Interhemispheric differences in changes of long-lived tracers in the middle stratosphere over the last decade

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[1] Long-lived chemical species are analyzed to investigate the temporal variations of mixing ratios in the stratosphere from April 1992 through August 2004 using HALOE satellite observations. HF concentrations in the upper stratosphere increase at similar rates in both hemispheres. HF in the extratropical mid-stratosphere, however, has increased more rapidly in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH). CH_4 and H_2O show the similar long-term intensifications in their interhemispheric differences. The characteristic features in the long-term variability of the observed tracers are related to the residual circulation and stratospheric planetary wave activity. The increasing hemispheric asymmetries of the tracer mixing ratios are in good agreement with the change in the calculated residual circulation, strengthening over the last 12 years in the NH. This change of residual circulation is caused by the intensification of the stratospheric wave activity associated with upward propagating planetary waves in the NH. **Citation:** Youn, D., W. Choi, H. Lee, and D. J. Wuebbles (2006), Interhemispheric differences in changes of long-lived tracers in the middle stratosphere over the last decade, *Geophys. Res. Lett.*, *33*, L03807, doi:10.1029/2005GL024274.

1. Introduction

[2] Mixing ratios of long-lived chemical species in the stratosphere show significant global trends over the last decade [*Nedoluha et al.*, 1998; *Randel et al.*, 1999a; *Considine et al.*, 1999; *Anderson et al.*, 2000; *Rosenlof*, 2002]. These trends are driven by both chemistry and dynamics, but not all the reasons for these trends are understood. We are particularly interested in the long-time variability (trend) which might be related to global climate change.

[3] The global-scale distribution of long-lived tracers in the stratosphere is dynamically determined by the strength of meridional circulation known as the "Brewer-Dobson" (B-D) circulation. The strength of B-D circulation in the middle-to-upper stratosphere is primarily controlled by wave drag associated with the breaking planetary wave activity in winter hemisphere [*Plumb*, 2002].

[4] The focus of this study is on long-lived trace gases observed by the Halogen Occultation Experiment (HALOE) [*Russell et al.*, 1993] onboard the Upper Atmosphere Research Satellite (UARS). Several gases show similar long-term intensification of the hemispheric differences (NH-SH asymmetry) in their mixing ratios in the extratropical middle stratosphere during the period May 1992 through August 2004. The purpose of this paper is to suggest a likely cause for this increasing interhemispheric asymmetry. Based on the United Kingdom Meteorological Office (UKMO) assimilated meteorological fields for the UARS time period [*Swinbank and O'Neill*, 1994; *Coy and Swinbank*, 1997] along with the observed tracers, we find relationships among the long-time variation of observed tracers, residual mean meridional circulation, and stratospheric wave activities (the eddy heat flux and the Eliassen-Palm flux divergence, EPFD).

[5] The UKMO assimilation system has undergone major changes, especially in November 2000 (http://badc.nerc.ac.uk/community/news/001115_assim.html), but analyses of the period before 2000 as well as comparisons with other data set indicate our results are not affected by this change. It is shown that the meridional distribution of observed tracer isolines related to the asymmetry in the extratropical middle stratosphere is well matched with changes in residual circulation and planetary wave activities.

2. NH-SH Asymmetry in Tracer Trends

[6] Zonally-averaged mixing ratios of HALOE trace gases were interpolated to produce the regularly-gridded data for the 15th day of each month to be used as "monthly mean" data. The Delaunay triangulation interpolation method [*de Berg et al.*, 2000] is used to construct connected triangles between the data points and use them to evaluate unknown values at target grid points by fitting a polynomial to their vertices. Figure 1 shows the resulting mixing ratios of hydrogen fluoride (HF) at mid-latitudes (42.5°) from May 1992 to August 2004. All the original observations between 40° and 45° are also shown. The averages of the original values within each month compare well to the interpolated values at 42.5°, indicating the interpolations were done properly.

[7] HF in the stratosphere has been increasing due to the increase of tropospheric halocarbons, particularly chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and hydrochlorofluorocarbons (HCFCs) [*Anderson et al.*, 2000; *Waugh et al.*, 2001]. The increases of HF in the upper stratosphere (Figure 1a) are dominated by photochemical production due to the increasing tropospheric halocarbons and are thus very similar in both hemispheres. At 10 hPa (~32 km), however, HF in the NH has been increasing more rapidly than in the SH (Figure 1b). The linear regression shows an apparent increase in the NH-SH asymmetry with time. Since our focus is on the trends of the

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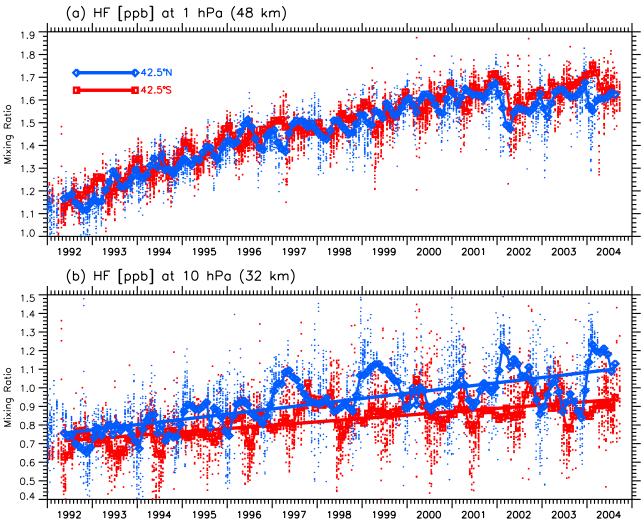

Figure 1. Zonal mean mixing ratios of HF (ppbv) at about (a) 1 hPa (∼48 km) and (b) 10 hPa (∼32 km) from May 1992 to August 2004 represented by blue and red curves at 42.5°N and 42.5°S, respectively. Slope of straight lines represent linear trend. Dots represent original observed data between 40° and 45°.

asymmetry, other features including interannual variations and changing trends are not discussed in detail.

[8] Figure 2 shows similar asymmetries in trends of methane (CH_4) and water vapor (H_2O) at 10 hPa. CH_4 at 42.5°S shows an increase in time while CH_4 at 42.5°N decreases slightly. The increasing trend of CH_4 at 42.5°S is 8.3 ppbv per year (0.9% per year), in reasonable agreement with that of the observed tropospheric source [*Dlugokencky et al.*, 2001; *Wuebbles and Hayhoe*, 2002], while the decreasing trend at 42.5°N is opposite of the tropospheric increase. H_2O shows an increase in the NH and a decrease in the SH. The temporal variations of H_2O in both hemispheres are mirrored by out of phase variations of CH_4. The asymmetry in the trends of CH_4 and H_2O over the period from April 1992 to April 2001 is discussed by *Rosenlof* [2002]. The interannual fluctuations of H_2O are very similar to (in phase with) those of HF.

[9] Latitude-height cross sections of NH-SH asymmetries in trends of these HALOE tracers have similar geometrical patterns for the subtropics to midlatitudes in the middle stratosphere (not shown). We choose 42.5°N and 42.5°S at 10 hPa since the asymmetry is most prominent near these regions. In addition to the NH-SH asymmetry in linear trends, CH_4, H_2O, and HF at these locations show increasing asymmetry in time during the QBO westerly phase. For instance, HF (CH_4) in the NH shows notable rises (drops) in winter-spring of 1997, 1999, and 2002 which draw a clear distinction between trends in the NH and SH. This feature is present throughout the extratropical middle-to-upper stratosphere (20°–60° latitude and 26–40 km height).

[10] CH_4 and HF are chemically unrelated, yet they show similar trends as well as interannual variations. Since the latitude of 42.5° is located in the region of the sinking branch of the B-D circulation, this implies that subsidence in the NH has been strengthening during the observed period. We suspect downward advection from the upper stratosphere dominates the tracer variation at this location.

3. Comparison With Residual Circulation

[11] A rapid increase (decrease) of HF (CH_4) in the NH implies stronger sinking. To verify this, the global residual circulation in the stratosphere was calculated using the thermodynamic energy and mass continuity equations, similarly to *Randel et al.* [1999b]. The radiative heating rates were estimated using the long-wave heating code described by *Olaguer et al.* [1992] and the short-wave heating code from the University of Illinois at Urbana-Champaign (UIUC) two-dimensional chemical-radiative-transport model [*Wuebbles et al.*, 2001] with UKMO temperature and HALOE O_3, CH_4, and H_2O concentrations. The HALOE species are also obtained by the Delaunay triangulation interpolation method in regular grids over space and time.

[12] Changes in the residual circulation are shown in Figure 3, by scaled vector arrows in March and September. The isolines of HF for April and October, considering the time lag of the distribution relative to its transport, are also shown. Contours of HF mixing ratio represent 1.0, 0.45, and 0.1 ppbv in 1993, 1995, 1997, 1999, and 2002. All five years share the same westerly phase of quasi-biennial oscillation (QBO), making it more straightforward to compare their HF distributions with the changed residual circulations. It is clear that the magnitude of the residual circulation for the upper stratosphere in early spring has been increasing. In the extratropics, the greater change in the strength of subsidence in the NH agrees well with the distributions of HF, that is, the more rapid increase of HF in the NH. The vertical residual velocity shows a stronger negative trend (stronger sinking) in midlatitudes of the NH upper stratosphere. These trends in the residual circulation are in good agreement with those reported by *Rosenlof* [2002]. The NH-SH asymmetries in long-lived tracers in Figures 1b and 2 are associated with the differences in the strength of the subsidence in earlier months. Plots for the easterly phase (not shown here) were

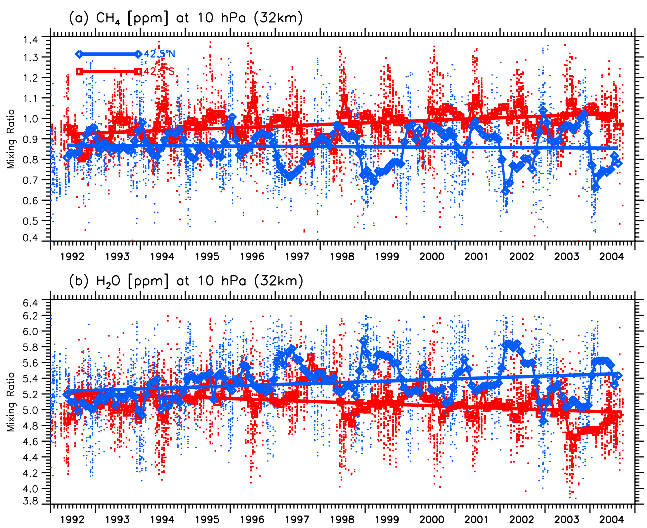

Figure 2. Same as Figure 1b, but for (a) CH_4 (ppmv) and (b) H_2O (ppmv).

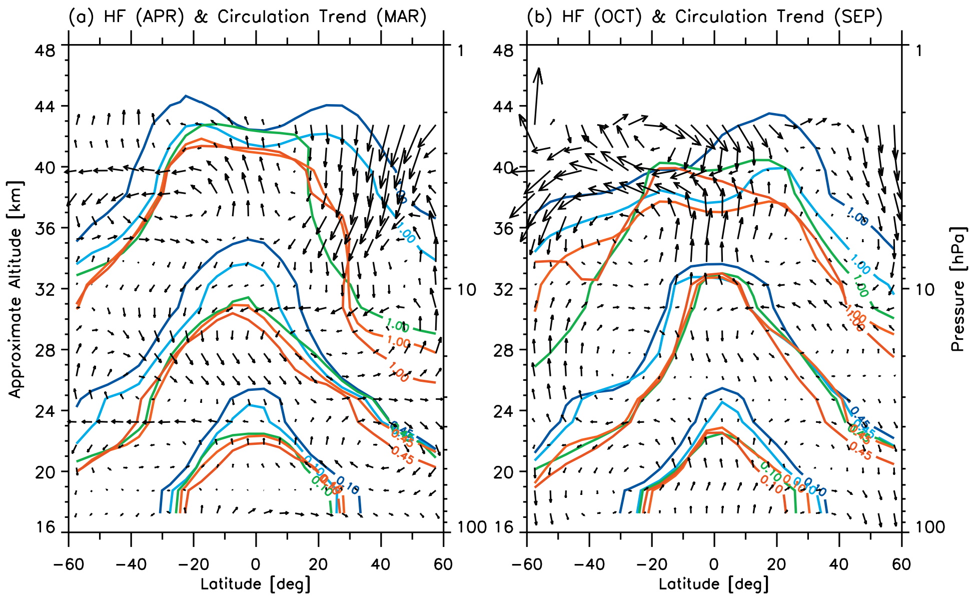

Figure 3. (a) Contours of HF mixing ratio for 1.0, 0.45, and 0.1 ppbv in the years of westerly QBO phase 1993 (navy), 1995 (blue), 1997 (green), 1999 (red), and 2002 (brown) in April and circulation changes in March, and (b) the same contours in October and circulation changes in September. The changes of the residual-mean circulations are represented by the scaled vector arrows of linear trend in their vertical and meridional components.

drawn for the years of 1994, 1996, 1998, 2000, and 2003, and look similar to Figure 3.

[13] We also investigated the changes in CH_4 (not shown). The shape of the CH_4 isolines is very similar to those of HF, but with the opposite direction of the gradient. This geometric similarity is strong evidence that transport or stratospheric dynamics determines the distribution and variation of tracer gases with sufficiently long chemical lifetimes, such as HF and CH_4 as previously noted by *Plumb* [2002].

4. Changes in the Stratospheric Wave Activity

[14] The residual circulation in the stratosphere is forced by the EPFD due to the planetary waves propagating from the troposphere. Since the residual circulation shows secular trends, the stratospheric wave activity is expected to show similar trends. There may be increasing differences in the EPFD between the hemispheres. A larger negative EPFD would induce more sinking at mid-latitudes. On the other hand, the larger negative EPFD would induce more meridional eddy mixing at the same time and thus the eddy mixing effect weakens the increase of HF mixing ratio due to the more sinking motion. The fact that HF has been increasing more rapidly in the NH implies that increase of eddy mixing is secondary to that of the meridional advection [*Holton*, 1986].

[15] Figure 4 shows the EPFD in the upper stratosphere and the eddy heat flux in the lower stratosphere for the winter months (DJF for the NH and JJA for the SH). These dynamic properties are estimated using UKMO data. Since the eddy heat flux is proportional to the vertical component of the EP flux and it has maxima near 60° on 100 hPa, the 100 hPa eddy heat flux in Figure 4b represents the strength of planetary waves propagating upward from the upper troposphere [see also *Newman et al.*, 2001]. Since enhanced EP fluxes from the high-latitude troposphere in the NH are directed and converged into the higher stratosphere [*Kuroda and Kodera*, 1999], the stronger (weaker) upward propagating planetary waves has resulted in larger (smaller) EPFD in the upper stratosphere of the NH (SH). Both the eddy heat flux at 100 hPa near 60° and the EPFD at 1.5 hPa near 42.5° show significant interhemispheric asymmetries. Although the wave activity in the SH experiences strong growth in the austral spring [*Quintanar and Mechoso*, 1995], the averages of other months including spring in the SH show the similar asymmetry in the stratospheric wave activity.

[16] The upper stratospheric changes in the EPFD are consistent with the changes in residual circulation. The increased wave forcing in the upper stratosphere of the winter NH leads to enhanced subsidence in early spring and

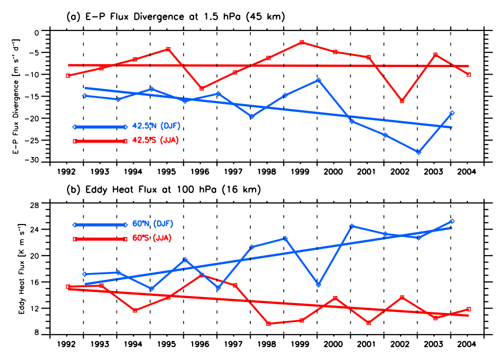

Figure 4. (a) EP flux divergence (m sec^{-1} day^{-1}) near 42.5°S and 42.5°N on 1.5 hPa, and (b) eddy heat flux (K m sec^{-1}) near 60°S and 60°N on 100 hPa for the winters of 1992–2004. Blue diamonds and red squares denote DJF averages for the NH and JJA averages for the SH, respectively.

then the downward displacement of HF in the following month, as in Figure 3.

[17] These changes in planetary wave activity, strengthening in the NH and weakening in the SH, are quite significant. Similar NH-SH asymmetry has been found in global climate model (GCM) experiments with increased greenhouse gases. *Butchart and Scaife* [2001] show that winter sinking is growing in both hemispheres, but the trend of sinking is larger in the NH than in the SH in their model simulations of changing climate.

5. Conclusion

[18] The mixing ratios of HALOE HF, CH_4, and H_2O show significant long-term increases in NH-SH asymmetry since the early 1990s. In the extratropical middle stratosphere, the increasing (decreasing) trend of HF (CH_4) in the NH is larger than in the SH, while the trends of HF in the upper stratosphere are similar in both hemispheres. The similarity in temporal variations and spatial distribution of the observed tracers suggests that the trends in the asymmetry have been caused by changes in the stratospheric circulation. The stronger trend of increasing subsidence in the NH is consistent with the increasing NH-SH asymmetries of the tracers. This trend in the circulation results from changes in planetary wave activity, which is increasing in the NH and decreasing in the SH.

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