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Decadal-scale responses in middle and upper stratospheric ozone from SAGE II Version 7 data

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Abstract

Stratospheric Aerosol and Gas Experiment (SAGE II) version 7 (v7) ozone profiles are analyzed for their decadal-scale responses and linear trends in the middle and upper stratosphere for the two periods of 1984 to 1998 and 1991 to 2005. Multiple linear regression (MLR) analysis is applied to time series of the v7 ozone number density vs. altitude data for a range of latitudes and altitudes. The MLR models that are fit to the data include a periodic 11 yr term, and it is in-phase with that of the 11-yr, solar uv-flux throughout most of the latitude/altitude domain of the middle and upper stratosphere. Max minus min, solar cycle (SC-like) responses for the SAGE II ozone at those altitudes and for the low to middle latitudes are similar for 1984–1998 and for 1991–2005 and of the order of 5 to 2.5 % from 35 to 50 km. This finding is important because the associated linear trend terms are clearly different from the MLR models of those two time spans. The SAGE II results for the upper stratosphere are also compared with those of the Halogen Occultation Experiment (HALOE) in terms of mixing ratio vs. pressure. The shapes of their respective, SC-like response profiles agree well for a time series from late 1992–2005, or after excluding the first 14 months of data following the Pinatubo eruption. Max minus min, SC-like responses from the SAGE II and HALOE time series vary from 2 to 4 % and from 0 to 2 %, respectively, and their differences in the upper stratosphere can be accounted for using the analyzed, SC-like response of the HALOE temperatures. The linear ozone trends of the upper stratosphere for 1992–2005 vary from about 0 to −4 % decade^{-1} from the Southern to the Northern Hemisphere from SAGE II, while they vary from 0 to −2 % decade^{-1} and are more nearly symmetric about the Equator from HALOE.

1 Introduction

Analysis results have been reported for the 11 yr solar cycle (SC) responses (max minus min from 2 to 4 %) and the trends in upper stratospheric ozone from long-

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term satellite measurements (e.g., Dhomse et al., 2011; McLinden and Fioletov, 2011; Remsberg and Lingenfelser, 2010; Frame and Gray, 2010; Fioletov, 2009; McCormack et al., 2007; Randel and Wu, 2007; Soukharev and Hood, 2006; Lee and Smith, 2003). However, there has been some disagreement between the response profiles from stratospheric models and from the analyzed datasets (WMO, 2007). Fioletov (2009) reported that he had difficulty in obtaining an accurate 11 yr response for observed upper stratosphere ozone from a time series of "merged, partial column ozone data" from the set of successive, satellite Solar Backscatter UltraViolet (SBUV) instruments, even though he was able to resolve the 27 day ozone response. McLinden and Fioletov (2011) went further and calculated from the version 6.2 (v6.2) data of the Stratospheric Aerosol and Gas Experiment (or SAGE II) an ozone partial column vs. pressure response that agreed with that from SBUV, but only after making use of responses and trends in temperature that were smaller than indicated by the operational temperatures archived along with the SAGE II ozone.

Ozone responses to variations of the uv-flux ought to be nearly the same for each solar cycle. However, SC responses diagnosed from the satellite data of the past three decades may also contain biases from concurrent trends in ozone due to changes in the reactive chlorine, due to perturbations from the major volcanic eruptions of 1982 and 1991, or because of uncertainties for the time series of ozone data from the SBUV sensors on successive operational satellites. Randel and Wu (2007), among others, used an equivalent effective stratospheric chlorine (EESC) quantity as a proxy for accounting for the ozone trends of 1979 to 2005, due to the non-linear changes in reactive chlorine. However, McLinden and Fioletev (2011) cautioned that the effects of EESC changes are dependent on the specific units for a given ozone data series, i.e., number density vs. altitude or partial column vs. pressure. Soukharev and Hood (2006) found that simple, linear trend terms were adequate in accounting for the effects of the changing chlorine in shorter ozone time series. To reduce the perturbing effects from volcanic activity, Lee and Smith (2003) also excluded data from their ozone series for many months following major eruptions.

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Remsberg and Lingenfelser (2010) (hereafter denoted RL) diagnosed decadal-scale responses from the SAGE II v6.2 ozone time series of 1991–2005, and they found good consistency with responses from a representative model and from the Halogen Occultation Experiment (or HALOE) ozone. Their SAGE II responses were in terms of number density vs. altitude, while the ones from HALOE were for mixing ratio vs. pressure. On the other hand, their two response profiles diverged sharply above 50 km, possibly due to the associated responses of the separate temperature time series that relate the SAGE II and HALOE ozone quantities (McLinden and Fioletov, 2011).

The current study is an update of the work of RL, using the newly released SAGE II, version 7 (or v7), ozone that is described in Kyrölä et al. (2013) and in Damadeo et al. (2013) (see also https://eosweb.larc.nasa.gov/project/sage2/sage2_release_v7_notes). Time series analyses are conducted for the period 1991–2005, as in RL, and also 1984–1998 to avoid the effect of end-point anomalies in the ozone following the Pinatubo eruption of 1991. In addition, results are shown for 1992–2005, in order to assess the effects of the eruption on the analyzed responses and trends. The use of linear trends for the three time series is similar to the piecewise linear trend approach used by Kyrölä et al. (2013). However, proxy terms for the quasi-biennial oscillation and the solar cycle are not used herein, in order to be consistent with the previous multiple linear regression (MLR) analyses of RL and in order to show results from just updating SAGE II ozone from v6.2 to v7. Section 2 illustrates one aspect of the v7 ozone that has led to the improvements in the current results. It is also shown that throughout the latitude/altitude domain, the 11 yr or decadal-scale responses are almost always in-phase with the solar flux maximum and are thereby essentially equivalent to those obtained from a solar uv-proxy. The 11 yr responses are similar throughout most of the upper stratosphere for 1984–1998 and 1991–2005, even though their associated ozone trends are clearly different. This finding is important because the 11 yr response term can be easily confounded with a linear trend in a regression model fit for a relatively short data series. Section 3 relates the SC-like responses from SAGE II and HALOE to the simulated responses of several representative models. It is also shown

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that their SC-like responses agree even better after excluding the first 14 months of data following the Pinatubo eruption. Section 4 shows the ozone trends in the upper stratosphere for the two time spans and relates them to published model simulations of the effects from changes in reactive chlorine. It also considers the trends from SAGE II (number density vs. altitude) and from HALOE (mixing ratio vs. pressure) in terms of recently reported temperature trends for the upper stratosphere. Section 5 summarizes the findings and concludes that both the SAGE II v7 ozone and the HALOE ozone are of very good quality for generating diagnostics of global-scale climate change for the stratosphere.

2 Analysis and results for the decadal-scale responses and trends in SAGE II ozone

Periodic and linear trend terms are applied in the MLR model fits of the SAGE II ozone time series for each altitude and latitude bin. The analysis follows a two-step approach to account for the effects of serial correlation at lag-1 in the data, following Tiao et al. (1990, Appendix A) and Remsberg (2008, Sect. 2.2). Initially, the MLR model terms are fit to the data time series for a given altitude and latitude bin. Next, the time series of the model/data residual is analyzed for its lag-1 autocorrelation coefficient, φ. Then, the model terms are reformulated to include the effects of φ, and the data time series are refit to get the final regression coefficients for each term. As in RL, proxy terms are not used for the MLR models. Instead, Fourier analyses of the time series of the residuals after removing the seasonal terms almost always indicate that there are two significant, interannual terms having periods of order 28 (QBO-like) and 21 months (sub-biennial term denoted as IA). The IA term is the result of the difference interaction between the QBO and annual cycles (Dunkerton, 2001; Tung and Yang, 1994). Its period varies from 20 to 22 months, most likely because of slight variations in the period of the actual QBO forcing. Remsberg et al. (2001, Fig. 4d) contains an example plot of the diagnostic that was used to check for the presence of periodic structure in the

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residual time series, and Remsberg (2008, Figs. 7 and 8) gives the latitude/pressure distributions of the amplitudes of the QBO and IA terms in the HALOE ozone data. Those two interannual terms are also present in the SAGE II v7 ozone time series, so they are included in the current MLR models along with the annual and semiannual terms. Amplitude of the IA term is often near to that of the QBO in the subtropical middle stratosphere, and its inclusion in the MLR models herein leads to improved fits for the 11 yr and trend terms at those latitudes.

Salby et al. (1997) and Baldwin and Dunkerton (1998) noted that there is a decadal-scale interaction between the QBO and biennial oscillations that can mimic the solar cycle, while Smith and Matthes (2008) modeled the response of ozone to the SC in the presence of the QBO cycle. However, the present analysis simply includes an 11 yr periodic term as part of the MLR fit to the data. Whenever its maximum occurs within one year of the time of the solar uv-flux maximum, the 11 yr term is judged as in-phase with and wholly in response to the solar uv-flux forcing. Regions where it is not in-phase may also be affected by a decadal-scale, dynamical forcing.

Several improvements for the SAGE II v7 data affect the results herein. The sunrise (SR) and sunset (SS) profiles are registered in altitude more accurately than before, as a result of a correction in the use of the associated solar ephemeris data within the SAGE II algorithms (Damadeo et al., 2013, Fig. 2). That update has led to a reduction in the MLR ozone residuals at low to middle latitudes. As a result, the coefficient φ for the transformed terms in the MLR models is now larger than before and affects the coefficients of the analyzed 11 yr and trend terms. The limited duration, solar scan events in the data from mid-1993 through early 1994 are absent from the v7 dataset. Some spuriously low, SR ozone data profiles were screened out for the low latitudes in September and November of 1991 because of excessive extinction effects from the Pinatubo aerosol layer. A very few v7 ozone profiles were also not retained because their associated errors exceed 10 % within the altitude range of 50 to 27.5 km of this study. Finally, continuous temperature time series from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) system (Rienecker et al., 2008) were

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employed for the removal of Rayleigh scattering effects in the v7 algorithm. Those Rayleigh effects are important for the retrieval of mesospheric ozone.

To acquaint the reader with the nature of the SAGE II data, Fig. 1 compares the v7 with the v6.2 ozone time series for 25° S and 37.5 km that was analyzed previously by RL (their Fig. 2). The solid oscillatory curve is the fit to the points based on all the terms of the MLR model, while the straight line is the sum of just the constant and linear trend terms. In addition to the seasonal terms, one can clearly see that there is an 11 yr (or SC-like) term that is closely in-phase with the solar uv-flux maxima that occurred in 1991 and in 2002. At this point it is noted that number density is plotted as increasing on the y-axis in Fig. 1, even though it undergoes a nearly exponential decrease with altitude in the upper atmosphere. Nevertheless, when the uv-flux reaches its maximum in 1991 and 2002, Fig. 1 shows that ozone also attains its maximum (production) value at those times. A primary difference in Fig. 1 between the time series for v7 vs. that for v6.2 is that the data points for v7 define the seasonal cycles more clearly. That outcome is due to the more correct application of the solar ephemeris data for the registration of the SR and SS profiles. As a result, the residuals are smaller from the MLR fit to the v7 data; the coefficient φ is 0.44 for v7, but only 0.05 for the v6.2 time series. It was also discovered that RL inadvertently obtained bin-averaged points for their SAGE II ozone time series of 1991–2005 based on poleward extremes for the latitudinal sweeps of the separate sunrise and sunset tangent track measurements, but using the dates for those extremes from the HALOE experiment rather than basing them on the actual beginning and ending dates for the sweeps of SAGE II. That incorrect grouping for the SAGE II profiles by RL also reduced slightly the accuracy of their fits for the seasonal terms. That error is corrected for the results of Fig. 1 and for the remaining analyses herein, even though the conclusions of RL are unchanged.

Figures 2–4 represent an update of the MLR analysis results shown in RL for v6.2 (their Figs. 6–8), based now on the v7 data. Figure 2 is the distribution of the max minus min responses (in %) for the 11 yr term as a function of altitude and latitude from the v7 ozone of 1991 to 2005. The responses for Fig. 2 were obtained at altitudes from

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27.5 km to 55 km at increments of 2.5 km and at twelve latitude bins spaced by 10° and centered from 55° S to 55° N. A total of 144 ozone time series were analyzed. The latitude increments for each of the bin-averaged, SR and SS points in an individual time series have a width of 10° for the higher latitudes (35, 45, and 55 °), but widen to 20° at the lower (5, 15, and 25 °) latitudes to account for the fewer samples there. Responses in Fig. 2 are of order 3 to 5 % throughout most of the region, but with a minimum near 2 % at the tropical stratopause. The analyzed responses increase to 6 % in the middle stratosphere of the northern subtropics, where Lee and Smith (2003) and RL indicated that there was an anomalous ozone forcing for some months following the Pinatubo event. Significance for the distribution of the amplitudes in Fig. 2 is indicated by the shading, which shows the domain of the probability or the 90 % confidence interval (CI) that the 11 yr term is present in the zonally-binned, ozone time series. Examples of further significance tests are given in Remsberg et al. (2001).

Figure 3 is a plot of the phases of the 11 yr terms as referenced to January 1991, which is the approximate midpoint time of the maximum for the solar uv-flux to the stratosphere. The dark shaded regions in Fig. 3 are where the phases are within ±1 yr of January 1991 and where the 11 yr terms are considered as in-phase with the solar uv-flux. Those 11 yr terms are interpreted as the response to the uv-flux variations and are denoted as SC-like. The 11 yr terms in the middle stratosphere of the northern subtropics are also closely in-phase in Fig. 3, even though they are partially the result of perturbing atmospheric effects following the Pinatubo event. Figure 4 shows the distribution of the coefficients of the associated linear trend terms for the SAGE II v7 ozone in units of % decade^{-1}, along with the shadings for their 90 % and their 70 to 90 % confidence intervals. The trends are or order −4 % decade^{-1} in the upper stratosphere, decreasing to about −2 % decade^{-1} in the middle stratosphere and in the lower mesosphere. The anomalously large negative trends above 50 km that were reported by RL from the v6.2 data are absent from the analysis of the v7 ozone. This improvement is most likely due to the use of the MERRA temperatures for the v7 retrieval algorithm.

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SAGE II v7 results for 1984–1998 are shown next in Figs. 5–7. Figure 5 is the distribution of the responses for the 11 yr terms. The max minus min responses range from 3 to 4 % in the upper stratosphere and decrease to 2–3 % near 30 km, although there is no minimum response at the tropical stratopause like that in Fig. 2 for 1991–2005. There is an anomalous response of near 5 % in a small region between 30 and 35 km at the Equator but no indication of perturbing effects from Pinatubo in the northern subtropics. Figure 6 shows the distribution of the phases of the 11 yr terms. Again, they are in-phase with the solar uv-flux throughout most of the latitude/altitude domain, indicating that there are no significant, out-of-phase dynamical forcings affecting the results in the upper stratosphere. However, at the Equator and between 30 and 35 km the 11 yr term has its diagnosed maximum closer to 1992–1993 than to January 1991. That phase lag of 1 to 2 yr exhibits good continuity across the latitude bins of the tropical middle stratosphere. The 11 yr terms are also not quite in-phase at the highest latitudes of Fig. 6, possibly due to the effects of decadal-scale, dynamical forcings. Figure 7 shows the distribution of the coefficients of the linear trend terms, and it is very similar to the results obtained by Wang et al. (2002) for the period of 1984–1999. The clear variation with latitude at 40–45 km is due to the effects of the reactive chlorine during this period (c.f., Fleming et al., 2011, their Fig. 3). The anomalously large, negative trend of $-8\,\%\,\mathrm{decade}^{-1}$ and centered at 32.5 km and 5° N in Fig. 7 is nearly offset in this 14 yr time span by the large positive, max minus min, response of 5 % (Fig. 5) that is not in-phase with the solar cycle (Fig. 6). Elsewhere, the successive trends from Figs. 7 and 4 reinforce the finding that the large declines in ozone of the 1980s were leveling out during 1991–2005 and beyond (WMO, 2007; WMO, 2011; Kyrölä, et al., 2013).

It is emphasized that the region of rather large, 11 yr responses at low latitudes of the middle stratosphere are much smaller in Fig. 5 than in Fig. 2, despite the fact that the data of late 1991 and in 1992 contribute to both time series distributions. Figure 8 depicts the ozone time series from 1984–1998 for 5° N, 30 km. The MLR model terms fit the data well, especially for the period of 1991–1992 following the Pinatubo event.

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However, when that perturbation acted at the beginning of the time series of 1991–2005, it became a so-called "end point anomaly" for the determination of the linear trend and confounded the coefficient of the 11 yr term. When that perturbation occurs midway of the time series, the diagnosed trend term is affected much less.

The responses for 1984–1998 have a 1–2 yr phase lag in the tropical middle stratosphere, according to Fig. 6. It is inferred that some feature of the time series prior to 1991 is not being fit very well. An important consideration for the acceptance of the terms of an MLR model is an examination of the time series of its residual to be sure that it contains no remaining periodic structure (Remsberg et al., 2001). The MLR fit to the ozone in Fig. 8 is systematically high in 1989–1990, followed by a low bias in 1991–1992. These results suggest that the true amplitude of the QBO was larger than average for those years and that this term of the MLR model did not account for that variation very well. As a result, the analyzed 11 yr term is influenced by the minimum in the observed ozone during 1989–1990; thus, the maximum for that diagnosed term occurs in 1992, rather than at the beginning of 1991.

Hood et al. (2010) and Dhomse et al. (2011) tested for the possibility of an additional perturbation from the El Nino-Southern Oscillation (ENSO) of 1988–1989 and its subsequent reinforcement of the amplitude of the QBO. Typically, ENSO anomalies at 16 km ascend to 30 km about 18 months later, or in this case, near to the time of the Pinatubo eruption in June 1991 (Garcia et al., 2007). Thus, Hood et al. (2010) and Dhomse et al. (2011) added a term to their regression models related to a lagging ENSO index, but they found that it had very little effect at 30 km and above. Further, Chipperfield et al. (1994) and Hood et al. (2010) reported on a negative correlation between tropical ozone and NO_2 at 30–32 km from the effects of vertical advection of NO_y associated with the QBO forcing. Since Fig. 6 shows good coherence for the 1 to 2 yr phase lag of the maxima of the 11 yr terms across tropical latitudes and from 30 to 35 km, it is presumed that those 11 yr terms are confounded with the ENSO or QBO forcing and with the associated chemical/transport effects at that time.

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3 Comparisons of the SC-like responses in SAGE II and HALOE ozone

The 11 yr responses from SAGE II for the two 14 yr time spans are similar and essentially in-phase with the solar uv-flux, at least in the upper stratosphere. Figure 9 displays the distribution of the SC-like response amplitudes for 1984–1998, according to the values that the 11 yr terms would have on January 1991. In other words, the 11 yr amplitudes of Fig. 5 were adjusted for the fact that the phases of Fig. 6 were slightly lagging or leading the assigned time for the solar uv-flux maximum. Since the 11 yr response maximum is lagging January 1991 by a year or more in the tropical middle stratosphere, its presumed SC-like response is reduced to less than 2 %. Maximum responses of 3 to 4 % in Fig. 9 are very similar to those from the effects from uv-flux variations in the early model results of Garcia et al. (1984). Analyzed responses of less than 2 % occur at higher latitudes, where the chemical loss of ozone due to wintertime descent and mixing of NO_x to lower latitudes is enhanced at solar maximum (Garcia et al., 1984).

Figure 10 is the analogous SC-like response distribution for 1991–2005, based on the results in Figs. 2 and 3. Maximum responses of order 2.5 to 4.5 % are also present in the upper stratosphere at low to middle latitudes, decreasing to about 2 % at the higher latitudes. Although the SC-like responses are less than 2 % in the middle stratosphere of the southern tropics, the phase-adjusted, SC-like responses of the northern subtropics are still anomalously large for this period because of the end-point anomalies for the trend term of the MLR model fit.

The major difference between Figs. 9 and 10 occurs near the tropical stratopause, where the analyzed SC-like responses are larger for 1984–1998 by nearly a factor of two. Solar flux values are larger for the solar maximum centered in 1990–1991 as compared with the maximum of 2002 (Smith and Matthes, 2008), but they explain only a small part of the difference for the analyzed SC-like responses. Figure 11 shows time series of the SAGE II ozone at 5° S and 47.5 km for the two periods, 1984–1998 and 1991–2005. The data indicate a pronounced amplitude minimum every year in

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January/February for the 1980s, but not for 1993 through 1998. Pronounced minima occur once again in 1999, 2001, 2003, and 2004, and they are a regular feature of the data of the 1980s but not afterward. Occurrences of the ozone minima near the tropical stratopause appear episodic and short-lived, and they must be due to a downward advection of air with lower ozone values. The first semi-annual term in the MLR model provides a better fit to the time series for 1984–1998 than for 1991–2005. However, the analyzed amplitudes of the semi-annual terms from the two time series show little to no change, while the amplitudes of the annual terms are larger for 1984–1998 (4.3 %) than for 1991–2005 (3.4 %). As a result, the MLR model residuals are larger for the 1991–2005 series, and its associated SC-like term is not resolved as well. It is hypothesized that the episodic ozone minima are the result of secondary, net circulations in response to extratropical gravity wave forcings (Shu et al., 2013) at times of polar winter warming activity (Hitchman and Leovy, 1986; Solomon et al., 1986). In particular, Pawson and Naujokat (1999) reported that the Northern Hemisphere, winter polar vortex was unusually stable during successive years through the middle 1990s, which would account for the smaller annual ozone amplitudes during that time span. Charlton and Polvani (2007) and Manney et al. (2005) also report that there was more frequent, sudden stratospheric warming activity in the 1980s and early in the 2000 decade, respectively.

RL obtained SC-like responses from the HALOE ozone mixing ratio vs. pressure profiles that ranged from 0.5 to 2.5 % for the period 1991–2005. Figure 12 compares the SC-like ozone response results from SAGE II and HALOE for just the low latitudes. Specifically, the separate response profiles are averaged for each dataset across the latitudes of 15° S, 5° S, 5° N, and 15° N. Because of the 20° width of each latitude bin, the average response profiles are characteristic of the latitude range of 25° S to 25° N. Figure 12 also shows the low latitude response profile from the interactive, chemical-dynamical-radiative model of Brasseur (1993). One can see that there is good agreement between the response profiles from HALOE and the model, both of which are given in terms of mixing ratio vs. pressure-altitude. They differ only in the lower meso-

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sphere, where it is noted that the SAGE II and HALOE results are for sunrise and sunset or when ozone is not strictly in chemical equilibrium. The SC-like response profiles from SAGE II are shown for both 1984–1998 and 1991–2005 in Fig. 12, and they vary between about 5 to 2.5 % from 35 to 50 km.

The SAGE II SC-like response profiles in Fig. 12 disagree below 35 km for the two time spans, and there is also an anomaly in the HALOE response near 13 hPa. It is likely that atmospheric forcings persisted for some months after the eruption of Pinatubo and that they represented end-point anomalies for the MLR analyses of time series beginning in late 1991 (e.g., Lee and Smith, 2003). Therefore, analyzed, SC-like responses are shown in Fig. 13 for the SAGE II and HALOE time series of late 1992–2005, or excluding the first 14 months of data following the Pinatubo event. The SC-like response of 0 to 2 % from the HALOE ozone in Fig. 13 is similar to that from the model, and the perturbed response near 13 hPa is reduced. The response profile from the SAGE II ozone has values of 3 to 4 % between about 35 to 40 km, decreasing to less than 2 % at 30 km and 50 km. The shape of the SAGE II response profile for 1992–2005 is now very similar to that from HALOE and from the model. Still, the SAGE II response is smaller in the upper stratosphere for 1992–2005 than for that of 1984–1998 (Fig. 12), perhaps related to decadal-scale differences for the net circulations mentioned earlier. It is also noted that the HALOE and SAGE II responses in Fig. 13 diverge in the mesosphere, even though the coefficients of their 11 yr terms are significant and in-phase with the solar uv-flux forcing.

The SAGE II response is about twice that from HALOE in the upper stratosphere in Fig. 13, but that difference could be explained by the SC-like temperature responses that relate the respective profile quantities. Remsberg (2009) obtained an SC-like response for $T(z)$ of 1 K for the uppermost stratosphere from time series of HALOE temperatures at low latitudes, and responses from the Brasseur model vary from 0.8 K at 40 km to nearly 1.5 K at 50 km. The observed responses from two widely-used, temperature reanalysis products vary from 1 to 2 K from 40 to 50 km, according to Dhomse et al. (2011). Yet, they were best able to simulate the responses in the SAGE II v6.2

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ozone by prescribing temperature responses that were closer to 1 K than 2 K. Their inferred temperature response of 1 K also explains the differing ozone responses for the SAGE II v7 ozone number density vs. HALOE mixing ratio of Fig. 13.

4 Comparisons of the linear ozone trends from SAGE II and HALOE

Ozone number density at an altitude is affected by changes in the reactive chlorine in the upper stratosphere. Figure 14 shows the linear trends at 45 km from the analyses of the SAGE II ozone for the two separate periods of 1984–1998 and 1992–2005. Ozone trends at middle latitudes of the Northern Hemisphere for the earlier period agree closely with the ozone decreases of −6 to −9 % decade^{-1} reported by Steinbrecht et al. (2009) from ground-based lidar measurements at 40 km from 1979 to the late 1990s. By 1992–2005 the ozone trends at northern middle latitudes are −3 to −5 % decade^{-1} from SAGE II. Fleming et al. (2011) calculated ozone trends of −3 to −4 % decade^{-1} and related them to the changing chlorine at the Equator; the trends from SAGE II v7 support their model result. It is noted that the tropical ozone trends are less negative for 1992–2005 but only by 1 to 2 % decade^{-1}; their 2σ uncertainties are of order 0.8 % decade^{-1}. All other things being equal, this finding implies that reactive chlorine did not change by much across the two periods. Average estimates of total chlorine in the form of HCl are 2.8 ppbv for 1984–1998 and 3.1 ppbv for 1992–2005, a difference of only 10 % (WMO, 2003).

SAGE II ozone will also show a decrease with time due to a cooling trend or a contraction of its density at an altitude. Radiative temperature changes due to ozone and CO_2 are largest at low latitudes of the upper stratosphere (Fleming et al., 2011). It is presumed that the rate of cooling in the upper stratosphere was greater in the 1980s when ozone was being depleted significantly, and the SAGE II results in Fig. 14 for the tropics show a negative trend that is slightly larger in 1984–1998 than in 1992–2005. How have the observed temperatures been changing for the stratosphere? Randel et al. (2009) report significant uncertainties for time series of the operational satellite

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temperatures of the middle and upper stratosphere. Therefore, since the MERRA temperatures that are part of the SAGE II dataset are based on those operational data, they may not be appropriate for diagnosing the corresponding changes in the ozone of the upper stratosphere. But, independent temperature time series data have also been reported for several ground-based lidar stations, and they indicate that the cooling trends of the upper stratosphere were larger for the period 1984–1998 than for 1992–2005 (Keckhut et al., 2011). Wang et al. (2012) and Thompson et al. (2012) have also reported recently that the global-mean, upper stratospheric temperature anomalies were of order $-2\,\mathrm{K\,decade^{-1}}$ from 1984 to 1995, but nearly constant thereafter. The HALOE experiment provides the only other near-global satellite temperature dataset that extends for more than one solar cycle for the 14 yr period of 1991–2005. Remsberg (2009) obtained a cooling trend in HALOE $T(z)$ that was only of the order of $-0.5\,\mathrm{K\,decade^{-1}}$ in the uppermost stratosphere during that later period; that result is similar to what has been reported from the other independent datasets.

To separate out diabatic effects due to changes in the greenhouse gases (GHG), it is helpful to look at the changes in ozone from HALOE (at a pressure level) vs. those from SAGE II (at an altitude). Previously, RL reported ozone trends in the upper stratosphere from HALOE that vary from $0\,\%\,\mathrm{decade^{-1}}$ at low latitudes to $-4\,\%\,\mathrm{decade^{-1}}$ at middle latitudes. Figure 14 also includes the ozone trends from HALOE near 1.7 hPa along with those from SAGE II at 45 km for the same period, 1992–2005. The two ozone trend curves agree in the Southern Hemisphere, but they differ by $3\,\%\,\mathrm{decade^{-1}}$ at the northern subtropical and middle latitudes. McLinden and Fioletov (2011, their Fig. 3) show that one can explain part of that ozone difference (or $2\,\%\,\mathrm{decade^{-1}}$) by considering a trend in $T(z)$ of $-1\,\mathrm{K\,decade^{-1}}$ for the conversion of mixing ratio vs. pressure to number density vs. altitude. Yet, the $T(z)$ trend from the HALOE analyses is no greater than $-0.5\,\mathrm{K\,decade^{-1}}$ (Remsberg, 2009). Thus, the larger HALOE minus SAGE II ozone trends of the northern latitudes suggest that another mechanism must be considered.

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To assist with the evaluation of the differences in the upper stratosphere in Fig. 14 for 1992–2005, similar results are shown in Fig. 15 for 1991–2005 that includes the 14 months of data following Pinatubo. One can see that the trend differences between the HALOE and SAGE II ozone are greater (of order 4 % decade^{-1}) and more uniform in Fig. 15 than in Fig. 14, and that they extend across the tropics and subtropics of both hemispheres. Such large, apparent differences in the ozone trends imply that the associated temperature changes are of order -2 K decade^{-1}, rather than the observed temperature trends that are less than half that value. Yet, it is cautioned that the time series results in Fig. 15 may be affected by slight, end-point anomalies in 1991–1992 or following the Pinatubo eruption. Alternatively, it may be that the net diabatic circulation was enhanced in response to wintertime, wave forcing effects in 1991–1992 (e.g., Shu et al., 2013; Gerber, 2012; Solomon et al., 1986) and that those effects are confounded between the analyzed SC-like and trend terms in Figs. 12 and 15. Because a further assessment of those issues is beyond the scope of this report it is judged that the SAGE II/HALOE trend differences of 1992–2005 (Fig. 14) are more trustworthy than those of 1991–2005 (Fig. 15).

5 Conclusions

This study is an extension of the analyses and findings in RL, but it is based now on the newly processed SAGE II v7 ozone. MLR analyses for the period 1991–2005 were conducted, as before, and then additional analyses were made for the SAGE II ozone time series of 1984–1998 and 1992–2005. The seasonal cycles are fitting the ozone time series of v7 much better than was the case for the previous v6.2, and the MLR residuals for v7 are smaller throughout much of the stratosphere. As a result, the interannual and trend terms are also resolved better and have greater significance than before. It is judged that the SAGE II v7 ozone is of very good quality.

The max minus min, 11 yr ozone responses from SAGE II for the period of 1984–1998 differ somewhat from those from 1991–2005 in the middle and upper strato-

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sphere, but they are in-phase with the solar cycle uv-flux at most altitudes and latitudes. Better agreement was found after excluding the first 14 months of data following the Pinatubo event from the beginning of the 1991–2005 time series. For most altitude/latitude regions the SC-like ozone responses are in good agreement for the two time spans of 1984–1998 and 1992–2005, despite the fact that the associated, analyzed linear trend terms are clearly different. The SC-like response profiles from the SAGE II and the HALOE ozone of the low latitudes also agree well with representative model profiles, after taking into account the geophysical units used in the simulation studies. At tropical latitudes and between 30 and 35 km the 11 yr responses from SAGE II for 1984–1998 were lagging the uv-flux maximum by 1 to 2 yr because of a separate perturbation that affected the ozone time series during 1989–1990.

Ozone trends in the upper stratosphere from SAGE II vary from about 0 to $-4\,\%\,\text{decade}^{-1}$ from the Southern to the Northern Hemisphere for 1992–2005; at the middle latitudes the trends for 1984–1998 extend to $-8\,\%\,\text{decade}^{-1}$. Differences in the ozone trends from SAGE II at 45 km and from HALOE at 1.7 hPa vary from near $0\,\%\,\text{decade}^{-1}$ in the southern subtropics to about $3\,\%\,\text{decade}^{-1}$ at northern middle latitudes. Based on published diagnostic studies of others, it is inferred that the effects of wintertime wave forcings and their associated, induced net circulations are contributing to the differences in their respective ozone trends for the two hemispheres.

Acknowledgements. E. E. Remsberg appreciates discussions with R. Damadeo, L. Thomason, and J. Zawodny of NASA Langley regarding the quality of the SAGE II v7 ozone. EER carried out this work while serving as a Distinguished Research Associate under the sponsorship of Malcolm Ko.

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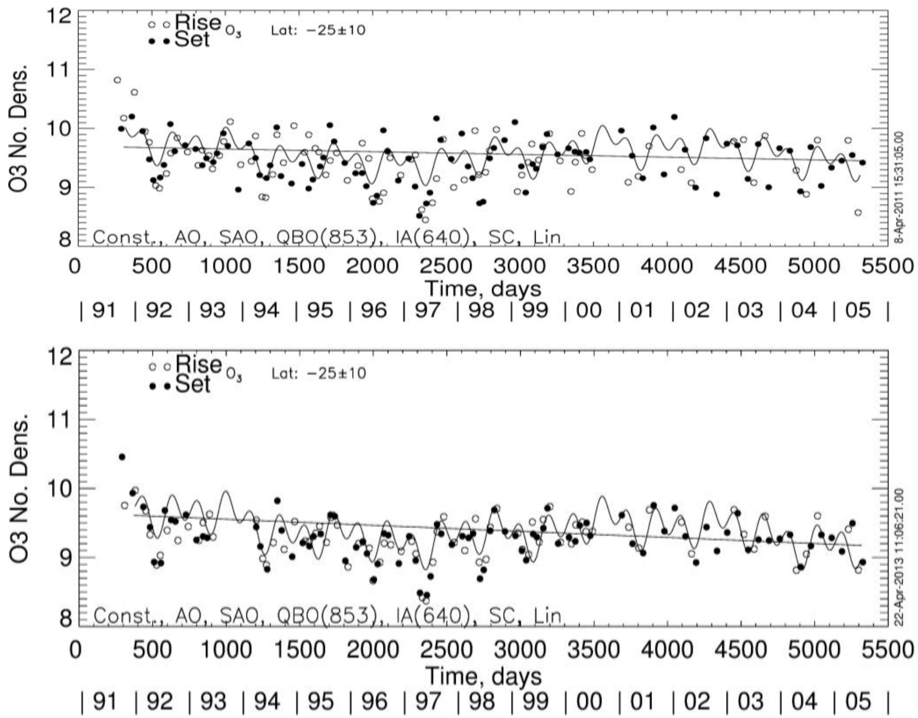

Fig. 1. Time series of bin-averaged, SAGE II SR and SS ozone number density measurements (in cm^{-3} multiplied by 10^{-11}) at 25° S and 37.5 km – (top) v6.2, (bottom) v7. Terms of the MLR model are indicated at the lower left, where SC refers to an 11 yr sinusoid term. The oscillating solid curve is the model fit to the data, while the straight line curve is the sum of just the constant and linear trend terms.

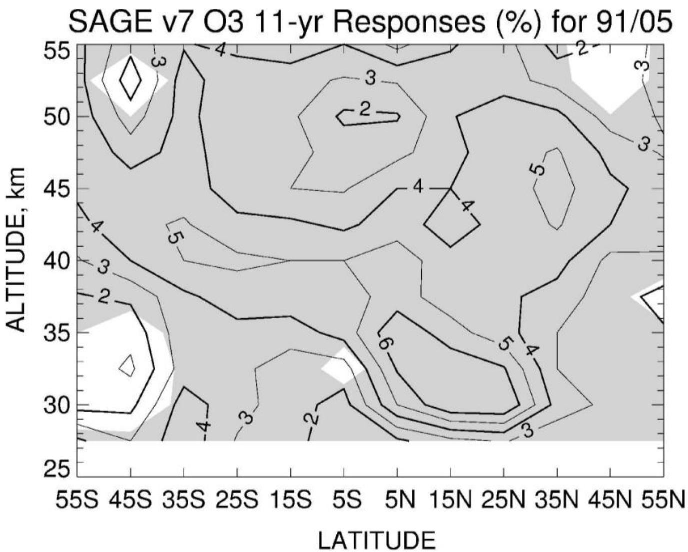

Fig. 2. Contour plot of the maximum minus minimum, 11 yr response (in percent) for the SAGE II v7 ozone of September 1991 through August 2005. Contour interval is 1.0 %. Shading denotes confidence intervals (CI) > 90 % for the responses.

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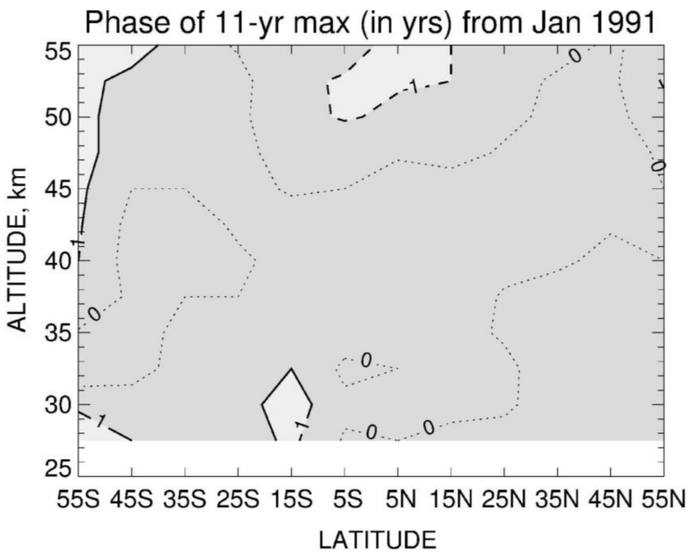

Fig. 3. Contour plot of the phase variations (in years from January 1991 or 2002) of the 11 yr response terms of Fig. 2. Contour interval is 1 yr. The phase domain of ±1 yr is shaded and is considered as in-phase with the solar uv-flux maximum.

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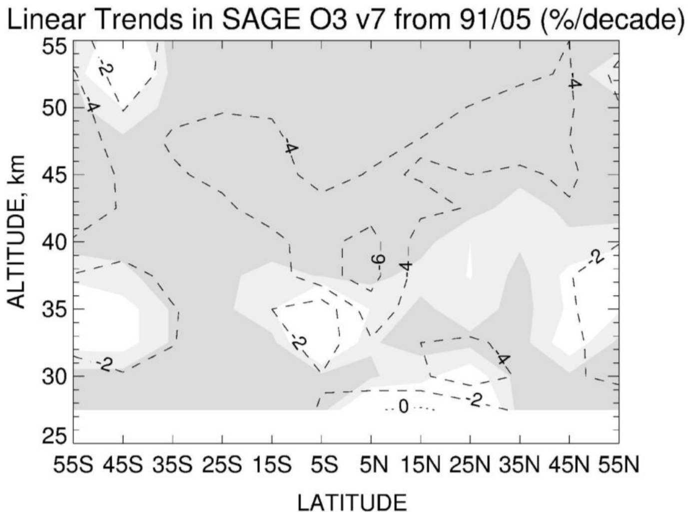

Fig. 4. Contour plot of the linear trend terms (in % decade^{-1}) from the MLR models for the SAGE II ozone data of 1991 to 2005. Contour interval is 2 % decade^{-1}. Dashed contours denote negative trends, and the dotted contour is where the trend is zero. Darker shading denotes where CI > 90 % for the trends; lighter shading has 70 % < CI < 90 %.

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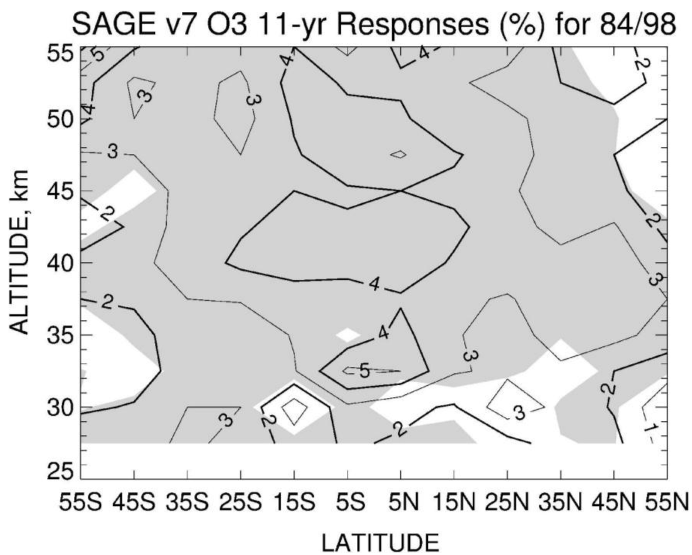

Fig. 5. As in Fig. 2, but the max minus min variations are from the SAGE II data from November 1984 through October 1998.

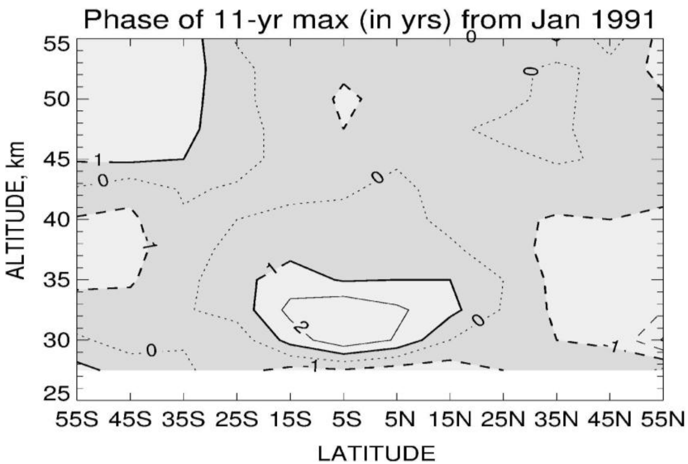

Fig. 6. As in Fig. 3, but the phases of the 11 yr terms are from the SAGE II data from November 1984 through October 1998.

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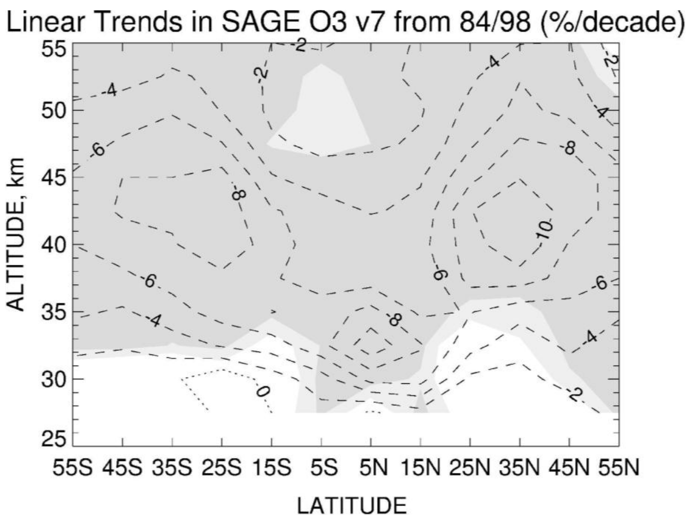

Fig. 7. As in Fig. 4, but the trends are from the SAGE II data from November 1984 through October 1998.

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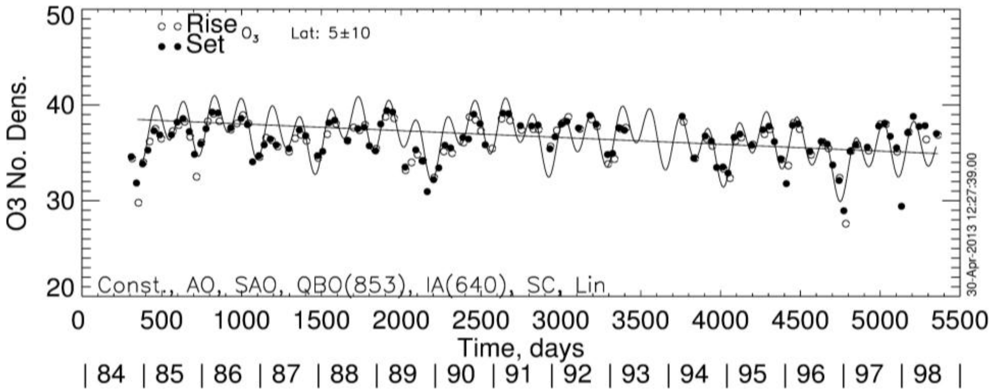

Fig. 8. As in Fig. 1, but for the v7 ozone at 5° N and 30 km for 1984–1998.

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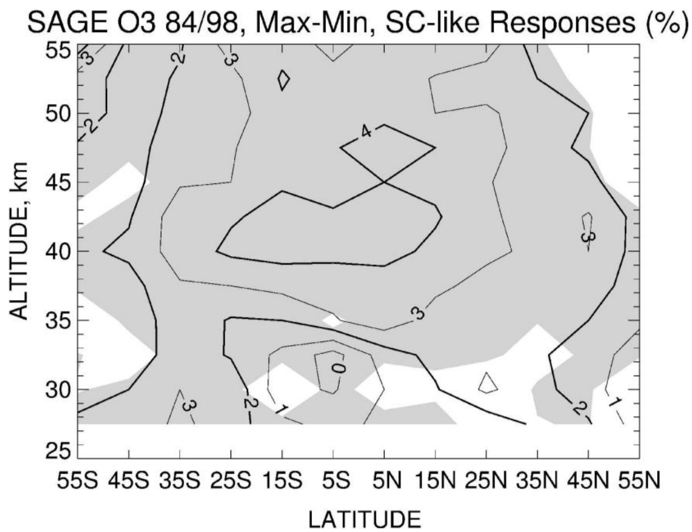

Fig. 9. As in Fig. 5, but the SAGE II max minus min, 11 yr responses have been adjusted to be in-phase for that of a solar uv-flux maximum in January 1991 – their SC-like responses for 1984–1998. Shading denotes where CI > 90 %.

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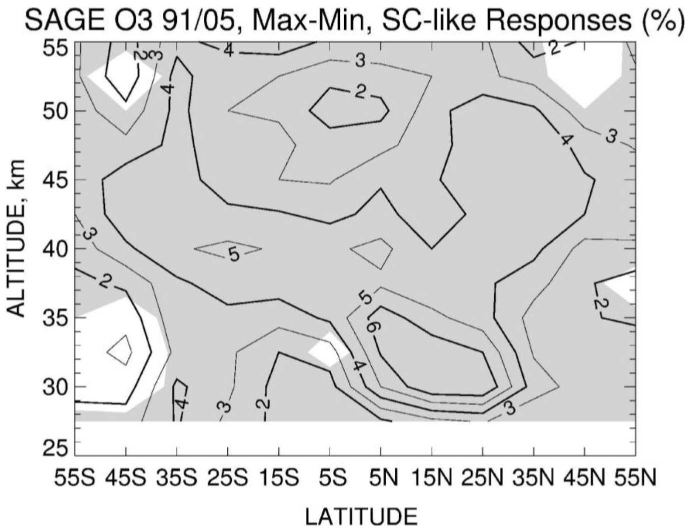

Fig. 10. As in Fig. 9, but the SC-like responses are based on adjustments to Fig. 2 for 1991–2005.

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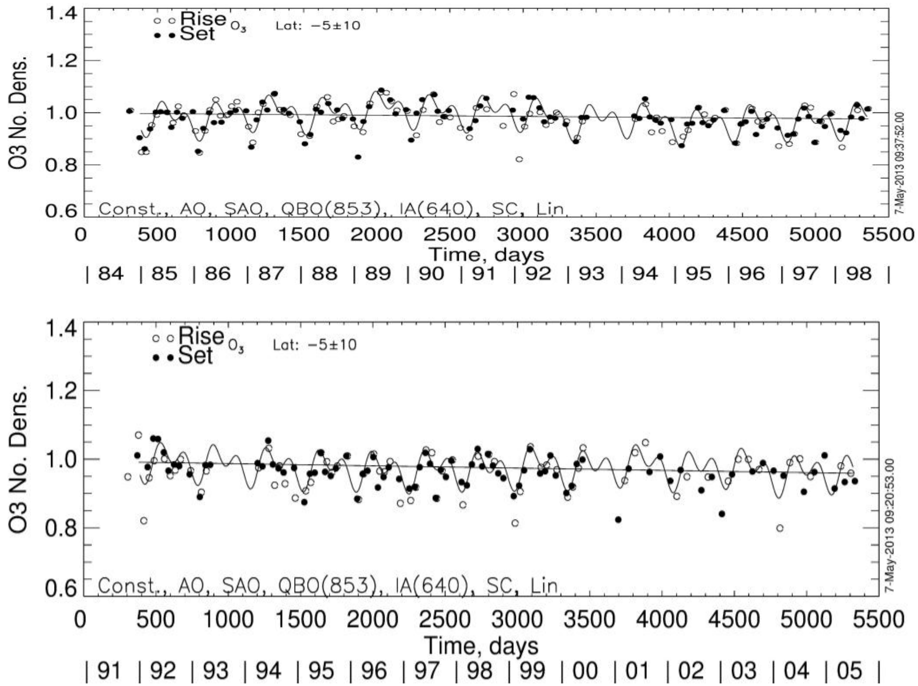

Fig. 11. Time series of SAGE II v7 ozone at 5° S and 47.5 km (at top) for 1984–1998 and (bottom) for 1991–2005.

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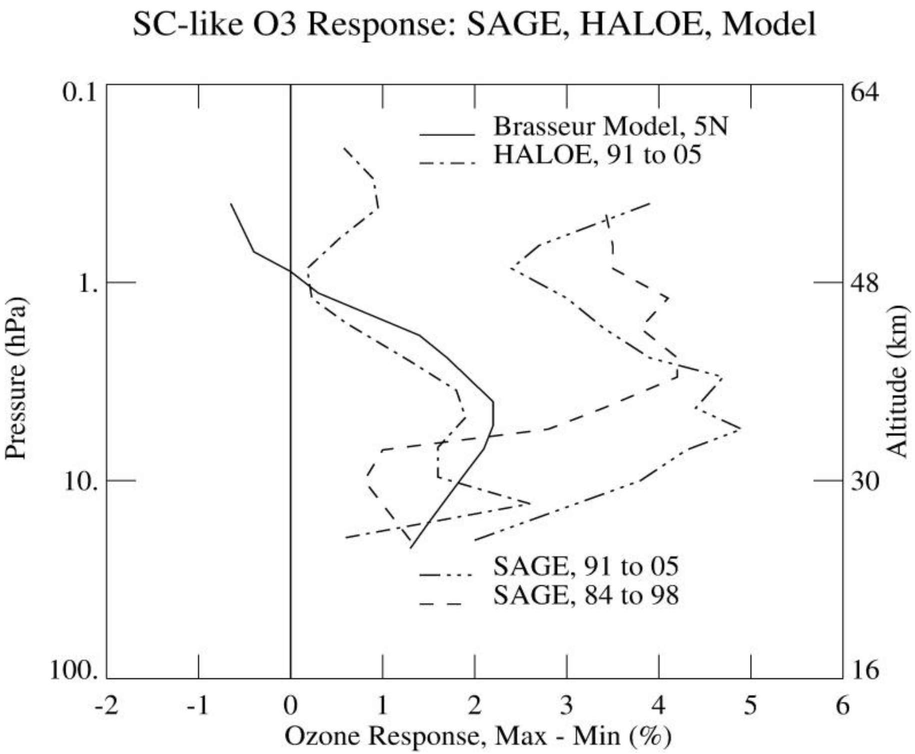

Fig. 12. Profiles of the average SC-like, ozone responses (in percent) at the lower latitudes from the Brasseur model (solid), the HALOE data (dash-dot), and the SAGE II v7 data for 1991 to 2005 (dash-dot-dot-dot) and for 1984 to 1998 (dashed).

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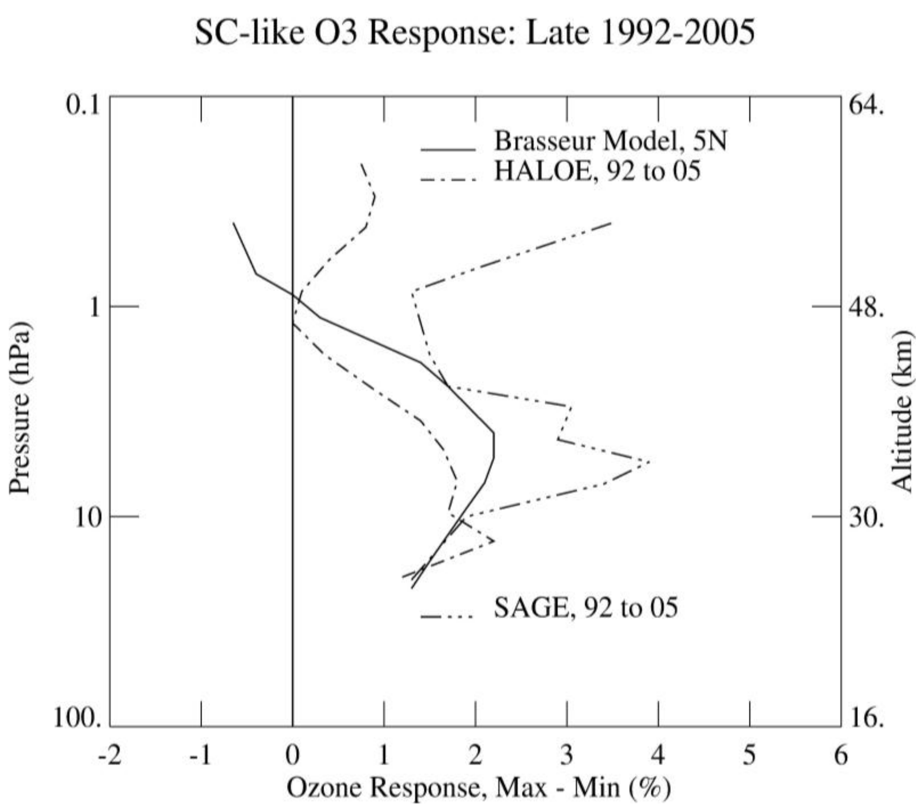

Fig. 13. As in Fig. 12, but for late 1992–2005.

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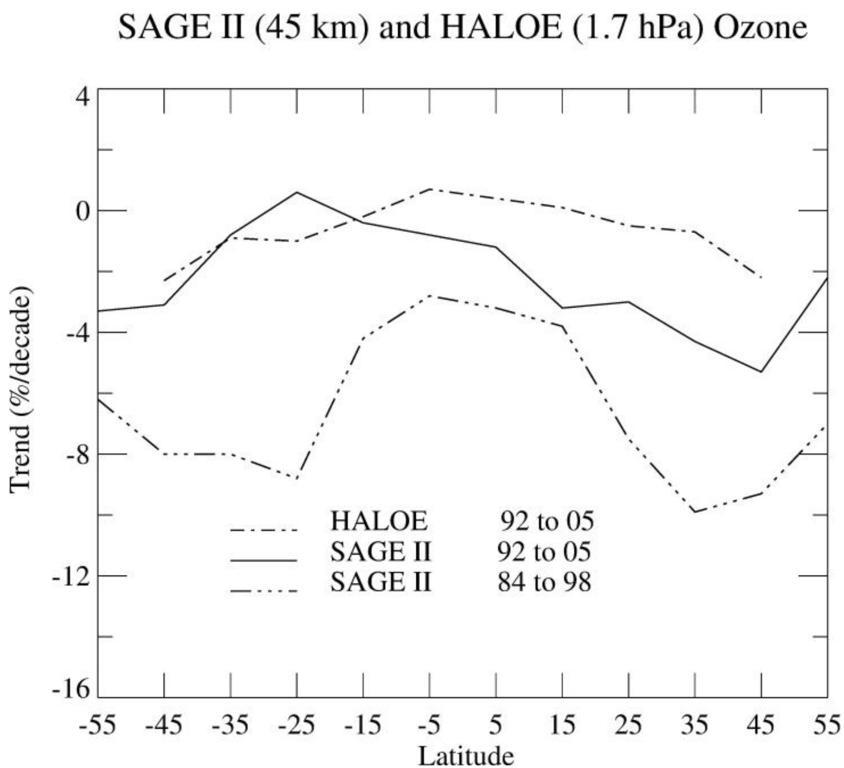

Fig. 14. Ozone trends (in % decade^{-1}) vs. latitude from SAGE II at 45 km for both 1984 to 1998 and late 1992 to 2005 and from HALOE at 1.7 hPa for 1992 to 2005.

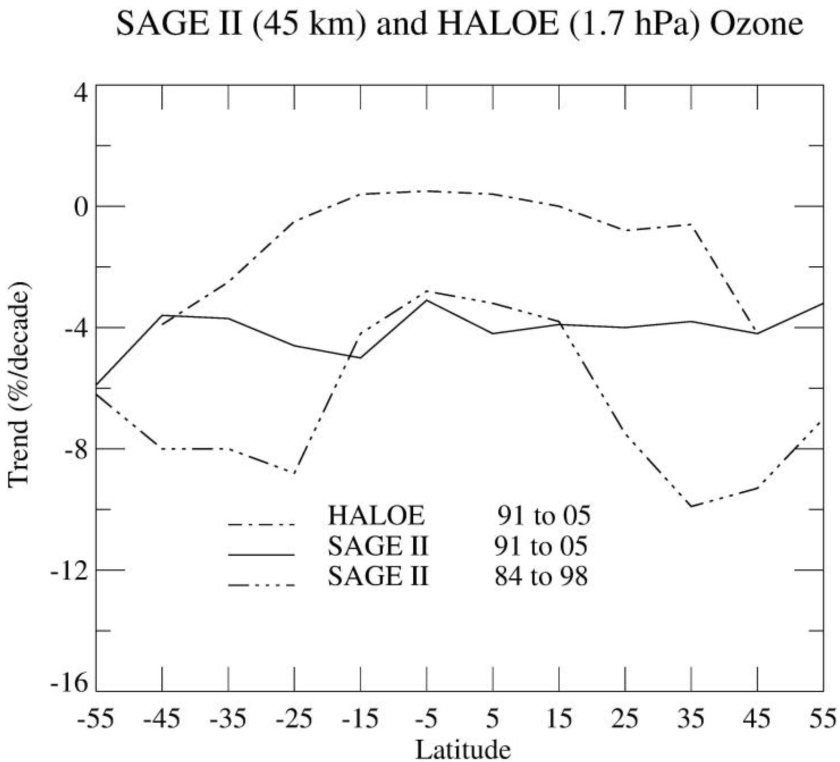

Fig. 15. As in Fig. 14, but showing results for 1991 to 2005, instead of for late 1992 to 2005.

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