

The Carbon Monoxide Tape Recorder

M. R. Schoeberl, B. N. Duncan, A. R. Douglass
NASA Goddard Space Flight Center, Greenbelt, Md.

J. Waters, N. Livesey, W. Read
NASA Jet Propulsion Laboratory, Pasadena, Ca.

M. Filipiak
School of GeoSciences
The University of Edinburgh
Edinburgh, UK

Abstract

Using Aura MLS data we have identified the stratospheric ‘tape recorder’ in carbon monoxide (CO). Unlike the water vapor tape recorder, which is controlled by upper troposphere processes, the CO tape recorder is linked to seasonal biomass burning. Since CO has a lifetime of only a few months, the CO tape recorder barely extends above 20 km. The tape head for CO appears to be close to 360K near the same location as the water vapor tape head [Read et al, 2004]. Both tape heads are below the equatorial cold point tropopause but above the base of the tropical tropopause layer. The tape recorder signal becomes more distinct from 360K to 380K suggesting that convective detrainment of plays a decreasingly important role with altitude. The Global Modeling Initiative chemical transport model forced by the climatology of biomass burning reproduces the CO tape recorder.

1. Introduction

The identification of a tropical lower stratosphere temporal oscillation in the water vapor field was one of the most important discoveries of the Upper Atmosphere Research Satellite (UARS) [Mote et al., 1996, Randel et al., 2001]. Dubbed the “tape recorder” the UARS measurements showed that the seasonal variation of tropical water vapor concentration at the tropopause rises slowly into the stratosphere to almost 35 km before being disrupted by the stratospheric semiannual oscillation. A similar tape recorder type signal is seen in aircraft CO₂ measurements [Andrews

et al., 1999]. It would not be surprising if other tracers with seasonal variations in tropical forcing showed similar behavior. However, what is of special interest is the altitude of the base of the tape recorder or the “tape-head” because it bears on the theories of tropical dehydration of air as it enters the stratosphere.

There are two basic dehydration theories. Convective dehydration theories argue that deep tropical convection rising to the cold-point tropical tropopause dehydrates air before entering the stratosphere [Newell and Gould-Stewart, 1981; Danielsen, 1982]. In this case the tape-head would be

located at the cold point tropopause (CPT) at 375K (~17-17.5 km) [Gettelman and Forester, 2002]. Support for convective dehydration comes from observation of convective events overshooting the tropopause and from measurements of HDO/H₂O fractionation [Moyer, et al., 1996; Webster and Heymsfield, 2003] that show that the stratosphere is isotopically heavy. Ice formation depletes HDO from the surrounding air mass. Thus if the stratosphere is isotopically heavier than predicted by the Rayleigh fractionation curve, then convection must be dominating the physics of the region.

Alternatively, cold-trap dehydration theories argue that the air is dehydrated as it slowly ascends through the upper troposphere [Brewer, 1949; Hartmann et al, 2001; Holton and Gettelman, 2001, Jensen and Pfister, 2004, Fueglistaler et al., 2005, and others]. In this case, the tape-head would be located below the cold-point tropopause. Read et al. [2004] using reprocessed UARS Microwave Limb Sounder (MLS) data noted that the water vapor tape-head appears to be located near 150-100 hPa - below the CPT.

If the tape head is located below the cold point tropopause, as found by Read et al [2004], wouldn't convective mixing and detrainment disrupt the tape recorder? Sherwood and Dessler [2002] point out that since convective detrainment decreases rapidly with altitude it is possible for the tape recorder to be

minimally impacted by convection between the tape head and the CPT, but convection could still act to dehydrate air in the upper tropopause [Sherwood and Dessler, 2000].

CO measurements provide an additional constraint on the transport of trace gases and water into the stratosphere. CO is lofted by deep tropical convection into the upper troposphere but, unlike H₂O, is not removed by condensation. Thus CO is a pure measure of transport processes.

Time variations of CO in the upper troposphere are due to a combination of the seasonal and spatial patterns of CO surface sources, especially agricultural burning [Duncan et al., 2003], and the seasonal movement of deep convection relative to the sources. In the troposphere, CO is produced by the oxidation of CH₄ and nonmethane hydrocarbons, and by incomplete combustion. It is predominantly removed by an oxidation reaction with OH [e.g., Levy, 1971; Crutzen, 1973].

2. MLS Observations of CO

The Aura MLS instrument and data are described in Waters et al. [2006] and the specifics of the level 2 data are described in JPL publication D-32381 available at <http://mls.jpl.nasa.gov>. CO is retrieved from the MLS 240 GHz channel. The vertical resolution is about 4 km in the upper troposphere and lower stratosphere.

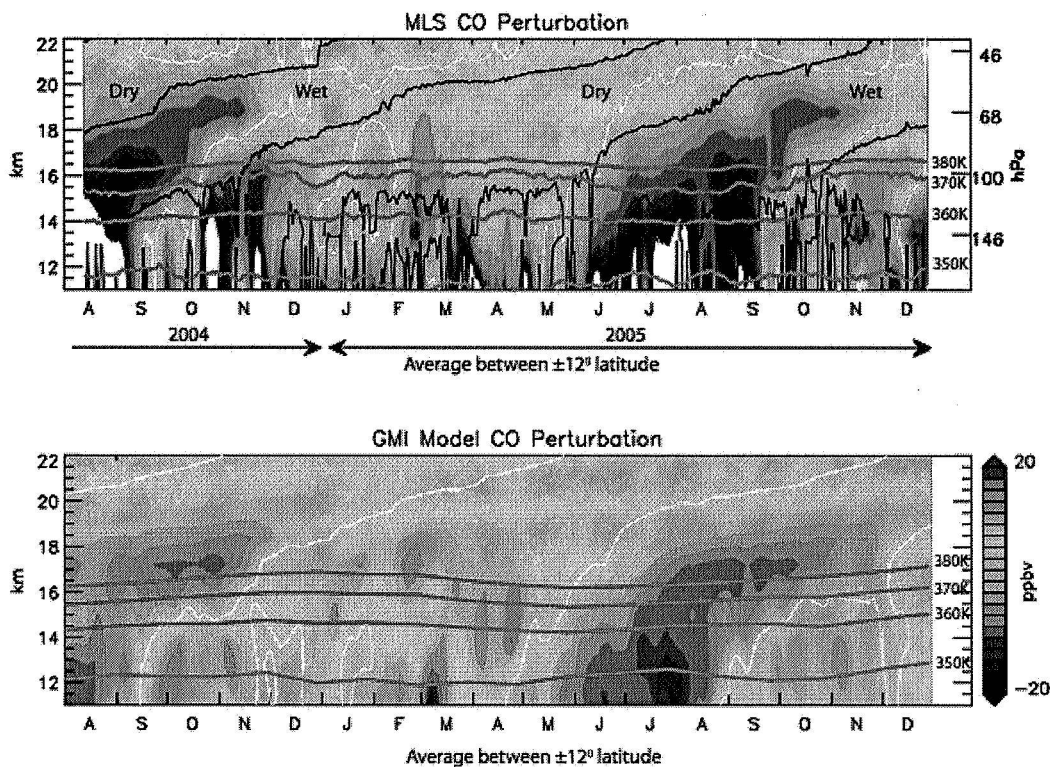


Figure 1. Part a, zonal mean MLS CO data with the annual average removed verses time (months). Altitude scale is $7 \text{ km} \log(1000/p)$ where p is pressure. Black lines show the zero contour for MLS water vapor tape recorder with 'wet' and 'dry' labels indicating the sign of the perturbation. White contours are zero lines for CO data. Right hand scale shows pressure levels for MLS level 2 data. Pink lines show the zonal mean potential temperature surfaces (350-380K). Part b, GMI chemical transport model CO simulation using climatological sources. The GMI chemical model is driven by the GEOS-4 GCM meteorology with 1994-5 observed sea surface temperature forcing.

Fig. 1a shows the zonal mean MLS CO with the annual average removed. Data is area averaged between $\pm 12^\circ$ latitude. Missing or bad data are filled in by interpolating from nearby days. The figure also shows the phase lines of the H_2O tape recorder. MLS H_2O measurements are averaged over the same region.

The figure shows a high degree of time variability below 360K associated with convective lofting of CO. Above 360K CO variations show a temporal phase lag with height. The H_2O tape recorder zero phase lines show that the CO and H_2O

have nearly the same phase change with height thus identifying the structure of CO above 16 km as the CO tape recorder.

The zone where the zero phase lines begin to tilt is the tape-head. This is likely the zone above which convective detrainment is less important than diabatic uplift. Overall, the tape head for CO roughly located at 360K ($\sim 14 \text{ km}$ or $\sim 130 \text{ hPa}$). This is below the CPT ($\sim 375\text{K}$) but above 350K, usually considered to be the base of the tropical tropopause layer (TTL). The cloud free diabatic heating rate changes sign at approximately 360K [Gettelman and

Forster, 2002]. The MLS H₂O observations also show that the “tape head” lays below the CPT but above the base of the TTL in agreement with Read et al. [2004].

The CO tape recorder signal fades out above 20 km. Since the CO lifetime is only 1-2 months at these altitudes the rapid decrease in CO abundance is expected.

To summarize, the CO tape recorder signal suggests that overall convection and detrainment in the TTL becomes less important than diabatic uplift above 360K. But exceptions occur. For example, in February and April 2005 intermittent high values of CO appear above 380K connected to very high values below. In general, Fig. 1a shows that the tape recorder signal in both CO and H₂O is somewhat ragged between 360K and 380K suggesting that some regular disruption by convection [Dessler, 2002].

Fig. 1b shows the Global Modeling Initiative (GMI) Chemical Transport Model (CTM) simulation of CO averaged between $\pm 2^\circ$ latitude. This simulation uses meteorological variables from the GEOS-4 atmospheric GCM with 1994-6 sea surface temperatures (SST), although only mid-1994-1995 are shown in Fig. 1b, and climatological CO sources. Variation in tropical SSTs, especially associated with the ENSO phenomenon, drive much of the interannual variations observed in tropical convection. The period of MLS observations, mid-2004-5, experienced weak/moderate El Niño conditions until mid-2005 when weak La Niña conditions developed. These SST

conditions were similar to the 1994-5 period.

A description of the GMI combined stratosphere-troposphere (COMBO) model can be found in Ziemke et al. [2006]. Convective transport is similar to that used in the MATCH model [Rasch et al., 1997]. GEOS-4 GCM meteorological fields [e.g., Bloom et al., 2005] are used as input to compute cloud mass fluxes, entrainment and detrainment fluxes, and large-scale downwelling. Both shallow and deep convection are considered, following the algorithms of Hack [1994] and Zhang and McFarlane [1995]. For the upper troposphere and lower stratosphere, Douglass et al. [2003] and Schoeberl et al. [2003] show that the large-scale circulation, including stratosphere-troposphere exchange (STE), is realistic in a CTM driven by the GCM fields.

Despite the different years represented by the observations and model, Figs. 1a and 1b show remarkable agreement. In the lower stratosphere, the tape recorder signal fades out at about the same altitude and the phase lines show roughly the same tilt. In the upper troposphere, the model simulates the variation in CO throughout the season. This shows that the climatological forcing of surface CO emissions accounts for most of the variation in CO seen near the tropopause. The model and the MLS data agree on the location of the tape head at 360K within the resolution of the MLS data.

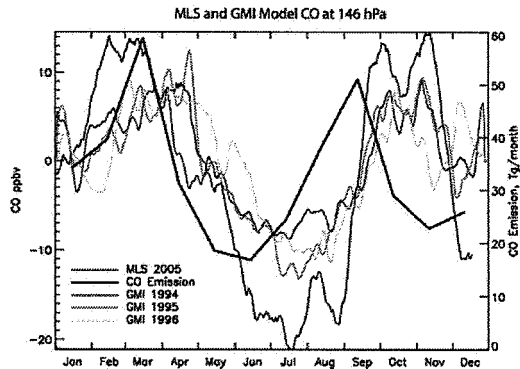


Figure 2. Comparison of three years of GMI model simulations (1994-6 SST) with 2005 MLS data at 146 hPa. Annual average has been removed. Also shown is the climatological biomass burning CO emission (30°N-30°S) used in the GMI model.

Fig. 2 shows a more detailed comparison between three years of GMI simulations and the 2005 CO observations from MLS at 146 hPa, roughly the altitude of the tape head. First, we note that the agreement between the model and the MLS observations is quite good. The two CO peaks are well simulated, but the GMI amplitudes are ~5-10 ppbv smaller than the observations. This could be due to weaker convective lofting and/or lower biomass burning emissions in the model than observed during the time of MLS measurements.

Comparing the climatological sources with the model and observed CO tells about which sources are feeding equatorial convection. Biomass burning CO is lofted by convection to the upper troposphere [Pickering et al., 1996] because of the proximity of the burning to large-scale monsoonal convection. Typically, fires are set preceding the arrival of seasonal rains to clear agricultural fields and pastures. The

relatively long lifetime (~1 month) of CO allows its regional and zonal burdens to grow throughout the burning season, increasing the likelihood that biomass burning CO will encounter convective transport to the upper troposphere.

The first peak in the model CO emission (Fig. 2) is largely due to biomass burning in Indochina while the second peak is mostly due to southern Africa and Brazil [Duncan et al., 2003]. The first peak in the MLS CO perturbation is earlier than in the model though the second peak is fairly coincident, indicating that the timing of emissions in early 2005 [BD1] is earlier than those in the model climatology consistent with observed fire counts. In some years the model CO remains elevated for a few weeks to more than a month after the decline in sources.

Figure 3[BD2] shows the 2005 MLS 146 hPa CO distribution for both peak periods. In Feb. and March, CO hot spots are largely centered on equatorial Africa and Indonesia. In October and November CO hot spots are in southern Africa and Brazil. In June-August, CO at 146 hPa is elevated over northern India and southeast Asia, but this is north of the tape recorder region. At 215 hPa, the CO maps (not shown here) show additional hot spots over Central America and along the ITCZ stretching from the Philippines to Hawaii. Apparently convection over these regions does not systematically penetrate to the 146 hPa level.

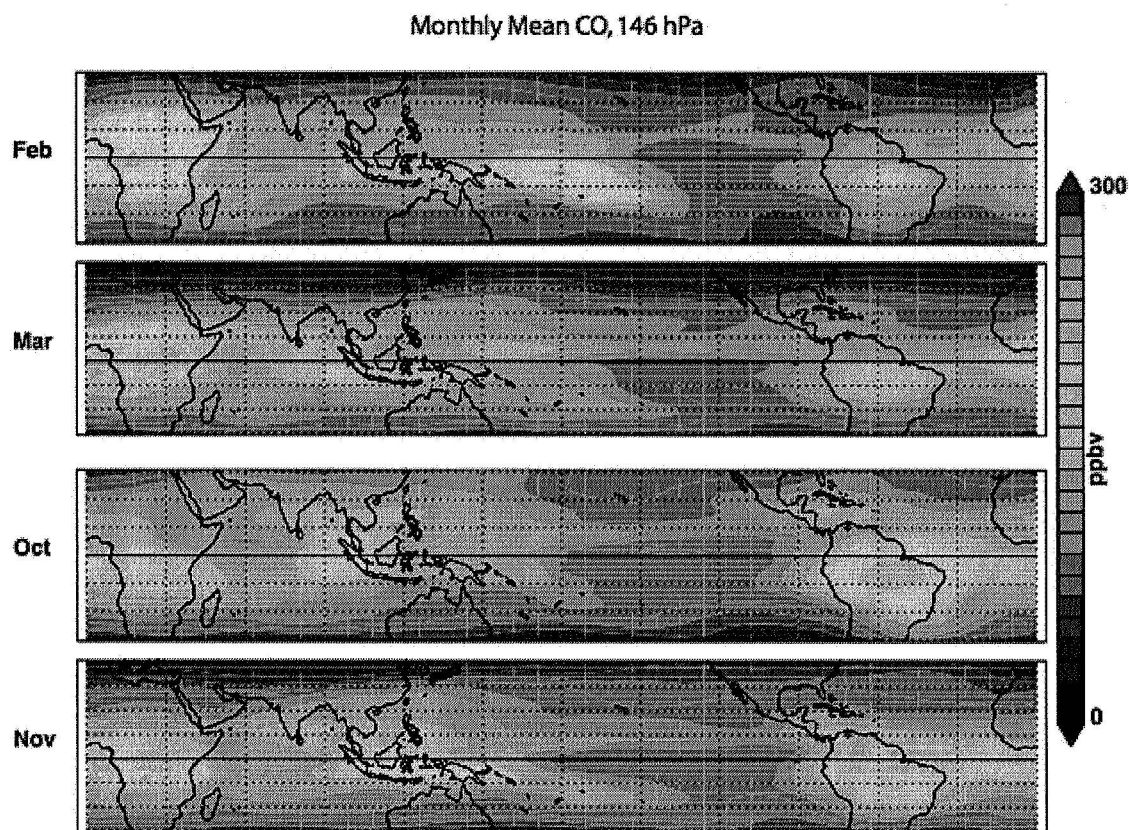


Figure 3 Monthly mean maps of MLS CO at 146 hPa for February, March, October and November.

3. Summary and conclusions

We have identified the CO tape recorder in the MLS data. The CO tape recorder owes its existence to the seasonal variation in CO surface sources and tropical convective transport to the TTL. The head of the tape recorder is located near 360K in agreement with the location of the tape head in the UARS MLS H₂O [Read et al., 2004]. This suggests that large scale diabatic processes dominate convective above 360K (~100 hPa). The boundary between these two regions is not sharp; however, and there occasionally periods where detraining convection appears to penetrate much higher than 380K.

Simulations of the CO tape recorder using the GMI CTM show good agreement with the observations. The twice-yearly peak in CO at the tropopause is due to the shift in biomass burning sources.

References

- Andrews, A. E., et al., Empirical age spectra for the lower tropical stratosphere from in situ observations of CO₂: Implications for stratospheric transport, *J. Geophys. Res.* 104, 26581-26595 1999.
- Brewer, A. W., Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere, *Q. J. R. Meteorol. Soc.*, 75, 351–363, 1949.
- Crutzen, P.J., A discussion of the chemistry of some minor constituents in the stratosphere and troposphere, *Pure App. Geophys.*, 106-109, 1385-1399, 1973.
- Danielsen, E. F., A dehydration mechanism for the stratosphere, *Geophys. Res. Lett.*, 9, 605–608, 1982.
- Dessler, A. E., The effect of deep, tropical convection on the tropical tropopause layer, *J. Geophys. Res.*, 107, 2002.
- Douglass, A. R., et al., Evaluation of transport in the lower tropical stratosphere in a global chemistry and transport model, *J. Geophys. Res.*, doi:10.1029/2002JD002696, 2003.
- Duncan, B. N., R. V. Martin, A. C. Staudt, R. Yevich, and J. A. Logan, Interannual and seasonal variability of biomass burning emissions constrained by satellite observations, *J. Geophys. Res.*, 108(D2), 4100, doi:10.1029/2002JD002378, 2003.
- Fueglistaler S., M. Bonazzola, P. H. Haynes, T. Peter, Stratospheric water vapor predicted from the Lagrangian temperature history of air entering the stratosphere in the tropics, *J. Geophys. Res.*, 110, D08107 2005
- Gettelman, A. and P. Forster, Definition and climatology of the tropical tropopause layer, *J. Met. Soc. Japan*, 80, 911-924, 2002.
- Gettelman, A. and C. R. Webster, Simulations of water isotope abundances in the upper troposphere and lower stratosphere and implications for stratosphere troposphere exchange, *J. Geophys. Res.*, 110, D17301, 2005
- Hartmann, D. L., J. R. Holton, and Q. Fu, The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration, *Geophys. Res. Lett.*, 28, 1969–1972, 2001
- Holton, J. R., and A. Gettelman, Horizontal transport and the dehydration of the stratosphere, *Geophys. Res. Lett.*, 28, 2799 –2802, 2001
- Jensen, E. J., and L. Pfister (2004), Transport and freeze-drying in the tropical tropopause layer, *J. Geophys. Res.*, 109, doi:10.1029/2003JD004022, 2004
- Levy, H. II, Normal atmosphere: Large radical and formaldehyde concentrations predicted, *Science*, 173, 141-143, 1971.
- Mote P. W. et al., An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor, *J. Geophys. Res.* 101, 3989-4006, 1996.

- Moyer, E. J., F. W. Irion, Y. L. Yung, and M. R. Gunson, ATMOS stratospheric deuterated water and implications for troposphere-stratosphere transport, *Geophys. Res. Lett.*, 23, 2385-2388, 1996.
- Newell, R. E., and S. Gould-Stewart (1981), A stratospheric fountain?, *J. Atmos. Sci.*, 38, 2789– 2796.
- Pickering, K.E., et al., Convective transport of biomass burning emissions over Brazil during TRACE A, *J. Geophys. Res.*, 101, 23,993-24,012, 1996.
- Randel, W. J. et al. Seasonal variation of water vapor in the lower stratosphere observed in Halogen Occultation Experiment data, *J. Geophys. Res.*, 106 14313-14325, 2001
- Rasch, P. J., et al., Representations of transport, convection, and the hydrologic cycle in chemical transport models : Implications for the modeling of short-lived and soluble species, *J. Geophys. Res.*, 102, 28,127-28,138, 1997.
- Read, W. G., D. L. Wu, J. W. Waters, and H. C. Pumphrey, Dehydration in the tropical tropopause layer: Implications from the UARS Microwave Limb Sounder, *J. Geophys. Res.*, 109, D06110, 2004.
- Schoeberl M. R., A. R. Douglass, Z. Zhu, and S. Pawson, A comparison of the lower stratospheric age spectra derived from a general circulation model and two data assimilation systems, *J. Geophys. Res.*, 108, 4113, doi:10.1029/2002JD002652, 2003.
- Sherwood, S. C., and A. E. Dessler, On the control of stratospheric humidity, *Geophys. Res. Lett.*, 27, 2513– 2516, 2000.
- Sherwood, S. C., and A. E. Dessler, A model for transport across the tropical tropopause, *J. Atmos. Sci.*, 58, 765–777, 2001.
- Waters, J., et al., The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite, *IEEE Trans. Geosci. and Remote Sensing*, (in press), 2006.
- Webster, C. R., and A. J. Heymsfeld, Water isotope ratios D/H, $^{18}\text{O}/^{16}\text{O}$, $^{17}\text{O}/^{16}\text{O}$ in and out of clouds map dehydration pathways, *Science*, 302, 1742-1745, 2003.
- Yevich, R., and J. A. Logan, An assessment of biofuel use and burning of agricultural waste in the developing world, *Global Biogeochem. Cycles*, 17 (4), 1095, doi:10.1029/2002GB001952, 2003.
- Ziemke, J.R., S. Chandra, B.N. Duncan, L. Froidevaux, and P.K. Bhartia, Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Tracer Model, under review in *J. Geophys. Res.*, 2006.

The Carbon Monoxide Tape Recorder

Popular Summary

As tropical air rises into the stratosphere it carries with it trace gases, such as CFC's that are responsible for ozone depletion. In 1996, scientists analyzing Upper Atmosphere Research Satellite water vapor data found to their surprise that tropical air once it entered the stratosphere did not mix rapidly, instead the air ascended very slowly retaining the trace gas signature imprinted in the lower atmosphere. This phenomenon was dubbed "the tape recorder". Water vapor values are "recorded" somewhere in the upper troposphere and the information ascends into the stratosphere like a magnetic tape moving away from the tape head. Water vapor amounts vary widely in the troposphere because water vapor is controlled by temperature which determines processes such as condensation and evaporation. The water vapor tape recorder thus carries information about the seasonal variation in the upper troposphere temperatures into the stratosphere.

In this paper we report the discovery of the carbon monoxide (CO) tape recorder using Aura Microwave Limb Sounding data. The imprint of CO at the tape head is quite unlike the imprint of water vapor because the CO concentration is not affected by temperature. The CO taper recorder instead carries information about the seasonal variations in tropical biomass burning, the major source of CO. The CO tape recorder can also tell us something new about the dynamics of the upper troposphere. In this paper we find that the tape head for CO and water vapor are approximately at the same altitude and that altitude is a few kilometers below the tropopause. This implies that tropical convection, which lofts CO from the boundary layer to the upper tropopause, does not control CO concentration all the way up to the tropopause. Convection's role in determining trace gas concentrations in the upper troposphere is limited and quickly fades above about 16 km (the tropopause is near 17.5 km). This result will help us improve our models of stratosphere-troposphere interaction and our ability to predict how the stratosphere will respond to climate change.

Schoeberl et al.