Interannual variability of ozone in the winter lower stratosphere and the relationship to lamina and irreversible transport

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[1] We use the high-resolution dynamic limb sounder (HIRDLS) high-vertical resolution ozone profiles in the northern hemisphere lower stratosphere to examine the meridional transport out of the tropics. We focus on February 2005–2007 when there are differences in the dynamical background in the lower stratosphere due to the states of the quasi-biennial oscillation and polar vortex. HIRDLS data reveal a large number of low ozone laminae that have the characteristics of tropical air at midlatitudes. More laminae are observed in February in 2006 than in 2005 or 2007. Because laminae can form, move out of the tropics, and return to the tropics without mixing into the midlatitude ozone field, the number of laminae is not directly related to the net transport. We use equivalent latitude coordinates to discriminate between reversible and irreversible laminar transport. The equivalent latitude analysis shows greater irreversible transport between the tropics and lower midlatitudes in both 2005 and 2007 compared to 2006 despite the higher number of laminae observed in 2006. Our conclusion that there was more irreversible transport of tropical air into the lower midlatitudes in 2005 and 2007 is supported by equivalent length analysis of mixing using microwave limb sounder N_2O measurements. This study shows that reversibility must be considered in order to infer the importance of lamination to net transport.

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1. Introduction

[2] Understanding the variability of ozone in the lower extratropical stratosphere is important for evaluating midlatitude ozone trends, attribution to changes in composition, and the development of reliable models for prediction. Two processes contribute to this variability. The first is the descent of ozone from the upper stratosphere into the lower stratosphere where ozone chemical lifetimes are long. Vertical propagation and dissipation of planetary waves that are linked to stratospheric warmings and the phase of the quasi-biennial oscillation (QBO) control the seasonal variation in the ozone descent rate. The second process is the direct eddy transport of low ozone air out of the tropics into the midlatitude stratosphere. Mass continuity assures that there must be some outflow from the tropics into the extratropical lower stratosphere since the mean vertical velocity does not increase with height as rapidly as the atmospheric density decreases, as confirmed by the vertical propagation of the tropical tape recorder signal [e.g., *Mote et al.*, 1996; *Schoeberl et al.*, 2008]. The phase of the QBO and state of the polar vortex are also associated with tropical outflow and mixing [e.g., *Shuckburgh et al.*, 2001; *Waugh*, 1993]. *Randel and Wu* [2007] show a strong correlation between the QBO and midlatitude lower stratospheric ozone. Modulation of the tropical outflow or the large-scale descent or both could produce this link.

[3] Low ozone laminae are created in the lower stratosphere as wave propagation and differential advection shear zones of tropical air into the higher background ozone of the middle latitudes. *Dobson* [1973] first identified these thin layers of ozone minima in the middle latitude, upper troposphere/lower stratosphere as signatures of poleward isentropic transport from the tropics. Studies of ozonesonde records indicate that lamination occurs most frequently during winter or spring around 14 to 15 km altitude [*Dobson*, 1973; *Reid and Vaughan*, 1991; *Hwang et al.*, 2007]. *Reid and Vaughan* [1991] examined multiyear ozonesonde records from 20 stations and found large interannual variability in the number of observed laminae.

[4] Theoretical studies have demonstrated that the formation and propagation of laminae is one of the principal means of meridional transport into the extratropical lower

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stratosphere [e.g., *Waugh*, 1996]. Contour advection calculations show laminae extending up to the middle stratosphere and the area of mass transported out of the tropics by filaments on the 425 K and 500 K potential temperature surfaces is greatest in the winter and least in the summer [*Waugh*, 1996]. The rate of lamination has also been used to evaluate simulations of meridional transport. *Weaver et al.* [2000] compared observed and simulated lamination rates to show that there was excessive tropical-extratropical transport by laminae in a chemistry and transport model (CTM) simulation driven by meteorological fields from an early version of an assimilation system. Relating vertical laminae to horizontal "streamers," *Eyring et al.* [2003] used a CTM simulation driven by 9 years of meteorological analyses to determine a streamer climatology between 21 and 25 km intended for the evaluation of chemistry-climate models. The streamers were identified by a reversal of the meridional gradient of N_2O and were found to be most prevalent during the winter.

[5] The relation of the laminae to the lower stratospheric mean ozone budget is not obvious. On interannual time scales, it is plausible to infer that observing a relatively large number of low ozone laminae in the middle latitude lower stratosphere indicates greater poleward transport, reducing the seasonal mean ozone mixing ratio, and vice versa. However, prior case studies using models to investigate the time evolution of observed tropical intrusion laminae demonstrate varying degrees of mixing of the intrusion with extratropical air, and some show much of the intrusion returning to lower latitudes and reconnecting with the tropics [e.g., *Vaughan and Timmis*, 1998; *Kouker et al.*, 1999; *Olsen et al.*, 2008]. We hypothesize that the importance of the laminae to the lower stratospheric ozone budget is modulated by the reversibility of the transport events. For example, a lamina might form, move away from the tropics, and then return to the tropics without mixing into the background flow. In this case the laminar transport is reversible. Highly reversible events will have little or no impact on the ozone budget. We postulate that both the lamina frequency and reversibility must be considered in evaluating their contribution to the ozone budget and variability in the lower stratosphere.

[6] Observations from the high-resolution dynamics limb sounder (HIRDLS) on NASA's Aura provide a unique opportunity to investigate meridional transport and its effect on the interannual variability of ozone in the lower stratosphere. Previous satellite instruments have lacked the vertical resolution of the HIRDLS instrument and were designed to measure in the middle and upper stratosphere; thus, previous investigations have focused on planetary wave breaking in that region [e.g., *Leovy et al.*, 1985; *Randel et al.*, 1993; *Kouker et al.*, 1999]. HIRDLS profiles extend into the upper troposphere. *Olsen et al.* [2008] and *Pan et al.* [2009] show that HIRDLS resolves ~2 km laminae in the midlatitude lower stratosphere. *Olsen et al.* [2008] follow the evolution of a poleward intrusion event in HIRDLS observations in late January and early February 2006. They also show that the event is well reproduced by the global modeling initiative CTM using assimilated winds. For this lamination event, both observations and the simulation showed that most of the intrusion returned to the subtropics.

[7] In this study we examine the year-to-year variability of extratropical lower stratospheric ozone during the three years of HIRDLS observations (2005–2007). The variability due to reversible transport is removed by exploiting the correlation of ozone and potential vorticity (PV) using equivalent latitude as the meridional coordinate. We focus our analysis on February of each year when there are clear differences in the lower stratospheric zonal mean winds and, consequently, different dynamical background states. We relate the interannual ozone variability to both the mixing of air masses evaluated using the equivalent length diagnostic [*Nakamura*, 1996] and the frequency of HIRDLS-observed laminae. We find that there are significant year-to-year differences in the midlatitude ozone, lamination frequency, and irreversible transport. Our results show that interannual variability in lamina reversibility or where the waves become nonconservative is important to the ozone distributions in the midlatitude lower stratosphere. The following section describes the satellite data. Section 3 presents a lamina identification algorithm, a discussion of the equivalent latitude coordinate, and a description of the equivalent length diagnostic. Section 4 describes the interannual differences in the February stratospheric zonal winds related to the polar vortex and phase of the QBO. Results are presented in section 5 followed by a discussion and summary in section 6.

2. Data

[8] We use v004 temperature and ozone vertical profile observations from HIRDLS on NASA's Aura platform [*Gille et al.*, 2008]. The v004 data span 21 January 2005 to 2 January 2008. The vertical resolution is ~1 km, and profiles are spaced ~65 km along the track of about fifteen polar, Sun-synchronous orbits per day. A precision estimate is given for each ozone measurement in the HIRDLS product based on the standard deviation of ozone binned by equivalent latitude and potential temperature. Thus, the precision estimate includes atmospheric variability and the measurement random error. *Nardi et al.* [2008] provide additional information on the HIRDLS ozone data set and validation.

[9] We also use v2.2 vertical profile observations of ozone and N_2O from the Aura microwave limb sounder (MLS) [*Livesey et al.*, 2007]. The vertical resolution of these measurements is ~3 km for ozone in the upper troposphere and lower stratosphere and 4–6 km for N_2O measurements made at altitudes above 100 hPa. The measurements have an along-track spacing of ~200 km. *Lambert et al.* [2007] provide more details of the N_2O observations and validation. *Froidevaux et al.* [2008], *Jiang et al.* [2007], and *Livesey et al.* [2008] discuss validation of the MLS ozone data. We screen all satellite data using the filters suggested by the HIRDLS and MLS data guides that may be obtained from http://www.eos.ucar.edu/hirdls/and http://mls.jpl.nasa.gov/, respectively.

3. Methods

3.1. Lamina Identification

[10] Various methods have been used to identify laminae or filaments, ranging from reversal of horizontal gradients of

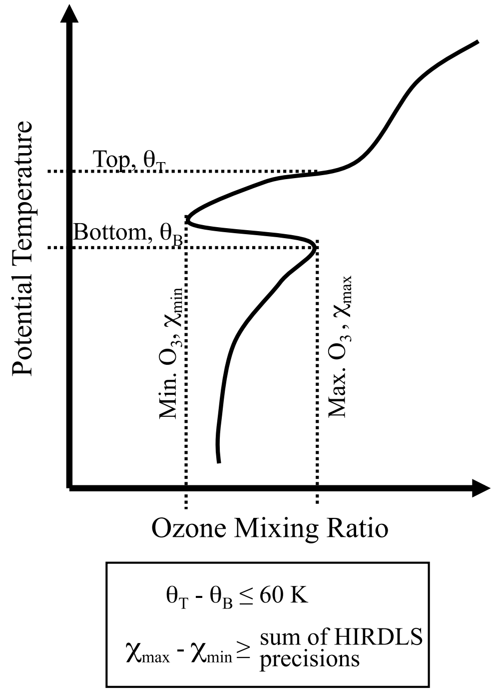

Figure 1. Ozone profile schematic identifying the features of a negative perturbation lamina. The bottom of the layer, θ_B, is where the ozone mixing ratio begins to decrease with height and is associated with the "maximum" ozone, χ_{max}. The top of the layer, θ_T, is the first level above θ_B where the mixing ratio is equal to or greater than χ_{max}. The "minimum" ozone is the smallest ozone value observed between the bottom and top of the layer.

tracers in model fields [e.g., *Eyring et al.*, 2003] to examining local extrema and the shape of ozone profiles from sondes [e.g., *Reid and Vaughan*, 1991; *Pierce and Grant*, 1998] and model output [e.g., *Weaver et al.*, 2000]. Methods based on profile shape have the advantage that they can be applied similarly to model output, satellite profiles, and relatively sparse ozonesonde data. Here we identify and quantify negative perturbation laminae (see Figure 1) associated with poleward transport based on the shape of HIRDLS ozone profiles. This method does not distinguish between reversible and irreversible laminar transport. To begin, we interpolate HIRDLS data to potential temperature surfaces in 5 K increments (~0.2 km spacing at these altitudes), using only data above 260 hPa. This vertical spacing is smaller than the HIRDLS 1 km resolution so each level is not independent. Next we average all profiles within 2° latitude bins (typically three to four profiles) along each orbit between 34°N and 70°N to reduce random noise in the profiles. We identify a possible "bottom" of a low ozone lamina by the lowest potential temperature at which the ozone begins to decrease with height (Figure 1). The "top" of the lamina is taken to be the potential temperature at which the ozone mixing ratio is equal to or greater than the mixing ratio at the bottom of the layer. This process can potentially identify several layers within a single mean profile.

[11] We apply additional criteria to lamina identification. First, we use the HIRDLS measurement precisions to provide a minimum "magnitude" of the layer. The difference of the ozone at the lamina bottom and the minimum ozone in the layer must be greater than the sum of the measurement precisions at those locations. Second, the potential temperature difference between the top and bottom of the lamina (the layer "thickness") must be less than or equal to 60 K. This roughly corresponds to 2.5 km at these altitudes, much larger than HIRDLS vertical resolution of ~1 km. This limit on the lamina thickness rejects identifications that can arise from profile noise and anomalous high ozone "spikes" at low altitudes that are retrieval artifacts as discussed in the HIRDLS data guide. *Reid and Vaughan* [1991] show that the vast majority of laminae have thicknesses between 1 and 2.5 km. Sensitivity tests of our results show that using a greater value than 60 K for the upper bound on the layer thickness does not alter the discussion of seasonal cycles and interannual differences in section 5.2. We also note that the 60 K limit is consistent with the thickness criteria used by *Reid and Vaughan* [1991]. The last criterion we use is that laminae must be coherent across three adjacent mean profiles (6° latitude). Specifically, the adjacent profiles must have identified laminae that overlap in vertical space. Although this final criterion may cause the algorithm to reject narrow zonally oriented laminae, it also eliminates false positives due to remaining random noise after interpolation and averaging.

3.2. Equivalent Latitude

[12] Potential vorticity (PV) is a quasi-conserved dynamical tracer in the absence of diabatic heating and momentum sources and sinks. For time scales of days to weeks, PV is well correlated with long-lived tracers such as ozone in the extratropical lower stratosphere [e.g., *Danielsen*, 1968; *Leovy et al.*, 1985]. However, ozone and PV typically vary greatly within a geometric latitude band during winter. It is common practice to consider the variability of such tracers within specified ranges of PV rather than with latitude. The meridional coordinate can be replaced by equivalent latitude, i.e., the latitude that encloses the same area as that enclosed by a specified PV contour [*Butchart and Remsberg*, 1986]. Air parcels at the same equivalent latitude and isentropic surface will have the same PV. Parcels of air with the same potential temperature and PV are likely to be of similar origin and composition since both are quasi-conserved following adiabatic motion. Thus, the zonal variability of ozone in equivalent latitude coordinates is greatly reduced, and probability distribution functions (PDFs) [*Sparling*, 2000] at an equivalent latitude value are much narrower compared to similar PDFs using geometric latitude coordinates.

[13] Use of the equivalent latitude coordinate separates the impact of the irreversible transport from the conservative, reversible transport. Reversible isentropic transport of air parcels will conserve PV. Irreversible poleward transport will be associated with an increase in parcel PV and motion across equivalent latitude lines. It follows then that changes in equivalent latitude imply irreversible transport. Changes of this type can be identified in zonal distributions of long-lived constituents using PDFs. For example, if PV and ozone are highly correlated on an isentropic surface in a

midlatitude equivalent latitude band, the PDF distribution of ozone in that band would be relatively narrow and Gaussian in shape. Now we consider irreversible isentropic transport of low ozone tropical air into a region of that equivalent latitude band (which implies an increase of PV for the air of tropical origin) through a nonconservative process such as wave breaking. The PV-ozone correlation would now be weaker in that band, and the distribution would be broader and more skewed toward lower values of ozone.

[14] Processes that may decouple ozone and PV in the midlatitude lower stratosphere include irreversible eddy transport, gravity wave mixing, and vertical heating gradients that are sources and sinks of PV. The latter two mechanisms are relatively unimportant in the lower stratosphere [*Chao and Schoeberl*, 1984; *Andrews et al.*, 1987], and the diabatic transport is relatively small compared to the horizontal transport in the lower stratospheric middle latitudes for the time scales considered in this study. The chemical lifetime of ozone is long in the midlatitude lower stratosphere, particularly in the winter and spring. Thus, irreversible eddy transport, either through nonlinearity or transience, is the predominant process of ozone-PV decoupling in the region examined here. It is possible that an apparent decoupling could occur due to the analysis system not being able to generate sufficiently small-scale PV as the observed ozone features approach the resolution of the model. We have tested this possibility using reverse domain filling analysis [*Sutton et al.*, 1994; *Newman and Schoeberl*, 1995] to generate small-scale PV fields. We find that the resolution of the PV fields used here do not contribute to the ozone-PV decoupling (not shown).

[15] Since one purpose of this investigation is to determine the interannual differences in irreversible transport, we interpolate the HIRDLS and MLS ozone profiles to potential temperature surfaces and, using PV to define equivalent latitude, consider observed variability with 4° ranges of equivalent latitude. Use of the equivalent latitude coordinate removes the variability due to adiabatic, reversible transport that does not affect the ozone budget. In the absence of processes that break the correlation between ozone and PV, we anticipate a symmetric, relatively narrow distribution of ozone values within an equivalent latitude band since the air mass is of similar origin and composition. As previously noted, if there is nonconservative, irreversible transport in an equivalent latitude band, we anticipate a greater range of ozone values and an irregular distribution [*Sparling*, 2000]. Air parcels that have been irreversibly transported poleward are then likely to mix with the higher latitude air through small-scale processes on either short or long time scales.

3.3. Equivalent Length

[16] We formally diagnose mixing as irreversible transport using the modified Lagrangian-mean equivalent length [*Nakamura*, 1996]. The equivalent length is proportional to the "effective diffusivity" and provides a measure of mixing across material surfaces. This diagnostic has previously been applied to both global observations [e.g., *Nakamura and Ma*, 1997; *Allen et al.*, 1999] and model output [e.g., *Shuckburgh et al.*, 2001; *Ma et al.*, 2003]. Equivalent length is a convenient diagnostic as knowledge of the wind fields and time rate of change is not needed; only tracer distributions are required. However, the tracer concentration must increase or decrease nearly monotonically with latitude. *Nakamura* [1996] provides a derivation and details of the diagnostic framework. Only the definition and a short discussion are presented here.

[17] The equivalent length, L_e, of a long-lived tracer on an isentropic surface is given by

$$L_e^2(A,t) = \left(\frac{\partial q}{\partial A}\right)^{-2} \left\langle |\nabla q|^2 \right\rangle \quad (1)$$

where q is the tracer mixing ratio, A is the area enclosed by a tracer contour, and angled brackets denote an average of the scalar quantity following the contour. The relative structure of the equivalent length field identifies regions of strong and weak mixing even though the magnitude of L_e depends on the resolution of the field analyzed. Greater mixing occurs in regions of relatively larger values of L_e and vice versa. Although the diagnostic is formulated in two dimensions, if there is adequate spatial coverage over time scales where the cross-isentrope transport is small relative to the horizontal transport, the atmospheric flow can be approximated as 2-D, and the diagnostic is useful with satellite observations of tracers [*Lingenfelser and Grose*, 2002]. *Shuckburgh et al.* [2001] discuss sensitivity studies of using both the divergent part of the winds and diabatic heating in the stratosphere and found only minor differences in the values of equivalent length. The diagnostic has been used in prior studies to evaluate mixing using satellite tracer observations, including those by *Nakamura and Ma* [1997], *Nakamura et al.* [1999], *Allen et al.* [1999], *Lingenfelser and Grose* [2002], and *Ma et al.* [2003]. In this work, we normalize the equivalent length to the nondimensional quantity $\ln(L_e^2/L_0^2)$, where L_0 is the Earth's circumference at a given equivalent latitude.

4. Stratospheric Conditions for February 2005–2007

[18] As stated above, we focus on the month of February in the 3 years of HIRDLS observations, 2005, 2006, 2007. There are important interannual differences in the dynamical state of the stratosphere and the midlatitude ozone distributions in each of those years. The February mean zonal winds from the Goddard Earth Observing System, version 5 Data Assimilation System (GEOS-5 DAS) [*Rienecker et al.*, 2008] are shown in Figure 2. A major stratospheric sudden warming occurred in the latter half of January 2006 accompanied by a reversal of the zonal winds to easterlies in much of the stratosphere poleward of 60°N through the middle of February [e.g., *Manney et al.*, 2009]. Thus, the climatological polar vortex around 60°N is clearly absent in 2006. The polar vortex is shifted slightly equatorward with greater maximum wind speeds in February 2005 compared with 2007. Differences in the phase of the QBO are seen from about 100 hPa up to 5 hPa. During 2006, the lower stratospheric winds are easterly and the middle stratospheric winds are westerly. In contrast, the mean winds in 2005 and 2007 are westerly in the lower stratosphere and easterly in the middle stratosphere. The zonal winds throughout nearly the entire stratosphere are markedly different in 2006 com-

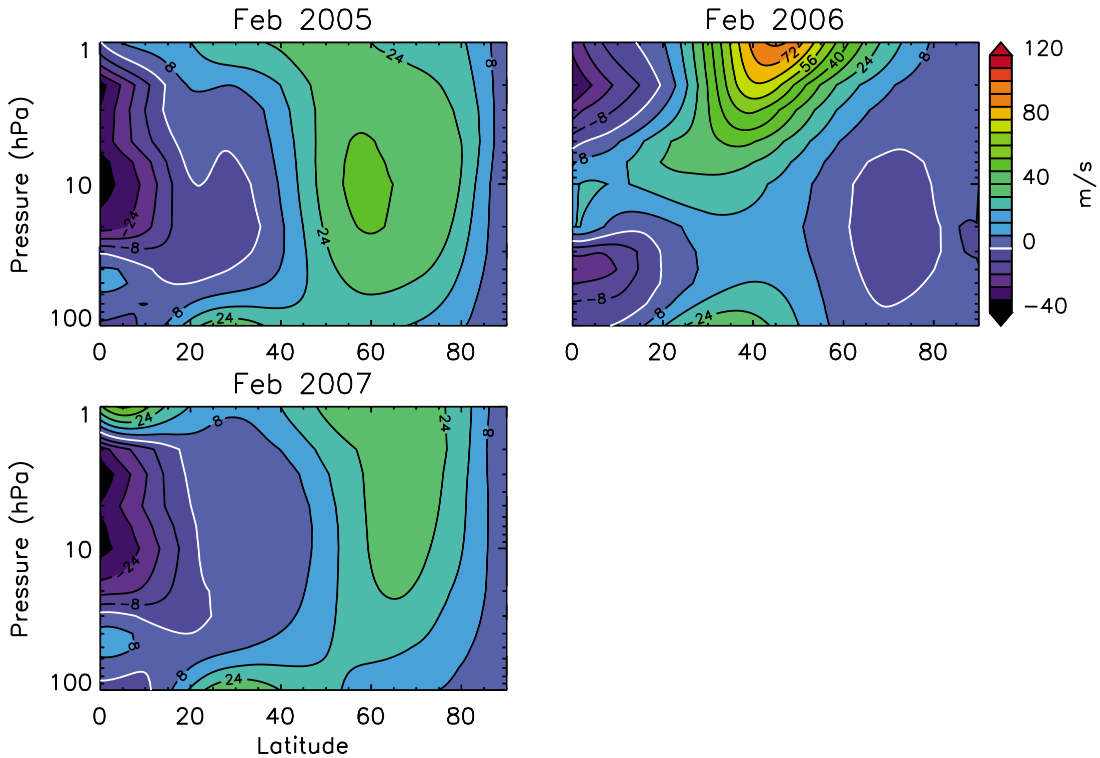

Figure 2. Zonal mean winds for February 2005, 2006, and 2007. Analysis winds are from GEOS-5 Data Assimilation System. Contour increment is 8 m s^{-1} and white lines are the zero contour.

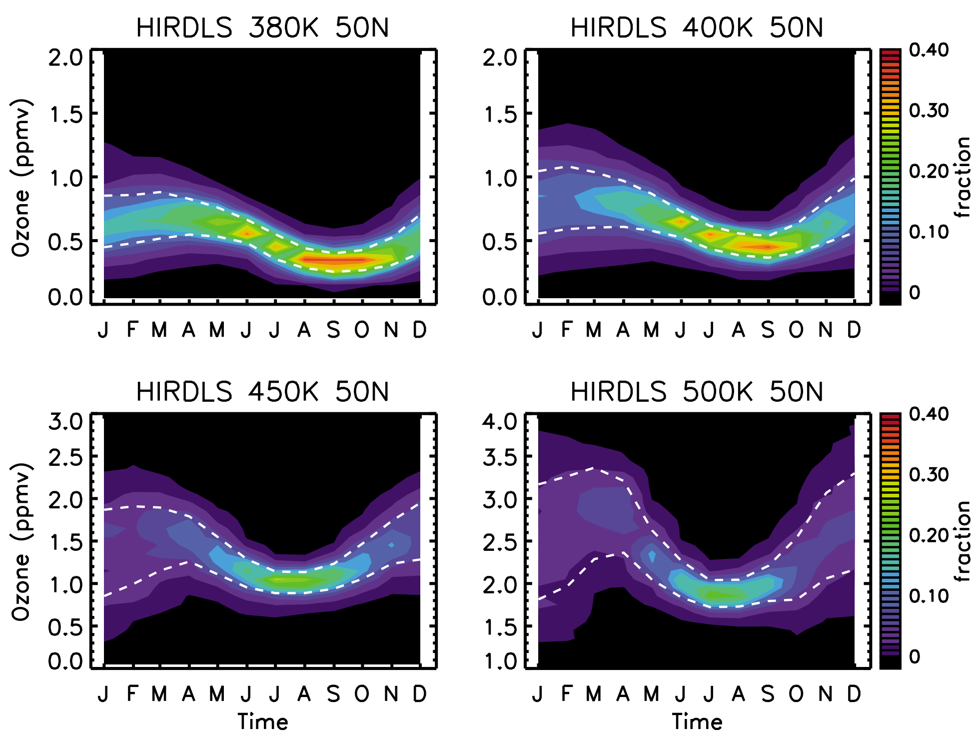

Figure 3. Monthly PDFs of HIRDLS ozone at 50°N equivalent latitude for 2007 on the 380, 400, 450, and 500 K potential temperature surfaces. The dashed lines denote one standard deviation from the mean at each latitude bin.

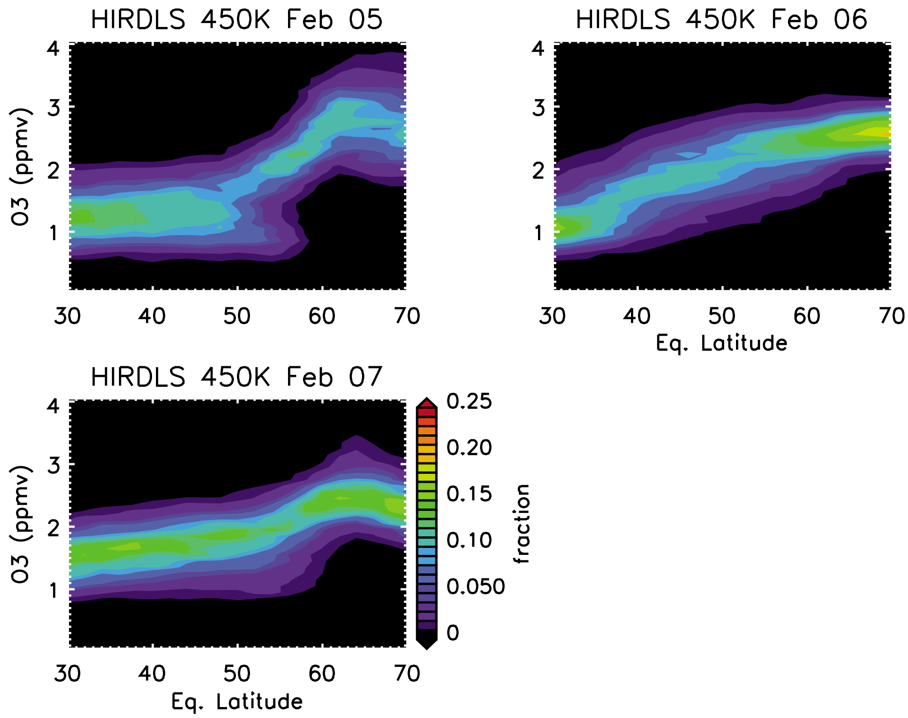

Figure 4. PDFs of HIRDLS ozone as a function of equivalent latitude at 450 K for February 2005–2007.

pared to 2005 and 2007. It follows that the background states for dynamical wave propagation, breaking, and dissipation are also dissimilar for these years.

5. Results

5.1. Variability of Extratropical Lower Stratospheric Ozone

[19] In this subsection we present results that demonstrate several aspects of the variability of lower stratospheric ozone. The variability of ozone within equivalent latitude bins is investigated using PDFs [*Sparling*, 2000]. The PDFs are normalized and show the fraction of the observations that fall in each bin. The variability is indicated by the width of the distribution. Wider distributions in the equivalent latitude bins imply a weaker correlation of ozone and PV.

[20] Figure 3 shows contours of the monthly probability distribution functions (PDFs) of HIRDLS ozone on lower stratospheric potential temperature surfaces at 50°N equivalent latitude for 2007. The monthly PDFs are determined using daily analyses from the GEOS-5 DAS with 0.67° × 0.5° longitude-latitude resolution corresponding to the date of each HIRDLS observation. The statistics are accumulated over a month. The PDFs demonstrate that the variability of ozone throughout the midlatitude lower stratosphere increases with potential temperature and the variability is greater in the winter/spring than in the summer/fall.

[21] Figure 4 focuses on interannual differences of the HIRDLS ozone distributions on the 450 K surface (around 18 km or 70 hPa at midlatitudes) for February 2005, 2006, and 2007. The distribution of ozone values is nearly independent of latitude between 30°N and 50°N equivalent latitude in 2005 but is clearly latitude dependent in 2006. In 2007 the distribution of ozone values closely resembles that in 2005 as it is relatively independent of latitude up to 50°N. The 2005 and 2007 distributions show low values between ~45°N and 55°N that are typical of values found at 30°N equivalent latitude. This is not apparent in 2006 when the distributions in the middle latitudes are more symmetrical.

[22] We examine the zonal mean ozone to show that similar interannual differences are discernible throughout the midlatitude lower stratosphere. Figure 5 shows HIRDLS and MLS observations of the February zonal mean ozone for 2005–2007. The HIRDLS and MLS observations are in good agreement, showing that the ~3 km vertical resolution of MLS is sufficient to resolve the time-averaged zonal mean structure and impact of irreversible horizontal transport. In February 2005 and 2007, the contours are relatively flat above ~450 K from about 30°N to 50°N equivalent latitude, whereas in 2006 the mean mixing ratio increases with latitude. The relatively constant PDFs at low latitudes in Figure 4 are consistent with the flat zonal mean contours at 450 K in Figure 5. In addition, the zonal mean contours are flattest in 2005 and most sloped in 2006, consistent with the latitude dependence of the PDFs each year.

[23] The ozone distributions at 50°N equivalent latitude and 480 K for February 2005 and 2006 are shown in Figure 6. For each year, the HIRDLS and MLS distributions are similar, but both the means and the shapes of the distributions differ. The means of the HIRDLS and MLS distributions are shifted to higher values in 2006 compared to 2005. This interannual difference of the mean is about 0.7 ppmv. The difference of the mean could occur from greater downwelling of ozone-rich air in 2006, more mixing of low ozone air from lower latitudes in 2005, or a combination of the two. The change in the shape of the distribution, con-

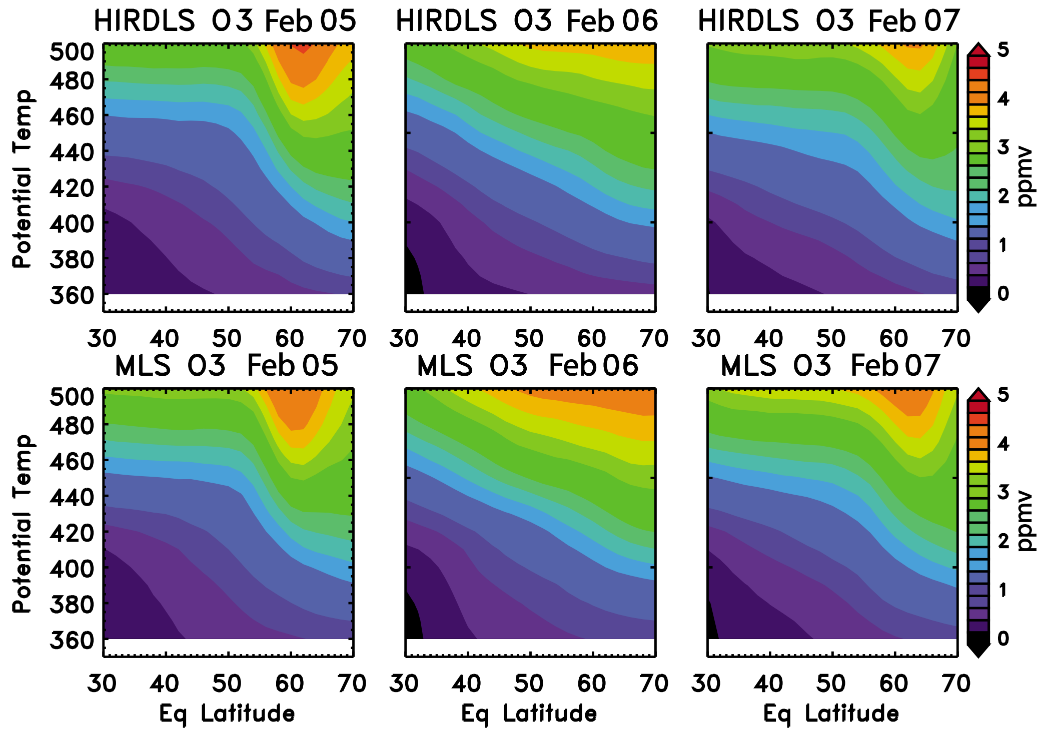

Figure 5. Equivalent latitude zonal mean ozone for HIRDLS (top row) and MLS (bottom row) during February 2005–2007.

sistent for both sensors but different each year, reveals interannual differences in irreversible transport. In 2006, the distributions are narrower and more Gaussian in shape. This suggests a more homogeneous air mass at this equivalent latitude and a strong correlation of ozone and PV. The 2005 distributions are broader and less Gaussian, due to a greater fraction of measurements with lower values of ozone mixing ratio. The right hand side of higher ozone values of the 2005 distribution is much more Gaussian in shape than the left-hand side. This skewed distribution in equivalent latitude coordinates indicates irreversible transport of tropical air into the extratropics [*Sparling*, 2000].

5.2. Observed Lamination Frequencies

[24] The ozone distributions in equivalent latitude coordinates (Figures 4 and 6) demonstrate that the irreversible transport of tropical air modulates the interannual variability of lower stratospheric ozone at middle latitudes. We next consider the frequency of observed low ozone laminae, indicative of transport from the tropics, and its relationship to the observed interannual ozone variability. We use the method outlined in section 3.1 to identify laminae in daily HIRDLS observations from 2005 through 2007. It is important to again note that the equivalent latitude coordinate used in the previous subsection removes the reversible transport from the variability analysis. In contrast, the lamina identification method used here with HIRDLS data does not distinguish between reversible and irreversible laminar transport.

[25] The daily average number of laminae identified in all the 2° mean HIRDLS profiles in the northern hemisphere between 400 K and 500 K is shown by month in Figure 7. The seasonal cycles of lamination frequency are similar each year, with spring maxima and late summer minima, consistent with the analysis of *Reid and Vaughan* [1991], who used a similar lamina identification scheme with ozonesonde profiles. *Eyring et al.* [2003] show a summer minimum similar to this analysis but the maximum occurs during early winter. This difference is likely due to the different identification scheme used by *Eyring et al.* [2003]. (Eyring et al. search for the reversal of meridional N_2O gradients simulated by a CTM nudged to ECMWF reanalysis. Thus, their method identifies streamers associated with breaking waves, while our profile analysis identifies lamination in both

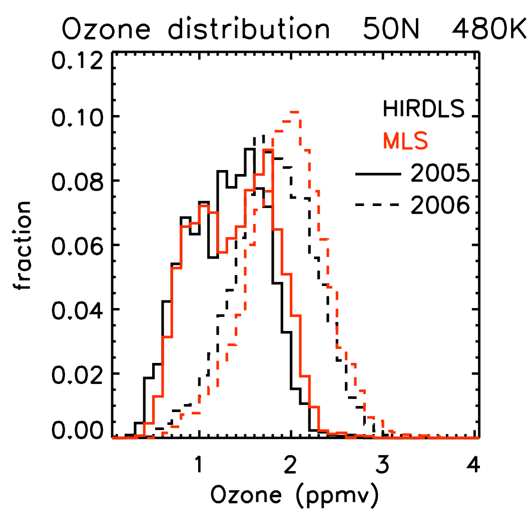

Figure 6. (a) Distribution of HIRDLS (black) and MLS (red) ozone observations at 50°N equivalent latitude and 480 K for February 2005 (solid) and 2006 (dashed).

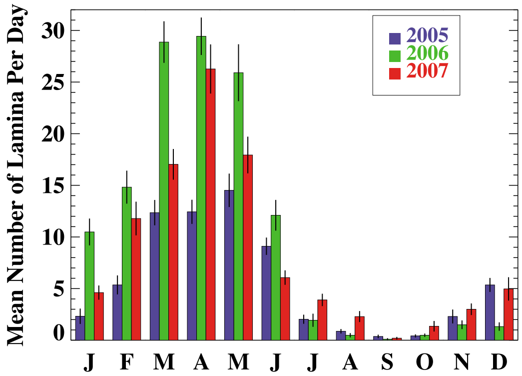

Figure 7. Average number of laminae per day for each month identified between 400 and 500 K potential temperature and 34°N to 70°N in the HIRDLS mean ozone profiles. Vertical lines at the top of each bar denote plus or minus one standard error of the mean.

breaking and non-breaking events.) This difference is discussed further in section 6.

[26] There is considerable interannual variability in the number of laminae identified in the winter and spring months of 2005–2007. More than twice as many laminae are counted in the HIRDLS data for each month of January–May 2006 than the corresponding month in 2005. In each of these months, the number of laminae identified in 2007 falls between the number identified in 2005 and 2006. We note that counting only lamina in the lower midlatitudes up to 50°N results in similar seasonal cycles and interannual differences although the frequency of observed laminae is roughly halved (not shown).

5.3. Irreversible Mixing

[27] For the 3 years examined, the ozone distributions shown in section 5.1 suggest that the "tropical influence" on the February lower midlatitude ozone budget from irreversible transport is greatest in 2005, least in 2006, and intermediate in 2007. However, although the primary communication of the tropics to middle latitudes is through laminar transport, the frequency of observed laminae in February exhibits an inverse relationship, greatest in 2006 and least in 2005. Reversible transport has no impact on the results presented in section 5.1 using the equivalent latitude coordinate. However, the identified laminae in section 5.2 may be either irreversible or reversible. Thus, the inverse relationship between the number of observed laminae and the "tropical influence" can only exist if there are significant interannual differences in the reversibility of the poleward transport in the lower midlatitudes. Highly reversible transport produces little or no mixing of tropical and extratropical air. In this case there will be little impact on the monthly mean ozone budget compared with highly irreversible events.

[28] As previously noted, irreversible poleward transport will weaken the PV-ozone correlation on isentropic surfaces. We obtain a phenomenological explanation of the irreversible tropical-extratropical transport differences by relating the ozone distributions to the zonal mean ozone at 30°N equivalent latitude. We express this relationship as a fraction of the number of observations at a given potential temperature and equivalent latitude that have mixing ratios less than the zonal mean mixing ratio at 30° equivalent latitude for each month. This fraction estimates the "tropical influence" at a given altitude and equivalent latitude. The results for February 2005–2007 for both HIRDLS and MLS

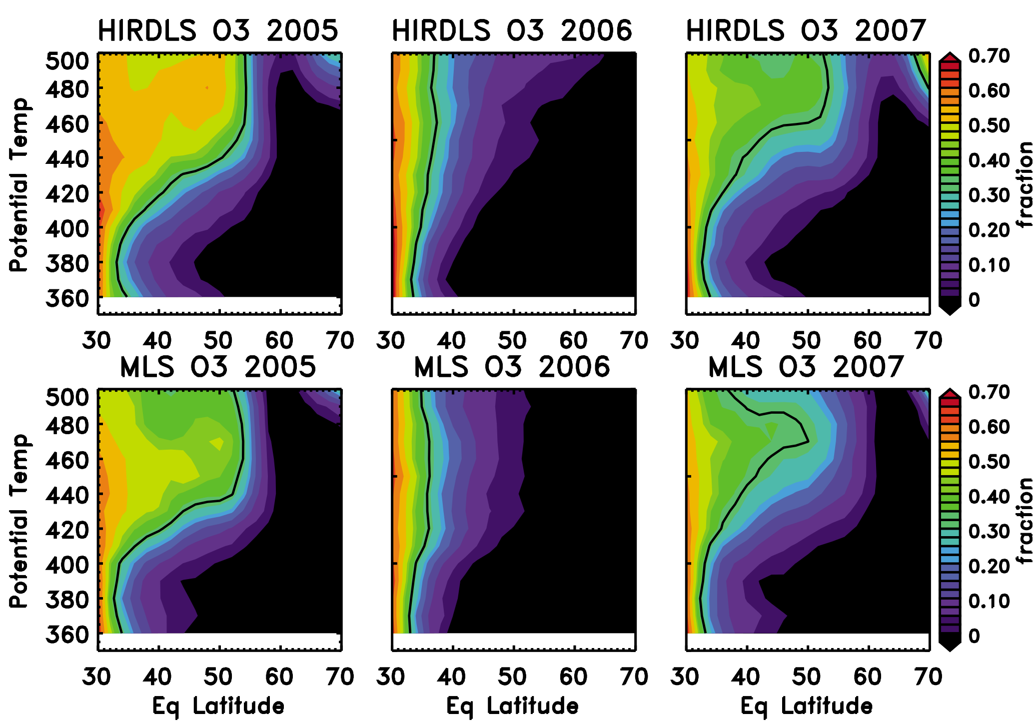

Figure 8. Fraction of observations with ozone mixing ratios less than the equivalent latitude zonal mean mixing ratio at 30°N for the month of February. Black line is the 0.3 contour.

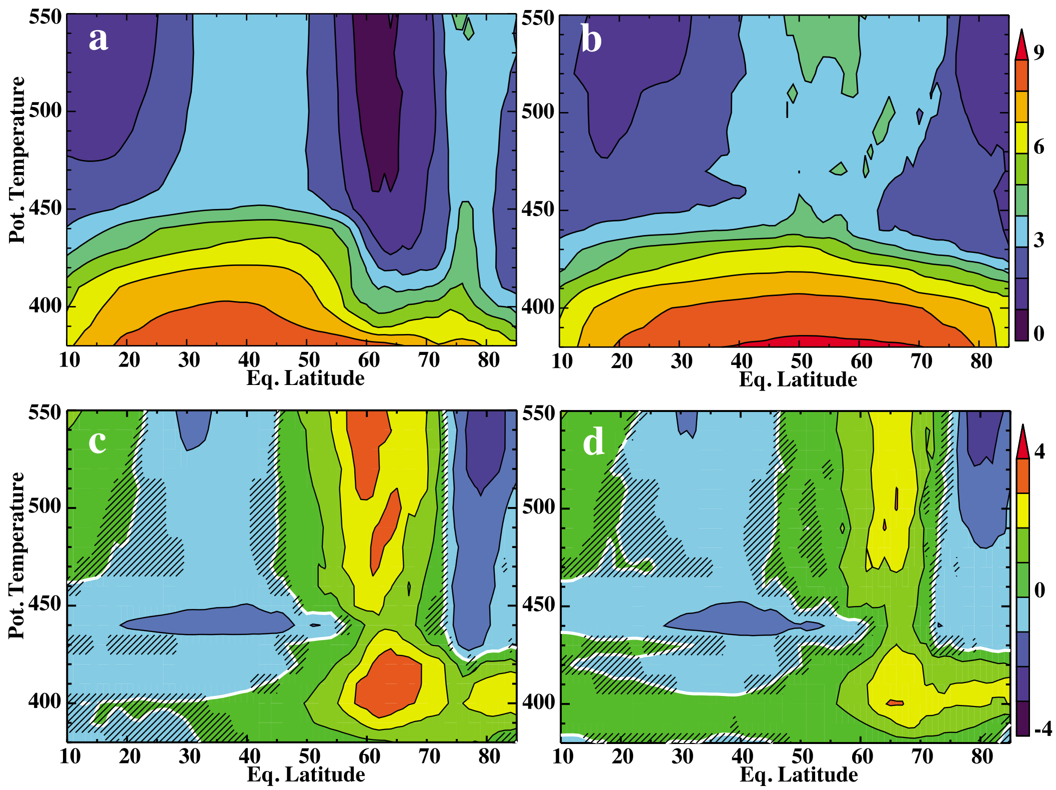

Figure 9. The February mean normalized equivalent length of MLS N_2O in the lower stratosphere for (a) 2005 and (b) 2006. (c) The February 2006–2005 difference of equivalent length. (d) The February 2006–2007 difference of equivalent length. Zero contour in Figures 9c and 9d denoted with white line. Hatched areas denote where the differences of the means are not significant at 95% confidence.

data are shown in Figure 8. The tropical influence above 400 K between 30°N and 55°N equivalent latitude is greatest in 2005. The 2007 result shows a similar shape but the magnitude is less than 2005. For 2006, this formulation shows that the tropical values of ozone mixing ratio that are observed at middle geometric latitudes are still usually associated with tropical values of PV. In 2005 and 2007, many "tropical" values of ozone mixing ratio are associated with higher PV values. For example, at 450 K and 50°N equivalent latitude, about 45% of the observations had tropical ozone values compared to less than 5% of the observations in 2006. Binning ozone values by equivalent latitude reduces the apparent variability in 2006 by removing the impact due to reversible transport. The correlation of ozone and PV is weaker in 2005 and 2007 than in 2006, indicating greater irreversible transport of air from the tropics into the lower middle latitudes.

[29] Following irreversible meridional transport, air parcels will mix into the environment as a result of small-scale processes such as diffusion. We formally evaluate the interannual variability of mixing in February of each year by calculating normalized equivalent lengths from daily MLS N_2O observations. N_2O is a long-lived trace gas with poleward decreasing zonal mixing ratios in the lower stratosphere. We use trajectory mapping to increase the effective horizontal resolution of the MLS data to 1° latitude and 1.25° longitude using the method described in the study of *Schoeberl et al.* [2007]. The trajectory-mapped data are interpolated to potential temperature surfaces from 380 to 550 K at 10 K increments for computing the equivalent length. The normalized equivalent lengths are calculated daily, and these results are used to determine the monthly mean. We note that the majority of the N_2O observations reported on the 147 hPa pressure level are flagged as having too large a priori influence, and the trajectory filling will not be as robust at near this altitude. Thus, although the equivalent lengths below ~400 K are shown for completeness, they should not be considered scientifically conclusive.

[30] The monthly mean normalized equivalent lengths for February 2005 are shown in Figure 9a. The polar vortex barrier to mixing is seen as a minimum in equivalent lengths above 400 K near 60°N [e.g., *Allen and Nakamura*, 2001]. The greater equivalent lengths between about 30°N and 50°N are identifiable with the subtropical/midlatitude "surf zone," a region of greater mixing [*McIntyre and Palmer*, 1984]. The most obvious difference in 2006 is the relative maximum in equivalent length near 60°N equivalent latitude (Figure 9b), corresponding to the lack of a polar vortex. Overall the equivalent lengths are smaller in the subtropics and at polar latitudes in 2006 compared with 2005.

[31] The 2006–2005 differences of the February mean equivalent length are shown in Figure 9c. The negative contours (blue shades) indicate greater mixing in 2005 over two regions: inside the polar vortex poleward of about 75°N equivalent latitude and between the tropics and middle latitudes above 400 K. The region of greater mixing in the lower midlatitudes extends to at least 45°N equivalent latitude throughout the lower stratosphere above 400 K and

Table 1. Summary of Differences

	February 2005	February 2006	February 2007
Polar state	Vortex	Major warming	Vortex
QBO state (100–50 hPa)	Westerly	Easterly	Westerly
Observed lamina frequency (reversible & irreversible)	Least	Greatest	Intermediate
Tropical influence on lower midlatitudes (irreversible)	Greatest	Least	Intermediate
Tropical-lower midlatitude mixing (equivalent length diagnostic)	High	Low	High

extends to about 55°N in a layer from about 440 to 450 K. In this region of greater equivalent lengths in the 2005 lower stratosphere, the mixing of tropical air with lower ozone concentrations into the lower midlatitudes is enhanced. This is consistent with the “tropical influence” on this region shown in Figure 8. We note that if the breakdown of the polar vortex had increased the mixing of high latitude, high ozone air into the lower midlatitudes, the equivalent lengths in the lower midlatitudes would be greater in 2006. There is greater mixing at higher latitudes in the vortex region during 2006 although the equivalent length diagnostic cannot indicate whether that mixing is of higher latitude air or lower latitude air or both into this region.

[32] The zonal mean and variability of lower stratospheric ozone and “tropical influence” in 2007 was most similar to 2005 (Figures 4, 5, and 8). The February 2006–2007 equivalent length differences in Figure 9d show the same pattern as the 2006–2005 comparison (Figure 9c). There is greater mixing in the 2007 tropical to midlatitude lower stratosphere above 400 K than in 2006. Again, the maximum difference in this region is in a layer near 450 K extending to about 60°N equivalent latitude. The magnitude of the positive difference near 60°N is not as great as the 2006–2005 case. This is due to the weaker polar vortex in 2007 compared with 2005 (Figure 2) resulting in slightly higher equivalent lengths near 60°N and a slightly weaker mixing barrier in 2007. The somewhat weaker horizontal gradient of the zonal mean ozone around 460 K and 60°N equivalent latitude in 2007 compared with 2005 (Figure 5) is likely a result of this weaker polar vortex mixing barrier in 2007. More high latitude, higher ozone air is transported to middle latitudes in 2007 than 2005. However, the absence of the vortex barrier in 2006 results in more equatorward mixing of air from the polar region and a weaker horizontal gradient of zonal ozone near 60°N than in either 2005 or 2007 (Figure 5).

[33] Although the number of lamination events may vary from year to year, some of the interannual differences in the observed lamina frequency can be explained by the amount of mixing as diagnosed by the equivalent length. Greater mixing reduces the laminae lifetime and the observation frequency because a single event experiencing greater mixing will be observed fewer times. We define the “magnitude” of a lamina as the difference of the maximum ozone mixing ratio (at the bottom of the layer) with the minimum mixing ratio in the layer expressed as a percent of the maximum. Mixing of a lamina with higher ozone extratropical air will decrease the lamina magnitude. In February 2005, the mean magnitude of all identified laminae from 400 to 500 K is 22.4% ± 0.7%, significantly less than the 26.2% ± 0.6% mean magnitude in 2006. Errors given are one standard deviation of the mean. The mean magnitude for the laminae in this altitude range in February 2007 is 23.1% ± 0.7%, also significantly less than in 2006. The difference between the 2007 and 2005 mean magnitudes is not statistically significant.

6. Discussion and Conclusion

[34] In this study we have shown significant interannual variability of both ozone concentrations in the midlatitude lower stratosphere using equivalent latitude coordinates and the lamination frequency in 3 years of HIRDLS ozone profiles. For ease of reference, the results are qualitatively summarized by year in Table 1. We find the frequency of observed low ozone laminae is inversely related to the tropical influence on the lower midlatitude ozone budget, i. e., the number of observed laminae is greatest in 2006 when there are the fewest occurrences of relatively low ozone observations with midlatitude values of PV. Likewise, in 2005, the probability of observing ozone mixing ratios typical of the tropics with PV typical of middle latitudes is greatest when the lamina frequency is least. Since the ozone distributions in the equivalent latitude analysis reflect only the irreversible transport while the identified laminae may be either reversible or irreversible, this can be explained by interannual differences in the reversibility of laminar transport at lower midlatitudes. Analysis of mixing using the equivalent length diagnostic is consistent, showing that more mixing in the lower midlatitudes occurs in the years with greater tropical influence. The poleward laminae in 2006 experience less mixing into the lower midlatitudes than the laminae in 2005 and 2007. This is consistent with more observations of laminae but the laminae have less of an impact on the ozone budget in this region. The laminar transport in 2006 must have been more reversible in the lower midlatitudes. In 2006, either more of the tropical air returned to the tropics or the laminae tended to mix at higher latitudes than in 2005 or 2007. Thus, the relative impact of laminae on the ozone budget cannot be solely deduced from the frequency of observed laminae in profile data. The entire lifecycle and reversibility must also be considered.

[35] Both the state of the polar vortex and the QBO may influence lamina formation and interannual variability in irreversible transport between the tropics and midlatitudes. Polar vortex disturbances and stratospheric warmings have been shown to increase the poleward transport from the tropics [e.g., *Leovy et al.*, 1985; *Manney et al.*, 2009]. *Manney et al.* [2009] discuss the 2006 major warming event and note that anomalous poleward transport in the lower stratosphere occurred with the breakdown of the vortex. Likewise, we find a relatively large number of low ozone laminae in 2006 compared with 2005 and 2007. We have

shown this most of this low ozone air must have reversibly returned to the tropics and/or was irreversibly transported to higher latitudes than in 2005 and 2007. The impact on the monthly mean lower stratospheric ozone budget at lower midlatitudes was minimal. We have examined the 30 hPa height field and found a suppression of planetary waves in the extratropics following the 2006 warming relative to 2005 and 2007 (not shown). This suppression is not evident at 70 hPa, suggesting that the changes to the stratospheric winds from the warming inhibited the vertical propagation of the large-scale planetary waves. Thus, the greater number of observed laminae may have been a result of greater differential advection in 2006 [e.g., *Newman and Schoeberl*, 1995]. However, whether these observed laminae and transport differences in the 2006 case are typical of major warmings cannot be established from the 3 years of HIRDLS observations.

[36] Our analysis is consistent with the results of *Shuckburgh et al.* [2001] who showed enhanced subtropical mixing during the westerly phase of the QBO through baratropic instability associated with the westerly jet and equatorward propagating planetary waves. Our results are also consistent with the findings of *Randel and Wu* [2007] who demonstrated a correlation of the westerly phase of the QBO with negative ozone anomalies up to 55°N in the lower stratosphere. While these prior studies reveal a link between the phase of the QBO and the ozone budget in the lower stratosphere, the present investigation identifies a process by which the QBO influences the transport and affects the lower stratospheric midlatitude ozone budget. However, while the state of the QBO impacts the mixing of tropical air into lower midlatitudes, suppression of this mixing may also be linked to the elimination of the polar vortex barrier as the subtropical air may be drawn to higher latitudes before mixing. Understanding of the polar vortex and QBO influences on the mixing of low ozone tropical air into midlatitudes, and their possible interaction, remains incomplete and is the subject of future study.

[37] Finally, the difference in the seasonal cycles between the lamination frequency here and the filamentation frequency results of *Eyring et al.* [2003] as discussed in section 5.2 is reconciled by considering the reversibility of these wave events. The maximum lamination frequency occurs in the spring when examining profile data as done here and by *Reid and Vaughan* [1991]. *Eyring et al.* [2003] note a winter maximum identifying filaments by the horizontal gradient. The horizontal gradient approach identifies only wave events that are breaking and thus associated with some degree of irreversibility and mixing. The profile-based scheme used here identifies laminae that may or may not be reversible. In all 3 years investigated here, about twice as many laminae are identified in April than in January (Figure 7), yet the ozone variability is not as great in the spring as in the winter (Figure 3). This suggests that the laminar transport is more reversible in the spring and implies less nonlinear wave breaking in the lower stratosphere at this time. This highlights that interannual differences in the number of waves that break and/or the meridional distribution of breaking in the lower stratosphere are likely the cause of the differences in the irreversible transport between the tropics and midlatitudes discussed in the present work. If a greater number of waves break then there will also be a greater amount of associated small scale mixing and diffusion. The results of this study underscore the importance of considering the reversibility and potential for mixing, not just the presence or rate of lamination in profile data, in studies of climatological ozone transport.

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