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Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models

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[1] Previous multiple regression analyses of the solar cycle variation of stratospheric ozone are improved by (1) analyzing three independent satellite ozone data sets with lengths extending up to 25 years and (2) comparing column ozone measurements with ozone profile data during the 1992–2003 period when no major volcanic eruptions occurred. Results show that the vertical structure of the tropical ozone solar cycle response has been consistently characterized by statistically significant positive responses in the upper and lower stratosphere and by statistically insignificant responses in the middle stratosphere (~28–38 km altitude). This vertical structure differs from that predicted by most models. The similar vertical structure in the tropics obtained for separate time intervals (with minimum response invariably near 10 hPa) is difficult to explain by random interference from the QBO and volcanic eruptions in the statistical analysis. The observed increase in tropical total column ozone approaching the cycle 23 maximum during the late 1990s occurred primarily in the lower stratosphere below the 30 hPa level. A mainly dynamical origin for the solar cycle total ozone variation at low latitudes is therefore likely. The amplitude of the solar cycle ozone variation in the tropical upper stratosphere derived here is somewhat reduced in comparison to earlier results. Additional data are needed to determine whether this upper stratospheric response is or is not larger than model estimates.

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1. Introduction

[2] The observed solar cycle variation of stratospheric ozone is a key constraint on climate models that include solar variability as a forcing mechanism and that account for the existence of the stratosphere [*Haigh*, 1994, 1996; *Shindell et al.*, 1999; *Rind*, 2002]. It is also important to determine and understand the solar cycle variation of ozone so that anthropogenic trends, including possible evidence for an ozone "recovery," can be more accurately evaluated using existing, temporally limited data records [*Newchurch et al.*, 2003; *Steinbrecht et al.*, 2004a, 2004b; *Cunnold et al.*, 2004]. Although not absolutely confirmed because of the limited record length, a solar cycle ozone variation appears to be present when column ozone time series data are averaged over low latitudes. To illustrate this, Figure 1 compares monthly column ozone data averaged over 35°S to 35°N to a daily time series of the core-to-wing flux ratio of the Mg II line at 280 nm, a close proxy for solar ultraviolet flux at wavelengths near ~200 nm that are important for molecular oxygen dissociation and ozone formation in the stratosphere [*Heath and Schlesinger*, 1986; *Viereck and Puga*, 1999].

[3] Observational estimates of the 11-year ozone response as a function of altitude and latitude have been reported by a number of analysts based mainly on Solar Backscattered Ultraviolet (SBUV) data and Stratospheric Aerosol and Gas Experiment (SAGE) I and II data using multiple regression methods [*Chandra*, 1991; *Hood et al.*, 1993; *Chandra and McPeters*, 1994; *McCormack and Hood*, 1996; *Wang et al.*, 1996]. For example, analyses of SBUV and SAGE records with lengths as long as ~16 years indicated that the mean low-latitude response in the upper stratosphere (1–3 hPa) is in the range of 2 to 4% but decreases to zero or slightly negative values in the middle stratosphere (5 to 10 hPa) before increasing again in the lower stratosphere [*McCormack and Hood*, 1996; *Lee and Smith*, 2003; *Hood*, 2004]. On the basis of a combination of Total Ozone Mapping Spectrometer (TOMS) data and SBUV data, it was proposed [see *Hood*, 1997, Table 1] that most (~85%) of the solar cycle variation of column ozone at low latitudes occurs in the lower stratosphere (pressures ≥30 hPa).

[4] In contrast to the observational results summarized above, most models that account for radiative and photochemical effects of observed solar UV spectral irradiance changes have predicted that solar cycle percent ozone

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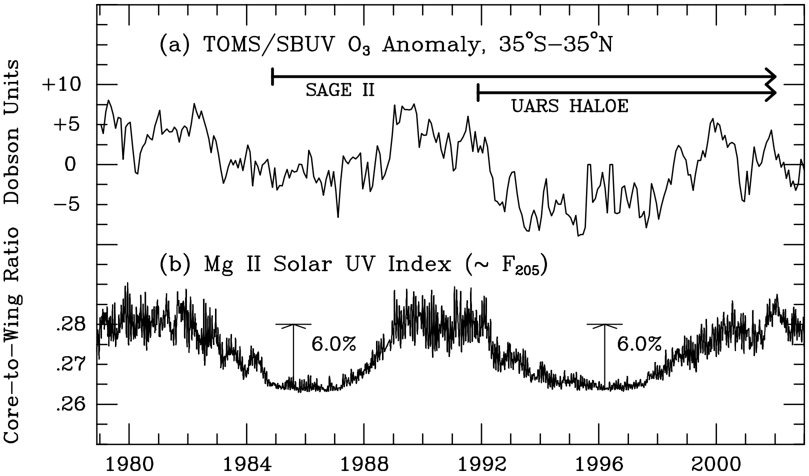

Figure 1. (a) Time series of the monthly mean version 8 TOMS/SBUV(/2) tropical (35°S to 35°N) total ozone anomaly and (b) time series of the monthly mean solar Mg II core-to-wing ratio, a satellite-based proxy for solar ultraviolet variations at wavelengths near 200 nm. Also indicated at the top are the time periods during which ozone profile data are available from the SAGE II and UARS HALOE instruments.

changes should be largest in the middle stratosphere (~5 hPa) and should be less in the upper and lower stratosphere [e.g., *Huang and Brasseur*, 1993; *Haigh*, 1994; *Shindell et al.*, 1999; *Austin*, 2002; *Tourpali et al.*, 2003; *Rozanov et al.*, 2004; *Egorova et al.*, 2004]. These same models predict that most of the contribution to the column ozone solar cycle variation occurs in the middle stratosphere. This disagreement on the 11-year time scale exists in spite of the fact that the observed ozone response to 27-day solar rotation UV variations agrees very well with model simulations in the tropical middle and upper stratosphere [see, e.g., *Chen et al.*, 1997]. Possible explanations for the discrepancy between solar cycle model results and observational results include (1) interference in the statistical regression analysis due to ozone changes associated with major volcanic eruptions and with the equatorial quasi-biennial wind oscillation (QBO) [*Solomon et al.*, 1996; *Lee and Smith*, 2003]; (2) solar cycle changes in particle precipitation-induced odd nitrogen production associated with energetic electron precipitation (EEP) [*Callis et al.*, 1998; *Rozanov et al.*, 2005; *Langematz et al.*, 2005]; and (3) solar cycle induced changes in stratospheric circulation, including the QBO, and effects on ozone transport and chemistry [e.g., *Hood and Soukharev*, 2003].

[5] In this paper, previous multiple regression analyses of the solar cycle variation of stratospheric ozone are improved in two main ways. First, the estimated vertical and meridional structures of the annual mean and seasonal ozone profile responses are updated and tested using three independent long-term satellite ozone data records: (1) the recently released version 8 SBUV and SBUV/2 internally calibrated ozone profile data set for the period from 1979 through 2003 [*Frith et al.*, 2004]; (2) the Stratospheric Aerosol and Gas Experiment II (SAGE II) ozone profile record for the period from late 1984 through 2003 [e.g., *Wang et al.*, 2002]; and (3) the Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE) ozone profile record for the period from late 1991 through 2003 [e.g., *Remsberg et al.*, 2001]. In particular, analyses of separate time intervals are carried out to test the reproducibility of earlier results indicating the existence of a minimum ozone response in the tropical middle stratosphere. Second, version 8 TOMS/SBUV(/2) column ozone measurements are compared to UARS HALOE ozone mixing ratio data in order to test previous conclusions that most of the solar cycle variation of column ozone occurs in the lower stratosphere. Comparisons are made during the 1992–2003 period during which no major volcanic eruptions occurred.

[6] In section 2, the satellite remote sensing data sets are described and sample time series are compared to the Mg II solar UV index. In section 3, the linear multiple regression statistical model is described and applied to 3-month time series of the SBUV(/2), SAGE II, and HALOE 3-month ozone profile data sets. Resulting annual mean ozone solar cycle regression coefficients for the time periods covered by each data set are compared. Solar regression coefficients for the two separate halves of the 25-year SBUV(/2) record are also calculated. In addition, seasonal (winter and summer) ozone solar regression coefficients obtained from the SBUV(/2) and SAGE II data sets are compared. In section 4, HALOE ozone mixing ratio time series in the tropical lower stratosphere are compared to the TOMS/SBUV(/2) column ozone time series for the same time period (1992–2003) in order to investigate further the contribution of this altitude range to the column ozone solar cycle variation. In section 5, the observationally estimated vertical ozone response structure in the tropics is compared further with model simulations and possible explanations for differences are discussed. Conclusions are summarized in section 6.

2. Data Description

2.1. SBUV(/2) Ozone Profile Data Set

[7] The version 8 SBUV(/2) ozone profile data set consists of internally calibrated ozone mixing ratios derived from backscattered radiances measured with the SBUV instrument on the Nimbus 7 satellite and the "SBUV/2" instruments on the National Oceanic and Atmospheric

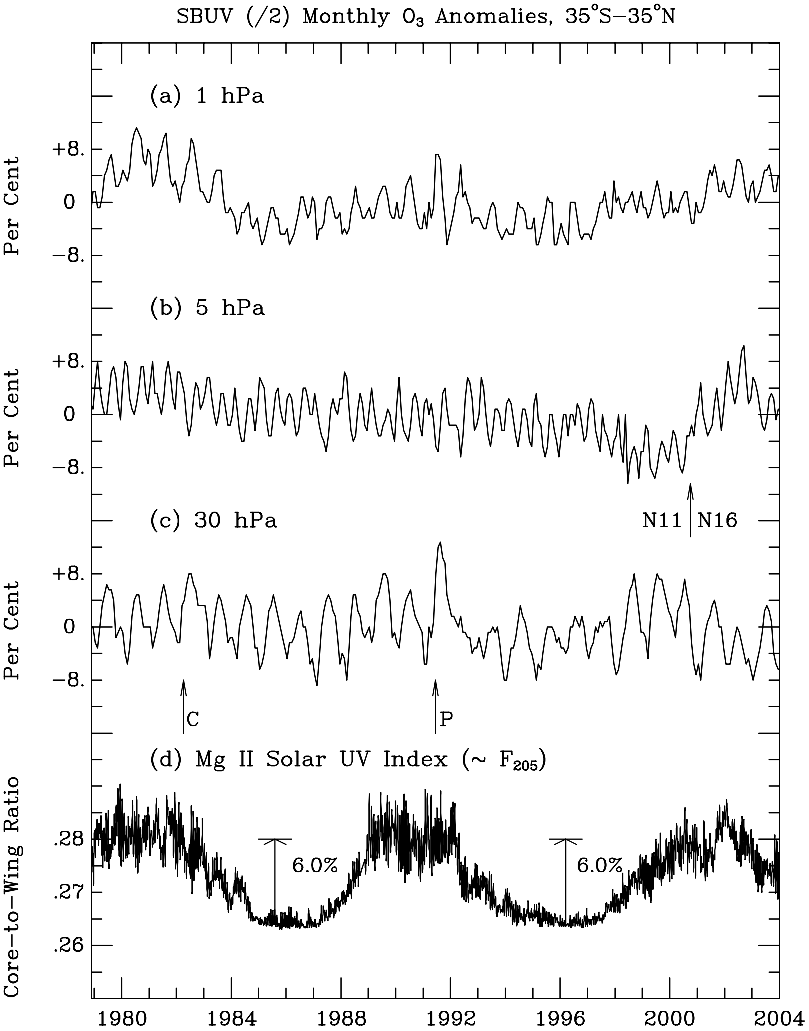

Figure 2. Time series of monthly zonal mean deviations of tropical (35°S to 35°N) SBUV(/2) ozone at (a) 1 hPa, (b) 5 hPa, and (c) 30 hPa over the 1979 to 2003 time period. (d) For comparison, time series of the daily Mg II solar UV index.

Administration (NOAA) 9, 11, and 16 satellites [*Frith et al.*, 2004]. For a full description of the version 8 data set, including differences from version 7 and intercalibration procedures, the reader is referred to the http://code916.gsfc.nasa.gov/Data_services/ internet site managed at Goddard Space Flight Center by R. Stolarski and S. Hollandsworth-Frith.

[8] Briefly, the Nimbus 7 and NOAA operational satellites were launched (at least initially) into near-polar, sun-synchronous orbits crossing the equator near local noon to facilitate daily measurements over most latitudes and at a series of ~12 longitudes. The SBUV instrument is a nadir-viewing double monochromator that samples backscattered radiances at 12 specific wavelengths in the Hartley and Huggins O_3 absorption bands [*Heath et al.*, 1975]. A description of the inversion algorithm used to calculate ozone profiles from the measured radiances has been given by *Bhartia et al.* [1996]. Vertical resolution is limited mainly by the effective width of the scattering layer or contribution function and is approximately 8 km [*McPeters et al.*, 1984]. However, *Bhartia et al.* [1996] show that the SBUV technique can detect short-term ozone variations in vertical layers with thicknesses of 5 km. The shortest wavelength used for profile inversion (273.5 nm) determines the uppermost pressure level for which useful measurements are obtained (0.8–1.1 hPa for solar zenith angles of 40° to 60° [*Frederick et al.*, 1983]). The lowermost useful pressure level is limited by the increased importance of multiple scattering and has been estimated to be in the range of 10–20 hPa [*Taylor et al.*, 1980]. *Bhartia et al.* [1996] specifically recommend that long-term trend estimation using SBUV data should be restricted to the 1 to 20 hPa range.

[9] The version 8 SBUV(/2) data set contains monthly zonal mean ozone profiles at fifteen stratospheric pressure levels ranging from 50 hPa to 0.5 hPa over the period from 1979 to 2003. Of these, we have selected ten levels (50, 40, 30, 20, 10, 5, 3, 2, 1, and 0.5 hPa) for detailed analysis. Although the uppermost and lowermost three pressure levels are not fully spatially resolved, we include them in the statistical analysis for completeness and to allow comparisons with other data sets.

[10] Figure 2 compares the solar Mg II core-to-wing ratio with time series of the version 8 SBUV(/2) data averaged

over 35°S to 35°N at several pressure levels (1, 5, and 30 hPa). Decadal variations that are approximately in phase with the solar cycle are evident at 1 and 30 hPa. At 5 hPa, no decadal variation is present. Although Figure 2 plots monthly zonal means of the SBUV(/2) data, for consistency with the analysis of UARS HALOE data (see below), 3-month seasonal averages (DJF, MAM, JJA, SON) are used in multiple regression analyses.

[11] As indicated by the vertical arrows in Figure 2c, there is some evidence at 30 hPa for elevated ozone values immediately following the El Chichòn ("C") and Pinatubo ("P") volcanic eruptions. Some of this increase may be an artificial consequence of increased backscatter from volcanic aerosol. These increases appear to be short-lived (∼1 year) so we have not deleted any of these data from the time series to be analyzed. We include a volcanic aerosol term in the statistical model (section 3) in order to minimize any contribution of aerosol-related variability to the calculated solar cycle regression coefficient [*McCormack et al.*, 1997]. However, repetition of the analysis without the aerosol term produces only minor changes in the solar regression coefficients.

[12] Finally, it should be noted that although the internal calibrations applied to the version 8 SBUV(/2) data have produced a continuous ozone record with nearly global coverage [*Frith et al.*, 2004], there is empirical evidence in the form of apparent offsets and anomalous values that some intercalibration errors remain in the data, especially during the last 10 years. Note, for example, the positive offset in Figure 2b (vertical arrow) occurring near the changeover time from the NOAA 11 to the NOAA 16 instrument. An effort to apply external calibrations to minimize these remaining problems is underway by several groups [*Frith and Stolarski*, 2005; *Wild et al.*, 2005]. Nevertheless, the version 8 SBUV(/2) data set is the longest available internally calibrated satellite ozone profile record (25 years). This characteristic, together with its relatively good spatial and temporal sampling (sufficient to allow accurate daily zonal means to be calculated during most time periods), makes the SBUV(/2) record a valuable resource of ozone profile data.

2.2. SAGE II Ozone Profile Data

[13] Although the SAGE mission began in 1979 (SAGE I; February 1979 to November 1981), in the present study we use only the data from SAGE II, which started with the launch of the Earth Radiation Budget satellite in October of 1984. As discussed on the Stratospheric Processes and their Role in Climate (SPARC) internet web site, because of some uncertainties in the absolute calibration of SAGE I data, special care must be taken when combining the SAGE I and II data for calculating long-term ozone changes [*Wang et al.*, 1996, 2002]. Therefore, in order to avoid these potential problems, we consider here only the version 6.2 SAGE II data, which are available since December 1984 and are most reliable at altitudes above 20 km (see http://www-sage2.larc.nasa.gov). To allow better comparisons with the version 8 SBUV(/2) record, we use only the SAGE II data through 2003.

[14] Like other solar occultation instruments such as HALOE, the SAGE II measurements have reduced spatial and temporal sampling compared to nadir-viewing sounders such as SBUV [*McCormick et al.*, 1989]. Specifically, on a given day, essentially only two latitudes are sampled, one during sunrise events and the other during sunset events. It takes about 1.5 months for the sampling latitude to shift from one latitudinal extreme to the other (∼50–80°S to 50–80°N, depending on the time of year). For either sunrise or sunset events, there are about 15 sampling opportunities per day with successive locations shifted by about 25° in longitude and a fraction of a degree in latitude. Thus it is possible to calculate reasonably accurate daily zonal means only at the two latitudes that are sampled on a given day. At a given latitude, one or two daily zonal means are available for any given month and year. Measurements are especially sparse in the tropics for geometrical reasons. After mid-2000, a failure of the azimuth gimbal in the pointing system reduced the instrument duty cycle so that it was no longer possible to take both sunrise and sunset observations on each orbit. Thereafter, the data contain events of one type in approximately 35-day blocks, switching to the other type after each spacecraft yaw maneuver. Approximate monthly zonal averages of the available SAGE II data have been calculated and generously provided to us by W. J. Randel and F. Wu (private communication, 2005). However, monthly zonal averages are characterized by large short-term variations that are caused by incomplete sampling, as described above. In order to reduce these random errors and to be consistent with the analysis of HALOE data (see below), 3-month averages (DJF, MAM, JJA, SON) have been used for multiple regression analyses in this study.

[15] Figure 3 plots SAGE II 3-month ozone deviations from long-term seasonal means at the same pressure levels and averaged over the same latitude range as was the case for the SBUV(/2) data of Figure 2. Compared to the SBUV(/2) data, the SAGE II data have the advantage of continuity of measurements using a single instrument from 1984 until the present. Other advantages of the SAGE II solar occultation data include improved vertical resolution (∼1 km) and improved ability to resolve the ozone profile in the lower stratosphere at altitudes above 20 km. However, as is evident in Figure 3, even though 3-month averages are used, the reduced sampling leads to increased random errors as compared to the monthly SBUV(/2) averages of Figure 2, for example.

[16] As indicated in Figure 3, a remaining problem with the SAGE II data is increased data errors following the Mt. Pinatubo volcanic eruption [*Cunnold et al.*, 1996, 2000; *Steele and Turco*, 1997]. Unlike the SBUV(/2) data, which show increases mainly in the lower stratosphere persisting for ∼1 year after the eruption, the SAGE II data show anomalous behavior extending over several years at most pressure levels. Specifically, as discussed on the SPARC web site, the SAGE II ozone measurements were anomalously variable in 1992–1993 and, during that time period, the SAGE II values were larger than UARS Microwave Limb Sounder values than in other years. The problem is more pronounced at levels of 20 km and below where aerosol concentrations remained high even at the end of 1993. For this reason, in the present study, we consider only SAGE measurements at levels above 20 km and exclude the period from June 1991 to November 1993 from the statistical analysis of the SAGE II data set (horizontal lines in Figure 3). This is a necessary correction because the solar

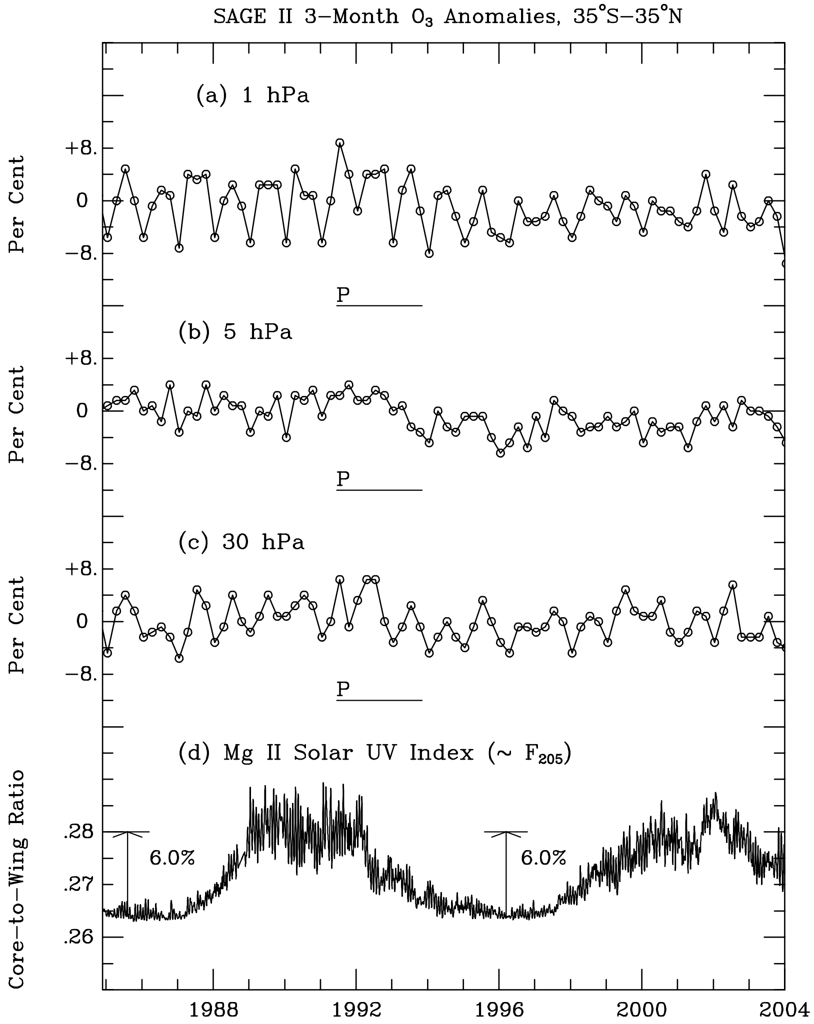

Figure 3. (a–d) Same format as Figure 2 but for SAGE II 3-month ozone deviations over the period from December 1984 through 2003. The horizontal lines indicate the period immediately after the Pinatubo eruption (June 1991 through November 1993) which was excluded from the statistical analysis because of reduced data quality (see the text).

regression coefficients are significantly modified if the post-Pinatubo data are retained, especially in the lower stratosphere.

2.3. HALOE Ozone Profile Data

[17] We use the version 19 UARS Halogen Occultation Experiment (HALOE) ozone data [e.g., *Remsberg et al.*, 2001], for the period from December 1991 to December 2003. (The ending date is chosen to match that of the version 8 SBUV(/2) record.) This data set is available from the http://haloedata.larc.nasa.gov internet site. For this data set, solar occultation radiance measurements are used to obtain the vertical profiles of O_3, HCL, HF, CH_4, H_2O, NO, NO_2, aerosol extinction, and temperature. The vertical resolution of the data is approximately 3 km and measurements typically extend from the upper troposphere to the lower mesosphere. In these respects, like the SAGE data, the HALOE data are greatly improved relative to measurements by vertical sounders such as SBUV.

[18] Since the UARS orbit inclination (57°) is the same as that of the Earth Radiation Budget satellite, it follows that the spatial and temporal sampling of the HALOE instrument is nearly identical to that of SAGE (see section 2.2). The HALOE ozone profile measurements therefore share the disadvantage of SAGE and other solar occultation instruments of sparseness of spatial and temporal coverage. In addition, data gaps are sometimes present so that measurements at a given latitude can be separated by longer time intervals than would otherwise be the case. Because of this, it is not possible to calculate true monthly zonal means using the HALOE data. Consistent with the SAGE II analysis, we have therefore elected to calculate 3-month zonal averages (e.g., DJF, MAM, JJA, and SON) within 10° latitude [*Nedoluha and Connor*, 1998] bands. Specifically, “3-month zonal means” are calculated by averaging together all “daily zonal means” for a given latitude band within the 3-month time interval. Although 15 longitudes are typically sampled during one measurement latitude “event,” the number of measurements within a given latitude band on a given day is sometimes less than this because of instrument down time, for example. After 1998, UARS power availability decreased so that fewer measurements were obtained near

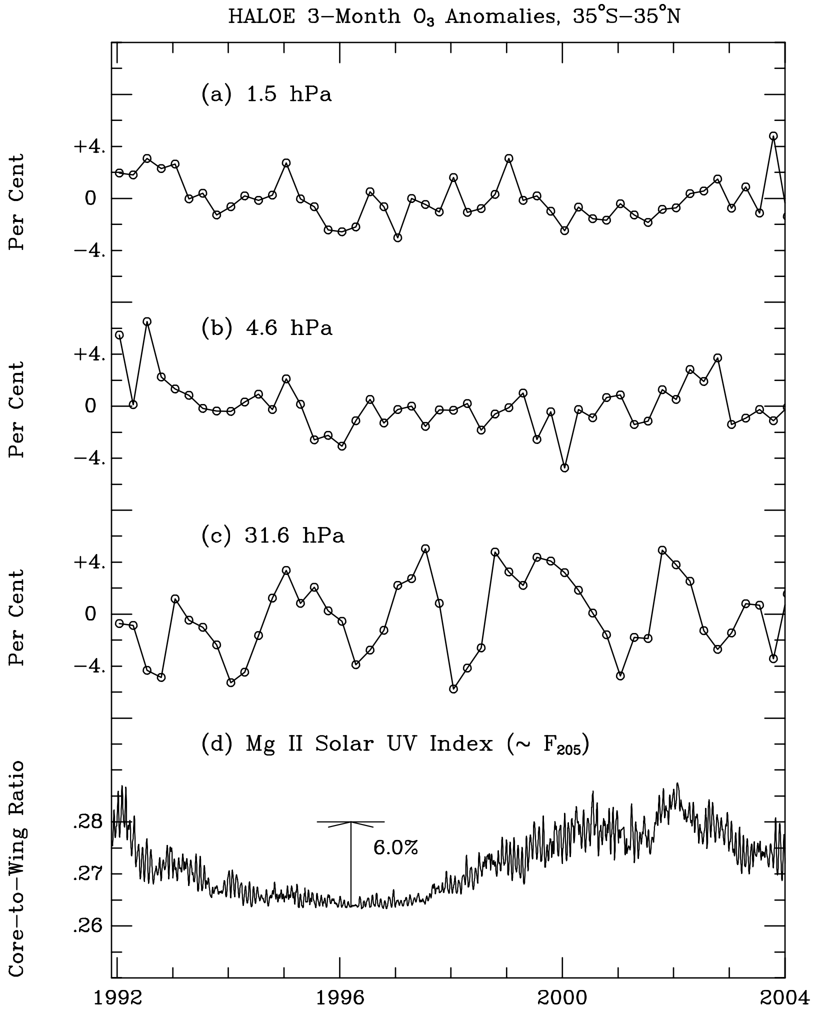

Figure 4. (a–d) Same format as Figure 2 but for 3-month averaged UARS HALOE ozone data over the period from DJF 1991–1992 through DJF 2003–2004. Note the smaller vertical scale as compared to Figures 2 and 3.

yaw cycles, especially at higher latitudes. Therefore, in the present work, a minimum of 10 measurements within a given latitude band is required before a "daily zonal mean" is accepted as valid.

[19] Figure 4 plots HALOE 3-month ozone deviations from long-term seasonal means at nearly the same pressure levels and averaged over the same latitude range as was the case for the SBUV(/2) data of Figure 2. (Note the much smaller vertical scale in Figure 4 as compared to Figures 2 and 3.) At 1.5 hPa (Figure 4a), the deviations are initially positive, become negative in ~1996, and increase again thereafter, roughly varying in phase with the solar cycle (Figure 4d). At 2.2 hPa (not shown here), the tropically averaged data vary decadally with a slightly larger amplitude. At 4.6 hPa (Figure 4b), however, no decadal variation is clearly present. At 31.6 hPa (Figure 4c), interannual variability associated with the QBO is dominant. There is some evidence for an increase in amplitude from the early 1990s to the late 1990s but no obvious solar cycle variation is present.

[20] As seen in Figure 4c, no clear evidence for enhanced ozone values in 1992 following the Pinatubo eruption is present in the HALOE data. We have therefore not eliminated any of the data from the statistical analysis. As in the case of the SBUV data, an aerosol term is included in the statistical model. However, solar regression results with and without the aerosol term differ only slightly.

3. Multiple Regression Analysis

3.1. Statistical Model Description

[21] Following earlier work [e.g., *Stolarski et al.*, 1991; *Hood and McCormack*, 1992; *McCormack et al.*, 1997], we assume that the temporal behavior of zonally averaged ozone mixing ratio, $O_3(t)$, can be represented by a multiple linear regression model of the form,

$$\begin{aligned} O_3(t) = {} & \mu(i) + \beta_{trend} t + \beta_{QBO} u_{30hPa}(t-L) + \beta_{volcanic} Aerosol(t) \\ & + \beta_{solar} MgII(t) + \epsilon(t) \end{aligned} \tag{1}$$

where t is the time in 3-month increments, $\mu(i)$ is a seasonal term equal to the long-term mean for the ith season of the year (i = 1, 2, … 4); u_{30hPa} is the 30 hPa equatorial zonal wind obtained from the Free University of

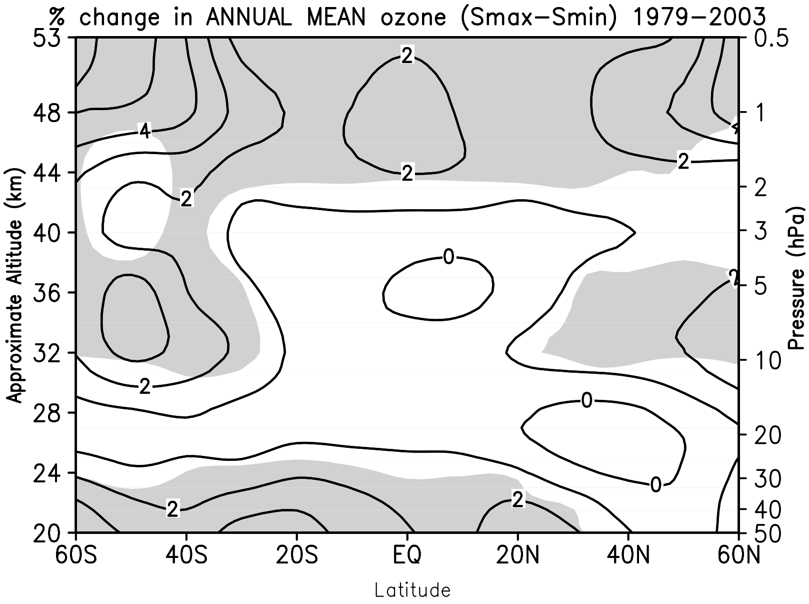

Figure 5. Annual mean solar regression coefficient calculated from the 3-month SBUV(/2) zonal mean time series (1979–2003), expressed as percent change from solar minimum to maximum. Shaded areas are statistically significant at the 95% confidence level.

Berlin (B. Naujokat, private communication, 2006; see http://strat-www.met.fu-berlin.de/products/cdrom/html/data.html); L is a lag time required to produce a maximum positive or negative correlation between the ozone time series at a given location and the 30 hPa equatorial wind; $Aerosol(t)$ is a stratospheric aerosol index based on a combination of SAM II and SAGE I/II optical depth measurements [*Thomason et al.*, 1997]; $MgII(t)$ is the core-to-wing ratio of the solar Mg II line at 280 nm based on Nimbus 7 SBUV, NOAA 9 and 11 SBUV/2, and UARS SUSIM data [e.g., *Viereck and Puga*, 1999]; and $\epsilon(t)$ is a residual error term. The coefficients β_{trend}, β_{QBO}, $\beta_{volcanic}$, and β_{solar} are determined by least squares regression. The aerosol index term is included in the model only for levels at 10 hPa and below because effects of volcanic perturbations on stratospheric ozone and temperature are observed primarily in the lower stratosphere [*Granier and Brasseur*, 1992; *Gleason et al.*, 1993]. In the case of the SAGE II data (1985–2003), the aerosol index term is not included at all because the period immediately following the eruption of Pinatubo (from JJA 1991 to SON 1993) is excluded from consideration. As in previous work, the residual error term $\varepsilon(t)$ is modeled as a first-order autoregressive process, i.e., $\epsilon(t) = r\epsilon(t-1) + w(t)$, where $w(t)$ is white noise and r is determined in an initial application of (1) [see, e.g., *Neter et al.*, 1985].

[22] An alternate approach to accounting for the influence of the QBO on ozone variability has been developed by *Randel and Wu* [1996]. Their approach consists of replacing the single QBO term in (1) with two terms, $\beta_{QBO1}\ QBO1 + \beta_{QBO2} \cdot QBO2$, where $QBO1$ and $QBO2$ are two orthogonal time series derived from equatorial zonal wind data. This approach has the advantage of accounting for the out-of-phase relationship between QBO winds in the upper and lower stratosphere. To test whether this approach would significantly modify the ozone solar regression coefficients calculated using (1), we have repeated the multiple regression analysis of the SBUV(/2) record using the 2-term QBO method. Several variants of the 2-term method were tried. First, a zero phase lag between ozone and $QBO1$ and between ozone and $QBO2$ was assumed. The resulting ozone solar regression coefficient plot (see Figure 5 below) was almost exactly identical to that obtained using (1). Second, both $QBO1$ and $QBO2$ time series were independently lagged according to the timing of their maximum correlation with ozone at a given latitude and pressure level. The results were again only slightly modified compared to that obtained using (1); only a few contours were changed. Therefore, although the 2-term method is valuable for better characterizing the ozone QBO [*Randel and Wu*, 1996], it apparently does not assist significantly in better characterizing the ozone solar cycle variation. On this basis, we report here only results obtained using (1).

[23] As emphasized by *Lee and Smith* [2003], the multiple linear regression method for separating the solar cycle and QBO components of ozone variability is imperfect in many ways. For example, the lagged 30 hPa equatorial zonal wind used as a predictor variable in the regression model is influenced by solar and volcanic forcings as well as by the upward propagating waves that dominantly drive the QBO. Thus the QBO, solar cycle, and volcanic indices in (1) are not completely independent of one another. In addition, if one phase of the QBO happens to dominate over the other during solar maximum periods within a limited sampling interval of one or two cycles, this can lead to biases in the solar regression coefficients. Lee and Smith specifically argue that the reduced ozone solar cycle response in the tropical middle stratosphere could be explained by such biases. However, over a sufficiently long sampling interval, if the QBO is entirely independent of the solar cycle, such biases should average to zero. Also, the vertical structure of the ozone solar cycle response should change from cycle to cycle if only accidental phasings of the

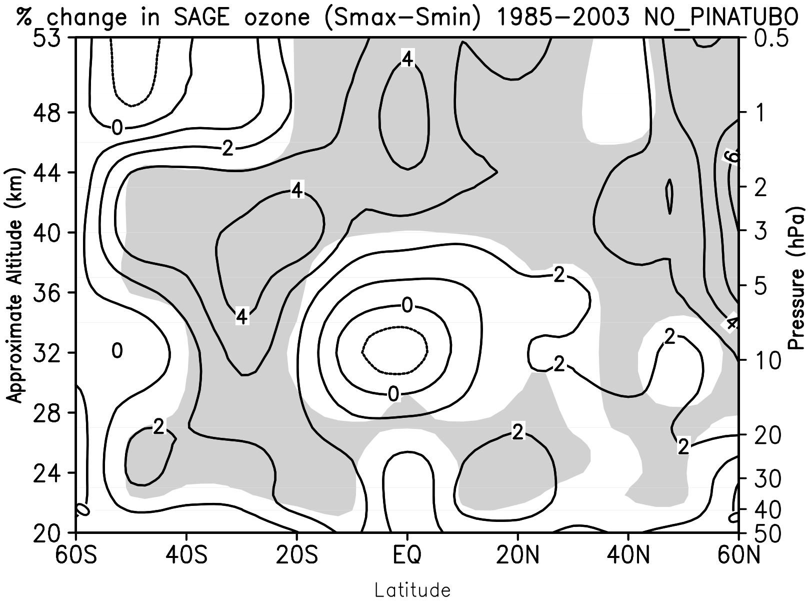

Figure 6. Same format as Figure 5 but as calculated from the 3-month SAGE II zonal mean time series (1985–2003).

QBO and solar cycle are responsible. The latter possibilities can be tested by applying the multiple regression model to longer data records and investigating separate time intervals. That is the approach taken in this paper.

[24] Finally, it is important to note that ozone trends in the stratosphere over the 25-year period considered here may not be linear (i.e., may not be describable using a single linear regression coefficient as in equation (1)). In particular, there is some evidence for a significant change in the column ozone trend at middle and high latitudes after 1996 [*Reinsel et al.*, 2005]. However, since the observed ozone trend at low latitudes is relatively small and since a major goal of the present analysis is to investigate the vertical structure of the solar regression coefficient in the tropics, use of a linear trend term is considered to be adequate for the present purpose. Nevertheless, it should be borne in mind that some small biases of the solar regression coefficient at middle and high latitudes may result from this procedure.

3.2. Solar Cycle Regression Results

[25] For each available latitude and pressure level (or altitude), the model (1) was applied to 100 data points in the case of the SBUV(/2) data (DJF 1979 to SON 2003), 66 data points in the case of the SAGE II data (DJF 1985 to MAM 1991 and DJF 1994 to SON 2003), and 48 data points in the case of the HALOE data (DJF 1992 to SON 2003). Only seasonally averaged ozone profile measurements at latitudes between 60°S and 60°N and at levels from approximately 0.5 to 50 hPa were statistically analyzed. The resulting annual mean solar regression coefficient derived for each level and latitude was normalized by the corresponding (SBUV(/2), SAGE II, or HALOE) long-term seasonal mean mixing ratio at that particular level and latitude, and was then multiplied by an appropriate scaling factor to yield the percentage change in ozone between solar minimum and solar maximum. This scaling factor is determined by assuming an average change of 0.0169 units in the solar Mg II core-to-wing ratio time series over the 11-year solar cycle based on the time period from 1979 to 2003 (Figure 1). As seen in Figure 1, the scaling factor is equivalent to a ~6% change in the Mg II index and, therefore, in the solar flux near 200 nm wavelength.

[26] The latitude and altitude dependences of the solar regression coefficients, expressed as the mean change from solar minimum to maximum, derived from the SBUV(/2), SAGE II, and HALOE ozone data sets are contoured in Figures 5, 6, and 7, respectively. In all three figures, the shaded areas indicate where the ozone response is statistically significant at the 95% confidence limit. As can be seen, although the SBUV(/2), SAGE II, and HALOE data sets cover different time periods, the measurement techniques are different, and the HALOE response is only marginally significant in the tropics, the structures of the vertical and latitude distributions of the ozone solar regression coefficients are qualitatively consistent between the three data sets. In all cases, the main common feature is that, averaged over tropical latitudes, the ozone response is positive and statistically significant in the upper stratosphere (between 0.5 and 3 hPa) and in the lower stratosphere (below 20 hPa), whereas it is zero or slightly negative and statistically insignificant in the middle stratosphere (5–10 hPa). In most regions where the response is significant, the amplitude is in the range of 2 to 4% from solar minimum to maximum. Although the HALOE signal is weak at the equator in the upper stratosphere, this may be caused by reduced sampling at these lowest latitudes. Positive responses are seen over a wide range of altitudes in the extratropical midlatitudes of both hemispheres, but with higher statistical significance in the Southern Hemisphere. In general, the extratropical responses tend to reach higher amplitudes than those at tropical latitudes.

[27] As an alternate approach toward investigating the ozone solar cycle response in the tropics, ozone profile data

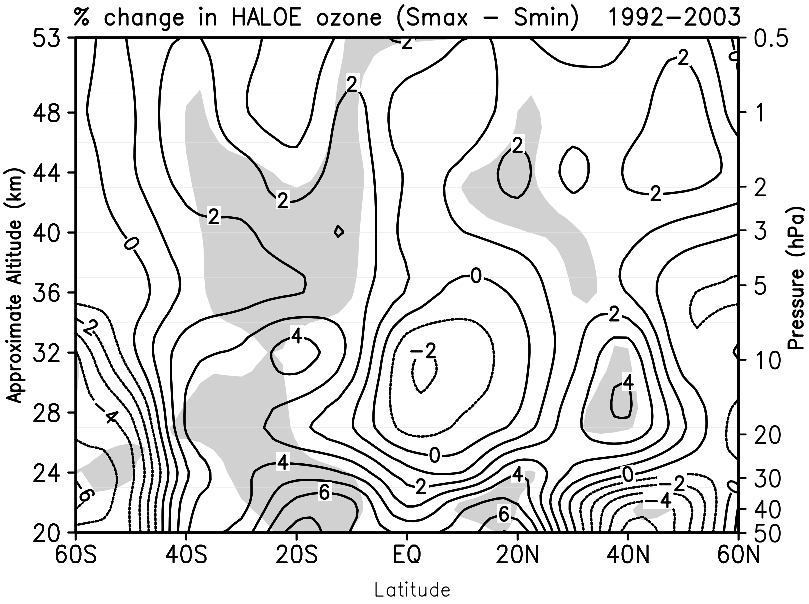

Figure 7. Same format as Figure 5 but as calculated from the UARS HALOE zonal mean time series (1992–2003).

for each of the three satellite data sets were averaged over the 25°S to 25°N latitude band and the averaged time series were then analyzed using the same multiple regression model (1). Results are plotted in Figure 8 as vertical profiles of the solar minimum to maximum regression coefficient with 95% confidence error bars for each data set. It is seen that the basic features of the SBUV(/2) tropical ozone response (Figure 8a) are also present in the SAGE II response (Figure 8b) and in the HALOE response (Figure 8c). In the lower stratosphere, a statistically significant positive response is obtained with a percent amplitude that increases with decreasing altitude (with the exception of the lowest level for the SAGE II data, which may be less reliable). In the middle stratosphere, the 2-σ error bars

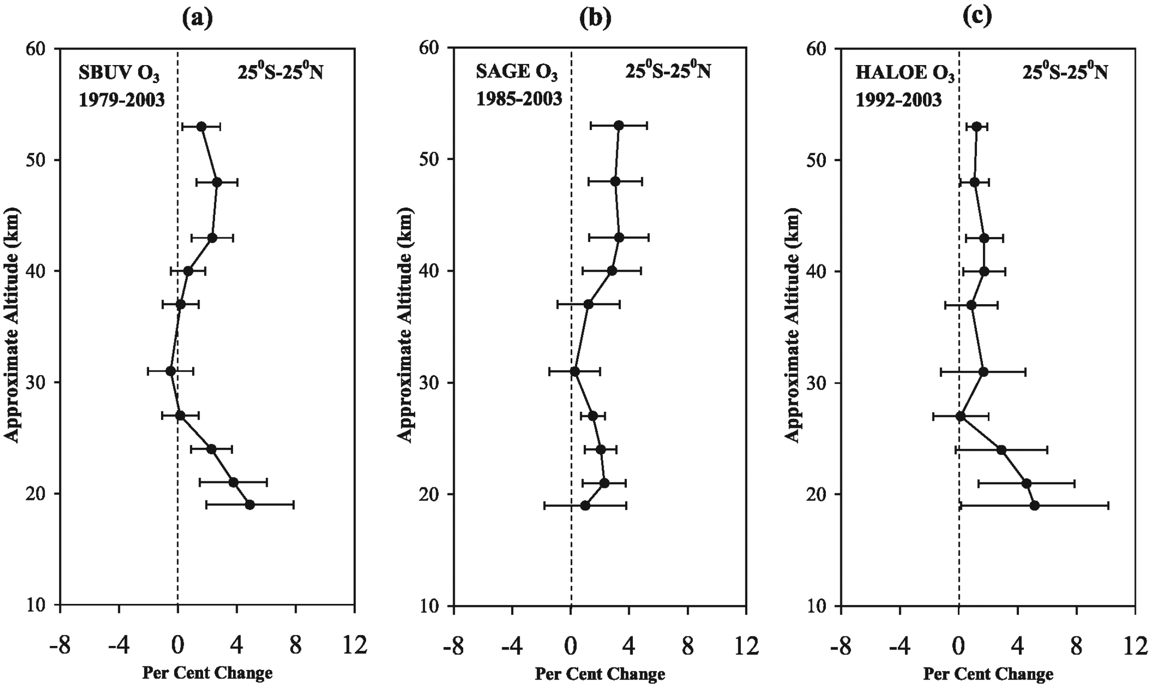

Figure 8. Solar cycle ozone regression coefficients (expressed as percent change from solar minimum to maximum) for (a) the SBUV(/2) data set, (b) the SAGE II data set, and (c) the HALOE data set. The regression coefficients were obtained by applying equation (1) to 3-month time series averaged over the 25°S to 25°N latitude band.

include zero and so the results at these levels are not statistically significant.

[28] In the upper stratosphere, the solar cycle response amplitude derived from the tropically averaged SBUV(/2) data (Figure 8a) is reduced somewhat in comparison to earlier results reviewed by *Hood* [2004] (~2 to 3% versus 4 to 5%). On the basis of the SBUV(/2) data alone, it is not clear whether this represents a more accurate measurement of the true response or whether increasing intercalibration problems in the SBUV(/2) record, for example, have artificially reduced the response. However, the reduced decadal ozone variation in the upper stratosphere is also reflected in the SAGE II time series at 1 hPa (Figure 3a), which seems to show a smaller decadal variation during the 1990s than during the 1980s. Overall, the results for HALOE are more irregular; this is to be expected because of the relatively short length of the data record. The HALOE data, which are not subject to significant calibration problems, also yield a significantly weaker upper stratospheric ozone response during the 1992–2003 period. Since HALOE was designed for upper stratospheric measurements, this increases the likelihood that the upper stratospheric ozone response during the last solar cycle was indeed smaller in amplitude than that observed by SBUV(/2) or SAGE during the previous cycle. On the other hand, the HALOE response is especially weak near the equator where the sampling is most sparse; it is therefore possible that the weaker HALOE response is partly artificial.

[29] Apart from common features, the ozone responses in Figures 5–7 also demonstrate some differences between the data sets, especially in the extratropics. For example, the magnitudes, altitudes and latitudes of the southern and northern extratropical maxima in the ozone responses are different. In the SBUV(/2) data set, the extratropical maxima are observed at the levels 0.5–1 hPa and 5–10 hPa at latitudes of 40° to 50° in both hemispheres (Figure 6). In the SAGE II data set, the extratropical maxima are most evident between 2 and 10 hPa at latitudes of 20° to 50° (Figure 6). In the HALOE data set, the same maxima are seen between 5 and 20 hPa in the latitude range 20° to 40° (Figure 7). These differences could be related to differences between the time periods analyzed for each data set, and differences between the measurements themselves. Comparing the solar regression coefficients calculated from all three data sets, we suggest that the extratropical results obtained from the SBUV(/2) data set are probably most reliable, since the time period analyzed (25 years from 1979 to 2003) encompasses more than two complete 11- year solar cycles (Figure 1).

[30] In addition to statistical criteria of significance and comparisons of independent data sets, another useful approach to evaluate the reality of the derived vertical structure in the tropics is a division of one data set into two parts as a test of whether the results obtained are consistent for both time periods. The SBUV(/2) ozone time series is most appropriate for such an analysis because of its greater length. Therefore we have divided the SBUV(/2) data set (1979–2003; 25 years) into two approximately equal parts: (1) the time period from 1979 to 1991 (13 years) and (2) the time period from 1992 to 2003 (12 years). Each of these time periods represents at least one complete 11-year solar cycle. The multiple regression model was then applied to the SBUV(/2) tropical (25°S–25°N) ozone data for each time period. Figure 9 shows the solar regression coefficients obtained for the entire time period from 1979 to 2003 (Figure 9a), the time period from 1979 to 1991 (Figure 9b), and the time period from 1992 to 2003 (Figure 9c). A comparison between Figures 9b and 9c shows that despite some differences between the two time periods in the magnitude of the ozone response at particular levels, the main pattern of the vertical distribution of the ozone response remains the same throughout both parts of the 25-year period of observations: The solar-induced tropical ozone response is positive and significant in the upper (1–3 hPa) and lower (30–50 hPa) stratosphere, and it is slightly negative and statistically insignificant in the middle stratosphere (5–10 hPa). Note that the 1979–2003 response at a given level is not necessarily equal to the average of the 1979–1991 and 1992–2003 responses. However, the 1979–2003 response usually falls within the 2σ errors of the responses for the shorter intervals. The increased irregularity of the derived response during the 1992–2003 period may be attributed to increased intercalibration errors caused by the necessary combination of data from multiple satellite SBUV(/2) instruments. The qualitative consistency between the results obtained for two different time periods (and two different 11-year solar cycles) gives additional support for the hypothesis that the main pattern of the vertical distribution of ozone response in the tropics seen in Figures 5–8 is a robust outcome of the application of the regression model (1) to long-term ozone data records. However, as mentioned above in connection with Figure 8, the upper stratospheric response observed by HALOE during the 1992–2003 period was weaker than that observed by SBUV(/2) or SAGE during the 1979–1991 period.

[31] Finally, Figures 10 and 11 compare solar cycle ozone regression coefficients for the winter (DJF) and summer (JJA) seasons using SBUV(/2) and SAGE II data, respectively. For the seasonal analysis, the number of data points is reduced by a factor of 4 so that these regression coefficients are less reliable than the annual mean coefficients of Figures 5–7. Nevertheless, some characteristics are worth noting. For the longer SBUV record (n = 25), the positive extratropical responses in the middle stratosphere appear to occur mainly in the winter season, especially in the Southern Hemisphere (SH). In the summer of both hemispheres, the response is mostly weak (1–2%) and statistically insignificant. This could represent a useful constraint on general circulation model simulations of the ozone response. For the shorter SAGE II record (n = 17 with the 2 years following Pinatubo removed), a strong response is again present in the winter extratropics of both hemispheres. However, unlike the SBUV(/2) results, the SH also shows a significant extratropical response in summer. In general, the SAGE results are much more variable at higher latitudes in the winter hemisphere because of increased dynamical variability combined with the reduced sampling of this instrument compared to SBUV. Note that this results in contours that overlap one another in Figure 11. We have nevertheless used the same contour interval as in Figure 10 so that direct comparisons

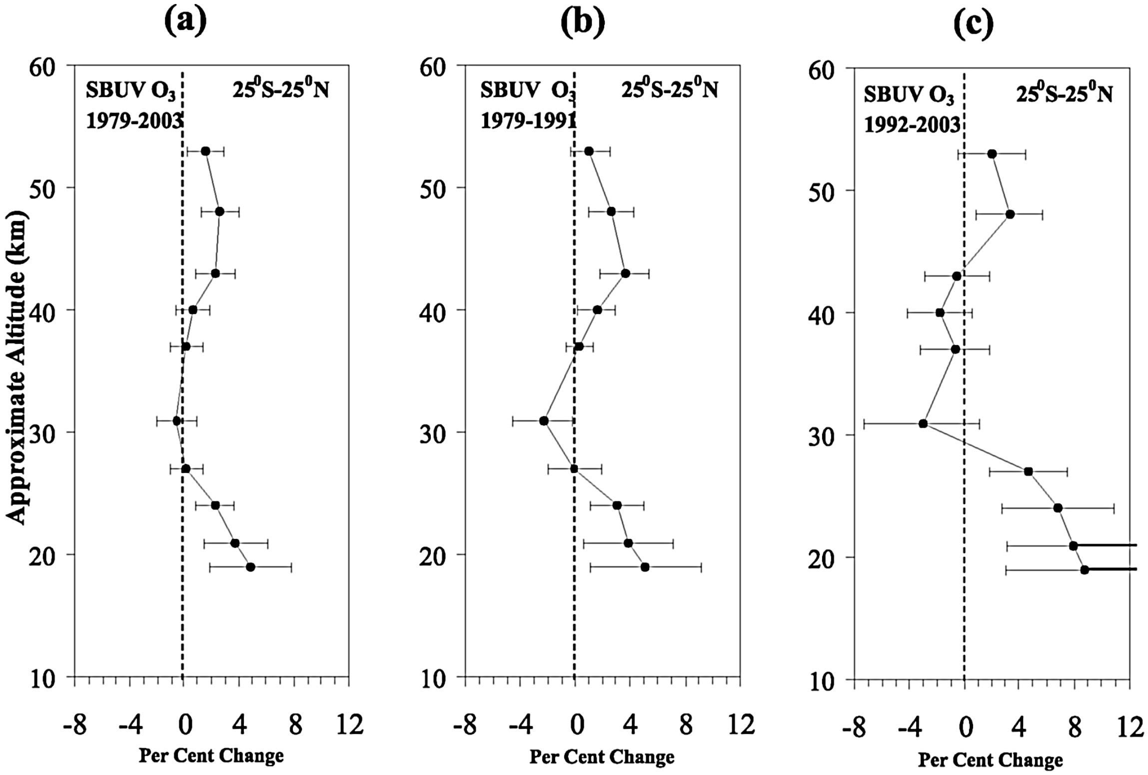

Figure 9. Comparison of (a) SBUV(/2) solar ozone regression coefficients obtained when the entire 25-year record is considered to (b) those obtained when only the 1979 to 1991 period is considered and (c) when only the 1992 to 2003 period is considered.

between the SAGE and SBUV results can be made at lower latitudes.

4. Lower Stratospheric Ozone Solar Cycle Variation

[32] As was mentioned in the Introduction, previous studies of SBUV ozone profile data and TOMS/SBUV column ozone data have inferred that a large majority of the apparent solar cycle variation of total ozone at tropical latitudes occurs in the lower stratosphere [e.g., *Hood*, 1997]. This result contrasts with models that predict most of the column ozone change should occur in the middle stratosphere (largest contribution near 10 hPa). Because the SBUV instrument does not resolve the ozone profile at levels below ~20–30 hPa, the existence of a lower-stratospheric ozone solar cycle variation was inferred by subtracting the measured ozone column above 30 hPa from the total ozone column measured by the TOMS instrument. However, since the vertical resolution of the SBUV instrument is 5 to 8 km (section 2.1), this method is not ideal. Therefore, in this section, it is of interest to consider measurements by the HALOE instrument, which resolves the lower-stratospheric ozone profile on vertical scales of ~3 km (section 2.3).

[33] As shown in Figure 1, HALOE data are available since late 1991 during a period when the tropically averaged version 8 TOMS/SBUV ozone column first decreased and then increased in approximate phase with the solar cycle. In addition, significant interannual variability is superposed on the decadal variation of tropical total ozone as is evident in Figure 1. One approach toward determining the pressure levels where the column ozone variation in Figure 1a is occurring is to calculate the correlation coefficient between the total ozone time series and time series of similarly averaged ozone mixing ratio at various pressure levels. Figure 12 shows the results of such calculations using the 3-month HALOE data. The TOMS/SBUV data were also averaged over the same 3-month intervals to facilitate the correlation calculation. For the 12 years of HALOE data considered here (48 data points), a correlation coefficient of 0.46 is positive at the 99% confidence level. As seen in Figure 12, correlations are weak in the upper and middle stratosphere but become positive below 30 km altitude and are statistically significant at the 95% level in the lowermost stratosphere (R = 0.51 at 46.3 hPa and R = 0.57 at 68.1 hPa for the levels analyzed). At 100 hPa, the correlation is again insignificant. However, the data sampling is much less at this level than at higher levels, apparently because of screening to prevent contamination from high tropical clouds [see, e.g., *Hervig and McHugh*, 2002]. It is therefore not clear whether the lack of a correlation at 100 hPa is real or is caused by reduced sampling.

[34] Figure 13 shows the result of summing the ozone column contributions at HALOE pressure levels ranging from 100 to 31.6 hPa. The tropically averaged lower-stratospheric column is compared to the TOMS/SBUV total ozone time series (R = 0.58). As expected from the correlative results of Figure 12, the lower-stratospheric column variation is very similar to the observed total ozone

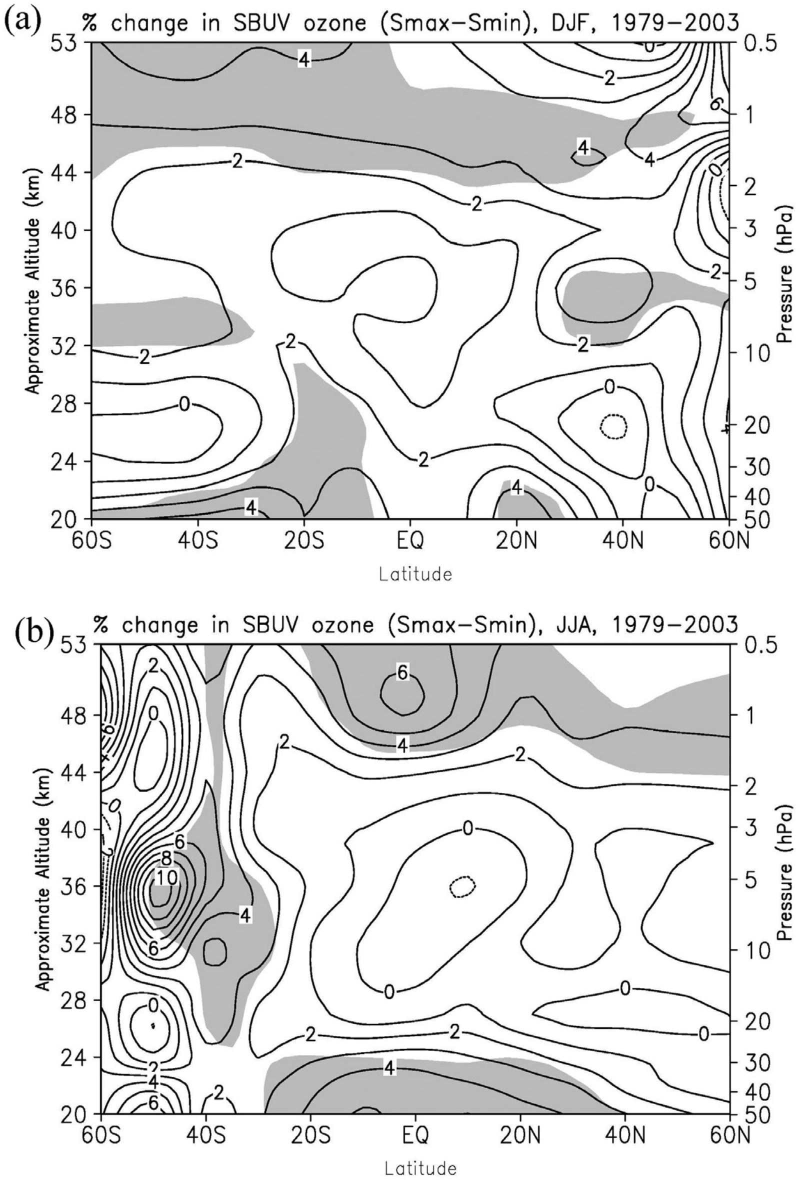

Figure 10. SBUV(/2) solar ozone regression coefficients for (a) the DJF season and (b) the JJA season. Same format as Figure 5.

decadal variation. Interannual variability associated with the QBO in the lower stratosphere is also evident. The lack of a perfect correlation is attributable to the greatly reduced sampling of the HALOE instrument compared to either the SBUV or the TOMS instruments.

5. Comparisons With Model Predictions and Discussion

[35] In Figure 14, the tropical ozone solar regression coefficients estimated here at selected pressure levels/altitudes (from Figure 8) are compared with simulated ozone changes by a series of models that account for observed 11-year changes in solar UV spectral irradiance. In the case of SBUV(/2), coefficients at levels below 30 hPa and above 1 hPa are excluded for reasons explained in section 2.1. In the case of SAGE II, coefficients for altitudes at or below 20 km are not shown for reasons given in section 2.2. In the case of HALOE, coefficients are not shown below 20 km because of the reduced sampling discussed in section 4. The model simulations are for both earlier two-dimensional models [*Brasseur*, 1993; *Haigh*, 1994] and for more recent three-dimensional models with fully interactive dynamics and chemistry [*Tourpali et al.*, 2003; *Egorova et al.*, 2004].

[36] According to Figure 14, in the upper stratosphere, the mean 1979–2003 responses derived using SBUV(/2) and SAGE II data are still generally larger than expected from most of the models. As indicated in Figure 14c, the HALOE 1992–2003 mean responses are in better agreement with model simulations at these levels (but note that these responses are especially small near the equator suggesting an influence of the sparser sampling there; see Figure 7). One suggested physical cause of an amplified ozone response in the upper stratosphere is a decadal variation of

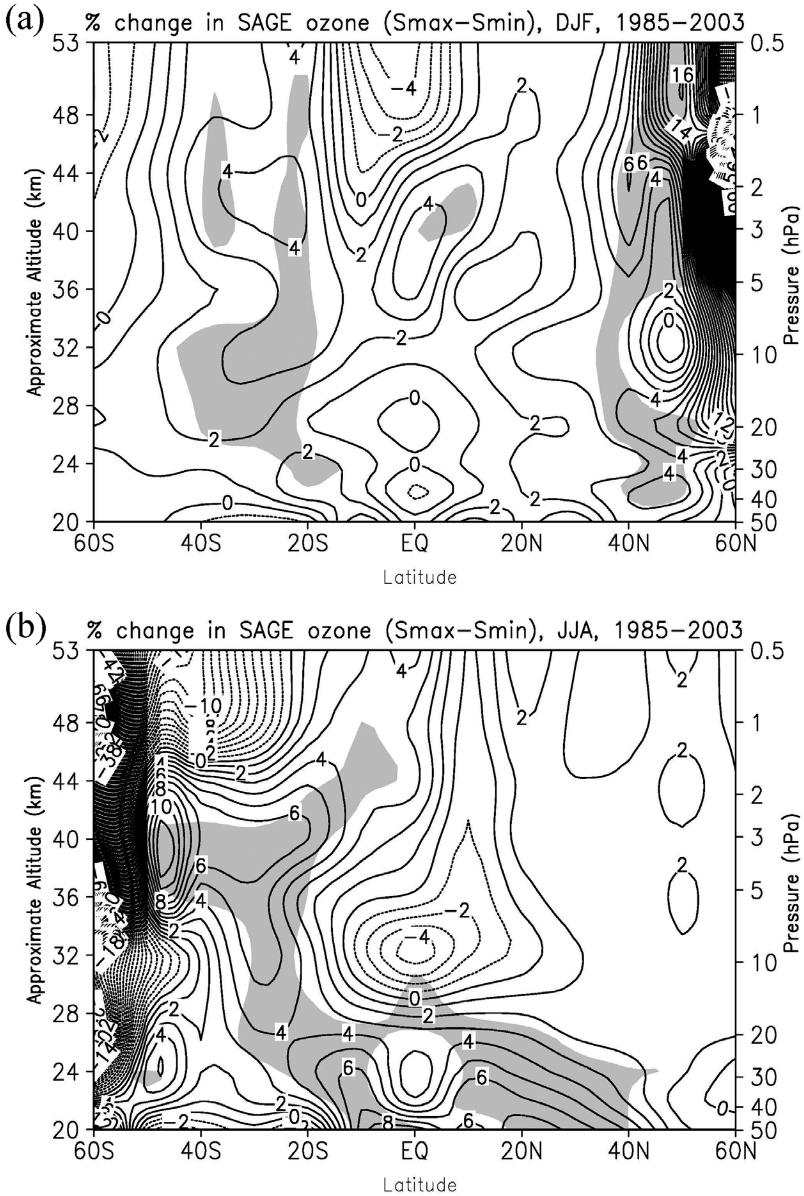

Figure 11. SAGE II solar ozone regression coefficients for (a) the DJF season and (b) the JJA season. Same format as Figure 6.

odd nitrogen caused by energetic electron precipitation [*Callis et al.*, 1998, 2000; *Langematz et al.*, 2005; *Rozanov et al.*, 2005]. However, recent studies of HALOE NO + NO_2 data at low latitudes have found statistically significant solar cycle variations only at and above the stratopause [*Hood and Soukharev*, 2006]. At these levels, ozone catalytic losses are dominated by odd hydrogen. It is therefore unlikely that particle precipitation effects on odd nitrogen were an important source of tropical stratospheric ozone decadal variability during the HALOE operation period. At this point in time, therefore, it may be concluded that it is uncertain whether there is any disagreement between measurements and models in the upper stratosphere. Further investigation of this issue should probably be deferred until at least one more solar cycle of data are acquired.

[37] The comparisons between TOMS/SBUV total ozone and HALOE lower-stratospheric ozone during the 1992–2003 period shown in section 4 increase the likelihood that there is a substantial solar cycle variation of lower-stratospheric ozone. As shown in Figure 14, this lower-stratospheric ozone variation is not predicted by most existing models. Since ozone variability at these altitudes is dominantly driven by dynamical processes and since photochemical models do not predict a response in this region, it is likely that this decadal variation has a dynamical origin. Although volcanic eruptions and the QBO could conceivably produce a decadal variation with a period near 11 years, it would be extremely coincidental if the phase of this variation were exactly matched with that of the solar cycle as appears to be the case in Figure 1. Also, the increase in tropical total ozone approaching the most recent solar maximum, when no major eruptions have occurred, supports the view that volcanic eruptions alone cannot explain this decadal variation. A remaining possibility is that the direct

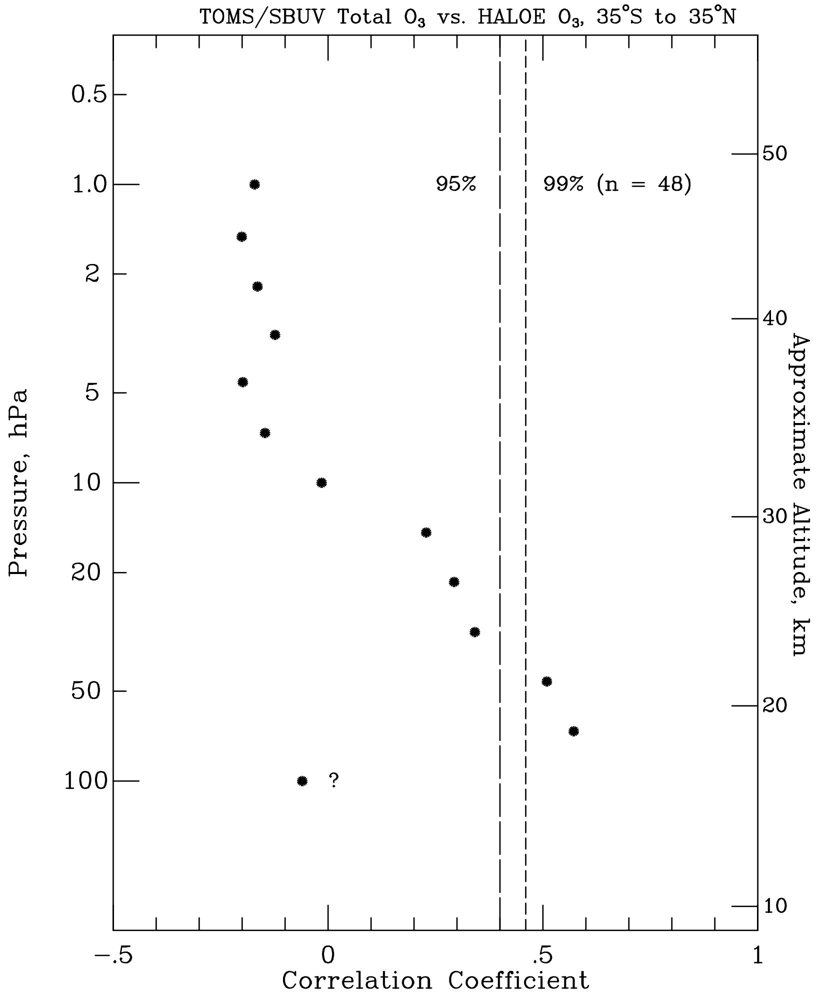

Figure 12. Correlation coefficients between 3-month averages of TOMS/SBUV data averaged over the 35°S to 35°N latitude band and similarly averaged HALOE profile data at a series of pressure levels in the stratosphere.

upper stratospheric effects of solar ultraviolet radiation and particle precipitation are able to modify the development of stratospheric circulation in such a way as to modify the effective upwelling rate in the tropical and subtropical lower stratosphere [*Kodera and Kuroda*, 2002]. Some evidence for a decadal variation of the extratropical wave forcing, which is an indirect measure of the strength of the mean residual (Brewer-Dobson) circulation, has been obtained from NCEP Reanalysis data [*Hood and Soukharev*, 2003]. Using empirical estimates of the sensitivity of tropical total ozone to changes in the wave forcing, it was suggested that the inferred decadal variation of the residual circulation may be sufficient to explain the observed solar cycle variation of lower-stratospheric ozone. However, this provisional result needs to be tested further using more accurate ozone profile data and planetary wave flux divergences.

[38] In the tropical middle stratosphere, it is clear that standard multiple regression analyses of the available data yield a reduced solar cycle ozone response in comparison to model simulations. This is true regardless of the time period or data set considered as shown in Figures 8, 9, and 14. Moreover, the 5 hPa ozone mixing ratio time series in Figures 2, 3, and 4 show little evidence for decadal variability at this level. The explanation for this apparent disagreement with models is uncertain. As mentioned already in section 3.1, *Lee and Smith* [2003] have argued that there is no real disagreement between models and measurements. Instead, they suggest that interference from ozone variations forced by the QBO and by major volcanic eruptions (El Chichón in April 1982 and Pinatubo in June 1991), combined with the short measurement record, have produced an artificially small ozone response in this region as measured using the multiple regression method. These authors reported simulations using a fully interactive two-dimensional model including an imposed QBO to show that a minimum solar regression coefficient amplitude in the tropics could potentially result from such interference. However, the altitude at which the simulated response minimum occurred depended on the time period that was selected during the simulation (i.e., ~34 km for the 1979–1989 period and ~24 km for the late 1984 to 1998 period; see their Figure 13). This differs from the observational results of Figures 8 and 9, which consistently show a minimum mean response near 10 hPa (~32 km altitude).

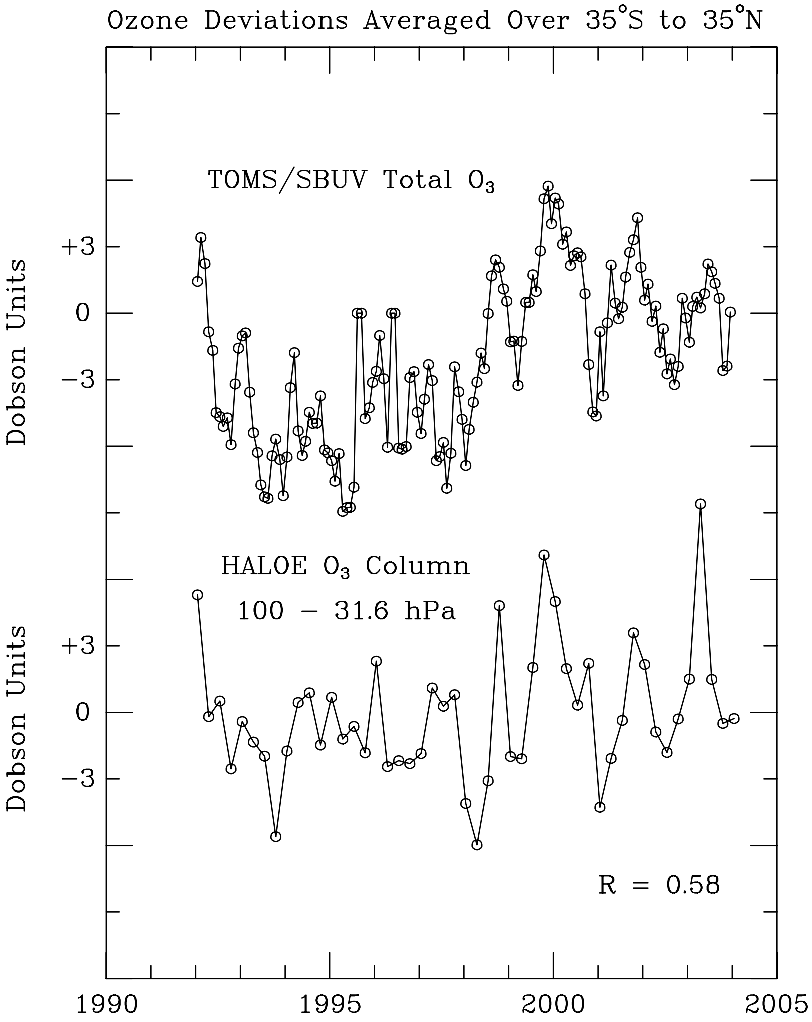

Figure 13. Comparison of (top) the monthly TOMS/SBUV total ozone record averaged over 35°S to 35°N to (bottom) the similarly averaged HALOE 3-month time series of column ozone in the lower stratosphere (100 to 31.6 hPa) during the 1992 to 2003 time period.

In addition, their prescribed QBO had an imposed period of 27 months, which beats with the annual cycle at a period of 9 years, not far from the solar cycle period. The actual QBO has a variable period with a mean of ~28 months [*Baldwin et al.*, 2001]. It was not shown that a more realistic QBO in the model would produce the same interference at a constant altitude as is observed. Until more complete model experiments including a more realistic QBO can be performed, it therefore remains uncertain whether this is the explanation for the observed tropical minimum ozone response.

[39] A second possibility is that a real solar cycle modulation of the QBO exists that could effectively produce a secondary negative ozone response in the tropical middle stratosphere. Near the 10 hPa level where the minimum observed ozone response occurs, ozone is dominantly under photochemical control. The ozone QBO at this level is mainly a consequence of dynamically induced changes in NO_y (the total reactive nitrogen reservoir), which in turn strongly contributes to the ozone catalytic loss rate [*Chipperfield and Gray*, 1992; *Politowicz and Hitchman*, 1997]. Therefore a solar modulation of the QBO leading to net relative downwelling in the tropical middle stratosphere under solar maximum conditions would produce an increase in NO_y and a photochemically induced decrease in ozone. In support of this possibility, some statistical evidence for an apparent minor dependence of certain properties of the QBO on the 11-year solar cycle has been reported [*Salby and Callaghan*, 2000; *Soukharev and Hood*, 2001; *Pascoe et al.*, 2005; see also *Hamilton*, 2002]. Some modeling studies have also suggested that a solar modulation of the QBO period is to be expected [*McCormack*, 2003]. However, it has not yet been demonstrated that this possible solar cycle modulation of the QBO would lead to the observed tropical ozone response minimum.

[40] Finally, it is possible that large-scale circulation changes in the stratosphere (independent of the QBO) between solar minimum and maximum are primarily responsible for the observed tropical ozone response minimum. An effective solar cycle modulation of the Brewer-Dobson circulation, resulting in relative downwelling in the tropical lower stratosphere near solar maxima, has been hypothesized [*Kodera and Kuroda*, 2002]. As

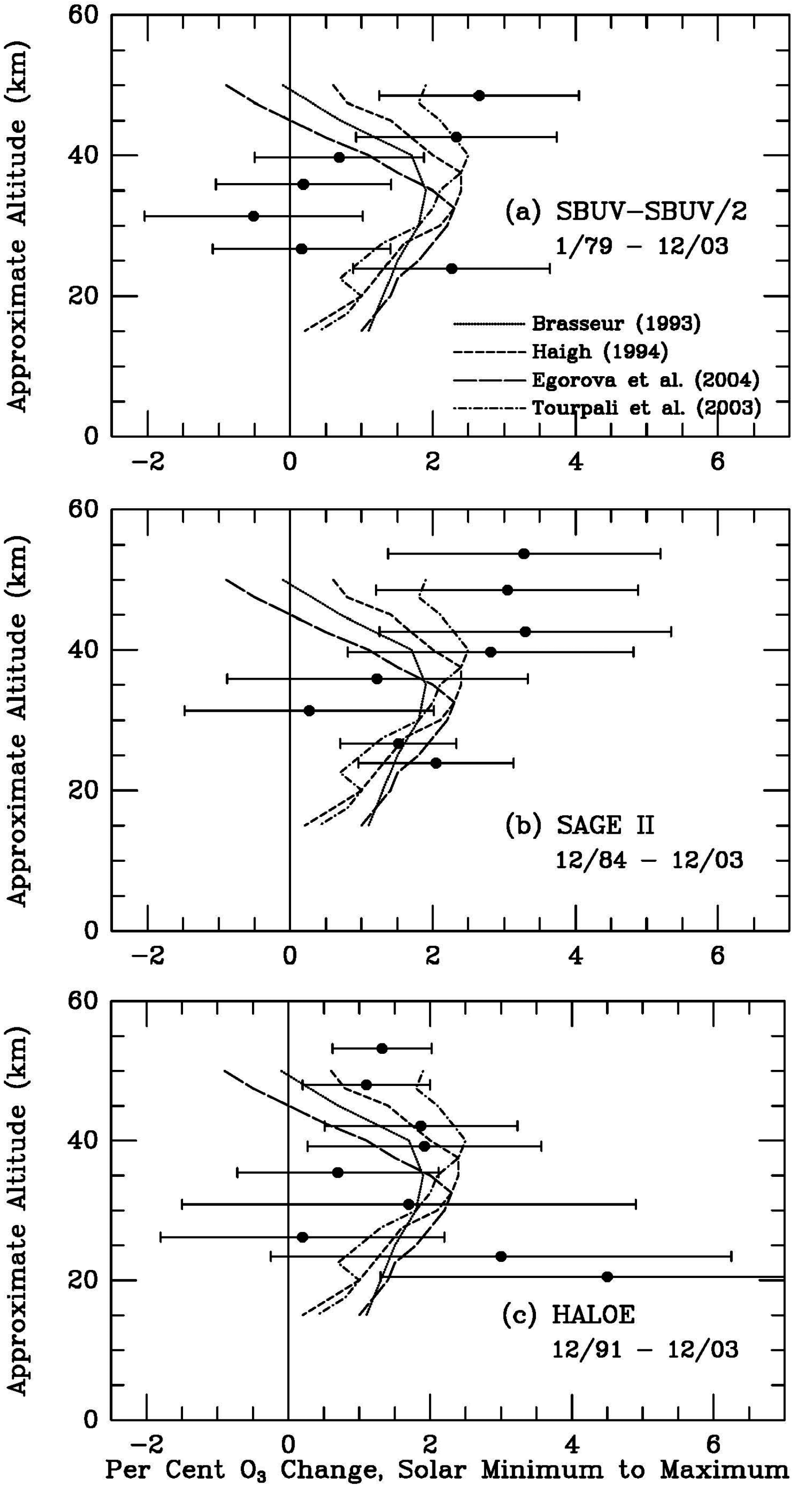

Figure 14. Comparison of annual mean solar regression coefficients calculated from (a) the SBUV(/2) analysis, (b) the SAGE II analysis, and (c) the HALOE analysis (taken from Figure 8) at selected levels to simulations by a series of two- and three-dimensional stratospheric models that account for observed 11-year changes in solar UV spectral irradiance. Error bars are 2σ (95% confidence) limits.

discussed already above, this mean difference between stratospheric circulation at solar minimum and maximum has previously been suggested to be the cause of the ozone response increase in the lower stratosphere [*Hood and Soukharev*, 2003]. If relative downwelling occurs, on average, also in the tropical middle stratosphere near solar maxima, then this could lead to increased NO_y concentrations there (the vertical gradient of NO_y mixing ratio is positive at 10 hPa) and, consequently, a chemically induced ozone decrease.

6. Conclusions

[41] The increase in tropical total column ozone approaching the cycle 23 maximum during the late 1990s occurred during a period with no major volcanic eruptions. As shown in Figures 12 and 13, HALOE ozone profile measurements, which are relatively accurate at lower altitudes, indicate that a large fraction of this increase in total ozone occurred in the lower stratosphere below the 30 hPa level. A dynamical origin for the solar cycle total ozone variation is therefore likely.

[42] As shown in Figures 8 and 9, during the 25-year period examined here, the vertical structure of the tropical ozone response to the 11-year solar cycle has been consistently characterized by statistically significant positive responses in the upper stratosphere (40–50 km altitude) and lower stratosphere (below 25 km altitude) and by statistically insignificant responses in the middle stratosphere (∼28–38 km altitude). The minimum mean response in the tropics invariably occurred near the 10 hPa level (∼32 km). As discussed in sections 3.1 and 5, if the reduced ozone solar cycle response in the tropical middle stratosphere is caused by random interference from the QBO in the multiple regression analysis, then the vertical structure of the response would likely change from one cycle to the next. Since no significant difference in the vertical structure is obtained for the 1979–1991 and 1992–2003 time periods (Figures 8c and 9), this hypothesis is not supported by the available data. Further model calculations similar to those reported by *Lee and Smith* [2003], but incorporating a more realistic QBO, would assist in clarifying this issue.

[43] The amplitude of the solar cycle ozone variation in the tropical upper stratosphere derived here is somewhat reduced in comparison to earlier results reviewed by *Hood* [2004]. This is especially true for the variation derived from HALOE data for the 1992–2003 period. As shown in Figure 14b, the latter variation is not significantly larger than model simulations. More measurements extending over at least one more solar cycle are therefore needed to establish whether the upper stratospheric ozone solar cycle variation is or is not larger than model estimates.

[44] **Acknowledgments.** The Ozone Processing Team at Goddard Space Flight Center (led by R. Stolarski and R. McPeters) provided the version 8 TOMS/SBUV(/2) column ozone and SBUV(/2) ozone profile data analyzed here. The SAGE II ozone profile monthly zonal means were provided by W. J. Randel and F. Wu of NCAR and were based on data originally obtained from the NASA Langley Research Center Radiation and Aerosols branch. The UARS HALOE data were obtained from the NASA Langley Research Center UARS data center (http://haloedata.larc.nasa.gov). We thank Ellis Remsberg for important advice and assistance in the acquisition and processing of the HALOE data. Important discussions with John McCormack of the Naval Research Laboratory in Washington, D. C., are gratefully acknowledged. Helpful critical comments by three anonymous reviewers on an earlier version of the manuscript are appreciated. This material is based on work supported by the National Science Foundation Climate Dynamics program under grant ATM-0424840. Additional support from NASA under a grant from the Living With a Star research program is also gratefully acknowledged.

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