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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The influence of mixing on stratospheric circulation changes in the 21st century" *by* Roland Eichinger et al.

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Dear anonymous referee #2,

thank you for investing time and effort to review the paper.

Please find below our point by point answers to your comments.

Best regards

Roland Eichinger, Simone Dietmüller and Hella Garny

The paper presents an analysis of the trends in the Brewer-Dobson circulation in 10 chemistry-climate models of CCMI-1. The contributions of residual circulation and mixing to the changes in AoA are separated by computing RCTT, A_mix, and mixing efficiency for each model. It is found that in most models the mixing efficiency decreases throughout the 21st century, and this explains about 10% of the AoA changes. It is shown that different evolutions of mixing efficiency can partly explain the spread in the AoA model trends. Finally, it is argued that the decrease in mixing efficiency can be attributed to changes in the PV gradient, which increases due to stronger stratospheric westerly jets in the future. The paper is very well suited for ACP and the CCMI special issue, provides novel results which make advances in understanding the future trends in the BDC and the role of mixing in predicting the future evolution of stratospheric circulation. I do not have major comments on the content, but the paper would benefit from some work on the writing to clarify and simplify the message (especially in sections 3.2 and 3.3). I recommend publication after the following suggestions to improve the writing are addressed.

Thanks, we appreciate your efforts providing suggestions to improve the paper. We have taken them into account and additionally corrected some more errors. Please see below and also the marked-up "diff" file that will be attached to the final resonse.

P1 L5 and P23 L9: could you provide a rough number to quantify the model spread in AoA trends? (also in the conclusions, on P23 L9)

$\sigma(\Delta AoA) = 0.18$ for $\mu(\Delta AoA) = 0.54$
We included this in the results and in the conclusions section, but, for the sake of readability, refrained from including it in the abstract.

P3 L31-32: It is not clear what is the difference with the previous sentence.

The difference is that one tackles climatologies, one differences between two climate states. This is now more clear, the sentences now read:

In the companion paper, Dietmueller et al. (2018) have already shown that the mixing efficiency can explain most of the AoA model spread in the climatologies from 1960 to 2010. In the present study, we quantify the impact of mixing efficiency (relative mixing strength) differences between two climate states in the individual model simulations.

P6 L20-21: I do not understand why a term is needed to correct for the altitude dependence of the vertical residual circulation, when w* is already expressed as a function of z in Eq. (1). Perhaps you could briefly explain this?

That is basically just the analytical solution of the TLP equation for an altitude-dependent w*. The term comes from the horizontal advection between z and z_T, so $M(z)w(z) - M(z_T)w(z_T)$.... However, as this is not really descriptive as an explanation, we will simply add:

(additional analytical solution term from horizontal advection, for details see Neu and Plumb (1999) and Garny (2014))

P6 L18: Is alpha a function of z? If so, it should be reflected in Eq. (1).

Done.

P6 L29: Did you use wstar provided by the models or compute it from vstar?

For consistency between the models, we also used v* here. We added this to the text. Please also refer to the Supplement of the companion paper Dietmüller et al. (2018) for this topic.

P6 L30: The tropical profiles provided for the TLP model: profiles of what variables?

$\overline{w}^*$, tropopause height and AoA. Included in the text now.

P7 L1: obtained by a best fit: of the TLP parameters to the model's age of air? (specify what is fitted)

Only epsilon is fitted. AoA and w* are the input and one calculates a best fit of these profiles for the TLP equations via the optimization. We have changed the sentece to read:

The mixing efficiency is then obtained by the TLP model's best fit to the CCM AoA profile. Here, the best fit is done for the altitude range from the tropopause to [32]km (details for the calculation of the mixing efficiency are given in Garny et al. (2014)).

P7 L32 – P8 L2: Remove this sentence, already mentioned before.

Done.

Figure 2: Perhaps it is worth mentioning that the observations have a much larger spread than the models' variability.

This is indeed an interesting detail, but we do not want to include it here. This is already the first step into the analysis of the observations in comparison with models. Other studies have done it before and this would open up a can of worms which we intended to leave closed as for this paper.

P9 L13-14: (as both ...) : this cannot be concluded from those papers

We have restructured the sentence to separate clearly which statement refers to the citations and which does not, it now reads:

Several studies (citations) have recently pointed out the importance of the role of ODSs for the trends in stratospheric dynamics. ODSs act as both, radiatively active greenhouse gases and chemically active gases controlling ozone depletion and recovery.

P10 L3-4: This separates ... : Not really separates, but you can argue that, based on the sensitivity experiments in Polvani et al. 2018 GRL showing that the change in the slope is due to ODS, one can capture the GHG effect alone by considering the net trends from 1970-2100.

Thanks, that is helpful. We changed the sentence to:

Based on the sensitivity simulations in Polvani et al. (2018), which shows that the change in the slope in the year 2000 is due to ODSs, this allows to capture the GHG effect alone.

P12 L11: GEOSCCM does not belong to this group in my opinion, it is more similar to SOCOL and WACCM. Also, NIWA and ACCESS are very similar.

Right! Thanks for checking carefully. The groups are now

(EMACL47, EMACL90, GEOSCCM, SOCOLv3)

and

(GEOSCCM, ACCESS, NIWA-UKCA, WACCM)

P12 L16: 'slightly positive': remind here that this means values of the ratio above 1.

Added:

(i.e. $\Delta AoA/\Delta RCTT>1$)

Figure 4b: over which latitude band do you average w* at 70 hPa?

Over the individual turn-around latitudes. We included that in the caption now.

P13 L14: '10 year moving average': this averaging is not mentioned in Section 2.2.

We included the sentence:

For analysis, we calculate the ten year running averages of ϵ to obtain climatologically representative values.

P14 L3-4: in MRI and EMAC-L90 the trends are near zero in the first period, the only model that shows a clear increase in epsilon in the first period is ULAQ. Figures 4 and 6: These correlations are based on ten points (one for each model). It would be interesting to see, perhaps not for the paper, what do the correlations look like for one single model on interannual variability. Do they show similar features?

Corrected, the paragraph now reads:

For example in MRI and in EMAC-L90, ϵ first is almost constant and then it decreases and in GEOSCCM and CMAM, ϵ first decreases and in the later period it rises. Only the ULAQ model shows a positive trend in both periods.

P16 L4: it would be clearer for the reader if the intermediate step $AOA'(2100) = A\_mix(1970) + RCTT(2100)$ were included.

Done.

P17 L9-13: This description of Table 3 is confusing. The sign of the fractional impact of mixing efficiency on AoA changes is negative for three models. It seems to me that this should be the first thing mentioned and explained clearly. The models in which this contribution is negative are the same only three models for which $\Delta\epsilon$ is positive. So in these models the mixing efficiency is increasing over time, and that is why they make an opposite contribution to AoA trends. Is this correct?

Thanks for pointing this out. To make the point more prominent, we have restructured the paragraph, it now reads:

NIWA-UKCA, ACCESS and ULAQ show a negative fractional impact of mixing efficiency on AoA changes. These are the three models that also show a positive $\Delta\epsilon$ (see Tab. 2). In contrast to the other models, the mixing efficiency therefore leads to an AoA increase over time. The negative ΔRCTT therefore accounts for more than the entire negative ΔAoA to compensate the effect of the ϵ change. With less than 5.5% and 3.5%, NIWA-UKCA and ACCESS have the lowest contribution of $\Delta\epsilon$ on the AoA change and with up to 29%, ULAQ and EMAC-L90 have the largest.

P18 L7-8: However, it is not strictly coincidental ... I do not understand this sentence.

Removed and rewritten, the part now reads:

The model range decreases here because being the model with the largest ΔAoA, EMAC-L90 has a negative $\Delta\epsilon$ and ULAQ, the model with the lowest ΔAoA has a positive $\Delta\epsilon$. A large/small (negative) $\Delta\epsilon$ causes a large/small ΔAoA.

P23 L3: AoA decreases

Done. (Meant was L8)

Technical:

We have also corrected all technical issues the referee mentioned

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