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Analysis of SAGE II ozone of the middle and upper stratosphere for its response to a decadal-scale forcing

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Abstract

Stratospheric Aerosol and Gas Experiment (SAGE II) Version 6.2 ozone profiles are analyzed for their decadal-scale responses in the middle and upper stratosphere from September 1991 to August 2005, a time span for which the trends in reactive chlorine are relatively small. The profile data are averaged within twelve, 20°-wide latitude bins from 55° S to 55° N and at eleven altitudes from 27.5 to 52.5 km. The separate, 14-yr data time series are analyzed using multiple linear regression (MLR) models that include seasonal, interannual, 11-yr sinusoid, and linear trend terms. Proxies are not used for the interannual, solar uv-flux, or reactive chlorine terms. Instead, the present analysis focuses on the periodic 11-yr terms to see whether they are in-phase with that of a direct, uv-flux forcing or are dominated by some other decadal-scale influence. It is shown that they are in-phase over most of the latitude/altitude domain and that they have max minus min variations between 25° S and 25° N that peak near 4% between 30 and 40 km. Model simulations of the direct effects of uv-flux forcings agree with this finding. Ozone in the middle stratosphere of the northern subtropics is perturbed during 1991–1992, following the eruption of Pinatubo. There are also pronounced decadal-scale variations in the ozone of the upper stratosphere for the middle latitudes of the Northern Hemisphere, presumably due to dynamical forcings. The 11-yr ozone responses of the Southern Hemisphere are relatively free of those extra influences. The associated linear trend terms from the analyses are negative (–2 to –4%/decade) for this 14-yr time period and are nearly constant across latitude in the upper stratosphere. This finding is consistent with the fact that total and reactive chlorine are not changing appreciably from 1991 to 2005. It is concluded that the satellite, solar occultation technique can be used to record the responses of stratospheric ozone to the decadal-scale forcings from the solar uv-flux, as well as those due to the long-term changes from dynamic forcings, reactive chlorine, and the greenhouse gases.

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1 Introduction and background

Chemistry-climate models of stratospheric ozone must be able to represent properly both the responses to the uv-flux variations of the solar cycle (SC), as well as those from any long-term changes in the chemical gas families that affect ozone. It is therefore important to analyze observed ozone time series for those same effects, in order to diagnose the performance of the models. Presently, there is some disagreement between analyses of the responses of ozone profiles to the SC based on satellite data between 25° S to 25° N versus the responses from representative models (e.g., Soukharev and Hood, 2006; Lee and Smith, 2003; SPARC CCMVal, 2010). In particular, the analyses from both the long-term Solar Backscatter Ultraviolet (SBUV) and Stratospheric Aerosol and Gas Experiment (SAGE) ozone data sets indicate a minimum ozone response from 25 to 35 km and maximum responses near 25 km and at 40 km and above. Although most models indicate a maximum response to the solar uv-flux from 30 to 40 km (see Fig. 3.19 of WMO (2007)), there are also decadal-scale periodicities in the stratosphere at low latitudes due to interactions with the quasi-biennial oscillation (QBO) that can mimic that of the solar cycle. Smith and Matthes (2008) report that the diagnosis of such interrelated responses can be problematic based on satellite ozone data that extend for only several decades.

Fioletov (2009) reported that photochemical models are in accord with the observed response of SBUV ozone profiles to 27-day, solar cycle variations. He then used that finding to estimate the ozone response to an 11-yr (or SC) forcing. He found good agreement between the SC response profiles from SBUV and from the models, at least above 35 km. Below 35 km his estimated, 11-yr response from SBUV was dampened, perhaps because of interannual, dynamical effects that do not affect the 27-day response. Soukharev and Hood (2006) also found similar SBUV/model disagreements based on their analyses of a merged ozone dataset (or MOD) from a succession of SBUV instruments. But, Fioletov (2009) pointed out that a part of their disagreement may be traceable to residual biases for the adjusted ozone values from the successive

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SBUV instruments and that another part may be a result of the relatively low sensitivity and vertical resolution of the SBUV measurement and its retrieval algorithm for ozone.

The limb, solar occultation technique provides better sensitivity to the variations of the ozone profile and with very good vertical resolution. The occultation method relies on an exo-atmospheric, calibration measurement of the Sun for each of its sunrise and sunset profiles. Solar occultation measurements are necessarily limited in their sampling frequency for a zone of latitude. Even so, their sampling is adequate for resolving the seasonal and longer-term variations in stratospheric ozone across most latitudes. For example, Remsberg (2008) analyzed 14-yr (1991–2005) time series of ozone-versus-pressure profiles from the Halogen Occultation Experiment (HALOE) instrument of the UARS satellite. He obtained an 11-yr response profile with a relative maximum at 4 to 5 hPa (near 37 km), which is in reasonable agreement with the SC response profiles from most models. Of equal importance, Gordley et al. (2009) checked on the performance of the HALOE instrument over its mission life. They found no changes that might have affected the ozone time series of HALOE and their analyzed, 11-yr responses.

Figure 1 shows that the SC-like ozone response profile obtained by Remsberg (2008) agrees with the result from the representative model of Brasseur (1993). The response profile from the SAGE satellite datasets (McCormick et al., 1989) of 1979–2005 is also shown in Fig. 1, as adopted from Fig. 3.19(b) of WMO (2007). An outstanding puzzle is the apparent disagreement for the SC response profiles from HALOE and models versus that from the ozone time series of the SAGE instruments, at least according to the analyses of its datasets of 1979–2005 (Randel and Wu, 2007; Soukharev and Hood, 2006; WMO, 2007). This finding is of concern because the SAGE measurements are believed to have been stable over time and because they are the benchmark for the determination of long-term trends in ozone (Yang et al., 2006).

The present study is an analysis of the SAGE II ozone data of the middle and upper stratosphere for its response to an 11-yr variation, but using only data from 1991 to 2005 – essentially the same time period as that of the HALOE analyses of Remsberg

(2008). There are several reasons for limiting the SAGE II analysis to this more recent time span. First, there is no need to make an adjustment for the lack of overlap between the SAGE (1979–1981) and the SAGE II (1984–2005) datasets. One can also avoid any biases from volcanic aerosols of El Chichon (1982) that may have affected their adjustment. Further, the effect of the proxy chlorine time series used by Randel and Wu (2007) can be neglected to first order because that term of their regression model was needed mainly to account for the large loss of upper stratospheric ozone through the 1980s and the early 1990s. The effects of the variations in total chlorine from 1991–2005 (shown in Figs. 1–12 of WMO, 2007) were also neglected in the HALOE analyses of Remsberg (2008).

In several respects the SAGE II ozone distributions ought to be of better quality than those of HALOE for analyses of the 11-yr SC response. For example, SAGE II provides a vertical resolution for ozone of order 1 km, obtaining good profiles throughout the stratosphere or at least down to the upper edge of the Pinatubo aerosol layer. SAGE II provided better seasonal sampling for the middle latitudes than HALOE, which was limited by the power restrictions of the UARS spacecraft at the times of its yaw maneuvers. The primary SAGE II profiles are in terms of ozone number density (cm^{-3}) versus altitude. Thus, the periodic terms of its time series should have slightly larger amplitudes than those for the HALOE ozone in Fig. 1, analyzed at pressure levels, because of the associated periodic variations of pressure (and temperature) versus altitude (Rosenfield et al., 2005). There are also small, systematic uncertainties in the temperature versus pressure time series from the NOAA operational satellite instruments that were used for the registration of the HALOE ozone transmission versus pressure profiles in the stratosphere (Shine et al., 2008; Remsberg and Deaver, 2005, their Fig. 4). Such biases can affect both the trends and the decadal-scale responses of the HALOE-retrieved ozone.

Analyses of the 14-yr time series of the SAGE II ozone are presented herein at altitude levels from 27.5 to 55 km at intervals of 2.5 km and for 20-degree wide latitude zones from 55° S to 55° N. Multiple linear regression (MLR) analysis techniques are

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applied to those time series for their seasonal, interannual, and 11-yr periodic terms and their linear trend terms. The amplitudes of the 11-yr terms are reported versus latitude and altitude; those terms will be shown to be closely in-phase with SC uv-flux proxies. Model estimates of the SC forcing agree reasonably with the SAGE II 11-yr response profiles herein for low and middle latitudes, particularly for the Southern Hemisphere. It will also be shown that the models agree better with the SAGE II responses in the subtropics of the Northern Hemisphere after making an allowance for the perturbing effects of the Pinatubo eruption on the ozone of 1991/1992. In Sect. 2 the SAGE II ozone data and the MLR analyses of their time series are described briefly. Examples are provided for several of the SAGE II ozone time series and of the MLR regression model for each of them. Section 3 contains the findings about the 11-yr (or decadal-scale) terms from the MLR model, based on the period September 1991 to August 2005 and then followed by analyses for the period beginning in September 1992. Section 3 also shows the associated distribution of the linear trend terms for the SAGE II ozone, providing an important check on the assumed lack of a net change in upper stratospheric ozone due to reactive chlorine for this time period. Section 4 compares the present 11-yr response profiles from SAGE II with those from HALOE and from published model responses to a solar cycle forcing. Section 5 is a summary of the findings.

2 SAGE II ozone data and analysis approach

The primary ozone product from SAGE II is its number density versus altitude profiles (McCormick et al., 1989; SPARC, 1998). Profiles from the SAGE II version 6.2 algorithms were obtained from (http://www-sage2.larc.nasa.gov/Version6-2Data.html) and used for the analyses herein. Besides the significant interfering effects from the stratospheric aerosols, the only uncertainty for the SAGE II retrieved ozone is from the removal of the Rayleigh extinction component of the measured, ozone channel transmission near 600 nm. However, the Rayleigh extinction becomes comparable to

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the ozone absorption only near 55 km and above. The retrieved ozone profiles were screened for several anomalies, as reported in Hassler et al. (2008). In particular, entire ozone profiles were excluded for the period 23 June 1993 to 11 April 1994, whenever their quoted errors exceeded 10% between 30 km and 55 km. Note that a more conservative, upper altitude limit of 55 km was used rather than the level of 50 km, recommended by Hassler et al. (2008). Another 67 sunrise (SR) and 2 sunset (SS) profiles were removed; in most cases their ozone densities were negative in the lowermost mesosphere. Separate SR and SS bin-averaged profiles were then obtained for each of twelve, 20°-wide latitude bins, centered at 55° S and extending to 55° N in increments of every 10° of latitude and providing an overlap of 10° with its adjacent bins. Such averages were obtained at 11 separate altitudes, beginning at 52.5 km and extending downward to 27.5 km at intervals of 2.5 km. A minimum of 5 scans was required in order to accept them as being representative for a bin-averaged SR or SS crossing of a latitude zone; in most instances many more profiles were included for each bin-averaged point. A screening was not performed to remove the slight biases in high-altitude SR profile segments that occurred when the SAGE measurements were taken for brief times (a few successive days) at a high beta angle (Wang et al., 1996). Instead, separate time series of SR and SS values at each altitude and latitude were combined in the manner of Remsberg (2008) to account for any mean SR/SS bias. Each of the combined time series contains over 200 SR plus SS points; the time spacing between points is variable but averages from 20 to 25 days. Due to the nature of the sampling of occultation measurements from a moderately-inclined satellite orbit, each average SAGE II SR or SS point represents only a few consecutive days at the low latitudes but nearly a week at the middle and high latitudes.

Figure 2 is an example time series for 25° S and at 37.5 km, where the bin-averaged ozone number density values have been multiplied by 10^{-11} for ease of display. The data time series begins in September 1991 and extends through August 2005. Due to a failure of the azimuth gimbal in its pointing system, the SAGE II measurements were taken alternately in a SS and then a SR mode at intervals of about 35 days beginning

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in mid 2000. Even so, that reduced sampling frequency is adequate for resolving the seasonal and longer-term variations in the ozone within a given 20°-wide latitude bin. MLR analyses were applied to each of the separate, 132 time series of this study in the manner of Remsberg (2008). Annual oscillation (AO), semi-annual oscillation (SAO), 853-day or quasi-biennial oscillation (28-mo or QBO), 640-day or sub-biennial (21-mo or IA), and 11-yr (or SC-like) periodic terms, plus constant and linear trend terms were fit to the data; their combined result for the data of Fig. 2 is shown as the oscillatory curve. The nearly horizontal line is the combination of the constant and linear trend terms. The MLR model curve for this latitude and altitude shows that there is an interaction between the AO and SAO terms. There is also an 11-yr term that is in-phase with the solar flux maxima of 1991 and 2002. Again, it is noted that proxy terms were not used in the present MLR regression models for the QBO, subbiennial (IA), and 11-yr (or SC-like) terms. The MLR models also do not account separately for the trends of reactive chlorine (WMO, 2007) or for the effects of the Pinatubo aerosols, except by the conduct of additional analyses beginning with September 1992 instead of September 1991 (see Sect. 3.2).

Figure 3 is the time series plot for 5° N and 35 km, and one can clearly see the dominance of the SAO variations in the data. There are also significant contributions from the two interannual terms and the 11-yr (or SC-like) term. Fourier analysis of the de-seasonalized residuals for this location from a preliminary run also reveals a biennial (or 24-mo) term or a multiple of the AO and SAO terms. More generally, weak-amplitude biennial terms are resolved at 30 to 35 km throughout the subtropics of the Northern Hemisphere, but not of the Southern Hemisphere. Separate biennial terms are not included in the final MLR models, however.

Figure 4 is an example time series for 32.5 km and 15° N. The seasonal and interannual terms of the MLR model for this time series have significant amplitudes, and the variations of the ozone with time are a result of their mutual interaction. There is also a significant 11-yr response at this level that is closely in-phase with the solar flux maxima (1991/1992 and 2002/2003). However, in Sect. 3 it will be postulated that

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part of the response maximum of 1991/1992 may well be due to the radiative and/or chemical effects for the ozone near the upper boundary of the Pinatubo aerosol layer, followed by a slow ascent of that perturbed ozone to this altitude (32.5 km). Decadal-scale responses can also arise at this level and latitude, due to interactions of the annual cycle and the QBO (Lee and Smith, 2003; Smith and Matthes, 2008).

A final example time series is shown in Fig. 5 for 27.5 km and 25° N or just above the top of the Pinatubo aerosol layer of 1991/1992. Generally, the SAGE II ozone time series of this study do not exhibit evidence for the effects of residual aerosol extinction after about December 1991, even in the northern subtropics and at this low altitude of 27.5 km. This finding is a testament to the value of the high vertical resolution of the SAGE II aerosol and ozone measurements. The annual (AO) term of the MLR model underestimates the observed ozone densities of late 1991 and early 1992 in Fig. 5, but not by much and not thereafter.

3 Decadal-scale ozone responses and trends

3.1 September 1991 through August 2005

At the outset it is stressed that the findings presented in this section are viewed as exploratory, as were the ones from the HALOE time series in Remsberg (2008). Instead of regressing against a solar proxy, the approach is to fit an 11-year sinusoidal term to the SAGE II ozone time series. Note that the phase of the 11-yr term is determined simply from its best fit to the data. That term is then checked to see whether its amplitude maximum is essentially in-phase with that of a solar flux proxy. It is recognized that the solar flux variations do not follow an exact, 11-yr sinusoid and that their peak magnitudes vary somewhat from one cycle to the next. A potential complication is that the effects of a direct uv-flux forcing on the ozone can be confounded with any underlying, long-term trends and with decadal-scale, dynamical forcings that impart comparable amplitudes. It is argued that one can make a judgment about that prospect

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by examining the distributions of the phases of the 11-yr terms of the MLR models. With the foregoing caveats in mind, the bin-averaged distribution of the analyzed, 11-yr responses is shown in Fig. 6 for the SAGE II data of 1991 to 2005. Contours are of the max minus min variations (in %), determined as twice the coefficient of the 11-yr term divided by the constant term and multiplied by 100. Note that Fig. 6 is based on separate time series analyses at each of the 132 points of the altitude/latitude grid. A measure of the fidelity of the analyses for this term is their good continuity. At the Equator the greatest response is of order 4 to 5% at about 35 km. Confidence intervals (CI) for the coefficients of the terms exceed 90% for most of the plot domain. The minimum equatorial response is 2% and occurs at 50 km and 27.5 km.

Figure 7 shows the distribution of the phases of the 11-yr terms. Solar cycle 22 had maximum uv-flux values occurring broadly from early 1989 to early 1992. The time of January 1991 (and 2002) is chosen arbitrarily as the estimate(s) for solar max (e.g., see Fig. 2 in Soukharev and Hood, 2006). The phase values in Fig. 7 are given with respect to that time and are shown at contour intervals of 1.0 year. Regions shaded gray are where the phases of the 11-yr terms are within ±1.0 year of those dates and are viewed as essentially in-phase with solar flux maximum. At the higher latitudes the 11-yr terms of the middle stratosphere have their maxima occurring just more than 1 year prior to January 1991/2002, and it may be that there are decadal-scale, dynamical forcings confounding the effects of the SC forcing in those regions during that 14-yr period. Still, the diagnosed, 11-yr terms are clearly in-phase with the SC over most of the latitude/altitude domain. Substitution of a solar uv-flux proxy term for the 11-yr terms in the present MLR models will lead to max minus min ozone responses that are very similar.

Qualitatively, the SAGE II results in Fig. 6 agree with those reported at 30° S by Randel and Wu (2007, their Fig. 12a), Soukharev and Hood (2006, their Fig. 6), and Lee and Smith (2003, their Fig. 2b), but not at tropical latitudes or in the Northern Hemisphere. In particular, there is a clear, SC-like response in Fig. 6 near 35 km at the tropical latitudes, unlike those of the foregoing published analyses. The amplitudes

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of the 11-yr responses in Fig. 6 are also somewhat larger than those reported from HALOE (Remsberg, 2008), possibly a consequence of the use of the operational temperature versus pressure analyses for the registration of the HALOE ozone transmission profiles.

Several aspects of the distribution of the 11-yr responses of Fig. 6 disagree with that expected from a direct, solar uv-forcing. First, there is a maximum response of order 5% in the subtropics of the Northern Hemisphere that is localized between 27.5 and 35 km. No similar feature is present in the Southern Hemisphere. Earlier, it was noted that the MLR model underestimates the observed ozone in 1991/1992 at 25° N and 27.5 km (Fig. 5). As Lee and Smith (2003) pointed out, it is likely that there are confounding effects for an analyzed solar cycle term at this location due to ozone forcings from the Pinatubo aerosol layer that coincided with the time of solar maximum. Further, radiative cooling at the top of the volcanic aerosol layer adds to the slow mean ascent in the tropics. It is very likely that air with lower values of NO_y were transported to higher altitudes as a result, and its associated lower NO_x would have led to slightly enhanced values of ozone at chemical equilibrium. In support of that prospect, Hood and Soukharev (2006) reported finding 10% reductions in HALOE NO_x at 10 hPa (∼ 30 km) and at the low latitudes in early 1992. Whatever were the true mechanism(s), the evidence from Fig. 6 is that those effects were not communicated to the southern subtropics.

Another hemispheric asymmetry in the results of Fig. 6 is an apparent solar cycle response at and above 45 km that is nearly twice as large at northern than southern middle latitudes (or 5% versus 3%). A similar asymmetrical response was found for the HALOE ozone (Remsberg, 2008). It is postulated that this feature is due to hemispheric asymmetries in the dynamical forcings during Northern Hemisphere winter, perhaps related to the Northern Hemisphere annular mode (or NAM) (e.g., Kiesewetter et al., 2010). Typically, there is a significant meridional gradient in the zonal mean ozone distribution at middle latitudes of the upper stratosphere in wintertime. If the polar vortex is stable through the winter, that gradient is maintained. However, the

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occurrence of a midwinter stratospheric warming will cause a net transport of ozone to higher latitudes, where its lifetime against destruction becomes longer. Midwinter warming events occurred in the early 1990s and again in the early years of the 2000 decade, or for those years near solar flux maximum (Manney et al., 2005). Conversely, no midwinter warming events occurred near solar minimum or during the middle part of the 1990s (Pawson and Naujokat, 1999). Thus, these changes for the occurrence of the warming events may have led to an enhancement of the diagnosed solar cycle response at northern middle latitudes. Similar midwinter warming events seldom occur in the Southern Hemisphere and, therefore, are unlikely to have affected its decadal scale ozone responses.

Figure 8 is a contour plot of the linear trend terms (in %/decade) from the MLR analyses of the SAGE II ozone. Those trends are negative nearly everywhere and are somewhat more negative in the upper stratosphere than those from the HALOE analyses at pressure levels of Remsberg (2008). It is noted that there has been a cooling trend in the time series of temperature versus altitude in the middle atmosphere, primarily due to the increasing CO_2 (Steinbrecht et al., 2009; Remsberg, 2009). Thus, ozone trends from SAGE II are more negative than those of HALOE. Where the trends in Fig. 8 are appreciably different than zero, their coefficients also have confidence intervals (CI values) greater than 90%. The pattern of the trends indicates their good continuity. Larger, negative trends at 30 to 35 km in the subtropics of the Northern Hemisphere may be related to the effects from the Pinatubo aerosols of 1991/1992. Trends in the upper stratosphere are slightly less negative (–2 to –4%/decade), and they do not vary much with latitude. Randel and Wu (2007, their Fig. 8a) reported that the effect of a gas phase, chlorine-induced ozone loss ought to yield negative ozone trends that are largest between 35 and 45 km and at the higher latitudes. The distribution of the trends in Fig. 8 does not appear that way. In fact, the lack of any chlorine-like signature in the results of Fig. 8 tends to confirm that it is not necessary to include a proxy term for reactive chlorine in the ozone regression models for 1991–2005. Curiously, the trends in Fig. 8 are increasingly negative with altitude at and above the stratopause

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(∼ 48 km). Remsberg (2009) analyzed temperature versus altitude (or $T(z)$) time series from HALOE and found cooling trends of order −0.5 to −1.0 K/decade in the lower mesosphere and for the lower latitudes. Such small, negative trends in $T(z)$ do not explain the larger, negative changes in ozone at and above the stratopause in Fig. 8 (but see Sect. 4).

3.2 September 1992 through August 2005

It is difficult to provide definitive errors for the coefficients of the 11-yr and the linear trend terms of the foregoing subsection, because these two terms may not be strictly orthogonal for a 14-yr time series. At subtropical latitudes they may also be sensitive to the forcings from the Pinatubo layer in the middle stratosphere and to a lesser extent to the changing effects of the reactive chlorine in the upper stratosphere during late 1991 and early 1992. It is perhaps more instructive to avoid that early period in a repeat of the MLR analyses. Thus, in this subsection the distributions of the amplitudes and phases of the 11-yr terms and of the linear trend terms are analyzed and shown for the period September 1992 through August 2005 – a 13-yr time span.

Figure 9 shows the max minus min responses for the 11-yr terms from that 13-yr time series. Now, the responses are of order 3% at 35 km and are more symmetric with latitude across the two hemispheres than in Fig. 6. Minimum responses of order 1% occur in the tropics at 27.5 km and at about 45 km. On the other hand, the maximum responses of about 5% near 35° N and 50 km are essentially unchanged from those of Fig. 6.

Figure 10 shows the distribution of the phases of the 11-yr terms. It is similar to that of Fig. 7, except for those small regions where the amplitudes of the 11-yr terms in Fig. 9 are also small (<1%) and not very significant. From 35 to 40 km at 5° N the 11-yr maximum occurs about 1.5 years after January 1991 or 2002. This region is where the associated, near-zero linear trend terms (in Fig. 11) may not be an accurate representation of the true trends for the effects of the reactive chlorine. Phase agreement with that of the SC uv-flux is still not observed from about 27.5 km to 35 km and poleward

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of 35° N, presumably due to contributions of similar amplitude from decadal-scale dynamical forcings.

The associated linear trend terms are shown in Fig. 11, and they are less negative than those of Fig. 8 in nearly all instances. The trends in Fig. 11 are zero near 40 km across most latitudes and very similar to those of the HALOE analyses in Remsberg (2008). Again, this finding is noteworthy because that is the altitude where the chemical effects on ozone due to trends in chlorine are predicted to be the largest. Total chlorine was increasing at a rate of about 3%/yr from October 1991 to 1996 (WMO, 2007, Figs. 1–12), so truncating the SAGE II time series by one year ought to have a noticeable effect on both the SC and the linear ozone response terms. Perturbations to the ozone trends are also nearly absent just above the top of the Pinatubo aerosol layer in Fig. 11. In fact, the underestimate of the SAGE II ozone by the MLR model in late 1991 and early 1992 in Fig. 5 is an excellent example of "end point anomaly" effects for time series analyses. Similar improvements were reported by Lee and Smith (2003) after they removed data in 1991–1992 from their SAGE II ozone time series.

4 Comparisons between SAGE, HALOE, and the Brasseur model

The 11-yr ozone response profiles from the analyses of the SAGE II data for 1991–2005 and for 1992–2005 have been averaged across the 20-degree wide, latitude zones of 15° S, 5° S, 5° N, and 15° N or effectively from 25° S to 25° N. Those results are plotted in Fig. 12 along with the published results from HALOE, SAGE, and the Brasseur model shown in Fig. 1. Again, it is noted that both the HALOE and the Brasseur model results are for ozone response profiles in pressure coordinates. The present responses from SAGE II at altitude levels are larger, as expected, because ozone variations are larger at an altitude than at a pressure level for the upper stratosphere (Rosenfield et al., 2005). Even so, the altitude of the peak response is similar for the HALOE and the SAGE II profiles. The altitude of the peak response to a direct, uv-flux forcing from the model also agrees with those from the data. On the other hand, the 11-yr ozone responses from the SAGE II data of 1991–2005 are clearly different from that in WMO (2007).

Figure 13 is a comparison of the SAGE II 11-yr ozone response profiles of the northern and the southern subtropics of 1992 to 2005 with that of the Brasseur model. In this case the SAGE II response profiles are averaged for the southern and then the northern subtropical latitudes of 15° and 25° or effectively from 5° S to 35° S and from 5° N to 35° N. The magnitude of the peak response is decreased in the Northern Hemisphere from that of Fig. 12 by the elimination of that first year of the time series data. Furthermore, the altitude of the peak SAGE II response for the subtropics of the Southern Hemisphere matches that from the model.

There is a secondary response near the stratopause in the subtropics of order 2% in the southern and 4% in the Northern Hemisphere of Fig. 13, part of which may be due to the changes for water vapor (H_2O) at this time. H_2O shows a positive trend during the decade of the 1990s in the middle atmosphere (Remsberg, 2010), and reaction with HO_x represents a significant chemical loss for ozone at the stratopause and in the mesosphere. To first order, that loss of ozone varies by the inverse cube root of H_2O at 50 km and by the inverse square root of H_2O at 70 km (Brasseur and Solomon, 1984). In other words, there is an increasing (inverse) dependence of the ozone on H_2O with altitude. Nedoluha et al. (2009) analyzed the HALOE H_2O time series at constant altitudes. They found that the H_2O values at 50 km increased by nearly 10% from 1991 to 1997 but were nearly constant, thereafter.

Figure 14 shows the results of an MLR model fit to the HALOE H_2O at 15° S and 0.5 hPa (~ 53 km). The MLR model in this instance includes a linear trend term, but no 11-yr term. SC variations of the Lyman-α flux for the dissociation of H_2O are very small near the stratopause. The linear trend at 15° S for H_2O is 2.3%/decade, and at 15° N it is 4.2%/decade (not shown). Therefore, it is unlikely that the SAGE II ozone responses in the southern and northern subtropics are due to a linear increase in H_2O. On the other hand, a nearly linear increase in H_2O from 1991 (near solar max) to 1997 (near solar min) can explain at least part of the SC-like responses in the SAGE II ozone

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of Figs. 12 and 13. The O_3 response profile from the Brasseur model would not have increased in that region, because its H_2O was not varied as observed. Because the 11-yr and trend terms of the MLR models are not easily separated, the analysis herein assigns part of the observed ozone change to the 11-yr term and part to the trend term. It is also emphasized that such lower mesospheric responses ought to be unique to this time period of the SAGE II dataset, if they are due to the changes in H_2O observed by HALOE.

5 Summary

Time series analyses of SAGE II data are undertaken for 1991–2005 to resolve decadal-scale effects in stratospheric ozone that are consistent with those predicted for the 11-yr, solar uv-flux forcing. The analyses are performed between 55° S and 55° N and from 27.5 km to 52.5 km, using an MLR model that includes seasonal, interannual, 11-yr, and linear trend terms. However, none of the terms are based on external, proxy data time series. Still, the simple, 11-yr sinusoid term is found to be essentially in-phase with that of solar proxies and has max minus min variations of about 4%, peaking between 30 and 40 km. The associated, linear trend terms are slightly negative (–2 to –4%/decade) for this 14-yr time span. There is a secondary, decadal-scale response near the stratopause that is also in-phase with the uv-flux forcing. That response is larger at the northern than the southern latitudes, most likely a result of decadal-scale dynamical forcings in Northern Hemisphere winter. If that is the case, the long-term, dynamical forcing is reinforcing the SC-like ozone response. A small part of the SAGE II ozone response near 50 km may also be a result of the H_2O trends of the 1990s.

The results of this study indicate that the SAGE II solar occultation technique can be used to record the response of stratospheric ozone to changes of the uv-flux forcing over the 11-yr solar cycle. For the long-term monitoring of ozone it would be reasonable for such SAGE-type instruments to operate from satellites in moderately inclined orbits,

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and hopefully with some overlap between successive satellites. It should also be clear that one can only resolve the various long-term responses from their data, if all other decadal-scale forcings and trends are either insignificant or accounted for in the regression model for the analysis of the observed ozone time series. For example, recent model studies have shown that at least two to three decades of data may be needed, in order to separate the long-term effects of the solar cycle forcing from those of the dynamical forcings (e.g., Smith and Matthes, 2008; Lu et al., 2009). It is also indicated from the present analyses that it is likely that any decadal-scale, dynamical influences will be more nearly absent in the southern than the Northern Hemisphere ozone.

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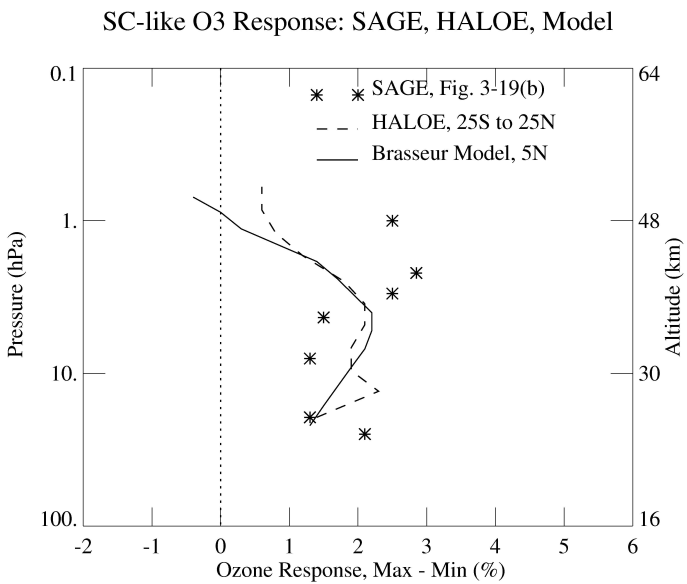

Fig. 1. Solar cycle (or SC-like) ozone response profiles for 25° S to 25° N from HALOE, from the published analyses of 1979–2005 SAGE data (WMO, 2007, their Fig. 3.19(b)), and at 5° N from the model of Brasseur (1993).

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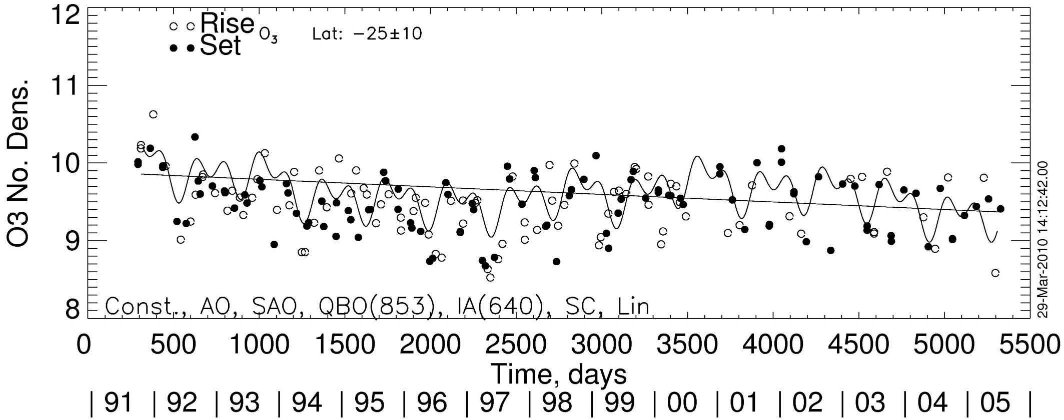

Fig. 2. Time series of bin-averaged, SAGE sunrise and sunset ozone number density measurements (in cm^{-3} multiplied by 10^{-11}) at 25° S and 37.5 km. Terms of the MLR model are indicated at the lower left, where SC refers to an 11-yr sinusoid term. The oscillating solid curve is the model fit to the data, while the straight line curve is the sum of just the constant and linear trend terms.

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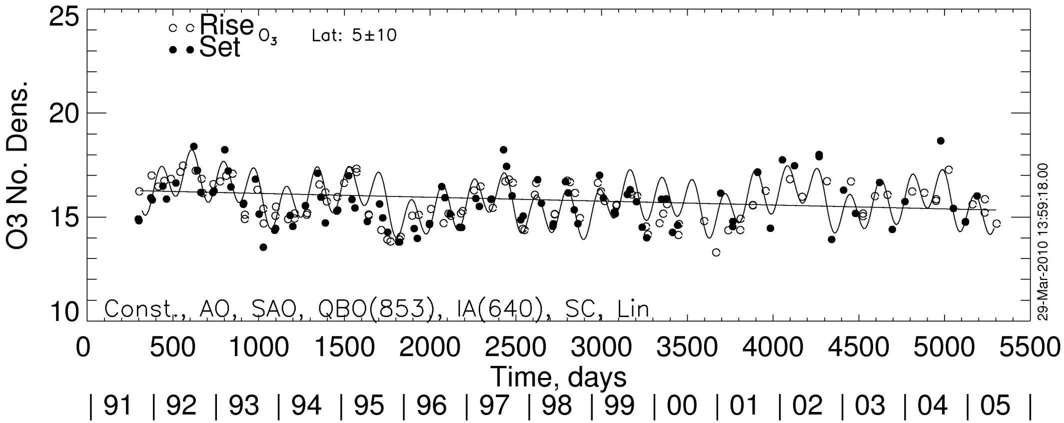

Fig. 3. As in Fig. 2, but for 5° N and 35 km.

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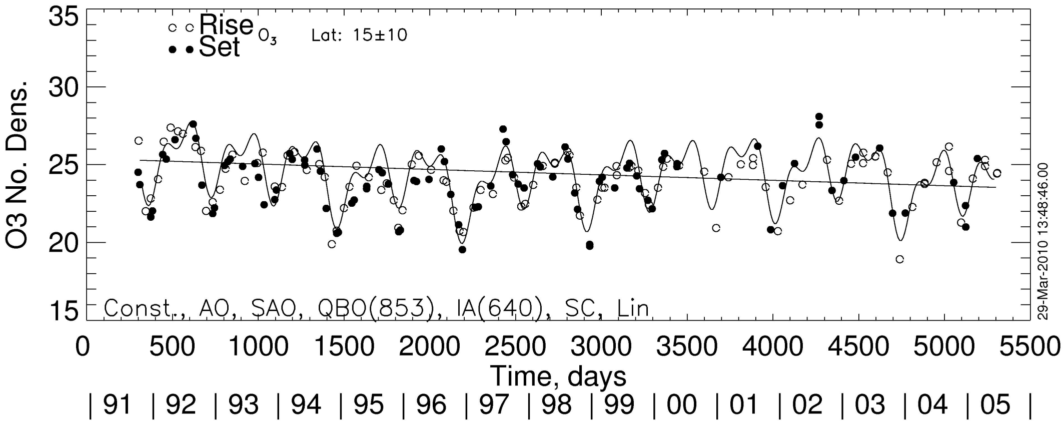

Fig. 4. As in Fig. 2, but for 15° N and 32.5 km.

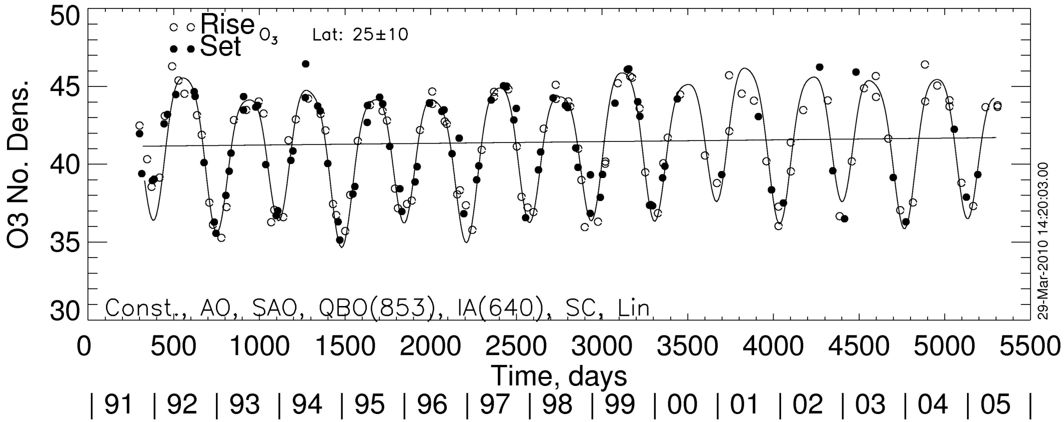

Fig. 5. As in Fig. 2, but for 25° N and 27.5 km.

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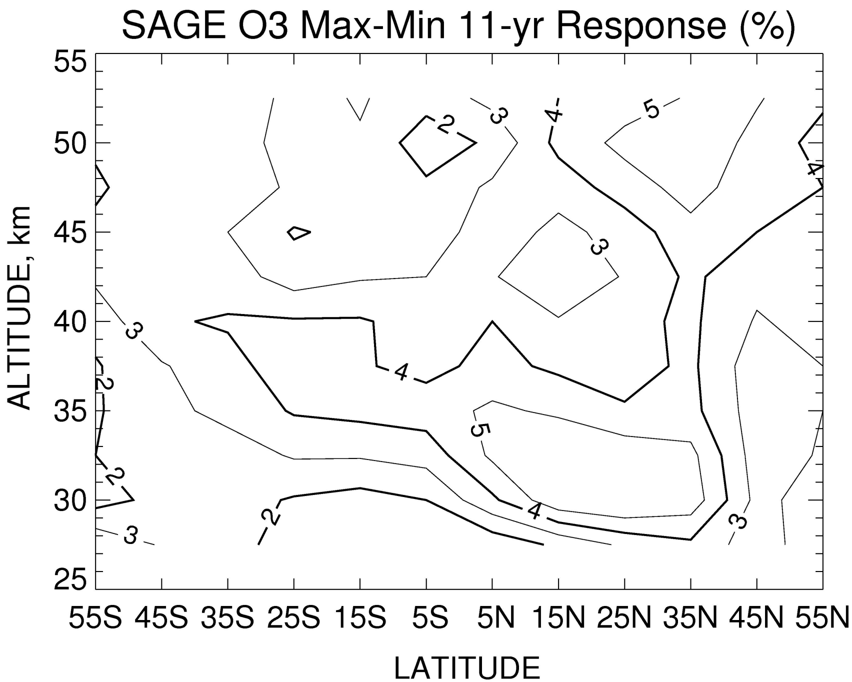

Fig. 6. Contour plot of the maximum minus minimum, 11-yr response (in percent) for the SAGE II ozone data of September 1991 through August 2005. Contour interval is 1.0%.

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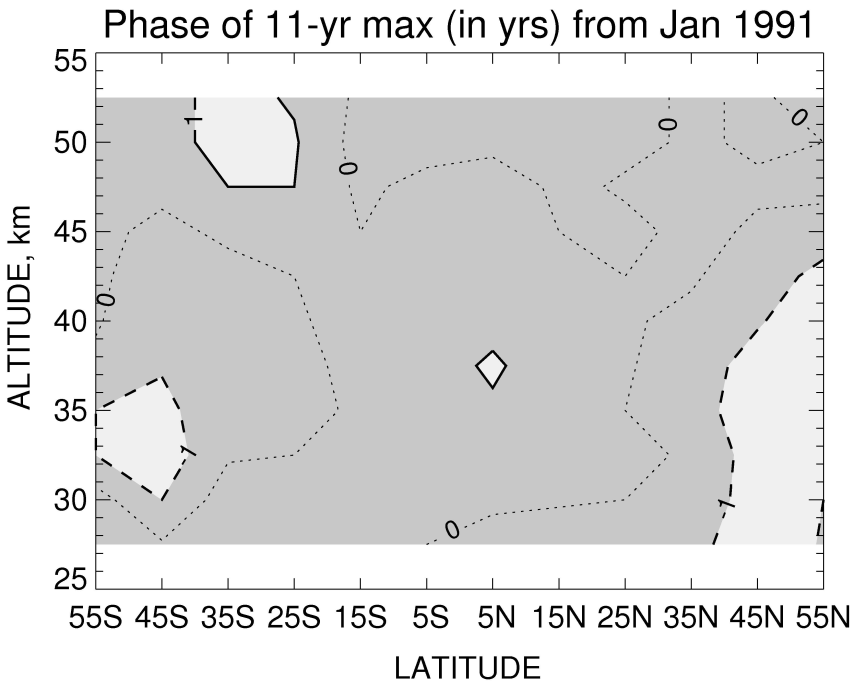

Fig. 7. Contour plot of the phase variations (in years from January 1991 or 2002) of the 11-yr response terms of Fig. 6. Contour interval is 1 year. The phase domain of ±1 year is shaded and is considered as in-phase with the solar uv-flux maximum.

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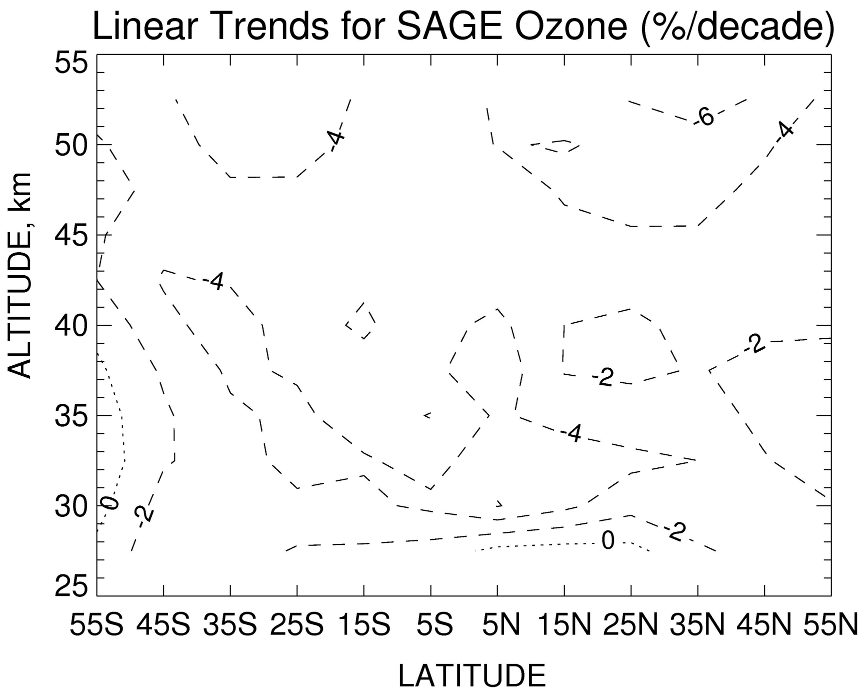

Fig. 8. Contour plot of the linear trend terms (in percent per decade) from the MLR models for the SAGE II ozone data of 1991 to 2005. Contour interval is 2%/decade. Dashed contours denote negative trends, and the dotted contour is where the trends are zero.

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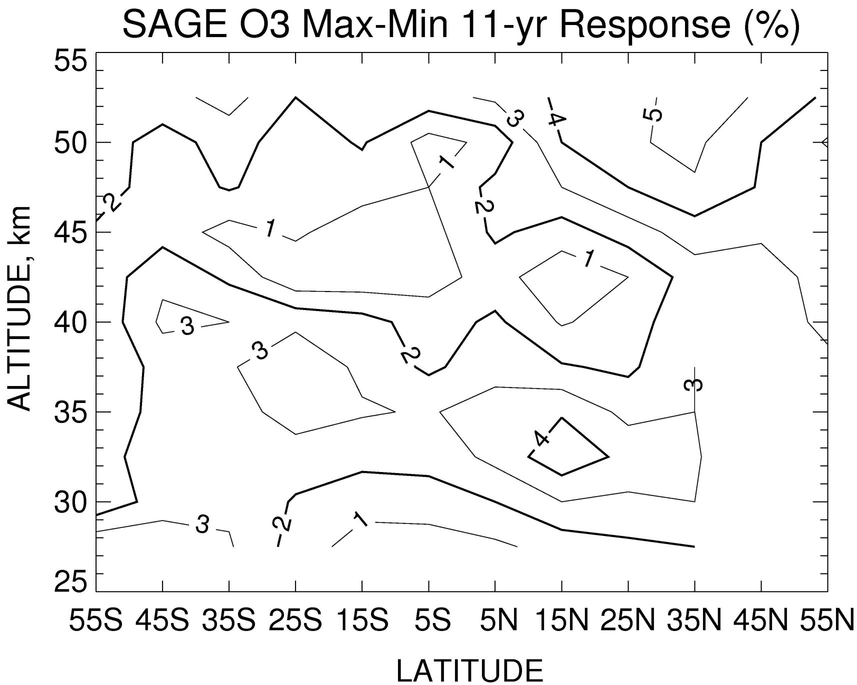

Fig. 9. As in Fig. 6, but the max minus min variations are from the SAGE II data from September 1992 through August 2005.

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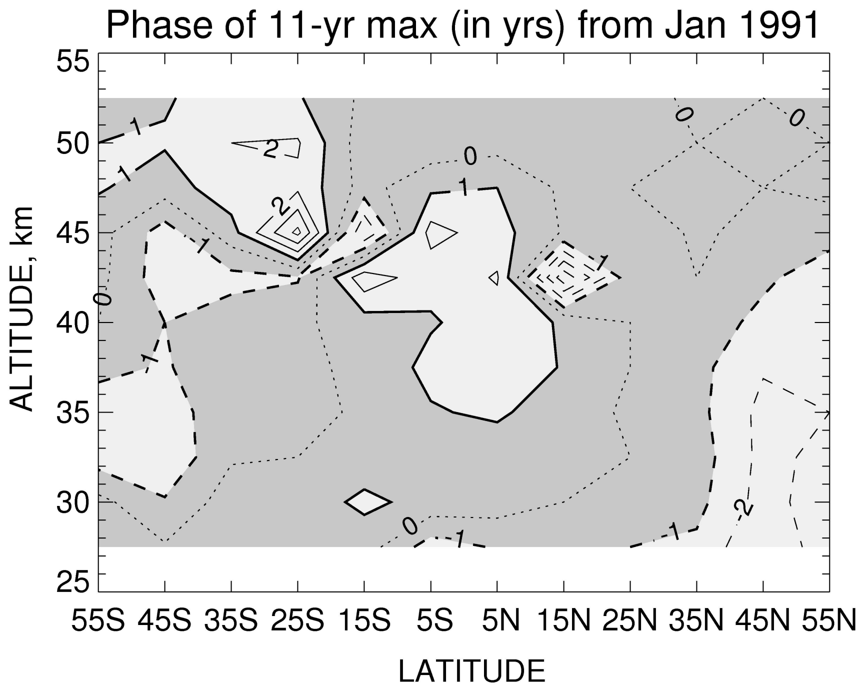

Fig. 10. As in Fig. 7, but the phases are from the SAGE II data from September 1992 through August 2005.

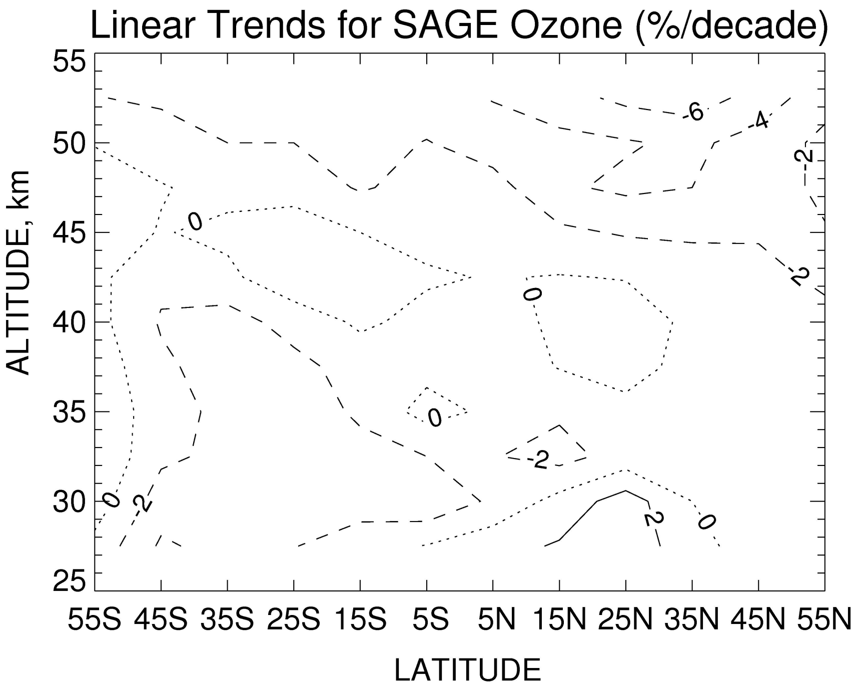

Fig. 11. As in Fig. 8, but the trends are from the SAGE II data from September 1992 through August 2005. The solid contour denotes a positive trend.

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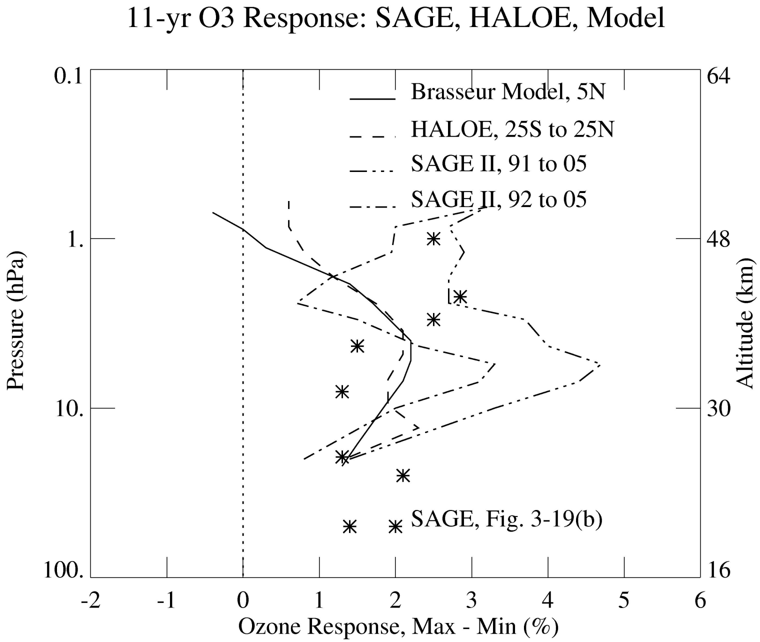

Fig. 12. Profiles of the 11-yr, max minus min responses (in percent) from the HALOE (dashed curve) data, from the 1991 to 2005 SAGE II (the dash-dot-dot-dot curve) data, from the 1992 to 2005 SAGE II (the dash-dot curve) data, and from the 1979 to 2005 SAGE analyses in WMO (2007). Responses from the satellite datasets are effectively for the latitudes of 25° S to 25° N. The solid curve is the ozone response at 5° N to the 11-yr, uv-flux forcing from the model of Brasseur (1993).

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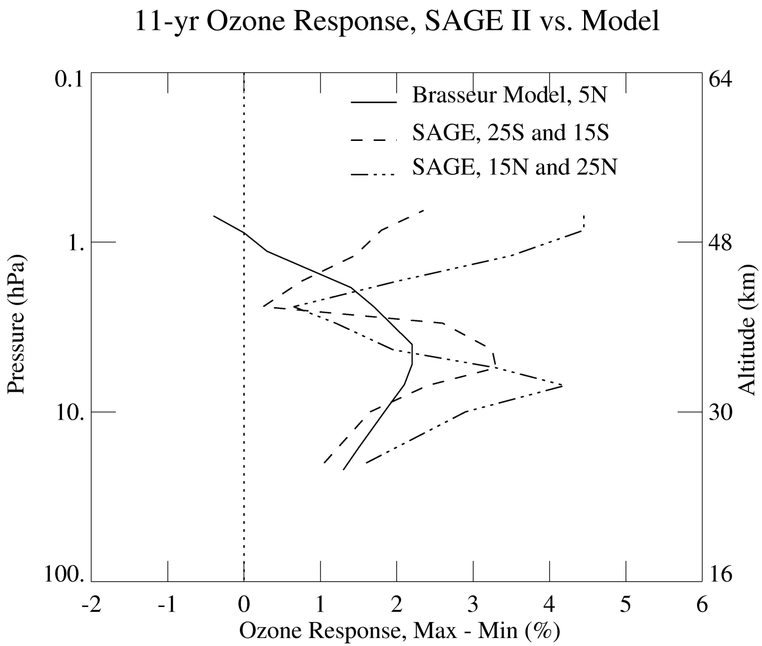

Fig. 13. As in Fig. 12, but for the response profiles from the 1992 to 2005 SAGE II data for the southern (dashed curve) and the northern (dash-dot-dot-dot curve) subtropics.

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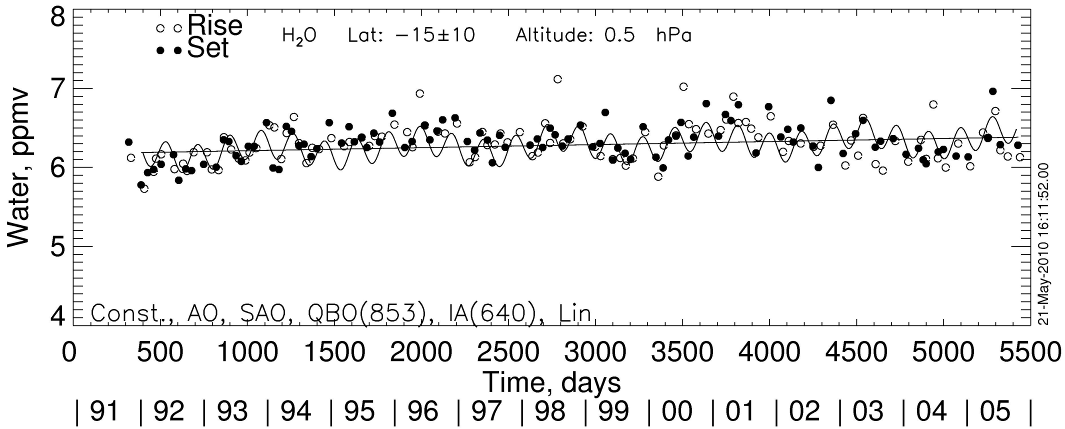

Fig. 14. Time series of bin-averaged, HALOE sunrise and sunset H_2O data (in ppmv) from October 1991 through November 2005 at 15° S and 0.5 hPa. Terms of the MLR model are indicated at the lower left. They consist of seasonal, interannual, and linear trend terms, but no 11-yr sinusoid term. The oscillating solid curve is the model fit to the data, while the straight line curve is the sum of just the constant and linear trend terms.

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