Atmos. Chem. Phys. Discuss., 11, 25011–25036, 2011
www.atmos-chem-phys-discuss.net/11/25011/2011/
doi:10.5194/acpd-11-25011-2011

Atmospheric Chemistry and Physics Discussions

Further analyses of the decadal-scale responses and trends in middle and upper stratospheric ozone from SAGE II and HALOE

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Received: 3 August 2011 – Accepted: 25 August 2011 – Published: 7 September 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Stratospheric Aerosol and Gas Experiment (SAGE II) Version 6.2 ozone profiles are analyzed for their decadal-scale responses and linear trends in the middle and upper stratosphere from 1984 through 1998. The results are compared with those of SAGE II and of the Halogen Occultation Experiment (HALOE) for 1991–2005, reported previously by Remsberg and Lingenfelser (2010). The regression model fit to the data includes a periodic 11- 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 responses for the upper stratosphere are of order 2 % from the HALOE time series that are in terms of mixing ratio versus pressure. Max minus min responses are of order 4 % from SAGE II in terms of number density versus altitude and for both 1984–1998 and 1991–2005, even though the concurrent linear trend term coefficients are much different for the two time spans. However, the analyzed 11-yr response from the SAGE II data of 1984–1998 lags that of the uv-flux by 1 to 2 yr in the tropical middle stratosphere, most likely due to the effects of ENSO forcings that are not represented in the regression models. The linear ozone trends in the upper stratosphere for 1991 to 2005 are of the order of −2 to −3 %/decade from SAGE II and 0 to −1 %/decade from HALOE. Those differences in the ozone trends must be principally due to the associated temperature trends for the analyzed data.

1 Introduction

Analysis results have been reported on the 11-yr solar cycle responses (max minus min of order 2 to 4 %) and the trends in upper stratospheric ozone from long-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; and Lee and Smith, 2003). However, there is still some disagreement between the response profiles from

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stratospheric models and from the analyzed datasets (WMO, 2007). The diagnosed solar cycle responses obtained from data of the past three decades may have biases resulting from concurrent trends in ozone due to changes in the reactive chlorine, due to perturbations from the major volcanic eruptions of 1982 and 1991, and because of uncertainties of the order of a percent or so for the operational ozone sensors on successive satellites. In one example, Randel and Wu (2007) 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. Chemical/transport models indicate that the annual average effects of an EESC proxy on ozone are varying but are greater for the middle latitudes than in the tropics (Fleming et al., 2011; WMO, 2011). Soukharev and Hood (2006) found that they could apply linear trend terms to shorter ozone data series to approximate the effects of the changing chlorine. Lee and Smith (2003), among others, handled perturbing effects from volcanic eruptions by excluding segments of ozone data for some months following a large event. Fioletov (2009) showed that although he could resolve a 27-day response in observed upper stratosphere ozone, he had some difficulty in obtaining a similar 11-yr response from a time series of "merged ozone data" from successive operational satellite instruments.

Remsberg and Lingenfelser (2010) (hereafter denoted RL) diagnosed decadal-scale responses, based on the Stratospheric Aerosol and Gas Experiment (or SAGE II) ozone time series for 1991–2005 and compared them with those from the Halogen Occultation Experiment (or HALOE) data of the same time span. They obtained solar cycle (or SC-like) response profiles that agreed well with model results for the middle and upper stratosphere, in part due to the good vertical resolution of those measured profiles. The current study extends that work and addresses two remaining issues that the reviewers of RL raised in their published discussions of the paper. First,the responses and linear trends in SAGE II ozone are presented herein, but now for the 14-yr period from 1984–1998 in addition to that of 1991–2005. The reviewers wondered whether the SC-like responses would be similar from the two separate periods. It is

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noted that Remsberg (2008) considered the effects of using the non-linear EESC proxy for the trend term but found that its inclusion had only a second-order effect on the analyzed 11-yr response terms from the HALOE data and that the EESC proxy had its own uncertainties. Therefore, linear trends are applied as before, in order to be consistent with the MLR model approach of RL and of Remsberg (2008) for the data period of 1991–2005 of their respective SAGE II and HALOE analyses. Secondly, Dhomse et al. (2011), McLinden and Fioletov (2011), and Rosenfield et al. (2005) reported on model studies of differences that one can expect, when the ozone responses and trends are considered in terms of the primary retrieved quantities of number density versus altitude (SAGE II) and of mixing ratio versus pressure (HALOE). McLinden and Fioletov (2011) also pointed out that EESC effects on ozone will vary slightly at an altitude versus at an equivalent pressure level. Another complicating factor for the ozone responses in the two coordinate systems comes from the trends in the associated temperature time series in response to the changing concentrations of the radiatively-active gases CO_2 and ozone. An estimate of that difference is also provided in this note by comparing the diagnosed ozone responses and trends from the primary quantities of the SAGE II and the HALOE experiments.

Periodic and linear trend terms are applied in multiple linear regression (MLR) model fits of each of the ozone time series. As in RL, proxy terms are not used for the MLR models. Instead, Fourier analyses of the time series points indicate that there are almost always two significant interannual terms having periods of order 28 (QBO-like) and 21 months (sub-biennial). Those periodic terms are included in the current MLR models, along with annual and semiannual terms. A simple, 11-yr periodic term is also part of the fit to the data. Whenever its maximum occurs within one year of the time of solar flux maximum, the 11-yr term is judged as in-phase with and a result of the solar uv-flux forcing. In effect, RL checked on whether there were decadal-scale, dynamical forcings affecting the ozone, particularly at the higher latitudes. One uncertainty for the extended SAGE ozone time series has been how to combine the separate datasets from SAGE I and SAGE II, where there is nearly a two-year gap between them (Wang

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et al., 1996; Randel and Wu, 2007). For this reason the results herein are based only on the SAGE II data. In addition, it was found that RL inadvertently obtained the bin-averages for their SAGE II ozone time series of 1991–2005 based on the poleward extremes of the latitudinal sweeps for the sunrise and sunset tangent track events, but according to the dates of those extremes from the HALOE experiment rather than based on the actual beginning and ending dates for the sweeps from the SAGE II measurements. The incorrect grouping of the SAGE II profiles by RL reduced the accuracy of their fits for the seasonal terms slightly and also affected the autocorrelation characteristics of their bin-averaged points with latitude. That error has been corrected in the present study, although it does not alter the conclusions of RL. The current SAGE II time series have also been screened of some additional, spuriously low sunrise ozone data at low latitudes in September and November of 1991, due to the extinction effects of the Pinatubo aerosol layer.

Section 2 shows that the decadal-scale responses from SAGE II are nearly the same in the upper stratosphere for the two 14-yr periods, even though their separate ozone trends are markedly different. Throughout the latitude/altitude domain, their 11-yr responses are almost always in-phase with that of solar flux maximum. Section 3 compares the SC-like response profiles and the trends from the time series of SAGE II (in altitude) and of HALOE (in pressure) and with those of several model results in the literature. RL reported finding an anomalous trend for the SAGE II ozone at 50 to 55 km for 1991–2005. A corresponding trend anomaly was not found for 1984–1998. Section 4 is a summary of the findings from the new analyses of this note.

2 Decadal-scale responses and trends in SAGE II ozone

To reacquaint the reader with the nature of the SAGE II data, Fig. 1 is the updated plot of the ozone series shown in RL (their Fig. 2) for 25° S and 37.5 km. 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

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the seasonal terms, one can clearly see that there is a decadal-scale (11-yr) term that is closely in-phase with the solar uv-flux maxima that occurred in 1991 and in 2002. Differences from the analysis of RL are very minor.

Figures 2–4 represent the updated analyses of the results shown in RL (their Figs. 6–8), and they are also very similar to them. Figure 2 is the updated distribution of the max minus min responses (in %) for the 11-yr term as a function of altitude and latitude from the SAGE II ozone of 1991 to 2005. A total of 144 ozone time series were analyzed. The responses for Fig. 2 were obtained at altitudes from 27.5 km to 55 km at increments of 2.5 km and at twelve latitude bins spaced by 10°, of 20° width, and centered at 55° S to 55° N. Responses are of order 3 to 4 %, but increasing to 6 % in the middle stratosphere of the northern subtropics, where Lee and Smith (2003) and RL indicated that there were anomalous ozone forcings following the Pinatubo event. Figure 3 is a plot of the phases of the 11-yr terms as referenced to January 1991, which is the assumed time of a maximum for the solar uv-flux to the stratosphere. Dark shaded regions are where the phases are within ±1 year of January 1991, or in-phase with the solar uv-flux. The magnitudes of those 11-yr terms of the upper stratosphere are presumed to be the responses to changes in the uv-flux and are denoted as SC-like. Note that the middle stratosphere region of the northern subtropics that had the largest response in Fig. 2 is also closely in-phase (Fig. 3). Figure 4 is the distribution of the coefficients of the linear trend terms for the SAGE II ozone in units of %/decade. Those trends are slightly negative and of similar magnitude across most of the domain. They are consistent with previous reports that the rather large declines in ozone of the 1980s had leveled out during 1991–2005 (WMO, 2007, 2011).

SAGE II results for 1984–1998 are shown next in Figs. 5–7. Figure 5 is the distribution of the responses for the 11-yr terms. They are of order 4 % in the upper stratosphere and agree with Fig. 2, but then they decrease to 2–3 % near 30 km. There is little indication of the perturbing effects from Pinatubo, although there is a small region between 30 and 35 km at the Equator where the responses are of order 4 %. Figure 6 shows the distribution of the phases of the 11-yr terms. Again they are in-phase with

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the solar uv-flux throughout much of the domain. However, at the Equator and between 30 and 35 km the 11-yr term has its diagnosed maximum closer to 1992–1993 than to 1990/91. That phase lag of 1 to 2 yr in Fig. 6 exhibits good continuity across the latitude bins of the tropical middle stratosphere. The 11-yr terms are also not quite in-phase at the higher latitudes of the southern hemisphere, possibly due to decadal-scale, dynamical forcings. Figure 7 is the distribution of the coefficients of the linear trend terms, and they indicate a clear variation with latitude due to the effects of the reactive chlorine near 40 km during this period (c.f., Fleming et al., 2011, their Fig. 3).

The 11-yr responses from the two 14-yr time spans are very similar and in-phase with the solar uv-flux, at least in the upper stratosphere. The responses of the middle stratosphere are smaller in Fig. 5 than in Fig. 2, despite the fact that the data of late 1991 and in 1992 are the same in both time series. However, those responses have a 1–2 yr phase lag, as shown in Fig. 6. It must be that some feature of the time series prior to 1991 is not being fit very well. As an example, Fig. 8 is the ozone time series from 1984–1998 for 5° N, 30 km. The MLR model terms fit the data well, especially for the Pinatubo period of 1991–1992. Note that when that perturbation occurred at the beginning of the time series of 1991–2005, it acted as a so-called "end point anomaly" for the determination of the linear trend and was confounded with the coefficient of the 11-yr term. That same perturbation occurs in the middle of the time series of Fig. 8 and affects the diagnosed trend much less.

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. The residual for the model of Fig. 8 is shown in Fig. 9. The only systematic feature in Fig. 9 is the predominantly negative residual in 1989–1990 followed by a positive residual in 1991–1992. Together, Figs. 8 and 9 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 of 1989; thus, the maximum for that term occurs in early 1993, rather than in early 1991. A possible explanation for the varying ozone

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residual is 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 near to the Pinatubo eruption in June 1991 (Garcia et al., 2007). No attempt was made to represent these combined effects in the MLR model. Chipperfield et al. (1994), Hood and Soukharev (2006), and Hood et al. (2010) also found a negative anomaly in tropical NO_2 and a positive anomaly in ozone at 30–32 km in 1991 due to the effects of vertical advection from the QBO. Since Fig. 6 shows good coherence for the 1 to 2-yr phase lag of the maximum of the 11-yr terms across tropical latitudes and from 30 to 35 km, it is concluded that those terms were confounded with the QBO and episodic ENSO forcing effects of that time.

Figure 10 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 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 SC-like response is reduced. That response from SAGE II at 30 km varies by less than 1 % in the tropics to 2–3 % at the middle latitudes. Figure 10 is very similar now to that reported by Soukharev and Hood (2006, their Fig. 6), wherein they regressed against a solar cycle proxy and a linear trend term for a longer SAGE II data span of 1985–2003. On the other hand, the amplitudes of the SC-like responses herein are somewhat larger than those of Randel and Wu (2007, their Fig. 12a), even after multiplying their results to yield max minus min percentage responses. That difference may be because Randel and Wu (2007) conducted their analyses on the combined SAGE I plus SAGE II ozone time series for 1979–2005, while the ones herein apply to shorter data series from only SAGE II.

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3 Solar cycle response and trend profiles for the low latitudes

The SC-like response profiles and the trends from SAGE II and HALOE are compared further in this section. 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 profile is characteristic of the latitude range of 25° S to 25° N. Their results are shown in Fig. 11, along with that from the model of Brasseur (1993). One can see that there is very good agreement between the response profiles from HALOE and the model, both of which are given in terms of pressure-altitude coordinates. They differ only in the lower mesosphere, where it is noted that the HALOE results are for sunrise and sunset, when ozone is not strictly in chemical equilibrium. There is also a hint of an anomaly in the HALOE response near 13 hPa, likely due to anomalous forcings following Pinatubo.

The SC-like response profiles from SAGE II in Fig. 11 are of order 4 % from about 35 to 55 km for both 1984–1998 and 1991–2005, even though the associated linear trend terms for those two periods are different. SAGE II responses in the upper stratosphere are at least twice those from HALOE and from the Brasseur model, reflecting the fact that the constant pressure surfaces are also varying with altitude due to the changes in the ozone heating over the solar cycle. Dhomse et al. (2011) reproduced much of the differences between the two response profiles with their simulations in terms of altitude versus pressure coordinates. On the other hand, the two SAGE II SC-like response profiles are clearly different from each other below about 35 km. Although there appears to be an in-phase perturbation response at those altitudes in the SAGE II analyses of 1991–2005 (Figs. 2 and 3), such is not the case for the responses of 1984–1998 (Figs. 5 and 6). As before, these differences indicate the biases that can arise from an ozone anomaly at the beginning of the 1991–2005 series or when structure remains in the residual for the 1984–1998 series.

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Figure 12 compares the average ozone trends from HALOE near 3 hPa with those from SAGE II at 40 km for the same period (1991 to 2005). The HALOE trends are for ozone mixing ratio versus pressure-altitude, while the SAGE II trends are for ozone number density versus geometric altitude. In both cases the trends are fairly constant with latitude and are consistent with the fact that reactive chlorine was not changing by much during this period. However, the trends from SAGE II are more negative than those from HALOE by about 2 %/decade, in part due to a trend in the associated temperatures of order −1 K/decade in the upper stratosphere (e.g., Shine et al., 2008). Ozone trend differences of order 2 %/decade are also consistent with the model results for the two ozone quantities, as reported by Rosenfield et al. (2005, their Fig. 6).

Figure 12 also shows the linear trends at 40 km from the analyses of the SAGE II ozone for the two separate periods of 1984–1998 and 1991–2005. The trends with latitude for the earlier period agree with decreases of 6 to 9 %/decade reported by Steinbrecht et al. (2009) from ground-based lidar measurements at 40 km from 1979 to the late 1990s. A larger negative ozone trend at southern versus northern middle latitudes in Fig. 12 is also consistent with trends in HCl from 1993–1996 that were 18 % more positive in the south (Jones et al., 2011). Fleming et al. (2011) calculated ozone trends at the Equator of order −3 to −4 %/decade, and they generally agree with those from SAGE II. It is noted that the tropical ozone trends in Fig. 12 are essentially the same for both SAGE II periods, and that their 2σ uncertainties are of order 0.8 %/decade. This finding implies that total chlorine was nearly the same for the two periods. Estimates from WMO (2003) indicate average values of HCl of 2.8 ppbv for 1984–1998 and 3.1 ppbv for 1991–2005 or a difference of 10 %. Temperature changes can affect ozone trends analyzed at an altitude level. Thus, there may have been a compensating trend in the temperature of the upper stratosphere at the Equator for one of those two periods. In support of that prospect, it is noted that Dhomse et al. (2011, their Fig. 3b) found a small, abrupt change after 1997 in the temperature reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA-40/Operational versus the ERA-Interim results). Further verification of the nature of

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that bias is needed.

Finally, RL reported finding anomalous trends in the SAGE II ozone above 50 km for 1991–2005. The increasingly negative trends of order −4 to −8 %/decade found by RL are still present in the revised analyses of that region and time period (Fig. 4), particularly for the higher latitudes. However, the trends above 50 km do not appear to be anomalous for 1984–1998 (Fig. 7). Therefore, it is tentatively concluded that the SAGE II ozone trends in the lower mesosphere are valid for 1984–1998, but perhaps not thereafter (see also Dhomse et al., 2011, Fig. 3b). A mesospheric anomaly was not found by RL in the ozone trends from HALOE.

4 Summary

This study is an extension of the analyses and findings in RL. Additional regression analyses were conducted for SAGE II ozone time series from 1984–1998. The distribution of the max minus min, 11-yr ozone responses from that time span are very similar to that from 1991–2005 for the upper stratosphere and are in-phase with the solar cycle uv-flux. Good agreement is found for those responses for the two time spans, even though the associated distributions of their linear trends are quite different. At tropical latitudes of the middle stratosphere the 11-yr responses for 1984–1998 clearly lag that of the uv-flux maximum by 1 to 2 yr, most likely in response to a perturbation from an ENSO event that was not modeled.

Comparisons were also shown of the SC-like ozone response profiles and the trend profiles from SAGE II and from HALOE. The trends from SAGE II (at 40 km) and from HALOE (at 3 hPa) do not change with latitude by much for 1991–2005, but differ by nearly 2 %/decade in accordance with modeled results for the primary ozone quantities from the two experiments. The trends from SAGE II (based on number density versus altitude) are more negative than those from HALOE. Ozone trends from the earlier SAGE II period of 1984–1998 are increasingly negative with latitude for the upper stratosphere, where the modeled effects of the changes in total chlorine have a similar characteristic impact on the ozone distribution.

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Acknowledgements. The SAGE II Version 6.2 data were generated by personnel of the Radiationand Aerosols Branch of NASA Langley. EER carried out this work while servingas a Distinguished Research Associate at NASA Langley under the sponsorship of Malcolm Ko.

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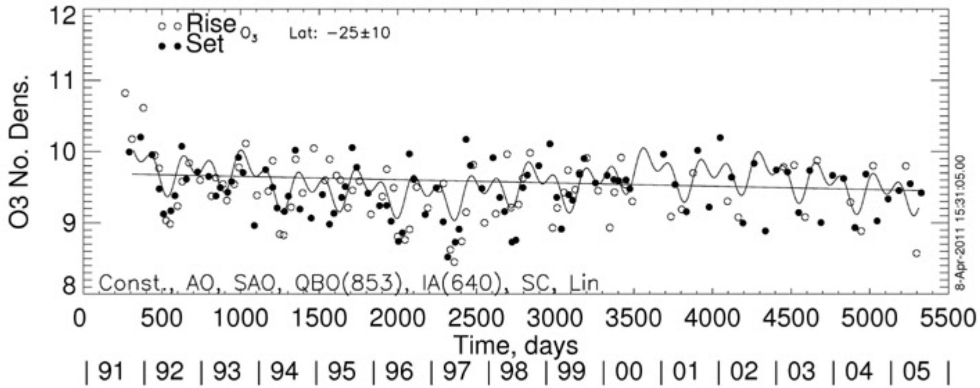

Fig. 1. Time series of bin-averaged, SAGE sunrise and sunset ozone number density measurements (in cm^{-3} multiplied by 10^{-11}) at 25° S and 37.5 km. Terms of the MLR model are indicated at the lower left, where SC refers to an 11-yr sinusoid term. The oscillating solid curve is the model fit to the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

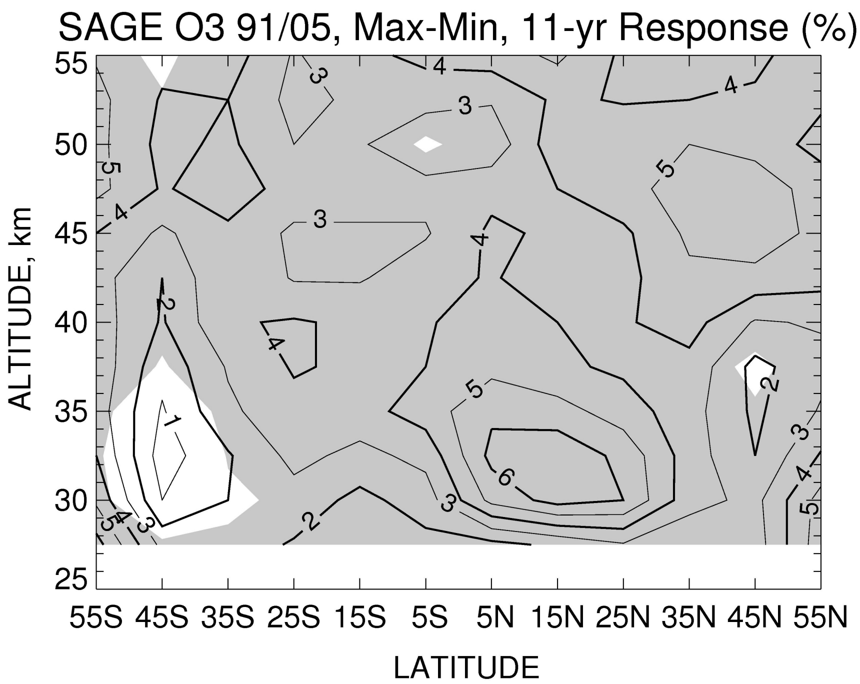

Fig. 2. Contour plot of the maximum minus minimum, 11-yr response (in percent) for the SAGE II ozone data of September 1991 through August 2005. Contour interval is 1.0 %. Shading denotes confidence intervals (CI) > 90 % for the responses. This plot updates RL (their Fig. 6).

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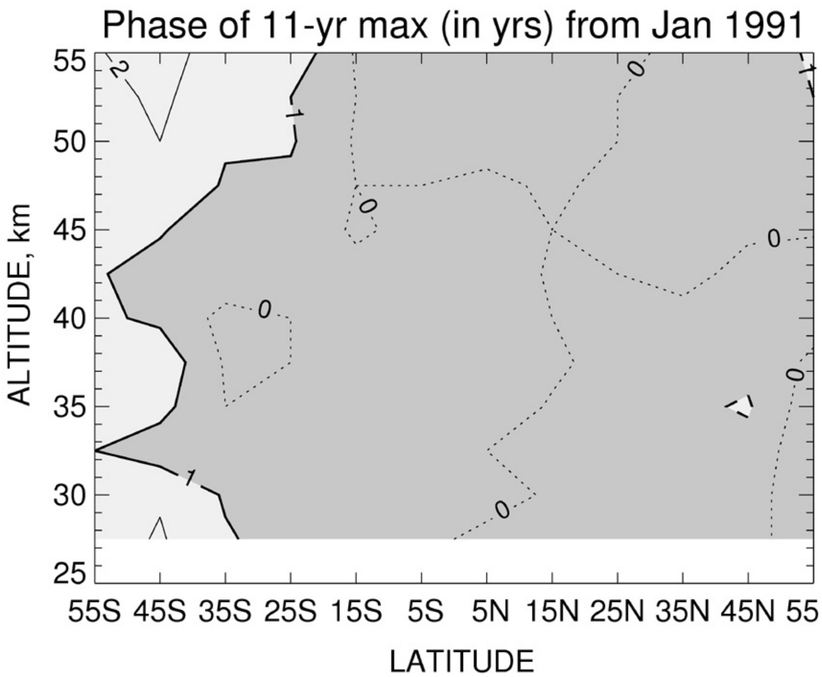

Fig. 3. Contour plot of the phase variations (in years from January 1991 or 2002) of the 11-yr response terms of Fig. 2. Contour interval is 1 yr. The phase domain of ±1 yr is shaded and is considered as in-phase with the solar uv-flux maximum.

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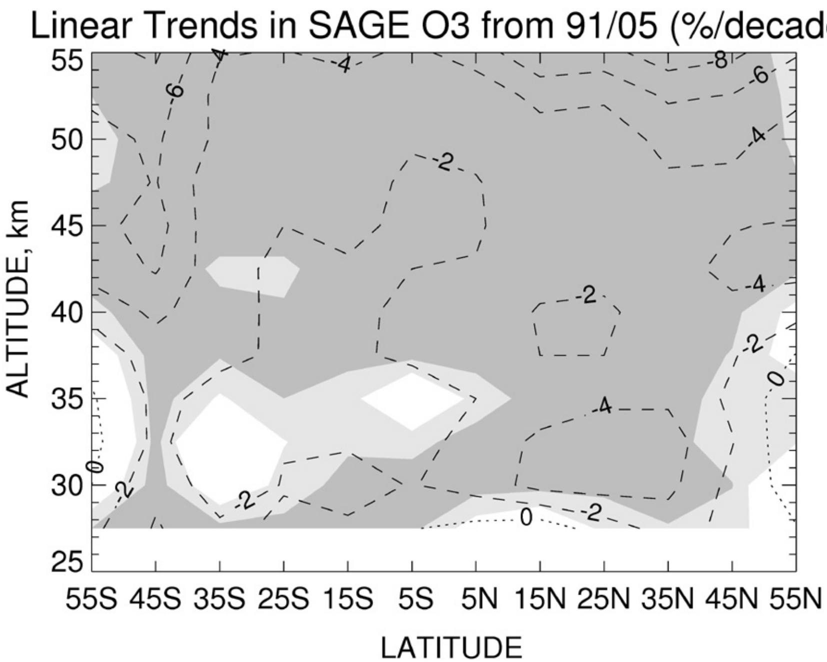

Fig. 4. Contour plot of the linear trend terms (in percent per decade) from the MLR models for the SAGE II ozone data of 1991 to 2005. Contour interval is 2 %/decade. Dashed contours denote negative trends, and the dotted contour is where the trend is zero. Darker shading denotes where CI > 90 % for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

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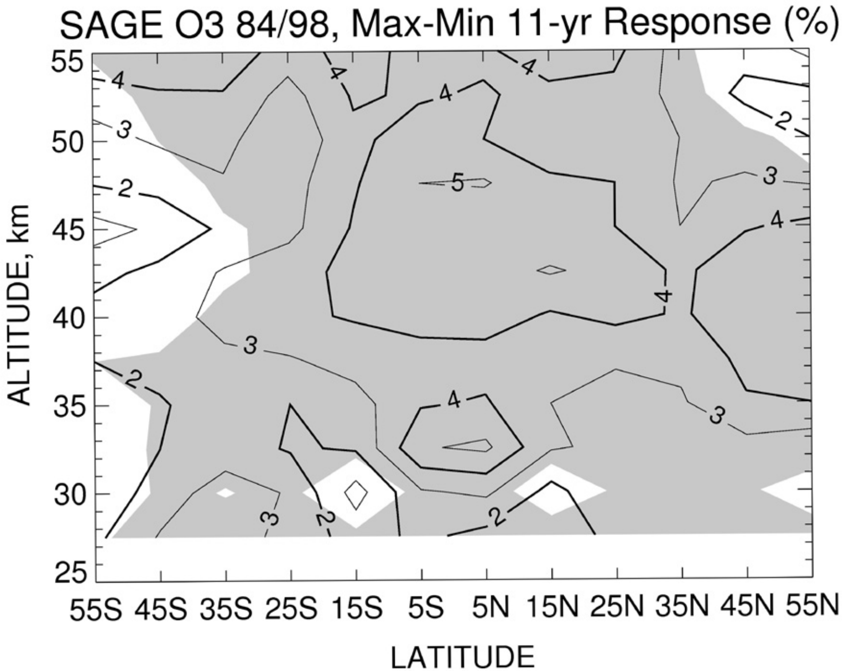

Fig. 5. As in Fig. 2, but the max minus min variations are from the SAGE II data from November 1984 through October 1998.

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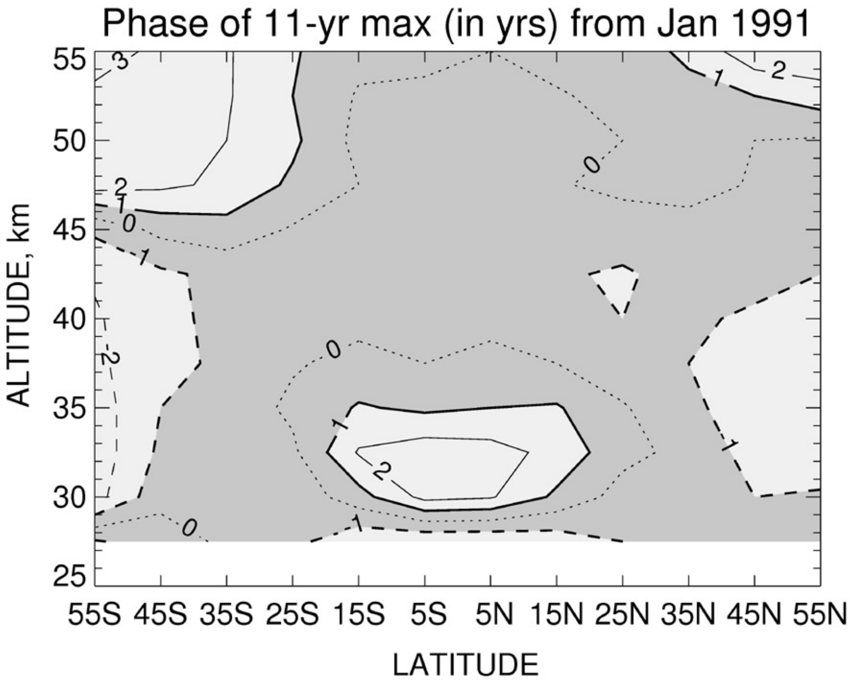

Fig. 6. As in Fig. 3, but the phases of the 11-yr terms are from the SAGE II data from November 1984 through October 1998.

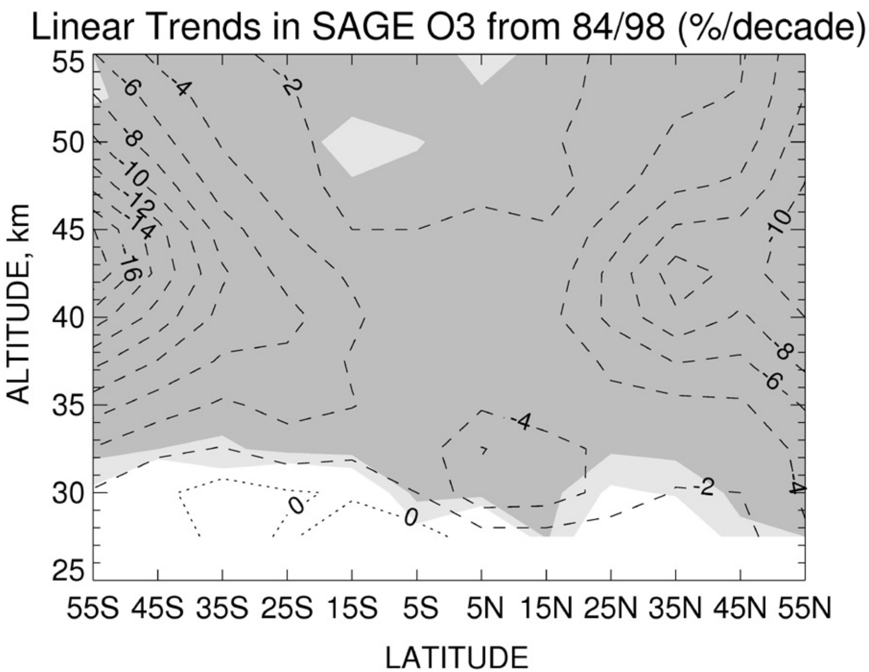

Fig. 7. As in Fig. 4, but the trends are from the SAGE II data from November 1984 through October 1998.

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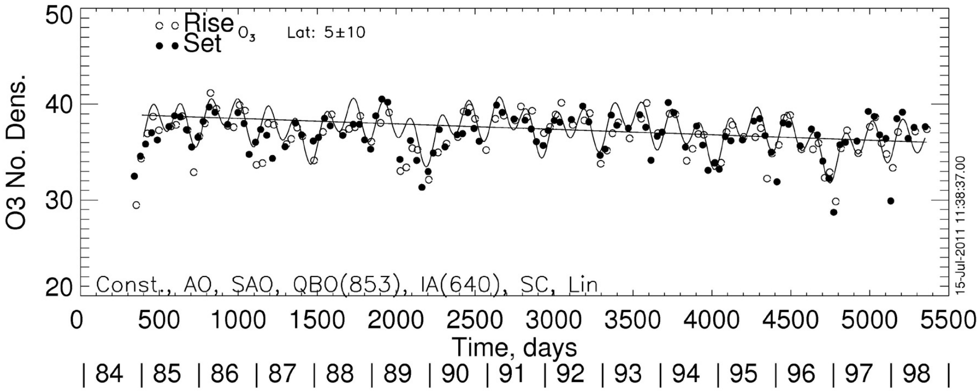

Fig. 8. As in Fig. 1, but for 5° N and 30 km from SAGE II for 1984–1998.

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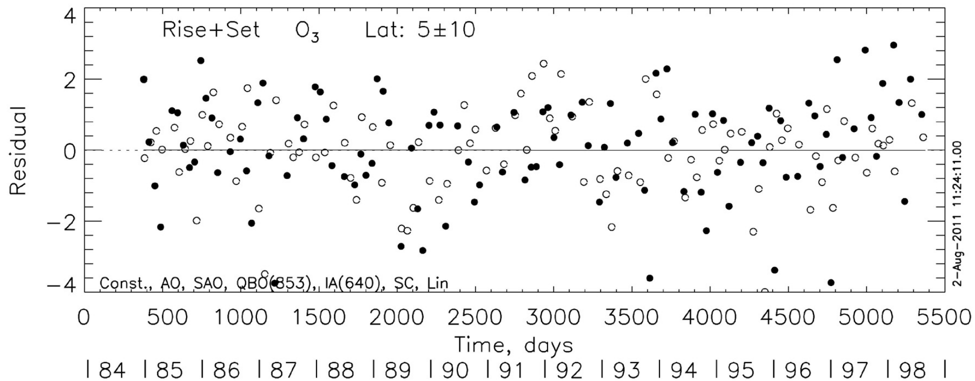

Fig. 9. Time series plot of the ozone residual for the MLR fit to the data of Fig. 8.

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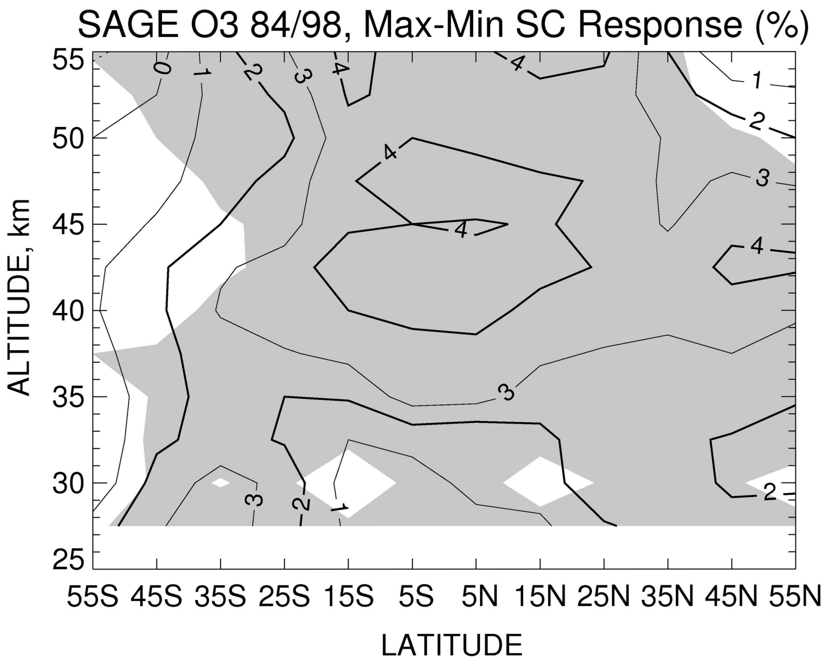

Fig. 10. As in Fig. 5, but the SAGE II max minus min, 11-yr responses have been adjusted to be in-phase for that of a solar uv-flux maximum in January 1991 – the SC responses. Darker shading denotes where CI > 90 %; lighter shading denotes 70 % < CI < 90 %.

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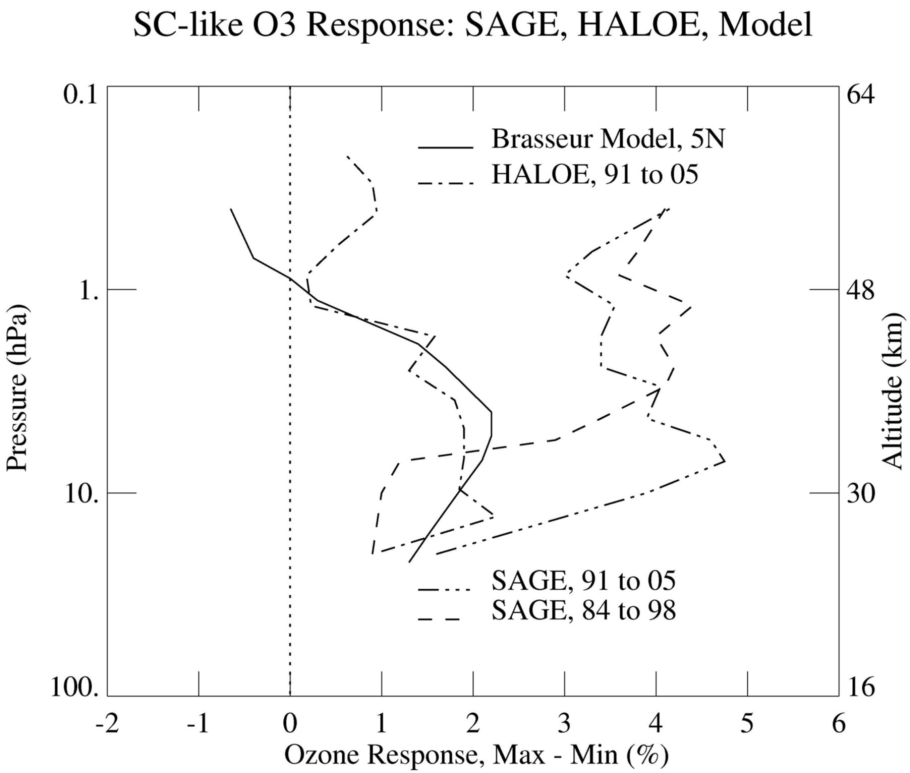

Fig. 11. Profiles of the average SC-like, ozone responses (in percent) at the lower latitudes from the Brasseur model (solid), the HALOE data (dash-dot), and the SAGE II data from 1991 to 2005 (dash-dot-dot-dot) and from 1984 to 1998.

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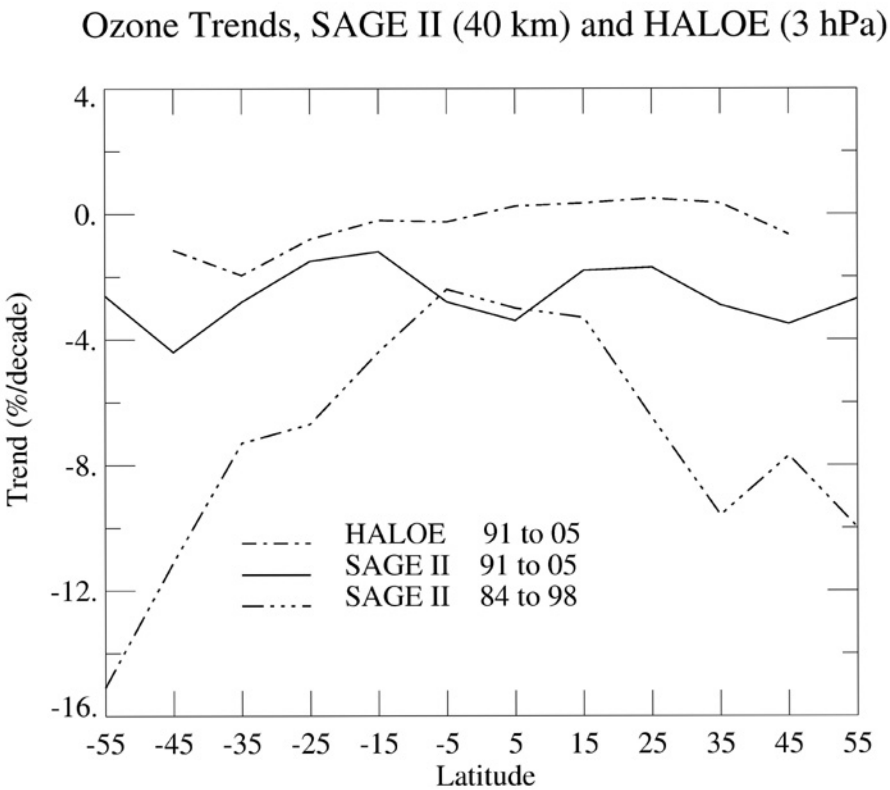

Fig. 12. Ozone trends (in %/decade) with latitude from HALOE at 3 hPa for 1991 to 2005 and from SAGE II at 40 m for both 1984 to 1998 and for 1991 to 2005.

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