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Interactive comment on "Modelling the residual mean meridional circulation at different stages of stratospheric warming events" *by* Andrey V. Koval et al.

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Reply to the Reviewer #2 of the paper by Koval et al. "Modelling the residual mean meridional circulation at different stages of stratospheric warming events"

We would like to thank the Anonymous Referee #2 for useful comments and suggestions. We considered all of them and added all the necessary edits to the revised manuscript. Our answers are given in the italic font below.

Question: The authors present simulations with the mechanistic model MUAM to analyse circulation changes in the middle atmosphere after SSW events. This topic is of

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general interest as SSWs have dramatic consequences on the dynamical state of the polar stratosphere with possible impact on tropospheric weather phenomena but also for the coupling of the stratosphere to the upper atmosphere. The authors perform idealistic model experiments by applying prescribed planetary wave activity and are able to excitate SSWs in their model. They analyze the change of the circulation in the middle atmosphere by means of the transformed Eulerian mean analysis and apply the residual circulation on the given ozone distribution to derive fluxes in the course of the SSW event. Whereas the topic and methodology seems to be an interesting approach, the authors miss in my opinion a deeper analysis.

Answer: We substantially extended the analysis and discussion of the results in the revised text.

Question: It is not clear for me to what extent the paper goes beyond previous studies. The authors are often very vague in their conclusions and seem not to reflect the current status of discussions in the literature.

Answer: We added discussions of previous results and comparisons with our simulations.

Question: With respect to tracer transport the authors do not use the TEM formulation for tracer transport, but only apply v* and w* to zonal mean values of their 3D ozone field, which I think is not consistent.

Answer: The reviewer is right that real motions are non-zonal and 3D. However, in theory, they are usually decomposed into the zonal-mean general circulation and non-zonal eddy components. We added Figure 1 with zonal-mean zonal velocity and Figure 4 analyzing contributions of non-zonal eddy motions. In addition, we moved from consideration of ozone fields to the discussion of the zonal-mean fluxes of atmospheric mass.

Question: In addition, their SSW seem to show no elevation of the stratosphere and

the corresponding strong downward transport in the upper mesosphere which is often observed and simulated after mid-winter SSWs. This could be related to their GW drag parameterization but this is not discussed in the paper.

Answer: We made additional analysis of temperature and zonal wind during SSWs simulated with the MUAM, which are shown in the new Figure 1. This Figure shows that the MUAM can reproduce downward shift of the stratopause during SSW, its recovering to higher altitudes after SSW and effects of elevated stratopause after intensive SSWs. These results are very similar to those obtained in simulations with the WACCM model by Chandran et al. (2013).

Question: I find the paper not publishable in its present form.

Answer: We added new results about changes of the stratopause heights, about the wave-induced eddy circulation and their connections and roles at different SSW stages, and we consider that the paper contains new information not existing in previous publications. In the revised text, we added new Figures 1 and 4 and substantially extended their discussion.

Question: More specific comments can be found in the attached pdf.

Answer: We thank the reviewer for considering the text of the manuscript in detail. We carefully, point by point, considered all the comments and questions, and added appropriate changes to the text. Below are our comments referring to the supplement file uploaded by the reviewer.

L.30 Question: I do not really understand your point here. Studies of the BDC were related to the analysis of ozone trends and their forecast.

Answer: The sentences are reformulated

L.34 Question: can you be more specific what waves you want to consider?

Answer: We consider planetary-scale waves. This is specified in the text

L 47 Question: I do not see how the process of wave excitation comes into play here.

Answer: The discussion is changed

L 58-60 Question: The dramatic role of SSWs for tracer transport is well known especially in the context of ozone depletion in the Arctic vortex. So, why are you so cautious (might alter, can be essential)?

Answer: We moved from the analysis of the ozone transport to considerations of the residual fluxes of atmospheric mass. This part was reformulated.

L 63-65 Question: You are changing the tempus several times. Please, stay with one.

Answer: Corrected

L 78 Question: ot really recent; perhaps you may use the well known term 'downward control principle'

Answer: This sentence was reformulated

L 86 Question: grammatically not consistent (parametrizations .. which are). I think you refer to the non-orographic, so be explicit. similar is very unspecific. Please detail or give reference with detailed description

Answer: Corrected, clarification was added

L 90 Question: is the setup similar to Gavrilov et al 2018?

Answer: The setup is similar to Gavrilov et al. (2019), except number of MUAM runs. Ensemble is extended from 12 to 19 SSWs. This is clarified in the text.

L95 Question: is that a special feature of the model and how does it impact the validity of your results? Savenkova is about analyses

Answer: We modified and extended description of SSW determination. In addition, we added Figure 1 with examples of the modeled SSWs.

L 106 Question: are these equations not just the definition of the TEMs?

Answer: Formulas (1) and (2) are convenient definitions of velocity components of the residual circulation

L117 Question: what is the difference to (1) and (2) besides applying some calculus?

Answer: Eq. (3) and (4) are just other forms of eq. (1) and (2), which were used in the present calculations. This part was rewritten.

L 134 Question: A quantitative comparison is not possible from Fig.1, as the contour lines have no labels.

Answer: Now Fig. 1 becomes Fig.2. A quantitative comparison is possible in its right part Fig. 2b, where the length of arrows is proportional to circulation velocity.

L 135 Question: From Fig. 1 I get the oimpression of a reltively fast BDC in the lower stratosphere compared to analyses. Could you comment on that?

Answer: Changes in troposphere and lower stratosphere can occur due to rather schematically representation of the tropospheric dynamics in the MUAM model. Clarification was added.

L 140 Question: As the model seems to be a more idealistic approach some motivation why this approach is appropriate for the problem would be helpful.

Answer: Some comments were added to the end of sect. 3

L 145 Question: ozone is quasi-inert only in the lower stratosphere!

Answer: We substantially shorten the discussion of ozone and specified that it can follow the fluxes of mass only below 30km

L 150 Question: It would be helpful if you could present also the zonal mean zonal wind up to the LT.

Answer: The zonal wind is shown in the right panels of the new Fig.1, which was added

to the paper.

L 166 Question: This is vague. Can you quantify the contribution?

Answer: We added Eq. (5) and made quantitative estimations of the rate of adiabatic heating/cooling.

L 180 Question: Please refer to the literature of the interhemispheric coupling during SSW events.

Answer: The inter-hemispheric coupling occur at altitudes above 60 km because the waveguides for planetary waves extend from the Northern to the Southern Hemisphere at high altitudes. We modified discussion and added more references.

L 186 Question: Again very, very vague. Please try to be more explicit and compare with the literature.

Answer: This part of the article was completely rewritten. Analysis was extended

L 190 Question: It is wellknown that mid-winter major warmings often produce an elevated stratopause caused by strong descent during and after the SSW event. This is not seen in your results. Can you comment on that?

Answer: We added Figure 1 showing effects of the elevated stratopause after strong SSW and added respective discussions.

L 213 – 250 Question: How meaningful are your fluxes when they do not correspond to the actual ozone distribution? Would you not better apply the TEM method to the longitude dependent ozone distribution? See Andrews, 1987.

Answer: In the revised text we moved from ozone to the consideration of residual and eddy fluxes of atmospheric mass.

Question: The tracer experiment seems to confirm that in your model the strong downward transport after midwinter SSW s is not reproduced.

Answer: New Figures 1 and 3 show that the MUAM model can reproduce downward transport after strong SSW.

Question: It is not clear for me what we can learn from that experiment.

Answer: We added Figure 4 showing wave-induced eddy circulation and considered changes of residual and eddy circulation and fluxes of atmospheric mass, their interactions and role at different SSW stages at altitudes up to 100 km, which we did not find in the literature.

L 510 Question: give some info what time period is considered, eg: during the simulated NH winter season

Answer: We added information about time period to the caption of Figure 3.

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