

## POPULAR SUMMARY

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

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The troposphere is the lowest layer of the atmosphere. It extends from the surface to an altitude of about 10.5 miles in the tropics and to about 7.5 miles altitude over places at middle latitudes like Washington, D.C. The next layer of air above the troposphere is the stratosphere, extending to about 30 miles altitude. Natural atmospheric ozone is primarily produced in the tropical upper stratosphere and transported towards the poles where it can descend into the troposphere. Approximately 90% of atmospheric ozone is in the stratosphere. The remaining 10% is found in the troposphere. The sources of tropospheric ozone include pollution, chemistry, and transport from the stratosphere. Determining how much tropospheric ozone exists due to human activity relies on knowing how much enters from the stratosphere. Thus, an understanding of what determines the ozone budget in the upper troposphere and lower stratosphere is required.

There is large-scale descent in the extratropical stratosphere, bringing ozone rich air from the upper stratosphere down to the lower stratosphere where it can descend into the troposphere. Smaller scale horizontal transport mixes ozone poor air into the extratropical lower stratosphere from the tropical upper troposphere and lower stratosphere. The amount of this mixing has yet to be determined. Previous satellite measurements have lacked the vertical detail to adequately observe these vertically thin mixing events. This study shows that the High Resolution Dynamic Limb Sounder (HIRDLS) on NASA's Aura satellite is capable of resolving these kinds of events. A January 2006 event is simulated using the Global Modeling Initiative (GMI) chemistry and transport model. The model output and HIRDLS observations are shown to agree well throughout the lifetime of the event, about eleven days. During this time, ozone poor air is transported from the tropical lower stratosphere to within 700 miles of the North Pole in a vertically thin and horizontally narrow layer. Both the simulation and observations show evidence of some mixing of the ozone poor air into the extratropical stratosphere. However, much of the air mass returns to the subtropics. This study using HIRDLS observations combined with simulation is a first step towards developing a better understanding of the lower stratospheric ozone budget.

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## **Abstract**

On 26 January 2006, the High Resolution Dynamic Limb Sounder (HIRDLS) observed low mixing ratios of ozone and nitric acid in a  $\sim 2$  km vertical layer near 100 hPa extending from the subtropics to  $55^\circ$  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  $80^\circ$ N. Although there is evidence of mixing with extratropical air and diabatic descent, much of the tropical intrusion returns to the subtropics. This study demonstrates that HIRDLS and the GMI model are capable of resolving thin intrusion events. The observations combined with simulation are a first step towards development of a quantitative understanding of the lower stratospheric ozone budget.

## 1. Introduction

Previous theoretical studies have shown that waves produce isentropic mixing in the upper troposphere and lower stratosphere (UTLS) and that wave mixing events are frequently relatively thin layers. Such isentropic transport can exchange mass directly between the troposphere and stratosphere, as well as between the tropical and extratropical lower stratosphere. In the case of cross-tropopause transport, *Dethof et al.* [2000] used the contour advection method with model analyses to demonstrate this wave-driven isentropic exchange of mass. *Vaughan and Timmis* [1998] studied a thin layer of low ozone mixing ratio observed by ozonesondes at midlatitudes. The layer was shown to be of subtropical origin. Part of the layer subsequently mixed with LMS air before the bulk of it returned to the subtropics.

Above the tropical tropopause, isentropic poleward advection has been shown to transport air with young stratospheric “age” and tropical UTLS composition to mid and high latitudes. *Waugh* [1996] used contour advection to show wave-driven poleward advection of subtropical air to the extratropics within the 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 the initial NH meridional transport was confined to altitudes just above the tropical tropopause. *Newman and Schoeberl* [1995] examined aircraft data from the Stratosphere Troposphere Exchange Project (STEP) and illustrated that differential advection by Rossby waves can generate vertically thin ozone laminae in the lower stratosphere.

Previous satellite instruments do not have sufficient vertical resolution to resolve vertically thin wave mixing events in the lower stratosphere. Thus, direct observational validation throughout the lifetime of an intrusion event simulation has not been possible. With  $\sim 1$  km vertical resolution, 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**

### *(a) HIRDLS*

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 v003 Level-2 HIRDLS observations of

ozone and nitric acid. The vertical resolution is  $\sim 1$  km and profiles are spaced  $\sim 65$  km along the track.

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 1-2 K warm from 10-100 hPa, but  $\sim 1$  K cool from there to 400 hPa. Reduction of these biases is expected in future versions of the 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  $\sim 200$  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.

*(b) Chemistry and transport model and simulation*

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 x 2.5° longitude.

### 3. Results

On 26 January 2006, HIRDLS measured relatively low concentrations of ozone in a thin layer around 100 hPa above North America. Figure 1a (top left) 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 ozone mixing ratios in this layer are typical of the tropical lower stratosphere. Like ozone, the lifetime of nitric acid (HNO<sub>3</sub>) is much greater in the lower stratosphere than the troposphere and can be useful in determining the origin of air. The HIRDLS profiles of nitric acid along the same track show a similar layer of low mixing ratios (Fig. 1b, top right). 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<sup>-6</sup> m<sup>2</sup> K kg<sup>-1</sup> s<sup>-1</sup>) potential vorticity contour in Figure 1b (white line), consistent with adiabatic, frictionless transport.

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. Overall, the structure of the ozone cross-section is very 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 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.

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 (Fig. 2) and with vertical cross-sections (Fig. 3). The 405 K surface is near the center of the simulated layer of low ozone (Fig. 1c, bottom left). We also provide a supplementary animation of reverse domain filled (RDF, [Sutton *et al.*, 1994; Newman and Schoeberl, 1995]) modified potential vorticity (MPV, [Lait, 1994]). 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.

On 26 January 2006 the simulation shows a broad ( $\sim 30^\circ$  longitude in width) northward excursion of air with low ozone concentrations over the Midwestern and Western United States (Fig. 2a, top left). The HIRDLS 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 origin of the air can be identified from the streamers of constant MPV in the supplementary animation. 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.

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 (Fig. 2b, top right). The region of the intrusion with lowest ozone (less than 0.4 ppmv) lies primarily between  $50^\circ$  N and  $60^\circ$  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,b show that the advection is primarily isentropic with little change in the potential temperature of the intrusion compared with 26 January (Figs. 1a,b). The structure of the ozone field above 11 km altitude is well simulated



compared to the observations. Similar to the profiles on 26 January, the HIRDLS retrievals indicate regions of high ozone below 11 km that are not simulated.

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 (Fig. 2c, bottom left). 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 Fig. 2c. The HIRDLS vertical profiles show low mixing ratios between about 380 K and 400 K (~ 12.5 km to 14 km) near 60° N extending from the minimum at 15 km altitude at 52° N (Fig. 3c). The simulation cross-section also shows relatively low values of ozone extending downward and poleward from the minimum at 15 km, suggesting diabatic descent of the intrusion.

The intrusion streamer has started to split by 4 February with higher ozone mixing ratios near 60° N just west of the prime meridian (Fig 2d). A large area of low mixing ratios from the streamer is found over the Norwegian Sea into Northern Europe. The northern part of the streamer remnant over the Norwegian Sea is ~ 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 from 380 K to 420 K between 37° N and 42° N (Fig. 3e). The simulated vertical structure and features in Fig. 3f agree well with the HIRDLS observations above ~ 200 hPa altitude. Although still less than the surrounding air, the

mixing ratio of ozone within the returning air mass is more than double of that within the intrusion on 28 January in both the observations and simulation.

#### **4. Discussion and Conclusions**

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.

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  $80^\circ$  N. Subsequently, much of the layer mass returns to low latitudes. However, the event is not entirely reversible. Cross-isentrope descent indicates diabatic cooling in both the observations and simulation after 28 January. Also, the increasing mixing ratios with time in the observed and simulated intrusion suggest mixing of the subtropical and extratropical air masses. 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].

Low ozone layers, similar to the event studied here, are seen relatively frequently in HIRDLS data. In the present case study, the locations where the analysis lapse rate is less than  $2 \text{ K km}^{-1}$

are noted in the vertical profiles (Figs. 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. 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.

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  $50^\circ$  N and  $60^\circ$  N on the 405 K surface. Likewise, on 4 February, the area of the streamer between  $65^\circ$  N and  $75^\circ$  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.

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.

## Acknowledgements

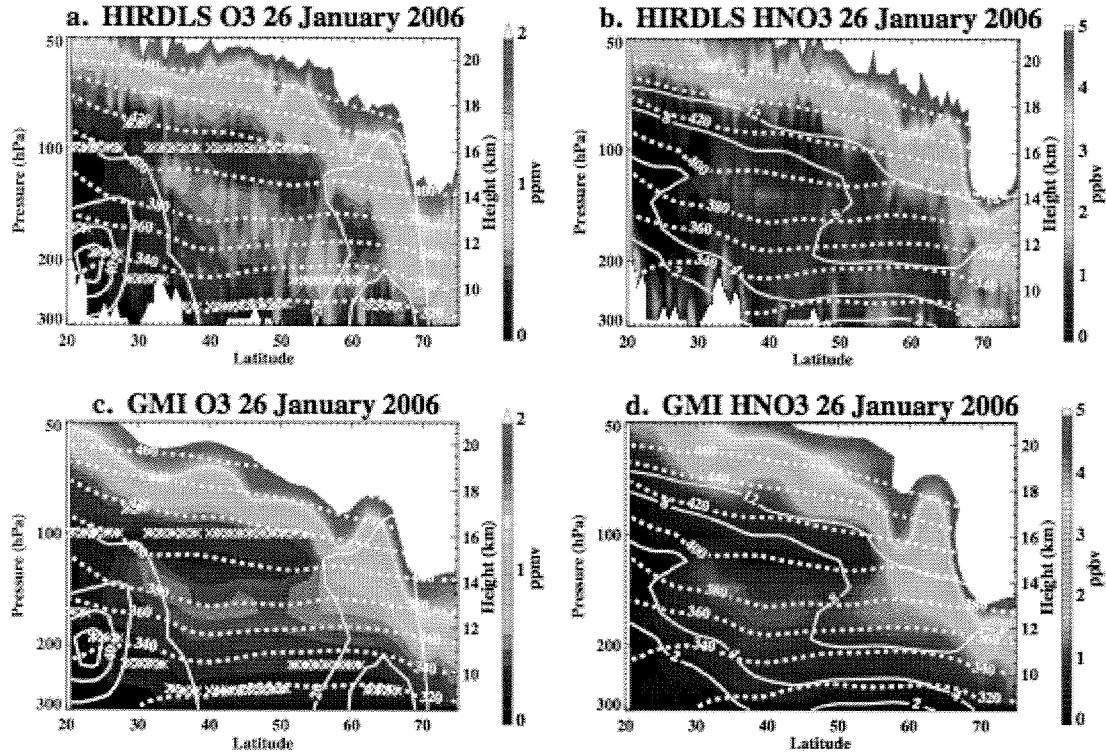
This work was supported by NASA's EOS IDS and ACMAP programs.

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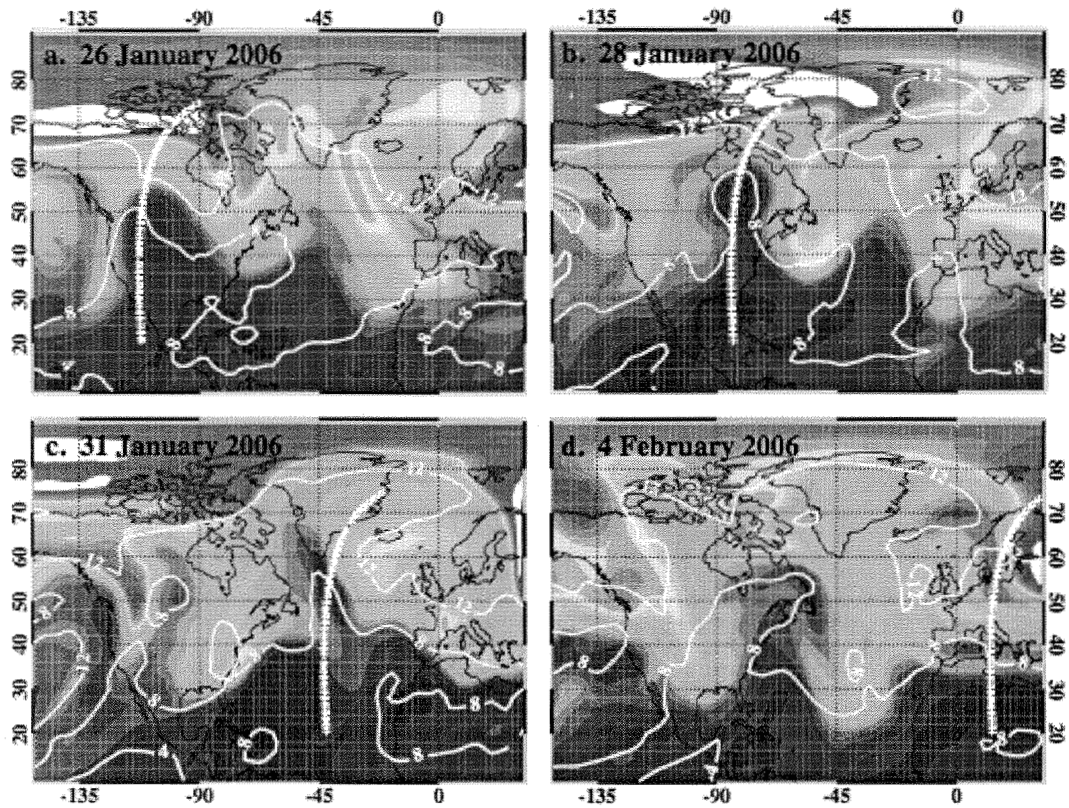
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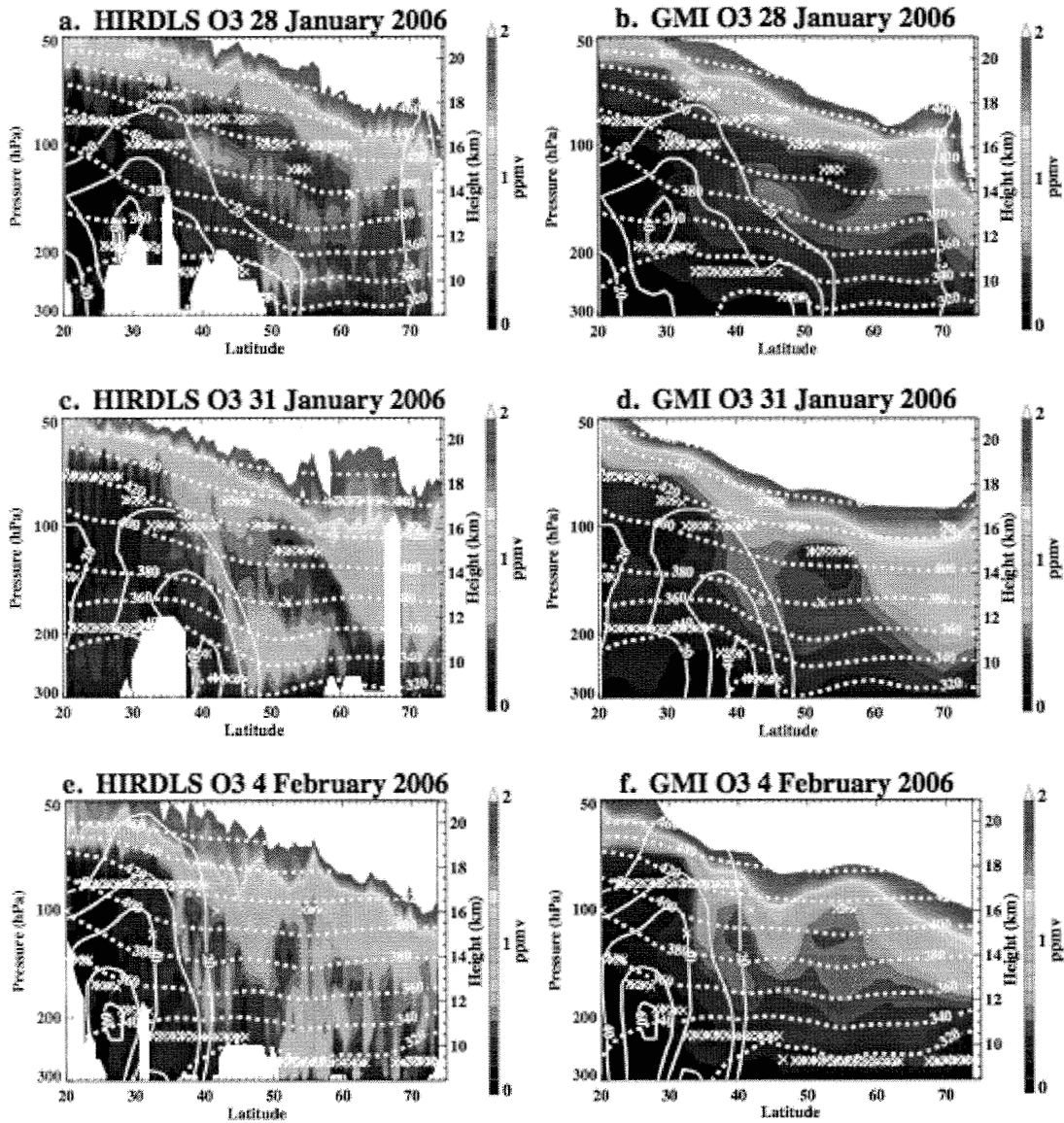
## Figures



**Figure 1.** (a) HIRDLS observations of ozone and (b) nitric acid on 26 January 2008. (c) GMI simulation of ozone and (d) nitric acid on 26 January 2008. 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 (a) and (c) are the zonal wind field in  $10 \text{ m s}^{-1}$  increments starting at  $20 \text{ m s}^{-1}$ . Solid white lines in (b) and (d) are the 2, 4, 8, and 12 PVU surfaces. The WMO lapse rate tropopause is indicated with a white "x" in (a) and (c). Meteorological fields are from the GEOS-4 DAS.



**Figure 2.** GMI simulated ozone on the 405 K surface for (a) 26 January 2008, (b) 28 January 2008, (c) 31 January 2008, and (d) 4 February 2008. Area shown is between 10° N and 90° N latitude and 150° W and 30° E longitude. 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. Color scale is the same as for the ozone profiles in Figures 1a,c and 3.



**Figure 3.** Cross-sections of HIRDLS ozone observations on (a) 28 January 2008, (b) 31 January 2008, and (c) 4 February 2008. Horizontal locations of the cross-sections are shown in Figure 2b-d. Dashed white lines are isentropic surfaces in 20 K increments. Solid white contours are the zonal wind field in 10 m s<sup>-1</sup> increments starting at 20 m s<sup>-1</sup>. The WMO lapse rate defined tropopause is indicated with a white “x”. Meteorological fields are from the GEOS-4 DAS.