Tracer lamination in the stratosphere: A global climatology

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Abstract. Vertical soundings of stratospheric ozone often exhibit laminated tracer structures characterized by strong vertical tracer gradients. The change in time of these gradients is used to define a tracer lamination rate. It is shown that this quantity can be calculated by the cross product of the horizontal temperature and horizontal tracer gradients. A climatology based on UARS satellite-borne ozone data and on ozone-like pseudotracer data is presented. Three stratospheric regions with high lamination rates were found: the part of the stratospheric overworld which is influenced by the polar vortex, the part of the lowermost stratosphere which is influenced by the tropopause and a third region in the subtropical lower stratosphere mainly characterized with strong vertical shear. High lamination rates in the stratospheric overworld were absent during summer, whereas in the lowermost stratosphere high lamination rates were found year-round. This is consistent with the occurrence and seasonal variation of the horizontal tracer gradient and vertical shear necessary for tilting the tracer surfaces. During winter, high lamination rates associated with the stratospheric polar vortex are present down to ~100 hPa. Several features of the derived climatology are roughly consistent with earlier balloon-borne studies. The patterns in the southern and northern hemisphere are comparable, but details differ as anticipated from a less disturbed and more symmetric southern polar vortex.

1. Introduction

The instantaneous distribution of a trace constituent in the atmosphere depends not only on its chemical sources and sinks but also on its redistribution due to transport induced by various dynamical processes. Large-scale advection such as vortex erosion and wave-breaking [e.g., McIntyre and Palmer, 1984; Juckes and McIntyre, 1987; Hess and Holton, 1985; Hess, 1990; Bowman, 1993; Bowman and Manges, 1993; Waugh et al., 1994] together with differential vertical shear [e.g., Murphy et al., 1989; Reid and Vaughan, 1991; Orsolini, 1995] provide the potential for folding and tilting of tracer surfaces that lead to filament-like tracer structures in the stratosphere. Concerns about ozone depletion within the polar vortex, and subsequent mixing of ozone depleted air into lower latitudes, have triggered much interest in these processes [World Meteorological Organization (WMO), 1986] since the induced horizontal and vertical scale reduction implies the mixing of air masses from substantially different origins, both in a dynamical and chemical context [e.g., Murphy et al., 1989; Pierse and Fairlie, 1993; Waugh et al., 1994; Plumb et al., 1994; Chen, 1994; Haynes and Angland, 1997].

In a vertical sounding, tracer filaments can appear as layers of enhanced or depleted concentration referred to as laminated tracer structure. Ozone laminae of varying depth and magnitude have been observed since balloon soundings were available [e.g., Dobson, 1973; Gardiner, 1988; Reid and Vaughan, 1991] and have also been found in lidar observations [Reid et al., 1993; Newman et al., 1996; Orsolini et al., 1997] and airborne in situ measurements [Murphy et al., 1989].

The distribution of laminae is highly variable both in space and time. Due to the lack of global stratospheric ozone measurements, only a limited number of climatological studies have been performed. Amplitudes of the local variations of the ozone mixing ratio typically show a peak in the mid stratosphere around 10 hPa [U.S. Standard Atmosphere, 1976; also Andrews et al., 1987] and a seasonal variation with a maximum in midwinter and a minimum in midsummer [Roeth and Ehnhall, 1987]. A particular class of laminae characterized by an anomaly in ozone partial pressure [Dobson, 1973; Reid and Vaughan, 1991; Reid et al., 1993] has been observed to occur most commonly in winter and spring at high latitude and with a peak altitude of occurrence around 14 to 16 km. In the summer season such strong ozone laminae were absent. The preferred occurrence near the winter polar vortex suggests that the likely cause of ozone laminae is differential advection of air masses of different origin which are interleaved in the vertical.

The above mentioned climatological studies are based on routinely performed balloon-borne ozone soundings using either a long time series for a single station or a pseudo-meridional cross section based on 13 sounding stations in the northern hemisphere and 5 in the southern hemisphere [Reid and Vaughan, 1991]. The recently available satellite-borne ozone measurements provide a much higher global coverage; however, these data have not yet been widely used to address the issue of tracer lamination. Satellite data typically have poor vertical resolution compared to balloon soundings. Fortunately, recently developed contour advection techniques provide a powerful tool to dramatically increase the effective vertical and horizontal data resolution [e.g., Waugh and...
Figure 1. Schematic diagram illustrating the flow situation leading to high lamination rates.

2. Theory of Production of Vertical Tracer Gradients

In Figure 1 the time development of a tracer lamina is schematically illustrated. The hypothetical tracer is assumed to have a horizontal distribution with a strong but localized tracer gradient near $x = 0$ and two different constant tracer concentrations outside this region. For such a distribution the surfaces (s) with constant tracer mixing ratio ($\chi$) are completely vertically oriented (Figure 1b) and a balloon sounding at any point in $x$ would show a constant tracer concentration (Figure 1d). Now assume that a vertical shear that is varying with height is acting on this tracer distribution (Figure 1a). After a certain time $t$ the tracer surfaces will be tilted away from their initial positions, thereby creating vertical tracer gradients of positive and negative signs (Figure 1c). In a balloon sounding near $x = 0$, the tilted tracer surfaces now appear as a tracer filament (Figure 1e). The strongest filament occurs in conjunction with the strongest horizontal tracer gradients. In essence, differential vertical shear that is not aligned with the tracer surfaces converts horizontal tracer gradients into vertical ones.

To quantify this mechanism, consider the conservation equation of a long-lived tracer with a volume mixing ratio ($\chi$):
Here a log pressure coordinate system as in Andrews et al. [1987] was used and
\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}
\]
represents the material derivative. \( S \) is the net source term and is assumed to be zero. Taking the vertical derivative of equation (1), the material rate of change of the vertical tracer gradient can be expressed as
\[
\frac{D}{Dt} \left( \frac{\partial \chi}{\partial z} \right) = - \frac{\partial u}{\partial x} \frac{\partial \chi}{\partial x} - \frac{\partial v}{\partial y} \frac{\partial \chi}{\partial y} - \frac{\partial w}{\partial z} \frac{\partial \chi}{\partial z}
\]
Using the geostrophic assumption the vertical shear is directly linked with the horizontal temperature gradient, i.e.,
\[
\left( \frac{\partial u}{\partial x}, \frac{\partial v}{\partial y} \right) = \left( - \frac{R}{H f} \frac{\partial T}{\partial y}, \frac{R}{H f} \frac{\partial T}{\partial x} \right)
\]
\( H \) represents the scale height, \( f \) the Coriolis parameter and \( R \) the gas constant. Equation (2) can therefore be rewritten as
\[
\frac{D}{Dt} \left( \frac{\partial \chi}{\partial z} \right) = - \frac{R}{H f} \left[ \frac{\partial T}{\partial y} \frac{\partial \chi}{\partial y} - \frac{\partial T}{\partial x} \frac{\partial \chi}{\partial x} \right] - \frac{\partial w}{\partial z} \frac{\partial \chi}{\partial z}
\]
Since large-scale motions are quasi nondivergent, scaling suggests that the last term in equation (4) can be neglected compared to the term in the brackets and equation (4) simplifies to
\[
\frac{D}{Dt} \left( \frac{\partial \chi}{\partial z} \right) \equiv - \frac{R}{H f} \left[ \nabla T \times \nabla \chi \right]
\]
The magnitude of the cross product of the horizontal gradients \( (\nabla T, \nabla \chi) \) is therefore a measure of the production of vertical tracer gradients following the motion. The absolute value of this production rate will be referred to as the tracer lamination rate \( \mathcal{L} \):
\[
\mathcal{L} = \left| \frac{D}{Dt} \left( \frac{\partial \chi}{\partial z} \right) \right| \equiv \frac{R}{H f} \left| \nabla T \times \nabla \chi \right|
\]
The three-dimensional distribution of \( \mathcal{L} \) can be calculated from isobaric temperature and tracer distributions. This is particularly useful for satellite-measured tracer data since these data have a comparatively low vertical resolution. For the analyses shown below, equation (6) was evaluated using spherical coordinates.

In the winter stratosphere near the edge of the polar vortex, typical horizontal temperature gradients are \( \nabla T \approx 20 \times 10^{-6} \ K \ m^{-1} \) and typical ozone gradients are \( \nabla \chi \approx 1.5 \times 10^{-6} \ ppmv m^{-1} \). For a hypothetical flow situation where the vertical shear is acting perpendicular to the tracer surfaces these values would result in lamination rates up to \( \mathcal{L} = 10 \times 10^{-9} \ ppmv \ m^{-1} \) (with \( R/H f = 400 \ J K^{-1} kg^{-1} m^{-1} \)). Or equivalently, to produce a hypothetical lamina with a relative amplitude of \( 0.5 \ ppmv \) and a vertical depth of \( 2 \ km \) about half a day would be needed.

3. Data

3.1. MLS Ozone and Temperature Data

The microwave limb sounder (MLS) from the Upper Atmosphere Research Satellite (UARS) provides stratospheric ozone and temperature measurements that can be used to construct daily global isobaric ozone charts (for more details about the MLS data see, e.g., the special issue dealing with UARS result in Geophysical Research Letters, 20, (12), 1993). In this study MLS Level 3b data were used and the 13 Fourier components were gridded onto a coarse longitude latitude grid (with a latitudinal coverage between 80°S and 80°N and a horizontal resolution of 2 ° longitude and 4 ° latitude). In the vertical (i.e., between 100 and 1 hPa) the data have been interpolated onto UARS standard pressure levels. For the mid to upper stratosphere the data are of high accuracy [Froidevaux et al., 1996] but the data quality decreases for pressure greater than \( -50 \ hPa \). Therefore in the lowest stratosphere the ozone data should not be used for any physical interpretation. The 3 year averages shown below were constructed using all available data in the period from November 1991 to October 1994.

3.2. Pseudotracer Potential Vorticity

The second data set used is a pseudotracer based on the atmosphere's potential vorticity (PV) structure. Since on synoptic timescales both PV and ozone are roughly conserved quantities following an air parcel and both tracers have a comparatively
strong meridional gradient, it can be anticipated that there
exists a strong similarity in the pattern of their horizontal
distribution. Strong horizontal gradients in both tracers can
in particular be anticipated near the polar vortex edge and the
tropopause. Unlike ozone, Ertel’s PV as conventionally defined
increases exponentially with height. Scaling of the Ertel PV as
suggested by Lait [1994],

\[ MPV = PV \left( \frac{\theta}{\Theta_0} \right)^{-9/2} \]  

allows for a vertical PV profile more comparable to that of
ozone (Figure 2) without losing the fundamental conserva-
tion properties [Ertel, 1942]. The modified potential vortici-
ty (MPV) was calculated from daily (00 GMT) global stratospheric analyses prepared by the United Kingdom
Meteorological Office (UKMO) [Swinbank and O’Neill, 1994].
Horizontal winds, geopotential heights, and temperature data
were used with a horizontal resolution of 2.5° latitude by 3.75°
longitude. In the vertical, UARS standard pressure levels were
used corresponding to a resolution of roughly 2.5 km ranging
from \( \sim 1000 \) hPa to 1 hPa. The pseudotracer is displayed
in standard PV units with 1 \( \text{pvu} = 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1} \).
Pseudotracer lamination rates were not calculated at the two
lowest pressure levels (i.e., 1000 and 681 hPa) as well as near
the equator (i.e., between -10 and 10 latitude) and at the poles.
It is important to keep in mind that these data represent a
blend of sparsely available operational stratospheric observa-
tions with the model’s own 6 hour forecast. Some of the
small-scale PV features might therefore be artificially

generated by the analysis procedure.

4. Results

4.1. Maps

Plate 1a shows an example of the northern hemisphere
stratospheric polar vortex at 10 hPa as seen by the MLS
measurements. Ozone (black curves) and temperature (color)
are shown. The temperature distribution was dominated by a
wave number 2 pattern with cold temperatures over the Atlantic
and warm ones over Siberia providing several regions with
strong temperature gradients. The ozone pattern revealed that
the polar vortex was shifted toward northern Europe and was
characterized by relative low ozone concentrations compared
to more southern latitudes. Relatively strong ozone gradients
were found at the edge of the polar vortex and also at
midlatitudes stretched across the Atlantic to the Pacific. As
anticipated, the overall horizontal pattern of the pseudotracer
MPV truncated to the low MLS resolution (Plate 2a) closely
resembled the observed ozone distribution (Plate 1a). Note the
opposite sign in meridional gradient.

In Plates 1b and 2b the corresponding tracer lamination
rates (equation (6)) are shown. Three regions with high lami-
nation rates were found for both tracers, all of which are linked
to the edge of the vortex: one over Europe, one over Siberia
and a third over northern Canada. In these regions the ozone
(pseudotracer MPV) gradients were relatively strong and not
parallel to the temperature gradients as anticipated. Over the
midlatitude Atlantic and the Pacific, the lamination rates were
substantially lower despite relatively strong ozone (MPV)
gradients.

The same calculations are shown in Plate 3, but using the
pseudotracer with full UKMO data resolution. The higher-
resolution data set leads to a much finer-scaled and more
localized tracer lamination field. Spots with high values
occurred again in the three regions mentioned above and were
in conjunction with strong pseudotracer gradients. Other
small-scale features like the one over eastern Siberia (160° E,
60° N) lead also to enhanced production rates. These pseudo-
tracer lamination rates were typically a factor 3/2 higher than
for the low-resolution data and a factor 10 higher compared to
low-resolution ozone. A second illustrative example in the
lower stratosphere (~100 hPa) is given in Plate 4. A tongue of
high pseudotracer values extends southwestward from the
polar vortex stretching across Eurasia into a region with high
temperature. Enhanced absolute values of tracer lamination
rates occurred on both sides of the streamer, indicating that the
vertical tracer gradients would increase on the southern and
decrease on the northern side.

4.2. Vertical Profiles

Two vertical MLS ozone soundings taken within the region
of high lamination rates over Europe (Plate 1b) are shown in
Figure 3. The vertical profiles above 10 hPa showed stronger
vertical gradients compared to a 3 year monthly mean taken at
the same grid points. This is consistent with the enhanced
lamination rates shown above. Due to the poor horizontal
and vertical resolution of the satellite data (i.e., roughly one
measurement every 5 km in the vertical) the soundings can
only resolve comparatively large-scale tracer structures and
any smaller-scale laminae-like features are not resolved.

4.3. Proxy Climatology

In order to construct a global and seasonal climatology the
tracer lamination rates were calculated for each day that tracer
data were available (between November 1991 and October
1994). Subsequently the values were grouped into two main
categories (see Table 1), group 1 containing no to weak
lamination rates, group 2 moderate to strong lamination rates.
A third group (group 3) was introduced to have some control
over extremely high values. The combined group 2 and 3 will
simply be referred to as high lamination rates. The results are
given in the form of averaged probability charts (ranging from
0 to 1) to observe a particular group of lamination rates. Note
that the longitude-latitude grid used is not equidistant in kilo-
meters. The threshold values were chosen subjectively based
on inspection of daily charts (compare with Plates 1 to 3) and
were kept as simple as possible. Moderately changing the
threshold value did not change the overall conclusion given
below.

Meridional cross sections of monthly averaged charts of the
probability to observe high (combined group 2 and 3) lamina-
tion rates are shown for low-resolution MLS ozone (Figure 4)
in the altitude range 100 to 1 hPa and for the high-resolution
pseudotracer MPV (Figure 5) in the altitude range 1000 to
1 hPa. The data represent a 3 year average for the time periods
January-February (Figures 4a and 5a) and July-August (Figures
4b and 5b).

In the stratospheric overworld a clear difference between
winter and summer season was found. In the winter season at
midlatitudes and high latitudes high lamination rates occurred
in both the MLS ozone (~20 to 30% of all the cases) and in
pseudotracer MPV (~30 to 40% of all the cases). In the summer
season, even moderate production rates were absent. The
pattern further suggests a slight asymmetry between the two
Plate 1. (a) Northern hemisphere ozone and temperature distribution as seen by MLS at 10 hPa on March 18, 1992. Ozone volume mixing ratio is given by black curves (black dotted curves below 8 ppmv, interval 0.5 ppmv) and temperature is given in color (contour interval 2.5 K). The area shown is northward of 20°N. (b) Same as Plate 1a, but calculated ozone lamination rates (colored, values given in units of $10^{-9}$ ppmv m$^{-1}$s$^{-1}$, contour interval $0.4 \times 10^{-9}$ ppmv m$^{-1}$s$^{-1}$) and ozone volume mixing ratio overlaid (contours as in Plate 1a).
Plate 2. (a) Same as Plate 1 but for pseudotracer MPV based on truncated UKMO potential vorticity structures. MPV is given by black curves (dotted curves below 10 pvu, interval 2 pvu) and temperature in color (contour interval 2.5 K). (b) Same as Plate 2a, but pseudotracer lamination rates based on truncated data (colored, values given in units of $10^{-9} \text{ pvu m}^{-1} \text{s}^{-1}$, contour interval $2.5 \times 10^{-9} \text{ ppmv m}^{-1} \text{s}^{-1}$) and pseudotracer MPV overlaid (contours as in Plate 2a).
hemispheres. In the northern hemisphere the number of events increases with latitude, whereas in the southern hemisphere the region where high production rates occur seems to be more localized around a maximum at -60° south.

The analyses based on the pseudotracer (Figure 5) suggest two other regions in the atmosphere where high lamination rates occur, the lowermost stratosphere and the subtropical lower stratosphere (in both these regions no reliable MLS ozone data were available). In the midlatitudes, high values typically occurred between 400 and 200 hPa, whereas in the subtropical region the maximum is located between ~120 hPa and 60 hPa. In contrast to the variation in the stratospheric overworld the high lamination rates in the lowermost stratosphere were also present in the summer months.
The complete seasonal variation of the probability of observing high lamination rates is shown in latitude time sections in Figure 6 (for MLS ozone) and Figure 7 (for the pseudotracer MPV). For better display the seasonal cycle is shown twice. The data have been vertically averaged in three subregions of the stratosphere.

In the stratospheric overworld (Figures 6 and 7a), high lamination rates for both tracers occurred during the winter half-year and mainly poleward of 30°. For the southern hemisphere the time period was longer than for the northern hemisphere, consistent with the longer southern hemisphere winter. The period with high lamination rates was slightly longer in MLS ozone than for the pseudotracer data. In the northern hemisphere the highest probability was again found

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>No.</th>
<th>£ MLS Ozone</th>
<th>£ Pseudotracer MPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak lamination</td>
<td>no to weak</td>
<td>1</td>
<td>£ &lt; 1 × 10^{-9}</td>
<td>£ &lt; 10 × 10^{-9}</td>
</tr>
<tr>
<td>Strong lamination</td>
<td>moderate to strong</td>
<td>2</td>
<td>£ &gt; 10 × 10^{-9}</td>
<td>£ &lt; 30 × 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>extremely strong</td>
<td>3</td>
<td>£ &gt; 30 × 10^{-9}</td>
<td>£ &gt; 30 × 10^{-9}</td>
</tr>
</tbody>
</table>

Units of £ are parts per million by volume for ozone and potential vorticity units per meter per second for pseudotracer MPV.
Figure 5. Same as Figure 4 but for the probability of finding high pseudotracer lamination. Data are based on UKMO analyses. Vertical axis ranges from 1000 to 1 hPa. Data below 650 hPa and near equator are omitted. Contour interval is 0.025.

at high latitudes, whereas in the southern hemisphere the maximum occurs again around 60°S (midwinter) and moved poleward during the spring season. Such a distribution is consistent with a less disturbed and more symmetric southern hemisphere polar vortex.

In the lowermost stratosphere (Figure 7b), high pseudotracer lamination rates were present throughout the year, but with substantially less probability and less horizontal extent during the summer season. The seasonal variation of the latitudinal coverage is consistent with the seasonal variation of the tropopause position [Appenzeller et al., 1996b]. In both hemispheres during the winter season a maximum occurred around +/-30° to +/-40° latitude near the subtropical tropopause break. It is interesting to note that Dobson [1973] suggested this to be the region where ozone poor air is entering the stratosphere.

Similar features can be observed at 100 hPa (Figure 7c), but at higher latitudes the lamination rates showed a more pronounced seasonal cycle. In the northern hemisphere, high tracer lamination rates occurred only from January to mid-May and were completely absent from late spring to fall. A comparable seasonal cycle was found in earlier balloon studies [Reid and Vaughan, 1991] that examined the frequency of partial pressure laminae at the same altitude. These high lamination rates are associated with the lower edge of the stratospheric polar vortex. In the southern hemisphere the corresponding high probability region was observed below 100 hPa, i.e., clearly in the lowermost stratosphere (Figure 7b). At 100 hPa the location of the maximum moved again poleward during the transition from winter to spring. In the northern hemisphere only a very weak indication of such a pattern could be found.

Finally, we note that extremely high lamination rates for both ozone and pseudotracer (characterized by the extra group 3 in Table 1) were only found in the stratospheric overworld (not shown separately). They occur in the 3 winter months pole-
Figure 6. Seasonal variation of the probability of finding high ozone lamination rates in the stratospheric overworld. Data as in Figure 4, but a zonal and vertical (between 68 and 1 hPa) average. For display purposes the 3 year average is shown twice. Contour interval is 0.025.

Figure 7. Same as Figure 6, but seasonal variation of the probability of observing high pseudotracer lamination rates. Data as in Figure 6. (a) Probability vertically averaged in the stratospheric overworld (between 68 and 1 hPa). (b) Probability vertically averaged in the lowermost stratosphere (between 316 and 146 hPa). (c) Probability at 100 hPa. Contour interval is 0.025.
ward of ~60°N and in the southern hemisphere around 60°S. The maximum probability of observing a class 3 lamination rate was ~10-15% in the northern and ~5-10% in the southern hemisphere. At 100 hPa and in the lowermost stratosphere their contribution was negligible.

5. Discussion

Several features of the derived climatology are consistent with earlier studies based on balloon ozone soundings. These features include the preferred occurrence of filaments near the edge of the polar vortex [Reid and Vaughan, 1991; Reid et al., 1993, 1994], the preferred occurrence near the subtropical and midlatitude tropopause [Dobson, 1973], an increase in tracer variability in the mid stratosphere [Roeth and Ehhalt, 1987; U.S. Standard Atmosphere, 1976], a strong seasonal cycle with weak variability in the summer season [Dobson, 1973; Reid and Vaughan, 1991; Roeth and Ehhalt, 1987], and a shift of the maximum of occurrence toward the pole during the transition from winter to spring [Reid et al., 1993]. Other features found by the balloon studies, such as the absence of laminae in the mid to upper stratosphere and in the subtropical lower
stratosphere [Dobson, 1973; Reid and Vaughan, 1991], as well as the occurrence of laminae at high latitudes well into early June, are not found in the derived climatology. Part of this difference is due to the different laminae concept applied (see below).

Most of the distribution of high lamination rates can be understood in terms of the occurrence of both strong horizontal tracer gradients and the dynamical activity providing the vertical shear for tilting the tracer surfaces. Figure 8a shows a latitude-height section of the zonally averaged magnitude of horizontal pseudotracer gradients. As anticipated, regions with high averaged horizontal tracer gradients such as the tropopause region and the polar vortex region coincide roughly with regions characterized by high lamination rates (Figure 5). Regions with strong zonally averaged magnitude in vertical shear are shown in Figure 8b (following equation (3), the shear is represented by the horizontal temperature gradient). High shear values also exist in regions with low lamination rates. An example is the subtropical lower stratosphere where strong vertical shears are present in both hemispheres but high pseudotracer lamination rates were only found in the northern (winter) hemisphere.

The summer middle stratosphere is not only characterized by weak pseudotracer gradients but also by weak vertical shear. The latter is consistent with the seasonal variation in wave activity in the stratospheric overworld that is strongly determined by whether the stratospheric flow allows upward propagation of synoptic scale tropospheric wave sources. Linear wave theory [Charney and Drazin, 1961; Andrews et al., 1987] indicates that upward propagation of Rossby waves is inhibited in easterly winds. Figure 9 shows the seasonal variation of the probability of observing a west wind (i.e., allowing upward propagation) in the stratospheric overworld. Regions with probability higher than 80% are shaded. The
tracer gradient by the large-scale vertical shear. The balloon ozone seasonal cycle.

gradients, since vertical shear is present throughout the year. stratosphere the occurrence of strong tracer lamination rates is vortex. consistent with the less disturbed southern hemisphere's polar

pressure), a laminae climatology based on a fixed partial laminae frequency found in the subtropical lower stratosphere, found in the stratospheric overworld. The same is true for the volume mixing ratio of ozone and decreases exponentially with height (i.e., \( p_{03} = p \cdot v_0 \)).

pressure anomalies are difficult to detect.

The observed climatology in the lower and lowermost stratosphere relies solely on the pseudotracer MPV. MLS ozone data could not be used to verify the existence of laminated ozone structures below the 50 hPa surface. The pseudotracer has a somewhat better resolution than MLS ozone, but its distribution has only an approximate relation with that of ozone. For example, its maximum occurs at a lower altitude than the ozone maximum, and it decays faster in the upper stratosphere than does ozone (see Figure 2). However, according to equation (6) the tracer lamination rates are proportional to the absolute value of the horizontal tracer gradients and not to the value of the tracer concentration itself. For the tropopause region both tracers are characterized by comparatively strong gradients [e.g., WMO, 1986], whereas for the region in the subtropical lower stratosphere only a little information is available that supports the existence of strong horizontal ozone gradients [Duetsch, 1978; Fahey et al., 1996]. Finally, note that the occurrence of high lamination rates within the winter polar stratospheric vortex might be overestimated by small-scale structures artificially generated by the analysis scheme. Ozone data with better horizontal resolution covering the entire stratosphere would substantially improve the quality of this analysis.

6. Conclusion

Vertical soundings of stratospheric ozone often exhibit laminated tracer structures characterized by strong vertical gradients in mixing ratio. These laminae indicate the possible mixing of air masses of dynamically and chemically substantially different origin. Examples are the potential mass transport across the relatively isolated stratospheric polar vortex [e.g., Murphy et al., 1989; Waugh et al., 1994; Chen et al., 1994] or across the extratropical tropopause [e.g., Holton et al., 1995]. Both of these mixing processes substantially influence the atmosphere's ozone distribution and chemistry. Dynamically induced variations in stratospheric tracer concentration are also important for data assimilation purposes. Since most of the laminae are at or below the current model resolution, tracer assimilation in regions and seasons with high tracer lamination may prove to be an extremely difficult task.

The aim of this study was to provide a global and seasonal climatology of laminated ozone-like tracer structures in the stratosphere. Using the geostrophic assumption it was shown that production rates of vertical tracer gradients can be calculated by the cross product of the isobaric temperature and tracer gradients. This method permits calculation of tracer lamination rates based on satellite data with relatively low vertical resolution. The climatology presented was based on grouping lamination rates calculated from daily three-dimensional data sets rather than counting explicitly observed tracer laminae as in earlier studies. A high tracer lamination rate was taken as a proxy for the production of a laminated tracer structure. Two tracer data sets have been used, UARS satellite-borne low-resolution ozone measurements and higher-resolution ozone-like pseudotracer data based on modified potential vorticity. The ozone data were only available in the stratospheric overworld; the pseudotracer covered the entire stratosphere and was calculated from UKMO assimilated analyses. Comparisons of

Figure 9. Seasonal variation of the probability of observing a west wind in the stratospheric overworld (averaged between 68 and 1 hPa). Regions with probabilities higher than 0.8 are solid shading, probability 0.6 is shown by solid lines, and probabilities less than 0.6 are dashed lines at 0.2 interval.
Acknowledgments. This research was supported by the National Aeronautics and Space Administration (NASA), grants NAG 5-3188 (UARS) and NAG 1-1803.

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(Received August 16, 1996; revised October 23, 1996; accepted December 6, 1996.)