Author response to review by Joanna D. Haigh

The representation of solar cycle signals in stratospheric ozone. Part II: Analysis of global models" by Amanda C. Maycock et al.

The paper presents an analysis of the responses found in the ozone fields of coupled chemistry-climate models to specification of solar spectral irradiance, how these compare to the ozone fields prescribed in IPCC climate models (and to the signals found in observational datasets). The work is carefully planned and thorough and provides a suitable background against which future work can be planned and studied.

We thank the reviewer for her supportive comments on the manuscript. We reply to her specific points below.

Minor comments

l.44 Tell reader that Maycock et al. (2016) is Part I
Added

l.121 Why only one ensemble member? The modellers have done several to provide you with stats!
We have updated the analysis to use all available ensemble members for the models.

l.179 ref l.671 Matthes (2017) now published (though with a weak explanation for the political expediency involved in the averaging of two datasets!).
Reference updated

l.184 Clarify "up_0.3%": presumably not 0.3% of signal but 0.3% on top of c. 2% (?)
Text has been changed for clarification

l.233 Have you looked at the impact of this choice of AR model (cf none or AR(1))?
Figure R1 below shows the decorrelation timescale for the MLR model residuals. The e-folding time is >2 months in some regions of the middle and lower stratosphere. Figure R2 below is as in Figure 3 of the main text but assuming no AR model for the residuals. The results are similar to those using an AR(2) model, with the main exception found in the polar lowermost stratosphere. Therefore to avoid giving potentially misleading information about the SOR in the polar lowermost stratosphere we have restricted the plots in the revised manuscript to a maximum pressure of 100 hPa.

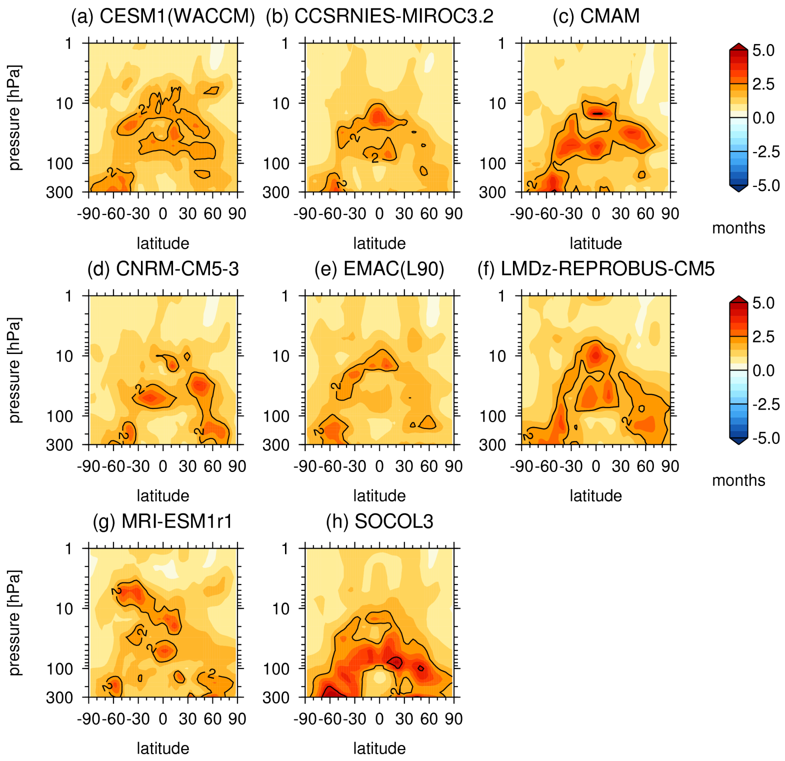

Figure R1: e-folding time [in months] of the ACF in the MLR residuals for the CCMI-1 models.

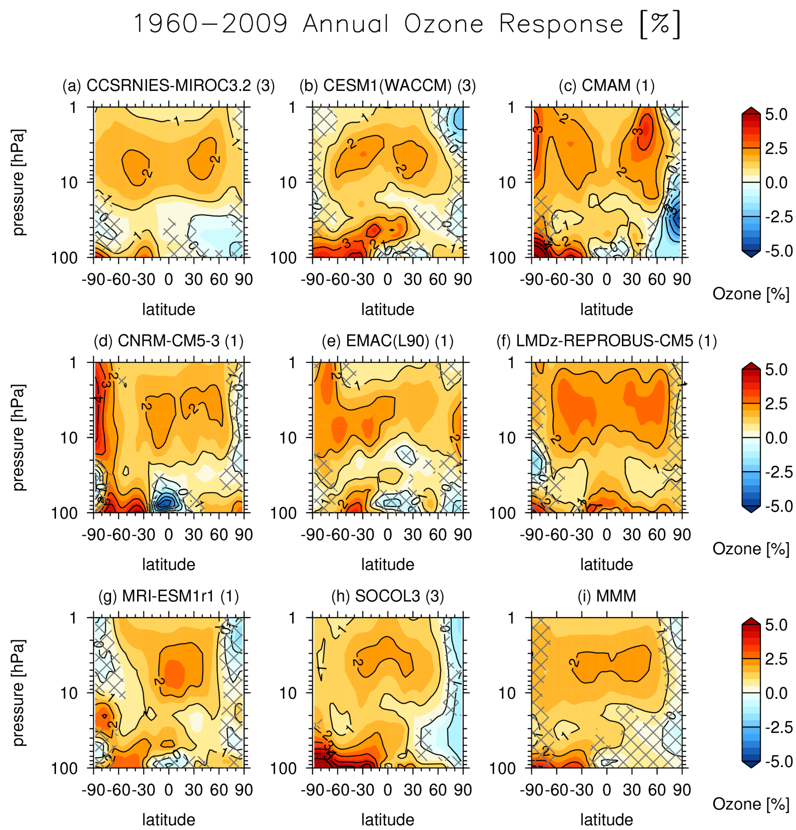

Figure R2: As in Figure 3 of the main text but assuming no AR model.

l.300, l.330 and elsewhere. Comparison to observational results of Part I interesting but difficult to extract from this text.

We have added timeseries of ozone anomalies from two satellite observation datasets described in Part I to Figures 2 and 4 to facilitate the comparison with results from Part I.

l.391-2 Indeed! Can you make any judgement on what is causing these differences between datasets?
l.491-494. Any conclusion on why these models produce a signal in the tropical lower stratosphere?

Both comments relate to the presence or absence of a significant SOR in the tropical lower stratosphere. There are some methodological sensitivities to the robustness of this feature. For example, this is one of the main regions where sensitivity to the choice of AR model is seen. This is particularly found in models where the regression residuals show long autocorrelation timescales in the tropical lower stratosphere (see e.g. SOCOL3 in Figure R1 above and compare Figure R2(h) and Figure 3(h) from the main text). Consequently, the estimated uncertainties in the magnitude of the SOR in the tropical lower stratosphere are larger than in the upper stratosphere (see e.g. Figure 6). In the revised manuscript, we have also altered the approach for accounting for volcanic effects by excluding 2 year periods following eruptions rather than including a volcanic term in the MLR. This also has a modest effect on the SOR in the tropical lower stratosphere in some models (compare Figure 3 in revised manuscript with original Figure 3).

Aside from the above methodological issues, additional analysis (not shown) has been performed on the Transformed Eulerian Mean residual vertical velocity fields for the models that provide this data for the refC1 experiment (CCSRNIES-MIROC3.2, CMAM, EMAC, MRI-ESMr1, SOCOL3). There is no evidence of a significant weakening in tropical lower stratospheric upwelling in the models that show some enhancement in the SOR in this region, as has been suggested in some earlier studies.

The following text has been added to the manuscript:
"One of the CCMI-1 models (SOCOL3) appears to show an enhanced SOR in the tropical lower stratosphere, which is similar in amplitude to that seen in some CCMVal-1 models. However, this feature shows some sensitivity to the choice of autoregressive model in the MLR model probably because the decorrelation timescale for the regression residuals in the tropical lower stratosphere is longer than two months in SOCOL3 and some of the other CCMs (not shown). Further analysis of the Transformed Eulerian Mean residual vertical velocity does not reveal a substantial change in the rate of upwelling in the tropical lower stratosphere in any of the models (not shown)."

l.515 Not sure that you have justified the statement that proper SOR and SSI are needed for solar-climate impacts. Of course I agree with that (!) but you have not discussed climate (troposphere) much at all in this paper, and only used models with fixed SSTs.
This sentence does not claim that proper SOR and SSI are needed to simulate solar-climate impacts, rather it is simply a request to CMIP6 modellers to document the implementation of SSI and the SOR to enable interpretation of the model output after the experiments are finished. For example, a model that does not include any representation of the SOR might be expected to have a weaker atmospheric response to the solar cycle than a model that does include a SOR. CMIP models are often set up in different ways and traceability can be a challenge. This statement in the manuscript is

therefore only intended as an appeal for documentation on how CMIP6 models implement the SOR and SSI in order to interpret model differences once data become available. We have therefore left the text as before.

l.533 A reasonable summary paragraph but it is a bit disappointing that we seem to be no nearer any understanding of the solar signal and the conclusion is just that more data is needed.
The last part of the conclusions has been edited to focus on the new findings of the study. The last paragraph now reads: "Parts I and II of this study have shown that uncertainties remain in understanding the SOR, which present a challenge for including these effects in model simulations. However, given the inclusion of variations in the SOR over the annual cycle, as well as the greater consistency of the amplitude of the SOR with CCM results, CMIP6 models without chemistry are encouraged to use the recommended CMIP6 ozone database in order to potentially improve the atmospheric response to the solar signal. Nevertheless, whatever approach is employed, all CMIP6 modelling groups are encouraged to document the representation of the SOR and SSI in their simulations to facilitate future analysis of solar-climate impacts."

Author response to review by Anonymous Referee 2

The representation of solar cycle signals in stratospheric ozone. Part II: Analysis of global models" by Amanda C. Maycock et al.

<u>Overview of study</u>

The authors look at how the ozone (mainly stratospheric) changes in response to solar cycle activity (not including many secondly solar effects, such as high energy particles). The use CMIP5 and 6 data, and compare with observations, mainly characterised in part 1 of these papers. I find the study comprehensive in its analysis, but not particularly novel in terms of the science, and certain not novel in terms of increased scientific understanding. The study essentially regresses out the solar signal from ozone in climate models, which has been done to death. I appreciate a lot of work has gone in to applying it to a new data set, but I can see little advancement in scientific knowledge in what is done. The authors' final summary seems testament to this, where their conclusion is essentially 'we need more data'. The scientific analysis is far from rigorous as well, with statistical significance very rarely performed, in unclear for the figures where it has been done.

We thank the reviewer for his/her detailed comments on the manuscript, which we address below. While the reviewer has raised some criticisms, which we have addressed and which have helped to improve the manuscript, we firmly believe that the manuscript contains relevant new results that will be of interest to the broad atmospheric and solar research communities, and therefore that the manuscript warrants publication in ACP.

<u>Concerns (major)</u>

1) The novelty to the study. Many studies have done very similar things to this study. Some of these studies are cited in the main text, but it is often not clear to a reader who is unfamiliar with the literature just how similar these studies really are. In many cases reproducing very similar figures. The authors need to be clear up front what is new here, and attribute all the repeated information to the correct papers.

a) Our study compares the representation of the solar-ozone response (SOR) in models with interactive chemistry (CCMs) against the prescribed SOR in GCMs. To our knowledge such a comparison has not been been performed before and therefore comprises an important advance to the field. It is particularly relevant for putting into context recent multi-model studies (e.g. Mitchell et al., 2015; Hood et al., 2015) that include CCMs and/or GCMs. Our results show that the representation of the SOR is crucial (arguably more important than changes to the SSI forcing dataset -- see Matthes et al (2017)) for determining differences in modeled solar cycle responses between CMIP5 and CMIP6. We deem these to be sufficiently interesting and important conclusions to justify publication in ACP.

b) To clarify that multiple regression methods have been widely employed to extract solar cycle variations in ozone datasets before, we have added the following text at the start of Section 2.2:
"Multiple linear regression models have been used to analyse drivers of secular trends and variability in stratospheric ozone for many decades (see e.g. Staehelin et al., 2001 and references therein). In the context of extracting solar cycle variability from ozone timeseries, there is a long history of similar methods being applied to both satellite observations (e.g., Soukharev and Hood, 2006; Remsberg 2008; Tourpali et al 2007;

Remsberg and Lingenfelser, 2010; Dhomse et al 2016; Lee and Smith, 2003; Lean 2014; Randel and Wu, 2007; Merkel et al 2011) and chemistry-climate models (Austin et al., 2008; Sekiyama et al., 2006; Lee and Smith, 2003; Egorova et al., 2004; Dhomse et al., 2011; Dhomse et al., 2016; Hood et al., 2015; SPARC CCMVal, 2010). Here we follow the methodology described by Maycock et al (2016), which is very similar to the methods described in those earlier studies."

We have also edited the Introduction to state an explicit set of novel objectives for the study:
"The objectives of this study are therefore:

- to provide an update to previous CCM studies by analysing the SOR in CCMI-1 models.
- to evaluate the SOR in three pre-calculated ozone databases for climate models from CMIP5, CMIP6 and Bodeker et al (2013).
- to compare the CCMs and ozone databases with satellite observations from Part I (Maycock et al, 2016).
- to perform atmospheric model experiments to quantify the impact of differences in the SOR between CMIP5 and CMIP6 on the simulated atmospheric response to the 11 year solar cycle.

Collectively these objectives provide a comprehensive assessment of the represention of the SOR in current CCMs and global climate models."

We have also added at appropriate points in the results section statements connecting our results to figures in earlier multi-model studies such as Austin et al (2008) and Hood et al (2015). While the CCMI-1 model analysis is an update on these earlier studies, the explicit comparison with pre-calculated ozone fields is new.

We hope that the reviewer agrees these changes adequately acknowledge the earlier work that our study builds on.

2) The statistical significance in this study. This is very poor, and often non-existent. The authors need to be clear about what their significance test is, what it is showing, and most importantly, they actually need to do some significance testing for most of the plots. In some plots, different significance tests will be needed for each panel. i.e. Figure 3, a different test will be needed for the individual model, as for the MMM. I am not even sure if the MMM has significance in the current study?

The reviewer is correct that in the original manuscript the MMM result in Figure 3i did not show any estimate of statistical significance. This has been added in the revised manuscript based on regions where the MMM response is smaller than ±2 standard deviations of the intermodel spread derived from Figures 3(a-h).

Hatching denoting regions where the central estimate of the regression coefficients is not statistically significant at the 95% confidence level has also been added to Figures 5 and 7.

We have added shading to Figure 9 denoting ±2 standard deviations of the interannual variations in temperature over the 50 year experiments as an estimate of the 2.5-97.5% confidence intervals for the ECHAM6.3 modelled responses.

All figures in the revised manuscript (with the exception of the raw timeseries) therefore now include appropriate estimates of the statistical significance of the results.

3) Regression methodology. The methodology the authors use has no measure of uncertainty in the basis functions. This is a fundamental problem, because some of the basis functions have a good deal of uncertainty associated with them. The authors should add this uncertainty in to better reflect the uncertainty in the final result. The regression method they use is cited as from Maycock et al, but in reality, it probably has roots in far earlier solar-regression studies (see my first point, of giving due where it is deserved, even if methods/results are slightly different). I expect the authors arguments to not including uncertainty in the basis functions will be 'it has been done multiple times before', and cite a number of studies. However, this does not mean it is correct, unfortunately. I feel at some point, one of these studies need to include these basis uncertainties, at the very least to show that it doesn't make a difference (although I expect that it does).

We have followed the reviewer's suggestion to add greater historical context for the regression methodology employed in the study in Section 2.2 (see response to major point 1). We agree with the reviewer that there are limitations of multiple regression analysis, which we emphasise are not limited to examination of the SOR. However, it is difficult to conceive of other current approaches that would have significantly less limitations. We have added the following text to the manuscript at the end of Section 2.2: "It is a challenge in geophysical science to develop statistical methods to extract forced signals from complex timeseries. The implementation of multiple regression analysis as described above has a number of limitations, including (but not limited to): assumption that the input basis functions have zero uncertainty; difficulties in separating a signal from noise in a relatively short or sparse record (Damadeo et al 2014); and potential issues with degeneracy between basis functions (Chiodo et al 2014). These limitations should be kept in mind when examining detailed aspects of the results."

We inform the reviewer that there is now a dedicated working group within the SPARC SOLARIS-HEPPA activity that will perform a detailed comparison of statistical methods for analysing solar-climate signals with the eventual aim of providing some recommendations for best practices.

4) Anomalies. Often the authors use anomalies of variables, rather than the absolute variables. It would be good to see who real values of the data. I realise this can not always be done, but in some figures, for instance Figure 4, this would be very informative. Anomalies often make things look better!

Since the focus of our study is on quasi-decadal variability in ozone, we believe it makes sense to show anomalies from the long-term annual cycle, so that the vertical scale on the timeseries in Figures 2 and 4 can be sufficiently narrow that interannual to quasi-decadal variations are visible. However, to respond to the reviewer's request we have added figures to the Supplementary Material showing timeseries of absolute tropical ozone mixing ratios in the CCMI models (Figure S1) and in the climate model ozone databases (Figure S3).

5) There is a lot of focus on the CMIP6 ozone data set. But seems to be absolutely no citation to documentation on this data set. I note that the creators of the data set are not authors on this paper, and perhaps some of that lack of knowledge is reflected in the text. Is there a CMIP6 ozone paper coming out? Should this current paper be kept out of publication till that exists? This should certainly be true if there is any overlap.

Throughout this work we have liaised closely with the creators of the CMIP6 ozone database, led by Michaela Hegglin. We have sent Michaela the draft manuscript for comment and she has even posted a comment on the discussion of this article in ACPD. At no point has it been indicated to us that our study should not be published. To the best of our knowledge the forthcoming publication in GMD describing the CMIP6 ozone database will not focus on the representation of the SOR, and thus we do not anticipate any significant overlap between the studies.

Two co-authors of our study (Dan Marsh and David Plummer) are the principal investigators of the CCMs (CMAM and CESM1(WACCM)) used to produce the CMIP6 ozone database. These co-authors have provided detailed information about the CCM simulations used to create the CMIP6 ozone database. The parts of this information that are particularly relevant to simulation of the SOR are described in Section 2.1.3 of the manuscript.

We remind the reviewer that the CMIP6 ozone database is publicly available and CMIP6 modellers are already implementing the dataset in their models: https://esgf-node.llnl.gov/projects/input4mips.

Concerns (minor)

1. Line 1: This alone would not fully capture the response
'fully capture' changed to 'to aid in capturing'

2. The SOR seems a little strange in this context, because it is not obvious (until later) that the SOR is not a 'set thing', it is only known within uncertainty bounds (and so different CCM give different SORs).
We use SOR throughout the manuscript for consistency with Part I. Here we have changed the text to say 'comparison of the representation of the solar-ozone response (SOR)….' to make clearer that this is something with variable representation across models.

3. Line 9: . . . ozone databases' – at this point it is not clear if the ozone data basis is the prescribed ozone, or simulated ozone from a CCMI.
Throughout the manuscript we distinguish between analysis of output from chemistry-climate models (in this case CCMI models), analysis of pre-calculated ozone databases for models without chemistry (which can be constructed from observations and/or CCMs), and analysis of ozone datasets (i.e. satellite observations taken from Part I). The use of 'database' in the manuscript is therefore solely reserved for pre-calculated ozone fields used in models without chemistry. We feel that the preceding sentence makes clear the distinction between the analysis of CCM results and of the pre-calculated ozone databases for CMIP5/CMIP6.

4. Line 11 Make clear that you refer to historical period ozone
Time period of analysis added.

5. Line 13: weak compared with what?
This clause has been removed.

6. Line 76 – a citation is really needed here (see major concern).
The dataset is publicly available at: https://esgf-node.llnl.gov/projects/input4mips. This link has been added to the text.

7. Line 89 – what time frequency is this data?
'monthly mean' added

8. Line 94 'transferring' – please revise this word.
Text changed to 'may play a role in driving the 'top-down' mechanism for the solar cycle influence on high latitude regional surface climate (see e.g. Gray et al. (2010)).'

9. L124. Why only 1 ensemble member? Please repeat with all of them. You need to capture the uncertainty.
We have updated the analysis to use all available ensemble members for the models. See Table 1.

10. Page 5 (top): This seems very similar to Hood et al, please state that.
We are unsure of what the reviewer is referring to as being similar to Hood et al (2015) and have therefore not changed the text.

11. Line 37: 5 x 5degree. This is not normal, why has the interpolation taken place?
This is the resolution at which the SPARC/AC&C CMIP5 ozone database is provided: see Cionni et al. (2011) doi:10.5194/acp-11-11267-2011. This is because the historical part of the CMIP5 database was derived from satellite observations (SAGE I and II) that are available on a 5 degree grid. We have not performed any further interpolation.

12. Equ 1: Please cite where this came from originally.
Additional references have been added at the start of Section 2.2 that make reference to earlier work using similar methods, including the review of Staehelin et al (2001) that discuss the history of multiple regression methods for ozone trends.

13. Equ 1: Do the authors have any views on the breakdown between the long terms solar response, and the 11-year response?
We tested the sensitivity of our results to removing >11 year variability from the F10.7cm solar flux timeseries and found that removing the lower frequency solar variability had virtually no effect on the results. For simplicity we therefore did not perform any pre-filtering to the timeseries of the solar basis function.

14. Figure 1: Surely these QBO signals are just from one model? These will change.
Yes, the QBO indices in Figure 1 are just an example based on the observed winds. This is now stated in the caption. The QBO indices for the models are calculated from the individual model wind fields as described in Section 2.2.

15. Line 218-219: 'better proxy' not convincing to me. Please cite a paper that compares these.
Floyd et al (2004, doi:10.1016/j.jastp.2004.07.013) show that F10.7cm and Mg-ii are correlated at >.95 for daily timeseries and >.99 for variability on timescales longer than several months. This reference has been added to the manuscript.

16. Line 220-225: This section on the volcanic signal is vague. The data sets the authors use are not long, in fact some figure just use ~30 years of data. Very short for regression. Volcanic signals will cause issues in the regression, and it is not clear the authors have dealt with the properly (nor in Part 1).

Following the reviewer's comment and after further discussions, in the revised manuscript we now adopt the approach of Maycock et al (2016) by removing data in the periods immediately following the three major tropical volcanic eruptions since 1960: Mt Agung, El Chichon and Mt Pinatubo. This is because the ozone response to volcanic eruptions is a non-linear function of chlorine amount and thus it is not appropriate to include a basis function for volcanic effects in the MLR model. The description in the Methods section has been updated to reflect this change.

17. Line 240. I think the authors need to show the autocorrelation plots to the reviewers, so we can assess this evidence. I agree they probably do not need to go in the main text.

Figure R2 below shows the e-folding time in months of the autocorrelation function (ACF) of the monthly regression residuals in the CCMI models. Areas where the e-folding time of the ACF is greater than 2 months are evident in all of the models in the mid and lower stratosphere and hence our choice to adopt an AR(2) model.

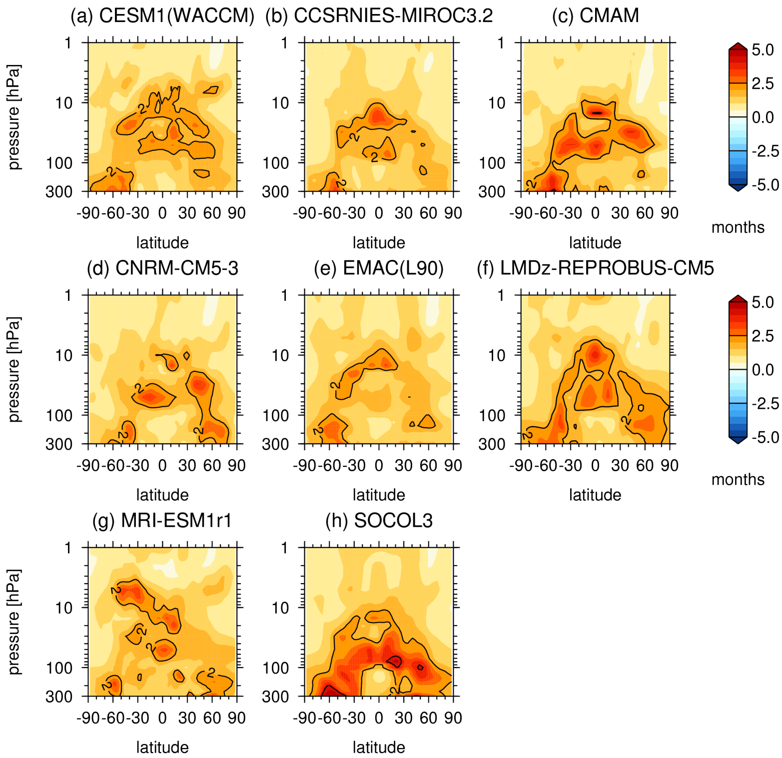

Figure R2: e-folding time [in months] of the autocorrelation function of the MLR residuals for each CCMI-1 model.

In testing the effects of the AR model choice, as requested by reviewer 1, we identified some sensitivity of the estimated SOR in the polar lowermost stratosphere, which may be related to the longer timescales of the ACF in that region in several models. The sensitivity to the AR model choice across the remainder of the stratosphere was small, which the exception of the tropical lower stratosphere in SOCOL, which is discussed in the revised text. Therefore to avoid giving potentially misleading information about the SOR in the polar lowermost stratosphere we have restricted the plots in the revised manuscript to a maximum pressure of 100 hPa.

18. Section 2.3: please describe more how this model fits into the wider models of CMIP5. Then we can assess suitability.

A detailed description of the model is given in Section 2.3 of the manuscript. The model has a well-resolved stratosphere (model lid height above 50 km) and simulates the major aspects of the stratospheric circulation e.g. sudden warmings, the QBO (see e.g. Charlton-Perez et al., 2013; Schmidt et al., 2013). The response to 11 year solar forcing in the CMIP5 version of ECHAM has been shown to be comparable to other high-top stratosphere resolving CMIP5 models (Mitchell et al., 2015).

Since the model does not include interactive chemistry, it provides a suitable test-bed for quantifying the effects of the pre-calculated ozone databases for CMIP5 and CMIP6.

19. Line 255-260: This is worrying that the lower signal might not be so well captured.
We are unsure what the reviewer means by 'lower signal' in this context. The impact of the short wavelength absorption below 200 nm that is not captured in the ECHAM6.3 radiative code is quantified by Sudhokolov et al (2014) – see lower right panel of their Figure 2. The underestimation of the solar max-min shortwave heating anomaly in the stratosphere is ~15-20%, but is much larger above 60 km and thus we restrict our analysis to the stratosphere (<50 km) where the errors in the model radiation code are smaller. The simulation of the atmospheric response to the solar cycle in the CMIP5 version of ECHAM (MPI-ESM) was comparable and indeed compared better with reanalysis data than several other high-top CMIP5 models (see e.g. Mitchell et al. (2015)).

20. Figure 2: Please just plot the SAGE2 and SBUV observations on this plot.
Done.

21. Line 291-295: power spectra would be useful here.
A plot showing the power spectra of tropical ozone anomalies at 3 hPa (roughly at the maximum of the SOR) for the CCMI models has been added to the Supplement as Figure S2. A peak around the decadal timescale is evident in the models.

22. Line 350-358: This is an important point the authors make. Are you saying this is a drawback of the CMIP6 ozone data set? Please expand on your recommendations here.

In our view it would be undesirable for a climate model to impose a QBO-ozone signal that is out of phase with its dynamical QBO. The counter-case is a model that simulates a dynamical-QBO, but that does not include realistic feedbacks from ozone. In practice, true consistency can only really be achieved in CCMs, but it seems potentially more problematic to impose an erroneous QBO-ozone signal than to neglect it altogether. Thus CMIP6 modelling groups may choose to post-process the CMIP6 ozone database in order to remove, or change the phase, of the QBO-ozone signal it contains to be consistent with their model. We are not making a specific recommendation, as we have not tested the impact of the QBO-ozone coupling on the simulation of the QBO; however, we feel this is an important feature of the CMIP6 ozone database to point out as it differs from the approach used in CMIP5.

23. Figure 3: What is the significance test here? Does the MMM have significance?
See response to major comment 2. For individuals models the significance test criterion identifies whether the magnitude of the regression coefficients is distinguishable from zero based on the 2.5-97.5% confidence interval. Statistical significance for the MMM has been added based on where the MMM signal is larger than ± 2 standard deviations of the intermodel spread.

24. Figure 3: Why are tropospheric values masked out?
The focus of the study (and of Part I) is on the stratospheric solar-ozone response. Hence tropospheric values are not shown.

25. Figure 4. Colors very similar

We have changed the colours of lines in Figure 4 so that they are hopefully more distinguishable.

26. Figure 5. Is there any significance on here? At this point (analysis of figure 5-9), I do not believe it constructive to have an in-depth review, because the significance is mainly missing, or hard to understand. You are interpreting potentially small signals compared to the noise.
See response to major comment 2. Significance testing has been added to Figure 5 and other Figures throughout.

27. Line 438-440: I think this is wrong, the SSTs do not constrain the upper tropospheric temperatures this much!

Figure R3 below shows the tropical mean (30°N-30°S) temperature response in a set of climate model experiments in which an idealised +2% increase in TSI has been imposed but the SSTs kept fixed at climatology. These experiments are not part of this study, but serve as a useful illustration to test the reviewer's hypothesis. Each model experiment is run for 30 years and the differences are taken with respect to a baseline experiment with the same fixed SSTs but without the TSI perturbation. With fixed SSTs, the tropospheric temperature change due to increased TSI mainly comes from increased shortwave absorption by water vapour and warming over land areas due to altered surface shortwave fluxes. The average tropospheric warming is ~0.2 K in the experiments. Note that the imposed solar perturbation of +2% is approximately 20 times larger than the solar max-min perturbation imposed in ECHAM6.3 in Figure 9. Therefore, from a simple scaling of the response in these fixed SST experiments, one could expect the tropospheric temperature response in ECHAM6.3 (which also uses fixed SSTs) to be around 0.01 K, which is consistent with the results in Figure 9. Therefore we conclude that the SSTs do impose a strong clamp on the upper tropospheric temperatures and we have therefore not changed the text.

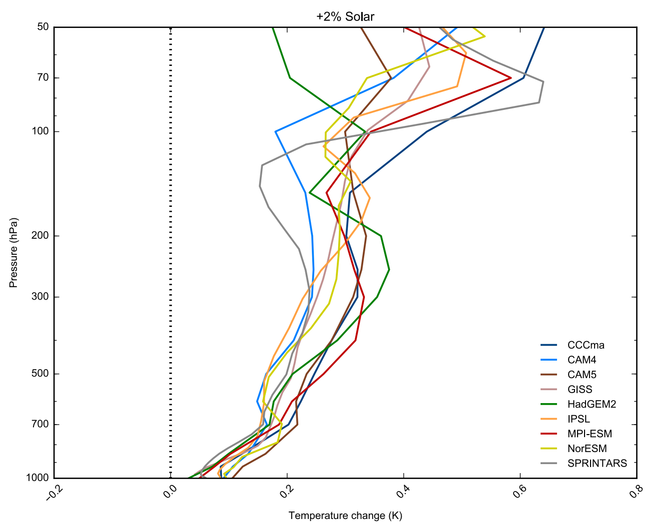

Figure R3: Difference in tropical averaged (30°N-30°S) temperature [K] in a set of climate model experiments forced with an idealised +2% TSI perturbation with fixed SSTs. The perturbation imposed here is approximately 20 times larger than that used in the ECHAM6.3 model in Figure 9 of the manuscript. With fixed SSTs, the tropospheric temperature changes to the imposed solar perturbation are relatively small. Figure credit: Dr Chris Smith (University of Leeds).

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The representation of solar cycle signals in stratospheric ozone. Part II: Analysis of global models

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Abstract. The impact of changes in incoming solar irradiance on stratospheric ozone abundances should be included in climate ~~model simulations to fully capture~~ simulations to aid in capturing the atmospheric response to solar cycle variability. This study presents the first systematic comparison of the ~~solar-ozone response (SOR) during~~ representation of the 11 year solar cycle ~~amongst different~~ ozone response (SOR) in chemistry-climate models (CCMs) and in pre-calculated ozone databases specified in climate models that do not include chemistry, with a special focus on comparing the recommended protocols for CMIP5 and CMIP6. We analyse the SOR in eight CCMs from the WCRP/SPARC Chemistry-Climate Model Initiative (CCMI-1) and compare these with results from three ozone databases for climate models: the Bodeker Scientific ozone database, the SPARC/AC&C ozone database for CMIP5, and the SPARC/CCMI ozone database for CMIP6. The ~~results reveal~~

~~substantial differences in the representation of the SOR between the CMIP5 and CMIP6 ozone databases. The~~ peak amplitude of the annual mean SOR in the tropical upper stratosphere (1-5 hPa) decreases ~~from~~ by more than a factor of two, from around 5% to 2%, between the CMIP5 and CMIP6 ozone databases. This ~~difference is because~~ substantial decrease can be traced to the CMIP5 ~~database was~~ ozone database being constructed from a regression model fit to satellite ~~observations, whereas~~ and ozonesonde measurements, while the CMIP6 database ~~is~~ has been constructed from CCM simulations~~, which use a spectral solar irradiance (SSI) dataset with relatively weak UV forcing~~. The SOR in the CMIP6 ozone database ~~is therefore implicitly more similar to~~ therefore implicitly resembles the SOR in the CCMI-1 models~~than to the CMIP5 ozone database, which shows a greater resemblance in amplitude and structure to the SOR in the Bodeker database. The latitudinal structure of the annual mean~~ . The structure in latitude of the SOR in the CMIP6 ozone database and CCMI-1 models is considerably smoother than in the CMIP5 database, which shows ~~strong~~ unrealistic sharp gradients in the SOR across the ~~midlatitudes~~ middle latitudes owing to the paucity of ~~observations at high latitudes~~long-term ozone measurements in polar regions. The SORs in the CMIP6 ozone database and ~~in~~ the CCMI-1 models show a ~~strong seasonal dependence , including large~~ seasonal dependence with enhanced meridional gradients at mid to high latitudes ~~during winter ; such~~ in the winter hemisphere. The CMIP5 ozone database does not account for seasonal variations in the SOR~~are not included in the CMIP5 ozone database~~, which is unrealistic. Sensitivity experiments with a global atmospheric model without chemistry (ECHAM6.3) are performed to assess the ~~impact~~ atmospheric impacts of changes in the representation of the SOR and ~~SSI~~ solar spectral irradiance (SSI) forcing between CMIP5 and CMIP6. The ~~experiments show that the smaller~~ larger amplitude of the SOR in the ~~CMIP6~~ CMIP5 ozone database compared to ~~CMIP5 causes a decrease in~~ CMIP6 causes a likely overestimation of the modelled tropical stratospheric temperature response ~~over the solar cycle of up to 0.6~~between 11 year solar cycle minimum and maximum by up to 0.55 K, or around ~~50~~80% of the total amplitude. ~~The changes in the SOR explain most of the difference in the amplitude of the tropical stratospheric temperature response in the case with combined changes in SOR and SSI~~ This effect is substantially larger than the change in temperature response due to differences in SSI forcing between CMIP5 and CMIP6. The results emphasise the importance of adequately representing the SOR in ~~climate~~ global models to capture the impact of ~~solar variability~~ the 11 year solar cycle on the atmosphere. Since a number of limitations in the representation of the SOR in the CMIP5 ozone database have been identified, we recommend that CMIP6 models without chemistry ~~are encouraged to~~ use the CMIP6 ozone database ~~to~~ and the CMIP6 SSI dataset to better capture the climate impacts of solar variability.

1 Introduction

Stratospheric heating rates are enhanced between the minimum and maximum phases of the approximately 11 year solar cycle through two main effects: (1) absorption of enhanced incoming ultraviolet (UV) radiation~~and~~ ; and (2) enhanced ozone concentrations (brought about by increased photochemical production) (e.g. Penner and Chang (1978); Brasseur and Simon (1981)). These radiative changes can drive feedbacks onto stratospheric dynamics, leading to amplified signals of solar cycle variability in regional surface climate via stratosphere-troposphere dynamical coupling (e.g. Kuroda and Kodera (2002)). To understand and model the impacts of solar cycle variability on the atmosphere ~~and climate~~ it is therefore necessary to account for the characteristics of ~~spectral solar~~ solar spectral irradiance (SSI) variability and the associated ~~solar-ozone~~ solar cycle ozone response (SOR) (e.g. Haigh (1994)).

In Part I of this study, Maycock et al. (2016) examined the SOR in a number of recently updated and merged satellite ozone datasets ~~. This study~~ from the instruments SAGE II, GOMOS, OSIRIS and SBUV. The present Part II focuses on the representation of the SOR in global climate and chemistry-climate models. At a minimum, models must include a sufficiently detailed representation of ~~both~~ SSI and the SOR to ~~properly~~ realistically simulate solar cycle impacts on the atmosphere. The global models routinely employed in ~~Intergovernmental Panel on Climate Change (IPCC) and World Meteorological Organisation (WMO) Ozone Assessment Reports~~ international scientific assessments (e.g. IPCC, WMO Ozone Assessments) typically represent atmospheric ozone in one of two ways. Chemistry-climate models (CCMs) include interactive stratospheric chemistry and explicitly simulate a SOR that is consistent with their photolysis, radiation and transport schemes provided that SSI variations are adequately (i.e. with sufficiently high spectral resolution) represented. A small ~~, but growing ,~~ but growing number of CCMs also include the chemical effects of galactic cosmic rays and solar energetic particles, though these effects are not explicitly considered in this study. Conversely, global climate models do not routinely include interactive chemistry and must therefore prescribe a ~~predefined~~ pre-calculated ozone distribution to the radiation scheme, which is usually taken from observations and/or chemical models. Thus, if climate models without chemistry are to capture the full atmospheric response to solar cycle variability, they must prescribe an ozone dataset that includes a representation of the SOR.

~~The~~ Understanding and constraining the SOR is a long-standing scientific issue and numerous studies have analysed its representation in observations (see Maycock et al. (2016) and references therein) and CCMs (e.g. Austin et al. (2008); Sekiyama et al. (2006); Lee and Smith (2003); Egorova et al. (2014); Dhomse et al. (2 Earlier generations of CCMs in CCMVal-1 and CCMVal-2 showed a positive annual mean SOR of up to ~2.5% peaking in the tropics between ~3-5 hPa and a maximum tropical mean temperature response in the upper stratosphere of ~0.5-1.1 K (Austin et al., 2008; SPARC CCMVal, 2010) . This study provides an update to those earlier studies by analysing the SOR in the latest World Climate Research Programme (WCRP) Stratosphere-troposphere Processes And their Role in Climate (SPARC) Chemistry Climate Model Initiative (CCMI-1) experiments.

A further motivation for this study are recent results from the WCRP fifth Coupled Model Intercomparison Project (CMIP5), which included models with and without interactive stratospheric chemistry. The CMIP5 models showed a large spread (∼0.3-1.2 K) in the peak amplitude of the tropical stratospheric temperature response between the minimum and maximum phases of the 11 year solar cycle (Mitchell et al., 2015). This spread may be due to differences in the prescription of SSI, in the accuracy of model radiative transfer schemes (Nissen et al., 2007; Forster et al., 2011), and/or in the representation of the SOR. However, the quantitative importance of any one of these factors is unclear. All CMIP5 models were recommended to ~~prescribe SSI using~~ use the Naval Research Laboratory Spectral Solar Irradiance 1 (NRLSSI-1) dataset (Wang et al., 2005)~~; those~~. Those without chemistry were further recommended to prescribe ozone from the ~~Stratosphere-troposphere Processes And their Role in Climate (SPARC)~~SPARC/Atmospheric Chemistry and Climate (AC&C; www.igacproject.org) ozone database (Cionni et al. (2011); hereafter referred to as CMIP5 ozone database). The historical part of this ozone database was largely based on multiple regression model fit to satellite observations (see Section 2.1.2). The remaining CMIP5 ~~CCMs that fully resolved the stratosphere show~~ models that did include interactive chemistry showed a large variation in the amplitude and structure of the modelled SOR (Hood et al., 2015). ~~This suggests that either the models implemented SSI differently, that there are large structural~~ It is therefore plausible that differences in the representation of ~~chemical, dynamical or radiative processes between the models, and/or that the time series are too short to derive a robust SOR~~.

~~Differences in the representation of the SOR across~~ SOR made an important contribution to the spread in atmospheric thermal and dynamical responses to the solar cycle in CMIP5 ~~models may have contributed to the large spread (∼0.3-1.2K) in the peak tropical stratospheric temperature response between solar minimum and maximum (Mitchell et al., 2015). Other factors could include differences in the prescription of SSI and in the accuracy of the model radiation schemes (Nissen et al., 2007; Forster et al., 2011), but the quantitative importance of any one of these factors to explain the spread in modelled solar-climate responses is unclear.~~

models; we investigate this hypothesis further in this study.

As was the case in CMIP5, CMIP6 will include a ~~mixture~~ mix of models with and without explicit stratospheric chemistry. A new SPARC/CCMI ozone database has been created for CMIP6 models without chemistry (hereafter referred to as CMIP6 ozone database; see https://esgf-node.llnl.gov/projects/input4mips). It is therefore important to compare the SOR in the ~~recommended~~ CMIP5 and CMIP6 ozone databases, since ~~any~~ these fields are routinely deployed in climate models and differences may lead to changes in the modelled responses to solar forcing between CMIP5 and CMIP6~~models~~.

~~In addition to analysis of CMIP5 models (Hood et al., 2015), comparisons of the SOR in CCMs have been performed through the WCRP/SPARC Chemistry Climate Model Validation Exercises~~

~~(CCMVal). The CCMVal-1 and CCMVal-2 models showed a positive annual mean SOR of up to ~2.5peaking in the tropics between ~3-5hPa and a maximum tropical mean temperature response in the upper stratosphere of ~0.5-1.1K (Austin et al., 2008; SPARC CCMVal, 2010) . Various developments have been made to models contributing to the latest SPARC Chemistry Climate Model Initiative (CCMI-1) experiments compared to previous versions, and it is therefore pertinent to evaluate the representation of the SOR in these new simulations.~~

~~Another potentially important~~ Another factor to consider for modelling ~~is the~~ solar cycle effects on the atmosphere is the representation of the annual cycle in the SOR ~~, which has been identified in available satellite observations (Maycock et al., 2016)~~ (Soukharev and Hood, 2006; Hood et al., 2015; Maycock et al., 2016) . Hood et al. (2015) found that the three CMIP5 CCMs ~~with the largest~~ that simulated large horizontal gradients in the ~~fractional~~ SOR in the upper stratosphere in early winter also showed Northern hemisphere high latitude dynamical responses ~~to the~~ over the 11 year solar cycle that compared more closely with reanalysis data. The enhancement of the SOR at high latitudes is related to coupling between ~~ozone and dynamics and~~ chemistry and transport processes for ozone and may play a role in ~~transferring the solar~~ driving the 'top-down' mechanism for the solar cycle influence on high latitude regional surface climate (see e.g. Gray et al. (2010)). It is therefore also important to compare the representation of the annual cycle ~~signal from the upper stratosphere to the troposphere.~~

~~This study evaluates both the annual mean and annual cycle~~ in the SOR in ~~the CMIP5 and CMIP6 ozone databases and compares these with results from~~ current CCMs and in the pre-calculated ozone databases used in climate models.

The objectives of this study are therefore:

- to provide an update to previous CCM studies by analysing the SOR in CCMI-1 models~~and satellite observations from Maycock et al. (2016) . In addition to the CMIP ozone databases , we also analyse the recent Bodeker et al. (2013) ozone database~~ .
- to evaluate the SOR in three pre-calculated ozone databases for climate models ~~(hereafter referred to as Bodeker ozone database). We further perform sensitivity experiments with a global atmospheric model~~ from CMIP5, CMIP6 and Bodeker et al. (2013) .
- to compare the CCMs and ozone databases with satellite observations from Part I (Maycock et al., 2016) .
- to perform atmospheric model experiments to quantify the impact of ~~changes~~ differences in the SOR between ~~the~~ CMIP5 and CMIP6 ~~ozone databases on the atmospheric response between the minimum and maximum phases of the~~ on the simulated atmospheric response to the 11 year solar cycle. ~~Collectively these analyses~~

Collectively these objectives provide a comprehensive ~~overview of the current~~ assessment of the represention of the SOR in ~~global models and the importance of this representation for modelling the~~

~~response to the solar cycle~~current CCMs and global climate models. The outline of the ~~manuscript~~ remainder of the paper is as follows: Section 2 describes the data and methods used to analyse the SOR, Section 3 presents the results, and Section 4 summarises our findings.

2 Methods

2.1 Models and ozone datasets

2.1.1 The CCMI-1 models

Data are analysed from eight CCMI-1 models ~~that were available~~ downloaded from the British Atmospheric Data Centre ~~archive at the time the study was being prepared (Hegglin and Lamarque, 2015) , and which include the minimum requirements for capturing the SOR (i. e. a prescription of SSI variability in the chemistry scheme).~~ (Hegglin and Lamarque, 2015) . The models analysed are: CCSRNIES-MIROC3.2, CESM1(WACCM), CMAM, CNRM-CM5-3, EMAC(L90), LMDz-REPROBUS-CM5 (L39), MRI-ESM1r1, and SOCOL3 (see Table 1). These models include the minimum requirements for capturing the SOR (i.e. a prescription of SSI variability in the chemistry scheme). A detailed description of the models is given by Morgenstern et al. (2017).

Data are analysed from the REF-C1 simulations, which include observed time-varying sea surface temperatures (SST) and sea ice~~from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003)~~ , well-mixed greenhouse gases, volcanic aerosols, and ~~the NRLSSI-1 SSI dataset that was also used in CMIP5 (Wang et al., 2005) . CESM1(WACCM) uses a merged SST dataset comprising of HadISST before 1981 and the NOAA Optimum Interpolation dataset after 1981.~~ SSI forcing from NRLSSI-1 (Eyring et al., 2013b) . Thus, in contrast to the coupled atmosphere-ocean CMIP5 models analysed by Hood et al. (2015), the CCMI-1 REF-C1 simulations ~~are run in AMIP mode and~~ do not include an interactive ocean. ~~All the~~ The REF-C1 simulations start in January 1960 ~~,~~ but terminate in different years for each model, so for consistency we analyse the 50 year period 1960-2009 ~~,~~ which is common to all the simulations. ~~We analyse one ensemble member (r1)~~ All available ensemble members are analysed for each model (see Table 1).

The representation of the QBO differs across the CCMI-1 models (Morgenstern et al., 2017) . Some of the models simulate a spontaneous QBO (MRI-ESM1r1, EMAC(L90)), some models include a QBO by nudging tropical stratospheric zonal winds towards observations (CCSRNIES-MIROC3.2, CESM1(WACCM), SOCOL3), and some include no representation of the QBO (CMAM, CNRM-CM5-3, LMDz-REPROBUS-CM5). In EMAC(L90) a weak nudging towards the observed QBO with a relaxation timescale of 58 days is applied to ensure the same phasing as the observed QBO, whereas in CCSRNIES-MIROC3.2, CESM1(WACCM) and SOCOL3 the QBO is nudged more strongly (5-10 day timescale). For those models that include QBO variability, two additional orthogonal QBO indices are included in the multiple linear regression (MLR) model ~~which are~~ calculated from the modelled ~~tropical zonal winds~~ zonal mean zonal wind fields (see Section 2.2).

2.1.2 The CMIP5 ozone database

The CMIP5 ozone database consists of monthly mean ozone mixing ratios on 24 pressure levels spanning 1000-1 hPa for the period 1850-2100 (Cionni et al., 2011) . Data are provided on a regular 5° × 5° longitude/latitude grid. Ozone values are provided as a 2-D (i.e. zonal mean) field in the stratosphere (at pressures less than 300 hPa) and as a 3-D field in the troposphere, with a blending across the tropopause. The tropospheric part of the database was constructed from CCM simulations. For the stratosphere, the historical ~~part~~ portion of the database (1850-2009) was constructed from observations using an MLR model (that includes solar variability as one of the independent variables) fit to SAGE I and SAGE II version 6.2 satellite data and polar ozonesondes following the method of Randel and Wu (2007). A SOR is therefore implicitly included in the historical ~~part~~ portion of the CMIP5 ozone database that will resemble the ~~input observations fitted with~~ observations input to the MLR model. However, owing to the paucity of long-term ozone measurements at high latitudes, the SOR was only included between ±60° latitude. This limitation led some CMIP5 modelling groups to make alterations to the CMIP5 ozone database, including extrapolation of the SOR coefficients at ±50° latitude to the poles using a cosine latitude weighting. The CMIP5 models known to have employed this 'Extended CMIP5 ozone database' include HadGEM2-CC (Osprey et al., 2013), MPI-ESM (Schmidt et al., 2013) and CMCC-CC (Cagnazzo, 2016, pers. comms.). Note that the historical portion of the CMIP5 ~~models with an upper boundary at pressures less than 1hPa also had to vertically extend the CMIP5~~ ozone database ~~to include their upper boundary (e.g. Schmidt et (2013); Schmidt et al.).~~ did not include a representation of QBO variability in ozone.

The future ~~part~~ portion of the CMIP5 ozone database for the stratosphere was based on CCM simulations from CCMVal-2 ~~model simulations~~ (Cionni et al., 2011). However, owing to uncertainties in how individual CMIP5 models would represent SSI variations over the 21st century, the future ~~part~~ portion of the CMIP5 ozone database did not include a SOR. ~~A SOR was then~~ For consistency, a SOR was thus added to the future period in the Extended CMIP5 ozone database using ~~the solar MLR coefficients~~ regression coefficients for the SOR derived from the historical period (Schmidt et al. (2013); Osprey et al. (2013); C. Cagnazzo, 2016, pers. comms.).

~~Results are presented here from both the CMIP5 ozone database and the Extended CMIP5 ozone database for the period 1960-2004.~~

The CMIP5 ozone database is described in full by Cionni et al. (2011) and is available ~~from~~ at the time of writing from: https:~~http://cmip-pcmdi~~cmip.llnl.gov/cmip5/forcing.html~~. Documentation~~ #ozone

SUBSCRIPTNBforcing. A description of the CMIP5 models that employed the CMIP5 ozone database is given by Eyring et al. (2013a).

2.1.3 The CMIP6 ozone database

The CMIP6 ozone database for the historical period (1850-2014) consists of monthly mean ozone mixing ratios on 66 pressure levels spanning 1000-0.0001 hPa. Data are provided as a 3-D field on a regular 2.5 × 1.9° longitude/latitude grid. The database ~~has been constructed using output from two CCMI-1 models~~ is constructed using a weighted average of simulations from two CCMs (CESM1(WACCM) and CMAM) ~~, which have been weighted according to an evaluation of various performance metrics for ozone~~ (M. Hegglin, pers. comms.). The ~~CCMs followed the REF-C1 experiment protocol with prescribed observed~~ CMIP6 ozone database was downloaded from: https://esgf-node.llnl.gov/projects/input4mips.

The simulations from the two constituent CCMs include prescribed SSTs, sea ice, well-mixed greenhouse gas concentrations and aerosols. ~~Observed estimates of surface~~ Surface emissions of NO_x and other tropospheric ozone precursor gases are ~~prescribed. The two~~ also prescribed. Both CCMs represent SSI variability in their radiation and chemical schemes. ~~Only~~ However, only CESM1(WACCM) includes the chemical effects of energetic ~~particles, which means the~~ particle precipitation.

—There are some differences in the set-up of the CCM simulations used to create the CMIP6 ~~ozone database will only partly capture these effects.~~

—We analyse data from the CMIP6 ozone database over the period 1960-2011. The CMIP6 ozone database ~~was accessed from: https://esgf-node.llnl.gov/projects/input4mips.~~

~~As is the case for all the~~ compared to the CCMI-1 ~~models, the two CCMs used to create the~~ versions of the same models (see Section 2.1.1), which may affect the representation of the SOR. The version of CMAM for the CMIP6 ozone database ~~were forced with the NRLSSI-1 dataset, whereas the CMIP6 models will be recommended to use a new merged SSI dataset described by Matthes et al. (2017) . The change in UV forcing between solar cycle minimum and maximum is smaller in NRLSSI-1 than in~~ used historical stratospheric aerosols and solar variability, similar to in REF-C1, extended back to 1850. However, SSTs and sea-ice were prescribed from a CanESM2 historical simulation performed for CMIP5 rather than from observations. The temporal variability in SSI for CMAM was taken from the CMIP6 ~~solar forcing dataset . Specifically, the variability in the 200-400nm band is around 30smaller in~~ SSI dataset (Matthes et al., 2017) , but the variations were applied to the long-term background spectrum from NRLSSI-1~~than in the CMIP6 SSI dataset (Matthes et al., 2017) . Sensitivity experiments with two CCMs reveal that the weaker UV forcing~~ . This is in slight contrast to the CCMI-1 version of CMAM that used both SSI variability and the background spectrum from NRLSSI-1. However, Matthes et al. (2017) showed that the slightly weaker variability over the solar cycle at shorter UV wavelengths in NRLSSI-1 ~~reduces~~ only reduced the amplitude of the tropical mean SOR in ~~the stratosphere by up~~ a CCM by ~0.3% compared to a ~~case forced with~~ reference of $\sim$2%. This difference is therefore likely to have only a small effect on the SOR in the configurations of CMAM implemented for CCMI-1 and the CMIP6 ~~solar forcing (see Figure 7(c) in (Matthes et al., 2017)). Therefore, there will be a small inconsistency between the amplitude of the SOR captured in the~~ ozone database. Neither CMAM simulation includes nudging of the QBO.

There are also some differences in the configuration of CESM1(WACCM) used for the CMIP6 ozone database ~~and the SOR that would otherwise be simulated in a CCM forced with the recommended~~ compared to CCMI-1. The CESM1(WACCM) CCMI-1 runs prescribed the NRLSSI-1 data at daily resolution, whereas the version for the CMIP6 ~~solar forcing dataset.~~ ozone database used annual values as these extend back to 1850. In the lower thermosphere, values of the F10.7cm flux and Kp index used to parametrize the chemical effects of energetic particle precipitation were taken from observations in CCMI-1 and from a proxy record in the simulation for the CMIP6 ozone database. Furthermore, the simulation for the CMIP6 ozone database did not include solar proton events or galactic cosmic ray effects. Both versions of CESM1(WACCM) used observed SSTs and include a nudged QBO towards observed tropical winds. In summary, there are some differences in the experimental set-ups of the two CCMs used to create the CMIP6 ozone database, in particular that they use slightly different representations of SSI variability, they do not both include QBO variability and they use different SST datasets.

2.1.4 The Bodeker ozone database

Bodeker et al. (2013) describe a new ~~observationally~~ observation based ozone database for climate models covering the period 1979-2007. Monthly and zonal mean ozone mixing ratios are provided on 70 pressure levels spanning 878-0.05 hPa on a regular 5° latitude grid. The ozone field is constructed ~~using~~ from a large number of satellite and ozonesonde observations from the Binary DataBase of Profiles (BDBP; Hassler et al. (2008)) ~~fitted with~~ used to fit an MLR model ~~including~~ that includes terms for equivalent effective stratospheric chlorine (EESC), a linear trend, the QBO, the El Niño Southern Oscillation (ENSO), the solar cycle, and the Mt Pinatubo volcanic eruption. We note that since the BDBP contains SAGE II v6.2 mixing ratio data, this is likely to provide a strong constraint on the SOR in the tropics and subtropics~~because SAGE II is a relatively long-term and stable ozone record. A~~. See Maycock et al. (2016) and Dhomse et al. (2016) for a discussion of the differences in the SOR in SAGE II v6.2 and v7.0 data. To generate a spatially complete ozone field a single MLR fit is performed for all points on a given pressure surface to enable regression coefficients to be derived for latitudes where the observations are relatively sparse (e.g. ~~at high latitudes~~in polar regions). We use the Tier 1.4 product from the Bodeker ozone database, which ~~is a spatially filled field that~~ includes contributions from all the MLR basis functions. The Bodeker ozone database was downloaded from http://www.bodekerscientific.com/data/monthly-mean-global-vertically-resolved-ozone.

2.2 The multiple linear regression (MLR) model

~~The SOR is analysed using an MLR model as~~

Multiple linear regression models have been used to analyse drivers of secular trends and variability in stratospheric ozone for many decades (see e.g. Staehelin et al. (2001) and references therein). In the context of extracting the SOR from ozone timeseries, there is a long history of similar methods being applied to both satellite observations (e.g., Soukharev and Hood (2006); Remsberg (2008); Tourpali et al. (2007); Remsberg ar chemistry-climate models (Austin et al., 2008; Sekiyama et al., 2006; Lee and Smith, 2003; Egorova et al., 2014; Dhomse et al., 20 Here we follow the methodology described by Maycock et al. (2016), which is very similar to the methods described in those earlier studies. Briefly, the zonal mean ozone data are deseasonalised by removing the long-term monthly mean at each latitude and pressure level. As in past studies, we then perform an MLR analysis on the timeseries of monthly mean anomalies at each location, $O_3^{'}(t)$, to diagnose the solar cycle component:

$$
\begin{aligned}
O_3^{'}(t) &= A\times F10.7(t)+B\times CO_2(t)+C\times EESC(t)\\
&+D\times ENSO(t)+E\times SAD_{volc}(t)+F\times QBO_A(t)\\
&+GF\times QBO_B(t)+r(t), \qquad (1)
\end{aligned}
$$

where *r(t)* is a residual. The annual-mean SOR is calculated by regressing all months as a single ~~ti~~timeseries. The monthly SOR is calculated by regressing ~~interannual timeseries of each month separately~~timeseries of year-to-year anomalies for individual months. The monthly mean basis functions in Equation 1 are the F10.7cm radio solar flux, the CO_2 concentration at Mauna Loa, the equivalent effective stratospheric chlorine (EESC), and the Nino 3.4 index to represent ENSO~~, and the volcanic aerosol surface area density (SAD_{VOLC}) averaged between ±30° latitude and 15-35km. For those CCMI-1 models and ozone databases that include QBO variability (see Table 1), the QBO indices are calculated as the first two principal component timeseries of the tropical (±10°, 5-70hPa) zonal mean zonal winds. Figure 1 shows example timeseries of the MLR basis functions from 1960-2009 in arbitrary units. The coefficients A–G in Equation 1 are calculated using linear least squares regression.~~

~~We use the~~ . The F10.7cm flux is used to represent solar activity because it has been shown to be ~~a better proxy~~ well correlated with indices for UV radiation (e.g. Floyd et al. (2005)), the key driver of the stratospheric ozone response~~, than other indices, e. g. total solar irradiance.~~ . The results presented in Section 3 assume a difference of 130 solar flux units (1 SFU = 10^{-22} $Wm^{-2}Hz^{-1}$) as a representative amplitude of the 11 year solar cycle. The Nino 3.4 index is computed as the standardised mean SST averaged over the region 5°S–5°N and 120°W–170°W.

~~The only difference in the MLR model in Eqn.~~ For those CCMI-1 models and ozone databases that include QBO variability (see Table 1~~compared to Maycock et al. (2016) is the addition of a basis function for stratospheric volcanic aerosol. This is because the analysis of longer timeseries, as~~

~~performed here, reduces the issue of aliasing between the solar and volcanic timeseries (Chiodo et al., 2014) . However, the inclusion of a volcanic basis function yields very similar results for the SOR to~~), the QBO indices are calculated as the ~~method of excluding the periods immediately following large volcanic eruptions as was done by Maycock et al. (2016) .~~ first two principal component timeseries of the tropical ($\pm 10°$, 5-70 hPa) zonal mean zonal winds. The ozone response to volcanic aerosols is non-linear through time owing to changing levels of inorganic chlorine in the atmosphere (Tie and Brasseur, 1995) . Thus, rather than including a term in the MLR model to represent volcanic effects on ozone, data from the 2 year periods following the three major tropical volcanic eruptions since 1960 are excluded from the analysis: Mount Agung (February 1963), El Chićhon (March 1982) and Mount Pinatubo (June 1991). Figure 1 shows example timeseries of the MLR basis functions from 1960-2009 in arbitrary units. In this example the ENSO and QBO indices are based on observations. The coefficients β in Equation 1 are calculated using linear least squares regression.

One important issue for MLR analysis is the handling of possible autocorrelation in the regression residuals, *r(t)*, and the effect on the estimation of statistical ~~uncertainties. Some of the satellite ozone datasets considered by Maycock et al. (2016) had incomplete temporal sampling at a given location, which reduces the likelihood of significant autocorrelation in the residuals. However, by design the ozone fields analysed here have complete temporal sampling, and a~~ uncertainty in the results. A Durbin-Watson test reveals significant serial correlation in the regression residuals in many locations for lags of one and two months, particularly in the ~~lower stratosphere and mesosphere~~middle and polar lower stratosphere. Such serial correlation can lead to spurious overestimation of the statistical significance of the regression coefficients and we therefore include an autoregressive term in the regression model. Given the significant serial correlations in some regions up to a lag of two months, a second order autoregressive noise process (AR2) is used, which assumes the residuals *r(t)* have the form:

$$r(t) = ar(t-1) + br(t-2) + w(t), \qquad (2)$$

where *a* and *b* are constants and *w(t)* is a white noise process. This is identical to the approach employed in Maycock et al. (2016) and the recent SPARC SI^{2}N analysis of ozone trends (Tummon et al., 2015; Harris et al., 2015). ~~No autocorrelation term for the residuals is~~ The autocorrelation term is not included in the analysis of the ~~SOR annual cycle~~ monthly SOR because the residuals ~~for any given month~~ are approximately uncorrelated from year-to-year. Unless otherwise stated, the statistical significance of the SOR extracted using the MLR model is assessed using a two-tailed Student's t-test with a null hypothesis that the magnitude of the SOR is indistinguishable from zero. We apply a threshold to determine whether the null hypothesis can be rejected at a 95% confidence level.

It is a challenge in geophysical science to develop statistical methods to extract forced signals from complex timeseries. The implementation of multiple linear regression analysis as described above may have a number of limitations, including (but not limited to): assumption that the input basis functions have zero uncertainty; difficulties in separating a signal from noise in relatively short or sparse records (Damadeo et al., 2014) ; and issues arising from degeneracy between basis functions (Chiodo et al., 2014) . We have not attempted to account for these factors in the results shown in Section 3.

2.3 Atmospheric model sensitivity experiments

To explore the atmospheric impacts of different representations of the SOR, simulations were carried out with the atmospheric general circulation model ECHAM6.3, which is an update of the ECHAM6.1 model (Stevens et al., 2013) used as atmospheric component of the Max Planck Institute Earth System Model (Giorgetta et al., 2013) in CMIP5 simulations. Model changes from version 6.1 to 6.3 are mainly related to fixes of bugs described by Stevens et al. (2013), efforts to ensure energy conservations, an update of the radiation scheme, which is now the PSrad (Pincus and Stevens, 2013) version of the RRTMG code (Iacono et al., 2008), and retuning. If the same forcings are used, temperature effects of solar cycle variability in ECHAM6.3 compare well to those described for ECHAM6.1 ~~by Schmidt et al. (2013) .~~ (Schmidt et al., 2013) . The model experiments performed here use a horizontal resolution of T63 ($\sim$140 $\times$ 210 km) with 47 vertical levels up to a lid of 80 km.

It is known that the ECHAM6.3 radiation code does not cover wavelengths below 200 nm and therefore the important Schumann-Runge bands and Lyman-alpha lines of ozone are not captured (Sukhodolov et al., 2014). This results in a too weak radiative response to the imposed solar forcing particularly in the mesosphere. Therefore we focus ~~the~~ our analysis on the ~~temperature response in the stratosphere~~ stratospheric response where most of the absorption occurs at higher ~~wavelengths~~ UV wavelengths, and the performance of ECHAM6.3 is comparable to models with a more comprehensive radiative code (Sukhodolov et al., 2014).

We have performed five time-slice simulations with ECHAM6.3 each lasting for 50 years. The control simulation uses average boundary conditions as specified for the CMIP5 AMIP simulation, i.e. for all boundary conditions such as SSTs, greenhouse gas concentrations, ~~solar irradiance~~ SSI and prescribed atmospheric ozone we have used multi-year averages of the CMIP5 recommended values for the years 1978 to 2008. Four sensitivity simulations have then been performed in which solar maximum minus solar minimum differences in either atmospheric ozone concentrations or both ozone and SSI have been added to the respective fields of the control simulation. For solar maximum and minimum conditions we have used average values over the years 1985-1986 and 1981-1982, respectively. According to the solar irradiance recommendations for CMIP6 (Matthes et al., 2017) these are characterized by a difference of 126.1 SFU, and are therefore closely comparable to the results presented for the SOR, which assume a representative solar cycle amplitude of 130 SFU. Ozone anomalies were either calculated from the respective years of the Extended CMIP5 ozone database (Schmidt et al. (2013)) or using the ~~MLR regression coefficients for~~ monthly SOR coefficients from the CMIP6 ozone database ~~calculated below. Solar irradiance~~ shown in Section 3.3. The corresponding SSI anomalies are either calculated from the CMIP5 recommended NRLSSI-1 dataset (Wang et al., 2005) or from the ~~recommended~~ CMIP6 recommended solar forcing dataset (Matthes et al., 2017).

3 Results

3.1 The SOR in CCMI-1 models

Figure 2 shows timeseries of deseasonalised tropical (30°S-30°N) and monthly mean percent ozone anomalies at select pressure levels (1, 3, 5, 10, 30 hPa) for the eight CCMI-1 models ~~considered in this study. The anomalies~~ described in Section 2.1.1. Anomalies are defined relative to the period ~~1960-2009. These can be compared to Figures 2 and 8 in Maycock et al. (2016) , which show equivalent timeseries for SAGE II and SBUV satellite ozone measurements~~1985-2009. Also plotted in Figure 2 are timeseries from two satellite datasets discussed in Part I of this study: SBUVMOD VN8.6 (Frith et al., 2014) (black dashed) and SAGE-GOMOS 1 (Kyrölä et al., 2015) (black solid). For completeness, the timeseries of absolute ozone mixing ratios from the models are shown in the Supplementary Material (Figure S1).

The CCMI-1 models show a long-term decline in stratospheric ozone abundances, particularly in the mid and upper stratosphere. This is ~~consistent with the impact on ozone of increasing stratospheric~~ the result of increasing atmospheric loading of inorganic chlorine and bromine ~~abundances~~ over this period ~~(SPARC CCMVal (2010)~~ and is consistent with results from earlier CCM studies (e.g. Eyring et al. (2006); SPARC CCMVal (2010)). At 1 hPa, the trend in ozone between 1979-1997 computed by linear regression ranges from -1.9 to -2.6 % decade^{-1} across the models. At 3 hPa, the range in trends is -4.1 to -5.1 % decade^{-1}. These values are within the uncertainty bounds of satellite observed ozone trends over this period (Harris et al., 2015).

In addition to a long-term decline~~in ozone~~, Figure 2 shows quasi-decadal variations in ozone in the upper stratosphere that are approximately in phase with the 11 year solar cycle~~; these~~. These are a marker of the SOR which is evident in the raw ozone timeseries ~~before the MLR analysis is applied~~and can be seen as a peak around the decadal timescale in the modelled ozone power spectra (see Supplementary Material Figure S2). There is larger interannual and multi-year variability in ozone at 10 and 30 hPa where some models show ~~QBO signals.~~ enhanced variability associated with the QBO. The modelled evolution of the tropical ozone anomalies is generally in good agreement with the observation data in Figure 2, with some exceptions where the satellite records show larger amplitude short-term fluctuations that may be related to incomplete spatial and temporal sampling.

Figure 3 shows latitude-pressure cross-sections of the annual mean SOR in the eight CCMI-1 models (Figure 3(a-h)) along with the multi-model mean (Figure 3(i)). For the individual models, the statistical significance of the SOR is assessed using a two-tailed Student's t-test with a threshold for rejecting the null hypothesis at the 95% confidence level (see Section 2.2). The robustness of the CCMI-1 multi-model mean SOR is assessed by distinguishing regions where the magnitude of the SOR is greater than ±2 s.d. of the intermodel spread. Figure 3 can be compared with Figure 1 in Austin et al. (2008) and Figure 1 in Hood et al. (2015) which show similar plots for the CCMVal-1 and CMIP5 models, respectively.

All of the ~~models show significant increases in ozone between solar minimum and maximum of around 1-2~~CCMI-1 models analysed show a significant positive SOR of up to ∼2% between 1-10 hPa~~, which~~. This is less than half ~~of~~ the peak amplitude of the SOR in the SAGE II v6.2 mixing ratio dataset ~~, but~~ and is more comparable to the SOR amplitude in SAGE II v7.0 mixing ratios and the SBUVMOD VN8.6 dataset (see Figures 4 and 12 in Maycock et al. (2016)).

~~The results in Figure 3~~ The results from the CCMI-1 models are broadly consistent with ~~previous analyses of CCMs (Austin et al., 2008; SPARC CCMVal, 2010)~~ the results from CCMVal-1 models (Austin et al., 2008) . The main exception ~~to this~~ is the absence in the multi-model mean of a ~~significantly enhanced~~ strong SOR in the tropical lower stratosphere. ~~Figure 4(d) in Austin et al. (2008) shows a~~ An enhanced SOR in the tropical lower stratosphere has been identified in satellite observations, albeit with large uncertainties (Gray et al., 2009; Austin et al., 2008; Soukharev and Hood, 2006; Maycock et al., 2016) , and it has been postulated this may be associated with a change in the strength of the Brewer Dobson circulation. The CCMVal-1 multi-model mean ~~SOR for the CCMVal-1 models~~ showed a SOR of around 5% per 130 SFU at ∼50 hPa (see Figure 4(d) in Austin et al. (2008)), as compared to around 1% in the CCMI-1 multi-model mean ~~in~~ (Figure 3(i)). However, there was large intermodel spread in this signal across the CCMVal-1 models and the multi-model mean SOR was dominated by strong responses in a few models that only ran for a short period (1980-2004) ~~over which aliasing with the effects of volcanic aerosols~~ during which aliasing effects with other climatic factors can be significant (Chiodo et al., 2014). Since the ~~CCMI-1 models are analysed~~ analysis shown here extends for a longer period ~~(1960-2009)~~and excludes the post-volcanic epochs, this is a plausible ~~explanation for the differences in~~ reason for the apparent difference in the SOR in the tropical lower stratospheric ~~SOR~~ between the CCMI-1 and CCMVal-1 ~~model responses.~~ models. One of the CCMI-1 models (SOCOL3) appears to show an enhanced SOR in the tropical lower stratosphere, which is similar in amplitude to that seen in some CCMVal-1 models. However, this feature shows some sensitivity to the choice of autoregressive model in the MLR model probably because the decorrelation timescale for the regression residuals in the tropical lower stratosphere is longer than two months in SOCOL3 and some of the other CCMs (not shown). Further analysis of the Transformed Eulerian Mean residual vertical velocity does not reveal a substantial change in the rate of upwelling in the tropical lower stratosphere in any of the models (not shown).

~~Outside of the tropics there are larger inter-model differences in the fractional SORs in Figure 3, with a range in the amplitude , sign and level of statistical significance of the diagnosed SOR in both hemispheres. One consistent feature across many of the models appears to be an enhanced SOR~~

~~in the Southern hemisphere high latitude lower stratosphere , which is evident in the multi-model mean. The annual cycles in the SOR in the individual~~ The month-by-month SORs in the individual CCMI-1 models (see Supplementary ~~Information) show that the strong gradients in the SOR~~ Material Figures S3-10) show a significant positive SOR in the tropical upper stratosphere throughout the year, but enhanced SOR amplitudes at high latitudes ~~found in some of the models tend to be more pronounced in the winter~~ particularly in the winter and spring seasons. This behaviour, which is also seen in some satellite ozone datasets ~~(Maycock et al., 2016)~~ (e.g. Maycock et al. (2016)), cannot be understood from photochemical processes alone and must therefore be related to stratospheric circulation changes ~~(Kuroda and Kodera, 2002) .Such~~ (e.g. Kuroda and Kodera (2002)). Such localised changes in ozone ~~at high latitudes~~ will be associated with a radiative perturbation that could lead to feedbacks onto circulation ~~; however, the quantitative importance of such ozone-radiative feedbacks for the stratospheric dynamical signal remains an open research question (Hood et al., 2015)~~ (Hood et al., 2015) , and thus it may be important to account for this seasonal variation in the SOR in model simulations.

3.2 The SOR in ozone databases for climate models

Figure 4 shows timeseries from ~~1960-2012~~ 1960-2011 of deseasonalised tropical and monthly mean fractional ozone anomalies at select stratospheric levels (1 to 30 hPa) from the Bodeker (orange line), CMIP5 (~~green~~red) and CMIP6 (~~black~~blue) ozone databases. Also plotted in black are the same satellite datasets as shown in Figure 2. Anomalies are defined relative to the period ~~1979-2007~~1985-2007. The Extended CMIP5 ozone database is not shown ~~since this~~ because it is identical to ~~the green line. The plots can be compared to Figure 2 and to Figures 2 and 8 in Maycock et al. (2016) , which show equivalent timeseries for the SAGE II and SBUV satellite records~~original CMIP5 database in the tropics.

Although the timeseries have been deseasonalised, the CMIP5 ~~ozone database shows~~ and Bodeker ozone databases show a residual annual cycle particularly in the upper stratosphere. This is ~~the result of the annual cycle amplitude being~~ because in these databases the amplitude of the ozone annual cycle is larger in the early part of the record, when ~~background ozone is relatively high~~the background levels are higher, and smaller in the ~~later~~ latter part of the record following the long-term decline in ozone. Since the ozone anomalies in Figure 4 are ~~plotted relative to 1979-2007~~shown as anomalies from the 1985-2007 mean, there is therefore a residual annual cycle ~~in the CMIP5 ozone database~~ particularly in the ~~pre-1980 period . A similar effect is also evident in the Bodeker database, whereas~~ period before 1985. Conversely, the CMIP6 database, which is ~~based on~~ constructed from CCM simulations, does not show a significant change in the amplitude of the ~~stratospheric~~ ozone annual cycle over time.

At 1 hPa, the CMIP5 and Bodeker databases show a larger ~~long-term~~ linear trend in ozone over 1979-2007 (diagnosed using linear regression~~over 1979-2007 of~~) of around -3.5 % decade^{-1} compared to ~~a smaller trend of~~ -1 % decade^{-1} in the CMIP6 database~~; the latter being~~. The latter is, as expected, similar to the long-term ozone trends in the CCMI-1 models shown in Figure 2. At 3 hPa, the CMIP5 ~~ozone database~~ database also shows a larger long-term ~~trend~~ decrease in ozone by around a factor of two compared to the Bodeker and CMIP6 databases. Thus, a model that uses the ~~CMIP6 models that use the~~ recommended CMIP6 ozone database might be expected to show ~~a smaller cooling of the upper stratosphere~~ weaker upper stratospheric cooling over recent decades compared to an equivalent simulation using the CMIP5 database, owing to the smaller ~~trend in~~ negative trend in upper stratospheric ozone.

At 10 and 30 hPa, the Bodeker and CMIP6 databases show a QBO signal in ozone, whereas the CMIP5 database does not include QBO variability. This is an important distinction because a model that employs the CMIP6 ozone database, but which does not simulate a dynamical QBO, will impose a QBO-ozone signal that may alter the model's behaviour. Alternatively, a model that internally generates a dynamical QBO that is not in phase with the prescribed QBO-ozone signal in the CMIP6 ozone database will be subject to a ~~forcing by~~ diabatic heating anomaly from ozone that is inconsistent with the model's dynamical evolution. Both of these cases would be physically unrealistic. However, a model that nudges a QBO towards observations and uses the CMIP6 ozone database should have a more consistent representation of ~~QBO~~ temporal variability in winds and ozone ~~. Conversely,~~ associated with the QBO. Modelling groups may therefore choose to post-process the CMIP6 ozone database in order to treat the QBO-ozone signal in a consistent manner for their model. Note that since the CMIP6 ozone database is produced by averaging two CCMs, one that does include QBO-ozone variability (CESM1(WACCM)) and one that does not (CMAM), the QBO-ozone signal is weaker in the CMIP6 ozone database than in the CESM1(WACCM) model alone (compare blue line in Figure 2 with dark pink line in Figure 4). The absence of a QBO-ozone signal in the CMIP5 ozone database means that CMIP5 models that simulated a QBO would have neglected any radiative ~~feedbacks from ozoneonto tropical variability~~QBO feedback from ozone.

Figure 5 shows latitude-pressure cross-sections of the annual mean SOR in the three ozone databases shown in Figure 4 and the Extended CMIP5 ozone database. In the tropics, the Bodeker ozone database, Figure 5(a), shows a positive SOR of up to 4% peaking at around 2-3 hPa with a distinct minimum at ∼10 hPa. The latitudinal structure of the SOR is smoother than in the SAGE II v6.2 mixing ratio data (~~see~~ cf. Figure 4(d) of ~~Maycock et al. (2016)~~ Part I) probably because the construction of the ~~database uses MLR fitted to data~~ Bodeker database fits an MLR model to all data points along pressure surfaces rather than ~~at individual latitudes~~to individual latitude bands. At high latitudes, the magnitude of the SOR in the Bodeker database is small and the spatial structure is noisy likely because of the small number of observations there. In the lower stratosphere, the ~~results show~~ Bodeker database indicates a positive SOR at most latitudes, as was found in a number of satellite ozone datasets ~~by Maycock et al. (2016) .~~ in Part I. However, the uncertainty in the magnitude of the SOR at these levels is comparatively large (see below).

The SOR in the CMIP5 ozone database, Figure 5(b), shows a very similar structure to that found in SAGE v6.2 mixing ratios (~~see~~ cf. Figure 4(d) ~~of Maycock et al. (2016)~~ in Part I), consistent with those data forming the backbone for the historical portion of the dataset (Cionni et al., 2011). Note that the MLR ~~fitting was~~ fits were applied separately at each latitude band in the construction of the CMIP5 database, and this likely explains why the horizontal structure of the SOR is more heterogeneous than in the Bodeker ozone database. In particular the three peaked structure of the SOR found in the tropical upper stratosphere in the SAGE II v6.2 mixing ratio dataset is evident in the CMIP5 ozone database. The sharp cut-offs in the SOR at ±60° latitude are spurious and result from a lack of data points to ~~constrain the~~ define a SOR at high latitudes. As described in Section 2.1.2, the Extended CMIP5 ozone database, Figure 5(c), applied a simple extrapolation to introduce a SOR in the extratropics. ~~This~~ The details of this structure, which shows a positive SOR ~~in~~ extending into the northern extratropics and in the southern hemisphere a negative SOR at pressures greater than ∼5 hPa ~~polewards~~ poleward of 60°S, is likely to be subject to considerable uncertainties owing ~~both to the large uncertainties in the observed SOR at these latitudes (Maycock et al., 2016) and the fact that the high latitudes are filled using a simple extrapolation method~~ to the simple spatial filling method employed.

In the CMIP6 ozone database, Figure 5(d)~~shows the SOR from the CMIP6 ozone database. The~~ , the amplitude of the SOR is around 1-2% in the upper stratosphere, which is as expected broadly consistent with the CCMI-1 results shown in Figure 3. ~~This is~~ The peak amplitude of the SOR is therefore 2-3 times smaller, and is considerably smoother in latitude, than ~~the SOR~~ in the CMIP5 ozone database. In the lowermost tropical stratosphere, the CMIP6 database shows a positive SOR of up to ∼3% in the southern tropics. ~~The Bodeker database, Figure 5(a), also shows a strong positive SOR above the tropical tropopause although the structure is considerably less smooth in latitude. An enhanced~~ This is slightly larger than the SOR in the tropical lower stratosphere ~~has been identified in satellite observations, albeit with large uncertainties (Gray et al., 2009; Austin et al., 2008; Soukharev and Hood, 2006; Maycock et~~ ~~It has been hypothesised that this feature may be dynamically forced by a weakening in the Brewer Dobson circulation between solar cycle minimum and maximum. However, some of the~~ simulated by the CCMI-1 ~~models in Figure 3 do not show an enhanced SOR in the tropical lower stratosphere, suggesting this feature is not captured consistently amongst models and ozone datasets.~~

~~To further compare the~~ versions of the two CCMs used to produce the CMIP6 ozone database (CESM1(WACCM) and CMAM) (see Figure 3(b-c)). To further investigate the vertical structure of the ~~SOR in the tropics~~tropical SOR and its uncertainties, Figure 6 shows ~~vertical profiles of the annual and~~ the best estimate tropical (30°S-30°N) mean SOR ~~in the CCMI-1 models and~~ along with the 2.5-97.5% confidence intervals for the climate model ozone databases ~~. The range in the best estimate SOR across the~~ and the two satellite datasets from Figure 2 (see Part I). Also shown in grey shading is the range of the best estimate SORs from the eight CCMI-1 ~~models is shown in dark grey shading, along with ±1 standard deviation of the intermodel spread. Observations from the~~

~~SBUVMOD VN8.6 (Frith et al., 2014) (black) and the SAGE-GOMOS 1 dataset (Kyrölä et al., 2015) (blue) are also shown (see Maycock et al. (2016) for details).~~

~~In the tropical lower stratosphere, the statistical uncertainties in the SOR are much larger than in the rest of the profile, and the~~ models. The best estimate SOR in the tropical lower stratosphere ranges from a small negative signal in the CMIP5 ozone database to +6% in the Bodeker ozone database. ~~The SOR in~~ In the CMIP6 ~~database shows a significant tropical mean SOR of~~ ozone database, the best estimate tropical SOR is 2% at 80 hPa, which is, as expected, within the range of the ~~spread~~ signals in the CCMI-1 ~~model signals. There is therefore a distinct difference in the representation of~~ models. The substantial spread amongst the estimates along with the large uncertainties reinforces the challenge of constraining the SOR in the tropical lower stratosphere ~~in the CMIP5 and~~ (e.g. Marsh and Garcia (2007)). Despite the relatively large uncertainties, the SOR in the tropical lower stratosphere is larger in the CMIP6 ~~ozone databases, which~~ database compared to in CMIP5; this may be important for the modelled atmospheric response to solar variability in CMIP5 and CMIP6 models (see Section 3.4). Figure 6 further confirms that the two climate model ozone databases that include SAGE II v6.2 mixing ratio data (CMIP5 and Bodeker), show a ~~substantially larger tropical mean~~ significantly stronger SOR in the tropical upper stratosphere. This is ~~consistent with Maycock et al. (2016) who concluded that the SAGE II v6.2~~ likely to be unrealistically large since the updated SAGE II v7.0 mixing ratio data~~showed a considerably larger~~ , which show a smaller SOR in the tropical upper stratosphere ~~compared to SAVE II v7.0 mixing ratios and SBUV based datasets~~(Maycock et al., 2016) , exhibit a more realistic representation of the relationship between upper stratospheric ozone and temperature compared to SAGE II v6.2 data (Dhomse et al., 2016) .

3.3 Comparison of SOR annual cycle in CMIP5 and CMIP6 ozone databases

~~Maycock et al. (2016) showed there are seasonal variations~~ Earlier studies have shown evidence for an annual cycle in the structure and amplitude of the SOR ~~estimated from satellite observations .~~ in satellite observations (e.g. Soukharev and Hood (2006); Maycock et al. (2016)). Figure 7 shows the monthly mean SOR in the Extended CMIP5 ozone database and Figure 8 shows the same for the CMIP6 ozone database. The SOR in the CMIP5 database has a fixed structure and constant amplitude in all months; the small annual cycle in the fractional SOR amplitude arises purely from the annual cycle in background ozone concentrations. There are well understood photochemical arguments for why the structure of the SOR is expected to track the position of the Sun through the year (Haigh, 1994). Furthermore, the coupling between ozone and stratospheric dynamics may lead to variations in the SOR at high latitudes in some months due to the formation in winter of the polar vortices and their subsequent break-up in spring (Hood et al., 2015). For these reasons a complete absence of seasonal variation in the SOR as found in the CMIP5 ozone database is unrealistic. In contrast, the SOR in the CMIP6 ozone database, Figure 8, shows greater seasonal variation. Locally enhanced signals in the SOR are found in the ~~southern high latitudes and in the northern high latitudes in winter~~ high latitudes in winter and spring, which may be linked to variations in the strength of the polar vortex (Kuroda and Kodera, 2002). Thus, ~~the seasonal variability of the SOR~~ including some semblence of an annual cycle in the SOR, as seen in Figure 8, is likely to be ~~more representative of the~~ a truer reflection of the behaviour of the real atmosphere than the complete absence of ~~seasonal variability~~ an SOR annual cycle as in Figure 7. However, the associated uncertainties in the monthly SORs are larger compared to the annual mean results presented in the previous section, and there are quantitative differences between the SOR annual cycle in the CMIP6 ozone database and that estimated from satellite observations (~~see~~ cf. e.g. Figure 13 of Maycock et al. (2016)). ~~These~~ Such differences may result from uncertainties in estimating the SOR from relatively short observational records, from errors in the representation of the SOR in the models used to construct the CMIP6 ozone database, or a combination of factors. Thus ~~there is a need for continued satellite measurements in order to reduce the large uncertainties in the observed SOR, particularly on seasonal timescales, and to provide a more stringent reference for ozone databases and models~~we should not consider the evolution of the monthly SOR in the CMIP6 ozone database as a precise representation of the true SOR, but it is likely an improvement compared to the representation in the CMIP5 ozone database.

3.4 Atmospheric impact of change in SOR between CMIP5 and CMIP6 ozone databases

We now explore the atmospheric impacts of the differences between the SOR in the CMIP5 and CMIP6 ozone databases using the ECHAM6.3 model sensitivity experiments described in Section 2.3. Figure 9 shows the tropical average annual mean temperature differences in the four ~~solar cycle perturbation simulations~~ perturbation simulations representing 11 year solar cycle maximum conditions with respect to the control simulation representing solar minimum. Note that the tropospheric temperature responses in all simulations are small because the model includes fixed SSTs and therefore the troposphere does not fully adjust to the imposed solar forcing (e.g. Misios et al. (2016)).

The experiments performed to capture the total (i.e. SSI + SOR) solar cycle impact (dashed lines) show considerable differences in the tropical mean stratospheric temperature response between the recommended CMIP5 (red line) and CMIP6 (blue line) solar forcings. In the CMIP5 case, the maximum temperature response is around 1.25 K near the stratopause, which can be compared to a much smaller response to the CMIP6 solar forcing inputs of ~~0.7~~0.8 K. The SOR-only sensitivity experiments (solid lines) reveal that much of the difference in the total temperature response can be attributed to the differences in the SOR between the CMIP5 and CMIP6 ozone databases. The SOR in the Extended CMIP5 ozone database induces a peak tropical temperature response of ~~0.9~~0.85 K (solid red), which is nearly three times larger than the maximum response to the SOR in the CMIP6 ozone database with an amplitude of 0.3 K (solid blue). In addition to the marked differences in the maximum temperature response, there are also distinct differences in vertical structure. In the CMIP5 case, there is a stronger vertical gradient in the temperature response to the imposed solar forcing, which can be attributed to the highly peaked structure of the SOR in the CMIP5 database at the stratopause compared to the smoother vertical structure of the SOR in the CMIP6 ozone database (cf. Figures 5(c) and 5(d)). The simulation forced with the SOR from the CMIP6 ozone database also shows a small secondary peak in tropical lower stratospheric temperature of ∼0.3 K due to the presence of a locally enhanced SOR of ∼3%, which is not present in the CMIP5 ozone database. The results show that the change in the representation of the SOR between the recommended CMIP5 and CMIP6 ozone databases induces a much larger difference in the temperature response between solar cycle minimum and maximum than do changes in the recommended SSI forcing (see also Figure 8 in Matthes et al. (2017)).

The ~~results from the~~ ECHAM6.3 model results help to elucidate the ~~results~~ findings of Mitchell et al. (2015), which show a clear difference in the annual mean stratospheric temperature response to the solar cycle between CMIP5 models that used the CMIP5 ozone database (HadGEM2-CC, MPI-ESM, CMCC) and those with interactive chemistry that simulated their own internally-consistent SOR (CESM1(WACCM), GFDL-CM3, GISS-E2-H, MIROC-ESM-CHEM, MRI-ESM1). Specifically, models that used the CMIP5 ozone database exhibit a markedly larger temperature response near the tropical stratopause, with a stronger vertical gradient, compared to the models with interactive chemistry (see Figure 5 in Mitchell et al. (2015)). One might therefore anticipate that the difference in the stratospheric temperature response between solar cycle minimum and maximum for models with and without interactive chemistry will be smaller in CMIP6 than was found in CMIP5 owing to the fact that the SOR in the CMIP6 ozone database is derived from CCM simulations, albeit ~~forced with the CMIP5 SSI dataset that contains weaker UV variability than in the~~ without full consistency with the other CMIP6 ~~SSI dataset~~external forcings such as SSI.

4 Conclusions

Changes in stratospheric ozone concentrations ~~make a significant contribution to~~ are a major part of the atmospheric response to ~~changes~~ variations in incoming solar radiation over the 11 year solar cycle (e.g. ~~Shibata and Kodera (2005); Gray et al. (2009)~~ Haigh (1994); Shibata and Kodera (2005); Gray et al. (2009)). The associated solar-ozone response (SOR) must therefore be included in global model simulations to realistically ~~represent solar influences on climate~~capture the effects of solar variability on the atmosphere.

This study ~~uses~~ has used a multiple linear regression (MLR) model to analyse the SOR in current satellite observations (Part I; Maycock et al. (2016)) and in global models (Part II). In the present Part II, the SOR is analysed in eight chemistry-climate models (CCMs) from the CCMI-1 project: CCSRNIES-MIROC3.2, CESM1(WACCM), CMAM, CNRM-CM5-3, EMAC(L90), LMDz-REPROBUS-CM5, MRI-ESM1r1, and SOCOL3. ~~We also analyse the SOR in three~~ These analyses complement earlier studies assessing the SOR in previous generations of CCMs (e.g. Austin et al. (2008); SPARC CCMVal (2010)).

In a novel step, we also analyse and compare the SORs in three pre-calculated ozone databases that are prescribed in climate models without interactive chemistry: the Bodeker et al. (2013) Tier 1.4 ozone database and the CMIP5 ozone database (Cionni et al., 2011), which are both based on regression models fit to ~~observations~~ozone measurements, and the CMIP6 ozone database, which is created from ~~historical~~ simulations from two CCMs (CESM1(WACCM) and CMAM).

The CCMI-1 models simulate ~~a~~ an annual mean SOR with a peak amplitude of 1-2% in the upper stratosphere (∼3-5 hPa). This is more than a factor of two smaller than the SOR found in SAGE II v6.2 mixing ratio data and is more consistent with results from SAGE II v7.0 and SBUV satellite datasets ~~(Maycock et al., 2016) .Some of the CCMs~~ (Maycock et al., 2016; Dhomse et al., 2016) and with previous CCM studies (e.g. Austin et al. (2008); Sekiyama et al. (2006); Lee and Smith (2003); Egorova et al. (2014); Dhomse Many of the CCMI models show larger fractional monthly SORs in the high ~~latitude winter stratosphere~~latitudes during winter and spring, which are ~~strongly influenced by dynamical processes , although the amplitude and structure of these features tend to be less consistent across the models than the response in the tropical upper stratosphere. In addition, some of the models, in particular CMAM, LMDz-REPROBUS-CM5, MRI-ESM1r1 and SOCOL3, show an enhanced SOR in~~ likely to be strongly coupled to dynamical processes such as the formation and evolution of the polar vortex. The spread in the best estimate SOR across the CCMI-1 models is around 4 times larger in the tropical lower stratosphere ~~, which has been identified in some satellite ozone datasets (Maycock et al., 2016) . As expected, the SOR in the CMIP6 ozone database generally resembles that in the CCMI-1 models, both in terms of its broad structure and magnitude and the fact that it includes seasonal variability. We note that since the UV variability in the SSI forcing dataset used in the CCMI-1 models is relatively weak, the SOR in~~ than in the ~~CMIP6 ozone database is smaller than would be simulated in a CCM forced with the CMIP6 SSI dataset, which includes larger UV variability (Matthes et al., 2017)~~ middle and upper stratosphere, and the statistical uncertainties in the SOR are also substantially larger in the lower stratosphere.

There are ~~stark differences between the~~ strong differences in the representations of the SOR in the ~~CMIP6 ozone database and those found in the~~ pre-calculated ozone databases. The peak amplitude of the SOR in the tropics in the CMIP5 and Bodeker ozone databases ~~. In particular, the peak amplitudes in the tropics are~~ is substantially larger (5%) ~~in the latter databases compared to in the~~ than in the CMIP6 database (1.5%). This is because ~~those~~ the former databases are derived from observations that include SAGE II v6.2 mixing ratios, which ~~as previously mentioned~~ exhibit a larger SOR than found in other satellite ozone datasets ~~(Maycock et al., 2016) .~~

~~In addition to differences in the peak magnitude~~ (see Part I). In contrast, the CMIP6 ozone database was constructed from CCM simulations and thus its SOR generally resembles that in the CCMI-1 models, both in terms of its broad structure and magnitude and the fact that it exhibits some variation over the annual cycle. Note that the amplitude of the SOR ~~, there are also marked differences in the spatial structure of the SOR amongst the ozone databases~~in the CMIP6 ozone database may have been slightly larger if both of the constituent CCMs had used the CMIP6 SSI forcing rather than the NRLSSI-1 forcing from CCMI-1 (Matthes et al., 2017) . The CMIP5 database ~~showed spurious large~~ exhibits spurious sharp horizontal gradients in the SOR across the extratropics, which were ~~reduced through implementation of~~ alleviated by a simple poleward extrapolation in the Extended CMIP5 ozone database~~(Schmidt et al., 2013; Osprey et al., 2013) . Furthermore, while the CMIP6 database implicitly includes seasonal variations in the SOR, as simulated by the CCMs used to construct the database, the~~ , albeit with considerable uncertainties in the detailed spatial structure. Furthermore, the CMIP5 ~~database has a fixed annual mean SOR in all months~~and Extended CMIP5 ozone databases include a fixed SOR throughout the year, which is ~~likely to be unrealistic.~~

Given the inclusion of seasonal variations in the SOR compared to CMIP5, as well as the greater consistency with CCM results, CMIP6 models without chemistry are encouraged to use the recommended CMIP6 ozone database (see esgf-node.llnl.gov/projects/input4mips). Nevertheless, whatever approach is adopted, all CMIP6 modelling groups are encouraged to document the representation ~~of~~ the SOR and SSI in their simulations to facilitate future analyses of solar-climate impacts.

unrealistic.

Sensitivity experiments were performed using a comprehensive global atmospheric model without chemistry (ECHAM6.3) to test how the changes in the recommended SOR and SSI between CMIP5 and CMIP6 affect the simulated annual mean temperature response over the 11 year solar cycle. The experiments show that changes in the SOR between CMIP5 and CMIP6 cause a decrease in the tropical average temperature response over the solar cycle of up to 0.6 K, or around 50% ~~. This is the combined result of the SOR in the CMIP5 ozone database being very large due to it being based on SAGE II v6.2 mixing ratio data, and the SOR in the CMIP6 ozone database being somewhat weak because it is based on CCMs forced by the NRLSSI-1 dataset. The impact of changes in the recommended SOR on tropical stratospheric temperatures~~ of the total amplitude. This impact on the simulated stratospheric temperature response over the solar cycle is many times larger than the separate impact (i.e. without ozone feedbacks) of changes in the recommended SSI forcing between CMIP5 and CMIP6. The results indicate that differences in the representation of the SOR amongst CMIP5 models is likely to be a major explanatory factor for the large spread in the stratospheric temperature responses to the solar cycle found in CMIP5 models (Mitchell et al., 2015). The broader relevance of different representations of the SOR for atmospheric dynamics and regional surface climate responses to the solar cycle remains to be explored. However, Hood et al. (2015) suggested CMIP5 models with an interactive representation of the SOR showed a stronger high latitude dynamical response to the solar cycle.

~~Substantial~~ Parts I and II of this study have shown that uncertainties remain in ~~various factors related to~~ understanding the SOR, which present ~~challenges~~ a challenge for including these effects in ~~global models. Key issues include: outstanding large uncertainties in the SOR derived from observations (Maycock et al., 2016) ; outstanding uncertainties in the characteristics of SSI~~

~~variability (Ermolli et al., 2013; Haigh et al., 2010; Dhomse et al., 2016; Matthes et al., 2017) ; uncertainties to the ability of models to represent the effects of SSI variability on atmospheric radiation, photochemistry and dynamics (Forster et al., 2011; Sukhodolov et al., 2016; Hood et al., 2015; Matthes et al., 2017) ; and uncertainties in the magnitude of the observed temperature response to the solar cycle (Ramaswamy et al, 2001; ?) . Despite these various issues, information about the observed SOR has been used to exclude implausible scenarios for SSI variability (Ball et al., 2016) and this offers hope for further advances in understanding the SOR in the future. Improved physical understanding and constraints for model performance rely on long-term high quality observational datasets and it is therefore vitally important that satellite measurements of stratospheric ozone continue in the future .~~

model simulations. However, given the inclusion of variations in the SOR over the annual cycle, as well as the greater consistency of the amplitude of the SOR with CCM results, CMIP6 models without chemistry are encouraged to use the recommended CMIP6 ozone database. Nevertheless, whatever approach is employed, all CMIP6 modelling groups are encouraged to document the representation of the SOR and SSI in their simulations to facilitate future analysis of solar-climate impacts.

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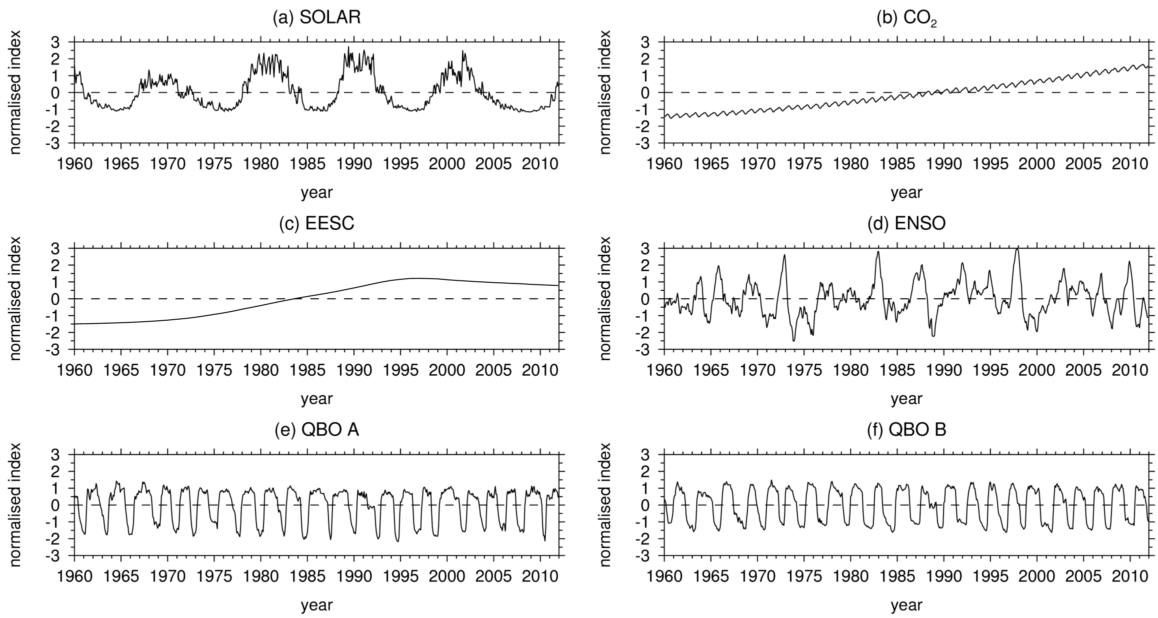

Figure 1. Timeseries of the ~~seven~~ six basis functions used in the MLR analysis. (a) Solar forcing based on F10.7cm flux; (b) ~~volcanic forcing based on the Sato AOD index; (c)~~ CO_2; (~~d~~c) equivalent effective stratospheric chlorine; (~~e~~d) ENSO index; (~~f~~e, ~~g~~f) two orthogonal QBO indices defined as the first two principal component timeseries of tropical zonal mean zonal winds (in this case taken from observations). The timeseries are in units of standard deviation.

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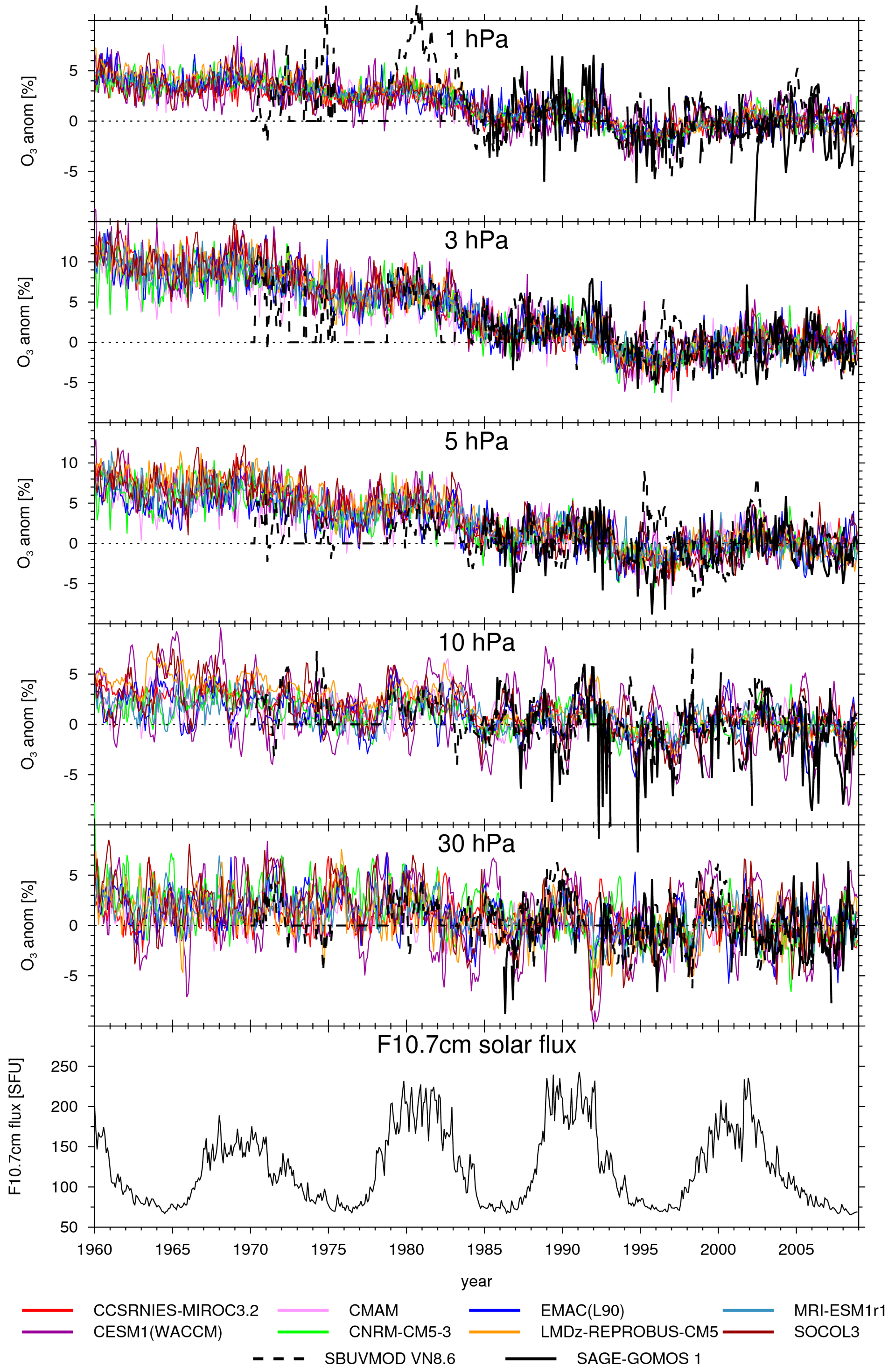

Figure 2. Timeseries of deseasonalised percent tropical (30°S-30°N) ozone anomalies in CCMI-1 models for 1960-2009 and two satellite datasets at 1 hPa, 3 hPa, 5 hPa, 10 hPa and 30 hPa. The lowest panel shows the F10.7 cm solar flux for reference. Anomalies are shown relative to a baseline period 1985-2009.

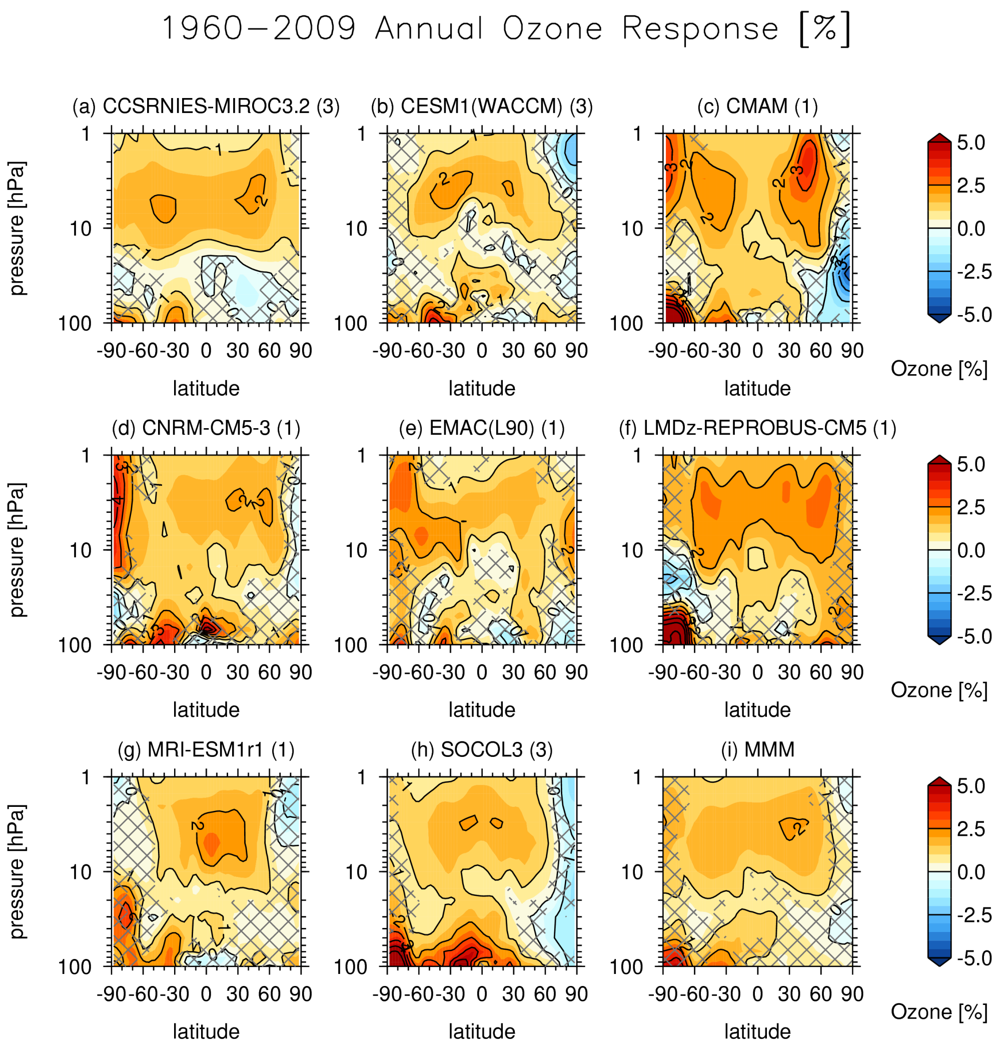

Figure 3. The percent (%) differences in stratospheric ozone mixing ratios per 130 SFU for 1960-2009 in the CCMI-1 models listed in Table 1. The solid contours denote 1% intervals. Hatching denotes regions where the regression coefficients are not significantly different from zero at the 95% confidence level. Panel (i) shows the multi-model mean (MMM) with hatching denoting where the MMM response is smaller than ± 2 sd of the intermodel spread.~~Tropospheric values have been masked out.~~

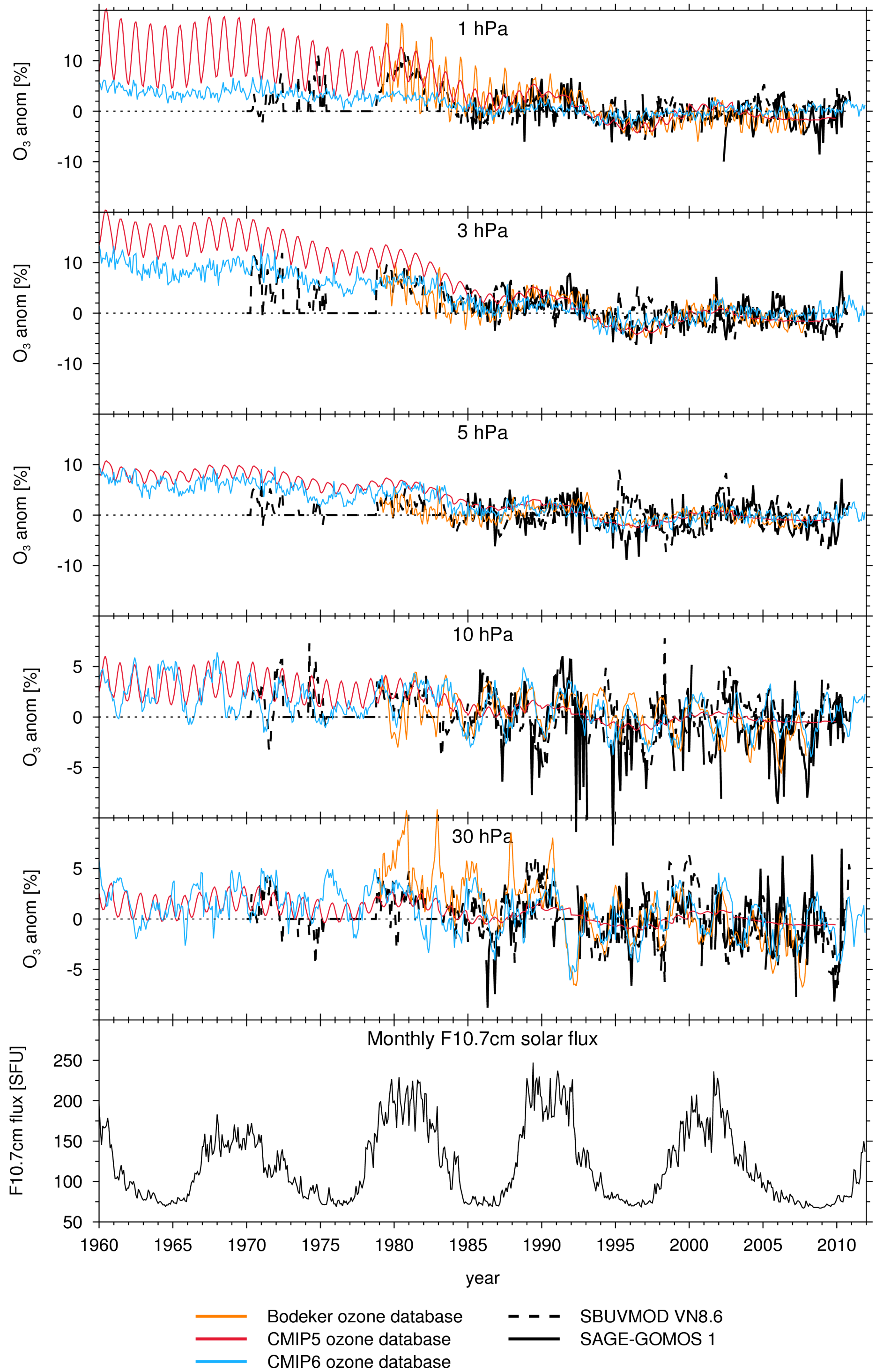

Figure 4. Timeseries of deseasonalised percent tropical (30°S-30°N) ozone anomalies from two satellite observation datasets (black) and the Bodeker (orange), CMIP5 (Cionni et al., 2011) (red), and CMIP6 (blue) ozone databases ~~for~~ over the period 1960-2011 at (a) 1 hPa, (b) 3 hPa, (c) 5 hPa, (d) 10 hPa and (e) 30 hPa. The lowest panel shows the F10.7 cm solar flux for reference. Anomalies are shown relative to a baseline period 1985-2009.

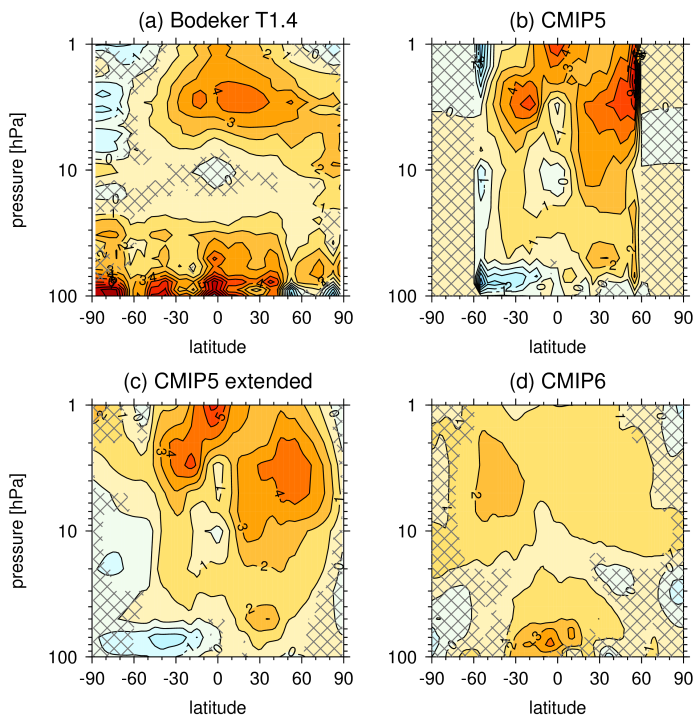

Figure 5. The annual mean percent (%) differences in ozone per 130 SFU ~~over 1979-2007~~ for the (a) Bodeker (1979-2007), (b) CMIP5 (1960-2005), (c) Extended CMIP5 (1960-2005) and (d) CMIP6 (1960-2011) ozone databases. The contour interval is 1%. The hatching in (d) is as in Figure 3.

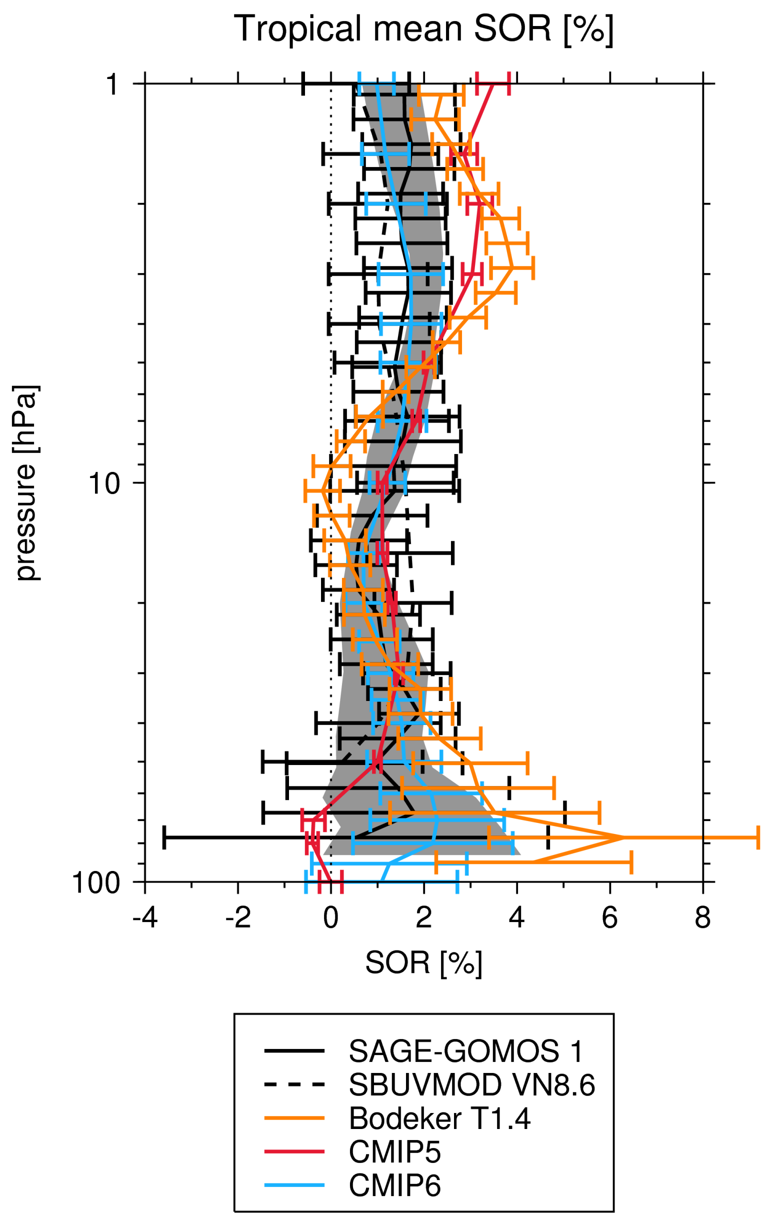

Figure 6. Vertical profiles of the tropical (30°S-30°N) average annual SOR per 130 SFU (%). The range of the best estimates across the eight CCMI-1 models is shown in the dark grey shading. The ~~light grey shading shows ±1 standard deviation of the intermodel spread in SOR across the CCMI-1 models. The coloured~~ lines show the tropical mean annual SOR in the three climate model ozone databases discussed in Section 3.2 and two satellite ozone datasets from Maycock et al. (2016) (SBUVMOD VN8.6 and SAGE-GOMOS 1). The whiskers denote 2.5-97.5% confidence intervals on the estimated SOR.

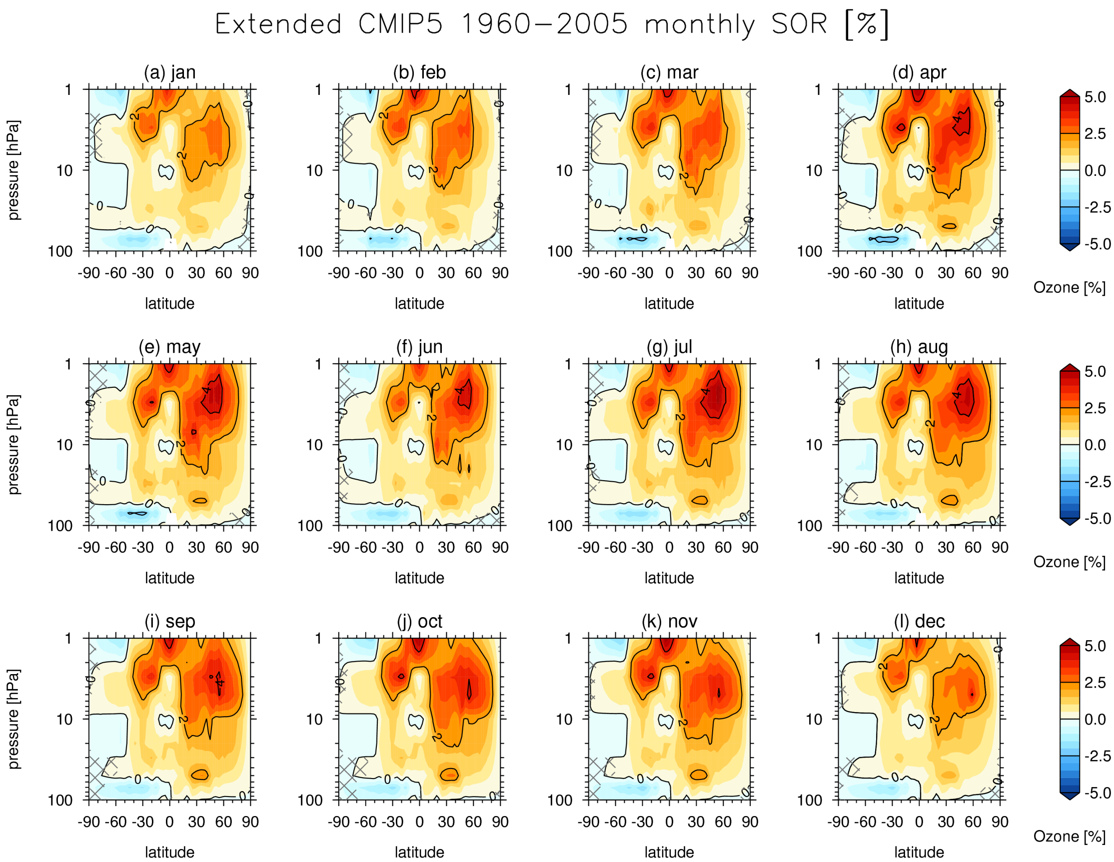

Figure 7. Monthly mean percent (%) ozone anomalies per 130 SFU for (a) January to (l) December in the Extended CMIP5 ozone database. The solid contours denote 2% intervals.

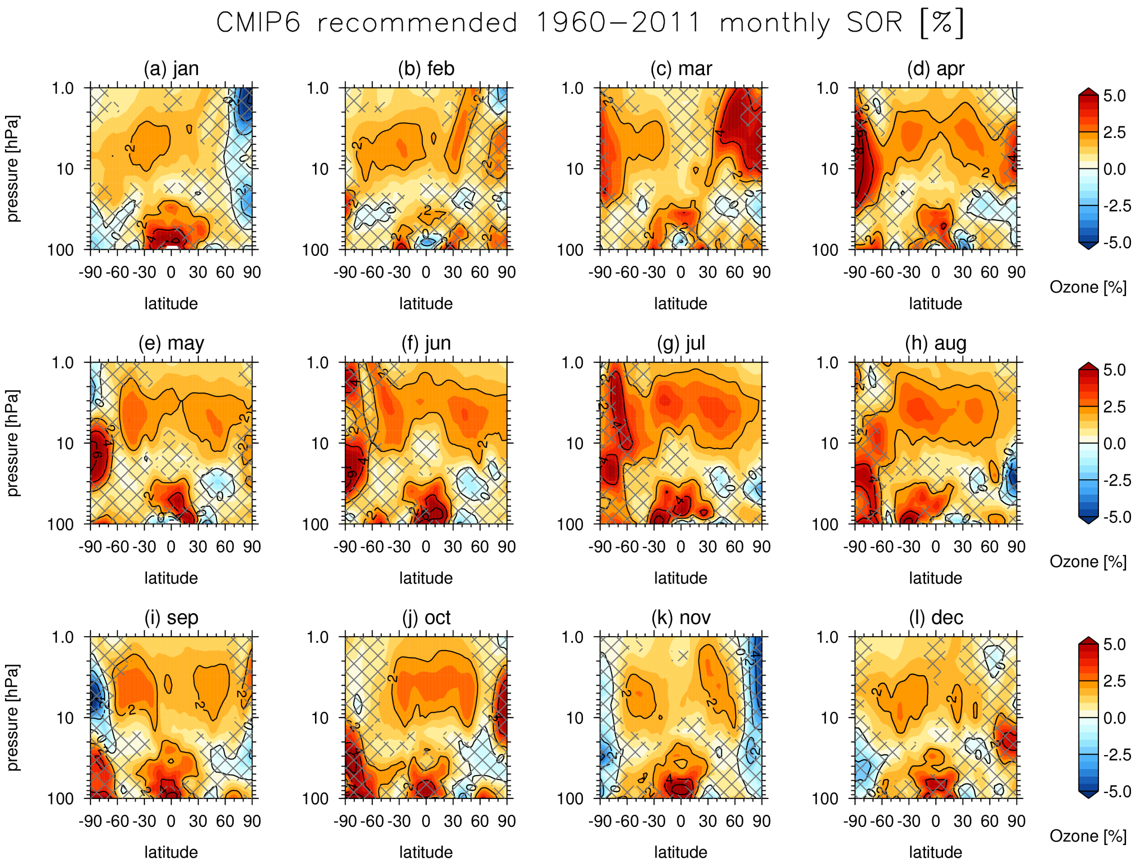

Figure 8. Monthly mean percent (%) ozone anomalies per 130 SFU for (a) January to (l) December in the CMIP6 ozone database. The solid contours denote 2% intervals. Hatching denotes regions where the regression coefficients are not significantly different from zero at the 95% confidence level.

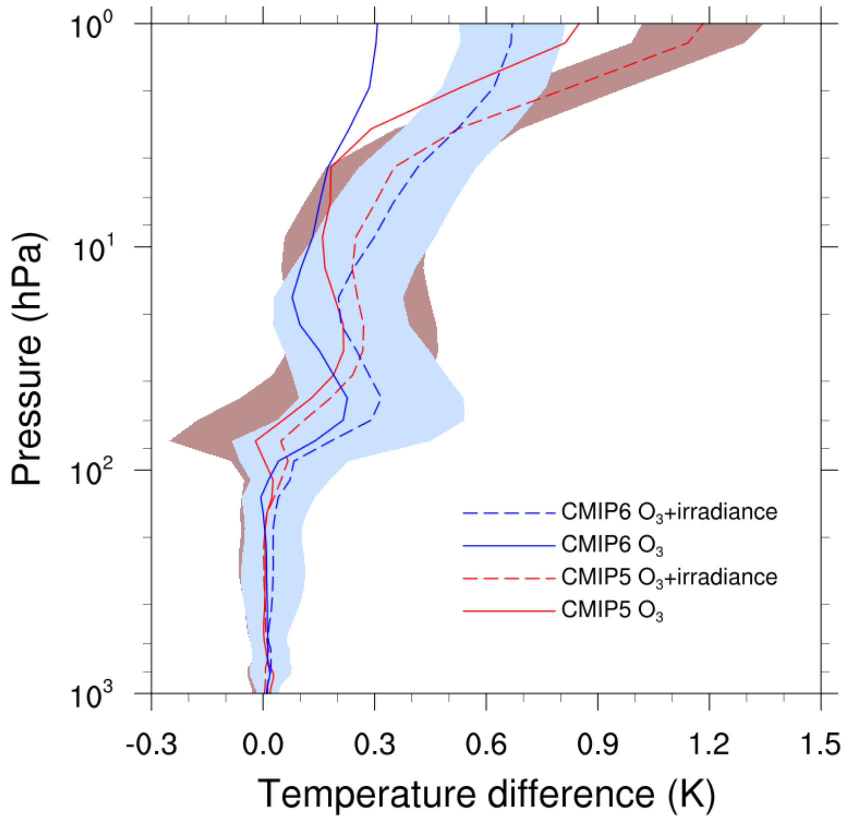

Figure 9. Average tropical (30°S-30°N) solar cycle (max-min) temperature anomalies as simulated by ECHAM6. Anomalies have been calculated between four sensitivity experiments representing different solar maximum conditions and a reference experiment representing solar minimum conditions. The sensitivity experiments are performed by prescribing: (red solid) SOR from the Extended CMIP5 ozone database; (red dashed) recommended SOR and ~~spectral~~ solar spectral irradiance anomalies for CMIP5; (blue solid) historical SOR from recommended CMIP6 ozone database; and (blue dashed) recommended SOR and ~~spectral~~ solar spectral irradiance anomalies for CMIP6. The shaded regions denote 2.5-97.5% confidence intervals on the combined forcing responses.

Model	**No. ensembles**	**QBO**	**No. shortwave bands**	**Reference**
CMAM	3	No	4	Jonsson et al. (2004); Scinocca et al. (2008)
CESM1(WACCM)	3	Nudged	19	Marsh et al. (2013); Solomon et al. (2015)
CCSRNIES-MIROC3.2	3	Nudged	20	Imai et al. (2011); Akiyoshi et al. (2016)
CNRM-CM5-3	1	No	6	Voldoire et al. (2011); Michou et al. (2011); http://www.cnrm-game-meteo.fr/
EMAC(L90)	1	Nudged	55 in the stratosphere (<70 hPa)	Jöckel et al. (2016)
LMDz-REPROBUS-CM5 (L39)	1	No	2	Marchand et al. (2011); Szopa et al. (2013); Dufresne et al. (2013)
MRI-ESM1r1	1	Internal	22	Yukimoto et al. (2011, 2012); Deushi and Shibata (2011)
SOCOL3	3	Nudged	6	Stenke et al. (2013); Revell et al. (2015)

Table 1. Details of the CCMI-1 models used in this study and the number of ensemble members available for the REFC1 experiment for the period 1960-2009. See Morgenstern et al. (2017) for more details.