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HIRDLS observations and simulation of a lower stratospheric intrusion of tropical air to high latitudes

Mark A. Olsen,[1] Anne R. Douglass,[2] Paul A. Newman,[2] John C. Gille,[3,4] Bruno Nardi,[4]
Valery A. Yudin,[4] Douglas E. Kinnison,[4] and Rashid Khosravi[4]

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[1] On 26 January 2006, the High Resolution Dynamic Limb Sounder (HIRDLS) observed low mixing ratios of ozone and nitric acid in a ~2 km layer near 100 hPa extending from the subtropics to 55°N over North America. The subsequent evolution of the layer is simulated with the Global Modeling Initiative model and substantiated with HIRDLS observations. Air with low mixing ratios of ozone is transported poleward to 80°N. Although there is evidence of mixing with extratropical air, much of the tropical intrusion returns to the subtropics. This study demonstrates that HIRDLS and the GMI model resolve thin intrusion events. The observations combined with simulation are a first step towards development of a quantitative understanding of the lower stratospheric ozone budget.

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1. Introduction

[2] Rapid isentropic poleward transport of air with young stratospheric "age" and tropical composition has been inferred from time- and spatially-averaged satellite observations of the lower stratosphere. *Trepte et al.* [1993] demonstrated quasi-isentropic, poleward mixing of air just above the tropical tropopause with observations of aerosols from the eruption of Pinatubo. Easterly winds are a barrier to wave-driven transport and thus the Northern Hemisphere meridional transport in the first months following the eruption was confined to altitudes just above the tropical tropopause. *Randel et al.* [2001] used Halogen Occultation Experiment (HALOE) water vapor data to show fast transport between the tropics and midlatitudes in the lower stratosphere between ~380–420 K isentropic surfaces. Evidence of similar transport is also found in observations of radioactive isotopes [e.g., *Feely and Spar*, 1960] and CO_2 [e.g., *Boering et al.*, 1995]. Theoretical studies have shown wave driven isentropic mixing between the tropics and extratropical lower stratosphere [e.g., *Waugh*, 1996]. These mixing events occur frequently in thin layers. *Newman and Schoeberl* [1995] examined aircraft data from the Stratosphere Troposphere Exchange Project (STEP) and showed that differential advection by Rossby waves can generate vertically thin ozone laminae in the lower stratosphere.

[3] Previous satellite observations have lacked the sensitivity, vertical resolution, and/or horizontal coverage to sufficiently resolve lower stratospheric laminar events. An observational synoptic view throughout the lifetime of an intrusion event has not been possible. Accordingly, synoptic scale validations of intrusion event simulations have been inadequate. The combination of high vertical resolution (~1 km), lower stratospheric sensitivity, and horizontal coverage of the High Resolution Dynamic Limb Sounder (HIRDLS) on NASA's Aura satellite provides the opportunity for unprecedented observations following these isentropic, quasi-horizontal transport events. Here we examine a January 2006 Northern Hemisphere poleward intrusion of low ozone air in a layer between 400 K and 420 K potential temperature simulated by the Global Modeling Initiative (GMI) chemistry and transport model (CTM) driven by meteorological analyses. HIRDLS made observations of the event for more than eleven days and we show that the event is represented well by the simulation. The evolution of the event is examined using both the simulation and HIRDLS data. This combined analysis of observations and simulation demonstrates the potential to quantify the relative contributions by processes that determine the lower stratospheric ozone budget.

2. Data and Model Description

2.1. HIRDLS

[4] HIRDLS is one of the instruments on NASA's Aura, which was launched 15 July 2004 [*Gille et al.*, 2008]. HIRDLS makes limb measurements of temperature, aerosols and constituents including ozone from the UTLS to the mesosphere with improved vertical resolution compared to prior space-based observations. We use the latest v004 Level-2 HIRDLS observations of ozone and nitric acid. The vertical resolution is ~1 km and profiles are spaced ~65 km along the track of about fifteen polar, sun-synchronous orbits per day.

[5] HIRDLS measurements of temperature, ozone, and nitric acid have been validated with sondes, lidar, satellite observations, and assimilated data [*Gille et al.*, 2008; *Nardi et al.*, 2008; *Kinnison et al.*, 2008]. HIRDLS ozone is biased high at lower altitudes compared with correlative observations, particularly below 50 hPa (100 hPa) at low (mid to high) latitudes. HIRDLS temperatures are ~1 K warm compared to ECMWF analyses from 10–100 hPa. Reduction of these biases is expected in future versions of the

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[1] Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

[2] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

[3] Center for Limb Atmospheric Sounding, University of Colorado, Boulder, Colorado, USA.

[4] National Center for Atmospheric Research, Boulder, Colorado, USA.

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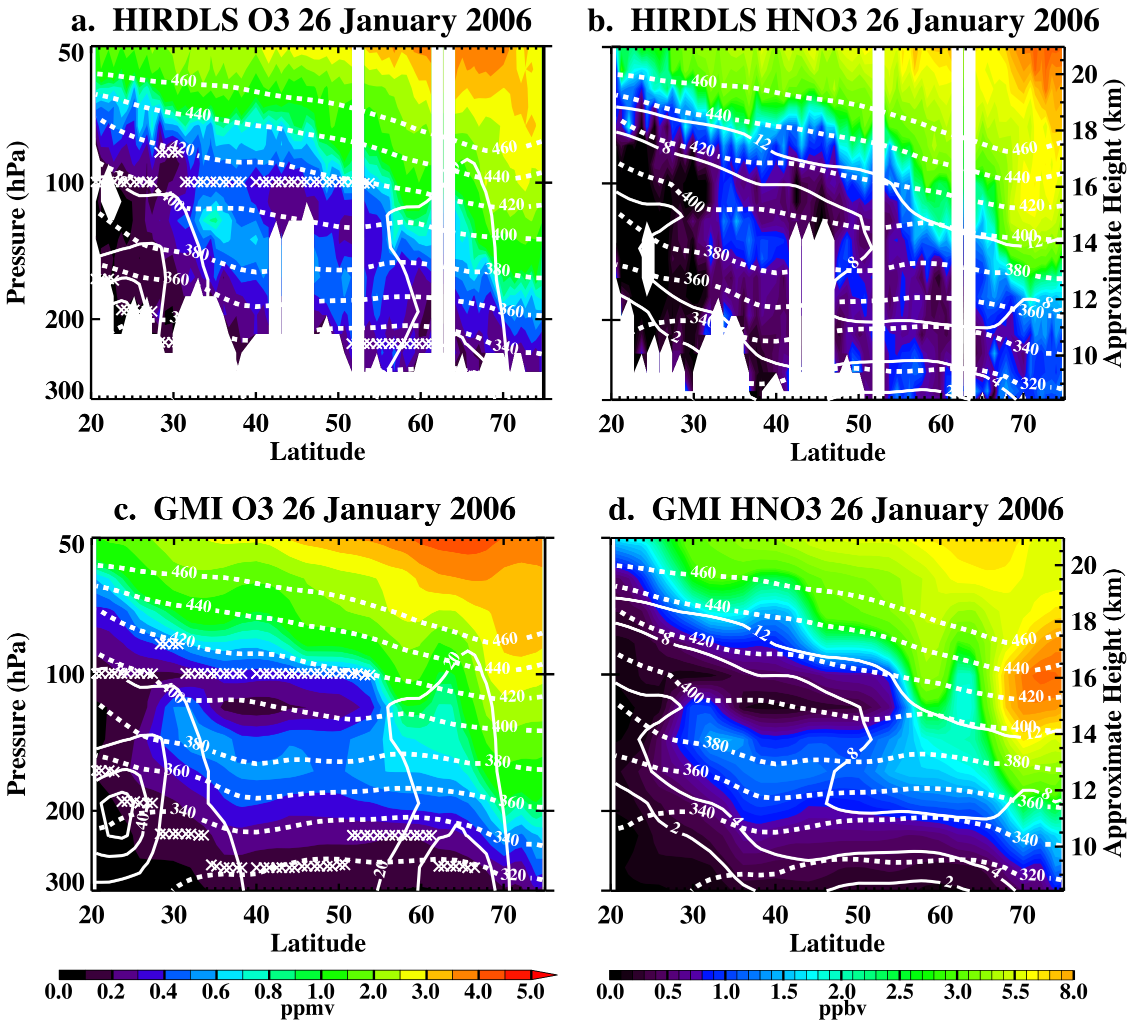

Figure 1. (a) HIRDLS observations of ozone and (b) nitric acid on 26 January 2006. (c) GMI simulation of ozone and (d) nitric acid on 26 January 2006. Horizontal location of the cross-section is shown in Figure 2a. Dashed white lines are isentropic surfaces in 20 K increments. Solid white contours in Figures 1a and 1c are the zonal wind field in 10 m s^{-1} increments starting at 20 m s^{-1}. Solid white lines in Figures 1b and 1d are the 2, 4, 8, and 12 PVU surfaces. The WMO lapse rate tropopause is indicated with a white "x" in Figures 1a and 1c. Meteorological fields are from the GEOS-4 DAS. Note nonlinear color scales.

retrieval algorithm that will incorporate refinements of the radiance correction needed to account for a partial blockage of the field of view and also include improved cloud detection and clearing algorithms. Here we demonstrate that the observed ozone and nitric acid structure agrees well with that produced using a chemistry and transport model (CTM), particularly at altitudes above ~200 hPa. The structure of the disturbance is emphasized, thus the biases are not considered in the comparisons and do not affect the conclusions of this work.

2.2. Chemistry and Transport Model and Simulation

[6] The chemical mechanism in this version of the GMI CTM represents photochemical processes in stratosphere and troposphere [*Strahan et al.*, 2007; *Duncan et al.*, 2007]. The model includes 117 species, 322 chemical reactions, and 81 photolytic reactions. Time-averaged meteorological fields from the Goddard Modeling and Assimilation Office (GMAO) GEOS-4 data assimilation system are input to the CTM. Time averaging the meteorological fields reduces spurious mixing and excessive residual circulation, thus improving the simulated transport [*Pawson et al.*, 2007]. The CTM has 42 levels with a vertical domain from the surface to 0.01 hPa. The vertical resolution is ~1 km in the UTLS and decreases with altitude. The horizontal resolution is 2° latitude × 2.5° longitude.

3. Results

[7] On 26 January 2006, HIRDLS measured relatively low concentrations of ozone in a thin layer around 100 hPa above North America. Figure 1a shows the vertical cross-section of observed ozone along the HIRDLS track. A ~ 2 km layer of low ozone mixing ratios between 400 K and 420 K potential temperature (near 100 hPa) extends over the subtropical jet to 55°N latitude. The minimum ozone mixing ratio in this layer is 0.21 ppmv, typical of the tropical lower stratosphere and substantially less than the monthly zonal mean. Like ozone, nitric acid (HNO_3) can be used to determine the origin of air in the lower stratosphere

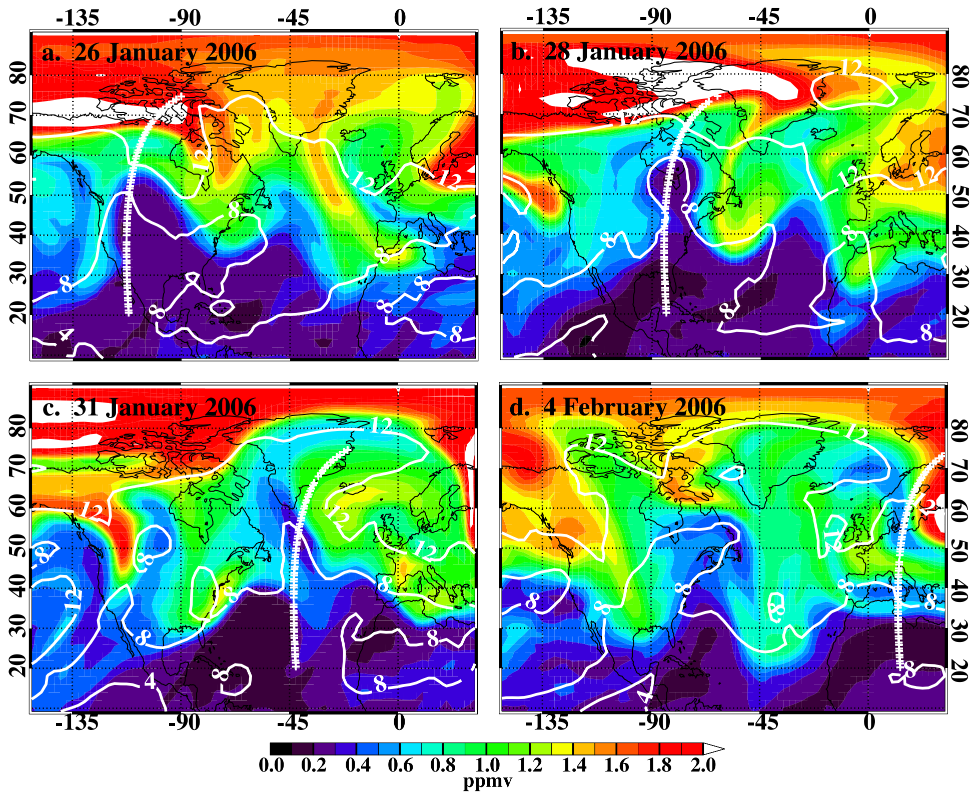

Figure 2. GMI simulated ozone on the 405 K surface for (a) 26 January 2006, (b) 28 January 2006, (c) 31 January 2006, and (d) 4 February 2006. Area shown is between 10°N and 90°N latitude and 150°W and 30°E longitude. Latitudes and longitudes are shown around outside edges. White lines are the 4, 8, and 12 PVU contours from GEOS-4 DAS. Plus symbols show the locations of HIRDLS measurements for the cross-sections shown in Figures 1 and 3. Note different color scale from the ozone profiles in Figures 1a, 1c, and 3.

because its lifetime is long and its mean stratospheric mixing ratio is much larger than its mean tropospheric mixing ratio. The HIRDLS profiles of nitric acid along the same track show a similar layer of low mixing ratios (Figure 1b). This suggests that the air in the layer has been transported from the tropical lower stratosphere. The low mixing ratio layer follows the 8 PVU (Potential Vorticity Units, where 1 PVU = 10^{-6} m^2 K kg^{-1} s^{-1}) potential vorticity contour in Figure 1b (white line), consistent with adiabatic, frictionless transport.

[8] Figures 1c and 1d show the GMI simulation of ozone and nitric acid, interpolated horizontally to the HIRDLS observation locations. The simulated cross-sections are smoother due to the coarse horizontal resolution of the CTM compared with HIRDLS and some point-to-point HIRDLS noise. Simulated layers of air with low mixing ratios of ozone and nitric acid between about 395 K and 415 K, extending to 55°N, correspond well with the feature observed by HIRDLS. The minimum ozone mixing ratio in the simulated layer is 0.13 ppmv, about 10% of the monthly zonal mean. Overall, the structure of the ozone cross-section is well-reproduced above 11 km. The simulated nitric acid is likewise consistent with the observations. In both cases (and in all later comparisons of the ozone field), the observations below 11 km are more variable and tend to have higher mixing ratios than in the simulation. For the remainder of this study we only consider the evolution of the observed and simulated ozone structure above 11 km (~200 hPa). The evolution of the nitric acid field is similar to that of ozone.

[9] The quasi-horizontal nature of the low ozone layer is consistent with isentropic poleward advection from the lower tropical stratosphere. We examine the evolution of this event on 405 K isentropic maps of simulated ozone (Figure 2) and with vertical cross-sections (Figure 3). The 405 K surface is near the center of the simulated layer of low ozone (Figure 1c). We also provide an auxiliary animation (Animation S1) of reverse domain filled (RDF) [*Sutton et al.*, 1994; *Newman and Schoeberl*, 1995] modified potential vorticity (MPV) [*Lait*, 1994].[1] The left panel of the animation displays the analysis MPV from the National Meteorological Center (NMC, now known as the National Centers for Environmental Prediction) reanalysis dataset. The right panel shows the RDF field. In this case, five-day back-trajectories are used for the RDF and are initialized every three hours. Each parcel's MPV at the earlier time is then mapped forward to the parcel's location at initialization. The conservative properties of the RDF MPV are used to determine the transport characteristics of the event.

[10] On 26 January 2006 the simulation shows a broad (~30° longitude in width) northward excursion of air with ozone concentrations less than 0.3 ppmv over the Midwestern and Western United States (Figure 2a). The HIRDLS

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL035514.

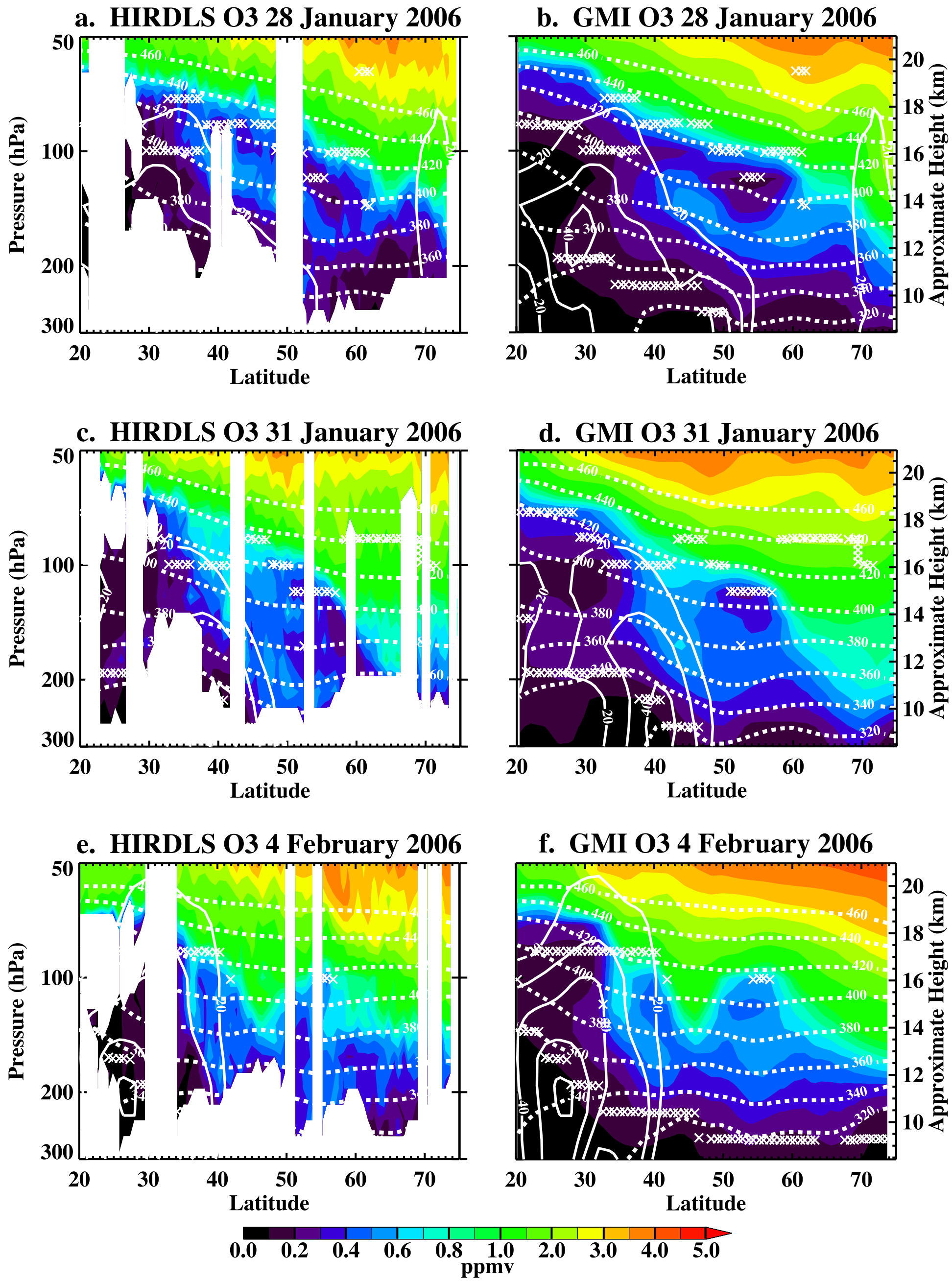

Figure 3. Cross-sections of HIRDLS ozone observations on (a) 28 January 2006, (c) 31 January 2006, and (e) 4 February 2006 and GMI ozone on (b) 28 January 2006, (d) 31 January 2006, and (f) 4 February 2006. Horizontal locations of the cross-sections are shown in Figure 2b–2d. Dashed white lines are isentropic surfaces in 20 K increments. Solid white contours are the zonal wind field in 10 m s^{-1} increments starting at 20 m s^{-1}. The WMO lapse rate defined tropopause is indicated with a white "x". Meteorological fields are from the GEOS-4 DAS. Note nonlinear color scale.

ground track, from which the vertical cross-section in Figure 1a was taken, passes through the western edge of the intrusion. The simulated layer is thinnest on this western side where the intrusion overruns air with mixing ratios typical of the extratropical lower stratosphere. The minimum simulated ozone mixing ratio interpolated to the HIRDLS track between 35°–53°N is 0.21 ppmv. The minimum HIRDLS mixing ratio interpolated to the 405 K surface is 0.27 ppmv. These values are typical of the tropical lower stratosphere as can be seen in Figure 2. The mean simulated ozone mixing ratio is 0.25 ppmv along the track at 405 K between 35°–53°N. Within these boundaries, the average measured ozone is 0.39 ppmv. The origin of the air can be identified from the streamers of constant MPV in Animation S1. The overrunning layer at 405K near the western edge of the low ozone intrusion is advected from the south and west of the HIRDLS track in Figure 2a. The middle to eastern area of the poleward excursion is less "layer-like" with low ozone mixing ratios extending down through the upper-troposphere in the simulation (not shown). The animation demonstrates that the air in this region at 405 K is advected from the relative south and east.

[11] Two days later, the minimum of the intrusion is pushed by southwesterly flow to Southern Canada near Hudson's Bay and has become more circular and cutoff, with only a narrow connection to the low ozone air over the Eastern United States (Figure 2b). The region of the intrusion with lowest ozone (less than 0.3 ppmv) lies primarily between 50°N and 60°N and covers about 5% of the total zonal area between these latitudes. The potential vorticity in the area of the intrusion is less than 8 PVU, consistent with the westernmost part of the intrusion two days earlier. The HIRDLS track crosses the minimum of the simulated intrusion. The vertical profiles of the observed and simulated ozone in Figures 3a and 3b show that the advection is primarily isentropic with little change in the potential temperature of the intrusion compared with 26 January (Figures 1a and 1b). The structure of the ozone field above 11 km altitude is well simulated compared to the observations.

[12] By 31 January, the intrusion has moved to the North Atlantic with the lowest ozone mixing ratios at 405 K occurring near 45°W south of Greenland (Figure 2c). A streamer of low latitude air stretches poleward and eastward at 80°N. HIRDLS profiles along the streamer (not shown) exhibit low ozone values at these altitudes, consistent with the simulation. A HIRDLS ground track passes through the ozone minimum between 50°N and 60°N as shown in Figure 2c. A region of low ozone values (less than about 0.4 ppmv) extends poleward and downward from around 15 km and 50° latitude (Figure 3c). The simulation cross-section also exhibits this poleward and downward structure (Figure 3d).

[13] The intrusion streamer has started to split by 4 February with higher ozone mixing ratios near 60°N just west of the prime meridian (Figure 2d). A large area of low mixing ratios from the streamer is found over the Norwegian Sea into Northern Europe. Along the HIRDLS track, the minimum mixing ratio in this part of the streamer is 0.49 ppmv and 0.54 ppmv as simulated and measured, respectively. The northern part of the streamer remnant over the Norwegian Sea is $\sim$8% of the total zonal area between 65°N and 75°N. However, most of the air mass of lowest ozone seen south of Greenland on 31 January has advected back to lower latitudes over the Mediterranean around 5°E and 40°N. The HIRDLS profiles show that this returning low ozone layer extends between about 37°N and 42°N (Figure 3e). The simulated vertical structure and features in Figure 3f agree well with the HIRDLS observations above $\sim$200 hPa altitude. In particular, both show a thin band of high mixing ratios at 36°N separating the returning layer from the subtropical air mass. The separation of this returning layer and the remnant around 54°N is also well simulated. The minimum simulated mixing ratio of ozone at 405 K along the HIRDLS track within the returning air mass is 0.48 ppmv and measured as 0.38 ppmv. The simulation is 0.27 ppmv greater than the minimum along the earlier track on 28 January, while the observation is 0.11 ppmv greater.

4. Discussion and Conclusions

[14] We have examined the evolution of a $\sim$2 km thin intrusion of tropical lower stratospheric air into the high latitude lower stratosphere using observations from HIRDLS and a GMI CTM simulation. We have shown that the observed and simulated ozone structure above $\sim$200 hPa and its evolution are represented well by the CTM. At higher pressures, the observations show much more variability and are inconsistent with the simulation.

[15] The initial intrusion (26 January) develops over the subtropical jet, consistent with the studies of *Haynes and Shuckburgh* [2000] and *Berthet et al.* [2007]. By 31 January, relatively low ozone air is advected up to 80°N. Subsequently, much of the layer mass returns to low latitudes. Increasing mixing ratios with time in the observed and simulated intrusion suggest mixing of the subtropical and extratropical air masses; thus the event is not entirely reversible. Such mixing is consistent with previous studies that have shown the potential for irreversible mixing increases across stretched structural boundaries [e.g., *Vaughan and Timmis*, 1998].

[16] Low ozone layers, similar to the event studied here, are seen relatively frequently in HIRDLS data at potential temperatures above the subtropical jet. In the present case study, the locations where the analysis lapse rate is less than 2 K km^{-1} are noted in the vertical profiles (Figures 1 and 3). This value corresponds to the WMO tropopause definition lapse rate criteria [*WMO*, 1986]. Throughout this event lifetime, the intrusion is associated with a secondary, extratropical tropopause near 100 hPa. *Randel et al.* [2007] notes the frequent occurrence of secondary extratropical tropopauses associated with low stability layers above the level of the subtropical jet. Similar to the event examined here, these secondary tropopauses are likely related to poleward intrusion events, as a layer of lower stability is transported poleward above the subtropical jet. Together, the common occurrence of low ozone layers seen by HIRDLS and secondary tropopauses found by *Randel et al.* [2007] suggest that this rapid poleward advection of air with relatively young stratospheric age is an important pathway for transporting air with low mixing ratios of ozone and high mixing ratios of tropospheric source gases into the lower extratropical stratosphere from the tropical upper troposphere and lower stratosphere.

[17] The amount of sub-tropical air transported poleward in a single intrusion can be a significant fraction of the total zonal mass at a given level. On 28 January, the simulated intrusion of the present study was $\sim$5% of the zonal area between 50°N and 60°N on the 405 K surface. Likewise, on 4 February, the area of the streamer between 65°N and 75°N was $\sim$8% of the zonal area. Ozone is an important radiative species at these altitudes and the presence of low ozone air can significantly impact the radiative balance [e.g., *Ramanathan et al.*, 1987]. Thus, these intrusion events and the associated transport must be well reproduced by simulations when considering the mean radiative budget.

[18] Finally, HIRDLS provides global constituent and tracer transport observations with high vertical resolution, comparable to that of many state of the art global chemistry and transport models. This study demonstrates the value of HIRDLS observations to model studies quantifying the importance of laminar isentropic transport to the lower stratospheric ozone budget.

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A. R. Douglass, P. A. Newman, and M. A. Olsen, NASA Goddard Space Flight Center, Mailstop 613.3, Greenbelt, MD 20771, USA. (mark.olsen@nasa.gov)

J. C. Gille, Center for Limb Atmospheric Sounding, University of Colorado, Boulder, CO 80309, USA.

R. Khosravi, D. E. Kinnison, B. Nardi, and V. A. Yudin, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, USA.