Reply

to the Reviewer #1 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 #1 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.

Line 50. Question: SSW, major and minor, do also occur in the Southern hemisphere, e.g., https://doi.org/10.3390/atmos11101063

Answer: In the revised text the phrase is modified as “the middle atmosphere during winter”

L. 64. Q: "studied for the first time". Further in the text, authors cite other papers on the same subject, so this work is not the first of its kind. May be the "first time with this model"?

A: The phrase is modified

L. 93. Q: How the normal modes were included? By adding additional disturbances at the lower boundary? Or they were generated by the model in response to daily variations of the solar flux?

A: The MUAM involves NM parameterization by adding terms to the heat balance equation in the troposphere, which have forms of time-dependent sinusoidal components with zonal wavenumbers m = 1 - 3. For setting the latitude structures of NM components, the parameterization uses respective Hough functions. Periods of NMs are equal to the resonant periods of atmospheric reaction to the wave forcing at low boundary (about 5, 10 for m = 1; 4, 7 days m = 2; 2 days m = 3). We added respective discussion to the revised text.

L. 95-96. Q: That is, at 50, but not 30 km? This is unclear from the text. Formulas (3) and (4). For me they look precisely equal to (1) and (2). Are they just another form of the latter, or am I missing something?

A: We modified the text. Eq. (3) and (4) are just other forms of eq. (1) and (2), which are used in our calculations.

L. 206. Q: "Increased downward ... velocities". As follows from Fig. 2b, the downward velocities between 20 and 60 km weaken during SSW. Is it a typo? L. 208. Again, if the downward velocities are weaker over high latitudes, they cannot help with heating the atmosphere.

A: In Fig. 2b2 at altitudes 20-40 km near the North Pole, one can see negative add-ons to the background downward vertical velocity shown in Fig. 3a2. This corresponds to increasing adiabatic heating of in the high-latitude stratosphere during SWs. We clarified this in the revised text.

L. 214. Q: "Parcels" rather than "particles" is more suitable word for gas elements.
A: Corrected.

L. 216. Q: "For short time intervals". Here it would be appropriate to give the characteristic chemical lifetime of ozone at these heights in comparison with 11-day intervals of interest.
A: We decided to moved from estimations of ozone transport to considerations of the residual and eddy fluxes of atmospheric mass. However, we added references showing that the photochemical lifetime of ozone exceeds 30 - 50 days below 30 km altitude, where the ozone can follow the fluxes of mass.

L. 217. Q: Specify what data the MUAM ozone model is based on.
A: We extended the MUAM description.

L. 214. Q: Is that really "monthly-mean" ozone? How good is to use monthly means for such rapid events as SSW? Or some sort of time interpolation was used?
A: We removed discussions of ozone fluxes from the revised text.

L. 245. Q: Ozone fluxes enhance the residual circulation? They just reflect it. A rewording is needed.
A: the discussion of residual and eddy mass fluxes is substantially extended and modified.

L. 248-250. Q: I would recommend to move reservations concerning the fixed ozone distribution to the beginning of the section. Readers would then understand from the beginning that this is just a rough estimate.
A: We moved from ozone to considerations of the residual fluxes of atmospheric mass in the revised text.

L. 266. Q: Aren't the fluxes decrease at this location, as Fig. 2b shows?
A: Fig. 3b2 shows negative add-ons to the residual vertical velocity at altitudes 20-50 km near the North Pole during SW. Accordingly, the downward mass fluxes are also enhancing in this region.

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 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.

Reply

to the Reviewer #3 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 #3 for useful comments and suggestions. We considered all of them and added all the necessary edits to the revised manuscript. Our answers are given below in the italic font.

Question: The authors describe a numerical study on the change of the residual mean circulation during sudden stratospheric warmings (SSW). This is in principal an interesting topic as SSW events cause important changes in the circulation for both the middle atmosphere dynamics and chemistry as well as for the troposphere.

After the presentation of an overall agreement of the MUAM model with the MERRA reanalysis, the authors go on in calculating the EP Fluxes of the Ensemble members for the RMC and the ozone fluxes during several SSW events. They find a transitional behaviour of these fluxes and in general a weakening of fluxes after such events. I think, such an analysis makes sense in general but needs to be described more carefully.

The motivation, why should one care about this, besides the usual academic curiosity? Please elaborate more on your motivation. Are there missing details in the description of the MA dynamics during SSWs where this method can improve or support the understanding?

Answer: We appreciate the reviewer for raising the helpful comments. Despite many studies, the mechanisms of SSW creation, evolution and their effects are not enough understood. In the revised text, we added discussions of variations of the stratopause height, zonal wind and eddy circulation produced by non-zonal wave motions. Combined with the analysis of the residual meridional circulation, this data allows us to analyze deeply some details of interactions of listed above characteristics at altitudes up to 100 km and their role in SSW formation, which we did not find in the literature. In addition, the residual and eddy circulation play an important role in the global transport of atmospheric tracers and conservative gas species. However, this transport is not the main goal of our paper and we concentrated on the fluxes of atmospheric mass, which are important for heat transport and adiabatic heating/cooling taking part in SSW formation and evolution.

Question: Are there important observed impacts of SSWs on the ozone distribution in the stratosphere that has not yet been understood so far? Are there dramatic changes in ozone distribution observed that need to be explained?

Answer: The ozone distribution is not the goal of our paper. We excluded ozone discussions from the paper and concentrated on considerations of the residual and eddy fluxes of atmospheric mass. These fluxes may reflect the ozone transport at altitudes below 30 km, where the ozone photochemical lifetime exceeds 1 month. We made respective modifications in the revised text.

Question: The ensemble setup, how strong is the ensemble spread, e.g. in the 10 hPa wind?

Answer: We added Figure 1 showing zonal wind for the most intensive and smallest simulated SSWs. This Figure can give information about the ensemble wind spread.

Question: Does an SW event really appear in every member for every run?

Answer: No, the ensemble of 24 model runs contains 19 runs with stratospheric warming events during simulations for January-February conditions. This clarification is added to the revised text.

Question: Comparison with reanalysis. It is a really nice result that MUAM as a mechanistic model comes so close to the MERRA reanalysis in terms of the RMC analysis. This comparison should be extended to the fluxes during SSW events as well.

Answer: Yes, such comparison is a good idea. However, obtaining a composite SSW need many individual events observed throughout several decades years and requires filtering possible climate changes during this period. This is a big job, which cannot be made within the present paper. We added references to already published RMC studies examining the reanalysis data during SSW.

Question: Conclusions: what do we learn qualitatively about this changed circulation, what effect should be taken into account in future when studying such events?

Answer: The conclusion chapter is rewritten in the revised text to better summarize the findings of the paper.

Question: Finally, this might not apply to the current manuscript, however, I noticed, that the forcing of the SPWs at the lower atmosphere in MUAM comes from a relatively old reanalysis from 1994. An update of this climatology or a change to MERRA or ERA5 or both would be desirable. It could even serve itself as a source of generating an ensemble by changing characteristics in these SPWs.

Answer: No, the old are only references describing existing reanalysis databases. The meteorological data required for preparation of background and initial data for simulations with the MUAM were taken from the UK Met Office and MERRA database for years up to 2011. We have added a clarification and new reference into the revised text.

Minor issues are:

L. 45: which ARE not compensated

// corrected

L. 51: reverseS its direction

// corrected

L. 70 ff. How many model levels has MUAM?

// 48 levels from the ground to 135 km. We added this information to the text.

L. 78 according to recent knowledge . . . this is relative as you quote papers from 1991 and 1994, which are already 30 years old.

// the rewording is made

L. 180 in Figures2c and may reflect (?)

// corrected

L. 205 which correspondS TO our results

// this part was rewritten

L. 214/215 Vertical transport . . . sentence is incomplete, please rephrase

// sentence is rephrased