Published in final edited form as:

J Geophys Res Atmos. 2019 June 27; 124(12): 6600–6611. doi:10.1029/2019JD030455.

Observation and Attribution of Temperature Trends Near the Stratopause From HALOE

Ellis Remsberg¹

¹Science Directorate, NASA Langley Research Center, Hampton, VA, USA

Abstract

This study considers time series of temperature versus pressure, $T(p)$, from the Halogen Occultation Experiment (HALOE) across the stratopause region, where the effects of radiative forcings from the greenhouse gases (CO_2 and H_2O) and from ozone are most pronounced. Trend analyses of HALOE $T(p)$ values for 1993–2005 are for six levels from 2.0 to 0.3 hPa with a vertical resolution of about 4 km and for eight latitude zones from 65°S to 65°N. The analyses account for the forcing effects from the 11-yr solar cycle. HALOE trends at 2.0 hPa are of the order of -1.0 K/decade across the tropics and subtropics but then become smaller (-0.5 K/decade) at the middle latitudes. Near-global $T(p)$ trends are of order -0.5 K/decade but have a minimum of -0.2 K/decade at 1.0 hPa; they are clearly negative in the southern but slightly positive in the northern hemisphere. The combined radiative forcings from CO_2 , H_2O , and ozone vary between -0.4 and -0.7 K/decade for 1993–2005 and are hemispherically symmetric. The HALOE temperature trend and total radiative cooling profiles differ from those reported from observations and calculations for 1980–2000, mainly because the ozone trends changed from clearly negative in the 1980s through mid-1990s to slightly positive during the time of HALOE. Trends at low latitudes for the tracer, methane (CH_4), increase from 2% to 4%/decade from 50 to 10 hPa and then to $\sim 6\%$ /decade by 5 hPa. Analyses of time series of CH_4 across the stratopause reveal subseasonal scale variability within the northern hemisphere that reduces the significance of the $T(p)$ trends.

1. Introduction and Objectives

A focus for chemistry climate model studies is how quickly stratospheric ozone is recovering and what the effect of this recovery is on temperature trends (e.g., Garcia et al., 2007; Langematz et al., 2003; Maycock et al., 2018; Ramaswamy et al., 2001; Stolarski et al., 2010). Shine et al. (2003) modeled temperature trends in the stratopause region for 1980–2000, due to the changes in ozone and in greenhouse gases (GHGs), mainly in CO_2 . Figure 1 shows the total, area-weighted model temperature trend profile plus the separate contributions from ozone, GHG, and H_2O , as adopted from Shine et al. (2003), their Figure

Correspondence to: E. Remsberg, ellis.e.remsberg@nasa.gov

Author Contributions:

Conceptualization: Ellis Remsberg

Formal analysis: Ellis Remsberg

Writing - original draft: Ellis Remsberg

Writing - review & editing: Ellis Remsberg

5). Trends in ozone mixing ratio at 3 and 1 hPa are negative by about 7% to 4%/decade, respectively, due to increases in ozone depleting substances (ODS) during that period (Randel & Wu, 1999). Decreases in ozone lead to cooling in the stratopause region. Figure 1 also shows a cooling of about -0.2 K/decade due to H_2O increases of $\sim 1\%$ /year (Rosenlof et al., 2001).

Observed stratospheric temperature trends agree reasonably with the model-simulated total trend profile in Figure 1 (e.g., see Seidel et al., 2016, their Figure 16). The observations are from merged series of operational satellite radiance data from stratospheric sounding unit (SSU) and microwave sounding unit (MSU) sensors (e.g., Randel et al., 2009; Zou & Qian, 2016). Seidel et al. (2016) found significant temperature trends for 1979–1994 of -0.7 to -1.2 K/decade from 40°S to 40°N , respectively, from SSU channel 3 radiances (SSU3 centered near 1.5 hPa or 43.5 km and spanning from about 30 to 55 km). Synthetic combinations of zonal-averaged radiances from several SSU channels extended that temperature record across the stratopause (Nash & Saunders, 2015).

The Advanced Microwave Sounding Unit-A (AMSU-A) sensor began measurements in 1998, although its top channel (#14 centered at 42 km and spanning from 36 to 48) was not operational until 2001. Since radiance contributions in channel 14 do not extend across the full altitude range of SSU3, Zou and Qian (2016) matched the SSU and AMSU measurements in terms of temperature according to the vertical weighting functions for their respective radiances and obtained a reliable long-term climate data record. Their analogous SSU3-like temperature trends are smaller for the longer time span of 1979–2015 or about -0.7 K/decade ($2\sigma = \pm 0.08$) across the same latitude range (see Figure 9 of Zou & Qian, 2016). Seidel et al. (2016) reported that the trends in the lower stratosphere from MSU for 1995–2013 and the trends from the merged SSU/AMSU record for 1995–2005 were smaller and not significant, as ODS and their effects on ozone were decreasing.

Randel et al. (2016) analyzed time series of merged, temperature versus pressure, or $T(p)$, from SSU/AMSU and compared them with those from Microwave Limb Sounder (MLS) for 2004 and onward and from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) satellite observations for 2002 and onward. They degraded the higher vertical resolution profiles of MLS and SABER, so that they were approximately consistent with the lower resolution, weighting functions of SSU and AMSU-A. Then they applied a regression model to the merged time series from their equivalent SSU3 channel and found global linear trends of -0.89 K/decade for 1979–1997 that slowed to -0.28 K/decade for 1998–2015. They attributed their trend changes to the significant loss of upper stratospheric ozone in the earlier period as compared to slightly increasing ozone values in the latter period. McLandress et al. (2015) merged SSU and AMSU global-average data records and reported that their temperature trends agreed with those from MLS for 2004–2012. However, these existing climate data records do not extend across the stratopause and so cannot be used for an investigation of effects of the primary forcings in that region (changes in GHG, ODSs, solar ultraviolet flux, and planetary-scale waves) and are not optimal for detailed comparisons with model results (e.g., Aquila et al., 2016; Checa-Garcia et al., 2018).

The present study focuses on analyses of temperature time series for the uppermost stratosphere and lowermost mesosphere, as obtained with the single, Halogen Occultation Experiment (HALOE) satellite instrument that operated from late 1991 to November 2005 (Russell et al., 1993) or at the specific time when the effects of ODS on ozone were leveling off. It also includes analyses of trends in HALOE ozone, H₂O, and methane in that region.

Section 2 reports some characteristics of the HALOE temperature profiles. Section 3 describes briefly the present regression modeling of HALOE T(p) for January 1993 to November 2005. Although the HALOE retrieval provides temperature profiles for the upper stratosphere and mesosphere that are well sampled vertically and in hydrostatic balance, the multiple linear regression (MLR) trend analyses herein are limited to six discrete pressure surfaces from 2.0 to 0.3 hPa and across eight different latitude zones to give a set of 48 separate time series. In addition to the analyzed trends, Section 3 gives responses of temperature to variations of the solar flux and compares them with results from SABER. Section 4 shows the analyzed HALOE temperature trends across the stratopause and as a function of latitude. Merged SSU3/AMSU data for the time span of HALOE are also fit using the same regression model for a qualitative comparison; absolute temperatures from SSU3/AMSU are comparable to the HALOE values from just below the 3-hPa level (near 40 km). As expected, the near-global T(p) trends from 1993 to 2005 HALOE are not as negative as the model-simulated trends for 1980–2000 of Shine et al. (2003) because the changes in ozone slowed to near zero by the late 1990s in the upper stratosphere (World Meteorological Organization, 2018). Section 5 reports on the associated trends for ozone and H₂O from the HALOE data. Near-global estimates of their radiative effects are added to those of CO₂ from Shine et al. (2003) to give an estimate of the total forcing for comparisons with the observed hemispheric and global HALOE T(p) trends. Section 6 considers HALOE methane (CH₄) as a tracer for evaluating whether dynamical activity might be affecting the T(p) trends. Section 7 summarizes findings on the T(p) trends and on their attribution across the stratopause from the HALOE data.

2. HALOE Temperature Data set

HALOE T(p) profiles are from its version 19 (v19) algorithm, as described in Thompson and Gordley (2009) and as validated in Remsburg et al. (2002). HALOE retrieved T(p) is from transmission measurements versus scan angle (or altitude) from its 2.8- μ m CO₂ channel. However, since there are slight inaccuracies in the HALOE forward model of CO₂ transmission in the middle stratosphere, there is a merger of the HALOE-retrieved temperatures with the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) temperature profiles supplied to the HALOE Project during the mission life of the Upper Atmosphere Research Satellite. There is a weighted merger of the HALOE and CPC temperatures beginning with all CPC data at 34.5 km and ending with all HALOE data at 43.5 km. HALOE T(p) retrievals then extend upward to about 80 km, where there is gradual tie-in to a mass spectrometer/incoherent scatter model climatology.

Remsberg and Deaver (2005) reported a discontinuity near May 2001 in the HALOE time series at 5 hPa and a large negative trend of -3.7 K/decade from 1991 to 2005, due mainly to the changeover from SSU to AMSU in the early CPC record. Figure 2 is an analogous series

of data points at 3 hPa, based on a binning of HALOE sunrise (SR) and sunset (SS) profiles for the latitude zone of $22.5 \pm 7.5^\circ\text{N}$; the oscillatory curve is a fit to the data from just 1993 to mid-2001, including seasonal and inter-annual terms. The straight line fit is the constant plus trend term, and its trend is -0.2 K/decade. The corresponding trend for the longer time span of 1993–2005 is -1.6 K/decade and indicates the residual effects from the discontinuity of 2001 even at 3 hPa. HALOE T(p) extends from there to the uppermost mesosphere, and those time series show no further evidence of the discontinuity. The forward model for the HALOE T(p) algorithm also incorporates annual changes of tropospheric CO_2 with a 4-year lag to account for its slow net ascent to the middle stratosphere. Gordley et al. (2009) reported finding no detectable false trend due to instrumental effects from the HALOE radiometer channels for CO_2 , ozone, and H_2O .

HALOE T(p) has a vertical resolution of about 4 km, which is better than that of MLS (5.5 to 8 km from 3.0 to 0.3 hPa) or of SSU and AMSU-A. Proper comparisons of HALOE T(p) trends with those from other satellite data sets require that the HALOE profiles be convolved with the lower vertical resolution weighting functions of those temperature sensors. Further, the weighting functions for SSU3 and AMSU (channel 14) extend well below the 3-hPa level, such that only qualitative comparisons are achievable with them. The resolution from SABER (~ 2.5 km) is nearer to that of HALOE, but its data series do not span the same years. The present study focuses on the trends in T(p) from HALOE in the uppermost stratosphere and lower mesosphere (2.0 to 0.3 hPa).

3. Analysis Approach

Remsburg (2008a), Figure 16) analyzed HALOE temperatures from 1991 to 2005 and found significant cooling trends at 1 to 2 hPa of the order of -0.5 to -1.0 K/decade. For that initial study, he simply fit a periodic 11-year term to the data, rather than considering a solar cycle proxy term, and he noted that his 11-year term was not exactly in-phase at the middle latitudes with the solar flux proxy—perhaps due to dynamical effects. Another concern with his initial study is that the 11-year and linear trend terms are not linearly independent and alias to each other. The updated analyses herein make use of time series of the Lyman α ($\text{Ly}\alpha$) flux as the proxy term for the 11-year solar cycle forcing plus a multivariate El Niño–Southern Oscillation (ENSO) index (MEI) term for the MLR modeling. There are also perturbations from the June 1991 eruption of Mt. Pinatubo that affect the temperature time series of both HALOE and SSU3/AMSU (e.g., Lee & Smith, 2003; Zou & Qian, 2016). Those atmospheric effects extend for several years in the operational temperature record, most likely because the SSU3/AMSU measurements have contributions that extend down to the middle stratosphere. For this reason, Randel et al. (2016) excluded 2 years of data following the 1991 eruption for their analyses of SSU3/AMSU. Volcanic influences are not apparent after 1992 in time series of HALOE T(p) near the stratopause.

HALOE v19 T(p) profiles are grouped into six, separate 15° -wide latitude bins (centered from 37.5°S to 37.5°N) plus two 20° -wide bins centered at 55° latitude to obtain time series of zonal-average estimates of T(p) at six levels from 2.0 to 0.3 hPa. The wider bins at 55° provide for adequate seasonal sampling in the latter years of the HALOE mission. As in Remsburg (2008a), the separate SS and SR points in a time series are on the dates when the

tangent layer of those HALOE occultation events occur in a given latitude zone. Each data point within the zone is a “bin average” of at least five profiles (usually many more). The separate SS and SR time series undergo an initial MLR fitting, and then there is a shift of the two series so that their means match at the average of the two. To first order, this approach accounts for the “short-period noise” of the diurnal effects from a series of alternating, SS and SR crossings of the latitude zone. Figure 3 shows the 13-year average distribution of those mean SS minus SR differences, extending through the mesosphere. They have vertical wavelengths and phase changes as a function of latitude and pressure-altitude that are similar to those for the diurnal and/or semidiurnal temperature tides (e.g., Andrews et al., 1987).

The two example time series of the combined SS and SR points are in Figure 4 for the $22.5 \pm 7.5^\circ\text{S}$ latitude bin at the 0.5- and 2-hPa levels, and they are fitted using MLR methods. Note that the scaling of the ordinate reverses for 0.5 versus 2.0 hPa to aid with visualizing the seasonal temperature cycling both above and below the stratopause. Terms for the MLR model are periodic annual (AO), semiannual (SAO), and 853-day (QBO) cycles. Remsburg (2008a) also included a 640-day (~21-month) subbiennial (SB) term that represents the difference frequency between the AO and QBO terms; that term is not as significant for $T(p)$ in the uppermost stratosphere and lower mesosphere and is not included here. The regression model also includes a normalized Lya solar flux proxy term, a term to represent ENSO forcings based on the MEI proxy series, and a linear (Lin) trend term; details of the application of the two proxy terms to temperature and H_2O throughout the mesosphere are in Remsburg et al. (2018). The normalized Lya data have an 81-day smoothing applied to them, to minimize the effects of flux variations from the 27-day solar rotation cycle. HALOE time series data are not deseasonalized; the present model fit gives realistic estimates of uncertainty by considering all terms at the same time. Grouping of HALOE profiles into 15° - or 20° -wide latitude bins provides adequate fittings for the seasonal as well as the longer-period and proxy terms. Each model term also contains an adjustment for autocorrelation effects at lag-1 (AR1) by the two-step approach of Cochrane and Orcutt (1949).

The MLR analyses of the data of Figure 4 begin with January 1993, although data points are shown from late 1991. As in Figure 2, terms of the regression model constitute the oscillating curve, and they are at bottom left. The straight line is just the sum of the constant and linear trend terms. Note that the amplitudes and interactions of the SAO and AO terms differ somewhat between 0.5 to 2 hPa; HALOE resolves them. Amplitudes of the QBO terms are only of order 1 K or less and occur mainly at subtropical latitudes. Forcings from ENSO are not very significant either, in agreement with findings from the regression analyses of Seidel et al. (2016). Figure 5 is the MLR analysis residuals from the fit at the 2-hPa level of Figure 4. There is no indication of a volcanic perturbation early in 1993 in Figure 5, nor any remaining periodic structures.

Table 1 (at top) contains numerical results from HALOE at 2 hPa for each of the latitude zones. Temperature responses to the maximum-minus-minimum, Lya flux are in terms of degrees kelvin. Those responses are mostly positive or in-phase, as expected from photochemical modeling studies (e.g., Marsh et al., 2007). Confidence intervals (CIs in %) indicate the degree to which Lya terms are present in the data. Responses are significant and

of order 0.7 to 1.0 K across the tropics and in the southern subtropics. They are near zero to slightly negative and not significant at high latitudes. The analyzed HALOE T(p) response values agree with those at 50 km from SABER, which are of the order of 1 K in the tropics and zero or negative near 40° latitude (Huang et al., 2016, their Figure A1).

The HALOE trend terms in Table 1 have units of K/decade, and they are essentially orthogonal to the solar flux terms. There is a significant cooling of the order of -1.0 K/decade at low latitudes, which is about twice that from SABER data for its later period of 2002–2012 (Huang et al., 2014, their Figure 2). Note that both data analyses are for time spans when major volcanic eruptions and their possible forcing effects should not be of concern. The temperature trend differences between HALOE and SABER indicate the effect of changing ODS forcings on ozone. ODS were leveling off during the HALOE period, so most of the observed total atmospheric cooling is likely due to the steadily increasing CO₂. The SABER T(p) trends are for the following decade, when ODS were in decline and ozone was increasing and providing some warming at middle latitudes (see also Figure 2 of Huang et al., 2014).

4. T(p) Trends From HALOE and From SSU3

Figure 6 shows the distribution of temperature trends from HALOE along with estimates of their uncertainty (CI values in %). The HALOE trends at 2.0 hPa are those given in Table 1; they are significant and vary smoothly with latitude. However, there is a clear hemispheric asymmetry in the T(p) trends for 1.0 and 0.7 hPa, where values are negative and significant in the subtropics of the southern hemisphere but not significantly so in the northern hemisphere subtropics. No similar asymmetry is present in the trend pattern from the SABER data (Huang et al., 2014). Such differences imply that the forcings from ODS, GHG, and/or from the effects of wave activity are not the same for the two hemispheres during the years of HALOE.

Figures 7 and 8 provide a qualitative comparison for the HALOE temperature trends using merged SSU data for 1993–2005. Figure 7 is an analysis of the merged SSU3 time series for the 15°-wide latitude bin centered at 22°S and based on zonal-averages of its gridded data obtained from the NOAA/Center for Satellite Applications and Research (STAR) website. Note that the SSU temperatures already include adjustments to account for the impact of changes in CO₂ on the measurement system and for changes in the CO₂ gas cell content over time (Wang et al., 2012). Merged SSU3 data also include adjustments for time-of-day differences of the observations from successive satellite sensors, and they have a time tag of 1200 LT (Zou & Qian, 2016). The mean of the SSU3 temperature time series at 22°S is 248.9 K or colder by about 10 K than the mean of the HALOE time series at 2.0 hPa (Figure 4). The primary reason for the difference is that the measured radiances for SSU3 and for AMSU-A channel 14 extend lower in the stratosphere.

Numerical results from SSU3 with latitude are in Table 1 (at bottom). Their T(p) responses to the maximum-minus-minimum solar flux proxy are about 0.5 K and significant, and their trends at the lower latitudes are between -0.2 and -0.5 K/decade. SSU3 has lower vertical resolution, and its mean temperature values vary from 244 to 249 K from high to low

latitudes; those values are also cooler by about 4 K than the ones from HALOE at 3.0 hPa. Nevertheless, 1.5 hPa is set as the pressure altitude of the analyzed SSU3 temperature trends, based on their joint contribution functions. Clearly, a disadvantage of $T(p)$ time series from the NOAA Joint Polar Satellite System sounders is that they do not resolve changes in the trends across the stratopause.

Figure 8 compares the trends from Table 1 for SSU3 and HALOE. Note that the trends from both are not as significant at the higher latitudes, where the seasonal amplitudes are large. Analyzed trends for SSU3 at 22°N carry an uncertainty (the small vertical bar) of only about ± 0.05 K/decade (2σ), which is very similar to the error estimates of Zou and Qian (2016), their Figure 9) after taking averages of the SSU3 data over six adjacent, 2.5° latitude bins as done here. On the other hand, the uncertainties for the HALOE trends for 1 and 2 hPa at 22°N are really an underestimate because they do not account for the fact that the HALOE time series points only approximate the zonal mean, particularly at the higher latitudes in winter when zonal variations are larger. For instance, the two separate HALOE curves for 2 hPa in Figure 8 are for trends based on averages of more than four profiles versus more than seven profiles for each given bin. In addition, the HALOE profiles do not always sample each latitude bin uniformly. Thus, the trend differences between those two HALOE curves are a better measure of their $T(p)$ uncertainty.

Figure 9 shows the two hemispheric HALOE temperature trend profiles from 2.0 to 0.3 hPa, produced as area-weighted averages of the four zonal bins in each hemisphere. The southern hemisphere trend profile is negative and significant, while the northern hemisphere trends are small and not significantly different from zero across the stratopause. The next two sections consider whether any of the primary forcings are also different for the two hemispheres. The near-global HALOE trend profile in Figure 9 is simply the average over both hemispheres, and it is clearly different from the calculated total temperature trend profile adopted from Shine et al. (2003). HALOE $T(p)$ shows a minimal cooling of -0.2 K/decade at 1 hPa, as opposed to the maximum radiative response of Figure 1 for GHG and for ozone when ODS were increasing in 1980–2000. These differences agree qualitatively with the conclusion of Aquila et al. (2016) that changing from a negative to a slightly positive ozone trend is the primary radiative forcing agent for the corresponding changes in global temperature trends from 1979–1997 to 2000–2011.

Figure 9 also includes the area-weighted, global trend from SSU3 (-0.3 K/decade) for 1993–2005, and the HALOE trend at 1.5 hPa agrees with it. The trend from SSU3 is smaller than the trends of -0.7 to -0.8 K/decade of Zou and Qian (2016) and of -0.5 to -0.6 K/decade of Randel et al. (2016) for their longer time spans of 1979–2015. However, it is identical to the value of Randel et al. (2016) for their shorter period of 1998–2015.

5. Estimates of Trend Attribution Using HALOE Data

Remsburg (2008b) reported ozone trends from HALOE that are near zero in the upper stratosphere, although he employed a simple 11-year sinusoid rather than a solar flux proxy time series to account for concurrent solar forcing effects. He also showed that there was little change in his MLR ozone trends, when he considered a time series proxy for the ODS

rather than a linear trend in his ozone modeling. That insensitivity to the exact nature of the ODS trends is due to their small changes during 1993–2005. Figure 10 shows updated ozone analysis results, based on the current latitude bins and regression model terms (including the proxy Lya solar term) for 1993–2005. The ozone trends in Figure 10 are slightly positive near the stratopause across the low and middle latitudes. However, there is no clear hemispheric asymmetry for the trends, presumably because ozone is under photochemical control at that altitude. Regions of dark shading show that the ozone trends in the middle stratosphere are negative and significant at the 90% confidence interval (CI), most notably at middle latitudes of the southern hemisphere. The reduced significance of the trends in the northern hemisphere indicate effects of wintertime mixing just below the region of transition from photochemical to dynamical control for the stratospheric ozone distribution (Leovy et al., 1985).

One can be more confident that the ozone trends in Figure 10 are representative by examining the distribution in Figure 11 of the associated MLR responses of the ozone time series to the maximum minus minimum solar flux forcing during those years. That ozone response distribution extends through most of the stratosphere. It is of order 2% to 3% and highly significant in the middle to upper stratosphere at middle latitudes. Figure 12 is the average response profile across 30°S to 30°N latitude, along with a representative profile of the modeled response to the solar cycle ultraviolet flux variations at 5°N from Brasseur (1993).

Trends in the secondary radiative forcing agent H₂O were near zero in the lowermost mesosphere in 1993–2005 (Nedoluha et al., 2017; Remsberg et al., 2018; Scherer et al., 2008), such that changes in H₂O cooling contribute minimally to the analyzed HALOE T(p) trend profile. Figure 13 shows the distribution of HALOE H₂O trends from 3 to 0.3 hPa for 1993–2005. The solar proxy term is not important for H₂O or for methane (see later in section 6) for the stratopause region. However, a 690-day subbiennial (SB) term is part of their MLR models because it is significant, especially for the northern subtropics. The H₂O trends in Figure 13 are hemispherically asymmetric and not significant in the northern hemisphere, in accord with the trends for HALOE T(p). HALOE H₂O trends are negative across most latitude zones.

Radiative effects from CO₂ comprise most all of the GHG forcings. CO₂ had an average growth rate of 15 ppmv/decade in the 1990s compared with only slightly larger rates in the 1980s and the early 2000s (World Meteorological Organization, 2011). Therefore, the HALOE GHG cooling profile is set the same as that from Shine et al. (2003) for the present study.

Attribution of radiative heating/cooling to GHG, ozone, and H₂O is as follows. There are adjustments made to the fixed dynamical heating calculations of Shine et al. (2003), according to the HALOE gas trends for 1993–2005. While effects of GHG are kept the same, the ozone trends from HALOE are much smaller than those from the Stratospheric Aerosol and Gas Experiment (SAGE) of Randel and Wu (1999) used in Shine et al. (2003). Thus, the ozone heating rates for the HALOE period are from a scaling of the ozone heating rate profile of Shine et al. (2003) by the ratio of the HALOE and SAGE average ozone trend

profiles for their respective time spans. Further, the SAGE ozone distributions of Randel and Wu (1999) extend from about 60°S to 60°N, which is nearly the same latitude range as the ozone trends from the HALOE data. Similarly, the heating rate profile for H₂O has a scaling by the ratio of the HALOE H₂O trend distribution to the constant H₂O profile of 1%/decade considered in Shine et al. (2003). Table 2 contains the near-global trend profile estimates for ozone and H₂O from Shine et al. (2003) along with those analyzed here from the HALOE data. Finally, the scaled, area-weighted heating rate profiles for HALOE are in Table 3, keeping in mind that the HALOE ozone and H₂O heating profiles are not quite global (lacking the area poleward of 65° latitude or by 10% of total area). Table 3 also has the HALOE total heating rate profile—a sum of ones for the GHG, ozone, and H₂O. Those values range between −0.7 and −0.4 K/decade.

Figure 14 compares that estimated near-global, total heating rate profile (+ signs) with the analyzed HALOE temperature trend profile from Figure 9 (asterisks), and their overall values agree well except at 1 hPa. The separate gas contributions to the HALOE heating/cooling rates are also in Figure 14; compare them with those for 1980–2000 shown in Figure 1, as adopted from Shine et al. (2003). The primary difference for the temperature trends comes from the changes in ozone over that time span. The HALOE temperature trends validate the modeled effects of radiative forcings in Checa-Garcia et al. (2018), their Figure 2), which show a near zero temperature trend at the stratopause due to changes in ozone between the 1990s and the 2000s.

6. Attribution of Hemispheric Differences in Temperature Trends

The minimum, near-global HALOE temperature trend of −0.2 K/decade at 1 hPa in Figure 14 is not matched by a corresponding minimum in the total cooling profile. That difference occurs at the level where there is a clear change in Figure 6 from negative to slightly positive HALOE temperature trends between the two hemispheres. Note that the radiative effects from H₂O based on Figure 13 are also asymmetric hemispherically, while those from chemically controlled ozone are not. It may be that the upper stratosphere and lower mesosphere experienced trends in the diabatic circulation or the closely related, mean residual circulation due to forcings from the dissipation of planetary waves, particularly when the zonal wind regime is westerly or from late autumn to early spring (e.g., Langematz et al., 2003; Linz et al., 2018). Examination of trends for dynamically controlled tracers, like H₂O and CH₄, may indicate whether such activity is important for the HALOE temperature time series.

The chemical lifetime for CH₄ increases from a minimum of about 3 months at 2.0 hPa to 6 months at 0.5 hPa, or longer than typical net transport times (Brasseur & Solomon, 2005). In fact, Fleming et al. (1999) used the monthly HALOE CH₄ distributions, as effective tracers of the seasonal circulations for diagnosing the net transport in zonal average models. They showed that the HALOE data indicate an upwelling of CH₄ to above the stratopause at subtropical latitudes from autumn to springtime. CH₄ also responds to a secondary tropical circulation associated with the descent of the SAO wind regime. Remsburg (2015) reported on initial analyses of HALOE CH₄ in an attempt to diagnose its longer-term changes due to wave-induced, net circulations. He found anticorrelations of the changes in CH₄ versus those

of H₂O, as expected, since CH₄ oxidizes to form H₂O in the upper stratosphere. CH₄ also has anticorrelations with HCl—a species having vertical and horizontal gradients opposite those of CH₄.

Trends for CH₄ in the troposphere are somewhat variable but positive and of the order of 2% to 3%/decade during the time of HALOE (Dlugokencky et al., 2009; Solomon et al., 2007). Remsberg (2015), his Figure 7) reported very similar tropical CH₄ trends from HALOE for the lowermost stratosphere (50 hPa). Figure 15 is an update of the stratospheric distribution of his analyzed CH₄ trends along with estimates of their significance. The data for Figure 15 are restricted to between 65°N/S, and the MLR modeling is for the same time span as for temperature, ozone, and H₂O and uses the same model terms as for H₂O.

There is good continuity with latitude and altitude for the trends in Figure 15 from the MLR analyses of the set of 96 separate time series. CH₄ trends in the upper stratosphere are larger (~4% to 7%/decade at low to middle latitudes) than those of the troposphere and tropical lower stratosphere. Although not very significant, the slightly negative trends in the lower stratosphere at southern hemisphere middle latitudes are unexpected and may result from the instrumental trend bias of –1.9%/decade for HALOE CH₄ (Gordley et al., 2009). To correct for that bias, one would need to add that amount to the distribution of trends in Figure 15.

Trends in the tropics and northern lower stratosphere are highly significant. Increasing CH₄ trends from the lower to the middle tropical stratosphere imply there is acceleration from the shallow, lower branch to the deeper, upper branch of the Brewer-Dobson circulation (BDC) during the years of the HALOE observations. The CH₄ trends for northern middle latitudes become smaller and even negative at high latitudes above the 30-hPa level, while those for the southern hemisphere remain positive with altitude. These findings are generally consistent with age-of-air estimates of the middle stratosphere for the northern hemisphere, but not for the southern hemisphere, based on atmospheric reanalyses for 1989 to 2010 (Diallo et al., 2012, Figure 13). In the upper stratosphere the CH₄ trends are nearly constant and of the order of 6% to 8%/decade across tropical and subtropical latitudes of both hemispheres, and they disagree with age-of-air estimates. Notably though, the trends in the upper stratosphere are more significant for subtropical and middle latitudes of the southern than for the northern hemisphere.

Figure 16 shows time series of HALOE CH₄ at 2.0 hPa for both the subtropics of the northern and the southern hemispheres. The seasonal cycle (AO and SAO) dominates CH₄ in the southern subtropics, while the influence of the QBO is evident in the northern subtropics. It is also apparent that the seasonal terms of the MLR model do not match the data as well in the northern hemisphere most years, giving rise to the lower significance for the fit of all its terms including the trends. The primary result for the stratopause region from Figures 15 and 16 is that the CH₄ trends are significant in the southern but not the northern hemisphere.

The current MLR modeling includes one term related to wave-induced effects, the ENSO index proxy. However, it does not account for the episodic forcings related to sudden stratospheric warming (SSW) activity, which occurs in the northern but not the southern hemisphere most winters (Remsberg, 2015). Dissipation of the propagating planetary waves

at those times impart a heating to the stratopause region at high latitudes, and there follows a compensating, meridional exchange of air between high and low latitudes (Langematz et al., 2003). Charlton and Polvani (2007) reported that major SSWs were absent from 1990 through 1997, but then occurred every year from 1998 to 2002. Because the HALOE analyses extend from 1993 to 2005, it may be that the pattern of hemispheric temperature trends in Figure 6 reflect the lack of and then the reoccurrence of wintertime wave activity and SSWs from the early to the later years of 1993–2005. An additional proxy term is missing for the representation of such episodic or subseasonal wave forcings in the present MLR modeling. While it may be possible to account for their effects using atmospheric reanalysis data, that effort is beyond the scope of this study.

7. Conclusions

Analyses of time series of HALOE profile data reveal the trends in temperature in the region of the stratopause (from 2.0 to 0.5 hPa) for 1993–2005. The HALOE trends at 2.0 hPa are of the order of -1.0 K/decade across the tropics and subtropics but then become smaller (-0.5 K/decade) at the middle latitudes. The near-global HALOE trend at 1.5 hPa is similar to that from merged SSU3 operational data. The corresponding HALOE trend profile has a minimum cooling rate of -0.2 K/decade at 1.0 hPa, but with a range of -0.6 K/decade for the southern hemisphere to 0.2 K/decade in the northern hemisphere.

Analyses for the concurrent trends in HALOE ozone and H_2O provide estimates of their contributions to the radiative heating/cooling in that region. In particular, the trends in upper stratospheric ozone during the time of HALOE are zero to weakly positive, leading to a slight warming. Trends in H_2O are near zero to slightly negative and lead to a slight warming, as well. Upon combining the forcings from ozone and H_2O with estimates of the concurrent cooling from the steadily increasing CO_2 , there is a near-global, total cooling trend of order -0.5 K/decade across the stratopause. That trend is nearly symmetric across the two hemispheres. Both the HALOE temperature trend and total radiative cooling profiles differ from those reported from observations and calculations for 1980–2000, mainly because the ozone trends changed from clearly negative in the 1980s to mid-1990s to slightly positive during the time of HALOE.

Trends in HALOE CH_4 , a separate tracer-like molecule, increase from about 2% to more than 4%/decade in the tropics from 50 to above 10 hPa, suggesting that there was an acceleration of the Brewer/Dobson circulation during 1993–2005. The trends for HALOE CH_4 and temperature in the region of the stratopause are significant only in the southern hemisphere. The CH_4 time series of the northern hemisphere reveal nonperiodic, subseasonal variability, especially during and following SSW events. Because major wintertime warmings were absent from 1993 to 1997, it may be that there is a trend in the wave activity and its effects on temperature that is specific to the years of the analyses herein (1993–2005) and not so representative for longer-term temperature trends. The present results from HALOE demonstrate that relatively high, vertical resolution measurements, like those from MLS and SABER, should also be able to provide trends in temperature across the stratopause as well as estimates of contributions to them based on their retrieved profiles of the primary, radiative forcing agents.

Acknowledgments

HALOE data are from <http://haloe.gats-inc.com/home/index.php/>, daily Ly- α fluxes are from <http://lasp.colorado.edu/lisird/lya/>, and ENSO MEI values are from <https://www.esrl.noaa.gov/psd/enso/mei/>. Trends in tropospheric methane are from NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends_ch4/). Gridded and merged SSU3/AMSU-A, version 3.0 data are available from NOAA STAR via ftp://ftp.star.nesdis.noaa.gov/pub/smcd/emb/mecat/data/SSU/SSU_v3.0/SSU_AMSU_Monthly_Layer_Temperature/. E. R. acknowledges Cheng-Zhi Zou of NOAA/NESDIS for his comments about the operational, merged SSU3/AMSU temperature data. Larry Gordley directed the study of possible instrument effects in the trends from the HALOE radiometer channels (for CO₂, ozone, and H₂O transmission), a critical part of the findings herein. E. R. appreciates the helpful comments from the two anonymous reviewers of the manuscript. E. R. performed this study as a Distinguished Research Associate (DRA) at NASA Langley, and he has no competing interests for the work.

References

- Andrews DG, Holton JR, & Leovy CB (1987). Middle atmosphere dynamics (p. 489). Orlando, FL: Academic Press, Inc.
- Aquila V, Swartz WH, Waugh DW, Colarco PR, Pawson S, Polvani LM, & Stolarski RS (2016). Isolating the roles of different forcing agents in global stratospheric temperature changes using model integrations with incrementally added single forcings. *Journal of Geophysical Research: Atmospheres*, 121, 8067–8082. 10.1002/2015JD023841
- Brasseur G (1993). The response of the middle atmosphere to long-term and short-term solar variability: a two-dimensional model. *Journal of Geophysical Research*, 98(D12), 23,079–23,090. 10.1029/93JD02406
- Brasseur G, & Solomon S (2005). *Aeronomy of the middle atmosphere*, Atmospheric and oceanographic sciences library (3rd ed., Vol. 32, 664). the Netherlands: Springer.
- Charlton AD, & Polvani LM (2007). A new look at stratospheric sudden warmings. Part I: climatology and modeling benchmarks. *Journal of Climate*, 20(3), 449–469. 10.1175/JCLI3996.1
- Checa-Garcia R, Hegglin MI, Kinnison D, Plummer DA, & Shine KP (2018). Historical tropospheric and stratospheric ozone radiative forcing using the CMIP6 database. *Geophysical Research Letters*, 45(7), 3264–3273. 10.1002/2017GL076720
- Cochrane D, & Orcutt G (1949). Application of least squares regression to relationships containing auto-correlated error terms. *Journal of the American Statistical Association*, 44(245), 32–61. 10.1080/0162459.1949.10483290
- Diallo M, Legras B, & Chedin A (2012). Age of stratospheric air in the ERA-Interim. *Atmospheric Chemistry and Physics*, 12(24), 12,133–12,154. 10.5194/acp-12-12133-2012
- Dlugokencky EJ, Bruhwiler L, White JWC, Emmons LK, Novelli PC, Montzka SA, et al. (2009). Observational constraints on recent increases in the atmospheric CH₄ burden. *Geophysical Research Letters*, 36, L18803 10.1029/2009GL039780
- Fleming EL, Jackman CH, Stolarski RS, & Considine DB (1999). Simulation of stratospheric tracers using an improved empirically based two-dimensional model transport formulation. *Journal of Geophysical Research*, 104(D19), 23,911–23,934. 10.1029/1999JD900332
- Garcia RR, Marsh DR, Kinnison DE, Boville BA, & Sassi F (2007). Simulation of secular trends in the middle atmosphere, 1950–2003. *Journal of Geophysical Research*, 112, D09301 10.1029/2006JD007485
- Gordley LL, Thompson E, McHugh M, Remsberg E, Russell J III, & Magill B (2009). Accuracy of atmospheric trends inferred from the halogen occultation experiment. *Journal of Applied Remote Sensing*, 3(1), 033526 10.1117/1.3131722
- Huang FT, Mayr HG, Russell JM III, & Mlynchak MG (2016). Ozone and temperature decadal responses to solar variability in the mesosphere and lower thermosphere, based on measurements from SABER on TIMED. *Annales de Geophysique*, 34(1), 29–40. 10.5194/angeo-34-29-2016
- Huang FT, Mayr HG, Russell JM III, & Mlynchak MG (2014). Ozone and temperature decadal trends in the stratosphere, mesosphere and lower thermosphere, based on measurements from SABER on TIMED. *Annales de Geophysique*, 32(8), 935–949. 10.5194/angeo-32-935-2014

- Langematz U, Kunze M, Kreuger K, & Labitzke K (2003). Thermal and dynamical changes of the stratosphere since 1979 and their link to ozone and CO₂ changes. *Journal of Geophysical Research*, 108(D1), 4027 10.1029/2002JD002069
- Lee H, & Smith AK (2003). Simulation of the combined effects of solar cycle, quasi-biennial oscillation, and volcanic forcing on stratospheric ozone changes in recent decades. *Journal of Geophysical Research*, 108(D2), 4049 10.1029/2001JD001503
- Leovy CB, Sun C-R, Hitchman MH, Remsberg EE, Russell JM III, Gordley LL, et al. (1985). Transport of ozone in the middle stratosphere: Evidence for planetary wave breaking. *Journal of the Atmospheric Sciences*, 42(3), 230–244. 10.1175/1520-0469(1985)042<0230:TOOITM>2.0.CO;2
- Linz M, Abalos M, Glanville AS, Kinnison DE, Ming A, & Neu J (2018). The global overturning diabatic circulation of the stratosphere as a metric for the Brewer-Dobson circulation. *Atmospheric Chemistry and Physics Discussions*, 1–27. 10.5194/acp-2018-972
- Marsh DR, Garcia RR, Kinnison DE, Boville BA, Sassi F, Solomon SC, & Matthes K (2007). Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing. *Journal of Geophysical Research*, 112, D23306 10.1029/2006JD008306
- Maycock AC, Randel WJ, Steiner AK, Karpechko AY, Christy J, Saunders R, et al. (2018). Revisiting the mystery of recent stratospheric temperature trends. *Geophysical Research Letters*, 45(18), 9919–9933. 10.1029/2018GL078035
- McLandress C, Shepherd TG, Jonsson AI, von Clarmann T, & Funke B (2015). A method for merging nadir-sounding climate records, with an application to the global-mean stratospheric temperature data sets from SSU and AMSU. *Atmospheric Chemistry and Physics*, 15(16), 9271–9284. 10.5194/acp-15-9271-2015
- Nash J, & Saunders R (2015). A review of stratospheric sounding unit radiance observations for climate trends and reanalyses. *Quarterly Journal of the Royal Meteorological Society*, 141(691), 2103–2113. 10.1002/qj.2505
- Nedoluha GE, Kiefer M, Lossow S, Gomez RM, Kämpfer N, Lainer M, et al. (2017). The SPARC water vapor assessment II: intercomparison of satellite and ground-based microwave measurements. *Atmospheric Chemistry and Physics*, 17(23), 14,543–14,558. 10.5194/acp-17-14543-2017
- Ramaswamy V, Chanin ML, Angell J, Barnett J, Gaffen D, Gelman M, et al. (2001). Stratospheric temperature trends: observations and model simulations. *Reviews of Geophysics*, 39(1), 71–122. 10.1029/1999RG000065
- Randel WJ, Shine KP, Austin J, Barnett J, Claud C, Gillett NP, et al. (2009). An update of observed stratospheric temperature trends. *Journal of Geophysical Research*, 114, D02107 10.1029/2008JD010421
- Randel WJ, Smith AK, Wu F, Zou C-Z, & Qian H (2016). Stratospheric temperature trends over 1979–2015 derived from combined SSU, MLS, and SABER satellite observations. *Journal of Climate*, 29(13), 4843–4859. 10.1175/JCLI-D-15-0629.1
- Randel WJ, & Wu F (1999). A stratospheric ozone trends data set for global modeling studies. *Geophysical Research Letters*, 26(20), 3089–3092. 10.1029/1999GL900615
- Remsberg E (2008b). On the response of Halogen Occultation Experiment (HALOE) stratospheric ozone and temperature to the 11-year solar cycle forcing. *Journal of Geophysical Research*, 113, D22304 10.1029/2008JD010189
- Remsberg E, Damadeo R, Natarajan M, & Bhatt P (2018). Observed responses of mesospheric water vapor to solar cycle and dynamical forcings. *Journal of Geophysical Research: Atmospheres*, 123(7), 3830–3843. 10.1002/2017JD028029
- Remsberg EE (2008a). On the observed changes in upper stratospheric and mesospheric temperatures from UARS HALOE. *Annales de Geophysique*, 26(5), 1287–1297. www.ann-geophys.net/26/1287/2008/, 10.5194/angeo-26-1287-2008
- Remsberg EE (2015). Methane as a diagnostic tracer of changes in the Brewer-Dobson circulation of the stratosphere. *Atmospheric Chemistry and Physics*, 15(7), 3739–3754. 10.5194/acp-15-3739-2015

- Remsberg EE, Deaver L, Wells J, Lingenfelser G, Bhatt P, Gordley L, et al. (2002). An assessment of the quality of Halogen Occultation Experiment temperature profiles in the mesosphere based on comparisons with Rayleigh backscatter lidar and inflatable falling sphere measurements. *Journal of Geophysical Research*, 107(D20), 4447. 10.1029/2001JD001521
- Remsberg EE, & Deaver LE (2005). Interannual, solar cycle, and trend terms in middle atmospheric temperature time series from HALOE. *Journal of Geophysical Research*, 110, D06106. 10.1029/2004JD004905
- Rosenlof KH, Oltmans SJ, Kley D, Russell JM III, Chiou EW, Chu WP, et al. (2001). Stratospheric water vapor increases over the past half-century. *Geophysical Research Letters*, 28(7), 1195–1198. 10.1029/2000GL012502
- Russell JM III, Gordley LL, Park JH, Drayson SR, Hesketh WD, Cicerone RJ, et al. (1993). The Halogen Occultation Experiment. *Journal of Geophysical Research*, 98(D6), 10,777–10,798. 10.1029/93JD00799
- Scherer M, Voemel H, Fueglistaler S, Oltmans SJ, & Staehelin J (2008). Trends and variability of midlatitude stratospheric water vapour deduced from the re-evaluated Boulder balloon series and HALOE. *Atmospheric Chemistry and Physics*, 8(5), 1391–1402. www.atmos-chem-phys.net/8/1391/2008/, 10.5194/acp-8-1391-2008
- Seidel DJ, Li J, Mears C, Moradi I, Nash J, Randel WJ, et al. (2016). Stratospheric temperature changes during the satellite era. *Journal of Geophysical Research: Atmospheres*, 121, 664–681. 10.1002/2015JD024039
- Shine KP, Bourqui MS, Forster PMF, Hare SHE, Langematz U, Braesicke P, et al. (2003). A comparison of model-simulation trends in stratospheric temperatures. *Quarterly Journal of the Royal Meteorological Society*, 129(590), 1565–1588. 10.1256/qj.02.186
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, et al. (2007). Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (p. 996). New York, USA: Cambridge University Press.
- Stolarski RS, Douglass AR, Newman PA, Pawson S, & Schoeberl MR (2010). Relative contribution of greenhouse gases and ozone-depleting substances to temperature trends in the stratosphere: a chemistry-climate model study. *Journal of Climate*, 23(1), 28–42. 10.1175/2009KC:O2955.1
- Thompson RE, & Gordley LL (2009). Retrieval algorithms for the Halogen Occultation Experiment NASA/Contractor Report 2009-215761 (106 pp.). NASA CASI, Hanover, MD.
- Wang L, Zou C-Z, & Qian H (2012). Construction of stratospheric temperature data records from Stratospheric Sounding Units. *Journal of Climate*, 25(8), 2931–2946. 10.1175/JCLI-D-11-00350.1
- World Meteorological Organization (2011). Scientific assessment of ozone depletion: 2010 Global Ozone Research and Monitoring Project —Report No. 52 (516 pp.). Geneva, Switzerland
- World Meteorological Organization (2018). Scientific assessment of ozone depletion: 2018 Executive summary, Global Ozone Research and Monitoring Project—Report No. 58. Geneva, Switzerland.
- Zou C-Z, & Qian H (2016). Stratospheric temperature climate data record from merged SSU and AMSU-A observations. *Journal of Atmospheric and Oceanic Technology*, 33(9), 1967–1984. 10.1175/JTECH-D-16-0018.1

Key Points:

- HALOE temperature profiles $T(p)$ span the stratopause region and indicate a near-global cooling of the order of -0.5 K/decade for 1993-2005
- Combined radiative forcings from CO_2 , H_2O , and ozone are similar to the observed $T(p)$ trend
- Stratopause trends for HALOE temperature, H_2O , and CH_4 are significant only in the southern hemisphere

Figure 1.

Total calculated temperature trends for 1980–2000, as adopted from Figure 5 of Shine et al. (2003). Separate contributions are from the trends in ozone (red), in the greenhouse gases (GHG in blue), and in H₂O.

Figure 2.

Time series of Halogen Occultation Experiment $T(p)$ at 3.0 hPa and 22.5°N latitude. Analyses are for 1993 to mid-2001. Terms of the regression model are at bottom left and constitute the oscillating curve. The straight line is a sum of the constant and linear trend terms.

Figure 3.
Distribution of average sunset minus sunrise temperatures (in K) from Halogen Occultation Experiment (HALOE) for the upper stratosphere and mesosphere and from 1993 to 2005.

Figure 4.

As in Figure 2 but for time series of Halogen Occultation Experiment $T(p)$ at 22.5°S at 0.5 hPa (top) and 2.0 hPa (bottom).

Figure 5.
Time series of temperature residuals from the multiple linear regression model fit in Figure 4 at 2.0 hPa.

Figure 6. Distribution of Halogen Occultation Experiment temperature trends (K/decade). Dashed contours are negative; contour interval is 0.5 K/decade. Dark shading denotes regions with confidence intervals (CIs) > 90% and lighter shading is for 90% > CI > 70%.

Figure 7.

Temperature time series from merged SSU3 data and for a 15° -wide latitude bin centered at 22°S . The oscillating curve is the multiple linear regression fit to the data (+) and the terms of the model are identical to those used for the analyses of the Halogen Occultation Experiment temperatures.

Figure 8. Halogen Occultation Experiment (HALOE) temperature trends versus latitude at 1.0 and 2.0 hPa in terms of K/decade. The solid and dashed curves show results from when more than four profiles or more than seven profiles are used to estimate the zonal or bin-averaged points. The black solid curve shows the trends from the merged SSU3 data of 1993–2005. Vertical bars at 22°N are 2σ uncertainties from the multiple linear regression trend analyses.

HALOE and SSU3 Temperature Trends 1993-2005

Figure 9.

The near-global and separate hemispheric temperature profiles for the upper stratosphere/ lower mesosphere from Halogen Occultation Experiment (HALOE), as compared with the total calculated $T(p)$ trends of Figure 1. The pressure location of the SSU3 trend is 1.5 hPa (see text).

Figure 10.

Trends of Halogen Occultation Experiment (HALOE) ozone mixing ratio in (%/decade). Dashed contours represent negative trends; contour interval is 1%. Dark shading denotes regions with confidence intervals (CIs) > 90% and lighter shading is for 90% > CI > 70%.

Figure 11.

Halogen Occultation Experiment (HALOE) ozone response (in %) to max minus min solar forcings from a Lyman α proxy. Negative response contours are dashed; contour intervals are 1%. Shading represents CI values as in Figure 10.

Figure 12. Halogen Occultation Experiment (HALOE) ozone response profile for the low latitudes and from the model of Brasseur (1993).

Figure 13. Distribution of trends for Halogen Occultation Experiment (HALOE) H₂O. Dashed lines show negative trends, and contour interval is 0.5 %/decade. Shading denotes confidence intervals (CIs), as in Figure 10.

T(p) Trends and Cooling Rates from HALOE

Figure 14.

Comparison of the estimated total cooling profile with the near-global temperature trend profiles from Halogen Occultation Experiment (HALOE) and from SSU3. There are separate contributions included from HALOE O₃ (red) and H₂O and from the greenhouse gases (GHG; blue) in the estimated total cooling profile.

Figure 15.

Distribution of trends (in %/decade) for Halogen Occultation Experiment (HALOE) CH₄ for 1993–2005. Solid contours are positive and contour interval is 2 %/decade. Shading represents confidence interval values as in Figure 10.

Figure 16.

Time series at 2.0 hPa for Halogen Occultation Experiment methane at (top) 22.5°N and at (bottom) 22.5°S.

Table 1

Analyzed Responses of Temperature (K) to Maximum-Minus-Minimum Solar Cycle Fluxes (Lya) and the Linear Trends (K/Decade) in Time Series of T(p) From (Top) HALOE at 2 hPa and From (Bottom) SSU3, as a Function of Latitude for 1993 to 2005

Latitude	55S	37.5S	22.7S	7.5S	7.5 N	22.5 N	37.5 N	55 N
HALOE								
Lya	0.1	-1.4	0.7	1.0	1.0	0.3	1.0	-0.1
CI, %	10	78	90	94	95	72	79	1
Trend	-0.7	-0.3	-1.2	-1.1	-0.9	-0.9	-0.8	0.2
CI, %	54	16	99	90	86	98	79	11
SSU3								
Lya	0.0	0.1	0.5	0.6	0.5	0.5	0.8	0.3
CI, %	6	38	97	88	92	94	65	47
Trend	-0.2	-0.2	-0.5	-0.5	-0.3	-0.2	0.0	-0.7
CI, %	2	38	99	71	69	51	5	43

Note. Confidence intervals (CI in %) denote the likelihood that the two separate terms are present in the time series. Lya – Lyman α ; HALOE = Halogen Occultation Experiment.

Table 2

Trend Profiles of Ozone and Water Vapor for 1980–2000 and for 1993–2005

Pressure- altitude (hPa)	O ₃ trends, 1980–2000 (%/decade)	H ₂ O trends, 1980–2000 (%/decade)	O ₃ trends, HALOE (%/ decade)	H ₂ O trend, HALOE (%/ decade)
0.3	–2.0	+1.0	+0.67	+0.98
0.5	–2.0	+1.0	+0.63	+0.45
0.7	–3.0	+1.0	+0.57	+0.04
1.0	–4.0	+1.0	+0.50	–0.14
1.5	–5.0	+1.0	+0.49	–0.36
2.0	–6.0	+1.0	+0.50	–0.56
3.0	–7.0	+1.0	+0.37	–1.04

Note. HALOE = Halogen Occultation Experiment.

Table 3

Contributions to Heating/Cooling for GHG, O₃, and H₂O in Shine et al. (2003) and from HALOE and Total Heating Rate Profile From HALOE (Last Column)

Pressure (hPa)	O ₃ heating from Shine(K/decade)	O ₃ heating HALOE(K/decade)	H ₂ O heating from Shine(K/decade)	H ₂ O heating HALOE(K/decade)	GHG heating, Shine and HALOE(K/decade)	Total heating HALOE(K/decade)
0.3	-0.40	+0.12	-0.2	-0.20	-0.50	-0.58
0.5	-0.65	+0.15	-0.2	-0.10	-0.75	-0.70
0.7	-0.85	+0.11	-0.2	+0.00	-0.80	-0.69
1.0	-0.95	+0.12	-0.2	+0.04	-0.80	-0.64
1.5	-0.83	+0.07	-0.2	+0.07	-0.75	-0.61
2.0	-0.70	+0.02	-0.2	+0.11	-0.70	-0.55
3.0	-0.40	+0.00	-0.2	+0.20	-0.60	-0.40

Note. HALOE = Halogen Occultation Experiment.