Anonymous Referee #1

The manuscript discusses the responses of the stratospheric ozone response to the solar irradiance variability on the Sun rotation cycle time scale. The authors analyzed the satellite observations by MLS instrument and results obtained with LMDZ model in free running and specified dynamics modes. The subject of the manuscript is appropriate for ACP. Despite many attempts to characterize ozone response to solar irradiance variability several aspects of the problem still remain open. The manuscript is well written and structured, the figures and explanations are clear. The conclusions about the dependence of the ozone response uncertainty on the signal strength and necessary numbers of cycles could be of interest for the scientists working in this area. There are, however, some flaws which do not allow me to recommend immediate publication.

We thank the reviewer for reading the manuscript and providing helpful comments and suggestions. We address the raised issues in turn below.

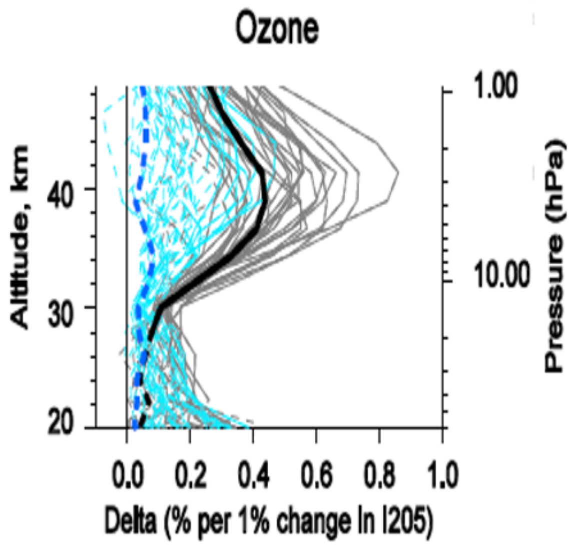
Our answers to comments and suggestions are written in blue and manuscript changes are written in italic type within double quotes ("*like this*").

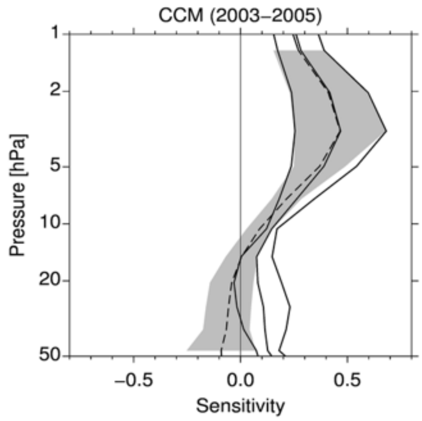
Major issues

1. It looks like the authors intentionally omitted the direct effects of the solar irradiance on the heating rates and temperature. After careful discussion of how important this process for the correct representation of the time lag between ozone and solar UV in the introduction they completely excluded this processes using not correct arguments. The importance of this process is clear even if we put aside the dynamical consequences of the direct radiative heating. I recall the importance of the direct heating was demonstrated in the recent paper by Sukhodolov et al., 2016.

We agree that neglecting the direct effect on heating rate must be considered carefully. To test the potential influence of the missing temperature feedback on ozone in our model setup, we performed additional analysis that we compared with recent model results of Sukhodolov et al. [2017].

In their recent study, Sukhodolov et al. [2017] performed an ensemble of 30 simulations for the period 2003-2005 with the SOCOL CCM model. In their experimental setup, they considered both (i) the effects of UV changes on the photolysis rates and (ii) the direct radiative effects on temperature which feeds back on ozone. Hence, their CCM formulation allows accounting for all photochemical and radiative effects. Their large number of simulations and the fact that they simulated the period 2003-2005 using NRLSSI data (like us) allows comparing with our CCM ensemble results in a fair way. Their UV-ozone cross-correlation analysis (see their Figure 3b) reveals a negative lag of 1 to 2 days in the upper stratosphere (above 3 hPa) which is consistent with the one we found in our study (see our Fig. 7c,f). When performing the UV-ozone cross-correlation analysis over the same period (i.e. 2003-2005), we also found a negative lag of 1 to 2 days. We also compared the analysis of the ozone sensitivity to F205 index (see below) over the period 2003-2005. Their ozone sensitivity profiles (left) are shown at optimum lag and ours (right) at optimum lag (solid) and zero lag (dashed). Results from both models compare very well, showing a maximum slightly larger than 0.4 at 3-4 hPa and decreases down to 0.25 near the stratopause. The very good agreement between the two CCMs, despite their different formulation, suggest that omitting the direct radiative heating does not have a strong effect on the ozone response and is therefore an acceptable approximation in our case.





Globally, the manuscript has been revised at several places to discuss the CCM configuration.

- More specifically in section 2.3, we modified the text as follows:

"Thus, the solar rotational cycle forcing is taken into account by using daily photolysis rates calculated by TUV in the photochemistry module of LMDz-Reprobus. *Note however that the direct effect on heating rates generated by UV variations associated with the 27-day rotational cycle is neglected: i.e. daily changes in the spectral irradiance are not considered by the model radiative scheme. As a consequence, part of the thermal and dynamical responses to the 27-day rotational cycle and hence their effect on ozone (through transport and temperature dependent chemical reactions, as described above) are missing. The impact of this approximation on our results seems to be small though, as discussed thereafter (sections 3 and 5). Note also that on timescales of the 11yr cycle, Swartz et al. (2012) found that their photolysis-only simulation captured almost all of the solar cycle effect on ozone.*"

- Discussion on results of Figure 6 (now Figure 7) has been extended as follows:

"*We now analyse the CCM ensemble results. The ensemble mean ozone sensitivity profiles (Figs. 7c and f) markedly differ with ozone sensitivity profiles derived from observations (Figs. 7a and d) and CTM (Figs. 7b and e) at the corresponding periods. These differences are particularly pronounced in the upper stratosphere (above ~5 hPa). On the other hand, despite the two different periods, the ensemble mean ozone sensitivity profiles show very similar features with positive sensitivity from 15 hPa to the stratopause and a maximum sensitivity of 0.4 at ~3 hPa (Figs. 7c and f). This maximum tropical sensitivity value and its altitude level is in good agreement with previous CCM estimates (e.g. Rozanov et al., 2006; Austin et al., 2007; Gruzdev et al., 2009; Kubin et al., 2011). The CCM ozone sensitivity analysis has also been repeated for the period 2003-2005 (not shown) to be directly comparable with the CCM results of Sukhodolov et al. (2017): we found very similar ozone sensitivity profiles.*"

- We added a full paragraph to discuss this aspect in section 5:

"*In our CCM experimental design, the direct radiative effect of UV on heating rates has been neglected leading to an underestimated temperature response to the 27day cycle. As a consequence, this may affect the ozone response by reducing the magnitude of the solar-induced temperature feedback on chemical reaction rates. Nevertheless, a detailed comparison of the ozone response in our analysis with results from previous independent CCM studies (Rozanov et al., 2006 ; Sukhodolov et al., 2017) revealed a very good correspondence, despite the fact that their* *experimental design included the direct radiative heating effect. This suggests that the feedback exerted by the solar-induced temperature fluctuations on ozone is modest, at least at the 27day time scales. This is in fact not surprising. In their recent study, Sukhodolov et al. (2017) shown that the atmospheric internal variability largely dominates the variability of the stratospheric temperature on 27day time scales, making the temperature response to the solar forcing difficult to identify and, hence, the influence of its feedback on ozone secondary. Nonetheless, we recognize that to quantify properly the impact of the neglected solar-induced temperature feedback on our results, additional CCM experiments including the direct radiative effect of UV on heating rate should be performed."*

- We added some details regarding the role of HOx on ozone in the upper stratosphere:

In the introduction, we added a short paragraph to describe the effect of HOx on ozone in the upper stratosphere and mesosphere: "*Fleming et al. (1995) further stressed the increasing importance with height of the solar-modulated HOx chemistry on the ozone response above 45 km. In the upper stratosphere and mesosphere, enhancement of HOx through photolysis of water vapour in Lyman-alpha line associated with an increasing solar irradiance contribute to destroy ozone. Above ~65 km and at zero-lag, the latter mechanism dominates over ozone production (i.e. by photolysis of oxygen) leading to a negative ozone-solar irradiance correlation. In the upper stratosphere and lower mesosphere (below 65 km), although ozone production dominates, increasing HOx at zero-lag contributes to the negative lag of the ozone response (Rozanov et al., 2006)."*

We also mention this mechanism in section 3.2 when we discuss the cross-correlation analysis shown in Figure 5: "*Above 3 hPa (~40 km), CCM cross-correlations of both periods (Fig. 5c,f) show a maximum at negative time lag (-2 days). As mentioned in the introductory section, this negative time lag can be induced by temperature feedback on ozone and by increasing HOx with solar irradiance which contributes to destroy ozone. While our model configuration allows to fully account for the HOx effect, the solar-induced temperature response is limited since the direct radiative heating effect is not included. The temperature response to the 27-days cycle is thus solely controlled by ozone production in the photolysis scheme. Although a temperature signal is found (not shown), it is small, reducing the likelihood for the solar-induced temperature feedback to be prominent in our experiments. Despite the approximation made in our model configuration, we notice however that the upper stratosphere negative lags compare very well with those found in CCM experiments of Sukhodolov et al. (2017) (see their Fig. 3) in which both HOx and solar-induced temperature feedback effects are fully included. Hence, this suggests that neglecting the direct effect on heating rates generated by UV variations has a limited effect on the ozone response, at least at 27-days timescale. More sensitivity experiments are required however to quantify accurately the impact of this approximation*."

2. It is also not clear why the authors used 3 year period to evaluate ozone response from the observation and model while they show that 3 year time period does not provide statistically robust results (uncertainty only below 50%). This should be somehow explained to the readers. The choice of the number of ensemble runs is also doubtful in the light of the obtained results. If the ensemble run is crucial it would be logical to estimate how many ensemble runs are necessary to reach some kind of convergence. Moreover, the obtained results with free running CCM will be more convincing if the analysis of the CCM runs without solar rotation variability is added.

Regarding the first part of the comment (about 3 year periods), section 3 of our paper, which considers the declining phases of cycles 22 and 23, actually serves as a case study where we compare observations and model results. It follows up on Bossay et al. [2015] which found some intriguing behavior in the response of the ozone to the 27-day solar cycle. Namely, that the correlation between the ozone and the forcing seems stronger when the amplitude of solar rotational fluctuations is small (more details are written in the introduction). In our study, we used in addition to observations, CTM and an ensemble of CCM simulations results. Section 3 allows illustrating clearly, with a concrete case, the effect of internal variability when retrieving the response of ozone to solar forcing at 27-day timescale.

To make the purpose of section 3 clearer, we revised the introductory part as follows:

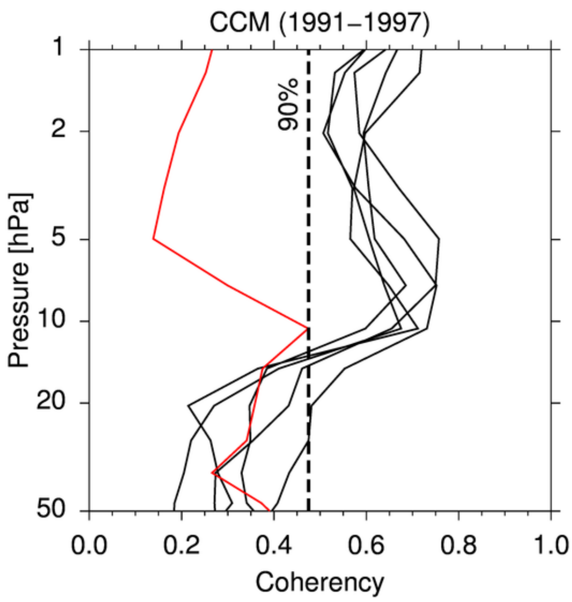
"As a first step, we follow up on the case study of Bossay et al. [2015] and make use of observations and modelling results comparison to provide a detailed picture of the ozone response to the solar rotational cycle during the declining phases of cycle 22 and cycle 23. We particularly aim to better understand the strong differences in the ozone response to solar rotational cycle found between the two periods. Two configurations of the LMDz-Reprobus chemistry climate model simulations are used, with specified dynamics (i.e. Chemistry Transport Model, or CTM) and in its free running mode (CCM). In the CTM configuration, temperature and wind fields calculated by the model are relaxed towards meteorological analysis; the dynamics is expected to be rather close to the reality, allowing direct comparisons with satellite observations for evaluating model chemical processes and its relevance to our study. In the CCM configuration, an ensemble of simulation is performed. Comparing the CCM ensemble results to CTM and observations during the declining phases of cycle 22 and cycle 23 allows to understand better the effect of internal dynamical variability on the ozone response. As a second step, we take advantage of the ensemble of CCM simulations and its large statistics to (i) assess the influence of the solar cycle phase on the ozone sensitivity to the rotational cycle and (ii) quantify the time window required for a robust estimation of the ozone sensitivity."

We also revised the introductory of section 3. part as follows:

"*In this section, we analyse the ozone response to the solar rotational cycle over the declining phase of solar cycles 22 and 23 in the observations and in the CTM and CCM model simulations. The analysis presented here follows up on Bossay et al. (2015) observational study. In particular, we aim to assess the model performances, understand better the differences in the results between the two solar declining phase periods and highlight the importance of internal dynamical variability*."

Regarding the second point (choice of the number of ensemble members), quantifying the number of ensemble members required to reach some kind of convergent was done in Sukhodolov et al. (2017). In our study, we address a similar problem in terms of size of time window (Figure 11) where a convergence is also reached.

Finally, as suggested by the reviewer, we added a figure (now Figure 5) to compare ozone/F205 coherency estimates of the unforced vs. forced experiment results.



"Figure 5. Vertical profile of the mean squared coherence between ozone and F205 averaged between 22 and 30 day periods and calculated for the time period 1991-1997. The black lines correspond to the results of individual ensemble members (five in total) and the red lines to the results of the experiment forced with constant solar forcing. The vertical dashed line indicates the 90% confidence limit."

We added the following part:

"To further test the robustness of the coherence signal, we perform an additional CCM simulation for the period 1991-1997 where the solar forcing is kept constant by using fixed (i.e. climatological) photolysis rates during the model simulation. Results are shown on Fig. 5. Below 15 hPa, the different experiments show no significant coherence between ozone and solar flux. Between 15 and 1 hPa, all forced experiments (black lines) reveal a similar and significant coherence signal while for the constant solar forcing experiment (red line), the coherence is weak and within the range of randomness. The absence of significant coherence found in the constant solar experiment confirms that the coherence found between F205 and stratospheric ozone is not fortuitous and primarily originates from photolysis processes"

Minor issues:

1. Page 7, line 1: It is clear since 2004 that two bands scheme cannot be used for the simulation of the atmospheric response to solar irradiance variability. It was confirmed in 2010,2011 and 2014. Several modifications of different complexity are known.

In its current version the LMDz-Reprobus radiative scheme has only 2 spectral bands resolved in the UV. This leads to an underestimation of the stratosphere temperature response to solar spectral variations (see also Figure 3.17 in chapter 3 of the CCMVal report). In the coming version of LMDz-Reprobus (prepared for CMIP6), the radiative scheme spectral resolution in the UV range has been improved.

2. Page 7, line 17: I do not understand how climatological temperature can be used in CCM. Please, elaborate. By the way the reference to TUV is confusing. If I am not mistaken in the cited 1999 paper the tropospheric version was described. Maybe it is better to use recent intercomparison of the codes where TUV showed excellent performance relative to reference models. I do not also understand whether or not daily NRL solar irradiance was used for the photolysis rate calculations.

In the off-line look-up tables, the temperature dependence of the absorption cross-section are computed using US standard atmosphere temperature profile in TUV, not in the CCM. This approximation has no significant impact on the results. We changed the sentence as follows: "*The temperature dependence of absorption cross-sections is calculated off-line in TUV using the US standard atmosphere*."

Regarding TUV, we now added the reference to Sukhodolov et al. (2016).

Finally, we clarified that daily NRL irradiance is used for photolysis rate calculation as follows: *"A separate photolysis look-up table is calculated every day using the daily NRLSSI as solar input"*

3. Page 7, line 21-24: I recommend to check carefully this sentence. I do not recall such a bold statement in the cited paper.

This sentence and the reference to Swartz et al. [2012] have been removed; the statements were indeed too strong. Instead, we now detail the potential effect of neglecting direct heating rates response on ozone (see also answer to comment 1):

"Thus, the solar rotational cycle forcing is taken into account by using daily photolysis rates calculated by TUV in the photochemistry module of LMDz-Reprobus. *Note however that the direct effect on heating rates generated by UV variations associated with the 27-day rotational cycle is neglected: i.e. daily changes in the spectral irradiance are not considered by the model radiative scheme. As a consequence, part of the thermal and dynamical responses to the 27-day rotational cycle and hence their effect on ozone (through transport and temperature dependent chemical reactions, as described above) are missing. The impact of this approximation on our results seems to be small though, as discussed thereafter (sections 3 and 5).*"

4. Page 12, line 9: I think this statement is not completely correct. In general, the magnitude of the rotational cycle depends on non-homogeneity of the dark/bright features distribution, which can be very small for very high level of solar activity.Fig.8 shows for example rather small variances in 2002, while the solar activity level is high.

We agree with the reviewer and modified the text as follows:

"The amplitude of the rotational cycle depends on the inhomogeneous brightness structure of the solar disc (i.e. distribution of sunspots and faculae). Given that the amount of sunspots and faculae increases with increasing solar activity, inhomogeneity in the brightness is likely to increase during solar maximum phases. One may thus expect minimum and maximum sensitivity during 11year solar maximum and minimum phases, respectively."