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Atmospheric Chemistry and Physics
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Discussions

Interactive comment on "On the detection of the solar signal in the tropical stratosphere" *by* G. Chiodo et al.

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We would like to thank the two anonymous reviewers for their constructive comments provided in the discussion phase. By addressing these issues, we feel the manuscript improved greatly. In our response, please note that the Figures included in this letter are indexed with the prefix R (i.e., Fig. R1), while the Figures in the original manuscript are indexed in the standard form Fig. #

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General comment for Referees #1 and #2:

A point of concern raised by both reviewers is the difficulty in following the discussion due to the multiple instances where alternative results are mentioned though not displayed in a Figure. This particularly applies to the comparison of the results obtained with the updated regression technique (Eq. A6), and standard multiple linear regression (MLR, Eq. A1). For this reason, the plots showing the regression coefficients obtained from the standard MLR for temperature and ozone (shown respectively in Figs. R1-R3), along with the results from the new technique (Figs. R5-R6) have been included in the revised paper. This aids the discussion of the comparison between techniques, and reduces the number of instances where results are referred to as “(not shown)”.

Response to Anonymous Referee #1:

1. ***It appears they also tested MLR without their new refinements (mentioned several times in Section 3.2 but indicated as “(not shown)". This makes it hard for readers to compare the more familiar signals found in many publications with the current analyses. For example, how much of the difference between this and previous studies is due to using different data or period (WACCM versus other models or observations) and how much to the different analysis technique? There are words in the paper about this but, in my opinion, it would be much easier to grasp if the signals using the more commonly used MLR were directly shown and compared with the new results.***

   In the new version, we have added plots showing the solar signal in tropical mean temperature and ozone, diagnosed from the standard MLR (Figs. R1-R3). For clarity, we show the profile of the UV regression coefficient from the standard MLR in the middle and lower stratosphere (10-100 hPa) in Figs. R2-R4. For a comparison, we also show the solar signal extracted from the updated MLR in Figs. R5-R6.

Both methods yield qualitatively similar results in the upper stratosphere, where a significant increase in temperature and ozone is extracted in all simulation sets. Some differences between the analysis methods are seen in the results obtained in the tropical lower stratosphere (50-70 hPa). In this region, the solar response derived from the standard MLR shows a larger spread among the simulation sets than the updated MLR. This particularly applies to the discrepancy between the temperature and ozone signals extracted from the reference case, and the simulations excluding ENSO and QBO. Both methods show a reduction of the solar response in temperature and ozone in the simulations without volcanic forcing, although this reduction is larger in the new technique. It thus follows that the major conclusion concerning the contribution of volcanic aliasing to the apparent solar response does not depend on the analysis method, although the new technique highlights the spurious contribution of volcanic aerosol to the apparent quasi-decadal variability in the tropical lower stratosphere. In addition, the new technique reduces aliasing from other forcings (i.e., QBO and ENSO). The revised paper contains a more detailed discussion of the differences in the **11 yr solar signal** section.

2. ***The axis labels are too small on the multi-panel figures.***

   We have increased the font size and thickness in the multi-panel figures of the revised manuscript.

3. ***Where did the SAD data used in the model come from? Were there observations available before SAGE II?***

   The SAD data are the same as those recommended for the SPARC CCMVal2 project. Details of the dataset are outlined in section 2.5.3.4 of *CCMVal-2* (2010). Briefly, they were created from a combination of different datasets: SAGE I (1979-

1981), SAGE II (1984-2005), and SME instruments. Data before 1979 were constructed based on assumptions of background aerosol and, in the case of the Agung eruption (1963), assuming a similar distribution of aerosol as after later volcanic eruptions. We clarify the source of the SAD data in the **Appendix** section of the revised paper.

4. ***Is the ozone MLR analysis done on relative amounts (percentages) or on absolute amounts with the percent taken later? Does it make any difference?***

   The ozone MLR analysis is done on absolute (i.e., mixing ratio) amounts, and the percent are taken on the climatological values of each pressure level. Since the regression is performed at each level separately, regressing onto relative amounts is equivalent to regressing onto a time-series multiplied with a height-dependent scalar quantity. Accordingly, no differences are expected. This point is clarified in the **Methods** section of the revised paper.

5. ***Section 3.1 jumps around a lot and is hard to follow. Perhaps it would flow better to finish discussing the lag in each forcing term before moving on to the next. The limit to lags of one year is mentioned several times with different motivations. Also, the final values used were not clear except the zero lags for SAD and N3.4.***

   We have followed the reviewer suggestion regarding the discussion of each lag term. In the revised manuscript, we discuss each lag term for both ozone and temperature at the same time, before moving on to the next term. Please note that the final values used for N3.4 are 0.25 years (or 3-5 months) for temperature, and 0.5 years (or 6-8 months) for ozone. A zero lag is used for the SAD index.

6. ***It seems that the values in Figure 4 are used for UV although this is not stated explicitly.***

Correct, the values in Figure 4 are used for UV index. In the revised version, we make this point more clear.

7. ***What lag was used for the QBO?***

   The QBO residuals used in Eq. A6 (i.e., $u30^*$ and $u10^*$) are not lagged. Since u30 and u10 are approximately orthogonal and sinusoidal, the optimal lag τ is achieved by attributing different fitting coefficients to each of the two indices, and therefore no lag is necessary or introduced. This is analogous to the trigonometric identity $sin(t-\tau) = sin(t)cos(\tau) - cos(t)sin(\tau)$. Furthermore, we also find that a lag τ in the QBO indices would not improve the regression fit. In the Appendix section of the revised manuscript, we now explicitly explain that no lag is used for the QBO, together with the reasons for the different treatment of the QBO in Eq. A6 compared to the other terms..

   Please note that we removed a lag term in the QBO indices, which was erroneously introduced in the regression that yielded the UV coefficients shown in Figs. 6-7. In the revised manuscript, Figures R5-R6 replace Figs. 6-7. There are only minor changes in both temperature and ozone compared to the original results (Figs. 6-7). The conclusions of the paper are not affected by this correction.

8. ***There are three volcanic eruptions indicated on Figure 5 but, in the discussion in Section 3.3 and Section 4, the SAD associated with the Mt. Agung eruption is ignored. The abstract mentions two major eruptions (El Chichón and Mt. Pinatubo) while the discussion of Figure 1 also mention two, but not the same (Agung and Mt. Pinatubo).***

   We have addressed this point, by mentioning the impact of the eruption of Agung on the solar cycle analysis in several parts of the manuscript. We have also marked this eruption in red in all window-sensitivity panels, as e.g., in Fig. R9. As it was shown in the manuscript in Fig. 1, the impact of the Agung eruption in the tropical lower stratospheric region is smaller than in the case of the Mt. Pinatubo eruption, but stronger than during El Chichón. However, since the Agung eruption (1963) occured during the minimum phase of solar cycle 19, the contribution to the apparent solar signal in temperature is of opposite sign than in the case of Mt. Pinatubo and El Chichón. In the context of linear regression analysis, the warming caused by the Agung eruption would be assigned as a solar-induced cooling. This effect can be partly seen at 50 hPa (Fig. R9d), where a sudden decrease in the temperature signal is found in coincidence with the Agung eruption. The fluctuation in the solar signal is much smaller than in the years of the El Chichón and Mt. Pinatubo eruptions. This is presumably due to the wider extension of the data window.

Response to Anonymous Referee #2:

1. ***The number of "not shown" is overwhelming. For some cases (e.g., when the authors discuss the difference between standard and new MLR) it is not possible to follow the discussion. I suggest adding more figures or changing the text to avoid it.***

   Please see the specific comment #1 to Reviewer #1.

2. ***I do not completely understand the physical meaning of the introduced time lag. I understand that the time lag is chosen on the basis of maximum correlation, but I have difficulties trying to understand what kind of physical processes can lead to 1 year time lag between UV and temperature response in the lower tropical stratosphere. It would be nice if the authors discuss not only statistics but also some physical processes.***

   To date, there is no well established mechanism for the solar response in the lower layers of the atmosphere, including the tropical lower stratosphere (*Gray et al.*, 2010), making it difficult to identify a mechanism for the lag. One candidate is the modulation of the Polar Night Jet (PNJ) in the polar stratosphere (*Kodera* *and Kuroda*, 2002). Given that this mechanism is mainly operative during the winter of each hemisphere, its effects in the tropical lower stratosphere will be expected to be seasonally dependent. Given that (i) the PNJ response to the solar cycle is correctly captured by WACCM (*Chiodo et al.*, 2012), and that (ii) the timescales for the downward propagation are consistent with the lags found in Fig. R7 in the middle and lower stratosphere (30-100 hPa), it is plausible that this mechanism is responsible for part of the lagged response in the tropical lower stratosphere. *Kodera and Kuroda* (2002) showed that solar-induced zonal wind anomalies originate at stratopause levels in October, and propagate to the lower stratosphere during boreal winter months, which also occurs in WACCM (*Chiodo et al.*, 2012). According to this mechanism, warm anomalies would appear in the tropical stratosphere due to the weakening in the Brewer-Dobson circulation, which is in turn related to the winter solar response in each hemisphere. These anomalies would be lagged by approximately 0.25-0.75 years (or 1-3 seasons) with respect to warm anomalies in the upper stratospheric levels, as it is shown in Fig R7 for WACCM.

A discussion of the physical mechanism behind the lagged solar response in temperature has been included in the revised manuscript.

3. ***Figure 1 shows the simulated tropical temperature anomalies at 50 hPa. It is interesting that the response to Pinatubo is more than 6 K, which is two-three times higher than in the observations and in the results of many other CCMs. Maybe the conclusion of the paper about absence of the temperature response in LTS to solar variability in the run w/o volcanic aerosol can be simply explained by the high (low) model sensitivity to volcanic eruptions (solar UV) and this conclusion is not hold for other CCMs. It should be discussed because it can undermine the importance of the obtained results for the community.***

Figure 1 showed an isolated peak of 5.5 K shortly after Pinatubo, which represents the SON-mean 1991 anomaly. Subsequently, the anomaly quickly decays to 4 K in 1992. This would make up a 4-4.5 K annual mean anomaly for 1992, whereas RICH radiosonde data show a 2 K anomaly (see Fig. R8). We note that WACCM is not the only model that produces a higher anomaly than the RICH estimate. This may be related to the SAD file recommended for use in the CCM-Val2 simulations. In any case, this bias may partly contribute to the misattribution of quasi decadal variability in the TLS in WACCM. However, we should also note that the observed response is a derived quantity with its own uncertainties.

To test whether the volcanic aliasing depends on the size of the underlying volcanic signature, we investigated the sensitivity of the solar signal to data windowing in MERRA data, which is displayed in Fig. R10 for the 26 years window (1979-2004). It is evident that the solar signals at 30, 50 and 70 hPa in Figs. R10c-e peak when the post-Pinatubo years are included in the analysis, similar to what occurs in WACCM simulations (Figs. R9c-e).

Moreover, as seen in Fig. 9 in the manuscript, the apparent signal in MERRA is strongly reduced when the two years after El Chichón and Pinatubo eruptions (1983-1984, 1992-1993) are excluded from the analysis. Accordingly, while the excessive volcanic heating may partly contribute to the aliasing of solar and volcanic signals in WACCM data, the potential misattribution of volcanic aerosols in regression analysis is not an artifact of WACCM data, since a similar behavior is found in MERRA reanalysis. Hence, the major conclusion concerning the potential of volcanic aliasing in the quasi-decadal variability of the TLS also holds for datasets with a more realistic volcanic signature. In the revised manuscript, we discuss the caveat of the oversized volcanic heating in WACCM. Due to the important implications for the analysis of observational data, we also include Fig. R10 displaying the window-sensitivity for MERRA data.

We disagree on the argued low model sensitivity to UV, since the model response to the UV in the upper levels (1 hPa) is significant in all simulation sets, including the “noVOLC” case (see Fig. R5). The temperature response in the upper tropical stratosphere is produced by absorption of UV radiation by ozone. Moreover, the additional ozone formed after recombination of photolyzed molecular oxygen contributes to the warming (*Pap and Fox*, 2003). The temperature change at 1 hPa is a good proxy for the model sensitivity to UV forcing, since it is the result of adjustment to the heating rates produced by radiation and photolysis codes. As displayed in Fig. R9a, the temperature increase of 0.8 $\pm$ 0.3 K estimated in the “all forcings” set in the 1979-2004 window is in agreement with estimates calculated at the same pressure level by using the same analysis technique from MERRA. This suggests that the model sensitivity to UV variability is realistic.

4. ***I do not understand also the difference in the ozone and temperature response in the “all forcing” and “no volcanic aerosol” runs. The volcanic eruptions lead to warming and ozone decrease in TLS. If a part of the warming appears in the solar UV coefficients as a result of MLR analysis, then a part of the ozone depletion should do the same. However, it is not what we see in Figure 7. Do the authors have some explanations for this result?***

   We understand the reviewer’s concern in the lack of a physical meaning, provided that volcanoes, on average, lead to heating and ozone reduction throughout the TLS. In such case, the volcanic aliasing in ozone, defined as the [“all forcings”]-[“noVOLC”] difference in β'_{uv}, should have negative sign in this region. As shown in Fig. R11, the volcanic aliasing is positive between 40-100 hPa, although there is switch to negative values between 10-30 hPa.

   In order to investigate the vertical dependence of the aliasing, we present an analysis of the the volcanic signal in zonal mean ozone in Fig. R12. The output from our new technique, defined as β'_{volc} , has been scaled with the mean average variation of 1 unity in the SAD index. It is shown that the ozone decrease due to volcanic aerosols, if averaged over the eruptions that occurred in the 1960-2004 period (i.e., Agung, El-Chichón, and Mt. Pinatubo), is only significant between 20-30 hPa. Hence, a volcanic aliasing of negative sign in the ozone solar signal should be expected at 20-30 hPa, rather than at lower levels. This is partly seen in Fig. R11, although this effect is very small. The strongest ozone depletion is simulated after the Mt. Pinatubo eruption, with a 5% decrease, which agrees well with observations (*Robock*, 2000). Interestingly, the ozone response to Mt. Pinatubo is positive in the 50-100 hPa region, although this feature is not statistically significant.

Note that quantifying an average ozone response to volcanic eruptions is challenging, since the impacts of each eruption on the ozone layer can be strikingly different (*Robock*, 2000). Hence, given the fact that volcanic eruptions do not always lead to ozone depletion throughout the tropical stratosphere, a volcanic aliasing of negative sign in the ozone solar signal should not be expected.

Also, please note that we do not necessarily expect any physically-based coherence in the sign of the volcanic aliasing, since temperature and ozone are not fitted simultaneously. Depending on the relative strength of the response in ozone and temperature to solar and volcanic forcing, the MLR may apportion the signal differently between the various terms.

The revised manuscript contains a more thorough discussion of the sign of the volcanic aliasing in temperature and ozone.

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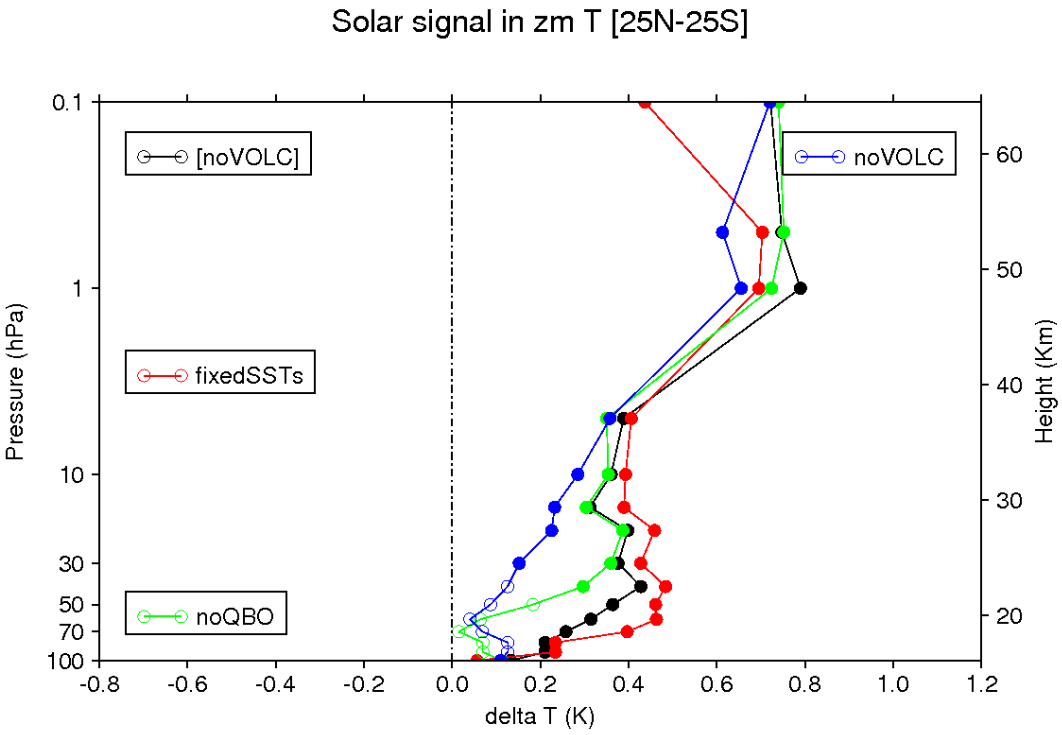

Fig. R1. Solar signal in tropical mean (25°N-25°S) zonal mean temperature, estimated as the UV regression coefficient from a standard MLR analysis (Eq.A1), multiplied by 2 sigma of the UV index

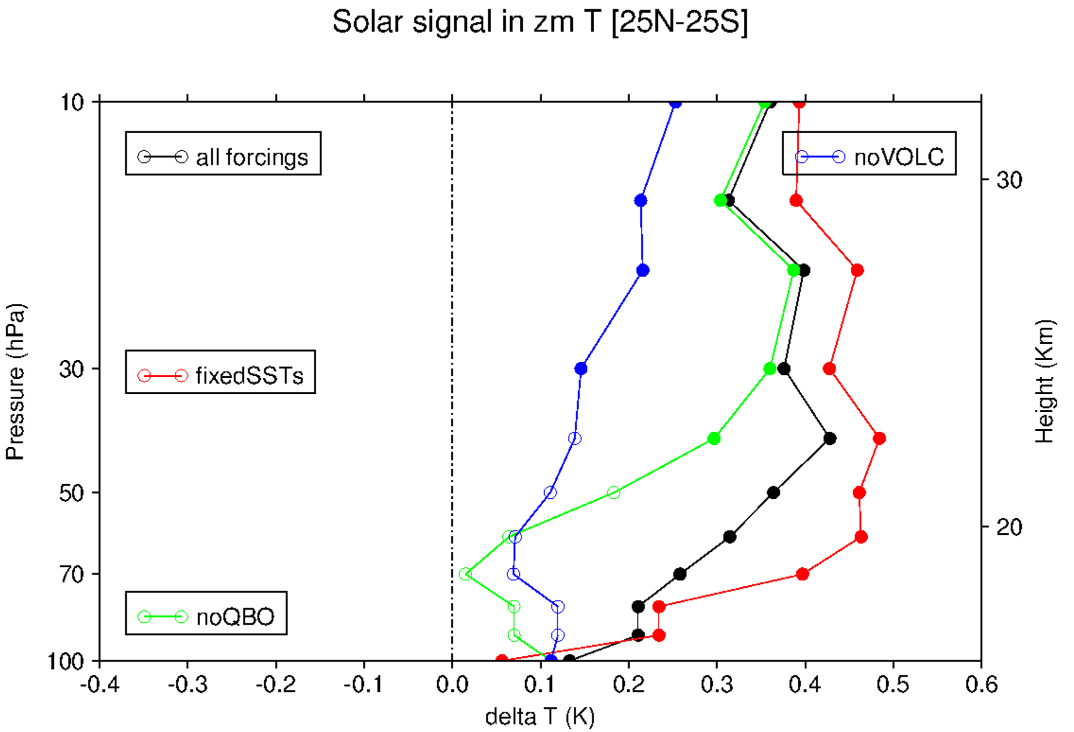

Fig. R2. Highlight of the 10-100 hPa region of Fig. R1

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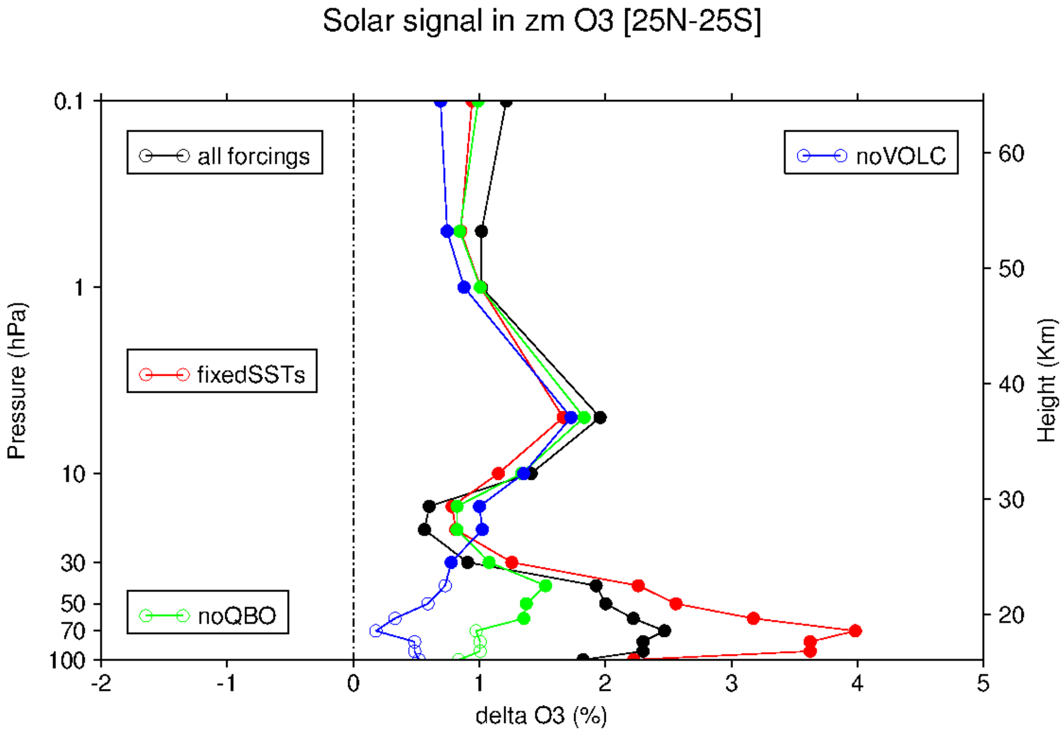

Fig. R3. As in Fig∼R1, for tropical mean zonal mean ozone. Delta % units denote the relative solar cycle peak to trough change in %.

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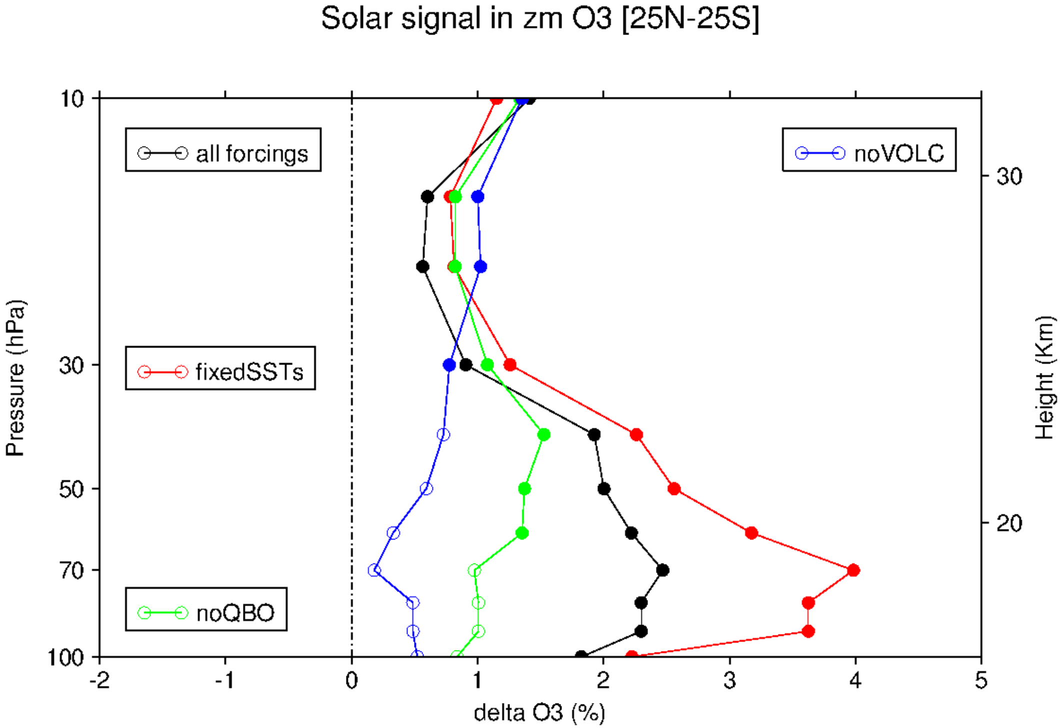

Fig. R4. Highlight of the 10-100 hPa region of Fig. R3

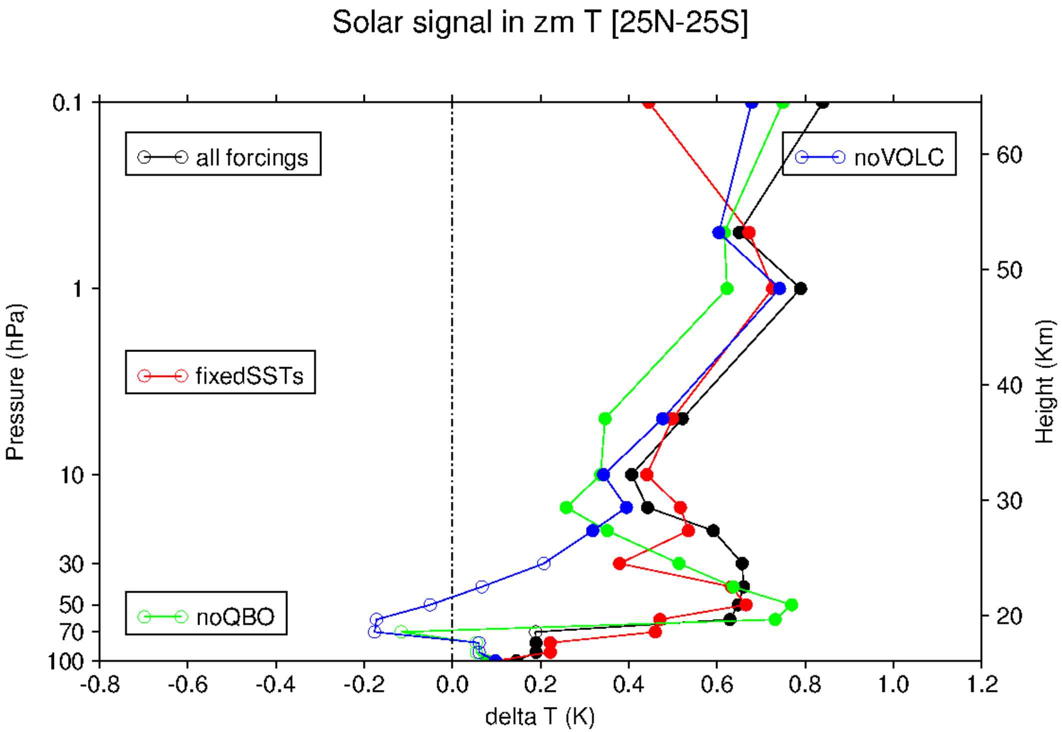

Fig. R5. Solar signal in tropical average zonal mean temperature, estimated as the UV regression coefficient from the new regression technique (Eq.A6), multiplied by 2 sigma of the UV index.

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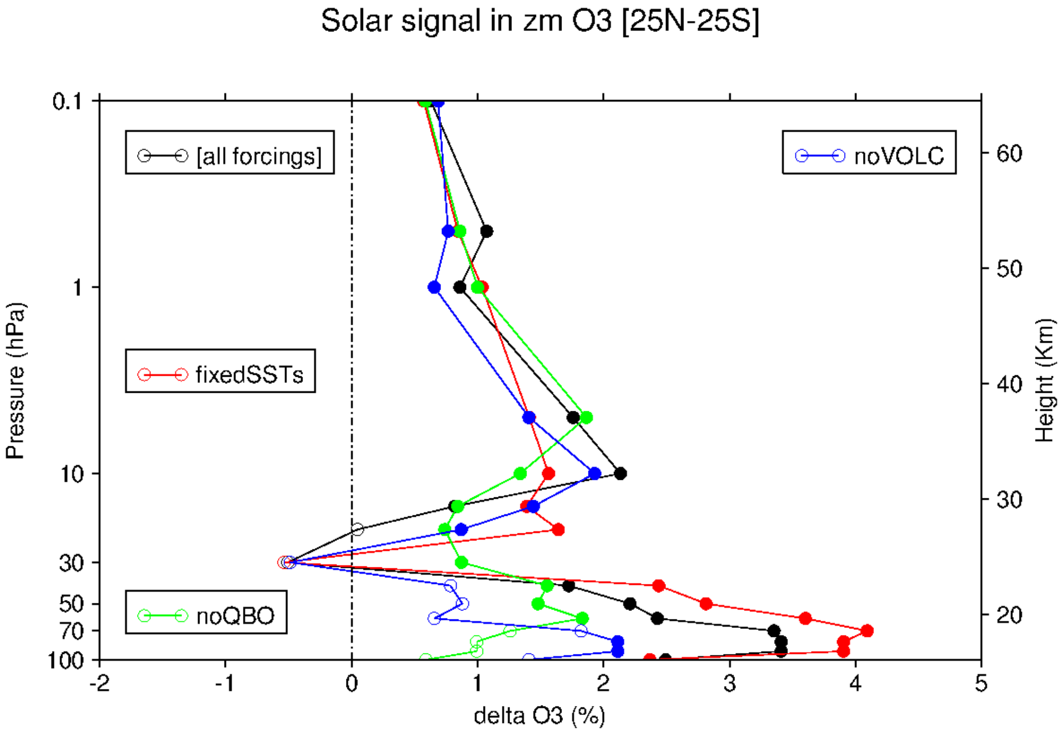

Fig. R6. As in Fig. R5, for zonal mean ozone. Delta % units denote the relative solar cycle peak to trough change in %.

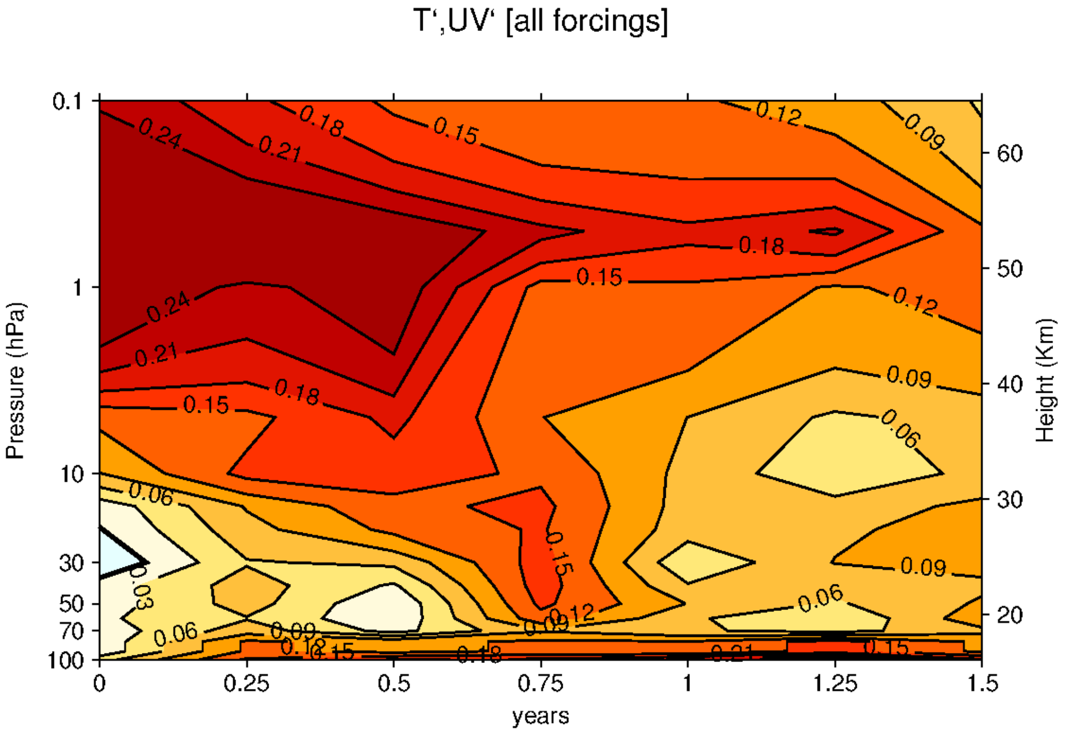

Fig. R7. Lag correlation between the tropical average prewhitened seasonal mean temperature from the “all forcings” case, and the UV radition index in the 0-1.5 year window.

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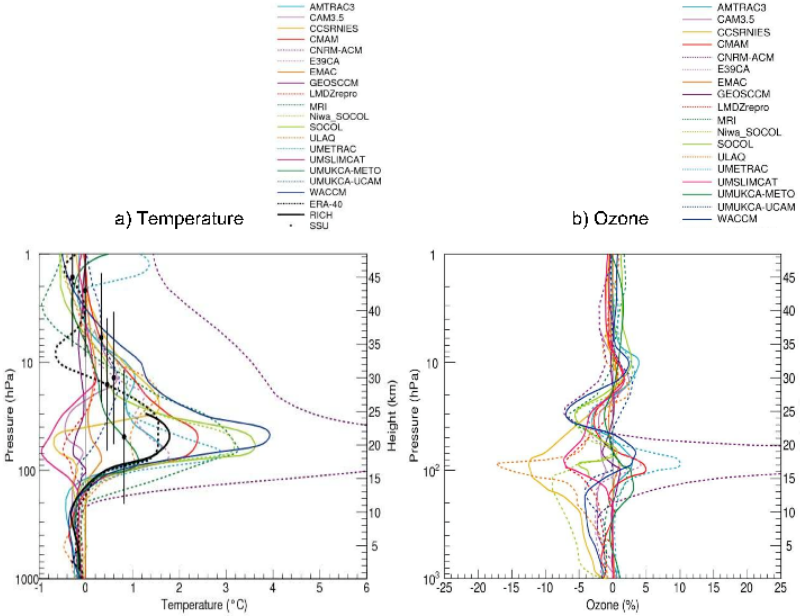

Figure 8.21: Annual mean tropical (25S-25N) contribution from the volcanic basis function from CCMVal-2 CCMs (1960-2004) and observations for Pinatubo (averaged over 24 months after the eruption) from 1000 to 1 hPa. (a) temperature in K; (ERA40, SSU and RICH), (b) ozone in %, no observations are shown due to large uncertainties.

Fig. R8. Figure reproduced from CCMVal (2010)

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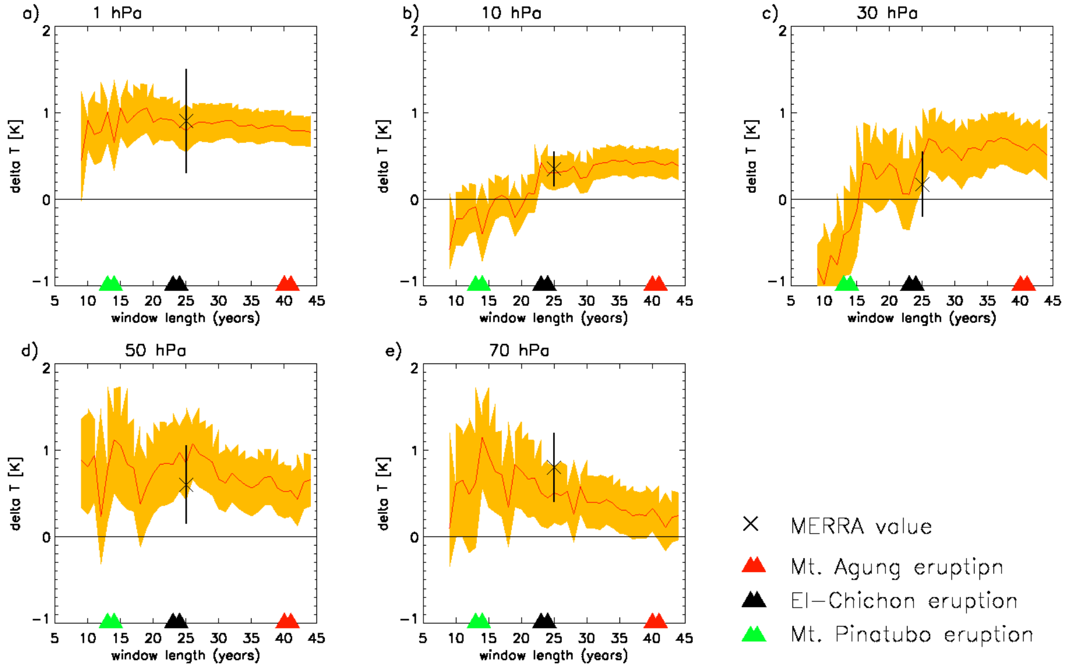

Fig. R9. Solar signal (UV coeff in Eq.A6) in tropical average zonal mean temperature (red line) along with the 2 sigma uncertainty (yellow shading) from the "all forcings" case, as function of the window.

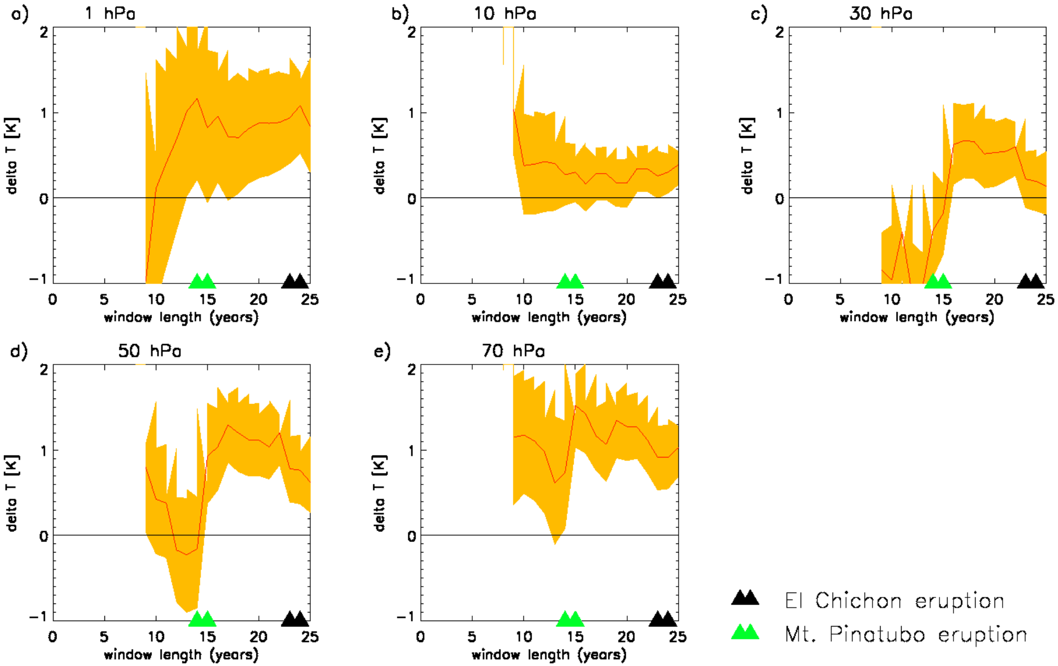

Fig. R10. Solar signal in tropical average zonal mean temperature from MERRA reanalysis,displayed as a function of the window used(in years). The signal is the UV coeff in Eq.A6, scaled by 0.175

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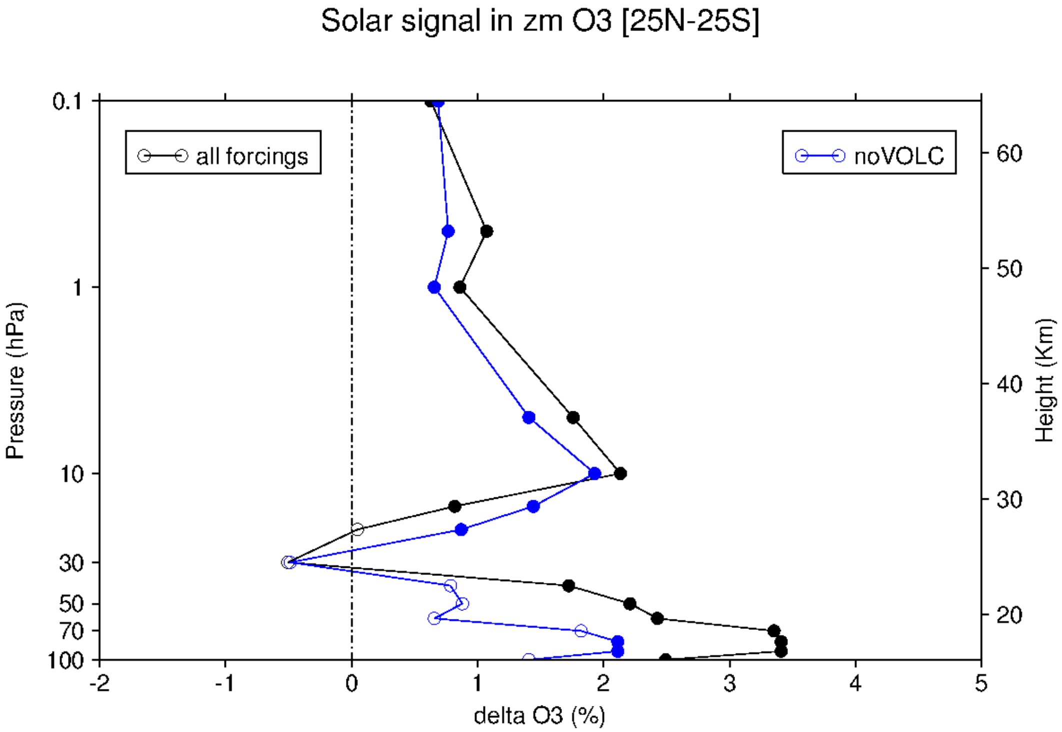

Fig. R11. Solar signal in tropical average zonal mean ozone, for the “all forcings” and “noVOLC” ensembles. Delta % units denote the relative solar cycle peak to trough change in %

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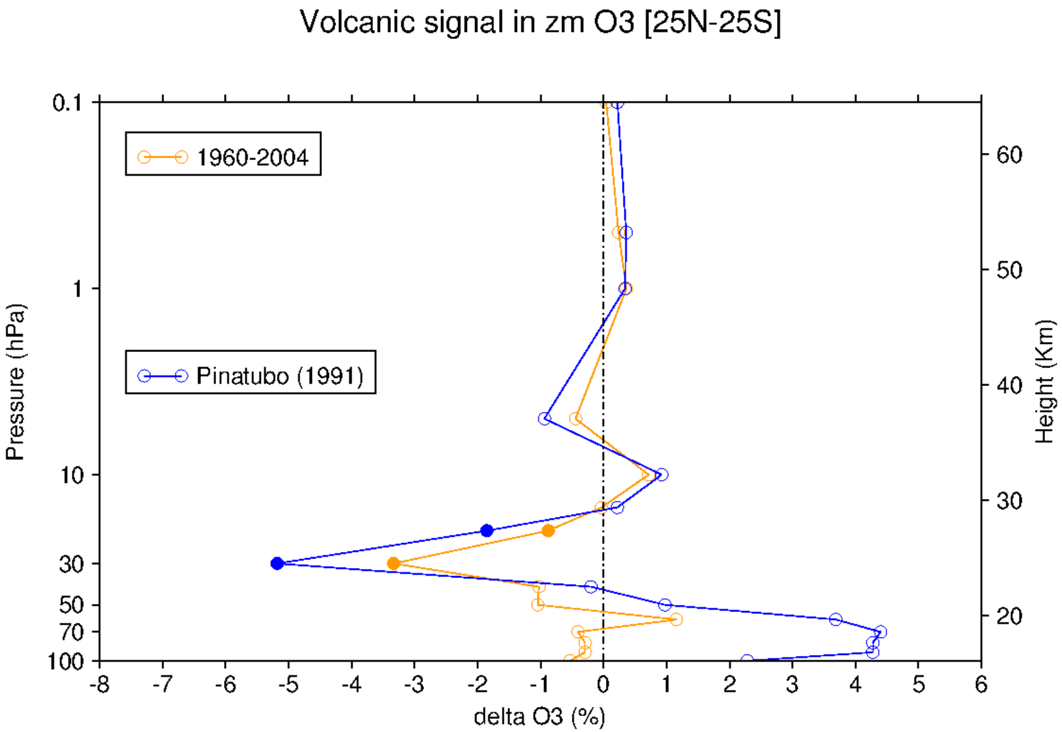

Fig. R12. Volcanic signal in ozone, shown as SAD regression coeff in Eq.A6. The Pinatubo response is the SAD regr coeff in the 1985-2004 window, scaled by 2, the annual mean value of the SAD index in 1992.