

Comments from Referee #1:

Box R1.1

General comments

The manuscript describes the response of the total column ozone to the variability of the solar irradiance simulated with CCM WACCM v.3.5 driven by different sets of spectral solar irradiance (SSI). The authors applied two SSI data sets: NRL reconstruction and the extrapolation of the recent data obtained by SORCE. The subject of the manuscript is relevant to the ACP scope and potentially interesting for the community. However, the manuscript has substantial flaws and I cannot recommend it for publication in the present form.

Specific comments

1. The applied SSI data sets are not properly described in the manuscript. It is not so crucial for well known NRL reconstructions, but absolutely necessary for the extrapolated SORCE SSI because Wang et al., (2012) paper is not available (in the reference list the status of this paper is “under review” and it is not clear what to do if this paper is not accepted for publication). Therefore, it is absolutely not clear what are the properties of the applied SORCE based SSI data set. Moreover, the extrapolated data set should be carefully justified, because there is no consensus in the community how to merge SORCE data with UARS measurements which are very close to NRL reconstructions.

We thank the referee for pointing this out. We agree that this information may be important and is worth of mentioning explicitly in this paper while Wang et al. (2012) is under reviewed. The extrapolated coefficients are shown a newly added figure in the supplementary material (Fig. S1). In response to this comment, lines 23–26 on page 1871 of the original manuscript:

“In order to simulate the modulation of a full solar cycle, we extrapolate the SORCE measurements back to the last solar maximum in 2002 using the Magnesium-II core-to-wing ratio (Mg-II c/w) index. The extrapolation procedure has been described in details by Wang et al. (2012).”

has been revised to

“To mimic a full solar cycle, the SORCE measurements are extrapolated back to the last solar maximum in 2002 using the Magnesium-II core-to-wing ratio (Mg-II c/w) index (Heath and Schlesinger, 1986). The Mg-II c/w index describes the variability of radiation from the solar chromosphere and is a good proxy for EUV wavelengths, especially at ~205 nm that is important for ozone chemistry. This index is defined as the ratio of the Mg-II H and K lines at ~280 nm to the wings of the absorption at ~276 and ~283 nm, which is less susceptible for instrument degradations. Long-term Mg-II c/w record has been constructed using different satellite measurements of exoatmospheric solar radiation since 1978, including SORCE after 2004 (Viereck et al., 2004; Snow et al., 2005). The

records from different measurements have been validated against each other and adjusted to composite a single continuous Mg-II c/w index (Viereck et al., 2004). Thus, for period during January 1, 2004 – November 30, 2007, correlation coefficients between the spectral variations observed by SORCE and the composite Mg-II c/w index are obtained for wavelengths between 115 and 340 nm. For wavelengths greater than 340 nm, the correlation coefficients between Mg-II c/w and the spectral variability are small and the correlation may not be robust. Using these correlation coefficients, the SORCE measurements are extrapolated back to January, 2002. As a result, the (extrapolated) UV variability during 2002 – 2007 is a factor of ~3 – 4 larger than those shown in Fig. 1 of Haigh et al. (2010); these scaling factors are shown in Fig. S1 in Supplementary Materials. For wavelengths greater than 340 nm, an arbitrary factor 3.5 is assigned. For comparison, the ratio of UV changes during 2002 – 2007 over that during 2004 – 2007 derived from the NRL model is also shown in Fig. S1. A similar extrapolation procedure has also been employed in Swartz et al. (2012), where $F_{10.7}$ is used instead of Mg-II c/w index.”

Box R1.2

The authors emphasized that the total ozone response to the solar irradiance variability simulated with the extrapolated SORCE SSI is close to the TOMS/SBUV data. The authors also mentioned that TOMS/SBUV data are better than ground based, therefore the overall conclusion is that the extrapolated SORCE SSI is closer to reality than UARS data. I do not think that this conclusion is solid and well supported by the presented results.

Our aim was to show the impact of using SORCE SSI variability on WACCM total column O_3 . We did conclude that the simulated response obtained using (extrapolated) SORCE SSI doubles that obtained using NRL SSI and the former is closer to the observed response from TOMS/SBUV data. However, we did not judge whether SORCE or NRL SSI data are more trust-worthy than the other nor did we say that the observed response from TOMS/SBUV is the only truth or “reality”. Indeed, we also showed the ground-based data to illustrate that TOMS/SBUV is only one of the available column O_3 measurements.

We cautioned the reader that the statistics of the ground-based measurements may be limited by the number of stations available in the tropics. We think that this is an objective statement. The TOMS/SBUV data has been validated against where there are ground-based station data. Any differences between these two datasets would likely come from geological factors that were not observed by the ground-based measurements. This argument seems to be supported by Figs. 1 and 2 of Fioletov et al. (2002), in which the difference between TOMS and ground-based data is smaller in the northern hemisphere, where there are more ground stations.

We appreciate the reviewer for pointing this out and agree that we may have confused the reader with this potentially biased statement. In response to this comment, we have revised lines 15–19 in the abstract (page 1868):

“The solar-cycle responses simulated using SORCE SSI agree with those obtained from the merged TOMS/SBUV satellite observations. Using NRL SSI as a model input yields solar-

cycle responses that are closer to the ground-based observations, although the accuracy of the latter is limited by the number of stations in the tropics.”

to

“In the tropical region 24°S–24°N, using the SORCE SSI as a model input leads to a solar-cycle response of ~ 5.4 DU/100 $F_{10.7}$, which agrees with those obtained from the merged TOMS/SBUV satellite observations. ... In contrast, using NRL SSI as input yields a X_{O_3} solar response of ~ 3 DU/100 $F_{10.7}$, which is only \sim half of that obtained using SORCE SSI but agrees better with the SAGE and ground-based observations.”

In addition, we highlighted both the shortcomings of using NRL or SORCE SSI as model inputs when comparing the vertical O₃ response with observations:

“The resultant vertical O₃ response [obtained using SORCE SSI] agrees with previous satellite measurements in the lower stratosphere but the negative response in the upper stratosphere disagrees with the observed ... [In contrast,] the resultant vertical O₃ response obtained using NRL SSI agrees with previous satellite measurements in the upper stratosphere but the lower stratospheric response is much weaker than the observed. This presents a dilemma to our current understanding of stratospheric O₃ response to UV perturbations.”

We have also removed the regression coefficients of TOMS/SBUV in Figs. 3 and 4.

Please also see Boxes R2.2 and R2.10.

Box R1.3

2. The choice of observation data for the comparison with model results is strange. In the text and in Figure 2 caption the authors said that they use TOMS/SBUV and ground-based data extracted from Randel and Wu, 2007 (I guess, the authors used Figure 12 and not Figure 6 as stated in the text).

We thank the reviewer for correcting us on the figure number in Randel and Wu (2007). We have revised the text accordingly.

Box R1.4

The paper by Randel and Wu (2007) is mostly devoted to the analysis of SAGE data complemented by ozone profiles measured by ozone-sondes. The response of the total ozone to solar variability depicted in their Figure 12 shows the SAGE and TOMS/SBUV data obtained by Randel and Wu (2007) in comparison with ground-based and SBUV data obtained from other sources (WMO, 2003). The authors used only TOMS/SBUV and ground-based data omitting SAGE data. Probably they did it because SAGE data are in better agreement with ground-based data and do not support the author’s conclusions.

We excluded SAGE data in our draft because SAGE “column O₃” shown in Figure 12 of Randel and Wu (2007) was partially integrated between 20 – 50 km. On the other hand, our aim was to discuss the total column O₃ response to the solar cycle modulation and TOMS was canonically designed for measuring total column O₃. In an attempt to explain the differences between the solar responses derived from SAGE and TOMS, Randel and Wu (2007) stated: “*The differences could be reconciled by an additional solar component in profile ozone below 20 km.*” But “[n]ote that Chandra et al. [1999] have deduced a solar signal in tropical tropospheric ozone, but that variation is out of phase with the stratospheric signal (i.e., of the wrong sign to account for the differences in Figure 12b).” Therefore, they concluded that “*given the uncertainties between results from the three column ozone data sets, it is difficult to critically evaluate the solar cycle derived from the integrated SAGE results.*”

We understand that omitting SAGE results might lead to a bias. We have added the SAGE results in our revised Fig. 2. In response to this comment, we revised the first paragraph on page 1870 of the original manuscript:

“Randel and Wu (2007) derived the meridional pattern of the 11-year solar-cycle sensitivity in X_{O₃} [in Dobson units (DU) per 100 units of 10.7-cm solar radio flux ($F_{10.7}$; Tapping and Detraçey, 1990) or DU/100 $F_{10.7}$] from the merged TOMS/SBUV data using multiple linear regression. In the equatorial region, the derived sensitivity is 5–6 DU/100 $F_{10.7}$. However, when the same regression is applied to the ground-based data, the resultant sensitivity is 2–3 DU/100 $F_{10.7}$, which is half of that derived from the satellite data. The discrepancy between the ground-based and the satellite measurements is serious but the satellite-derived result is probably more reliable because there are few ground stations in the tropics (Fioletov et al., 2002; Randel and Wu, 2007).”

to

“Randel and Wu (2007) derived the meridional pattern of the 11-year solar-cycle sensitivity in X_{O₃} [in Dobson units (DU) per 100 units of 10.7-cm solar radio flux ($F_{10.7}$; Tapping and Detraçey, 1990) or DU/100 $F_{10.7}$] from the merged TOMS/SBUV data using multiple linear regression. In the equatorial region, the derived sensitivity from TOMS/SBUV data was 5–6 DU/100 $F_{10.7}$. They compared this sensitivity to that of the partial column O₃ between 20–50 km integrated from the SAGE measurements during 1979–2005. The resultant sensitivity from SAGE was 2–3 DU/100 $F_{10.7}$ only, which is half of that derived from the TOMS data but agrees with those derived from the ground-based X_{O₃} measurements.”

Box R1.5

Moreover, the total ozone response to the solar irradiance variability was analyzed in WMO (2003, section 4.2.6.1) and the disagreement between the ground-based and merged satellite data was partially explained (see also Appendix 4A) by some problems with TOMS data. I think all these issues should be properly discussed to avoid any misinterpreting of the results.

We thank the reviewer for mentioning this important information about the TOMS data.

The TOMS data used in WMO (2003) were based on version 7 processing. On the other hand, the TOMS data used by Randel and Wu (2007) and in our work were based on version 8 processing. We contacted with Dr. Richard D. McPeters at Goddard Space Flight Center. He confirmed with us that version 8 processing has corrected that particular retrieval error in version 7 processing. Therefore, we believe that the disagreement between the ground-based, SAGE and TOMS data were not due to that retrieval error. In response to this comment, we added the following descriptions at the end of the first paragraph on page 1870 of the original manuscript:

“There has been concern whether an erroneous treatment of an instrumental toggling of TOMS in 1983 might have created the apparently large X_{O_3} solar response (WMO, 2004, Appendix 4A.2). However, this error has been corrected in the latest TOMS retrieval algorithm (version 8) and Randel and Wu (2007) used version 8 retrievals for their analysis. Therefore, the discrepancy among the TOMS/SBUV, SAGE, and ground-based X_{O_3} solar responses are unlikely due to the toggling problem.”

Box R1.6

3. The performed model runs are useful and help to understand the model sensitivity to the external forcing; however the lack of volcanic aerosol, QBO as well as constant chlorine loading (and possibly constant greenhouse gases) makes the comparison of the model results with observation data very doubtful. To justify the absence of volcanic aerosol the authors stated that “Aerosol effects are considered to be negligible (Randel and Wu, 2007)”. I think this statement is completely wrong. Randel and Wu (2007) excluded volcanic term from their regression analysis due to the problem with SAGE data. They stated “Note that we do not include a volcanic aerosol proxy term in our statistical analysis (as in work by Stolarski et al. [2006]), because there are no SAGE data available for post-volcanic periods (the eruption of El Chichon (April 1982) occurred during the SAGE I and II data gap, and SAGE II data are unavailable after the eruption of Mt. Pinatubo in June 1991, as discussed above).

We thank the reviewer for this comment. We have removed the quoted statement. Our simulation does not have volcanic aerosol emissions. Therefore, our regression analysis of the model outputs is not subject to the major eruptions in 1982 and 1991. Please also see Box R1.7. In response to this comment, we added a paragraph at the end of Section 3 “Multiple linear regression”:

“Note that Randel and Wu (2007) omitted about two years of O_3 observations after the volcanic eruption in 1982 (El Chichon) and 1992 (Pinatubo) to reduce aliasing effects with aerosol loadings. Since we have fixed the background aerosol level, we don’t omit these years in our regression analysis.”

Box R1.7

The importance of volcanic aerosol for the total ozone and especially for the proper detection of the solar signal (due to possible aliasing) has been widely discussed in the literature during last 30 years.

We agree that the presence of volcanic aerosol may lead to lower O₃ level in the lower stratosphere. However, how the aerosol effects may couple/statistically contaminate the observed solar O₃ response is not our focus. On the other hand, to avoid any statistical aliasing in our estimated model O₃ response, we made our model runs without volcanic aerosol emissions. This should allow more accurate extraction of the model O₃ solar response.

In response to this comment, we added a paragraph after line 24 in page 1872 of the original manuscript:

“The presence of enhanced aerosol loading due to major volcanic eruptions (e.g. El Chichon in 1982 and Pinatubo in 1992) may reduce O₃ concentrations in the lower stratosphere due to enhanced chlorine activation. In a model study, Dhomse et al. (2011) showed that the estimation of the lower stratospheric O₃ responses can be amplified through the aliasing with volcanic aerosol emissions. They demonstrated that running the model with fixed dynamics or constant aerosols will help minimize the aliasing effect. Thus, in our simulations, we will adopt a constant background aerosol loading.”

Box R1.8

The role of QBO is also very important and discussed in the literature. The absence of these important drivers is crucial for the proper validation of the simulated solar response against observation data.

We agree that studying the subtle interaction between QBO and the solar forcing in model O₃ would be an important subject. However, Austin et al. (2008) have shown that the simulated O₃ solar responses from 7 chemistry-transport models (including WACCM without QBO) agree with each other, whether or not the models have a QBO implementation. Schmidt et al. (2010) and Dhomse et al. (2011) [both new references in the revised manuscript] also concluded that the simulated O₃ solar response is insensitive to the QBO effect. Unfortunately the version of the WACCM model being used in this study does not have a QBO implementation and we cannot repeat Austin et al.’s experiment. Nonetheless, we are well aware of the QBO effects and we stated explicitly in Section 5 of the original manuscript that future investigations must also include QBO in the simulations. Performing a more realistic simulation of O₃ with more natural forcings (e.g. aerosols and QBO) is one of our future goals.

Box R1.9

4. The last paragraph of the section 5 is really mysterious. The authors discuss warming in the lower stratosphere without any explanation/illustration. The reader cannot even guess where this effect is coming from.

We agree that such description may not be mature. We have removed the related statements in the abstract and Section 5 as requested. Please also see Box R2.3.

Box R1.10

5. The reasons for the total ozone enhancement for the solar maximum conditions are not properly discussed. In most cases the authors say that "... an enhanced production of stratospheric O₃ at wavelength below 240 nm ..." is responsible. However, this photochemical process cannot explain the secondary maximum of ozone and temperature responses to the solar irradiance variability observed in the lower tropical stratosphere. The chain of processes responsible for this feature has been widely discussed in the literature and should be mentioned in the text and illustrated using the model results.

We thank the reviewer for asking the underlying mechanism of the O₃ response. We think this problem is still under debate.

The discrepancy between model and observed profile O₃ response to the 11-year can be traced back to early 1990s, when satellite records of stratospheric O₃ and temperature started exceeding a length of one solar cycle. Hood et al. (1993) derived the first 11-year solar cycle O₃ response using satellite data and they found that the response has a primary maximum in the upper stratosphere, a secondary maximum in the lower stratosphere, and an insignificant response in the middle stratosphere. In contrast, Brasseur (1993), who was among the first who used a 2-D chemistry-radiative-dynamics model to simulate the solar cycle O₃ response, predicted a very different O₃ response profile which has only a single peak in the middle stratosphere. This discrepancy persisted for more than a decade since their work (e.g. Fleming et al., 1995; Haigh, 1994; Shindell et al., 1999*; Soukharev and Hood, 2006).

Recently, Austin et al. (2008) showed that 3-D chemistry-radiative-dynamics models are able to produce the observed double-peak structure in the O₃ response. Their result may have suggested that stratospheric dynamical response, e.g. weakened Brewer-Dobson circulation (Kuroda and Kodera, 2002) as a result of changes in stratospheric thermal structures, should be responsible for the secondary peak in the lower stratosphere. Other hypotheses include solar-QBO and solar-ENSO interactions. However, Dhomse et al. (2011) have shown that the simulated vertical O₃ solar response is insensitive to QBO or ENSO effects. A more recent study by Swartz et al. (2012; a new reference in the revised manuscript) has shown (based on the NRL flux) that the lower stratospheric maximum can also be produced in GOES-CCM with the solar-cycle response in photolysis only, where QBO and ENSO are absent in the model. They also showed that the solar-cycle response in atmospheric heating does not impact the simulated O₃ response significantly. Swartz et al.'s result thus agrees with our assertion that enhanced O₃ production at wavelengths below 240 nm seems to be a major factor that determines the O₃ response to the solar cycle modulation. Dhomse et al. (2011) have also argued that the tropical lower stratospheric response should mostly be photochemically driven, although their model does not simulate the temperature response correctly.

We agree that if we are to make the quoted statement, a more detailed explanation would be needed. We defer detailed model diagnostic to our future work. Thus we have removed the quoted statement in the revised manuscript. As requested by the review, we added a new second paragraph in “Introduction” which briefly summarizes previous efforts on simulating the vertical O₃ response (excerpted):

“Based on long-term satellite measurements from Halogen Occultation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment (SAGE) and Solar Backscatter Ultraviolet (SBUV), the observed stratospheric O₃ response to the 11-year solar cycle forcing shows a double-peak structure: There are two positive peaks of a few percents in the upper (~45 km) and lower (~20 km) stratosphere and an insignificant response in the middle stratosphere (~30 km) (Hood et al., 1993; McCormack and Hood, 1996; Soukharev and Hood, 2006). However, standard photochemistry only predicts a single peak of a few percents at ~35 km. (Brasseur, 1993; Haigh, 1994; Tourpali et al., 2003; Egorova et al., 2004) ... Austin et al. (2008) summarized the O₃ responses to the 11-year solar cycle forcing in seven CCMs (including the model to be used in this study) ... The O₃ responses show a significant spread among the models in the lower stratosphere, which may be a result of aliasing with volcanic aerosol emissions and/or effects of El Niño/Southern oscillation (ENSO) (Marsh and Garcia, 2007; Dhomse et al., 2011). Nevertheless, the mean of the model O₃ responses does exhibit a double-peak structure that resembles the observations. The upper stratospheric peak is likely related to direct photolysis of molecular oxygen at wavelengths less than 240 nm. The exact mechanism that leads to the lower stratospheric peak is not clear; it has been argued that dynamical responses, e.g. weakened Brewer-Dobson circulation (Kodera and Kuroda, 2002) resulted from stratospheric temperature changes, may be responsible. But a recent study by Swartz et al. (2012) suggests that the lower stratospheric response is largely dependent on photolysis and is insensitive to the thermal feedback. Finally, it has been argued that the middle stratospheric minimum may be due to the coupling between the solar forcing and the quasi-biennial oscillation (QBO) (McCormack et al., 2007). However, Austin et al. (2008) have shown that the simulated O₃ solar responses from the seven CCMs agree with each other, whether or not the models have a QBO implementation. Schmidt et al. (2010) and Dhomse et al. (2011) also concluded that the simulated O₃ solar response is insensitive to the QBO effect.”

* Shindell, D., D. Rind, N. Balachandran, J. Lean, and P. Lonergan: Solar cycle variability, ozone, and climate, *Science*, 284, 305–308, doi:10.1126/science.284.5412.305, 1999.

Box R1.11

I think, it is necessary to show not only the total ozone response but also the vertical structure of the ozone and temperature responses to understand which layers and mechanisms are responsible for the total ozone changes.

As mentioned in Box R1.10, discussions on the dynamical/temperature responses would be much involved. We will focus on O₃ in the paper and discuss other interesting factors in the future.

The vertical structure of the ozone response simulated by WACCM has already been published by Merkel et al. (2011). Quantitatively, Merkel et al. only showed the response for 2004 – 2007, whereas we report sensitivity in 100 units of $F_{10.7}$. Our simulated responses are very similar to Merkel et al.'s. As requested by the reviewer, we have added a new figure (Fig. 6), which compares the simulated tropical O₃ response between 25°N and 25°S with the observations reported in Soukharev and Hood (2006). In response to this comment, a new subsection (Section 4.4) has been added to describe the comparison.

Box R1.12

Minor comments and technical corrections

I think that the manuscript should be completely rewritten; therefore I do not describe many minor errors and unclear statements in the text.

We appreciate for the reviewer's time. Our manuscript cannot be improved without the reviewer's comments.

Comments from Referee #2:

Box R2.1

General Comments:

This paper contains a lot of interesting and timely information. It compares the atmospheric response in total column ozone in the WACCM model using the 11-year solar cycles in solar spectral irradiance (SSI) according to (a) the Naval Research Laboratory (NRL) reconstruction and (b) the SORCE mission. It has a good discussion of the recent literature and issues. I cannot recommend publication in its current form, however. A major conclusion of this paper, as I read it, is that the total column ozone simulated with the WACCM model using the SORCE SSI agrees better with TOMS/SBUV than when the NRL SSI is used, so therefore SORCE must be correct. Insufficient evidence for this conclusion is provided. Figure 2 summarizes the results: WACCM/SORCE agrees better with TOMS/SBUV; WACCM/NRL agrees better with ground-based observations. I suspect if the uncertainty in the solar cycle inferred from the ground-based measurements were included in Fig. 2 that we would see that the satellite and ground-based data are actually in statistical agreement. Further, quoting Randal and Wu, "Overall, given the uncertainties between results from the three column ozone data sets [ground-based, SBUV, and TOMS/SBUV], it is difficult to critically evaluate the solar cycle derived from the integrated SAGE results" (Randal and Wu, 2007).

This comment is similar to that in Box R1.2. To further clarify our neutrality about SORCE/NRL SSI, we added a new third paragraph in "Introduction" (excerpted):

"In most of previous modeling studies (e.g. Marsh and Garcia, 2007; Austin et al., 2008; Dhomse et al., 2011), the 11-year solar forcings in UV are reconstructed by the Naval Research Laboratory (NRL) using long-term sunspot and faculae records (Lean, 1997, 2000) ... It has been shown that SORCE SSI may lead to solar-cycle responses in the middle atmospheric O₃ and temperature that are significantly different from those obtained using NRL SSI (Cahalan et al., 2010; Haigh et al., 2010; Merkel et al., 2011). For example, Haigh et al. (2010) showed that the simulated O₃ trend between 2004–2007 becomes negative in the tropical upper stratosphere above 45 km if the SORCE SSI is used. This is in contrast to the model simulation if the NRL SSI is used, which predicts positive O₃ trends in the whole tropical stratosphere ... Merkel et al. (2011) showed that the simulated negative O₃ trend in the tropical mesosphere is much larger when SORCE SSI is used and agrees better with SABER observations during 2002–2009. But they also noticed that the model response in the middle stratospheric O₃ does not agree with the observations ... Continuous investigations are required to resolve the discrepancies between models and observations."

Box R2.2

I think the logic applied to SAGE in their paper could be applied to the WACCM results in the present paper. Li et al. reject the ground-based measurements on the grounds that they are “probably [less] reliable because there are few ground stations in the tropics (Fioletov et al., 2002; Randel and Wu, 2007)” (see present paper p. 1870, lines 7–10). This is not an obvious conclusion of the two papers cited, so if the verdict concerning NRL vs. SORCE hinges on this tenuous decision to throw out the ground-based observations, then it needs to be argued convincingly. (And in any event, using a CCM is a very indirect way to resolve the NRL–SORCE discrepancy.)

This comment is similar to that in Box R1.4. We have removed the quoted statement and have added SAGE data in our revised manuscript. Please see our reply in Box R1.4.

Box R2.3

Specific Comments:

[Abstract] “The solar-cycle response obtained using SORCE SSI implies a maximum change in lower stratospheric temperature of 0.8 K.” This is not shown in this paper and not even mentioned until the last paragraph of the entire paper, in the Summary and discussions. Please remove from Abstract and final section unless the details are added to the body of the paper.

We have removed the quoted statement. Please also see Box R1.9.

Box R2.4

[Sect. 1–Introduction] “... enhanced during a solar-cycle maximum through the absorption of anomalously high UV radiation . . .” This is solar maximum, not anomalous.

In that statement (line 10, page 1869 of the original manuscript), “anomalously high” is replaced by “enhanced”.

Box R2.5

[Sect. 2–Model setup] SORCE SSI description: As noted by Reviewer #1, both the SSI and extrapolation to solar maximum conditions must be described/shown. The Wang et al. PNAS reference is apparently still not available, as of today. Also, what is the source of the SORCE/SIM data? Only wavelengths >310nm are publicly available on-line.

For the extrapolation procedure, please refer to our reply in Box R1.1. Our SORCE/SIM data has been provided directly by the SORCE/SIM team. We added a statement in Acknowledgement:

“SORCE/SIM data for wavelengths greater than 300 nm have been kindly provided by the SORCE/SIM team.”

Box R2.6

[Sect. 2–Model setup] The authors say that WACCM uses $F_{10.7}$ as a proxy of the solar cycle, along with sunspot number, etc. What does this mean in the context of specified SSI (extrapolated using the Mg II index in the case of SORCE)? What is the model actually using for SSI as a function of time?

We apologize for the unclear description. Given a reference UV spectrum, WACCM first defines the solar-cycle UV variability by the ratio of solar max over solar min at individual wavelengths. Then the spectral solar variability for all wavelengths at intermediate solar cycle phases follows that of $F_{10.7}$. In response to this comment, we have revised the following paragraph:

“In the WACCM model, $F_{10.7}$ serves as a proxy for the solar cycle. The corresponding variability in the UV region is characterized by the fractional changes from the (extrapolated) solar maximum of Solar Cycle 23 in 2002 to the solar minimum in 2007. The spectral variability is assumed to follow the phase of $F_{10.7}$. The model also requires other solar quantities including the sunspot number and the daily planetary K and a indices. The stratospheric chlorine has been fixed in the simulations.”

to

“To drive a solar cycle variation in WACCM, the solar variability in the UV region is characterized by the fractional changes from the (extrapolated) solar maximum of Solar Cycle 23 in 2002 to the solar minimum in 2007. Then for all wavelengths, the evolution from a solar maximum to a solar minimum is assumed to follow that of $F_{10.7}$. The stratospheric chlorine has been fixed in the simulations.”

Box R2.7

[Sect. 2–Model setup] “... the realistic SST/ice also includes a tiny solar-cycle variability of 0.1 K peak-to-trough (Zhou and Tung, 2010).” Ironically, the solar cycle variability embedded in the SSTs is in phase with TSI, whereas the SORCE mission claims that visible wavelengths are out of phase. This is probably not a significant inconsistency, however, as this study finds that the effect from the SST solar cycle is not statistically significant.

We are aware of this issue in the visible wavelengths but there are controversies over the topic. Our concern is in UV. We want to avoid discussing the variability at visible wavelengths and their tropospheric consequences in this work. However, we are interested in exploring this issue more deeply in the future.

Box R2.8

[Sect. 4.1–Topical averages ...] “This is because of an enhanced production of stratospheric O3 at wavelengths below 240nm as revealed in the SORCE SSI.” This quite possibly is the case, but it is not shown in this paper. In fact, the SSI is not even revealed (see comment, above).

This comment is similar to that in Box R1.10. To reiterate, our assertion has been supported by the work of Swartz et al. (2012), who has shown, by switching on/off the solar forcings in heating and photolysis independently, that photolysis is the major contributor of the ozone response in the stratosphere. But we agree that if we would like to make that assertion, then more detailed descriptions will be required. Therefore, we have removed that statement in our revised manuscript. Please also refer to Box R1.10.

Box R2.9

*[Sect. 4.2–Latitudinal patterns ...] “This should also highlight the use of the latest **SORCE SSI data since the larger UV variability would lead to a stronger signal . . .**” Would like to, but the **SORCE/SIM data are not publicly available below 310 nm.***

We agree that the quoted statement is not appropriate before the **SORCE/SIM** becomes public. We have removed the quoted statement.

Box R2.10

*[Sect. 4.3–Tropical spatial patterns ...] “For comparison, we apply the same regression analysis to the monthly-averaged **TOMS/SBUV data (Randel and Wu, 2007; Stolarski et al., 2006).**” Note that **Stolarski et al. did, in fact, include volcanic eruptions in their regression analysis. Why is it all right to exclude them in this case?***

Thanks for pointing this out. We followed the procedure of Randel and Wu (2007) and excluded 2 years of O₃ data after El Chichon (April 1982) and Pinatubo (June 1991). This is slightly different from the regression adopted by Stolarski et al. (2006). In any case, we have removed the regression analysis of TOMS/SBUV data from this work.

Box R2.11

*[Sect. 5–Summary and discussions] “... using **spectral solar variability in UV derived from a conventional model developed in NRL and that from the SORCE measurements.**” One could infer from this statement that the **NRL SSI is pure model and the SORCE SSI is pure measurement. This is most definitely not the case. The NRL SSI is a reconstruction that includes many years of pre-SORCE satellite observations. And the SORCE solar cycle in SSI has to be inferred assuming instrument degradation and other factors.***

We agree with this comment. The quoted statement has been rewritten as:

“... spectral solar variability in UV reconstructed by NRL using long-term sunspot and faculae records as proxies ...”

Box R2.12

*[Sect. 5–Summary and discussions] “The reason is an enhanced production of stratospheric O3 at wavelengths below 240nm as revealed in the **SORCE SSI**.” Please see comment on enhanced O3 production, above.*

Same as Box R2.8.

Box R2.13

*[Sect. 5–Summary and discussions] “Final paragraph, starting **The above results may lead to . . .**” This discussion, largely on solar cycle heating, should either be shown/explained in greater detail in the body of the paper or removed.*

We have removed this paragraph in the revised manuscript as requested.

Box R2.14

Technical Corrections:

- **[p. 1872, line 13]** *In other to isolate the effects due . . . “other” should be “order.”*
- **[p. 1876, line 13]** *Fig. 6 of Randal and Wu (2007). Should be Fig. 12. Same for caption of the present paper’s Fig. 2.*

Thanks for pointing these out. We have made the revision accordingly.

Comments from S. Dhomse

Box D.1

I think this manuscript present some interesting results. And although Authors do not discuss vertical structure of the solar response in the tropical stratosphere, some of these results are consistent with our conclusions in Dhomse et. al, ACP, 2011. Authors should try to include some of the following points in the introduction and discussion.

1. SORCE data - There are some uncertainties in SORCE irradiances. Authors should include some discussion about these issues. (Also see Kopp and Lean, GRL, 2011)

We thank for this note. We are aware of recent analyses of the SORCE irradiances. Uncorrected instrumental drifts have been reported during the review process of this work. We caution the reader about these instrumental drifts in the revised manuscript in “Introduction” and “Summary and Conclusions”. In the second last paragraph of “Introduction”, we added:

“Recent analyses of SORCE data (Lean and DeLand, 2012; DeLand and Cebula, 2012) reveal that uncorrected instrumental drifts may have resulted in an overestimated UV variations during 2004 – 2007 as reported in Haigh et al. (2010). The work here thus presents an upper limit of the impact associated with the difference of UV changes suggested by these two measurements.”

Box D.2

2. Lower stratospheric solar response is the main contributor to the total ozone response. In our paper, we have shown that this lower stratospheric solar response in excellent agreement with the observed (HALOE, SAGE, SBUV) solar response if we use fixed dynamical conditions for our simulations. However, transient simulations with ERA-40 and ERA-interim give much larger lower stratospheric response. And our conclusion is that enhanced chlorine activation during high volcanic aerosol loading and some of the inhomogeneities in reanalysis data sets (both ERA-40 and ERA-interim) give rise to this response. This is consistent with Exp E in present study, as WACCM should not have any inhomogeneity issues. However, author should clarify if they use volcanic aerosols or not.

We did not impose volcanic aerosols in our simulation. In response to this comment, we added the paragraph quoted in Box R1.7 in Section 2 “Model setup”.

Box D.3

3. Very little differences in TOZ between transient and fixed SST i.e. ENSO does not play important role in modifying lower stratospheric solar response - Again this is consistent with our conclusions. Similar to Hood et al., 2010.

In response to this, we added in “Summary and Conclusions”:

“We have also shown that the inclusion of ENSO in the model runs does not statistically modify the simulated solar sensitivity, which is consistent with the conclusion by Dhomse et al. (2011).”

Box D.4

4. Authors can also add some discussion that lower stratospheric solar response (which is very important for solar response in total ozone) is probably of photo-chemical origin and QBO-SST are not important to simulate this response

We have added a new subsection (Section 4.4) describing the vertical responses. Please refer to Box R1.11.

Box D.4

5. Authors should also clarify if solar variations are included in both chemistry and radiation scheme or just in chemistry scheme.

At the end of “Introduction”, we added

“Swartz et al. (2012) examined individual effects of photolysis and direct heating separately; in our study, the solar variations are included in both chemistry and radiation.”

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Simulation of solar-cycle response in tropical total column ozone using **SORCE** irradiance

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Abstract

The solar-cycle signal of tropical total column ozone X_{O_3} in the Whole Atmosphere Community Climate Model (WACCM) model has been examined using solar spectral irradiance (SSI) estimated from the Naval Research Laboratory (NRL) solar model and that from recent satellite measurements observed by the Solar Radiation and Climate Experiment (SORCE). Four experiments have been conducted with NRL/SORCE SSI and climatological/realistic sea surface temperatures and ice, and all other variability is fixed to test the robustness of the simulated solar response in O_3 against the presence of El Niño/Southern Oscillation (ENSO). We found that potential aliasing effects from ENSO occurs below 20 km where tropical O_3 concentration is low and has little impact (less than $\sim 0.6 \text{ DU}/100F_{10.7}$) on the regressed X_{O_3} response. In the tropical region 24°S – 24°N , using the SORCE SSI as a model input leads to a solar-cycle response of $\sim 5.4 \text{ DU}/100F_{10.7}$, which agrees with those obtained from the merged Total Ozone Mapping Spectrometer (TOMS)/Solar Backscatter Ultraviolet (SBUV) satellite observations. The resultant vertical O_3 response agrees with previous satellite measurements in the lower stratosphere but the negative response in the upper stratosphere disagrees with the observed. In contrast, using NRL SSI as input leads to a solar response of $\sim 3 \text{ DU}/100F_{10.7}$, which is only \sim half of that obtained using SORCE SSI but agrees better with the Stratospheric Aerosol and Gas Experiment (SAGE) and ground-based observations. Furthermore, the resultant vertical O_3 response obtained using NRL SSI agrees with previous satellite measurements in the upper stratosphere but the lower stratospheric response is much weaker than the observed. This presents a dilemma to our current understanding of stratospheric O_3 response to UV perturbations. Continuous O_3 measurements through the next solar maximum (expected in 2013–2014) will be valuable for resolving this dilemma.

1 Introduction

The solar-cycle variability has long been believed to have impacts on Earth's climate (Her-

schel, 1801). Of only $\sim 0.1\%$ peak-to-trough variations in the total solar irradiance, the 11-year solar-cycle variability is most noticeable in the ultraviolet (UV) regions. The variability ranges from $\sim 70\%$ at the hydrogen Lyman- α transition line (121.57 nm) to $\sim 10\%$ in 200–300 nm (Marsh et al., 2007). Therefore, any impacts on Earth's climate are likely to be linked through upper atmospheric regions where UV is absorbed. For example, Meehl et al. (2009) suggests a top-down mechanism, wherein the production of tropical stratospheric ozone (O_3) is enhanced during a solar-cycle maximum through the absorption of enhanced UV radiation by the oxygen molecule in the Schumann-Runge band (150–240 nm), which in turn leads to an enhanced UV absorption by ozone in the Hartley band (240–310 nm) (Brasseur and Solomon, 1984; Herzberg, 1965). The different heating of the stratosphere as a function of latitude due to these absorption processes may modify the tropospheric circulation, leading to changes in the hydrological cycle (van Loon et al., 2007; Meehl et al., 2009). Since the solar irradiance is strongest over the equatorial region and the stratospheric O_3 is produced mainly in the tropical area, we expect maximum solar-cycle modulation in the tropical O_3 (Camp et al., 2003). Such solar-cycle modulation can also be transported to higher latitudes by the Brewer-Dobson circulation in the middle atmosphere (Brasseur, 1993; Ineson et al., 2011).

Based on long-term satellite measurements from Halogen Occultation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment (SAGE) and Solar Backscatter Ultraviolet (SBUV), the observed stratospheric O_3 response to the 11-year solar cycle forcing shows a double-peak structure: There are two positive peaks of a few percents in the upper (~ 45 km) and lower (~ 20 km) stratosphere and an insignificant response in the middle stratosphere (~ 30 km) (Hood et al., 1993; McCormack and Hood, 1996; Soukharev and Hood, 2006). However, standard photochemistry only predicts a single peak of a few percents at ~ 35 km. (Brasseur, 1993; Haigh, 1994; Tourpali et al., 2003; Egorova et al., 2004). A number of groups have tried to simulate the O_3 response using three-dimensional (3-D) coupled radiation-dynamics-chemistry models, which are also known as chemistry-climate models (CCMs) (Marsh et al., 2007; Schmidt et al., 2010; Dhomse et al., 2011; Swartz et al., 2012 and references therein). Austin et al. (2008) summarized the O_3 responses to the 11-year solar cycle forcing in seven CCMs (including the model to be used in this study). They performed transient simulations with anthropogenic

forcings, observed sea surface temperature and atmospheric aerosol concentration. The O₃ responses show a significant spread among the models in the lower stratosphere, which may be a result of aliasing with volcanic aerosol emissions and/or effects of El Niño/Southern oscillation (ENSO) (Marsh and Garcia, 2007; Dhomse et al., 2011). Nevertheless, the mean of the model O₃ responses does exhibit a double-peak structure that resembles the observations. The upper stratospheric peak is likely related to direct photolysis of molecular oxygen at wavelengths less than 240 nm. The exact mechanism that leads to the lower stratospheric peak is not clear; it has been argued that dynamical responses, e.g. weakened Brewer-Dobson circulation (Kodera and Kuroda, 2002) resulted from stratospheric temperature changes, may be responsible. But a recent study by Swartz et al. (2012) suggests that the lower stratospheric response is largely dependent on photolysis and is insensitive to thermal feedback. Finally, it has been argued that the middle stratospheric minimum may be due to the coupling between the solar forcing and the quasi-biennial oscillation (QBO) (McCormack et al., 2007). However, Austin et al. (2008) have shown that the simulated O₃ solar responses from the seven CCMs agree with each other, whether or not the models have a QBO implementation. Schmidt et al. (2010) and Dhomse et al. (2011) also concluded that the simulated O₃ solar response is insensitive to the QBO effect.

In most of previous modeling studies (e.g. Marsh and Garcia, 2007; Austin et al., 2008; Dhomse et al., 2011), the 11-year solar forcings in UV are reconstructed by the Naval Research Laboratory (NRL) using long-term sunspot and faculae records as proxies (Lean, 1997, 2000). Recent spaceborne observations of exoatmospheric spectral solar irradiance (SSI) by the Solar Radiation and Climate Experiment (SORCE) reveal unexpectedly large solar-cycle variability from UV to visible regions during the declining phase of Solar Cycle 23 (since 2004), which may lead to different climate responses from what has been conventionally accepted (Haigh et al., 2010). It has been shown that SORCE SSI may lead to solar-cycle responses in the middle atmospheric O₃ and temperature that are significantly different from those obtained using NRL SSI (Cahalan et al., 2010; Haigh et al., 2010; Merkel et al., 2011). For example, Haigh et al. (2010) showed that the simulated O₃ trend between 2004–2007 becomes negative in the tropical upper stratosphere above 45 km if the SORCE SSI is used. This is in contrast to the model simulation if the NRL SSI is used, which predicts positive O₃ trends in the whole

tropical stratosphere. Their simulation seems to be supported by the recent observation by the Microwave Limb Sounder (MLS). Meanwhile, using the three-dimensional Whole Atmosphere Community Climate Model (WACCM), Merkel et al. (2011) showed that the simulated negative O_3 trend in the tropical mesosphere is much larger when *SORCE* SSI is used and agrees better with *SABER* observations during 2002–2009. But they also noticed that the model response in the middle stratospheric O_3 does not agree with the observations. In addition, *SORCE*, *MLS* and *SABER* data only cover part of the declining Solar Cycle 23 and great care must be taken when interpreting these trend comparisons. Continuous investigations are required to resolve the discrepancies between models and observations.

Besides the vertical O_3 profiles, there have also been long-term spaceborne measurements of total column O_3 (hereafter denoted by X_{O_3}) during 1978–2004 by the Total Ozone Mapping Spectrometer (*TOMS*) and *SBUV* (Stolarski et al., 2006). X_{O_3} after 2004 has been measured by Ozone Monitoring Instrument aboard *Aura*, which is the successor of *TOMS*. These observations merged together provide the longest satellite record of X_{O_3} for exploring interannual and decadal variabilities. These X_{O_3} measurements use UV bands that are different from those used for profile O_3 retrievals. In addition, since the lower stratospheric response to the 11-year solar forcing is the main contributor to the X_{O_3} response, comparing the observed and model X_{O_3} responses may serve as an independent test for model sensitivity to the 11-year solar forcing in the lower stratosphere. There are also long-term ground-based measurements of total column O_3 which are sparse in both space and time (Fioletov et al., 2002).

Randel and Wu (2007) derived the meridional pattern of the 11-year solar-cycle sensitivity in X_{O_3} [in Dobson units (DU) per 100 units of 10.7-cm solar radio flux ($F_{10.7}$; Tapping and Detraycey, 1990) or $DU/100F_{10.7}$] from the merged *TOMS/SBUV* data using multiple linear regression. In the equatorial region, the derived sensitivity from *TOMS/SBUV* data was 5–6 $DU/100F_{10.7}$. They compared this sensitivity to that of the partial column O_3 between 20–50 km integrated from the *SAGE* measurements during 1979–2005. The resultant sensitivity from *SAGE* was 2–3 $DU/100F_{10.7}$ only, which is half of that derived from the *TOMS* data but agrees with those derived from the ground-based X_{O_3} measurements. There has been concern whether an erroneous treatment of an instrumental toggling of *TOMS* in 1983 might

have created the apparently large X_{O_3} solar response (WMO, 2002, Appendix 4A.2). However, this error has been corrected in the latest TOMS retrieval algorithm (version 8) and Randel and Wu (2007) used version 8 retrievals for their analysis. Therefore, the discrepancy among TOMS/SBUV, SAGE, and ground-based X_{O_3} solar responses are unlikely due to the toggling problem.

This work aims to simulate the X_{O_3} solar responses using WACCM. We will study the impacts of NRL and SORCE SSIs on the solar-cycle response of tropical X_{O_3} . Recent analyses of SORCE data (Lean and DeLand, 2012; DeLand and Cebula, 2012) reveal that uncorrected instrumental drifts may have resulted in an overestimated UV variations during 2004–2007 as reported in Haigh et al. (2010). The work here thus presents an upper limit of the impact associated with the difference of UV changes suggested by these two measurements. Lastly, since the solar-cycle modulation is stronger in the equatorial region than that in the global averages (see, e.g., Fig. 6 of Austin et al., 2008) and photochemical production of O_3 decreases with increasing latitude, atmospheric dynamics may interact with the solar-cycle modulations and make the interpretation difficult in the extratropics for both model and observational results (see, e.g., Jiang et al., 2008a, b), which is out of the scope of this work. Thus latitudes away from tropics will be avoided in this study.

We note that our study is similar to that of Swartz et al. (2012), who also examined the X_{O_3} solar response in a CCM using both NRL and SORCE SSIs. However, Swartz et al. performed steady-state simulations, where the solar flux was fixed at either solar maximum or solar minimum conditions. As will be explained in the next section, we will perform transient runs as in previous studies (e.g. Marsh and Garcia, 2007; Austin et al., 2008; Dhomse et al., 2011). This also allows us to evaluate possible effects in the lower stratosphere due to ENSO. Swartz et al. (2012) examined individual effects of photolysis and direct heating separately; in our study, the solar variations are included in both chemistry and radiation.

2 Model setup

WACCM is a global atmospheric model with fully coupled chemistry, radiation and dynamics extending from the surface to the thermosphere based on version 3 of the Community Atmosphere Model (CAM3) (Marsh et al., 2007). An older version of WACCM was employed in the study of Austin et al. (2008). The version that is used in this study has a horizontal resolution of 5° longitude \times 4° latitude. There is a resolved stratosphere with fully interactive ozone chemistry that can respond to the UV part of the solar forcing. This model is one of the participants of the CCMVal activity and has been employed to project the ozone trend in the 21st century (Morgenstern et al., 2010; Oman et al., 2010). This version does not have an internal mechanism for generating QBOs, although there have been efforts where relaxation methods have been employed to externally impose the QBO in the simulations (Matthes et al., 2010). A parametrized gravity wave drag has been used to drive the Brewer-Dobson circulation (Richter et al., 2010). No volcanic aerosol emissions have been included in our simulations.

We shall explore the impact of two sets of SSI inputs derived from NRL solar model and from the recent SORCE measurements on the model X_{O_3} . The spectral variability between 115–400 nm for 2004–2007 depicted by these two spectral datasets as well as their implications for stratospheric chemistry have been studied in details by several groups (Cahalan et al., 2010; Haigh et al., 2010; Merkel et al., 2011; Swartz et al., 2012). Some of their model results have also been compared against vertically resolved satellite data that are available during the same period (e.g. Haigh et al., 2010; Merkel et al., 2011; Swartz et al., 2012).

To mimic a full solar cycle, the SORCE measurements are extrapolated back to the last solar maximum in 2002 using the Magnesium-II core-to-wing ratio (Mg-II c/w) index (Heath and Schlesinger, 1986). The Mg-II c/w index describes the variability of radiation from the solar chromosphere and is a good proxy for EUV wavelengths, especially at 205 nm that is important for ozone chemistry. This index is defined as the ratio of the Mg-II H and K lines at ~ 280 nm to the wings of the absorption at ~ 276 and ~ 283 nm, which is less susceptible for instrument degradations. Long-term Mg-II c/w record has been constructed using different satellite measurements of exoatmospheric solar radiation since 1978, including SORCE after

2004 (Viereck et al., 2004; Snow et al., 2005). The records from different measurements have been validated against each other and adjusted to composite a single continuous Mg-II c/w index (Viereck et al., 2004). Thus, for period during January 1, 2004 – November 30, 2007, correlation coefficients between the SORCE spectral variations and the composite Mg-II c/w index are obtained for wavelengths between 115 and 340 nm. For wavelengths greater than 340 nm, the correlation coefficients are small, and the correlation may not be robust. Using these correlation coefficients, the SORCE measurements are extrapolated back to January, 2002. The (extrapolated) UV variability between 115–340 nm during 2002–2007 is a factor of $\sim 3-4$ larger than those shown in Fig. 1 of Haigh et al. (2010); these scaling factors are shown in Fig. S1 in Supplementary Materials. For wavelengths greater than 340 nm, an arbitrary factor 3.5 is assigned. For comparison, the ratio of UV changes during 2002–2007 over that during 2004–2007 derived from the NRL model is also shown in Fig. S1. A similar extrapolation procedure has also been employed in Swartz et al. (2012), where $F_{10.7}$ is used instead of Mg-II c/w index.

In this work, wavelengths below 240 nm are derived from the spectral measurements by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) aboard SORCE, whereas wavelengths above 240 nm are derived from the measurements by the Spectral Irradiance Monitor (SIM) aboard SORCE. To drive a solar cycle variation in WACCM, the solar variability in the UV region is characterized by the fractional changes from the (extrapolated) solar maximum of Solar Cycle 23 in 2002 to the solar minimum in 2007. Then for all wavelengths, the evolution from a solar maximum to a solar minimum is assumed to follow that of $F_{10.7}$. The stratospheric chlorine has been fixed in the simulations.

The WACCM model is run with the atmospheric module only so that there is no dynamical coupling between the atmosphere and the ocean. The oceanic variability is prescribed by putting in the sea surface temperatures and ice (SST/ice) as boundary conditions. In order to isolate the effects due to the solar cycle, we run the model with monthly climatological SST/ice (experiments A & C). This reduces the interaction or aliasing with oceanic long-term modes such as the ENSO. To evaluate the effects due to natural oceanic modes, we conduct another set of simulations with realistic SST/ice (Hurrell et al., 2008) (experiments B & D). Besides the ENSO,

the realistic SST/ice also includes a tiny solar-cycle variability of ~ 0.1 K peak-to-trough (Zhou and Tung, 2010). Therefore, such prescription may mimic a coupled atmosphere-ocean system and provide an estimate of the bottom-up effect on the ozone column abundance due to the solar cycle (Meehl et al., 2009). Lastly, in order to estimate the relative contribution of the simulated solar response due to that tiny solar-cycle variability in the SST/ice, we conduct a control run with realistic SST/ice where the solar constant is time-independent (experiment E).

The presence of enhanced aerosol loading due to major volcanic eruptions (e.g. El Chichon in 1982 and Pinatubo in 1992) may reduce O_3 concentrations in the lower stratosphere due to enhanced chlorine activation. In a model study, Dhomse et al. (2011) showed that the estimation of the lower stratospheric O_3 responses can be amplified through the aliasing with volcanic aerosol emissions. They demonstrated that running the model with fixed dynamics or constant aerosols will help minimize the aliasing effect. Thus, in our simulations, we will adopt a constant background aerosol loading.

The model was run from January 1960 to November 2009. To avoid analyzing transient signals, we omit the first 10 year of simulations and analyze data only from January 1970 to the end of the simulations. We summarize and define the assumptions for these experimental setups in Table 1.

3 Multiple linear regression

We follow the procedure for multiple linear regression as described in Randel and Cobb (1994). The simulated X_{O_3} time series are first deseasonalized to obtain monthly anomalies, to which a smoothing 1-2-1 filter is then applied. Subsequently, the solar-cycle modulation is retrieved using a simplified regression model delineated in Li et al. (2008):

$$\begin{aligned}
 X_{O_3}(t) = & \alpha(t) \cdot t \\
 & + \beta(t) \cdot F_{10.7}(t) \\
 & + \gamma(t) \cdot ENSO(t) \\
 & + \text{residual}
 \end{aligned}
 \tag{1}$$

where X_{O_3} represents the monthly anomaly of total column ozone, $F_{10.7}(t)$ is the 10.7-cm solar radio flux. Since QBO is not simulated in WACCM and atmospheric aerosol is fixed, we have omitted these terms in the regression model. ENSO(t) is the ENSO index described by the Multivariate ENSO Index (MEI) (Wolter and Timlin, 2011). The time-varying coefficients α , β , and γ are the sum of a constant term and annual harmonics:

$$\alpha(t) = A_1 + A_2 \cos\omega t + A_3 \sin\omega t \quad (2)$$

where $\omega = 2\pi/12$ months. Therefore a total of 9 parameters are retrieved from the analysis. The uncertainties of the above 3 coefficients are related to the 9 retrieved parameters via the following relation (Bevington and Robinson, 1992):

$$\begin{aligned} \text{var}[\alpha(t)] = & \text{var}(A_1) \\ & + \text{var}(A_2)\cos^2\omega t \\ & + \text{var}(A_3)\sin^2\omega t \\ & + 2 \text{cov}(A_1, A_2) \cos\omega t \\ & + 2 \text{cov}(A_1, A_3) \sin\omega t \\ & + 2 \text{cov}(A_2, A_3) \cos\omega t \sin\omega t \end{aligned} \quad (3)$$

The time-averaged coefficients and the corresponding uncertainties are thus given by

$$\overline{\alpha(t)} = A_1 \quad (4)$$

$$\overline{\text{var}[\alpha(t)]} = \text{var}(A_1) + \frac{1}{2} [\text{var}(A_2) + \text{var}(A_3)] \quad (5)$$

where the overbar denotes temporal averages.

Note that Randel and Wu (2007) omitted about two years of O_3 observations after the volcanic eruption in 1982 (El Chichon) and 1992 (Pinatubo) to reduce aliasing effects with aerosol loadings. Since we have fixed the background aerosol level, we don't omit these years in our regression analysis.

4 Results

In this section, we first establish the solar-cycle responses in the tropical averages. The relative importance of the modulations due to the solar cycle and the ENSO are studied through the regression coefficients and their uncertainties. Then the latitudinal patterns are presented and are compared with observations derived in previous studies. Finally, the spatial patterns in the tropical area are also discussed.

4.1 Tropical averages and regression coefficients

Figure 1 shows the simulated monthly mean of tropical X_{O_3} averaged over 24° N– 24° S. Latitudinal area weighting has been applied. The color code for the time series corresponds to those of the average contour shown in Fig. 3; see below and Table 1. Regression is then applied to the equatorial average using Eq. (1). The $F_{10.7}$ index multiplied by the time-averaged fitting coefficients, $\bar{\beta}F_{10.7}(t)$, of the respective experiments are shown as black lines.

In all experiments, the regression uncertainties (2σ) of $\bar{\beta}$ are about 0.6 – 0.7 DU/ $100F_{10.7}$ (Table 2). The regressed coefficients $\bar{\alpha}$ for the trends are insignificant for those runs with climatological SST/ice (experiments A and C). On the other hand, there are non-zero trends for experiments B, D and E with realistic SST/ice inputs. Part of them may be due to the trends in the realistic SST/ice in the last three decades (~ 0.3 – 0.6 K) over the tropics (Keihm et al., 2009). We note that the regressed coefficients remain statistically the same when the linear trend is absent in Eq. (1). Therefore, we shall not discuss $\bar{\alpha}$ further. Finally, the regressed coefficients $\bar{\gamma}$ for ENSO are -1.15 ± 0.33 DU/MEI, -1.39 ± 0.36 DU/MEI, and -1.41 ± 0.33 DU/MEI for experiments B, D, and E, respectively, and these values are mutually consistent within uncertainties. The anti-correlation implies that X_{O_3} is primarily controlled by the vertical motion of the tropopause related to the ENSO modulations, likely through the strengthening/weakening of Brewer-Dobson circulation over the anomalously warm/cool sea surface (Camp et al., 2003).

In experiments A and B where NRL SSI is used, the regressed solar-cycle responses $\bar{\beta}$ are 3.17 DU/ $100F_{10.7}$ and 2.77 DU/ $100F_{10.7}$, respectively, but these values are again mutually consistent within uncertainties. The decrease in the regressed response in experiment B is likely

due to modulations by the ENSO signal. Such modulation is most notable during the simulation years 1973–1976, when there were strong and prolonged La Niña events (indicated in Fig. 1 by the green bars) which enhances X_{O_3} during the solar minimum. Similarly, in experiments C and D where SORCE SSI is used, the fitted solar-cycle responses $\bar{\beta}$ are 5.53 DU/100 $F_{10.7}$ and 5.56 DU/100 $F_{10.7}$ respectively, and they are mutually consistent within uncertainties (~ 0.7 DU/100 $F_{10.7}$). Therefore, the solar-cycle response in X_{O_3} obtained using SORCE SSI is almost two times that obtained using NRL SSI. Furthermore, the difference in the solar-cycle responses obtained using two different SSI settings is statistically significant. The solar-cycle response obtained using SORCE SSI is close to the observed value over 24° S–24° N, which is 5.54 DU/100 $F_{10.7}$ (Randel and Wu, 2007).

When the solar constant is fixed but the realistic SST/ice is employed in experiment E, the regressed solar response $\bar{\beta}$ is only -0.34 DU/100 $F_{10.7}$ and is much smaller than the regression uncertainty 0.71 DU/100 $F_{10.7}$. Therefore we conclude that even if there is a tiny modulation due to the solar-cycle signal in the realistic SST/ice, the simulated response would not be discernible against the natural variability through our regression model.

4.2 Latitudinal patterns and the equatorial paradox

Figure 2 shows the latitudinal patterns of the time-averaged solar-cycle response between 24° S–24° N. To obtain these results, the regression analysis has been applied to individual zonal averages at different latitudes. The regression uncertainty (2σ) is roughly equal to the error bar shown in Fig. 2, which is ~ 0.6 DU/100 $F_{10.7}$. Also shown are the solar-cycle response derived from the TOMS/SBUV data (cyan shade), the ground-based measurements made using Dobson and Brewer spectrophotometer, and the filter ozonometer (dashed line) (Fioletov et al., 2002). These data are extracted from Fig. 6 of Randel and Wu (2007).

For experiments A and B with NRL SSI input, the solar-cycle responses are ~ 3 DU/100 $F_{10.7}$. This agrees with those derived from the ground-based measurements (Austin et al., 2008). In contrast, experiments C and D with SORCE SSI input produce solar-cycle responses of ~ 5.4 DU/100 $F_{10.7}$, about a factor of 2 larger than those in experiments A and B, and they agree with those derived from TOMS/SBUV.

In all experiments with solar-cycle forcings, the values of $\bar{\beta}$ corresponding to the WACCM runs are relatively constant over the tropics, consistent with previous modeling studies (Brasseur, 1993; Lee and Smith, 2003; Tourpali et al., 2003; Egorova et al., 2004; Austin et al., 2008). In contrast, the latitudinal patterns in TOMS/SBUV and ground-based measurements are slightly lower at the equatorial region below 20° N/S. Previous simulations by Lee and Smith (2003) and McCormack et al. (2007) using 2-D chemical transport models with solar-cycle forcings only predict a constant response in the equatorial region. When QBO is included in the simulations, they both found that the solar-cycle response near the equator becomes lower than that in the mid-latitudes. Nonetheless, they drew totally different conclusions: Lee et al. assert that such decrease in the response could be statistical interferences between the solar-cycle modulation and QBO in the regression analysis while McCormack et al. assert that it is caused by genuine dynamical interactions. Hood and Soukharev (2003) arrive at the same assertion proposed by McCormack et al. (2007). However, Camp et al. (2003), who apply a different statistical technique (the empirical orthogonal functions) to the merged TOMS/SBUV data, seem to support Lee et al.'s assertions. Moreover, an examination of the CCMVal 3-D models by Austin et al. (2008) does not reveal such a decrease in the solar-cycle response near the equatorial region. However, given that the implementation of a realistic QBO in 3-D models has not matured, it is hard to conclude which assertion is more plausible. We therefore urge more definitive 3-D simulations of X_{O_3} with more realistic components of solar-cycle variability and QBO mechanisms to discern their individual effects.

There is no significant solar response simulated in experiment E. The regression coefficient $\bar{\beta}$ is about $-0.3 \text{ DU}/100F_{10.7}$ in the tropics but is smaller than the regression uncertainty.

4.3 Tropical spatial patterns

Finally, the regression analysis has also been applied to the time series at individual model grid points. Figure 3 shows the equatorial spatial patterns of $\bar{\beta}$ between 24° S–24° N. The corresponding regression errors (2σ) are shown in Fig. 4.

Overall, the solar-cycle responses are close to the respective equatorial averages and are relatively constant over the tropics within $\pm 0.5 \text{ DU}/100F_{10.7}$, which is of the same order of the re-

gression uncertainties. For experiments B and D when realistic SST/ice are used the solar-cycle responses are anomalously low in the Equatorial Pacific. As in the case as QBO, this is likely due to the statistical interference from the ENSO modulation. This can be seen by noticing that the spatial patterns of the regression uncertainties have a lot more structures when the realistic SST/ice are included, especially over the Cold Tongue and the Warm Pool regions (Fig. 4). In the subtropics, the uncertainties are generally $\sim 1 \text{ DU}/100F_{10.7}$ and can be greater than 1.3 DU in the Northern Hemisphere. In the Central Pacific, the minimum uncertainties can be as low as $0.4 \text{ DU}/100F_{10.7}$ for experiments A and C; they are slightly higher ($\sim 0.6 \text{ DU}/100F_{10.7}$) for experiments B and D. These clearly show the effects of ENSO. It also becomes obvious when one examines the spatial pattern of the regressed coefficients $\bar{\gamma}$ related to ENSO, shown in Fig. 5 only for experiments B, D, and E. The coefficients $\bar{\gamma}$ are negative all over the tropics. The strongest ENSO modulations of $\sim 3 \text{ DU}/\text{MEI}$ are found over the Northern and Southern Eastern Pacific. The modulations are almost zero over the Warm Pool region, demonstrating the dipole structures of the ENSO effects. These spatial patterns are similar to the fourth EOF obtained by Camp et al. (2003).

As in previous sections, the regressed solar response of $-0.3 \text{ DU}/100F_{10.7}$ in experiment E is insignificant compared to the regression uncertainty shown in Fig. 4, implying that the modulation due to the solar-cycle signal in the realistic SST/ice is tiny. We also point out that the regression uncertainty seems to be independent of the input solar flux and SST/ice. Rather, it depends largely on the internal variability of the model.

4.4 Vertical responses

Lower stratospheric O_3 response between 20–30 km is the main contributor to X_{O_3} response. To further elucidate the sensitivity of WACCM to the UV perturbations, we show the tropical vertical O_3 responses between 25°N – 25°S in Fig. 6. These vertical profiles are derived from monthly averaged model outputs. The uncertainties of the model responses are $\sim 0.5 \text{ \%}/100F_{10.7}$ above 20 km and $\sim 2 \text{ \%}/100F_{10.7}$ below 20 km. The averaged HALOE, SAGE, and SBUV observations reported by Soukharev and Hood (2006) are represented by the dots with error bars. Observationally, there is an upper stratospheric peak of $2 \text{ \%}/100F_{10.7}$

between 40–60 km and a lower stratospheric peak of 3 %/100 $F_{10.7}$ near 20 km. At 30 km, the observed middle stratospheric response is statistically insignificant.

For experiments A & B where NRL SSI is used, a double-peak structure is apparent in the simulated O₃ response shows, although it is not as pronounced as the observed. The model O₃ response shows a primary peak of 2 %/100 $F_{10.7}$ at 40 km which is close to the observed response at those altitudes. The secondary peak of 1 %/100 $F_{10.7}$ at 20 km is much weaker than the observed response in the lower stratosphere. In contrast, in experiments C & D where SORCE SSI is used, the double-peak structure is absent and the upper stratospheric response between 40 km and 60 km is negative (~ 1 %/100 $F_{10.7}$), disagreeing with the observed. However, in the lower stratosphere between 20–30 km, the simulated O₃ response agrees better with the observed and is more than 3 times larger than that simulated using NRL SSI and ranges between 2–3 %/100 $F_{10.7}$. In the middle stratosphere, both the use of NRL and SORCE SSI lead to significant enhancement of O₃, disagreeing with the insignificant response as observed at those altitudes. These results are consistent with those obtained by Swartz et al. (2012). Further investigations are required to understand the relative contributions to the simulated O₃ response from photolysis, O₃ catalytic chemistry, and dynamics due to UV perturbations.

Above 20 km, the model O₃ response is insensitive to the SST boundary conditions. On the other hand, the model responses show a large spread below 20 km, likely due to aliasing with the ENSO effect. This assertion of the aliasing effect is supported by the control experiment (experiment E), where there is no significant solar signal above 20 km, but there is an artificial negative solar response below 20 km. However, since majority of tropical O₃ is located above 20 km, this aliasing does not impact on the X_{O₃} response significantly.

5 Summary and discussions

This work extends the modeling studies of Haigh et al. (2010) and Merkel et al. (2011) for middle atmospheric O₃ concentrations. Our simulations were done with much longer periods (1960–2009) in attempt to minimize statistical uncertainties. The solar-cycle responses of total

column ozone (X_{O_3}) over the tropics in the WACCM model were simulated using spectral solar variability in UV derived from NRL and SORCE SSIs. For SORCE where the measurements cover only from 2004 to 2010, a full Solar Cycle 23 has been extrapolated based on the Mg-II c/w index.

5 Using the (extrapolated) SORCE spectral UV data, the stimulated solar-cycle modulation in tropical X_{O_3} has a sensitivity $\sim 5.4 \text{ DU}/100F_{10.7}$ or $\sim 2\%/100F_{10.7}$. This agrees with the sensitivity observed by TOMS/SBUV, although TOMS/SBUV observations suggest a local minimum of $\sim 4.5 \pm 1.5 \text{ DU}/100F_{10.7}$ at the equator, which is not simulated in the model. However, this is \sim twice larger than the sensitivity observed by SAGE and ground-based measurements. On the other hand, using NRL spectral UV data, the simulated tropical X_{O_3} response is $\sim 3 \text{ DU}/100F_{10.7}$ or $\sim 1\%/100F_{10.7}$ and agrees well with the SAGE and ground-based measurements. 10

The difference in the simulated X_{O_3} responses that were obtained using NRL and SORCE SSI mainly comes from the lower stratosphere. The SORCE simulation yields a lower stratospheric O_3 response ~ 3 times larger than the NRL simulation and agrees better with previous satellite observations. In contrast, the SORCE simulation suggests a negative response in the upper stratosphere which does not agree with the observed whereas the NRL simulation agrees better with the observations in that region. This presents a dilemma to our current understanding on stratospheric O_3 sensitivity to UV perturbations. However, we note that recent studies 15 (Lean and DeLand, 2012; DeLand and Cebula, 2012) reveal that uncorrected instrumental drifts may have caused an unexpectedly large UV variations during 2004–2007 as reported in Haigh et al. (2010). Therefore, the simulated X_{O_3} solar response may have been overestimated. More observation-model comparisons are required to determine which of NRL/SORCE SSI lead to more realistic simulations of the atmospheric solar response. 20

25 Multiple linear regression has been frequently used for examining solar-cycle modulations and other forcings in global ozone data as well as other atmospheric variables (Hood and Soukharev, 2006; Soukharev and Hood, 2006; Randel and Wu, 2007; Hood et al., 2010; Zhou and Tung, 2010). It is easy to implement but it also has to assume that the forcings are independent of each other and that the responses are linear. However, in reality these assumptions may

not always hold. For example, Meehl et al. (2009) suggests that the net effect of increased solar insolation during solar maximum conditions may result in stronger trade winds in the tropical Pacific, which may also impact the Walker circulation and hence ENSO. It is thus important to consider the regression uncertainties when interpreting the results. In our work, we have shown that the inclusion of ENSO in the model runs does not statistically modify the simulated solar sensitivity, which is consistent with the conclusion by Dhomse et al. (2011).

When studying the potential impacts in our regression coefficients due to the presence of ENSO, we have used the same regression model on different simulations with and without ENSO forcings. This is slightly different from the work of Marsh and Garcia (2007), where they applied two different regression models with and without the ENSO term on the same simulation. On the other hand, Zhou and Tung (2010) examined the solar-cycle modulation in a 150-year record of global SST and found that the resultant solar response is neither La Niña-like nor El Niño-like. Their conclusion emphasizes the use of long-term records for establishing a statistically robust signal. Therefore, a longer simulation up to a centennial time scale may be required to clarify the interaction between the ENSO and the solar cycle in model O₃.

Unfortunately our model does not have a prescribed/simulated QBO to further investigate its effect (generic/statistical alias) on the extracted X_{O₃} response (Schmidt et al., 2010; Dhomse et al., 2011). Kuai et al. (2009) has shown that QBO may interact with the solar cycle nonlinearly through wave-semiannual oscillation. This effect must be considered in future modeling studies.

The difference in the X_{O₃} solar-cycle sensitivity to UV we found in this work is likely to be applicable to other CCMVal models, although there may be some nonlinearity due to dynamical changes. Analogous simulations using other CCMVal models help evaluate the robustness of these changes in solar-cycle sensitivities (e.g. Swartz et al., 2012).

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References

- 5 Austin, J., Tourpali, K., Rozanov, E., Akiyoshi, H., Bekki, S., Bodeker, G., Bruhl, C., Butchart, N., Chipperfield, M., Deushi, M., Fomichev, V. I., Giorgetta, M. A., Gray, L., Kodera, K., Lott, F., Manzini, E., Marsh, D., Matthes, K., Nagashima, T., Shibata, K., Stolarski, R. S., Struthers, H., and Tian, W.: Coupled chemistry climate model simulations of the solar cycle in ozone and temperature, *J. Geophys. Res.-Atmos.*, 113, D11306, doi:10.1029/2007JD009391, 2008.
- 10 Bevington, P. R. and Robinson, D. K.: *Data Reduction and Error Analysis for the Physical Sciences*, 3rd ed., McGraw-Hill, New York, 336 pp., 1992.
- Brasseur, G.: The response of the Middle Atmosphere to long-term and short-term solar variability – a 2-dimensional model, *J. Geophys. Res.-Atmos.*, 98, 23079–23090, doi:10.1029/93JD02406, 1993.
- 15 Brasseur, G. and Solomon, S.: *Aeronomy of the Middle Atmosphere: Chemistry and Physics of the Stratosphere and Mesosphere*, Springer, Dordrecht, 1984.
- Cahalan, R. F., Wen, G., Harder, J. W., and Pilewskie, P.: Temperature responses to spectral solar variability on decadal time scales, *Geophys. Res. Lett.*, 37, L07705, doi:10.1029/2009GL041898, 2010.
- 20 Camp, C. D., Roulston, M. S., and Yung, Y. L.: Temporal and spatial patterns of the interannual variability of total ozone in the tropics, *J. Geophys. Res.-Atmos.*, 108, 4643, doi:10.1029/2001JD001504, 2003.
- Egorova, T., Rozanov, E., Manzini, E., Haberreiter, M., Schmutz, W., Zubov, V., and Peter, T.: Chemical and dynamical response to the 11-year variability of the solar irradiance simulated with a chemistry-climate model, *Geophys. Res. Lett.*, 31, L06119, doi:10.1029/2003GL019294, 2004.
- 25 Fioletov, V. E., Bodeker, G. E., Miller, A. J., McPeters, R. D., and Stolarski, R.: Global and zonal total ozone variations estimated from ground-based and satellite measurements: 1964–2000, *J. Geophys. Res.-Atmos.*, 107, 4647, doi:10.1029/2001JD001350, 2002.
- Frame, T. H. A. and Gray, L. J.: The 11-year solar cycle in ERA-40 data: an update to 2008, *J. Clim.*, 23, 2213–2222, doi:10.1175/2009JCLI3150.1, 2010.

- Haigh, J. D.: The role of stratospheric ozone in modulating the solar radiative forcing of climate, *Nature*, 370, 544–546, doi:10.1038/370544a0, 1994.
- Haigh, J. D., Blackburn, M., and Day, R.: The response of tropospheric circulation to perturbations in lower-stratospheric temperature, *J. Clim.*, 18, 3672–3685, doi:10.1175/JCLI3472.1, 2005.
- 5 Haigh, J. D., Winning, A. R., Toumi, R., and Harder, J. W.: An influence of solar spectral variations on radiative forcing of climate, *Nature*, 467, 696–699, doi:10.1038/nature09426, 2010.
- Herschel, F. W.: Observations tending to investigate the nature of the Sun, in order to find the causes or symptoms of its variable emission of light and heat; with remarks on the use that may possibly be drawn from solar observations, *Philos. Trans. R. Soc. London*, 91, 265–318, 1801.
- 10 Herzberg, L.: Solar optical radiation and its role in upper atmospheric processes, in: *Physics of the Earth's Upper Atmosphere*, edited by: Hines, C. O., Paglis, I., Hartz, R., and Fejer, J. A., Prentice Hall, New Jersey, 31–45, 1965.
- Hood, L. L., Jirikowic, J. L., and McCormack, J. P.: Quasi-Decadal Variability of the Stratosphere: Influence of Long-Term Solar Ultraviolet Variations, *J. Atmos. Sci.*, 50, 3941–3958, doi:10.1175/1520-0469(1993)050<3941:QDVOTS>2.0.CO;2, 1993.
- 15 Hood, L. L. and Soukharev, B. E.: Quasi-decadal variability of the tropical lower stratosphere: the role of extratropical wave forcing, *J. Atmos. Sci.*, 60, 2389–2403, doi:10.1175/1520-0469(2003)060<2389:QVOTTL>2.0.CO;2, 2003.
- Hood, L. L. and Soukharev, B. E.: Solar induced variations of odd nitrogen: Multiple regression analysis of UARS HALOE data, *Geophys. Res. Lett.*, 33, L22805, doi:10.1029/2006GL028122, 2006.
- 20 Hood, L. L., Soukharev, B. E., and McCormack, J. P.: Decadal variability of the tropical stratosphere: Secondary influence of the El Niño-Southern Oscillation, *J. Geophys. Res.-Atmos.*, 115, D11113, doi:10.1029/2009JD012291, 2010.
- Hurrell, J. W., Hack, J. J., Shea, D., Caron, J. M., and Rosinski, J.: A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model, *J. Clim.*, 21, 5145–5153, doi:10.1175/2008jcli2292.1, 2008.
- 25 Ineson, S., Scaife, A. A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J., and Haigh, J. D.: Solar forcing of winter climate variability in the Northern Hemisphere, *Nature Geosci.*, 4, 753–757, doi:10.1038/ngeo1282, 2011.
- 30 Jiang, X., Pawson, S., Camp, C. D., Nielsen, J. E., Shia, R. L., Liao, T., Limpasuvan, V., and Yung, Y. L.: Interannual variability and trends of extratropical ozone. Part I: Northern Hemisphere, *J. Atmos. Sci.*, 65, 3013–3029, doi:10.1175/2008JAS2665.1, 2008a.
- Jiang, X., Pawson, S., Camp, C. D., Nielsen, J. E., Shia, R. L., Liao, T., Limpasuvan, V., and Yung, Y. L.:

- Interannual variability and trends of extratropical ozone. Part II: Southern Hemisphere, *J. Atmos. Sci.*, 65, 3030–3041, doi:10.1175/2008JAS2793.1, 2008b.
- Keihm, S., Brown, S., Teixeira, J., Desai, S., Lu, W., Fetzer, E., Ruf, C., Huang, X. L., and Yung, Y.: Ocean water vapor and cloud liquid water trends from 1992 to 2005 TOPEX Microwave Radiometer data, *J. Geophys. Res.-Atmos.*, 114, D18101, doi:10.1029/2009JD012145, 2009.
- 5 Kuai, L., Shia, R.-L., Jiang, X., Tung, K. K., and Yung, Y. L.: Modulation of the Period of the Quasi-Biennial Oscillation by the Solar Cycle, *J. Atmos. Sci.*, 66, 2418–2428, doi:10.1175/2009JAS2958.1, 2009.
- Lean, J.: Evolution of the sun’s spectral irradiance since the Maunder Minimum, *Geophys. Res. Lett.*, 10 27, 2425–2428, doi:10.1029/2000GL000043, 2000.
- Lean, J. L., Rottman, G. J., Kyle, H. L., Woods, T. N., Hickey, J. R., and Puga, L. C.: Detection and parameterization of variations in solar mid- and near-ultraviolet radiation (200–400 nm), *J Geophys Res-Atmos* 102, 29939–29956, doi:10.1029/97JD02092, 1997.
- Lee, H. and Smith, A. K.: Simulation of the combined effects of solar cycle, quasi-biennial oscillation, and volcanic forcing on stratospheric ozone changes in recent decades, *J. Geophys. Res.-Atmos.*, 108, 15 4049, doi:10.1029/2001JD001503, 2003.
- Levelt, P. F., Hilsenrath, E., Leppelmeier, G. W., van den Oord, G. H. J., Bhartia, P. K., Tamminen, J., de Haan, J. F., and Veefkind, J. P.: Science objectives of the Ozone Monitoring Instrument, *IEEE T. Geosci. Remote*, 44, 1199–1208, doi:10.1109/tgrs.2006.872336, 2006.
- 20 Li, T., Leblanc, T., and McDermid, I. S.: Interannual variations of middle atmospheric temperature as measured by the JPL lidar at Mauna Loa Observatory, Hawaii (19.5° N, 155.6° W), *J. Geophys. Res.-Atmos.*, 113, D14109, doi:10.1029/2007JD009764, 2008.
- Marsh, D. R. and Garcia, R. R.: Attribution of decadal variability in lower-stratospheric tropical ozone, *Geophys. Res. Lett.*, 34, L21807, doi:10.1029/2007GL030935, 2007.
- 25 Marsh, D. R., Garcia, R. R., Kinnison, D. E., Boville, B. A., Sassi, F., Solomon, S. C., and Matthes, K.: Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing, *J. Geophys. Res.-Atmos.*, 112, D23306, doi:10.1029/2006JD008306, 2007.
- Matthes, K., Marsh, D. R., Garcia, R. R., Kinnison, D. E., Sassi, F., and Walters, S.: Role of the QBO in modulating the influence of the 11 year solar cycle on the atmosphere using constant forcings, *J. Geophys. Res.-Atmos.*, 115, D18110, doi:10.1029/2009JD013020, 2010.
- 30 McCormack, J. P., and Hood, L. L.: Apparent solar cycle variations of upper stratospheric ozone and temperature: Latitude and seasonal dependences, *J. Geophys. Res.*, 101, 20,933–20,944, doi:10.1029/96JD01817, 1996.

- McCormack, J. P., Siskind, D. E., and Hood, L. L.: Solar-QBO interaction and its impact on stratospheric ozone in a zonally averaged photochemical transport model of the middle atmosphere, *J. Geophys. Res.-Atmos.*, 112, D16109, doi:10.1029/2006JD008369, 2007.
- 5 Meehl, G. A., Arblaster, J. M., Matthes, K., Sassi, F., and van Loon, H.: Amplifying the Pacific climate system response to a small 11-year solar cycle forcing, *Science*, 325, 1114–1118, doi:10.1126/science.1172872, 2009.
- Merkel, A. W., Harder, J. W., Marsh, D. R., Smith, A. K., Fontenla, J. M., and Woods, T. N.: The impact of solar spectral irradiance variability on middle atmospheric ozone, *Geophys. Res. Lett.*, 38, L13802, doi:10.1029/2011GL047561, 2011.
- 10 Morgenstern, O., Giorgetta, M. A., Shibata, K., Eyering, V., Waugh, D. W., Shepherd, T. G., Akiyoshi, H., Austin, J., Baumgaertner, A. J. G., Bekki, S., Braesicke, P., Bruhl, C., Chipperfield, M. P., Cugnet, D., Dameris, M., Dhomse, S., Frith, S. M., Garny, H., Gettelman, A., Hardiman, S. C., Hegglin, M. I., Jockel, P., Kinnison, D. E., Lamarque, J. F., Mancini, E., Manzini, E., Marchand, M., Michou, M., Nakamura, T., Nielsen, J. E., Olivie, D., Pitari, G., Plummer, D. A.,
- 15 Rozanov, E., Scinocca, J. F., Smale, D., Teyssedre, H., Toohey, M., Tian, W., and Yamashita, Y.: Review of the formulation of present-generation stratospheric chemistry-climate models and associated external forcings, *J. Geophys. Res.-Atmos.*, 115, D00M02, doi:10.1029/2009JD013728, 2010.
- Oman, L. D., Plummer, D. A., Waugh, D. W., Austin, J., Scinocca, J. F., Douglass, A. R., Salawitch, R. J., Canty, T., Akiyoshi, H., Bekki, S., Braesicke, P., Butchart, N., Chipperfield, M. P., Cugnet, D.,
- 20 Dhomse, S., Eyering, V., Frith, S., Hardiman, S. C., Kinnison, D. E., Lamarque, J. F., Mancini, E., Marchand, M., Michou, M., Morgenstern, O., Nakamura, T., Nielsen, J. E., Olivie, D., Pitari, G., Pyle, J., Rozanov, E., Shepherd, T. G., Shibata, K., Stolarski, R. S., Teyssedre, H., Tian, W., Yamashita, Y., and Ziemke, J. R.: Multimodel assessment of the factors driving stratospheric ozone evolution over the 21st century, *J. Geophys. Res.-Atmos.*, 115, D24306, doi:10.1029/2010JD014362,
- 25 2010.
- Randel, W. J. and Cobb, J. B.: Coherent variations of monthly mean total ozone and lower stratospheric temperature, *J. Geophys. Res.-Atmos.*, 99, 5433–5447, 1994.
- Randel, W. J. and Wu, F.: Isolation of the ozone QBO in SAGE II data by singular-value decomposition, *J. Atmos. Sci.*, 53, 2546–2559, 1996.
- 30 Randel, W. J. and Wu, F.: A stratospheric ozone profile data set for 1979–2005: Variability, trends, and comparisons with column ozone data, *J. Geophys. Res.-Atmos.*, 112, D06313, doi:10.1029/2006JD007339, 2007.
- Richter, J. H., Sassi, F., and Garcia, R. R.: Toward a physically based gravity wave source param-

- terization in a general circulation model, *J. Atmos. Sci.*, 67, 136–156, doi:10.1175/2009JAS3112.1, 2010.
- Schmidt, H., Brasseur, G. P., and Giorgetta, M. A.: Solar cycle signal in a general circulation and chemistry model with internally generated quasi-biennial oscillation, *J. Geophys. Res.-Atmos.*, 115, D00I14, doi:10.1029/2009JD012542, 2010.
- 5 Soukharev, B. E. and Hood, L. L.: Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models, *J. Geophys. Res.-Atmos.*, 111, D20314, doi:10.1029/2006JD007107, 2006.
- Stolarski, R. S., Douglass, A. R., Steenrod, S., and Pawson, S.: Trends in stratospheric ozone: lessons learned from a 3D chemical transport model, *J. Atmos. Sci.*, 63, 1028–1041, doi:10.1175/JAS3650.1, 2006.
- 10 Swartz, W. H., Stolarski, R. S., Oman, L. D., Fleming, E. L., and Jackman, C. H.: Middle atmosphere response to different descriptions of the 11-year solar cycle in spectral irradiance in a chemistry-climate model, *Atmos. Chem. Phys.*, 12, 5937–5948, doi:10.5194/acp-12-5937-2012, 2012.
- 15 Tapping, K. F. and Detracey, B.: The origin of the 10.7 cm Flux, *Solar Phys.*, 127, 321–332, doi:10.1007/BF00152171, 1990.
- Tourpali, K., Schuurmans, C. J. E., van Dorland, R., Steil, B., and Bruhl, C.: Stratospheric and tropospheric response to enhanced solar UV radiation: a model study, *Geophys. Res. Lett.*, 30, 1231, doi:10.1029/2002GL016650, 2003.
- 20 van Loon, H., Meehl, G. A., and Shea, D. J.: Coupled air-sea response to solar forcing in the Pacific region during northern winter, *J. Geophys. Res.-Atmos.*, 112, D02108, doi:10.1029/2006JD007378, 2007.
- Wallace, J. M., Panetta, R. L., and Estberg, J.: Representation of the equatorial stratospheric quasi-biennial oscillation in EOF phase space, *J. Atmos. Sci.*, 50, 1751–1762, 1993.
- 25 Wang, S., Li, K.-F., Pongetti, T. J., Sander, S. P., Yung, Y. L., Liang, M.-C., Livesey, N. J., Santee, M. L., Harder, J. W., Snow, M., and Mills, F. P.: Atmospheric OH response to the 11-year solar cycle – could the gap between model and observations be filled by SORCE measurements?, *P. Natl. Acad. Sci. USA*, in review, 2012.
- WMO: Scientific assessment of ozone depletion: 2006, Global Ozone Research and Monitoring Project – Report No. 50, World Meteorological Organization, Geneva, 2007.
- 30 Wolter, K. and Timlin, M. S.: El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext), *Int. J. Climatol.*, 31, 1074–1087, doi:10.1002/joc.2336, 2011.

Zhou, J. and Tung, K.-K.: Solar cycles in 150 years of global sea surface temperature data, *J. Clim.*, 23, 3234–3248, doi:10.1175/2010JCLI3232.1, 2010.

Table 1: Model simulations in this study and their identities. The color codes are assigned in accordance with the average contour colors shown in Fig. 3. Experiment A is run with solar spectral irradiance (SSI) from the Naval Research Laboratory (NRL) solar model and climatological sea surface temperature and ice (SST/ice). Experiment B is similar to experiment A except that the realistic SST/ice is used from 1960 to 2009. Similarly, experiment C is run with exoatmospheric SSI observed by the Solar Radiation and Climate Experiment (SORCE) and climatological SST/ice. Experiment D is similar to experiment C except that the realistic SST/ice is used. Experiment E is run with no solar-cycle variability in SSI and the realistic SST/ice is used.

Experiment	SSI			SST/ice	
	NRL	SORCE	fixed	Climatological	Realistic
A	●			●	
B	●				●
C		●		●	
D		●			●
E			●		●

Table 2: Regression coefficients and corresponding uncertainties ($\pm 2\sigma$) described in Eqs. (1) and (2). They are temporally averaged according to Eqs. (3) and (4).

Experiment ID	$\bar{\alpha}$ (DU/year)	$\bar{\beta}$ (DU/100 $F_{10.7}$)	$\bar{\gamma}$ (DU/MEI)
A	-0.01 ± 0.03	3.17 ± 0.69	0.02 ± 0.32
B	-0.05 ± 0.03	2.77 ± 0.71	-1.15 ± 0.33
C	0.00 ± 0.02	5.53 ± 0.66	0.08 ± 0.31
D	-0.03 ± 0.03	5.56 ± 0.77	-1.39 ± 0.36
E	-0.04 ± 0.03	-0.34 ± 0.71	-1.41 ± 0.33

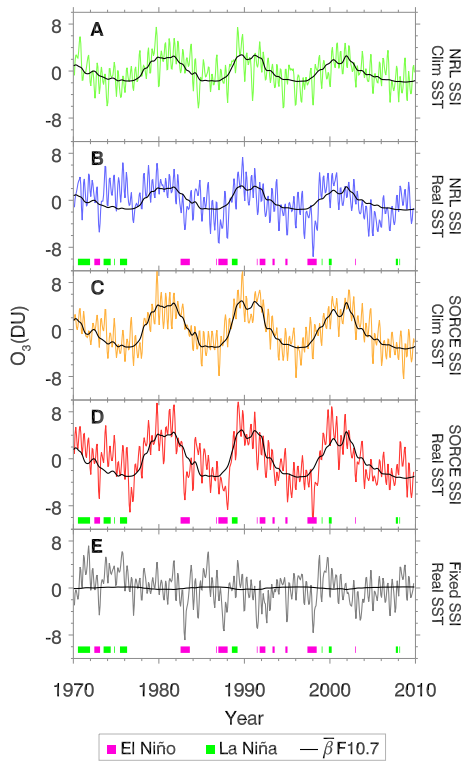


Fig. 1: Tropical averages of total column ozone X_{O_3} between 24° N and 24° S simulated by WACCM for four experimental setups identified in Table 1. The color codes are assigned in accordance with the average contour colors shown in Fig. 3. Overlaid black line is the regressed time series related to the solar variability described by the product $\bar{\beta}F_{10.7}$, where $\bar{\beta}$ is the time-averaged regression coefficient and $F_{10.7}$ is the 10.7-cm solar radio flux. Also shown by pink and green strokes are strong El Niño/La Niña events when the absolute values of the Multivariate El Niño/Southern Oscillation Index (MEI) are greater than 1.

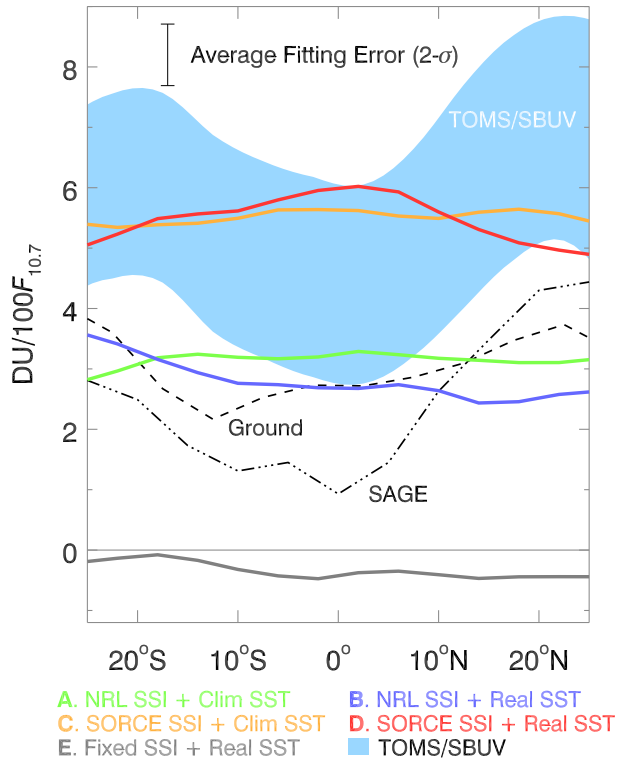


Fig. 2: Values of $\bar{\beta}$ as a function of latitudes for four experiments identified in Table 1. The color codes are assigned in accordance with the average contour colors shown in Fig. 3. Also shown in cyan shade is the solar-cycle sensitivity of X_{O_3} derived from satellite measurements by the Total Ozone Mapping Spectrometer (TOMS) merged with the Solar Backscatter Ultraviolet (SBUV). The dashed and dash-dotted line are the corresponding sensitivity derived from ground-based measurements and Stratospheric Aerosol and Gas Experiment (SAGE) respectively. All data of TOMS/SBUV, SAGE, and ground-based measurements are extracted from Fig. 12 of Randel and Wu (2007). The error bar shows the average regression error, which is $0.6 \text{ DU}/100F_{10.7}$ (2σ).

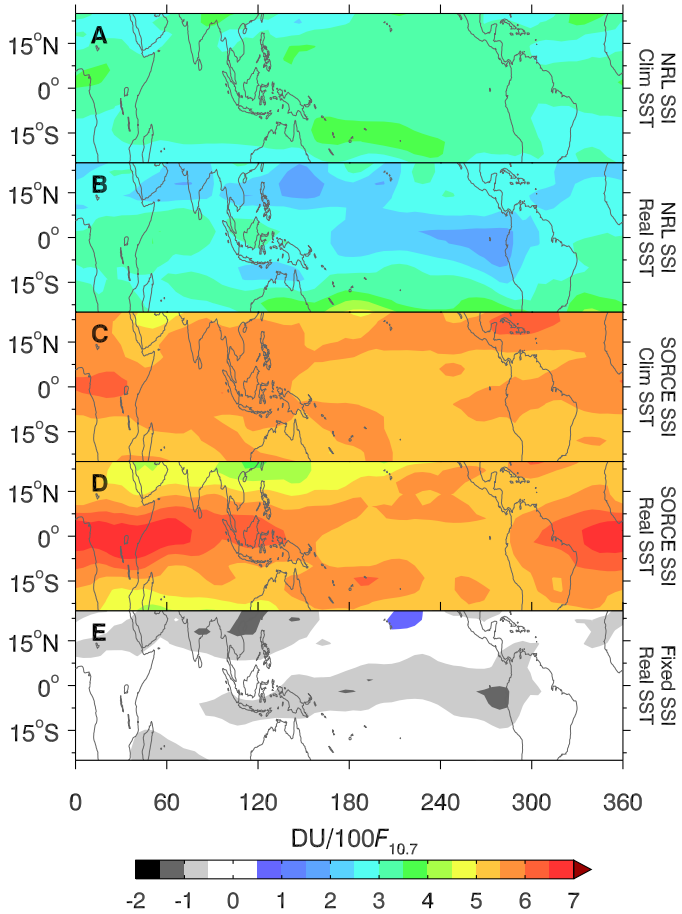


Fig. 3: Time-averaged regressed coefficients $\bar{\beta}$ for all experiments in the tropics. The multiple linear regression is applied to all individual grid points.

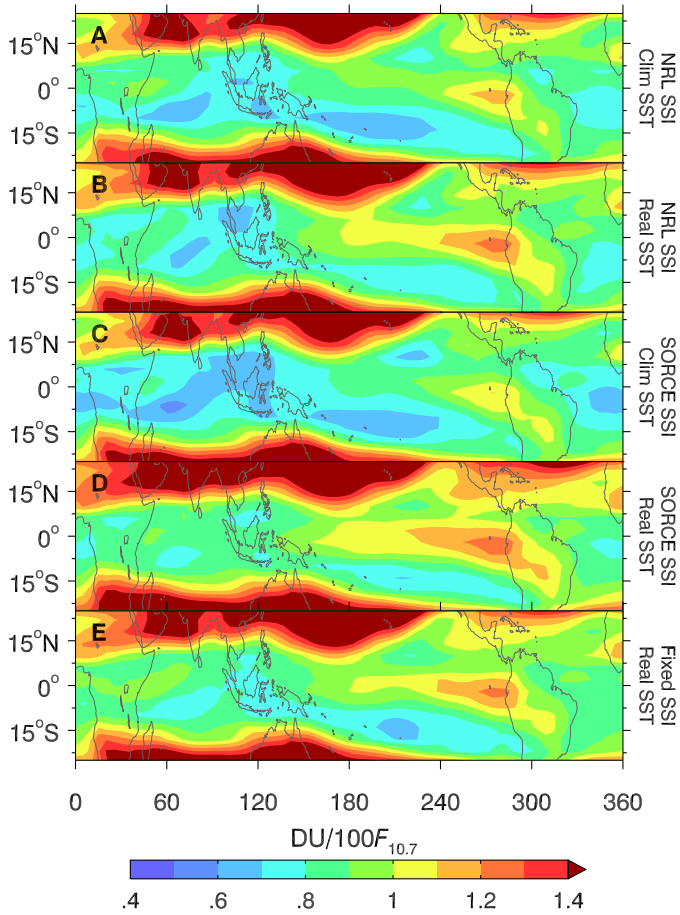


Fig. 4: Same as Fig. 3 except for the uncertainty (2σ) of the regressed coefficient, $\text{var}\bar{\beta}$, on individual model grid points.

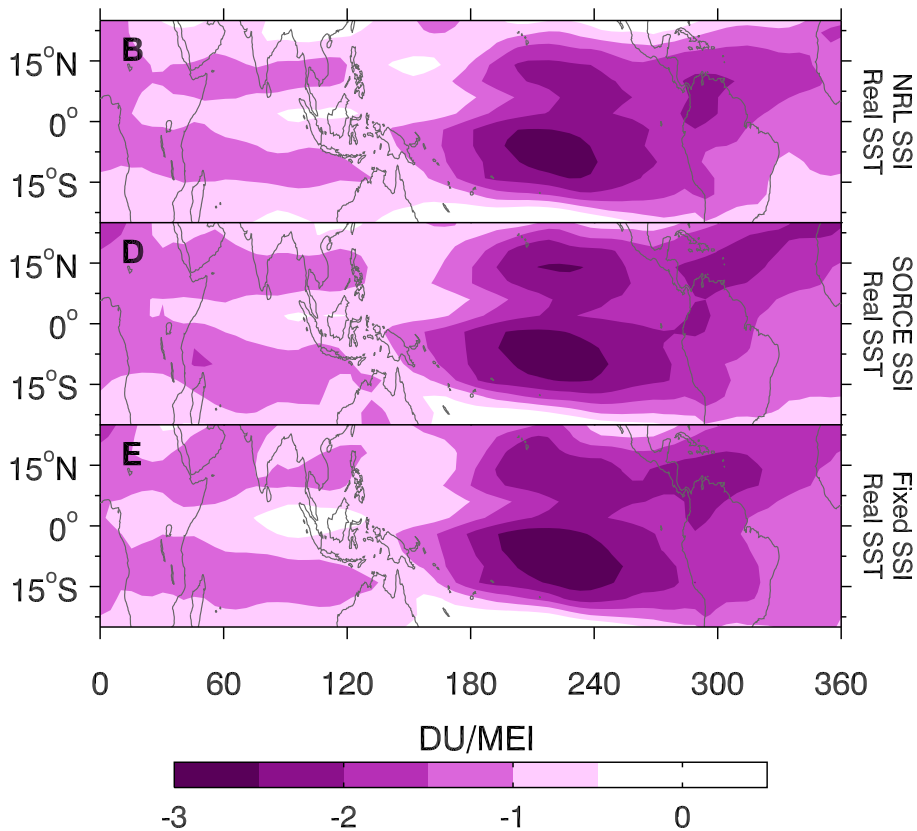


Fig. 5: The spatial pattern of the time-averaged regressed coefficients $\bar{\gamma}$ related to ENSO for experiments B, D and E.

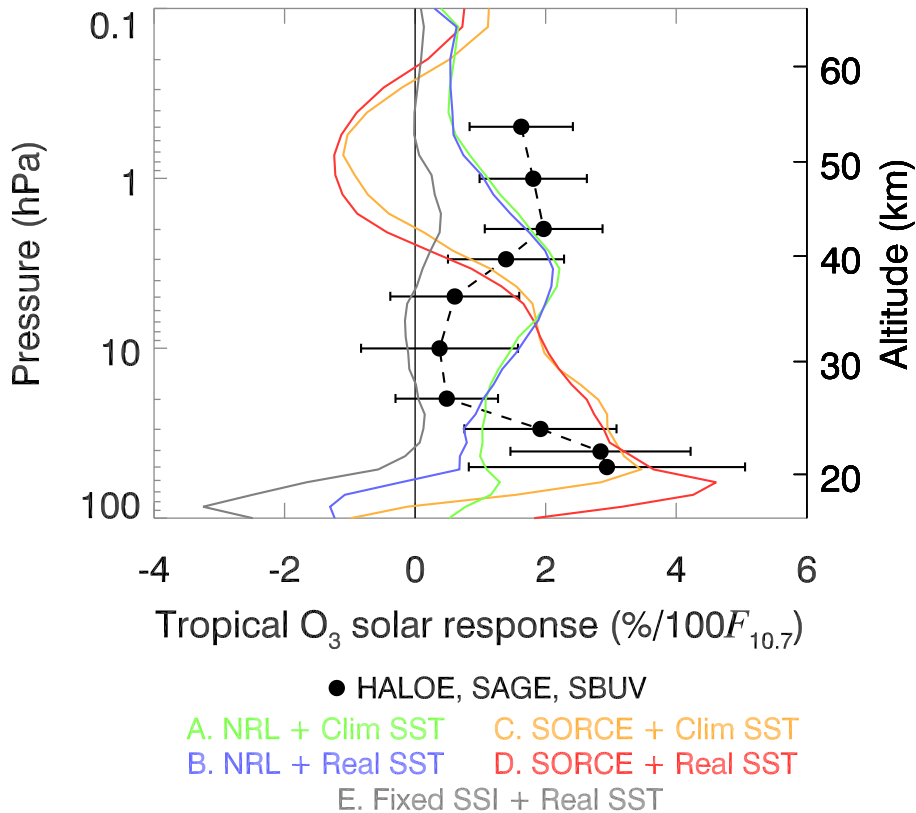


Fig. 6: Tropical average vertical O_3 response between $25^\circ N$ – $25^\circ S$. The color scheme follows that in Table 1. The satellite averages from HALOE, SAGE, and SBUV measurements and their uncertainties are extracted from Soukharev and Hood (2006). The uncertainty of the regressed model responses are $\sim 0.5 \text{ } \%/100F_{10.7}$ above 20 km and $\sim 2 \text{ } \%/100F_{10.7}$ below 20 km.

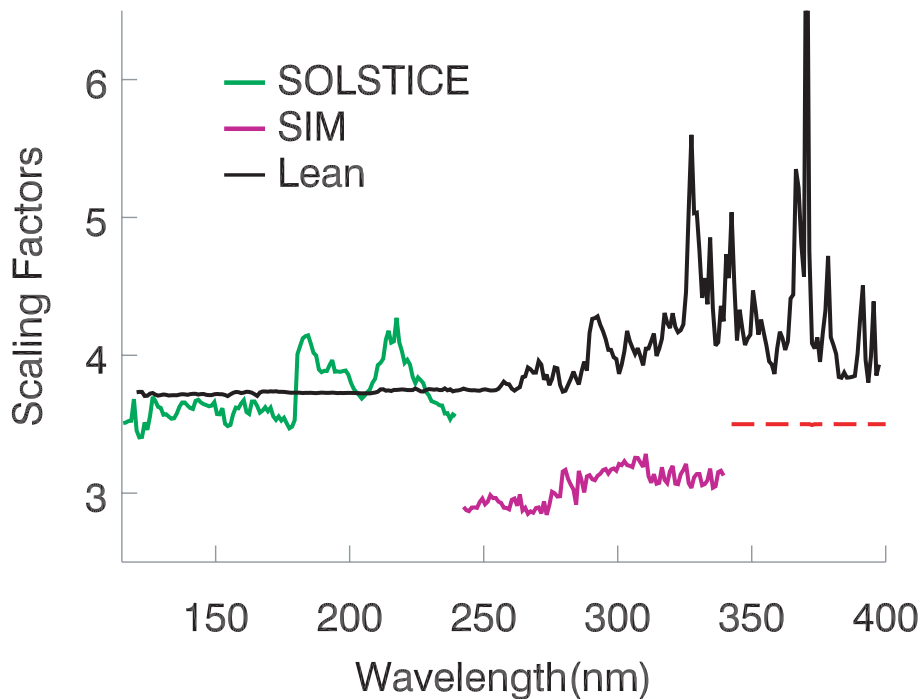


Fig. S1: Solar UV spectral variability derived from SORCE SSI. The green and purple lines correspond to SSI data from SOLSTICE and SIM, respectively. The black line is the NRL SSI variation. All spectra have been convolved to the model grid. The inset shows the spectral scaling factors for extrapolating the observed SSI (April 2004 – November 2007) to the solar max in January 2002. For above 340 nm, an arbitrary factor of 3.5 is applied (red, dashed).