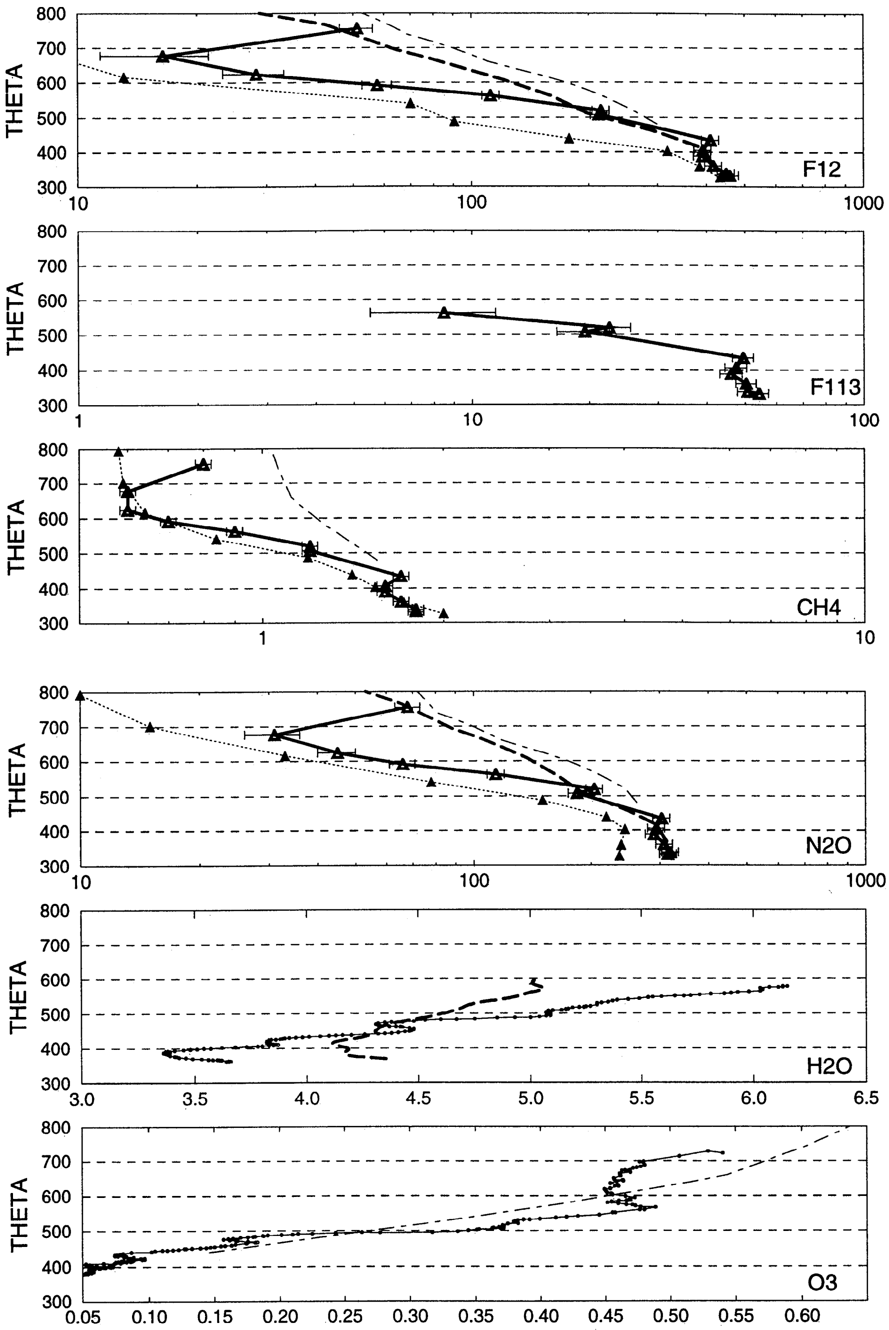

Figure 1. Balloon-borne grab sampler observations of the profiles of F12 (in ppt), F113 (in ppt), CH_4 (in ppm) and N_2O (in ppb). The tropospheric source gases profiles are derived from 13 samples (thick line with triangles). Also shown are high-resolution profiles of H_2O in ppm and O_3 in tens of ppm (black line with dots); mid latitude reference balloon-borne profiles (see text) of F12, N_2O and H_2O (thick dashed line); mid latitude averaged (see text) profiles from UARS observations of F12, CH_4, N_2O, and O_3 (dotted-dashed line); instantaneous (see text) CLAES profiles of F12, CH_4 and N_2O (dotted line with solid triangles).

typical of vortex air. CH_4 and O_3 also strongly increase above 700 K. The question arises whether these profile reversals above 700 K (near 15 mbar) are due to a rapid change in the vertical structure of the vortex, so that the upper sample was collected outside of the vortex. Alternatively, the reversal at 750 K could be the signature of mixing processes near the vortex edge. Such profile reversals in tropospheric source gases have been observed during previous flights of the grab samplers, especially in late winter [*Petzoldt et al.*, 1990; *Bauer et al.*, 1994; *Schmidt et al.*, 1994].

B) Several laminae below 500 K : All the profiles of tropospheric source gases also show evidence of laminae below 500 K; for example, a layer slightly enhanced with respect to the mid latitude reference profiles is clearly seen in F12 and N_2O at 430 K. Coincident local maxima are also seen in CH_4 and F113. This enhancement indicates the southward origin of the air mass. The occurrence of the laminae at low levels is further supported by the high resolution profiles of O_3 ; for example the ozone-poor layer at 430 K confirms the southward origin of the sampled air mass. The high-resolution profile of H_2O, taken nearly 16 hours later, also shows several laminae below 500 K. All the tropospheric source gases profiles show a weak variation at 500 K.

3. Meteorological and Satellite Data

3.1. Data and Models

The advection of tracers is performed with two models, both forced by global meteorological analyses from the ECMWF. The first one is an accurate isentropic Eulerian transport model, which uses the advection scheme of Prather conserving second-order moments [*Orsolini et al.*, 1995; *Orsolini*, 1995]. The 10-day simulations were initialized on February 26 (0000 UT), 1993; a lapse of time of 10 days is sufficient to allow generation of filaments. The second one is a reverse-domain-filling trajectory model [*Manney et al.*, 1996], like that developed by *Sutton et al.* [1994], for which 10-day back trajectories were computed on a local domain, 10° wide in longitude and latitude centered over Aire-sur-Adour. The back trajectories are initiated on March 7 (0600 UT), the closest time for which meteorological data was available, and 1 hour before the grab sampler was operated. The equal spacing of parcels is a tenth of a degree; hence 10.000 parcels were advected. The first model is used for global transport, while the other model has been used for obtaining finer tracer distributions on a limited domain.

The uppermost analyzed level in the ECMWF data used in this study is 10 mbar. Because the simulation at 750 K is performed so close to the model lid and because the computation of PV is inaccurate near the lid, we have done a corresponding simulation with winds derived from the NASA Goddard Earth Observing System (GEOS) stratospheric analyses, which extend to the stratopause.

Several tracers were passively transported: analyzed PV as a proxy tracer but also several trace species with initial distributions derived from UARS observations, that is, O_3, CH_4, F12 and N_2O. Further details on the use of analyses and satellite data are provided in the appendix.

The UARS trace species observations were also used for comparison with balloon-borne measurements. Mid latitude profiles, averaged over the latitude band 30°N-60°N, of F12, CH_4, N_2O are shown in Figure 1 (dashed-dotted lines), using CLAES observations on the initial day (February 26). Although the balloon-borne reference profiles are based on October-November measurements, there is good agreement with the satellite mid latitude profiles. Hence air sampled at 750 K has tracer concentrations representative of midlatitude air. Also shown in Figure 1 are CLAES profiles of F12, CH_4 and N_2O acquired on March 7 near 1600 UT at 46.6°N and 8°E, the closest satellite profile to the grab sampler measurements. These soundings were taken inside of the vortex. They depart from the grab sampler profiles above 700 K while they are consistent with them between 500 K and 700 K; of course, they show no finescale vertical structure.

The low-level tracer structure is examined with the PV tracer; independent isentropic simulations were run every 5 K between 425 K and 500 K. Simulations were also done at 675 K and 750 K initialized with F12, CH_4, N_2O and O_3. The simulation driven by winds from the GEOS analyses is only performed at 750 K using N_2O.

3.2 Meteorological Conditions

In the winter of 1992/1993 the final breakdown did not occur until late March [*Manney et al.*, 1994c; *Newman et al.*, 1996]. During February and March two

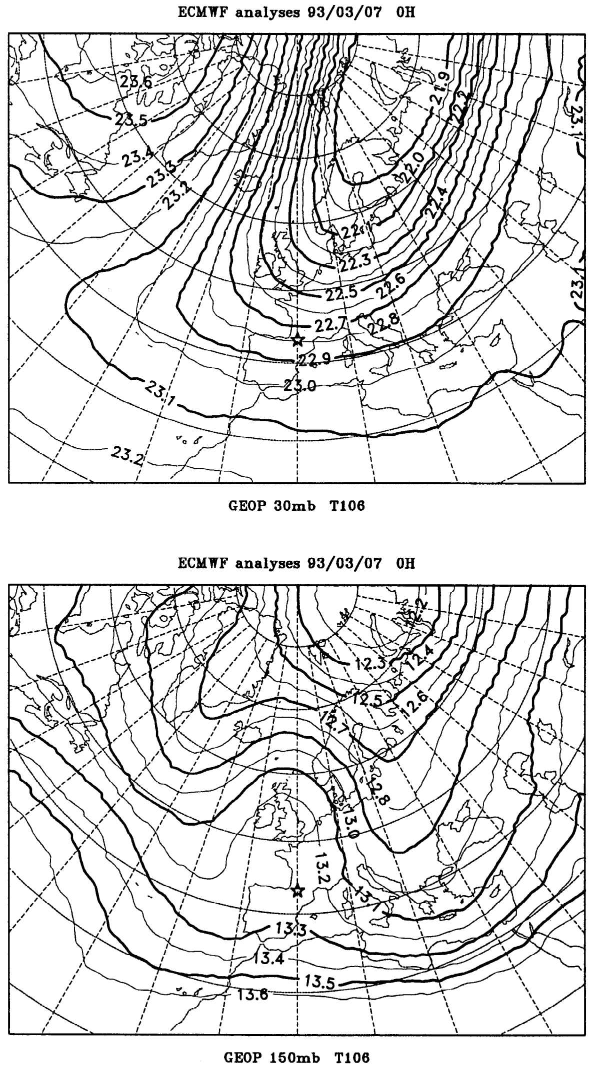

Figure 2. Geopotential height (in kilometers) at 30 and 150 mbar on March 7 (0000 UT) derived from the ECMWF analyses.

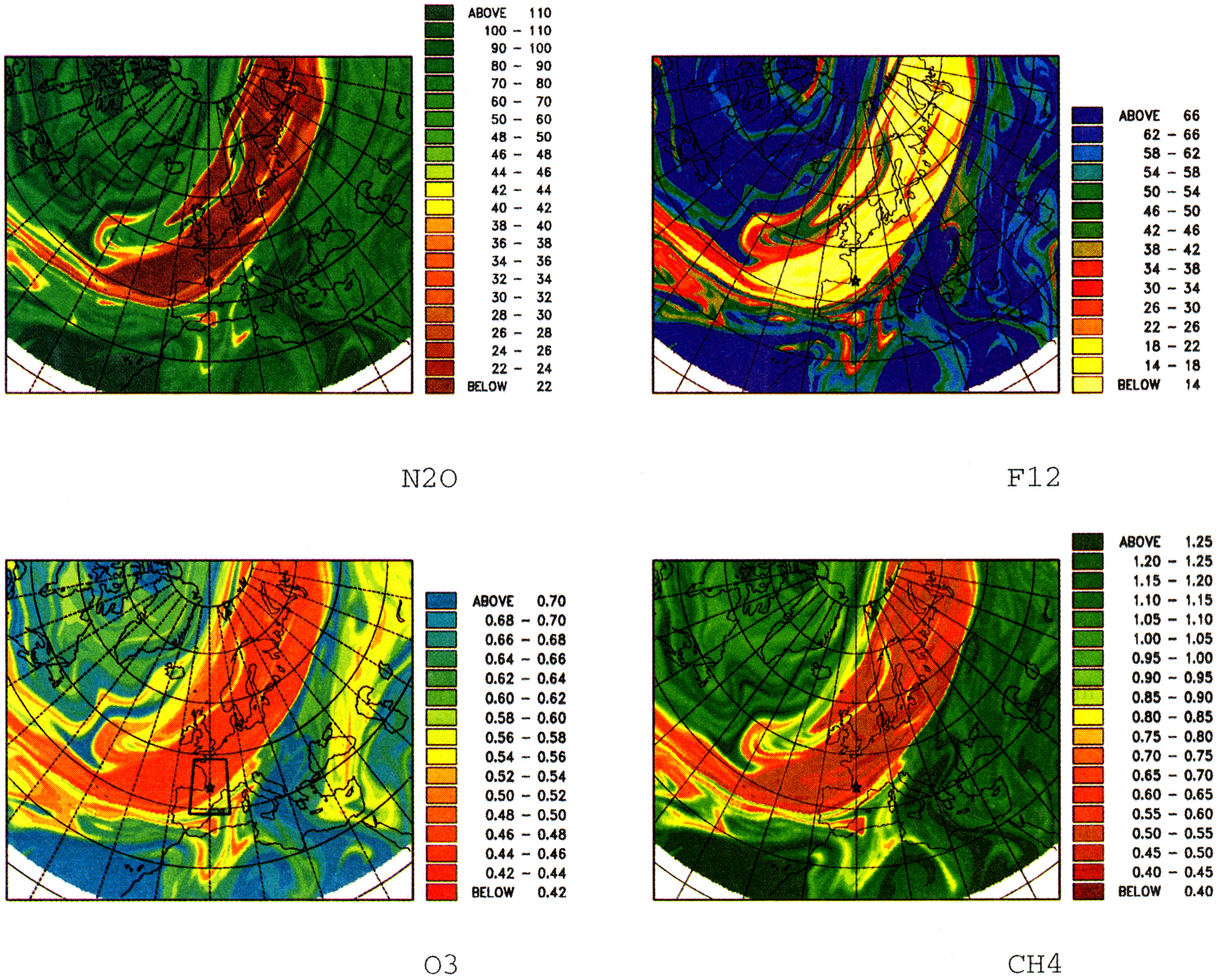

Plate 1. N_2O, F12, O_3 and CH_4 distributions at 750 K. The date is March 7 (0600 UT). The units are the same as in Figure 1. The star indicates Aire-sur-Adour (44°N, 0°E). On the O_3 plot the box used for the domain-filling trajectory model is drawn.

stratospheric sudden warmings occurred, associated not only with the magnitude increase of a dominant planetary wave 1 but also of waves 2 and 3 [*Manney et al.*, 1994a]. During the first week of March the vortex was strongly disturbed. The geopotential height on March 7 (0000 UT) at 30 mbar (Figure 2) from the ECMWF analyses reveal that the elongated vortex reached southern France. At 150 mbar (Figure 2) one finds a ridge located over France and the British Isles, which pushed polar air northward. This geopotential-high anomaly can be traced down to 500 mbar and up to 50 mbar. Aire-sur-Adour is near the vortex edge at 30 mbar. The ECMWF geopotential and potential vorticity analyses (not shown) indicate that the vortex is still well defined at 10 mbar and that it is nearly vertically aligned between 10 and 30 mbar. It was confirmed by a comparison with the GEOS analyses that this barotropic character of the vortex was not an artifact of the ECMWF analyses near the top analyzed level.

4. Simulation of Trace Species' Distributions

4.1. The Intrusion at 750 K

The distributions of N_2O, F12, O_3 and CH_4 are shown in Plate 1 at 750 K on March 7 (0600 UT), the closest output time to the grab-sampler measurements.

These distributions show a highly elongated vortex with considerable filamentation occurring. At that time, Aire-sur-Adour was on the inner-side of the vortex edge, where filaments of air with polar and mid latitude origins were interlaced. A filament slightly enhanced in F12, CH_4, N_2O and O_3 passed just above Aire-sur-Adour at that time. It had a signature stronger in CH_4, N_2O and F12 than in O_3, as the contrast between vortex air and extravortex air is stronger for these species than for ozone.

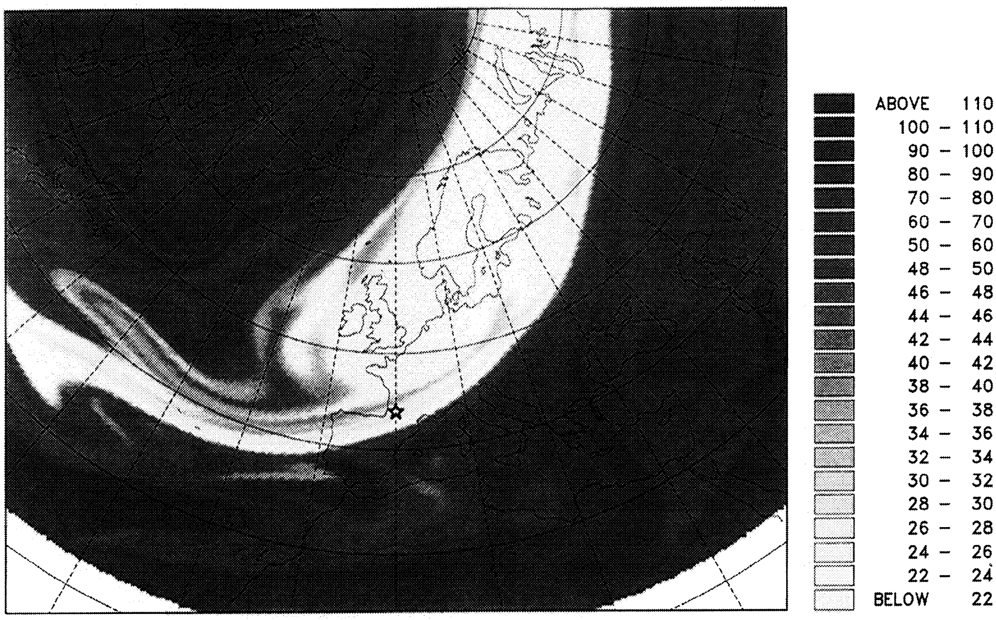

Figure 3. N_2O distribution at 750 K for the GEOS simulation. The date is March 7 (0600 UT).

The thin filamentary intrusion ends with a chevron pattern over the south coast of the Baltic Sea (see the CH_4 and N_2O maps in particular, near 25°E-55°N). This filament qualitatively explains the balloon-borne sample at 750 K being enriched in long-lived trace gases. The feature in the simulations is a weak one however, with air coming from the vortex edge, rather than the mid latitudes. The concentrations measured in situ however showed values representative of mid latitude air. This might be due to the fact that the transversal scale of the filament is close to the half-degree resolution of the model; hence the filament may mix down too rapidly due to numerical diffusion.

Although the various long-lived tracer distributions (Plate 1) are seemingly redundant, the consistency of these distributions, derived from initialization with observations from different instruments, ensures that the small-scale filamentary features under study are not associated with inaccuracies in a particular tracer field used for initialization.

The passing of enriched filaments above Aire-sur-Adour at the time of the measurements also appears in the GEOS simulations (Figure 3). There is a remarkable agreement on the position of the polar vortex in both simulations.

4.2. Low-Level Laminae

Figure 4a shows the O_3 distribution at 425 K, also on March 7 (0600 UT). At these low levels, the O_3 distribution nicely shows the effect of the ridging, with a patch of low O_3 over France, Spain and part of the British Isles.

Profiles above Aire-sur-Adour (43.95°N,0°E) of the PV tracer below 550 K are shown in Figure 4b for March 7 at 0000 and 1200 UT. The PV tracer displays well marked laminae below 500 K. Also shown are profiles typical of mid latitude and polar PV tracer, the latter being defined as the zonal average at 65°N on the initial day, and the former as the 45°N zonal average on March 8. It is clear that the PV tracer is fluctuating around mid latitude values below 500 K, because of the vortex ridging, while it is more characteristic of polar air aloft. *Mariotti et al.* [1997] also used ECMWF winds in a contour advection model study of filamentation; although they did not focus on thin-scale laminae, their study implied that the quality of the lower stratospheric winds was adequate to locate the edge of the vortex, its vertical slope, and sudden jumps due to ridging. Note the low-level lamina of southerly origin in the PV-tracer profiles between 425 K and 450 K on March 7 (1200 UT), as suggested by the flow pattern in Figure 2 and 4a. Measurements also indicated a southerly origin for the air mass sampled near 430 K.

4.3. Higher-Resolution Simulations With a Trajectory Model

In an attempt to understand why the modeled filament above Aire-sur-Adour was not enriched enough in trace gases, compared with the balloon data, we performed even higher resolution simulations with the trajectory model of *Manney et al.* [1996]. Isentropic back trajectories were calculated at 675 K and 750 K, ending on March 7 (0600 UT), that is, the closest time to the measurements for which ECMWF data is available.

The distributions of N_2O, F12, O_3 and CH_4 on the limited domain, centered at 44°N and 0°E, are shown in Plate 2 at 750 K for March 7 (0600 UT). One can see that the filament identified in the transport model simulations has some inner structure: It consists of a bundle of filaments. For any transported trace species, some of the inner filaments contain air with mid latitude characteristics. For example, N_2O values of about 70 ppb

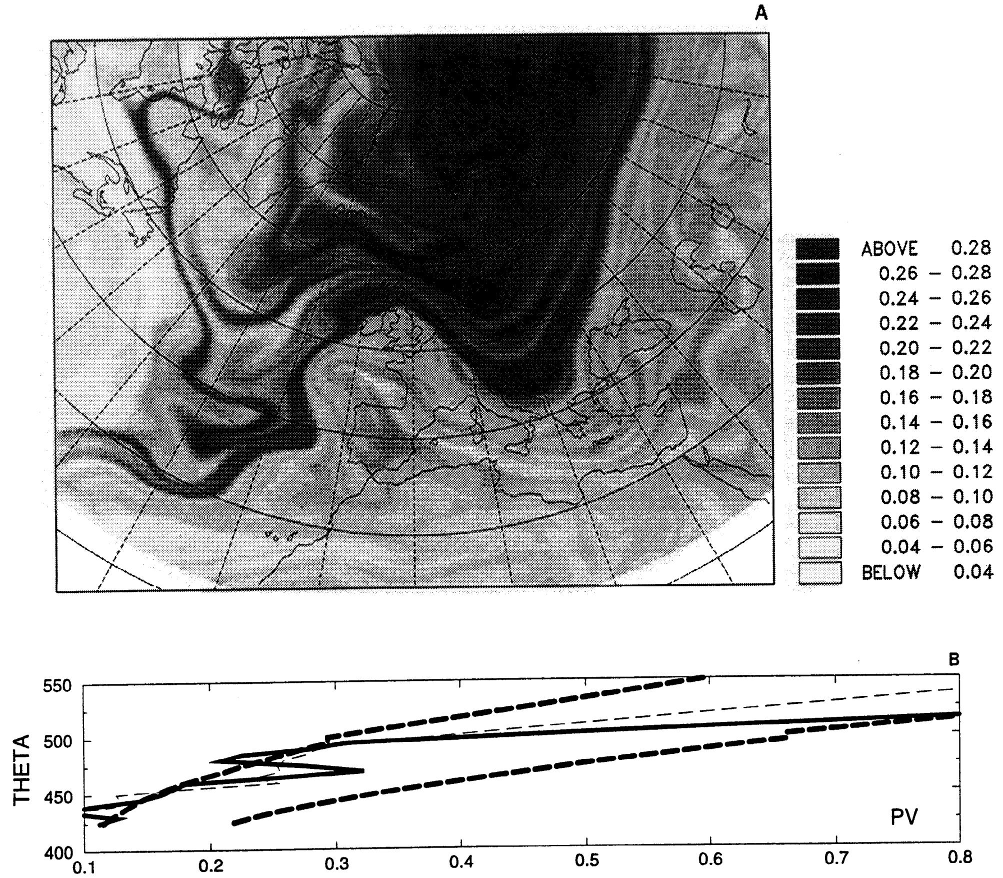

Figure 4. (A) O_3 distribution at 425 K. The date is 7 March (0600 UT). (B) A series of profiles of PV tracer at (43.95°N,0°E) on March 7 0000 and 1200 UT in the range 400 K to 550 K. Also shown are typical (see text) mid latitude and polar profiles (thick dashed lines).

are found near the center of Plate 2, in quantitative agreement with the balloon-borne observations. This is further shown in Figure 5 which displays meridional profiles of F12, CH_4, N_2O and O_3 along the Greenwich meridian at 750 K and 675 K for the trajectory model (black lines). The diamonds indicate the concentrations measured by the grab sampler. The agreement between the in situ measurements and the trajectory model at 750 K and 675 K, is quite remarkable. The values predicted at 675 K are indeed representative of polar air, while those predicted at 750 K are representative of mid latitude air; hence the poleward tilt of the bundle of filaments with height was captured. Note that the relative magnitudes of filaments in a tracer are sensitive to the tracer initial distribution. For example, in the bundle of filaments in the band 41°N-45°N, and at 750 K (Figure 5), the most enriched values are found near 42.5°N. This is true for all the trace gases except N_2O. Between 43°N-44°N and at 750 K, near constant mixing ratios are found in all tracers except CH_4.

Also shown in Figure 5 are the results of the transport model at 750 K for all tracers (dotted lines) and at 675 K for CH_4 and O_3. For N_2O the results obtained with the GEOS winds are also displayed (dashed line). The transport model shows local maxima, that is, enrichment, in tracers near the locus of the measurements but weakly so. Note that the shapes of the filaments in these meridional cross sections are different in the two models. In the former the filaments are smoother, with a core and slowly decaying wings. In the latter, however, the cross sections show rapid changes between mid latitude and polar values; in other words the filaments tend to have sharp edges. The formation and the ensuing fragmentation of a main filament through splitting in a shear flow is likely to exhibit such characteristics. The smooth filaments generated by the transport model are caused by numerical diffusion operating on the scale of the model grid. Numerical diffusion is acting continuously; hence at a given time, like in Figure 5, cross sections are not simply smoothed versions of the cross sections from the Lagrangian trajectory model. Note also the discrepancies between the transport model and the trajectory model at 750 K and at the northern edge of the domain, where filaments have coiled up within the vortex and hence have been much attenuated in the Eulerian transport calculations. Some thin filaments in Plate 2 seem discontinuous; this is due to the number of particles still being too small, and these discontinuities might explain some of the smallest mixing ratio fluctuations in Figure 5 (thick lines).

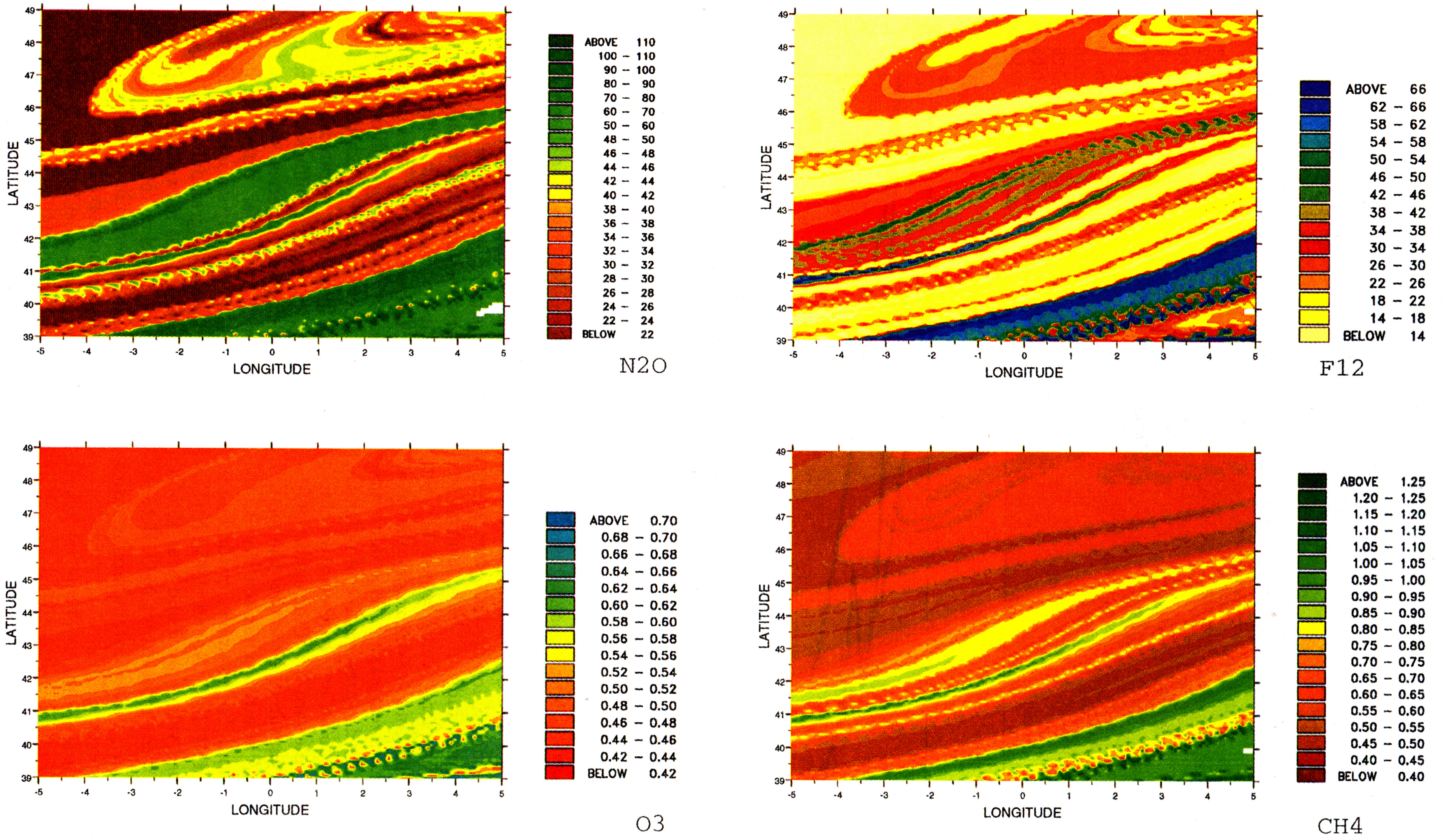

Plate 2. N_2O, F12, O_3 and CH_4 distributions at 750 K with the domain-filling trajectory method. The date is March 7 (0600 UT). The domain center is at (0°E,44°N).

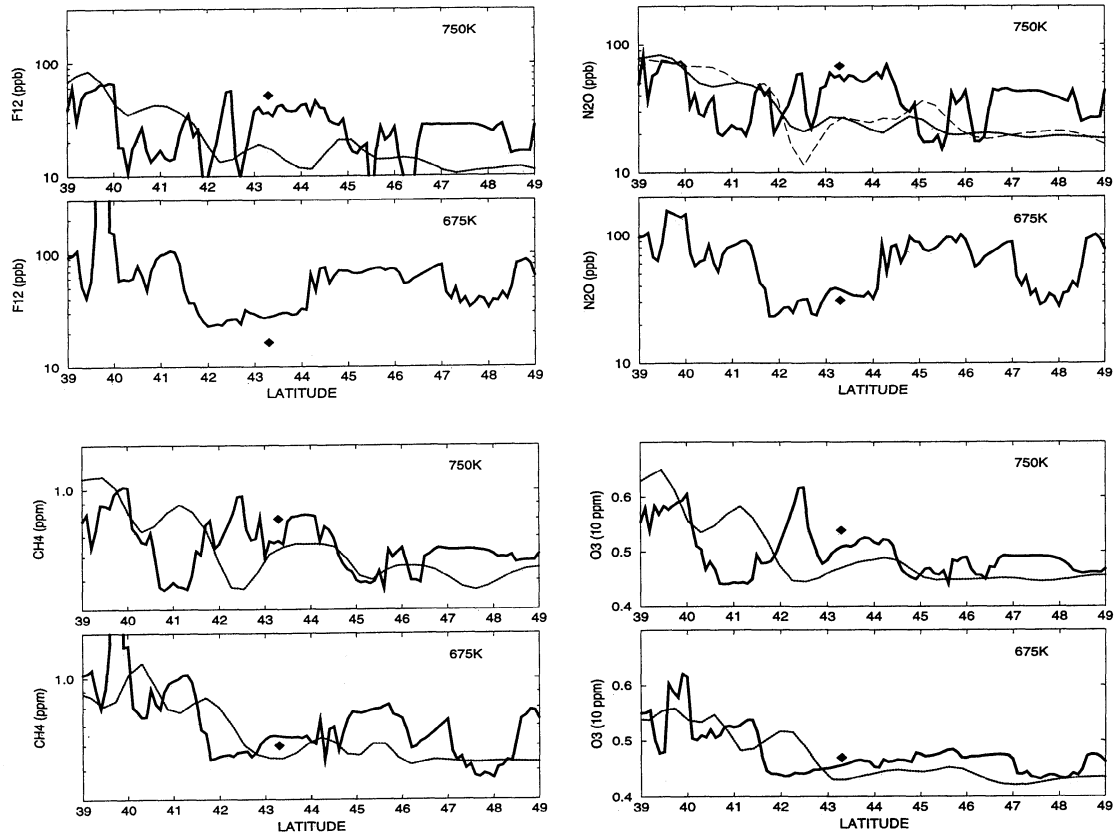

Figure 5. Meridional profiles of F12, CH_4, N_2O and O_3 at 750 K and 675 K along the Greenwich meridian: trajectory method (black line), transport model (dotted line). The date is March 7 (0600 UT). Also shown is the transport model with GEOS winds for N_2O at 750 K (dashed line). The balloon-borne measurements at 750 K and 650 K are also shown (diamonds).

5. Summary and Discussion

By combining global satellite measurements of trace species and high-resolution advection models, we have examined trace species' filamentation and lamination near the vortex edge during late winter 1993 and have made a detailed comparison with balloon-borne measurements carried over a large height range. This study was done to explain how a balloon flight conducted in March 1993 from Aire-sur-Adour in southern France, revealed coincident laminations in long-lived tropospheric source gases, such as nitrous oxide, methane and halocarbons. The novelty in our approach to laminae modeling has been to transport several trace species derived from satellite data; we also attempted to make quantitative model predictions.

Low-level laminae appeared clearly in all trace gases. A well-marked intrusion of mid latitude air was detected at the highest sampled level, near 15 mbar, inducing a kink in the tropospheric source gases and ozone profiles. At that height the vertical resolution and extent of these measurements were not sufficient to resolve the feature as lamina.

Meteorological analyses indicate that the inner edge of the stratospheric polar vortex was sampled and that the vortex was barotropic above 30 mbar, thereby demonstrating that the kink in observed profiles above 700 K (Figure 1) could not be due to the vortex being strongly sloping on the vertical. High-resolution simulations nevertheless support that such profile reversals can be explained by dynamical motions, namely height-dependent filamentation in the vortex edge region [*Plumb et al.*, 1994; *Orsolini*, 1995; *Newman et al.*, 1996].

The high-resolution maps of long-lived tracers such as F12, CH_4, N_2O and O_3 obtained with two models do show enriched filaments at 750 K above Aire-sur-Adour. These features are robust, appearing in two simulations using two sets of meteorological analyses, the ECMWF and GEOS analyses, although other filamentary features do differ in their detailed structure in the two simulations.

The Lagrangian calculations improve the qualitative prediction by the Eulerian model of a filament enriched in trace gases above Aire-sur-Adour. However, the prediction of the details in the bundle of filaments, that is, of the exact timely position of the inner filaments seen in Plate 2, would be extremely difficult to achieve because of inaccuracies of the analyzed winds. Furthermore, the particle horizontal spacing is only 10 km. At that scale mesoscale atmospheric turbulence can be expected to play a role, and such turbulent velocity fields are obviously not represented in the analyzed winds. *Haynes and Anglade* [1997] made the point that the collapse of filament vertical scale through lamination implies that vertical turbulent diffusion, for example that resulting from gravity wave breaking, would strongly interact with the layerwise filamentation processes. The trajectory model convincingly shows that the measurements at 750 K were made at a latitude where mid latitude and polar air masses were interlaced, while at 675 K, these interlaced structures are slightly to the north. However, a true prediction of balloon-borne in situ measurements, showing skill over a large number of cases, will probably remain very difficult to achieve.

Appendix: Meteorological and Satellite Data

Six-hourly ECMWF winds are de-archived at a horizontal resolution of about 1°, and extrapolated on the Gaussian T213 model grid, corresponding to a resolution of 0.5°. The ECMWF winds are linearly interpolated on isentropes from winds archived on 11 pressure levels. The GEOS-UARS analysis is a stratospheric version of the GEOS-1 system [*Schubert et al.*, 1993] that covers the first 2 years of the UARS mission. GEOS-UARS has a top near 0.1 mbar, 46 vertical sigma levels, and a 4° by 5° degree latitude by longitude horizontal resolution. Winds are provided every 6 hours.

The O_3 simulations were initialized with the local mean of asynoptically mapped O_3 from the Microwave Limb Sounder (MLS) observations, valid for February 26 (1200 UT) and for February 25 (1200 UT). The CH_4, F12 and N_2O simulations were initialized with the local mean of daily gridded Cryogenic Limb Array Etalon Spectrometer (CLAES) observations of February 25 and 26. Mixing ratios retrieved on pressure surfaces were interpolated on the desired isentropic level using the UKMO analyzed temperatures. Further details about the UARS constituents mapping and interpolation, as well as examples of their use in diagnostic studies of the stratospheric circulation are given in *Manney et al.* [1994a, b]. Output from the PV simulations was stored at 0000 and 1200 UT, while output from the tracer simulations was stored every 6 hours.

The accuracy of the MLS retrievals degrades below 450 K, as do the ones from CLAES below 500 K in mid and low latitudes, and below about 450 K in polar regions. Hence we used analyzed PV as a proxy tracer at low levels.

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References

Appenzeller, C., and J. R. Holton, Tracer lamination in the stratosphere: A global climatology, *J. Geophys. Res., 102*, 13,555-13,569, 1997.

Bauer, R., A. Engel, H. Franken, E. Klein, G. Kulessa, C. Schiller and U. Schmidt, Monitoring the vertical structure of the Arctic polar vortex over northern Scandinavia during EASOE: regular N_2O profile observations. *Geophys. Res. Lett., 21*, 1211-1214, 1994.

Bird, J., S. R. Pal, A. I. Carswell, D. P. Donovan, G. L. Manney, J. M. Harris and O. Uchino, Observations of ozone structures in the Arctic polar vortex, *J. Geophys. Res., 102*, 10,785-10,800, 1997.

Engel, A., R. Bauer and U. Schmidt, Observations of long lived trace gases in the arctic polar vortex displaced toward mid latitudes during TRAVERSE, Proceedings of the Third European Workshop on Polar Stratospheric Ozone, Schliersee, Bavaria, edited by J.A. Pyle et al., pp 72-75, Eur. Comm., Brussels, 1996.

Haynes, P., and J. Anglade, Vertical scale cascade in tracer fields, *J. Atmos. Sci., 54*, 1121-1136, 1997.

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, 1994a.

Manney, G. L., et al., Chemical depletion of ozone in the Arctic lower stratosphere during winter 1992-93, *Nature, 370*, 429-434, 1994b.

Manney, G. L., R. W. Zurek, M. E. Gelman, A. J. Miller and R. Nagatani, The anomalous Arctic lower stratospheric polar vortex of 1992-1993, *Geophys. Res. Lett., 21*, 2405-2408, 1994c.

Manney, G. L., M. L. Santee, L. Froidevaux, J. W. Waters, and R. W. Zurek, Polar vortex conditions during the 1995-1996 Arctic winter: Meteorology and MLS ozone, *Geophys. Res. Lett., 23*, 3203-3206, 1996.

Mariotti, A., M. Moustaoui, B. Legras and H. Teitelbaum, Comparison between vertical ozone soundings and reconstructed potential vorticity maps by contour advection with surgery, *J. Geophys. Res., 102*, 6131-6142, 1997.

Mlch, P., and J. Lastovicka, Analysis of laminated structure in ozone vertical profiles in Central Europe, *Ann. Geophys., 14*, 744-752, 1996.

Newman, P. A., et al., Measurements of polar vortex air in midlatitudes, *J. Geophys. Res., 101*, 12,879-12,891, 1996.

Orsolini, Y. J., On the formation of ozone laminae at the edge of the Arctic polar vortex, *Q. J. R. Meteorol. Soc., 121*, 1923-1941, 1995.

Orsolini, Y., P. Simon, and D. Cariolle, Filamentation and layering of an idealized tracer by observed winds in the lower stratosphere, *Geophys. Res. Lett., 22*, 839-842, 1995.

Orsolini, Y. J., G. Hansen, U-P. Hoppe, G. L. Manney, and K. H. Fricke, Dynamical modelling of wintertime lidar observations in the Arctic: Ozone laminae and ozone depletion, *Quart. J. Roy. Met. Soc., 123*, 785-800, 1997.

Ovarlez, J., and H. Ovarlez, Stratospheric water vapor content evolution during EASOE, *Geophys. Res. Lett., 21*, 1235-1238, 1994.

Petzoldt, K., B. Naujokat, and U. Schmidt, The effect of stratospheric dynamics displayed in springtime in situ observations of source gases at mid latitudes, *Adv. Space Res.*, vol. 10, 10,161-10,165, 1990.

Plumb, R. A., et al., Intrusions into the lower stratospheric

Arctic vortex during the winter of 1991/1992, *J. Geophys. Res.*, *99*, 1089-1106, 1994.

Reid, S. J., and G. Vaughan, Lamination in ozone profiles in the lower stratosphere, *Q. J. R. Meteorol. Soc.*, *117*, 825-844, 1991.

Reid, S. J., et al., A study of ozone laminae using quasi-isentropic trajectories, contour advection and photochemical trajectory model simulations, *J. of Atm. Chem.*, in press, 1998.

Schmidt, U., R. Bauer, A. Engel, R. Borchers, and J. Lee, The variation of available chlorine, CLy, in the Arctic polar vortex during EASOE, *Geophys. Res. Lett.*, *21*, 1215-1218, 1994.

Schoeberl, M. R., and P. A. Newman, A multiple-level trajectory analysis of vortex filaments, *J. Geophys. Res.*, *100*, 25,801-25,815, 1995.

Schubert, S. D., J. Pfaendtner, and R. Rood, An assimilated data set for Earth Science applications, *Bull. Am. Meteorol. Soc.*, *74*, 2331-2342, 1993.

Sutton, R. T., H. Maclean, R. Swinbank, A. O'Neill, and F. W. Taylor, High resolution middle atmosphere tracer fields estimated from satellite observations using Lagrangian trajectory calculations, *J. Atmos. Sci.*, *51*, 2995-3005, 1994.

Teitelbaum, H., M. Moustaoui, J. Ovarlez, and H. Kelder, The role of atmospheric waves in the laminated structure of ozone profiles at high latitude, *Tellus*, *48A*, 442-455, 1996.

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