On the response of HALOE stratospheric ozone and temperature to the 11-yr solar cycle forcing

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Abstract.

Results are presented on responses in 14-yr time series of stratospheric ozone and temperature from the Halogen Occultation Experiment (HALOE) of the Upper Atmosphere Research Satellite (UARS) to a solar cycle (SC-like) variation. The ozone time series are for ten, 20-degree wide, latitude bins from 45S to 45N and for thirteen “half-Umkehr” layers of about 2.5 km thickness and extending from 63 hPa to 0.7 hPa. The temperature time series analyses were restricted to pressure levels in the range of 2 hPa to 0.7 hPa. Multiple linear regression (MLR) techniques were applied to each of the 130 time series of zonally-averaged, sunrise plus sunset ozone points over that latitude/pressure domain. A simple, 11-yr periodic term and a linear trend term were added to the final MLR models after their seasonal and interannual terms had been determined. Where the amplitudes of the 11-yr terms were significant, they were in-phase with those of the more standard proxies for the solar uv-flux. The max minus min response for ozone is of order 2 to 3% from about 2 to 5 hPa and for the latitudes of 45S to 45N. There is also a significant max minus min response of order 1 K for temperature between 15S and 15N and from 2 to 0.7 hPa. The associated linear trends for ozone are near zero in the upper stratosphere. Negative ozone trends of 4 to 6%/decade were found at 10 to 20 hPa across the low to middle latitudes of both hemispheres. It is concluded that the analyzed responses from the HALOE data are of good quality and can be used to evaluate the responses of climate/chemistry models to a solar cycle forcing.
1. Introduction

There have been a number of model studies focused on the response of middle atmosphere ozone to the 11-yr cycle of the solar ultraviolet (uv)-flux forcing (e.g., Garcia et al., 1984; Brasseur, 1993; Huang and Brasseur, 1993; Fleming et al., 1995; Harris et al., 1998; Shindell et al., 1999; Callis et al., 2000; Lee and Smith, 2003; Marsh et al., 2003; Rozanov et al., 2004; Austin et al., 2007; Marsh et al., 2007; McCormack et al., 2007; Nissen et al., 2007; Smith and Matthes, 2008; Austin et al., 2008). It is important to verify those modeled responses as a function of altitude, latitude, and season using high quality, global-scale observations of ozone. Analyses of the long-term satellite ozone data sets from the Stratospheric Aerosol and Gas Experiments (SAGE I/II) and from the series of Solar Backscatter Ultra-Violet (SBUV) instruments have yielded zonal-mean solar-cycle (SC) response patterns having maxima at middle latitudes from about 3 to 1.5 hPa (or ~40 to 45 km) [e.g., Wang et al., 1996; Chandra and McPeters, 1994; McCormack and Hood, 1996; Lee and Smith, 2003; Soukharev and Hood, 2006; Randel and Wu, 2007]. However, the patterns for those responses do not agree so well with many of the simulations, which tend to peak at somewhat lower altitudes and lower latitudes. In addition, the SC amplitudes derived from the observations are about twice those from many of the models. On the other hand, Chandra and McPeters [1994] reported very good agreement between modeled and observed responses to the uv-flux variations associated with the 27-day solar rotation cycle.

Wang et al. [1996] found that the apparent SC response in the SAGE dataset was larger and occurred at higher latitudes for the northern hemisphere (NH) than for the southern
hemisphere (SH). Conversely, *Lee and Smith* [2003] found a SC response in the SBUV data that was larger in the SH, but they also cautioned that the observed responses may depend on the specific decade(s) for the given datasets. Those apparent differences have led researchers to consider the role of decadal-scale dynamical interactions for ozone, particularly for the middle and lower stratosphere [*Nedoluha et al.*, 1998; *Randel et al.*, 2000; *Tian et al.*, 2006; *McCormack et al.*, 2007; *Smith and Matthes*, 2008]. Such considerations have prompted further model studies that include the effects of atmospheric interactions with the semi-annual oscillation (SAO) and quasi-biennial oscillation (QBO) cycles, as well as influences from volcanic events and from the El Nino/Southern Oscillation (ENSO). All of these forcings could alter a decadal-scale ozone response, perhaps even having a maximum that is in-phase with the SC for the stratosphere but located at middle latitudes rather than at tropical latitudes—or more like those obtained from the preceding data analysis studies [e.g., *Matthes et al.*, 2004; *Lee and Smith*, 2003; *Kodera and Kuroda*, 2002]. *Hood* [2004] summarized the nature of the model/data discrepancies for the 11-yr SC response.

A proper characterization of the SC response in ozone is also critical to a search for a slowdown for the decline of ozone during the 1990s and/or for its recovery since then, in association with the effects of the mandated reductions for the release of chlorofluorocarbon compounds into the atmosphere [*Reinsel*, 2002; *Reinsel et al.*, 2002; *Newchurch et al.*, 2003; *Steinbrecht et al.*, 2004a; *Cunnold et al.*, 2004; *Steinbrecht et al.*, 2004b; *Weatherhead et al.*, 1998; *Randel and Wu*, 2007]. For example, *Anderson and Russell* [2004] and *WMO* [2007, Figure 1-12] report that the total chlorine derived from
measurements of HCl obtained with the Halogen Occultation Experiment (HALOE) leveled-off after about 1997 and began to decline after 2001. Thus, it is reasonable that the trends for upper stratospheric ozone have been changing due to its chemical interactions, too [Siskind et al., 1998]. Rosenfield et al. [2005] reported that the chemical response of ozone ought to be asymmetric between the northern and southern hemispheres because of their differences for the distributions of the species responsible for ozone loss.

A proper characterization of the solar cycle or any other decadal-scale variation is also important for the determination of the ozone trend. For example, Soukharev and Hood [2006] analyzed for interannual, SC and trend effects, as part of their regression modeling of the SBUV, SAGE II, and HALOE ozone datasets. They focused primarily on the SC terms from their regression modeling, although they did show that the SC terms that they obtained from the SBUV dataset had response profiles at low latitudes that were similar for 1979-1991 and from 1992-2003—decadal periods when the trends in upper stratosphere ozone were quite different.

Another important aspect of the fidelity of the observed SC response in ozone is how it relates to the SC response in temperature versus pressure, or T(p). Up until recently, that response in temperature had been obtained only with data from the NOAA operational sounding instruments, which provide relatively low vertical resolution radiance profiles for its retrieval in the stratosphere. Three distinct versions of the T(p) derived from the radiance data lead to SC responses that have a maximum at low latitudes, but which have
different magnitudes and are occurring over a different range of pressure-altitudes

[McCormack and Hood, 1996; Scaife et al., 2000; Crooks and Gray, 2005]. There is also

a problem with the drifting local time of the NOAA instruments, which could introduce

long-term temperature variations because different times of the daily temperature cycle

are sampled [Shine et al., 2008]. As a result, there is some uncertainty about which T(p)

dataset is more appropriate for comparison with the observed SC ozone responses.

This paper contains results of analyses for the decadal-scale responses and trends in

ozone and T(p) based on data for 1991-2005 from the single, well-calibrated HALOE

instrument. In particular, it is focused on the characterization of the response of its upper

stratospheric ozone and temperature to the 11-yr SC, keeping in mind that the HALOE

measurements span only one complete SC. For this reason the results herein may be

considered somewhat exploratory, rather than definitive. Because the trends in upper

stratospheric ozone due to its interaction with chlorine were small during the time span of

the HALOE measurements [Rosenfield et al., 2005; Yang et al., 2006], it was felt that one

could have better success with isolating a SC-like response for the time period of

HALOE rather than for the datasets that included the 1980s, too. Also different from the

two previous solar maxima, there was no interference from a volcanic eruption near the

solar maximum of 2001 [Solomon et al, 1996]. Because the calculated percentage SC-

like response in ozone is much larger than its percentage response in T(p) it ought to be

easier to isolate an SC-like signal in ozone. Nevertheless, one must still be aware that it

is easy to confound the effects of a SC term and a trend term, especially when adjacent
points in the time series of the zonal means are correlated, and/or when the end portions of the time series are anomalous (e.g., Tiao et al. [1990]).

Section 2 reviews the attributes of the HALOE ozone profiles, along with the time series approach to their analysis. Section 3 includes the findings from those analyses and describes the important similarities and differences with the SC responses from the several other published, observed and modeled studies. Section 3 also relates the SC-like responses from analyses of the HALOE temperature time series [Remsberg and Deaver, 2005; Remsberg, 2007; Remsberg, 2008] and reviews how it compares with results from zonal-mean models and observations. In general, there is good agreement with the model predictions of the SC responses in ozone and T(p) of Brasseur [1993], Marsh et al. [2007], and Austin et al. [2008] versus those found in the HALOE data, except in the tropical upper stratosphere. Linear trends from the ozone analyses are presented in Section 4, along with similar findings for the temperature from the more restricted pressure-altitude range of 2 to 0.7 hPa. Section 4 also comments on a tropical to subtropical anomaly in the SC-like responses of the HALOE ozone in the lower stratosphere, at least as compared to the modeled responses of ozone to just the 11-yr uv-flux forcing. Summary findings are in Section 5.
2. Approach

a. Data characteristics

HALOE is a solar occultation instrument that operated successfully on the Upper Atmosphere Research Satellite (UARS) from October 1991 through late November 2005. A description of the HALOE experiment is given in Russell et al. [1993], and a first characterization of its ozone profiles is provided in Brühl et al. [1996]. An update of the quality of the current operational ozone dataset is given in Randall et al. [2003] for the so-called Version 19 (or V19) Level 2 profiles that are used for the present study. The HALOE Project Team monitored the performance of the HALOE instrument over its mission lifetime, and they found no long-term degradation of its measurement characteristics that would impact the determination of a SC or long-term trend in ozone [Gordley et al., 2006; Hervig et al., 2007].

The HALOE ozone profiles were obtained with excellent signal-to-noise (S/N) and with no a priori constraints for their retrievals. They have a vertical resolution of about 2.3 km and are registered in pressure-altitude, in particular as derived from a retrieval of its own temperature profiles from about 4 hPa (near 38 km) to 0.004 hPa (near 85 km). The vertical resolution and the measurement and retrieval sensitivity of the HALOE ozone ought to be providing an accurate SC response profile, as compared with that of the more standard SBUV sounding technique, for example.

The T(p) profile information in the HALOE dataset below about the 4-hPa level was obtained from the daily 12Z operational analyses provided to the UARS Project by the
NOAA/Climate Prediction Center (CPC) and has relatively low vertical resolution. The HALOE T(p) information above that level has a vertical resolution of 3-4 km and is representative of the local times of the occultation measurements, both of which also provide advantages when compared with the CPC T(p) data [Remsberg, 2007; Remsberg, 2008]. Thus, the HALOE ozone and T(p) datasets are compatible above the 4-hPa level for obtaining SC-like responses from the upper stratosphere to the lower mesosphere and for relating them to each other.

The HALOE measurements are for sunrise (SR) and sunset (SS), and there are significant variations in ozone at those two times in the low to middle mesosphere due to rapidly-changing, photochemical effects. First-order, diurnal corrections are included in the forward model for HALOE V19 ozone above about 37 km to account for those changes along the limb tangent paths for the retrieved profiles. Natarajan et al. [2005] re-evaluated the adequacy of those corrections and developed further modifications that ought to be applied to updated HALOE algorithms for the retrieval of its mesospheric ozone, especially for SR conditions and above about 61 km (or about 0.2 hPa). In addition, Marsh et al. [2003] showed that seasonal cycles for upper mesospheric ozone are small at SR, but not at SS, and that it is not a good idea to combine their SR and SS data for the mid mesosphere when searching for its SC response. For these reasons the analyses for a SC response in this study are restricted to HALOE V19 profile segments below the 0.7-hPa level (or about 53 km).
Figure 1 shows the measurement pattern of the tangent point locations from HALOE for each day of 2001. One can see that the measurements were less frequent poleward of about 50 degrees latitude and are missing at 40 and 50 degrees during summer. Prior to 1996, the summertime and mid latitude gaps are not as large because of the greater power availability for instrument operations during the early years of the UARS mission. The intervals for adjacent samples within a latitude zone from solar occultation measurements vary from a few days to more than a month. Although rather infrequent and variable, such sampling intervals are still adequate for resolving the seasonal and longer-term variations from the total data record and with sufficient accuracy.

b. Analysis procedure

Some initial studies of the seasonal and longer-period variations in HALOE ozone were conducted for the lower stratosphere by Remsberg et al. [2001] using multiple linear regression (MLR) techniques, and they found that annual and quasi-biennial (QBO) terms accounted for almost all of its variations. In the current study MLR was applied to HALOE time series of averages of the ozone points for a given pressure layer and for 20-degree wide latitude bins centered every 10 degrees from 45N to 45S. Latitude bins of this width provide a high probability of having enough samples to adequately represent the zonal mean. The MLR technique also accounts for the fact that the data points from occultation measurements are inherently non-orthogonal. The HALOE Level 2 profiles are tabulated with a spacing of 300 m. However, the precision of the data points for an ozone time series was improved by linearly integrating the individual ozone profiles in log pressure over “half-Umkehr layers” (about 2.5 km thick or very near to the vertical
resolution of the retrieved profiles). The resulting ozone amounts for those layers are given in terms of Dobson Units (DU). Table 1 defines the half-Umkehr layers for this study. The total pressure-altitude range is 63.3 hPa to 0.70 hPa or a range of 13 half-Umkehr layers labeled from 4L to 10L, respectively.

Other researchers have reported on how the SC ozone response in the lower stratosphere is confounded with and possibly dominated by decadal-scale dynamical effects [e.g., Dunkerton and Baldwin, 1992; Salby et al., 1997]. Thus, the current study is focused on the middle and upper stratosphere, where the dynamical effects are weaker and hopefully more easily resolved. In most other respects the analysis approaches in Remsberg et al. [2001] and especially in Remsberg [2007; 2008] were followed. Annual (AO) and semi-annual (SAO) cycles were fit to the time series, and the time series residuals were analyzed for their remaining interannual structure. Weak quasi-biennial or QBO-like (28 mo.) and sub-biennial or IA (21 mo.) terms were also found consistently in the upper stratosphere. The QBO periods became more variable in the middle and lower stratosphere (25 to 31 months), in accord with the power spectral analysis results of HALOE ozone by Witte et al. [2008]. The corresponding subbiennial periods changed, as well. An overall objective was to account for any significant, periodic structure in the time series before analyzing for the underlying SC-like and trend terms.

The average separation in time for the points in the HALOE time series is about 25 days. Even so, because zonal-average ozone values at time n have considerable memory of the atmospheric state at time n-1, the time series have autoregressive characteristics. The
appropriate MLR result for that situation is obtained by a two-step process (see Appendix A of Tiao et al. [1990]). Initially, a model of the form,

\[ O_3(n) = a + bX + e \sin(Z) + f \cos(Z) + \ldots + N(n), \]  

was used, where \( O_3(n) \) is the sum of the components of ozone at the \( n \)th point in the time series. The model has a constant term ‘a’ and a linear term in \( X = (t_n - t_1) / T \), where \( t_n \) is the time of the \( n \)th observation point, \( t_1 \) is the first point in the time series, \( T \) is the total length of the time series, and \( b \) is the coefficient of the linear term. The model has seasonal and longer-period terms that are represented by Fourier components in \( Z \), where \( Z = 2\pi t_n / P \), and \( P \) is the period of a given cycle. Periodic terms that were considered are AO, SAO, QBO-like, sub-biennial (or IA), and an 11-yr (4017-dy) term. Note that the seasonal terms were almost always found to have a probability of at least 99% of being present. The QBO, IA, 11-yr, and linear terms were allowed to have lower probabilities, in order to accommodate their existence in the time series across all latitudes and pressure-altitudes. Finally, the term \( N(n) \) is the autoregressive (AR) noise residual that is given by

\[ N(n) = \varphi N(n-1) + E(n), \]  

for a first order (or AR1) process. The factor \( \varphi \) is the autocorrelation of the noise residual and \( E(n) \) is the white noise component. Thus, the MLR method consists of a fit for all the terms of Eq. (1) and the generation of its model residuals \( N(n) \). The autocorrelation
coefficient $\varphi$ for this model is found from the residuals. The model terms of Eq. (1) are then transformed to those of Eq. (3),

$$O_3(n) - \varphi O_3(n-1) = a [1 - \varphi] + b [X(n) - \varphi X(n-1)] + e [\sin(Z(n)) - \varphi \sin(Z(n-1))] + f [\cos(Z(n)) - \varphi \cos(Z(n-1))] + \ldots + E(n),$$

and the data time series is refit to get new coefficients. Initially, $\varphi$ was set to zero for the MLR analyses using the relevant terms of Equation (1), $\varphi$ was calculated from the model residuals, and then final coefficients for the terms were obtained with Equation (3). Because MLR provides for a combined fitting of all the model terms, the absolute ozone uncertainties are nearly the same for each term of the model. Percentage deviations and the probabilities of their respective terms depend on their amplitude.

Figure 2 is an example of a HALOE data time series (Layer 8U centered at about 42 km and at the latitude of 25N), where the SR and SS data have been fit with a regression model (the solid oscillatory curve) that contains the seasonal, AO and SAO terms, a QBO-like (853-dy) term, a subbiennial (640-dy) term, and an 11-yr term. The horizontal straight line is the constant term from the model, and all terms are highly significant. An 11-yr term was fit to the time series rather than regressing against a proxy term for the uv-flux, to determine whether there might be other decadal-scale terms that were affecting the ozone. The 11-yr response in Figure 2 is essentially in-phase with the time series of the solar flux for SC 22 and 23 (see following subsection, too). In other words, there is a maximum in the ozone in this case that is very near to the time of a maximum
in the solar flux (i.e., 0.9 yr from January 1991 and 2002), as expected from increases for
the UV-photodissociation of molecular oxygen [Brasseur and Solomon, 1984]. One can
also see that the maxima for the annual cycles do not exceed the horizontal line in 1996
and 1998, or near solar minimum; its 11-yr, maximum minus minimum response is 2.7%.
For this layer the amplitudes of the seasonal and interannual terms are small and of the
order of the amplitude of the estimated 11-yr or SC-like term. At this point it is noted
that the zonal mean distribution of ozone can have significant meridional variations at
mid and higher latitudes of the middle and upper stratosphere, yet Eq. (3) does not
contain a term to account for variance with latitude. Such variations are embedded
mainly in the coefficients of the seasonal terms. Since the latitude bins are relatively
narrow (20 degrees wide) compared with the meridional gradients in the zonal-average
ozone, the data time series provide good estimates of the true seasonal coefficients for
zonal-mean ozone. The aperiodic ENSO or volcanic forcings were not modeled; their
effects may be important for ozone in the lower stratosphere (see later).

The model fit in Figure 2 does not include a linear term, although that term is included
for the MLR results of Sections 3 and 4. Figure 3 is a plot of the residuals for the ozone
model of Figure 2. It shows that there is no remaining apparent periodic structure, which
is an important acceptance test for the set of terms of the final MLR model. There are
also no significant, non-random autocorrelations in the residuals for this final model (not
shown, but see Remsberg et al. [2001] for a diagnostic plot of this statistical test). The
solid horizontal line is the linear fit to the residuals; and in this case it is not significantly
different from zero. A polynomial trend term may account for a chemical response of
ozone to the long term changes in total reactive chlorine [e.g., Randel and Wu, 2007; Yang et al., 2006], but it was not included in the MLR models because reactive chlorine is not the dominant loss mechanism for ozone throughout the stratosphere. Furthermore, the time series of the residuals in Figure 3 does not indicate the presence of such an underlying, polynomial trend term due to that chemical loss. However, since total reactive chlorine reached its peak value in the upper stratosphere in the late 1990s [WMO, 2007], any enhanced chemical loss at that time would tend to reinforce the minimum response of ozone to the SC forcing. Thus, the 2.7% max minus min, SC-like response of the MLR model fit in Figure 2 may overestimate the amplitude of the true SC effect on ozone.

Ozone is in photochemical equilibrium in the upper stratosphere, and its seasonal variations are anti-correlated with the corresponding seasonal variations for HALOE T(p), as shown in Figure 4 for 25N and 2 hPa. A linear trend term is included in its model, and its diagnosed value is -1.1 K/decade. The 11-yr variation in T(p) is much less apparent (max minus min is 0.6 K). That percentage response (0.23%) is smaller than for the ozone but in accord with at least some model predictions [Austin et al., 2008]. Even so, the diagnosed phase for the maximum of the 11-yr term in T(p) occurs 1.7 years prior to solar max and leads the 11-yr response of ozone by 2.6 years based on its MLR model in Figure 2. The adjusted, in-phase, max minus min SC response is more like 0.3 K for T(p). Therefore, it may be that there are other effects contributing to the analyzed, 11-yr response in T(p) for this layer and latitude (see later in Section 4).
Finally, one should note that the SR and SS samples in the HALOE time series of Figures 2 and 4 tend to alternate, due to the sequential crossings of the orbital sampling patterns for the SR and SS measurements of Figure 1. This character for the sampling leads to largely real, diurnal variations in both the ozone and temperature data in the mesosphere. Its occurrence enhances the ‘noisy’ appearance of the HALOE time series residuals after removal of the seasonal and interannual terms. In addition, those alternating SR/SS residuals are negatively correlated, obscuring the otherwise positive autocorrelation of the residuals at lag-1 and higher lags. A first-order, average adjustment for those small, SR/SS differences was obtained for these higher altitude data; mean values of the separate time series of the SR and of the SS data were determined and half the difference of those two means was then applied to the respective SR and SS points. This step reduces the short-term, point-to-point, fluctuations in the time series and increases the significance of the AR1 term and, thus, the other small amplitude terms for the regression models of Figures 2 and 4, but it has essentially no effect on the phases of the periodic terms. Therefore, for each time series the adjusted SR and SS points were combined, giving about 200 points in all. A clearer example of this effect for the temperature tides of the mesosphere can be found in Remsberg [2008, their Figures 1 and 2]). On the other hand, almost no systematic, SR/SS differences were found for the time series of the HALOE ozone in the mid and lower stratosphere, as expected based on model calculations of its weak diurnal variations.
c. Signatures of interannual terms from the MLR models

Traditional proxies for the QBO term were tried during the early development of the MLR models for this study. However, QBO cycles based on the tropical lower stratospheric winds did not provide for a highly significant fit of the interannual variations in upper stratospheric ozone, particularly for the subtropics of the NH. Similar deficiencies for those QBO-proxies were reported for time series analyses of SC effects in temperature by Crooks and Gray [2005]. In the present study the QBO-like terms that were fitted to the ozone residuals for the low latitudes had significant changes of phase from 50 to 10 hPa, not unlike that reported by Pascoe et al. [2005] for the zonal winds. Thus, a QBO wind proxy that is averaged over that pressure range may not be so representative of the true forcings of that term. Furthermore, the effect of a QBO forcing in ozone is a bit more complicated because it also depends on the zonal-mean ozone distribution and its gradients, which change in magnitude and sign for the vertical range of the subtropical stratosphere. Instead, the periods and phases of the dominant interannual terms were obtained for the present study from a Fourier analysis of the points of each of the time series.

Figure 5 shows the time series of HALOE ozone observations for 25N and Layer 6L (11.2 - 15.8 hPa). The combination of the AO and SAO terms of the MLR model provides a very good fit to the seasonal variations for this layer. Amplitudes for the interannual and SC-like terms are weaker, although it is obvious that there are significant interannual variations in the data. Those variations are fit well by a combination of a 26-month QBO-like term and a 22-month subbiennial term.
The ozone of Figure 5 for 1991-92 is clearly elevated compared with that of the other years, most likely a result of physical processes associated with the major volcanic aerosol layer from the Mt. Pinatubo eruption of June 1991. In fact, the ozone is somewhat anomalous during this period for other low to middle stratospheric layers in the tropics and subtropics of both hemispheres, and Section 4 contains some discussion about possible causes of the excess ozone of 1991-92. A model fit of the entire time series of Figure 5 was attempted, including both a linear trend term and a periodic term of 11-yr period. However, the excess ozone of 1992 represents an “endpoint anomaly” for the analysis. It leads to a rather large, decreasing trend and affects the nature of the associated 11-yr term. Instead, for those layers that showed anomalies in this early period, it was found that much more reasonable results were obtained for those two terms by starting the MLR model in early September 1992 or in January 1993. That modification was applied to the analyses of the layers 6U through 4L. The solid oscillating curve in Figure 5 is the MLR model fit to the data using all terms, but beginning in September 1992. Note also that the solid curve actually begins several points later because of the need to allow for the autoregressive nature of the time series.

The 11-yr term of the model fit in Figure 5 has a “max minus min” value of 2.7%, but the phase of its maximum occurs 1.0 year prior to January 1991 (or 2002). A decreasing trend of 5.1%/decade was also realized from the analysis. The results for the 11-yr terms from each of the 130 ozone time series are presented in Section 3. Results from similar analyses of the HALOE T(p) are given there, as well, but only for the pressure layers of
Findings for the linear trend terms are presented and discussed in Section 4. The rest of this subsection considers the QBO-like terms and their interactions with the seasonal terms.

A typical example of the zonal mean ozone distribution is shown in Figure 6 from a sequence of HALOE SS observations that eventually covered most latitudes during the period of February 26 to April 5, 1995. The QBO cycle has its largest effect on the zonal mean ozone at the tropical latitudes and at those pressure altitudes where the vertical ozone gradient is large. In fact, one can check on the realism of the current QBO signal in ozone by examining its amplitudes from the analyses of the 130 separate time series, as shown in Figure 7. QBO amplitudes are nearly hemispherically-symmetric throughout the stratosphere. The largest amplitudes (in %) occur in the tropical stratosphere near 7 hPa and 30 to 40 hPa. Photochemistry controls the distribution of ozone above about the 5-hPa level and thus dampens the effect of the QBO on the vertical ozone gradient of the upper stratosphere. Its amplitudes are also relatively weak at about 20 hPa for the latitudes of 15 to 45 degrees of both hemispheres, which is where the meridional gradients of ozone are weak, as well (c.f., Figures 6 and 7).

*Dunkerton* [2001] explained that a subbiennial term occurs in ozone due to the difference interaction of the annual and QBO cycles. Figure 8 is a plot of the amplitudes of the subbiennial terms. Again there is good continuity for the features of their distribution, and their amplitudes decrease with altitude in the region of transition from dynamical to photochemical control. Maximum amplitudes occur in the subtropics of the middle
stratosphere, where the combined effects due to the annual cycle and the QBO are largest for ozone. In the tropics near 30 hPa and 7 hPa the subbiennial amplitudes are weaker than that for the QBO forcing alone because the annual cycle is weak at low latitudes. The subbiennial amplitudes are somewhat larger in the northern than the southern hemisphere subtropics at about 10 hPa. The annual cycle amplitude is also larger for the northern hemisphere in this region, presumably an indication of the zonal mean effects of the more vigorous and sustained net transport during winter and springtime for the northern hemisphere. The region of maximum values near 50 hPa and 30 degrees of latitude is also where the annual cycle in ozone is relatively large.
3. Solar Cycle Responses in HALOE Data

a. Ozone

Initially, the time series of F10.7 cm solar radio flux data was employed as a proxy for the SC term, but its fit to the HALOE ozone was not significant at the 90% confidence level. That proxy term exhibited shorter period structure that was not present in the ozone time series of HALOE even after applying a smoothing to the daily values of the proxy with an 81-dy running mean to avoid the effects of the 27-dy solar rotation cycle in the daily fluxes. As mentioned earlier, there may also have been a confounding of the effects of the solar uv-flux with those from reactive chlorine during 1991-2005, at least in the upper stratosphere. Therefore, it was decided that it would to be instructive to fit an 11-yr periodic term to the time series but to allow its phase to be determined simply from its best fit to the data.

Figure 9 shows the max minus min ozone values (in percent) for its 11-yr terms over the domain of latitude and pressure-altitude. Maximum responses of order 2 to 3% were found in the upper stratosphere at subtropical to middle latitudes, and they are somewhat asymmetric between the two hemispheres. The dark shading shows where the 11-yr terms have a confidence interval (CI) of greater than 90% for their partial rank order correlations [Remsberg et al., 2001], and the lighter shading indicates where they have a CI value between 70 and 90%. Max minus min values of up to 2% extend through the tropics near 3 hPa, and they remain significant at the 90% level. This finding indicates that the sampling from HALOE was adequate for representing the zonal average ozone in the tropics. In the lower stratosphere the largest percentage responses occur in the
subtropics of the southern hemisphere and in the tropical latitudes (although larger than expected at 50 hPa). Smaller and much less significant responses occur in the tropics near 1 hPa (0.5%) and from 7 to 30 hPa (1%), at low to middle latitudes of the southern hemisphere near 7 hPa (1 to 1.5%), and at middle latitudes of the northern hemisphere at 40 hPa (1%). However, it is stressed that the estimates of significance assume that all the relevant structure in the time series has been accounted for.

To see how well the diagnosed, 11-yr terms are related to the solar cycle flux, their phases are given in Figure 10 in units of years from January, 1991. Due to the fact that the maximum for SC 22 was broad and nearly flat over 2 years, it was assumed that the 11-yr signal in ozone was in-phase if it was within ±1 yr of solar uv-flux maximum (the regions delineated by shading in Figure 10). SC 22 had its final peak in early 1992 followed by a sharp decline, and it has been argued by some that phase maximum for the uv-flux occurred at that time rather than a year earlier in January 1991. But in order to be consistent with the estimates of the phase of the SC maximum for \textit{T(p)} of Remsberg [2007; 2008], that January 1991 time of reference was kept for the ozone results, too.

Generally, the 11-yr terms for ozone are in-phase with that of the uv-flux, with the exception of the upper stratosphere at tropical latitudes and near 30 hPa from the tropics to northern hemisphere middle latitudes. It is presumed that the lower stratosphere anomaly is indicative of an interannual, dynamical forcing mechanism that is dominating the effects of the uv-forcing. In fact, \textit{Marsh and Garcia} [2007] reported ozone at 52 hPa that was anti-correlated with a lagged ENSO index; they found that this dynamical forcing tended to reduce the response of ozone to a solar forcing in the lower stratosphere.
Figure 10 is showing that the 11-yr term has a maximum that lags that of the uv-flux by several years in the tropical stratosphere from 4 to 1 hPa. This anomaly may be an indication of an enhanced chemical loss of ozone due to reactive chlorine, sometime after solar minimum. It is noted that such losses for annual-averaged ozone ought to be most clearly evident in the upper tropical stratosphere because that is where the effects of the chlorine would began to compete with those of the uv-flux [Brasseur and Solomon, 1984]. In support of this idea, it is noted that the largest values of total chlorine, as inferred from the HALOE measurements, occurred from 1997 to 2002 (see Figure 1-12 of WMO [2007]). In this instance the inclusion of a simple linear, rather than a polynomial, trend term in the MLR models may not adequately represent the changing effects of the chlorine. Indeed, if this process is contributing to the out-of-phase, 11-yr ozone response, it would be unique to the time span of the HALOE observations; that is, total chlorine reached its maximum values in the upper stratosphere in the middle of its 14-yr period.

b. Temperature

A test of the fidelity of the ozone results is an assessment of the analogous 11-yr response in temperature from HALOE, even though model simulations indicate that the percentage change for T(p) ought to be much smaller than that for ozone (e.g., Smith and Matthes [2008]). Remsberg and Deaver [2005] analyzed for that response using 10-degree
latitude bins for the upper stratosphere, as well as the mesosphere. Their MLR analysis approach was essentially the same as that used here. However, they were not confident of their results at and below the 3-hPa level because of concerns about the long-term accuracy of the temperature time series from the NOAA/CPC to which the HALOE T(p) retrievals were merged. As a result, the HALOE findings for the 11-yr and trend terms in T(p) are only appropriate above the 3-hPa level for comparisons with those of ozone [Remsberg, 2007; 2008].

The 11-yr temperature responses were obtained for 20-degree wide latitude bins in the present study, in order to be compatible with the ozone results. Those responses are shown in Figure 11 along with their phase deviations (in years) from January 1991 in Figure 12, but only for the pressure levels of 0.7 to 2.0 hPa. The 11-yr temperature maximum is in phase (within ±1 yr) with the uv-flux forcing from about 25S through 15N. There are transitions to somewhat out-of-phase values at 35S and at 25N, but where the responses in Figure 11 are weaker and not very significant.

The HALOE 11-yr response is smaller than reported from several analyses of the long-term temperature data sets from the operational satellites [Hood, 2004]. On the other hand, the magnitude and variation with latitude and altitude for the HALOE terms at 2 and 1 hPa agree very well with the observed responses based on the recent findings of Crooks and Gray [2005, their Fig. 2] for the period 1979-2001, as based on the ERA-40 reanalysis dataset.
The response in HALOE T(p) near the tropical stratopause is about two-thirds that found from the simulations of Brasseur [1993, their Figure 14b] and about half that from the fixed dynamical heating model of McCormack and Hood [1996]. However, the variation with latitude of the HALOE response compares favorably with the model results of Marsh et al. [2007] and of Smith and Matthes [2008], at least after a scaling of the latter results to the actual max minus min values of the solar flux. The solar cycle response from the AMTRAC model of Austin et al. [2008] most closely matches that reported here.

The temperature response in the HALOE data is in-phase with the solar uv-flux near the tropical stratopause. Thus, it is the HALOE ozone response that appears anomalous in that region. However, the amplitude of the 11-yr term in ozone is becoming small and is not significant at the Equator at 1 hPa. It is also noted that there was a peak in the uv-flux in about January 1992, rather than January 1991. An allowance for that fact reduces the phase discrepancy for ozone by 1 year without affecting the phase agreement of the temperature response noticeably.

c. Solar cycle (or SC-like) responses of HALOE ozone and temperature

In order to obtain estimates of the actual response of atmospheric ozone and temperature to a proxy for the direct forcing from the uv-flux, their sets of responses from Figures 9 and 11 have been adjusted by the amount that they were not exactly in-phase from Figures 10 and 12. Those adjustments were made by multiplying the responses by the factor, \( \cos \left[ \frac{2\pi p}{11} \right] \), where \( p \) is the deviation of phase of the maximum (in years) from
January 1991. Even after applying the adjustments, there is good continuity among the ozone responses from the 130 separate time series.

The separate, 11-yr responses for ozone of Figure 9 have been averaged for the latitude bins that extend from 25S and 25N, and those profiles are shown in Figure 13. The corresponding, SC-like response profile is shown as well, but there is very little difference between the two. There is good similarity between the results in Figure 13 and the SC response profile obtained from the seasonally-averaged HALOE data points over the same latitude range in Soukharev and Hood [2006, their Figure 14], if one excludes their analyzed value at about 35 km. The magnitude and variation of the HALOE response profiles agree very well with the response at low latitudes from the representative, zonal-mean models of Brasseur [1993, his Figures 9a and Figure 14a] and of Huang and Brasseur [1993, their Figure 8a]. They also agree qualitatively with the results of Austin et al. [2007] and of several other models, as shown in Soukharev and Hood [2006, their Figure 14]. In addition, there is no discrepancy for this HALOE ozone response across most of the stratosphere versus the responses from the chemistry/climate models, AMTRAC and WACCM, in Austin et al. [2008].

Lee and Smith [2003] analyzed both the SAGE II and SBUV data for a solar cycle response. Their results from SAGE II are similar to the zonal mean contour values of Figure 9, at least for the upper stratosphere at most latitudes; their results from SBUV do not agree as well though, especially in the tropics (see also the analyzed results from SAGE and SBUV in Soukharev and Hood [2006]). Lee and Smith [2003] conducted
model studies of the SC response, but modified to account for the relative phases of the
QBO over specific decades. The interaction with the QBO in their model leads to larger
positive responses in the subtropical upper stratosphere of both hemispheres, but their
results are also sensitive to the QBO indexes that they employed. However, it is noted
that for the present HALOE analyses the interactions with the QBO and its associated
subbiennial term have been accounted for to first order based on the structure of those
terms in the HALOE time series. Austin et al. [2007] were able to simulate the minimum
ozone response at about 20 to 30 hPa, but not the analyzed, sharply increasing response at
about 50 hPa in Figure 13. The model simulations reported in Marsh et al. [2007, their
Figure 8] indicated a positive ozone response near 50 hPa at low latitudes for the period
of 1979 to 2003, but not for the longer period of 1950 to 2003. It is presumed that the
large response diagnosed from the HALOE data is not strictly related to the solar cycle.

The SC-like, max minus min responses for ozone (in percent) and for temperature (in K)
are summarized in Table 2 for the region of the stratopause and for three distinct latitude
zones, 45S to 35S, 15S to 5N, and 25N to 45N. For the tropical latitude zone the adjusted
ozone response is small and not significant, while the associated temperature response is
1.0 K and highly significant. For the middle latitude zones the ozone response varies
between 1.9 and 2.8% and is highly significant, while the temperature response decreases
to near zero.
4. Trends in HALOE ozone

Figure 14 shows the linear trends (in %/decade) obtained from the MLR analyses of the HALOE ozone. Darker shading is where those terms have a CI of greater than 90%; lighter shading denotes a CI between 70 and 90%. The trends are near zero in the upper stratosphere across most of the latitude domain and for this 14-yr time span, when the total chlorine levels had leveled off and started to decline slowly \cite{WMO2007}. The trends are decreasing by 4 to 6 %/decade across most latitudes of the middle stratosphere, and they are significant. There are net increases in the ozone of the lower stratosphere in the subtropics of both hemispheres, but slight decreases in the tropics. Those trends are not significant, however. Overall, there is very good continuity in the patterns of the trends for the latitude and pressure-altitude domain of Figure 14.

The trends shown in Figure 14 appear to be somewhat weaker than those reported from HALOE, SAGE II, and lidar in \textit{WMO} \cite{2007}. However, those analyses were for data time series on constant altitude surfaces, and it is noted that the effects of a long-term cooling of the atmosphere will lead to a lowering in altitude of a pressure surface and its ozone \cite{Rosenfield2005}. For example, the temperature trends reported by Remsberg \cite{2007,2008} for 25S to 25N are of order -0.8 to -1.2 K/decade for the pressure surfaces of 0.7 to 2.0 hPa, respectively, or for those levels where it is possible to conduct reliable analyses for a temperature trend from retrievals of the HALOE measurements themselves. Thus, a negative ozone trend at an altitude level will appear as a weaker trend at a corresponding pressure level.
There may also be slight biases in the analyzed trends from the HALOE zonal-averaged ozone versus pressure profiles at all latitudes for the layers 7L to 4U. This prospect is because the HALOE T(p) profiles for those layers were based on the data from the NOAA operational temperature sounders that were not corrected for the trends in the atmospheric CO₂, as they affect the vertical weighting functions of their several measurement channels [Shine et al., 2008]. However, any such effects should not alter the trends with latitude in Figure 14 for a given pressure layer.

A number of investigators have wondered to what extent the eruption of Mt. Pinatubo may have affected the SC-like and trend terms for ozone [e.g., Lee and Smith, 2003; Al-Saadi et al., 2001]. Furthermore, Crooks and Gray [2005] point out that there were interactions between the QBO and ENSO that were altering the zonal winds of the subtropical middle stratosphere both prior to and just following the eruption of Mt. Pinatubo. Recall from Figure 5 that there was an excess of ozone in layer 6L at 25N during late 1991 to mid 1992. That excess may be related to atmospheric effects due to the presence of the Pinatubo aerosol layer [Mickley et al., 1997]. For example, the radiative heating at the top boundary of the aerosol layer (near 20 hPa) can lead to an enhanced, net ascent at the low latitudes. As a result, air having a relatively low mixing ratio of NOy would have been transported upward from the lower stratosphere, and the associated chemical loss of ozone due to the reactive, NOx component of the NOy would have been diminished at that time. There are similar excess ozone anomalies in the layers 6U through 5U (or about 10 to 20 hPa), at least for the latitude bins of 25S through 25N, and they lead to excessively negative linear trends when the time series analyses are
started at October 1991 rather than September 1992 or January 1993. In addition, there are greater uncertainties for the ozone signals that were attenuated by the aerosols of the lower layers of the low latitudes during this early period, so the analyses of their time series were begun at those later times, too. A further diagnosis of the true cause of the enhanced HALOE ozone in 1991-92 at 10 to 20 hPa is outside the scope of this study, but that ozone excess represents an "end point anomaly" for the determination of the trend terms (and for the coefficients of the associated 11-yr terms to a lesser extent). By delaying the start date of the time series analyses by at least one year after the eruption but only for layers 6U to 4U of the lower latitudes, the effects from the volcanic aerosol layer have been reduced for the results of this present study.

The narrow pressure-altitude zone of rather large negative trends at 10 to 20 hPa in Figure 14 may have contributions from structures in those time series that were not accounted for. To understand that possibility, it is useful to refer to the representative zonal mean cross section of the HALOE ozone mixing ratio in Figure 6. In the low to middle stratosphere the ozone mixing ratio should be very nearly conserved during transport. Any change for its net transport at those altitudes ought to be most noticeable where the meridional gradients of the ozone mixing ratio are greatest, or in the subtropics near 10 hPa. The latitudes of 15 to 25 degrees are where the diagnosed 11-yr ozone responses of Figure 9 are larger. That region is also where the amplitudes of both the QBO and subbiennial terms are pronounced (see Figures 7 and 8). It may be that the larger negative trends and the enhanced SC-like responses in that region have a contribution from a decadal-scale, dynamical forcing. On the other hand, because the
meridional gradients for the ozone mixing ratio are nearly flat at about 20 hPa, the
presence of a similar dynamical forcing would be much less apparent in the ozone at that
level. There are also larger negative trends that are marginally significant at 45S and 45N
and from 30 to 50 hPa. Perhaps those trends are indicating an extension of so-called
“polar ozone hole” effects to lower latitudes during this 14-yr period. If that is the case,
it is noted that the effects of the QBO term for the lower stratospheric ozone distributions
have already been accounted for as part of the present MLR analyses.
5. Summary and Conclusions

This study has been based on ozone and temperature data from a single, well-characterized instrument, HALOE, and for slightly more than one complete solar cycle. An exploratory search for a solar cycle response was performed, but only for those latitudes where HALOE provided good seasonal sampling. This consideration is important for the accurate accounting of the generally, larger-amplitude seasonal terms in the time series. The HALOE ozone profiles have good S/N and a relatively high vertical resolution, both of which are important for resolving the vertical response of ozone to the relatively, small amplitude of the 11-yr, max minus min, uv-flux forcing. Analyses of temperature time series were restricted to the upper stratosphere and lower mesosphere, 2.0 to 0.7 hPa.

The analyzed QBO terms for ozone have their largest amplitudes at the low latitudes and in the lower stratosphere, and their amplitudes are nearly symmetric with latitude across the two hemispheres. On the other hand, there is some asymmetry for the amplitudes of the sub-biennial terms, in accord with the small differences for its associated annual cycles in the two hemispheres. There may also be interactions between the QBO and sub-biennial terms, but their longer-period terms were not included in the analyses.

A simple, 11-yr periodic term was fit to the ozone residuals, and its phase was noted. Where the amplitude of that term was significant, its phase fit with that of the SC flux proxies, or at least within about one year of January 1991 (or 2002)—the approximate midpoint for the flux maximum of SC 22 (or SC 23). Because the effects of trend terms
can be confounded with those of the 11-yr terms, linear trend terms were included in the MLR analysis model. Generally, there is very good continuity for the analyzed trends with latitude and pressure-altitude, and their signs and magnitudes are reasonable for the time period of 1991-2005 from the HALOE measurements. However, it is noted that there may still be decadal-scale processes that were important, but not accounted for—particularly in the upper stratosphere of the tropics and in the lower stratosphere across all latitudes.

There is a significant SC-like, max minus min response of order 2 to 3% in the HALOE ozone from about 2 to 5 hPa and for the latitudes of 45S to 45N. Weaker and much less significant responses occur in the tropics near 1 hPa and from 7 to 30 hPa. There is a significant max minus min, SC-like response of order 1 K in the HALOE temperatures between 15S and 15N and from 2 to 0.7 hPa. The temperature response at mid latitudes is about half that value and much less significant. Several chemistry/climate models are yielding response profiles for both ozone and temperature that are very similar to those analyzed here [Austin et al., 2008].

As noted above, linear trends were diagnosed along with the other terms of the MLR analyses of the HALOE ozone, and they were near zero throughout the upper stratosphere. Negative trends of order 4 to 6%/decade were found at 10 to 20 hPa across the low to middle latitudes of both hemispheres. Weak, positive trends were found in the lower stratosphere for the subtropics of both hemispheres. Conversely, there were weak,
negative trends from 30 to 50 hPa in the tropics and poleward of about 25 degrees latitude of both hemispheres.

It is concluded that there is no real discrepancy between the SC-like response profiles from some current models and from the stratospheric ozone from the HALOE observations, at least where its SC-like terms are significant. The MLR analysis approach used herein has made it possible to separate that response from those of the expected interannual forcings and to first order from the confounding effects of any long-term trends. The precision, calibration, vertical resolution, spatial sampling, and retrieval approach of the HALOE solar occultation experiment along with the MLR analysis techniques used herein appear to be quite adequate for future determinations of the middle atmosphere responses of both ozone and temperature to the uv-flux forcing of the 11-yr solar cycle.
Acknowledgments. The author embarked on this analysis as a result of his invitation to participate in a Workshop hosted by Dr. Kunihiko Kodera at the 2004 Fall AGU Meeting. The author appreciates discussions about this work that he has had with two colleagues—Murali Natarajan, concerning comparisons of the findings with published results from model studies, and Gretchen Lingenfelser concerning the MLR analyses. Special thanks go to Jim Russell, HALOE Principal Investigator, and Larry Gordley and colleagues of GATS, Inc., for producing the high quality HALOE dataset. He also appreciates the comments of the three anonymous reviewers. Support for this work was provided by the UARS Program Office at NASA Headquarters and the UARS Project Office at NASA/GSFC.
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Figure 1. Tangent point locations of the HALOE SR and SS measurements for 2001.

Figure 2. Time series of ozone (in DU) for half-Umkehr layer 8U (near 2.4 hPa) at 25N. MLR model terms are indicated at the lower left.

Figure 3. Time series residuals for the ozone model of Figure 2. The solid horizontal line is the least squares linear regression fit to the residuals.

Figure 4. Time series of temperature (in K) at 2 hPa and 25N. MLR model terms are indicated at the lower left. The solid horizontal line is the sum of its constant and linear trend terms.

Figure 5. Time series of ozone for half-Umkehr layer 6L (near 13 hPa) at 25N. MLR model terms are indicated at the lower left, and the fit to the data starts in September, 1992.

Figure 6. Zonal mean cross section of the HALOE ozone mixing ratio (in ppmv) for sunset (SS) from February 26 to April 5, 1995. Contour interval is 1 ppmv.

Figure 7. Contour plot of the amplitude (in %) of the QBO term for the HALOE ozone from the MLR models. Contour interval is 0.5% from 0.0 to 5.0 and 2.0% thereafter. Darker shading is where the amplitudes exceed 2%.
Figure 8. As in Figure 7, but for the amplitudes of the sub-biennial terms.

Figure 9. Contour plot of the max minus min 11-yr response (in percent) for HALOE ozone. Contour interval is 0.5% from 0.0 to 5% and is 2% thereafter. Darker shading denotes regions where the response exceeds a CI of 90%; lighter shading has a CI of between 70 and 90%.

Figure 10. Phase variation of the 11-yr term of Figure 9 (in yrs from January 1991). Contours are: dashed—negative, solid—positive, and dotted—zero, and the interval is 1 yr. The domain within the bold contours of +1 and -1 is considered as in-phase with the SC uv-flux and that region is shaded darker.

Figure 11. Contour plot of the max minus min 11-yr response (in K) for HALOE temperature. Contour interval is 0.2 K. Darker shading denotes regions where the response exceeds a CI of 90%; lighter shading has a CI of between 70 and 90%.

Figure 12. Phase variation of the 11-yr term of Figure 11 (in years from January 1991). Contours are: dashed—negative, solid—positive, and dotted—zero, and the interval is 1 yr. The domain within the bold contours of +1 and -1 is considered as in-phase with the SC uv-flux and that region is shaded darker.
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Table 1—Pressure Intervals and Half-Umkehr Layer Designations

<table>
<thead>
<tr>
<th>Pressure Range in (hPa)</th>
<th>Half-Umkehr Layer</th>
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<td>0.7 - 1.0</td>
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Table 2—SC-like, max minus min responses for ozone (%) and temperature (K)

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<td>0.1</td>
<td>1.0</td>
<td>2.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>
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