Author response to Referee, Mark Weber

1 Summary of New Results

In the Technical Note under review I provided new results from additional analyses in response to several concerns of both reviewers of the original paper of Remsberg and Lingenfelser (RL, 2010). In my revision of that Note I will correct for an error in the way I accounted for the effects of the lag-1 correlation coefficient (AR1) in the SAGE II results for 84 to 98, and I will revise Figures 5, 6, 7, and 10. I had used an AR1 value for 84 to 98 in the original Note that did not include the effects of the linear trend term. Qualitatively, the new results are very similar to those original figures, except that the revised trends in the upper stratosphere are smaller now (see new Figure 13 below) and in good agreement with those of Wang et al. (their Figure 13b, JGR, 2002) for the period 1984-99. In addition, I conducted new analyses of the HALOE and SAGE II time series beginning one year later or from 1 September 1992 to the end of their data in 2005, in order to estimate the sensitivity of my findings to atmospheric effects during the year following the Pinatubo eruption. New Figure 12 shows those results for comparison with Figure 11; the previous Figure 12 was updated and is now Figure 13 (all 3 figures are attached below).

An important goal of my study is to determine whether there is consistency between the SAGE II and HALOE data with regard to the response of their upper stratosphere ozone to a solar cycle forcing. Although the solar cycle (SC) response in mixing ratio versus pressure from the HALOE data of September 1992 onward (new Figure 12) is nearly unchanged from that beginning in 1991 (Figure 11), the SC response from SAGE II in number density at an altitude of 40 km, for example, is reduced and closer to that from HALOE after deleting the year of data from September 1991 to 1992. Solar uv-flux peaked in early 1992 followed by a significant decline thereafter. In other words, SAGE II and HALOE obtained similar and smaller ozone responses at 40 km for the period of late 1992 to 2005 with its less intense solar maximum of 1992-02. On the other hand, there is consistency in the rather large SC-like ozone responses at 40 km from the SAGE II data for the periods of 1984-98 and 1991-2005, both of which contain the data following the Pinatubo eruption. Thus, the response from the SAGE II data of 1991-2005 is not an end point anomaly effect from the analysis of that time series.

These findings indicate that the SAGE II experiment recorded a positive response in the tropical ozone number density at 40 km during the broad solar maximum of 1989-92 that is somewhat larger than expected based on recent simulation studies of Dhomse et al. (see their Figure 5, ACPD, 2011), which used the associated solar cycle responses (max minus min of 2K) from analyses of operational satellite temperature data. Yet, I obtained trends and SC-like responses in temperature versus altitude that are no greater than 1 K/decade and 1 K, respectively, in the tropical upper stratosphere from analyses of the independent temperature time series from HALOE (Remsberg, JGR, 2009), indicating that the temperature variations from the operational analyses are too large and must be corrected, most likely, for the changes with time of the SSU CO2 weighting functions (Shine et al., GRL, 2008), particularly when the trends in ozone were near zero in the upper stratosphere. Use of the weaker HALOE temperature response in simulations would lead to better agreement with the observed SC-like responses in ozone of Dhomse et al. from both SAGE II and SBUV, whose data series are in terms of Dobson units per km and Dobson units per pressure layer, respectively, or equivalent to the profiles of SAGE II ozone number density versus altitude in my Note. I will also include in my revised Note the plot of the SC-like response in temperature from HALOE of Remsberg (Figure 6, JGR, 2009).

2 Regression model

In my original Note I only said that "Figures 8 and 9 suggest that the true amplitude of the QBO was larger than average", not that its phase lasted longer. In fact, although the period of the QBO is more variable in the lower stratosphere, it is quite regular and very near to 28 months in the middle and upper stratosphere. For the altitude levels of my study I find that the fit is highly significant for my prescribed 28 month term, even during the late 1980s and early 1990s.

The phase anomaly for my diagnosed 11-yr terms in the SAGE II ozone occurs only in the tropics and between 30 and 35 km (Figure 6). Figure 8 shows that tropical ozone at 30 km was lower than normal in 1989 to 1990, and my regression model does not fit the data points very well during that time. That was a time of a significant change in the El Nino index from +2 to about -2, and Randel et al. (GRL, 2009) showed that El Nino forcings are associated with changes in temperature and ozone in the LOWER stratosphere. Hood et al. (JGR, 2010) and Dhomse et al., (2011) added an El Nino indexed term to their regression model analyses of SAGE II and HALOE data, but they found that applying this proxy term with its expected 1+ yr lag at 30 km actually made very little difference to their analyzed solar cycle responses in the middle stratosphere. Based on their studies, I am not including an El Nino index term in my model. Nevertheless, Hood et al. (2010) provided the following, more likely explanation for the anomalous SC phase, although it is not so easy to characterize with a suitable proxy. Specifically, they relied on the evidence reported by Free and Seidel (JGR, 2009) of a tropical lower stratospheric cooling in boreal winter at the time of an El Nino warm (positive) event, which also gives rise to enhanced Rossby wave activity and to an acceleration of the Brewer-Dobson (BD) circulation with almost no lag—i.e., net ascent at the Equator and descent at higher latitudes. Chipperfield et al. (GRL, 1994) and Randel and Wu (JGR, 1996) showed further that there is a strong anticorrelation between SAGE II ozone and NO2 from about 20 to 7 hPa. Thus, a net tropical ascent of low NOx from 10 hPa to 7 hPa, followed by a slow relaxation of that perturbed BD circulation can explain at least part of the observed oscillation with time of the tropical ozone from 1988-90 at 30 km in Figures 8 and 9 and of the anomalous phase of the 11-yr term in Figure 6. I will modify the abstract and my discussion (lines 169-178 of the original manuscript) of the phase anomaly in Figures 8 and 9 based on that prospect.

3 Role of stratospheric aerosols

Results in the middle stratosphere in Figure 11 for 1991-05 and in new Figure 12 for 1992-05 give a clearer indication of the lingering sensitivity of the SAGE II (visible channel) ozone responses at an altitude level to the perturbing effects following the Pinatubo event, as compared with the responses from the HALOE (mid infrared) ozone at pressure levels. A significant SC ozone response of 4% is also apparent at 40-45 km from the SAGE II data of 1984-98 that is no longer present in the SAGE II results for 1992-05. I checked about whether the large responses in 1984-98 were because of my representation of the effects of the changes in the chlorine using a simple linear trend term. Certainly the positive trends in stratospheric chlorine were becoming small by the mid 1990s. Note also that the linear trends and 11-yr response terms will be confounded in a regression model fit to the data. Accordingly, I conducted new analyses of the SAGE II ozone, but for its time series from 1984-96 rather than extending to 1998. Still, I found that the SC-like amplitudes and phases and the trends are essentially unchanged from my analyses of the shortened time series. It thus appears more likely that atmospheric temperature perturbations in the year following the eruption of Pinatubo amplified the ozone response in the mid to upper stratosphere, coincidentally near the time of solar flux maximum. However, I find it difficult to verify that prospect from data series of the operational temperatures.

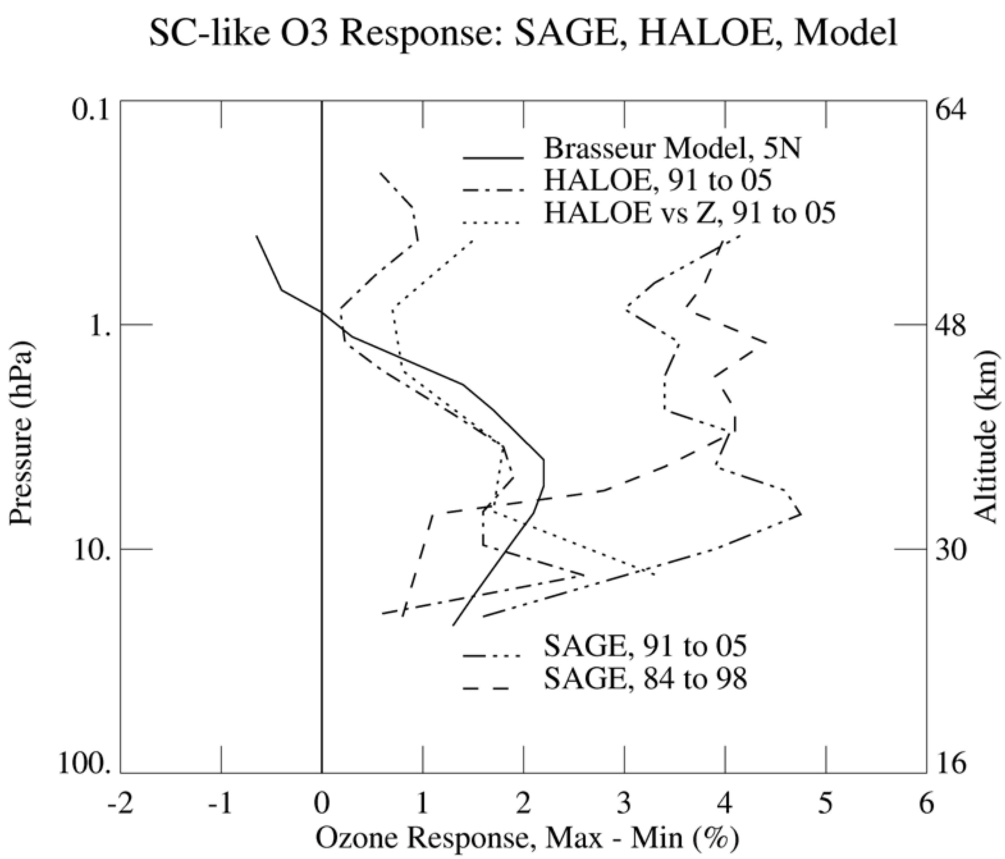
4 Comparison to a 2D model

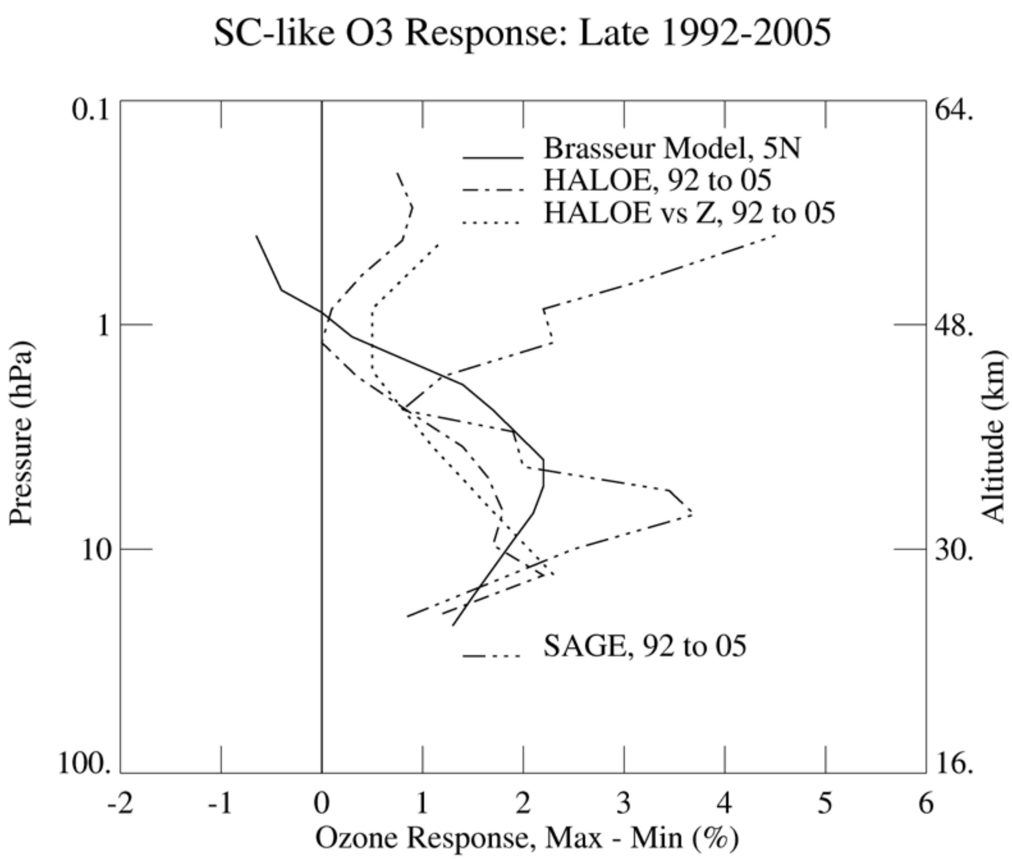
I referred to the model results of WMO (2007) in the first paragraph of the Introduction. Even so, the early result from Brasseur (1993) is very representative of the model results of just the effects of the SC uv-flux forcing on upper stratospheric ozone mixing ratio versus pressure, i.e., absent any temperature feedback. Dhomse et al. (2011) provide simulation results in terms of ozone number density versus altitude, both with and without the temperature feedback. I will refer to their results in my revision.

5 HALOE and SAGE long-term trends

I am aware that it would be helpful to convert ozone mixing ratio versus pressure to ozone number density (or Dobson units) versus altitude. However, there are important issues about what temperatures to use for the conversion. For instance, it has already been shown by others that the trends in the operational temperatures are not trustworthy. In addition, atmospheric temperature trends in the upper stratosphere are small from HALOE and from ground-based lidar instruments from the mid 1990s to 2010 but are much larger from lidar for the 1980s and the early 1990s (Remsberg, JGR, 2009; Berger and Lubken, GRL, 2011). I will make the point in my revision that the HALOE algorithm uses operational temperature profiles from NOAA CPC below about 40 km but only for an initial registration of its 2.8 micrometer CO2 channel transmission for the purpose of obtaining the pressure registration of the transmission profiles from all its channels, including ozone. A hydrostatic constraint maintains the proper pressure/altitude relation for each transmission profile, and above 40 km HALOE was able to provide its own T(p) information assuming the CO2 mixing ratio is known and constant. The forward model for the HALOE pressure retrieval makes an annual adjustment for the increasing CO2 with time, based on ground-based measurements of that trend. A similar adjustment was not made to the operational temperature series from NOAA CPC. Nevertheless, the NOAA CPC temperatures were carried along and output as part of the HALOE profile dataset below about 36 km and were merged with the retrieved HALOE temperatures from there to near 42 km. I have also confirmed the altitude region where the retrieved temperatures are no longer affected by the operational data by examining the HALOE temperature time series as a function of altitude. In particular, there is a clear, 4K decrease in the NOAA CPC temperature time series at 37 km in May 2001, when the operational data stream began to use radiances from AMSU instead of from the SSU. The discontinuity is about 2 K at 40 km and is absent at 43 km and above.

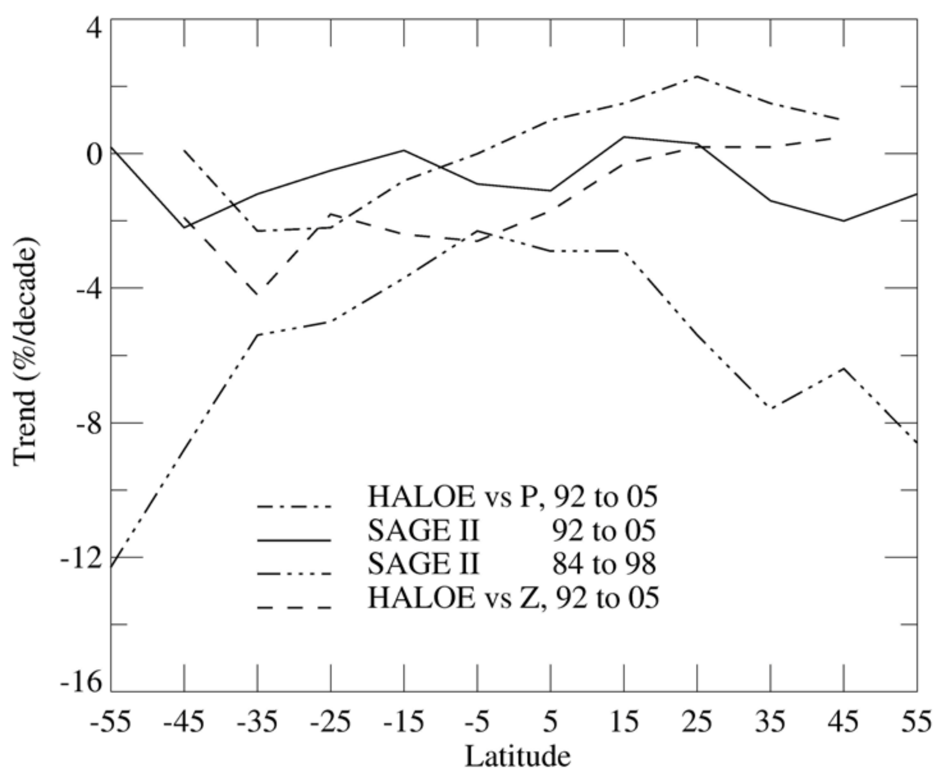
For the above reasons it is very unlikely that I would be able to obtain accurate profiles of the time series of ozone number density by applying a simple conversion relation using the HALOE temperatures (or the operational temperatures). What I have done is to add to Figures 11 and 12 my analyzed profiles of the SC-like responses from the HALOE ozone in terms of mixing ratio versus altitude; differences from its ozone response profiles versus pressure are small. Thus, the vertical movement of the pressure surface versus altitude is quite small due to the solar uv-forcing. Admittedly, my analyses of the quantity HALOE ozone mixing ratio versus altitude, or HALOE vs Z in the new Figures, does not account for the effect of the long-term temperature trend, but that quantity is at least hydrostatic throughout the stratosphere. The small difference in pressure versus altitude for the HALOE ozone responses in the uppermost stratosphere is also consistent with the small responses in HALOE temperature versus altitude. I will make the above points in my revised manuscript.


SC-like O3 Response: SAGE, HALOE, Model
Brasseur Model, 5N
HALOE, 91 to 05
HALOE vs Z, 91 to 05
SAGE, 91 to 05
SAGE, 84 to 98
Pressure (hPa)
0.1
1.
10.
100.
Altitude (km)
64
48
30
16
-2
-1
0
1
2
3
4
5
6
Ozone Response, Max - Min (%)



SC-like O3 Response: Late 1992-2005
Brasseur Model, 5N
HALOE, 92 to 05
HALOE vs Z, 92 to 05
SAGE, 92 to 05
Pressure (hPa)
0.1
1
10
100.
Altitude (km)
64.
48.
30.
16.
-2
-1
0
1
2
3
4
5
6
Ozone Response, Max - Min (%)

SAGE II (40 km) and HALOE (3.4 hPa or 40 km) Ozone



Response to anonymous Referee #1

General comments

Rather than repeating myself, please see also my rather lengthy reply and the three figures in answer to the comments of the review of Mark Weber. I can now see that I ought to submit my revision as a research article upon your reminder to me of the criteria for a Technical Note to ACP.

The light and dark shadings of Figures 2-7 and Figure 10 indicate the domains, where the confidence intervals for the presence of the 11-yr or trend terms and of the significance of their amplitudes and phases in the zonally-binned, ozone time series at each altitude and latitude. In almost every instance the terms are quite significant. Of course, that conclusion also assumes that there is no remaining significant, periodic structure in the residual time series, and I routinely conduct a Fourier analysis of the residual to check for that possibility as part of my analysis. Early on in my regression analyses and when an additional periodic cycle was indicated, I added that additional term and checked to see whether it had significant amplitude. In almost every case its amplitude was small, and that term had little effect of the amplitudes and phases of the other terms. The presence of a sub-biennial term of period 21 or so months has been well documented for the middle and upper stratosphere by others (e.g., Dunkerton, JAS, 2001). That term is the result of a modulation between the QBO and annual cycles, and its amplitude is often of the same order as that of the QBO itself. I found that the period of this term varied between 20 and 22 months across the altitudes of the subtropical middle stratosphere, most likely because of slight variations in the period of the QBO forcing. I will include this discussion in the revised manuscript.

p. 25014, l 20—Figures 8 and 9 are an example of how well the regression model is fitting a given ozone time series. Figures 2-5 in Remsberg and Lingenfelser (RL, 2010) are also intended to convey the impression that the models are providing good fits to the observed variations in most cases. Of course, when the atmospheric ozone variations are small, the amplitudes of the individual terms are obscured somewhat by the more random-like variations for the measured transmission profiles and for the small number of occultation profiles making up the time series data points in a given latitude bin.

p. 25017 ff—Based on the work of Hood et al. (JGR, 2010) and Dhomse et al. (ACPD, 2011), I infer that the inclusion of a specific ENSO index term will make no difference in my results. I will delete my previous “speculative explanation” about the cause of the anomalous phase in the tropics, and refer the reader to the work of Hood et al. and references therein, instead. The inclusion of SAGE II analyses for the time span of 1984-98 is important because my results show that the rather large, SC-like upper stratospheric responses from the data of 1991-05 are not the result of a so-called "end point anomaly" in 1991-92. I also considered a case where I shortened the SAGE II ozone time series of 1984-98 by truncating the last two years of data. However, I found essentially no difference in the SC-like coefficients for the tropical upper stratosphere, indicating that my linear approximation of the declining effects of chlorine at those altitudes was adequate for the results from the entire 14 years.

Figure 9—I rechecked the residuals for any remaining periodic terms of significant amplitude and did not find any. This finding supports the conclusion that the altered phase in Figure 6 is because some other forcing is overwhelming the normal solar cycle effects at that time. This anomaly may be due to an episodic occurrence for the ozone that appears to have lasted for some months—possibly a result of a change in the Brewer/Dobson circulation and the associated perturbation in NOy (and NOx) at 30 to 35 km (e.g., Hood et al, JGR, 2010).

Figures 11 and 12 and related discussion—The most illuminating model result that I have found is from the recent studies of Dhomse et al., (2011), and I plan to refer to their findings more closely in my revised manuscript. The main point that I can add about their work is to remind readers about the trends and the SC-like responses that I reported from the HALOE temperatures at 43 km and higher (Remsberg, JGR, 2009). To my knowledge, the HALOE near-global temperature time series are the only other ones that are of good quality and continue for a span of years that encompasses one complete solar cycle. My analyzed temperature responses from HALOE are less than half those from analyses of the operational satellite temperature. Yet, the HALOE temperature responses and trends are able to explain most of the observed SAGE II ozone responses of the tropical upper stratosphere. Thus, it is clear that in order to monitor and interpret the expected, long-term recovery of ozone in the middle and upper stratosphere, one must obtain high-quality temperature time series, as well.