On the formation of ozone laminae at the edge of the Arctic polar vortex

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SUMMARY

Ozone vertical profiles commonly display thin-layered structures, or laminae, in the lower stratosphere of the extratropics, predominantly during winter and spring. The mechanism for their formation is still uncertain.

In this study, high-resolution isentropic transport of a passive tracer on synoptic time-scales is performed with an off-line transport model, which is forced by winds derived from global meteorological analyses or forecasts. The study focuses on a meteorological situation which occurred in late January 1992. On isentropic surfaces, the tracer distribution, initialized as the analysed potential vorticity, is eroded into filamentary structures in the mid-latitude surf-zone. Repeated poleward intrusions of mid-latitude air are shown to lead to the formation of convoluted filamentary structures at high latitudes.

By performing isentropic advection on many closely spaced independent levels, the vertical structure of these tracer filaments can be studied. They are shown to be part of tracer sheets which are vertically tilted in the shear zone in the vicinity of the polar jet. Thin laminar structures in the tracer vertical profiles appear as the result of isentropic wrapping and vertical shearing of such tracer sheets. A comparison is made with ozone laminae, found in balloon-borne soundings during the European Arctic Stratospheric Ozone Experiment.

KEYWORDS: Arctic polar vortex Isentropic advection Ozone laminae Stratosphere Tracer filaments

1. INTRODUCTION

The distribution of ozone in the lower extratropical stratosphere is strongly governed by dynamical factors, ranging from large-scale planetary or synoptic motions down to small-scale gravity waves. For example, it had been long recognized that tropospheric weather systems which affect the lower stratosphere can influence the ozone column abundance (see Dobson 1968). The ozone transport by large-scale stratospheric eddies, both transient and quasi-stationary, has been extensively documented by observational studies.

The coarsely resolved, or time-averaged, isentropic distributions of ozone in the lower stratosphere show a strong meridional gradient in the vicinity of the winter polar jet. However, along-flight aircraft measurements do not always reveal an abrupt transition in the ozone concentration in the vortex-edge region. Rather, both in the Arctic and the Antarctic, these aircraft measurements show strong spatial variability in ozone and in other trace constituents in the boundary of the lower stratospheric vortex (Murphy et al. 1989; Tuck et al. 1992; Waugh et al. 1994).

Understanding the mixing of air masses of different origins near the edge of the polar vortex has become a subject of great scientific importance because of concern about ozone depletion and the dilution of the air masses which are chemically perturbed mostly in the high latitudes. The height range over which meridional mixing prevails, at the base of the polar vortex, is likely to extend higher up in the Arctic, as the Arctic vortex is more disturbed by planetary and synoptic waves than the more intense and zonal Antarctic one.

Based on observations and modelling, the extent and magnitude of meridional mixing at the base of the winter polar vortex were evaluated by several authors (Hartmann et al. 1989; McKenna et al. 1989; Profitt et al. 1989, 1990; Schoeberl et al. 1992; Bowman 1993; Dahlberg and Bowman 1994). There have been considerable advances in the modelling of such exchange processes at the edge of the polar vortex. On time-scales of 10–15 days, the large-scale atmospheric motions are near-isentropic in the lower stratosphere, i.e. they occur on constant potential-temperature surfaces. The advent in meteorology of

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Lagrangian techniques, such as the contour-advection approach (Norton 1994; Waugh and Plumb 1994) or the domain-filling trajectory approach (Bowman 1993; Sutton et al. 1994), has allowed the fine details to be modelled of how wind shears can generate filamentary tracer structures of ever-thinning scales through a process of two-dimensional, and in this case isentropic, advection. In particular, studies of meteorological situations have shown strong evidence for the interpretation of the subsynoptic-scale extrartorcal regions with vortex-like vorticity or composition as filamentary structures being eroded from the polar vortex (Plumb et al. 1994, hereafter P94; Waugh et al. 1994). In fact P94 also showed that vortex intrusions also occur during strong ridging events, during which the polar vortex is distorted by one or several large-scale ridges. Mid-latitude air masses can then flush into the disrupted vortex. Although such intrusions are large-scale phenomena, they can lead to the formation of elongated filaments of mid-latitude air inside the polar vortex which persist while the vortex reforms. These events are more sporadic than the formation of filaments by erosion of the polar vortex which is more common.

The vertical distribution of ozone is also highly variable both spatially and temporally, as revealed by the ozone soundings routinely performed worldwide since the 1950s. Dobson (1973) showed that ozone profiles often exhibit a laminar structure. Layers of relative enhancement or depletion in ozone and of variable thicknesses are found throughout the year in the extrartorcs. A comprehensive study by Reid and Vaughan (1991) of ozone sondes launched over several decades over the globe reveals that these laminae are observed most prominently during winter and spring in the extrartorcs of both hemispheres. Laminae in ozone partial pressures with thicknesses (i.e. vertical scale) ranging from 500 m to 2500 m and magnitudes greater than 2 mPa were statistically analysed. They showed that laminae mostly occur in an altitude range of 12 to 18 km and near the polar vortex edge, and that their dominant thickness was found to be about 1.2 km at high latitudes. They also showed that at high latitudes laminae were more confined to lower altitudes, and strong interannual variability in laminae occurrence prevailed. Strong synoptic variability is a general rule: laminae often vanish between soundings taken only a few hours apart, and simultaneous soundings taken a few hundred kilometres away do not necessarily exhibit similar lamination.

Such laminae were also found in soundings launched in the Antarctic during late winter or spring (Gardiner 1988). Moreover, Murphy et al. (1989) have shown the existence of laminated structure in trace-constituents data recorded with a high-flying aircraft in the high latitudes of the southern hemisphere. They suggested that the transition region, which separates the inner polar vortex from the mid-latitude air, is characterized by horizontal interchange of air masses, and vertical layering.

These laminae are thought to be of dynamical origin, but the precise generation mechanism remains uncertain. Destruction in situ of ozone is unlikely, as laminae were observed in other trace constituents and volcanic aerosols (Murphy et al. 1989; Tuck 1989; di Sarra et al. 1992). Large-scale advection and mixing by gravity waves have been proposed as possible dynamical mechanisms. Reid and Vaughan (1991) linked them to the presence, and ultimate spring break-up, of the polar vortex. The effect of gravity waves was also investigated by Reid et al. (1994) and by Teitelbaum et al. (1994); Danielsen et al. (1991) considered transport by low-frequency gravity waves.

The purpose of this paper is to demonstrate in a meteorological situation that such laminae appear in a model as a consequence of a realistic isentropic advection. More precisely, such isentropic advection leads to filamentation of a tracer distribution, which has gradients near the vortex edge. Because of vertical wind shears, the filamentation is height-dependent, and the filaments can be thought of as part of three-dimensional tracer sheets. Sheets with high tracer content will be shown to be eroded from the polar vortex,
and vertically tilted in the shear zone in the vicinity of the polar jets. During the strongly perturbed event studied in this paper, sheets with low tracer content also intrude into the vortex, creating an inner-vortex interleaved tracer structure. Sloping or strongly deformed sheets appear as laminae in tracer vertical profiles. Hence, this study attempts to bridge recent developments in high-resolution tracer transport with observations of ozone vertical variability.

2. Data and model

In the following, examples are shown of the kind of laminae which can be frequently observed in ozone profiles. The period studied is the second half of January 1992. The prevailing meteorological situation has been studied elsewhere (Norton and Carver 1994; Orsolini et al. 1994, 1995a, 1995b; Waugh et al. 1994; P94). In the lower stratosphere, the polar vortex was displaced over Europe during the second half of January, and distorted by a series of large-scale ridging events which developed over the northern Atlantic and were associated with strong tropospheric forcing. Two major near-barotropic vortex intrusions occurred during the later part of January, extending high in the lower stratosphere up to 20–25 km.

(a) Ozone soundings

Eleven ozone balloon soundings taken on 29 January 1992 over northern Europe and the northern Atlantic during the European Arctic Stratospheric Ozone Experiment (EASOE) are shown in Fig. 1. Ozone mixing ratio is plotted as a function of potential temperature, which is calculated from the temperature measured by the balloon as it ascends. The height range is approximately between 14 and 20 km. All soundings were launched within plus or minus 2 hours of noon (gmt), except for the ones at Hohenpeissenberg and Dikson which were, respectively, taken around 7 a.m. and 6 a.m. on the same day. Note that the soundings on Fig. 1 do not all have the same vertical resolution. Although the ozone mixing ratio tends generally to increase with height up to about 3–4 parts per million by volume (p.p.m.v.), this increase with height is not monotonic. Many profiles exhibit a laminar structure. In this study, we will broadly use the term laminae for enriched or depleted layers, even outside of the thickness range of 200–2500 m considered by Reid and Vaughan (1991). They considered profile lamination in ozone partial pressure, but here ozone mixing ratio is used to compare with the quantity transported by the advective model. Using partial pressure instead of mixing ratio tends to amplify the low-level laminae. The high gradients in the isentropic map of potential vorticity at 475 K in Fig. 2 coarsely delimit the location of the polar vortex. This map is derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses at T106 resolution and is valid for noon (gmt) on 29 January 1992. The locations of the sounding stations are also indicated on this map. The high number of sounding locations in the vicinity or inside of the polar vortex makes this data set useful for studying mixing processes in the polar stratosphere. Fig. 2 indicates that several soundings measured ozone clearly outside of the polar vortex at the 475 K level. This is the case for the soundings at Lerwick, Gardemoen and Hohenpeissenberg, while the soundings at Polarfront and Rejkjavik were taken in the vortex-edge region.

By examination of Fig. 1, one can notice that the soundings taken at Polarfront and Gardemoen tend to show a thick layer depleted in ozone, with a 'thickness' of 40 to 60 K above the 410 K level, and a thin enhanced layer underneath. The sounding at Rejkjavik exhibits a similarly depleted lamina, but with additional layered structure within the main lamina. The profiles taken at higher latitudes have a more variable and complex vertical
Figure 1. Ozone mixing-ratio profiles (in 10 parts per million by volume) taken over northern Europe and the northern Atlantic by ozone sondes on 29 January 1992. Height is measured by potential temperature (K).
Figure 1. Continued.

Figure 2. Isentropic potential vorticity (PV) at 475 K from the ECMWF analyses for 1200 GMT 29 January 1992. The map is in stereographic projection, and the 60°N latitude circle is drawn. The ozone-sonde launching stations corresponding to profiles of Fig. 1 are also indicated on the map. PV is in units of $10^{-6}$ K m$^2$kg$^{-1}$s$^{-1}$. 
lamination. Several profiles display laminae with an approximate thickness of 1 km (about 25 K). The one at Sodankyla is depleted in a 25 K layer centred at 450 K. The profile at Thule shows three depleted layers of comparable thicknesses, between 425–450 K, 385–410 K and 355–380 K. The profile at Egedesminde has a well defined depleted layer centred near 425 K. A more complex structure, with many unevenly layered laminae, appears at Dikson and Nyalesund. Layering in these observed profiles indicates that laminae formation is active at high levels during this period, e.g. 450 K. Statistical studies (Reid et al. 1994) show that laminae in partial pressure, extending to levels as high as 500 K, were present during January 1992. Hence the occurrence of high-level laminae is higher during that period than in the laminae climatology for January–February established by Reid et al. (1993).

(b) Model simulations

In this study, high-resolution isentropic tracer transport during the second half of January 1992 is simulated in order to examine whether such lamination can occur solely from advection. The model is an off-line transport model with an accurate advection based on the scheme of Prather (1986). It is used here in a high-resolution version on the Gaussian grid T106, i.e. with a resolution of about 1.125°. The advecting winds are derived from the six-hourly analyses from the ECMWF, also at T106 resolution. The winds are interpolated onto isentropic surfaces from pressure-level archived winds. There are five levels between 50 and 200 mb. The isentropic advection of a purely passive tracer is then performed independently on the 25 levels, equally spaced between 375 K and 500 K, roughly between 14 and 20 km. The model effective vertical resolution is 5 K (or about 200 m). Note that although the isentropic calculations are done independently, the advecting winds are not independent on all levels. The grid resolution is quite high for a transport model, and simulations are performed with high-resolution archived meteorological fields.

On a time-scale of one to two weeks, the motions are nearly adiabatic in the lower stratosphere. As we are interested in reconstructing the fine-scale structure of the ozone field around 29 January, the calculations were started on 16 January 1992. Two auxiliary calculations were also done, starting 5 days earlier and 5 days later than that date. The rate of diabatic descent in the lower polar stratosphere is not known precisely, but it is a limitation of the model that there is no advection across isentropes. The transported tracer is initialized as the analysed potential vorticity (PV) on the day of initialization, a procedure which allows the tracer to be initially confined within the polar vortex, and to be vertically stratified. The tracer, used as a proxy tracer for ozone, has meridional gradient at the polar vortex edge initially; it also has a weaker meridional gradient in the subtropics. The proxy tracer is actually the PV, scaled so that its range is between 0 and 1, and it is hereafter referred to as a mixing ratio. The proxy tracer is freely referred to as model ozone. The proxy tracer is then passively advected by the winds derived from the analyses on a series of closely spaced isentropic surfaces. The three-dimensional time-evolving distribution of the tracer is then reconstructed by stacking the tracer distributions calculated at each isentropic level.

3. Filamentation and Layering in the Model

(a) Isentropic filamentation of model tracer

After several days of advection by the analysed winds, the tracer distribution shows the formation of filaments on all isentropic surfaces. It has to be stressed that it is the large-scale component of the wind field which governs the filamentation process (P94).
Figure 3 shows the tracer field on the 475 K, 450 K and 410 K isentropes for 1200 GMT 29 January 1992, that is after 13.5 days of simulation. The filamentation takes the form of either:

(i) erosion out of the polar vortex: high-ozone material is drawn out of the vortex into the mid latitudes in a filamentary manner. See, for example, the long ribbon being detached out of the vortex and undulating over a whole hemisphere near the 60°N latitude circle on the 475 K isentrope.

(ii) intrusion into the polar vortex: ozone-poor filaments are drawn into the polar vortex (see Fig. 2 for identifying the vortex boundary at 475 K), and this leads to a convoluted and interleaved structure inside the polar vortex.

This meteorological situation has been studied by P94, and the isentropic tracer distributions of Fig. 3 compare well with their contour-advection calculations (see their Figs. 3 and 4). In Fig. 3, one can note that tracer-poor vortex intrusions are present at both the 475 K and 450 K levels, but are not exactly coincident. The long ribbon near 60°N is seen to meander slightly differently at the 450 K level than it does at the 475 K level.

(b) Vertical layering of model profiles

Figure 4 shows the model vertical ozone profiles above grid points which are the closest to the sounding locations displayed in Fig. 1. The model profiles correspond to 1200 GMT 29 January 1992. Many profiles in Fig. 4 exhibit lamination in layers as thin as 25 K, i.e. about 1 km. It is shown thereafter that such a lamination is the product of an accurate isentropic multi-level advection. In this study, isentropic filaments of a scale of about a degree are resolved.

The profile at Sodankyla shows a well defined depleted 1 km thick lamina near 425–450 K. Some thicker or thinner laminae are also found: some 2 km thick above the 410 K level at Gardemoen and Egedesminde, or at higher latitudes, a lamina between 410–450 K at Thule, and a very narrow one at Nyalesund between 460 and 470 K. The mid-latitude site of Hohenpeissenberg does not show any significant lamination in the model, in agreement with the sounding. The model also shows thin and weak enhanced laminae just above 400 K at Rejkjavik, Thule and Gardemoen. The advective model is hence able to resolve the dominant scale of 1 km found by Reid and Vaughan (1991).

While the model can occasionally place a lamina at the same potential temperature as in the sounding, the best example being the one at Sodankyla in the range 425–450 K, the height localization is at best qualitative, and some observed laminae are missed by the model altogether, such as the one at Egedesminde at 425 K.

The focus of this study was the mechanism for formation of ozone laminae, not a prediction of laminae occurrences and magnitudes. There are several reasons for which only qualitative agreement is to be sought. Owing to the turbulent nature of the mixing by such complex time-dependent flows, one could not reasonably expect that a model driven by meteorological analyses can predict the exact position of a thin filament, of the order of a degree, at a given time. The vertical wind shears are coarsely resolved by the analyses, and inaccuracies on the wind shears in the analysed data will lead to time-amplifying errors in the prediction of the filament positions. Such filamentary structures, such as the above-mentioned ribbon on the 475 K isentrope, or some of the inner ozone-poor filaments inside the vortex, may correspond with observations: the work of P94 indeed shows that aerosol measurements from an airborne lidar during the second half of January 1992 reveal localized subsynoptic-scale features, which correspond with the results of their contour-advection model. However, the timely prediction above a given location is a very stringent condition.
There are other factors for not looking at exact matching between forecast model ozone and ozone measured by the ozone sondes. The tracer in the model is a proxy tracer which does not have the exact same vertical and horizontal gradients as the instantaneous atmospheric ozone. Potential temperature is defined in the model using temperature from analyses. Balloon-measured temperatures may differ by several degrees, hence a mismatch of potential temperatures. The balloons carrying the sondes also drift, occasionally by a hundred kilometres or about 1° during ascent. For these reasons, the model profiles have not been exactly matched in time and position with the ozone sondes. Instead, we are looking for a corresponding lamination process in the model, which can tell us about the vortex-edge mixing processes in the real atmosphere. Indeed, further insight into the origin of model laminae can be gained by looking at the three-dimensional tracer field.

The depleted lamina near the level of 450 K at Sodankyla (Fig. 4) can be seen in Fig. 3 to be caused by an ozone-poor filament streaming along the poleward side of the ozone distribution edge. The one at Nyalesund near 475 K is associated with another ozone-poor filament, deeper inside the vortex (see the crosses in Fig. 3).

(c) Cross-sections of model tracer

Latitude–height cross-sections at 26°E and 11°E (the longitudes of Sodankyla and Nyalesund respectively) show the vertical extent of two model laminae at noon on 29 January 1992 (Figs. 5(a) and (b)). The lamina above Sodankyla corresponds to the localized minimum near 450 K and 65–70°N, while the one above Nyalesund is associated with the minimum near 475 K and 80–82°N (see the crosses on the corresponding cross-sections). In fact, at 78°N, Nyalesund is located at the edge of the model filament, and a much thicker lamina of larger magnitude would be found in the model a few degrees to the north.

The cross-sections reveal that the meridional extent of these filaments is no more than a few degrees at the height where they are the broadest. It can also be seen on these cross-sections, how some of the tracer sheets tilt with height. The equatorward edge of the region of high ozone in Fig. 5 (that is near 65°N at 11°E, or near 60°N at 26°E, at the 475 K level) is sloping equatorwards with height. Note the complex structure poleward of that edge with interleaved vertical sheets of high or low ozone. This results from the isentropic wrapping into a convoluted structure of the tracer in a height-dependent manner, as seen for example on the maps of Fig. 3. That the tracer undergoes vertical shearing at the longitude of Sodankyla and near the edge of the vortex, can be seen in Fig. 6: cross-sections of the zonal and meridional wind components derived from the ECMWF analyses show that the shear zone extends in latitude from about 55°N to 70°N at 1200 GMT 29 January. Note that although the southward component of the wind is stronger at low levels on that day, how sheared the filaments are will depend on the cumulative effect of advection during the preceding days. On the 475 K isentrope (Fig. 3), a folded high-tracer ribbon was seen being detached out of the vortex along the 60°N latitude circle. A longitude/height cross-section along 60°N (Fig. 5(c)) shows that the ribbon is part of a tracer sheet sloping with height, and which is intersected by the 60°N parallel near three longitudes. Such tracer sheets, made of high model ozone, are eroded into the mid latitudes. They have a horizontal scale of hundreds of kilometres and a vertical scale of a few kilometres.

Reid et al. (1993) showed cross-sections of ozone mixing ratios measured with an airborne lidar during the Arctic winter of 1989 along several flights underneath the polar vortex (see also Browell et al. 1990). These data had horizontal resolution of about 60 km and vertical resolution of about 1 km, and ozone was recorded between 13 and 18 km. Ozone laminae were found in that height range with characteristic thicknesses of 1 to 1.5 km. The flights were nearly transverse to the vortex edge. The lidar detected nearly barotropic ozone-poor sheets; these were thin horizontal structures of the order of a degree.
Figure 3. Model tracer distribution at (a) 475 K, (b) 450 K, and (c) 410 K for 1200 GMT 29 January 1992. The simulation was started on 16 January. The crosses on the 475 K and 450 K maps designate filaments which are responsible for the depleted laminae at Nyalesund and Sodankyla. Units are arbitrary.
Figure 4. Model tracer mixing-ratio profiles taken over grid points that are the closest to the eleven sounding stations of Fig. 1 for 1200 GMT 29 January 1992. Height is measured by potential temperature (K).
It also detected sloping ozone-rich sheets with scales compatible with cross-sections of Fig. 5, i.e. sloping by several hundred kilometres over a height of a few kilometres.

(d) Comparison with aerosol measurements

To my knowledge, there was no instrument able to measure the vertical ozone profile flown on an aeroplane over the Arctic during the period studied in this paper. However, P94 analysed the vertical structure in aerosol content as measured by an airborne lidar during a vortex-crossing flight which took place on 23–24 January. Browell et al. (1993) describe the experiments. Although aerosol and ozone do not have the same vertical distribution, they undergo a similar passive isentropic mixing on synoptic time-scales. Figure 7(a) shows a vertical cross-section along the flight path of the aerosol total-scattering ratio at a wavelength of 604 nm. Vertical profiles are shown along the flight track, each sounding being a one-minute average. The vertical coordinate is height, and the vertical resolution of the data is about 225 m. The on-flight measurements started around 2100 GMT on 23 January, at a location near 50°N 66°W. The aeroplane went northward approximately along the 60°W meridian, then veered to the west approximately along the 68°N parallel, before turning south-easterly toward the western coast of the United States. The cross-section in Fig. 7(b) shows the model tracer structure for 0000 GMT 24 January, along the same flight path. Tongues of polar air are poor in aerosol, and have a high tracer content in the model. Although isentropic surfaces are not constant height surfaces, one can identify on the two cross-sections of Fig. 7 three broad tongues of polar air extending downwards from the 20 km (or 500 K) level. The middle tongue, seen in soundings 75 to 200, does not penetrate below about 17 km in the flight data. The first and last encountered tongues extend down to about 14 km. In the altitude range between 20 and 17 km, these three tongues of polar air
Figure 5. (a) Height/latitude cross-section of the model tracer distribution of potential vorticity (units $10^{-9} \text{K m}^2\text{kg}^{-1}\text{s}^{-1}$) at the longitude of Sodankyla (26°E) on 1200 GMT 29 January 1992. (b) Similar cross-section at the longitude of Nyalesund (11°E). The tracer-poor filaments responsible for the depleted laminae at these two stations are designated by crosses. (c) Height/longitude cross-section at the latitude of 60°N, between 90 and 180°E. Height is measured by potential temperature (K).
are separated by two interleaved tongues of mid-latitude air, which are thinning upwards.
By comparing with contour-advection calculations on the 450 K isentrope, P94 showed
that the two aerosol-rich tongues seen at that level are a consequence of the flight track
twice intersecting a filamentary intrusion of mid-latitude air into the polar vortex. Such an
intrusion is also produced by our model, and the whole vertical structure of these aerosol
tongues observed in the 14 to 20 km layer is well reproduced (Fig. 7(b)). In particular,
the vertical tilt of the model tracer sheets agrees well with the one seen in aerosol data.
P94 also showed that, along the last leg of the flight, a process of filamentary mixing
was occurring at the vortex edge in their contour advection model (see plate 3 of P94).
The aerosol data do show a tongue of aerosol-poor air sloping equatorward with height,
between 15.5 and 18.5 km, and centred near sounding 300 (Fig. 7(a)). The equatorward
slope of the feature was, however, not captured by their model. Our model produces only
a weak tracer-rich tongue of polar air extending downwards to the 445 K level (soundings
280-300 in Fig. 7(b)), and sloping equatorward with height.

Hence, ozone-rich sheets sloping with height, and similar to the ones produced by our
model are likely to have been present on 24 January near the vortex boundary, although
there may not be ozone observations to trace them.

4. Sensitivity studies

Several other simulations were carried out to test the robustness of filaments and
laminae formation. The dependence upon the choice of the initial date was tested in two
simulations which started five days earlier and later than 16 January. Sensitivity to horizontal resolution of the wind data was examined in another paper (Orsolini et al. 1995b). Simulations performed with the wind fields spectrally truncated to coarser resolutions gave nearly identical results. The model tracer distribution at the initial date does not contain filamentary structures, whereas such structures are likely to be present in the real atmosphere. In the model, the tracer variance is transferred to smaller scales as existing filaments are thinning and breaking down to scales where the model numerical diffusion becomes active. At the same time, the wind shears tend to create new filaments. The cascading process is not likely to be uniform in time as, for example, the creation of ozone-poor filaments by vortex intrusions will depend on how distorted the vortex is, hence the need for sensitivity studies. Tracer distributions on the 475 K isentrope for 1200 GMT 29 January 1992, are shown in Fig. 8 for the simulation starting on 21 January. The main filaments found in Fig. 3 at 475 K can again be traced, although small changes in secondary structures or in locations of filaments are evident. This has an influence on tracer profiles. The resemblance between Fig. 3 and Fig. 8 tends to show that the inner vortex ozone-poor filaments were formed by the strong vortex disruption which takes place after 21 January (P94).
Plumb and Waugh (1994) and P94 showed that the filamentation process was largely independent of the wind-data source in the northern hemisphere. They made comparisons using winds from both the National Meteorological Center and ECMWF analyses, and from the assimilated STRATAN data of the National Aeronautics and Space Administration, Goddard. They also showed in a short 5-day simulation that, when winds were derived from model forecasts rather than meteorological analyses, the filaments were less deformed. Yet another simulation was run with forecast winds, and indeed it was found that the filaments were indeed smoother. In the simulation using forecast winds, the winds were constructed from 6-hourly forecasts for 48-hour periods. Several sets of such 48-hour forecasts were put together to cover the last two weeks of January 1992. Figure 9 shows the tracer distribution for 1200 GMT 29 January 1992, for a simulation using such forecast winds, and starting on 21 January. Again the major filaments and intrusions found in Fig. 3 can be traced to Fig. 9, but again there are differences in the details. Wind data from forecasts and analyses have both been shown to give rise to tracer filamentation (Plumb and Waugh 1994). Similarly, tracer lamination is generated both by forecast and by analysis winds: a profile taken at Sodankyla is shown in Fig. 10 for a forecast simulation started on 21 January as well as for several simulations performed with wind fields derived from analyses.

5. DISCUSSION

These modelling results confirm the link between ozone laminae and differential advection proposed by Reid and collaborators (1991, 1993, 1994). The source of high-level (i.e. up to near 500 K) laminae activity during late January 1992 is the disruption of the lower stratosphere polar vortex. In the model, depleted laminae at high latitudes are signatures of vortex intrusions from the mid latitudes, which are advected along by the mostly cyclonic vortical flow.

If these laminae are indeed a signature of exchange across the vortex, then further statistical studies on laminae occurrences could provide some indication on the vertical extent of the region of cross-vortex mixing. During the northern hemisphere winter, laminae in ozone partial pressures occur up to at least 450 K, and in the case of January 1992 laminae were found as high as 500 K. General-circulation model studies of the late January 1992 vortex-ridging event also showed ridges extending high into the stratosphere (Norton and Carver 1994; Orsolini et al. 1995a).

Gravity waves are a well known mechanism for generating coherent fluctuations in temperature and ozone with a vertical scale of a few kilometres. Teitelbaum et al. (1994) detected gravity waves from the analysis of ozone and temperature profiles during the winter of the EASOE campaign. Many laminae in the observed ozone profiles encountered in this study are very localized on the vertical, and of large magnitude, hence their generation by gravity waves is unlikely. Nevertheless, a small-amplitude gravity-wave signature may be present in some soundings. It is possible moreover that turbulent vertical mixing induced by breaking gravity waves does affect the lower range of lamina thicknesses.

The current model is able to resolve the dominant thickness of laminae, which was shown by Reid and Vaughan (1991) to be between 1 and 1.5 km. Moreover, the dipolar nature of some laminae is reproduced, arising from the occurrence of a depleted lamina with an enhanced lamina underneath. Such a pattern can appear at the vortex edge, owing to vertical shearing of interleaved sheets, alternatingly ozone-poor and ozone-rich (see, for example, a profile through the cross-sections of Fig. 5(a) near 65°N, in Fig. 5(b) in the latitude band of 65–75°N, or also in Fig. 5(c) at longitudes 105–135°E). Analogous
patterns also appear in the model profiles taken over northern Europe outside of the vortex (e.g. Gardemoen) and, in this case, one has a thin enhanced lamina near 400 K.

In agreement with Reid et al. (1993), the present modelling results indicate that laminae can extend several hundreds or even thousands of kilometres away from the vortex edge in the form of extrusions. Hence they involve motions on horizontal scales much longer than gravity waves. The high-resolution transport model demonstrates the filamentary nature of such extrusions, as did the contour-advective model of Waugh et al. (1994). The present modelling study implies that lamination of tracers is produced by a smooth, coarsely resolved vertical shear. The exact role of fine-scale vertical variations in the winds needs to be further elucidated.

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OZONE LAMINAE FORMATION


