3.3 VERTICAL PROFILE OF THE STRATOSPHERIC SOLAR CYCLE OZONE VARIATION AT LOW LATITUDES: OBSERVATIONS AND MECHANISMS

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1. INTRODUCTION

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,b; Cunnold et al., 2004).

In this paper, recent observational estimates of the 11-year ozone response are first reviewed and compared with a series of two- and three-dimensional model simulations. Apparent significant differences between the observational estimates at tropical latitudes and those simulated in most models are noted. In particular, evidence is discussed for the absence of a statistically significant response in the middle stratosphere and for the existence of a significant positive response in the lower stratosphere. The possibility that the lower stratospheric response is dominantly responsible for the observed solar cycle variation of tropical total ozone is also discussed. Second, in section 2, candidate mechanisms for explaining these differences are reviewed and discussed. Conclusions are summarized in section 3.

2. OBSERVATIONAL RESPONSE ESTIMATES

Observational estimates of the solar 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). Figure 1 shows the mean solar cycle ozone variation (in per cent) as obtained from recent multiple regression statistical analyses of updated versions of these two independent long-term satellite ozone profile data sets. Figure 1a shows the solar cycle ozone variation as estimated by Soukharev and Hood (2006) using Version 8 SBUV and SBUV/2 measurements on the Nimbus 7, NOAA 9, 11, and 1;6 satellites over the period from 1979 through 2003 (Frith et al., 2004). Figure 1b shows the same variation as estimated using Version 6.20 SAGE I and II data over the 1979 through 2005 period, excluding several years between the end of SAGE I and the start of SAGE II and several years after the Pinatubo volcanic eruption. (SAGE I/II data were provided by W. Randel and F. Wu.) The ozone variation shown in this figure is nearly identical to that reported by Randel and Wu (2006). Shaded areas in both diagrams indicate ozone variations that are formally statistically significant at the 95% confidence level. A comparison of Figures 1a and 1b provides an alternate empirical measure of true uncertainties in the estimated ozone solar cycle variation. Common features of Figures 1a and 1b include (i) a statistically significant response in the upper stratosphere (~ 2 to 4%) where solar UV variations directly affect ozone production rates; (ii) a statistically insignificant response in the tropical middle stratosphere

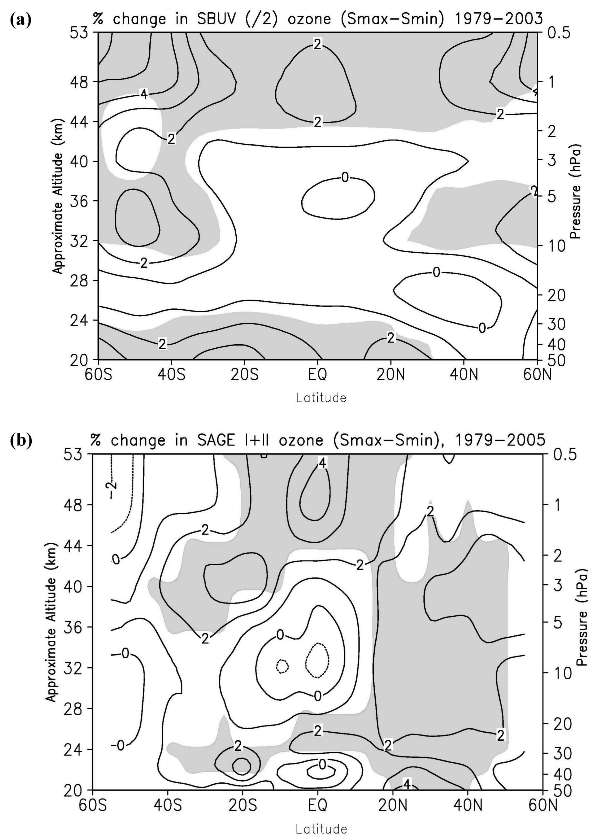

Figure 1. (a) Ozone change (%) from solar minimum to maximum based on multiple regression analysis of SBUV(/2) data (Soukharev and Hood, 2006). (b) Same format but using SAGE I and II data over the 1979 to 2005 period. In both diagrams, shaded areas are significant at the 95% confidence level.

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and (iii) a statistically significant response in the lower stratosphere with amplitude ~ 1 to 3%.

The validity of this vertical structure has recently been investigated in more detail (Soukharev and Hood, 2006) by (1) analyzing three independent satellite ozone data sets over several time intervals up to 25 years in length and (2) comparing column ozone measurements with ozone profile data during the 1992-2003 period when no major volcanic eruptions occurred. In addition to the SBUV(/2) and SAGE II data sets, UARS Halogen Occultation Experiment (HALOE) data for the period from Dec. 1991 through Dec. 2003 were also analyzed (see, e.g., Remsberg et al., 2001). Results showed that the vertical structure seen in Figure 1 is consistently obtained in the tropics for separate time intervals and for separate satellite data sets. For example, the HALOE ozone response structure is qualitatively similar to that shown in Figures 1a and 1b although the structure is more variable as expected from the short measurement record and low sampling frequency. Also, the same basic vertical structure (with larger error bars) is obtained when the 25-year continuous SBUV(/2) record is divided into two equal parts and the analysis is repeated for each subinterval.

The validity of the hypothesis (e.g., Hood, 1997) that a large majority of the solar cycle variation of total ozone at tropical latitudes occurs in the lower stratosphere was also investigated further by Soukharev and Hood (2006). This was done by comparing Version 8 Total Ozone Mapping Spectrometer (TOMS) and SBUV column ozone measurements with ozone profile data for the lower stratosphere during a period when no major volcanic eruptions occurred. HALOE ozone profile data were used during the 1992-2003 period since HALOE resolves the lower stratospheric ozone profile on vertical scales of ~ 3 km. First, as a simple approach toward investigating the altitude range of the total ozone variation, correlation coefficients between 3-month, tropically averaged TOMS/SBUV total ozone and tropically averaged HALOE ozone mixing ratios at a series of pressure levels were calculated. Positive correlation coefficients, significant at more than the 95% confidence level were obtained only at ~ 50 and ~ 70 hPa. Second, 3-month, tropically averaged TOMS / SBUV ozone data were compared to the HALOE ozone column in the 100 – 30 hPa pressure range. The correlation coefficient was significant at the 99% confidence level. These comparisons showed that the observed increase in tropical column ozone approaching the cycle 23 maximum in the late 1990's and early 2000's occurred primarily in the lower stratosphere below the 30 hPa level.

In the upper stratosphere where solar UV variations directly affect ozone production rates, a statistically significant response with an amplitude ranging from 2 to 4% is obtained in both analyses. Positive responses are also obtained at middle and higher latitudes in the middle stratosphere and in the tropics below the 20 hPa level. A statistically insignificant response is obtained in the tropical middle stratosphere. In part because of the higher atmospheric number density at lower altitudes, the ozone response in the lower stratosphere is believed to be the main cause of the observed solar cycle variation of total column ozone (Hood, 1997; Soukharev and Hood, 2006).

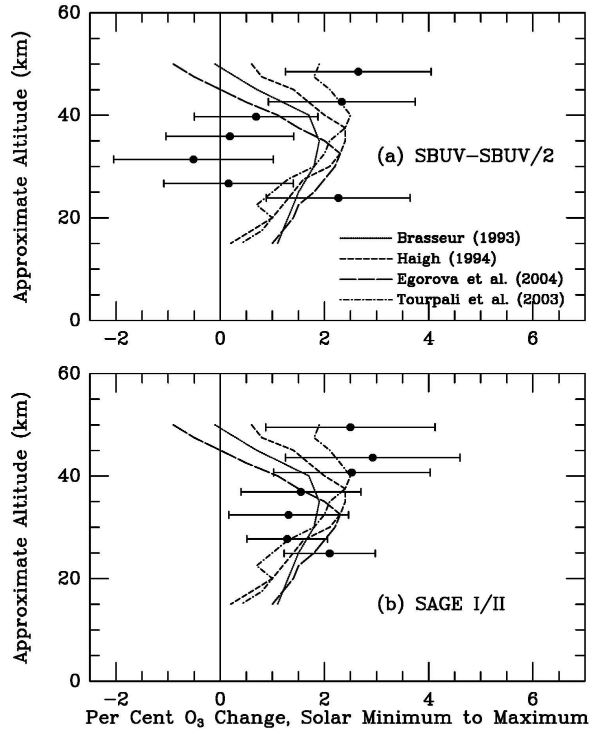

Figure 2. Comparison between annual mean solar cycle ozone regression coefficients averaged over low latitudes (25S to 25N) calculated from (a) the SBUV(/2) data set (Soukharev and Hood, 2006) and (b) the SAGE I/II data set (Randel and Wu, 2006) to simulations by a series of 2D and 3D models. Error bars are 95% confidence limits.

Figure 2 compares the tropically averaged ozone solar cycle variation as derived from (a) Version 8 SBUV(/2) data) and (b) SAGE I/II data over the 1979-2005 period to a series of model simulations. In the case of SBUV(/2), regression coefficients at levels below 30 hPa are excluded since the ozone profile is not accurately resolved by the SBUV instrument at these levels. In the case of SAGE II, coefficients for altitudes at or below 20 km are not shown because of evidence for increased data uncertainties at these levels in the presence of lower stratospheric aerosols (e.g., Cunnold et al., 1996, 2000). The model simulations are for both earlier 2D models (Brasseur, 1993; Haigh, 1994) and for more recent 3D models with fully interactive dynamics and chemistry (Tourpali et al., 2003; Egorova et al., 2004). According to this figure, in the upper stratosphere, the mean 1979-2003 tropical SBUV(/2) and SAGE II responses are still generally larger than expected from most of the models. Also, in the lower stratosphere, the observed positive response is not predicted by most existing models. Finally, 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 most model simulations. This was found to be the case regardless of the time period or data set considered in the analysis of Soukharev and Hood (2006).

3. MECHANISMS

The upper stratospheric response occurs in the region where ozone is nearly in photochemical equilibrium and where direct photochemical responses of ozone production rate to solar UV variations are expected theoretically. It therefore undoubtedly has a dominantly direct photochemical origin. However, as seen in Figure 2, the observed mean ozone response is somewhat larger than expected by most models. If this difference is not caused by the short measurement record, then solar induced variations of minor constituents that affect the ozone concentration in the upper stratosphere are probably implicated. It has been proposed by Callis et al. (2000), for example, that particle precipitation induced odd nitrogen variations are responsible for the enhanced ozone response in the upper stratosphere. Specifically, during some solar cycles, energetic electron precipitation tends to be strongest during the declining phase of the solar cycle approaching solar minima (Callis et al., 2001; Rozanov et al., 2005). This would increase ozone losses approaching solar minima, effectively amplifying the upper stratospheric ozone response. However, a recent analysis of UARS HALOE odd nitrogen data yields no significant evidence for a solar cycle variation throughout most of the stratosphere except at high latitudes (Hood and Soukharev, 2006). Evidence for an inverse solar cycle variation of odd nitrogen was only found at and above the 1 hPa level. At these altitudes, ozone catalytic losses are dominated by odd hydrogen. There is no evidence for decadal odd nitrogen variations at lower altitudes in the upper stratosphere where odd nitrogen catalytic losses are more important. Also, as concluded by Hood and Soukharev, the inverse solar cycle variation of odd nitrogen above the stratopause is most probably caused by increased photolysis of NO near solar maximum (Minschwaner and Siskind, 1993) rather than by changes in particle precipitation. It is therefore concluded that solar induced odd nitrogen variations (whether caused by particle precipitation or UV flux changes) can not easily explain the differences between the observed and modeled upper stratospheric ozone response evident in Figure 2. Long-term measurements of other minor constituents, especially odd hydrogen, would be necessary to investigate this possibility further.

As discussed in section 2, the lower stratospheric ozone response appears to be mainly responsible for the solar cycle variation of total column ozone at low latitudes. Since ozone is primarily under dynamical control in this region, a dynamical origin for the lower stratospheric ozone variation is suggested. Because of its long chemical lifetime and large vertical gradient at these altitudes, ozone in the lower stratosphere is very sensitive to changes in vertical transport. As proposed originally by Kodera and Kuroda (2002), one likely dynamical response to the direct chemical and radiative effects of solar UV flux changes in the upper stratosphere may be a change in the ascending branch of the Brewer-Dobson circulation, which would modify upwelling rates at low latitudes. They specifically suggested that the tropical upwelling rate should be weakened near solar maxima. Hood and Soukharev (2003; hereafter HS03) investigated whether decadal changes in the tropical upwelling rate caused by solar-induced changes in extratropical wave forcing could be sufficient to explain the observed solar cycle ozone variation in the tropical lower stratosphere. They reported some evidence for a decadal variation of the wave forcing in both hemispheres based on an analysis of National Centers for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996). Using a simplified analytic model together with empirically determined sensitivities of tropical total ozone tendencies to short-term changes in the wave forcing, they found that the inferred decadal changes in upwelling rates could produce decadal total ozone variations with amplitudes of several per cent, comparable to that which is observed at low latitudes. However, the wave flux statistics that were employed in their analysis are subject to observational uncertainties. This is especially true in the Southern Hemisphere because of the sparsity of radiosonde stations at southern middle to high latitudes.

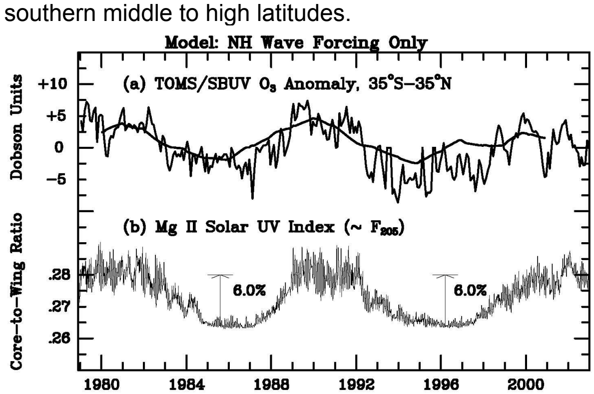

Figure 3. (a) The continuous line is calculated using equation (1) together with NCEP eddy heat flux data for the Northern Hemisphere as described in the text. (b) The Mg II solar UV index.

Figure 3 shows the result of a calculation similar to that reported by HS03 but improved in several respects. First, only wave forcing statistics in the Northern Hemisphere (NH), which are larger in amplitude and more accurately determined, are used. Second, the effective odd oxygen lifetime in the tropical lower stratosphere is assumed to be 800 days rather than 180 days, as assumed by HS03; a lifetime of 800 days is more appropriate for ozone in the lowermost stratosphere at and below 50 hPa (e.g., Jackman et al., 1996). The analytic model used by HS03 to estimate the expected decadal total ozone variation is based on a simplified form of the ozone continuity equation:

$$dO_3/dt \sim A_N v'T'_{60N} - O_3/\tau_c \qquad (1)$$

where A_N is a regression coefficient derived from observations of short-term deviations, O_3 is the approximate ozone column in the tropical lower stratosphere, and all variables represent deviations from equilibrium values at t = 0. In (1), the tropical upwelling velocity is assumed to be inversely proportional to the wave driving as represented by the eddy heat flux, v'T', at 60^o N. Integrating forward in time with τ_c = 800 days and using the observed long-term variation of eddy heat flux in the NH extratropics shown in Figure 13c of HS03, the estimated decadal variation of total ozone in the tropics is shown by the superposed curve in Figure 3a. Note that a linear trend is present in the observed ozone time series that is of non-solar origin. If the linear trend is removed, the fit of the model to the data is better than that shown in Figure 3a. While simplified, this calculation suggests that much of the amplitude and the phase of the tropical total ozone variation could be caused by decadal variations of the upwelling rate driven by solar-induced changes in planetary wave forcing.

Possible explanations for the apparent difference between models and observations in the tropical middle stratosphere can be roughly grouped into three main categories: (1) Interference in the statistical analysis due to ozone changes associated with the QBO and with major volcanic eruptions (Solomon et al., 1996; Lee and Smith, 2003); (2) solar cycle changes in stratospheric odd nitrogen resulting from energetic particle precipitation (Callis et al., 2001; Rozanov et al., 2005; Langematz et al., 2005); and (3) solar cycle induced changes in stratospheric circulation, including the QBO, and resulting effects on ozone transport and chemistry (Kodera and Kuroda, 2002; Hood and Soukharev, 2003).

Lee and Smith (2003) point out that the equatorial zonal wind used as a predictor variable in multiple regression statistical models is affected by solar and volcanic forcings as well as by the tropospheric waves that dominantly drive the QBO. Thus the QBO, solar cycle, and volcanic indices in the statistical models are not entirely independent of one another. Also, if one phase of the QBO happens to dominate over the other during solar maximum periods within a short measurement record of one or two cycles, the solar regression coefficients may be biased because of the large amplitude of the QBO induced variations. Lee and Smith reported simulations using a fully interactive 2D model including an imposed QBO to show that a minimum ozone solar regression response could potentially result from interference of this type. However, if only accidental phasings of the QBO and solar cycle are responsible for this interference, the vertical structure of the ozone solar cycle response should change from cycle to cycle. This expectation is supported by their simulations which showed that the altitude at which the artificial 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 behavior does not appear to be in agreement with the observational results, which consistently show a minimum mean response near 10 hPa (~ 32 km altitude) (Soukharev and Hood, 2006). In addition, their prescribed QBO had a constant period with a mean of ~ 27 months while the actual QBO period is variable with a mean of more than 28 months (Baldwin et al., 2001; Pascoe et al., 2005). Therefore, it remains unclear at present whether interference by the QBO and volcanic forcing can explain the observed tropical ozone minimum.

Second, as already discussed above in relation to the upper stratospheric ozone response, it has been suggested that odd nitrogen, which is the leading source of ozone catalytic losses at most altitudes in the stratosphere, has been influenced by solar variability and that this is the main cause of apparent differences between observed and model-simulated solar cycle ozone variations (Callis et al., 2000; 2001; see also Rozanov et al., 2005; Langematz et al., 2005). However, recent studies of UARS HALOE data indicate that detectable solar-induced changes in odd nitrogen occur in the middle and lower stratosphere only at high latitudes (Hood and Soukharev, 2006). It therefore seems unlikely that odd nitrogen variations caused by particle precipitation can explain the tropical ozone response minimum in the middle stratosphere.

Finally, it is possible that the QBO is itself modified by the solar cycle in such a way as to produce a minimum in the ozone response in the tropical middle stratosphere. This mechanism could, in principle, produce a minimum response consistently in the same approximate location during each solar cycle, as has been observed during the ~ 2.5 available cycles. Near the 10 hPa level where the ozone response minimum occurs, ozone is dominantly under photochemical control; ozone interannual variability at this level is caused dominantly by the QBO, which is in turn driven by dynamically induced changes in odd nitrogen (Chipperfield and Gray, 1992; Politowicz and Hitchman, 1997; Baldwin et al., 2001). Therefore, a solar-induced modulation of the QBO that effectively produces relative downwelling at the equator near 10 hPa under solar maximum conditions would produce an increase in odd nitrogen and a decrease in ozone, thereby tending to cancel out the UV-induced ozone solar cycle variation at that location.

Possible evidence for a solar cycle modulation of certain properties of the QBO was first reported by Salby and Callaghan (2000) who found that the length of the QBO westerly phase at 45 hPa tended to be longer, on average, near solar minima (see also Soukharev and Hood, 2001, and Hamilton, 2002). McCormack (2003) later showed that a longer duration of the QBO westerly phase under solar minimum conditions could be partially simulated in a 2D model that includes a realistic semiannual oscillation and that accounts for solar UV induced changes in radiative heating and the residual circulation. In particular, it was found that reduced tropical upwelling under solar maximum conditions would affect the descent rate of the QBO wind shear zones, producing an effective decrease in the QBO west phase period near solar maxima.

A more detailed observational study of the QBO, including possible solar cycle influences, has been reported by Pascoe et al. (2005) using the ERA-40 data set prepared by the European Center for Medium Range Weather Forecasting for the 1958 to 2001 period. These authors first confirmed several previously established properties of the QBO including (a) a slower and more variable descent rate of the easterly QBO shear zone as compared to the westerly shear zone; and (b) a tendency for the easterlies to descend to the lower stratosphere near 40 hPa only during the months of May, June, and July (see Baldwin et al., 2001, for a more complete review of QBO properties). The latter three months coincide with the time of year when the tropical Brewer-Dobson upwelling rate is weakest and it has therefore been argued using model simulations that a stronger upwelling rate inhibits the descent of the easterly shear zone (Kinnersley and Pawson, 1996).

It follows that if there is a solar cycle modulation of the tropical upwelling rate (Kodera and Kuroda, 2002), then there should be a corresponding decadal modulation of the descent rate of the QBO easterlies. Pascoe et al. reported evidence for such a decadal modulation in the sense that the descent rate tended to be faster under solar maximum conditions. Specifically, the mean time required for the easterlies to descend from 20 to 44 hPa was about 7.4 months under solar maximum conditions and about 9.4 months under solar minimum conditions over the 1958 to 2001 period. The slower easterly descent rate near solar minima allowed the westerly phase to persist longer, thereby apparently explaining the earlier evidence for a longer west phase duration under solar minimum conditions. Accepting the arguments of Kinnersley and Pawson, the more rapid easterly descent rate near solar maxima also implies a weaker tropical upwelling rate, which would be consistent with the low-latitude dynamical response to upper stratospheric solar UV forcing proposed by Kodera and Kuroda (2002). Finally, the inferred weaker tropical upwelling rate near solar maxima may be consistent with evidence for a decadal variation of extratropical wave forcing and with the solar cycle variation of lower stratospheric ozone at these latitudes as discussed above in relation to Figure 3.

To first order, the above results suggest a dominance of the easterly QBO phase near 40 hPa under solar maximum conditions. During the east phase as measured at 40 hPa, the equatorial wind field at 10 hPa is characterized by westerly vertical shear and the equatorial branch of the QBO meridional circulation is downward at 10 hPa. This produces a transport-induced increase in odd nitrogen and a corresponding decrease in ozone near 10 hPa during the QBO easterly phase (as monitored at 40 hPa). Figure 4 compares 3-month time series of HALOE odd nitrogen and ozone over the 1992 to 2003 period at the location of the most extreme ozone response minimum: 10 hPa, equator. Also shown is the solar Mg II UV index. Multiple regression analysis of the HALOE data also yields a minimum ozone solar cycle response at 10 hPa, equator, similar to that seen in Figure 1 (Soukharev and Hood, 2006; their Figure 7). In Figure 4, a strong inverse correlation between the odd nitrogen and ozone interannual variations is evident as expected from photochemistry at this altitude. In general, positive odd nitrogen maxima and negative ozone minima separated by several years occur during periods when the QBO was in its easterly phase as measured at 40 hPa. However, the QBO modulation of ozone and odd nitrogen at this location is not constant with time as can be seen in the figure. Specifically, during the first seven years when solar minimum conditions prevailed, the amplitude and duration of the ozone and odd nitrogen variations was smaller while, during the last five years under solar maximum conditions, the variations had larger amplitudes and durations. In particular, two large and broad east phase ozone minima (labeled ``E'' in the figure) occurred under solar maximum conditions that effectively reduced the mean ozone concentration during this interval. Without these large and deep east-phase minima, a positive solar cycle variation would have been measured at this location by the multiple regression analysis. Figure 4 therefore provides some empirical evidence that the easterly QBO phase as measured at 40 hPa effectively produces deeper and longer ozone minima at 10 hPa under solar maximum conditions, thereby reducing the amplitude of the solar cycle ozone signal at that location. An examination of SAGE II data (not shown here), which include an additional solar maximum period, supports this interpretation. SBUV(/2) ozone data are less useful for this purpose because of the lower vertical resolution of the SBUV measurements, which do not allow the ozone QBO near 10 hPa to be fully resolved.

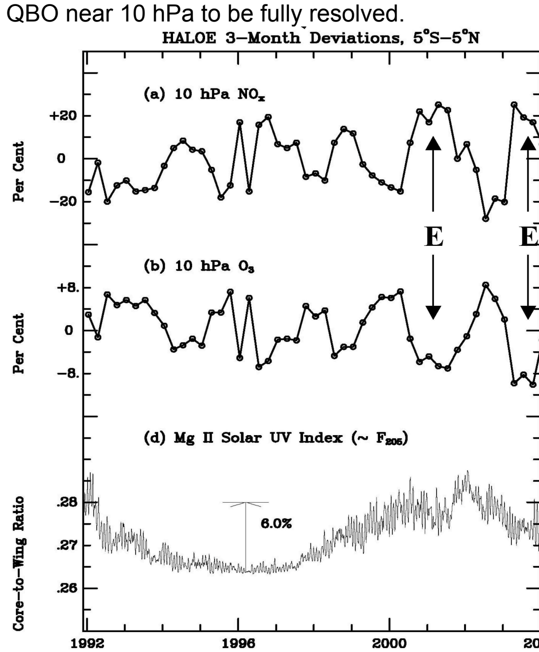

Figure 4. Comparison of 3-month zonally averaged UARS HALOE measurements of (a) odd nitrogen and (b) ozone at 10 hPa, equator to a daily time series of (c) the Mg II solar UV index. See the text.

Very recently, McCormack et al. (2007) have reported simulations using an updated version of the

NRL CHEM2D model with reduced Rayleigh friction drag. It was found that the duration of the westerly QBO phase is 2 months shorter at solar maximum than at solar minimum (compared to 1 month shorter as found by McCormack, 2003). A multiple regression statistical model was then applied to the 2D model output to determine the model solar cycle ozone response. For a model simulation including the effects of solar UV variations (which modulates the QBO) and an assumed 11-year variation in planetary wave 1 amplitude (to modulate the tropical upwelling rate), it was found that the vertical profile of the model ozone response was more in agreement with observations. Specifically, in the tropics, an enhanced upper stratospheric ozone response of ~1% was produced between 45 and 55 km and an enhanced lower stratospheric ozone response of ~2.5% was produced. The maximum model ozone response of ~3% occurred near 38 km altitude, which is still in moderate disagreement with the SBUV(/2) response estimates of Figure 2.

Also very recently, Austin et al. (2006) have reported results from three 45-year simulations of a 3D coupled chemistry climate model. The simulations included UV forcing at the top of the atmosphere, including those occurring on short-term (~27-day) time scales as well as the 11-year time scale. The model contained no QBO and no energetic particle precipitation effects but used observed sea surface temperatures as a lower boundary condition. The resulting model ozone profile response at low latitudes was characterized by a maximum response (min to max) of ~ 1.7% near the 5 hPa level, a minimum response of ~ 0.9% near the 20 hPa level, and a secondary maximum response of ~ 2.3% near the 50 hPa level. This improved agreement with observational analyses, despite the absence of a QBO in the model, was suggested to be caused, at least in part, by the prescribed SST's, which have apparently been phase locked to the solar cycle (White et al., 2003). No clear evidence for a decrease in tropical upwelling under solar maximum conditions could be detected in the model results.

3. CONCLUSIONS AND DISCUSSION

Although progress has been made in characterizing and understanding the response of stratospheric ozone to 11-year solar forcing, more work is needed to obtain a complete understanding allowing full constraints on climate models to be imposed. There is increasing agreement among the available long-term satellite ozone data sets that the annual mean ozone response at low latitudes is significantly positive in the upper and lower stratosphere but is statistically significant in the middle stratosphere. A pronounced minimum in the response is often found at the equatorial 10 hPa level. This vertical structure differs in major ways from most simulations by both 2D and 3D models. The enhanced upper stratospheric response, if not an artifact of the short measurement record, is not likely to be caused by particle precipitation induced increases in odd nitrogen approaching solar minimum conditions. Long-term measurements of odd hydrogen near the tropical stratopause are needed to investigate this issue further.

The minimum response centered on the equatorial 10 hPa level may be caused, at least in part, by a solar modulated QBO. One hypothesis that needs further study is that reduced tropical upwelling under solar maximum conditions increases the descent rate of QBO easterlies, thereby decreasing the length of the west QBO phase (Pascoe et al., 2005). The effective dominance of the east phase near solar maxima (as measured near 40 hPa) results in relative equatorial downwelling near 10 hPa, increasing the odd nitrogen concentration and decreasing the ozone concentration. This may act to at least partially cancel the solar UV induced ozone variation at that location. A recent 2D model simulation by McCormack et al. (2007) supports this possibility.

The unexpected positive ozone response in the tropical lower stratosphere may be caused by transport induced ozone changes associated with a weakened ascent branch of the Brewer-Dobson circulation under solar maximum conditions (Kodera and Kuroda, 2002; Hood and Soukharev, 2003). This possibility is supported by evidence for a decadal variation of extratropical wave forcing and by 2D model simulations that assume a decadal variation of planetary wave 1 amplitude (McCormack et al., 2007).

On the other hand, recent simulations of a 3D coupled chemistry climate model (Austin et al., 2006) have shown that some aspects of the observed tropical vertical structure can be obtained using a model with no QBO and no detectable changes in tropical upwelling rate. Unlike most other models, the latter model included both short-term (27-day) and long-term (11-year) solar UV forcing. Observed SST's were applied as a lower boundary condition and may have played a significant role in modifying the vertical structure of the ozone response. However, a more detailed diagnosis of these model simulations is needed.

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