

Reply to referee comment #01

We appreciate the kind words on our manuscript and thank the reviewer for the constructive comments and proposed suggestions. These helped to substantially improve the manuscript. Please note that we changed figures 1, 2, 7, 8, 10, 12 based on comments of the reviewers. We also added an appendix in which we briefly describe the idealized model setup in more detail.

We will answer to all comments of reviewer #01 below point by point. Referee comments are given in bold, answers in standard, and changes to the manuscript in italic font.

The paper is very well written, the analysis is thorough and convincing. It's one of those manuscripts that seem to anticipate the reader's questions and answer them. And I really like the photo in Fig. 2! I think that the study is suitable for publication in ACP almost as is. I only have very few, mainly technical comments.

Minor comments:

P2. L14-17. I'm confused about the terminology here. In my reading of, e.g. Birner and Bönisch 2011 and Abalos et al. 2017 the distinction between the shallow and deep branches of the Brewer-Dobson circulation is not identical with a separation between mean advection in mixing. Rather, the shallow branch transport is comprised of both two-way eddy mixing and slower advection by the residual circulation, the two largely balancing each other. The definitions of the two branches have more to do with transit times, stratospheric entry regions, etc. Am I wrong on this? It may be true that it is eddy mixing that connects the tropics with the high latitudes (as in Krause et al.) but in the region considered in the present manuscript, with latitudes south of 60N it seems the mean advection also plays a role. All this is tangential to the subject of this study and all I mean is that the terminology used here doesn't seem consistent with the literature. Also, I think that Birner and Bönisch 2011 could be cited here.

Thanks for pointing this out. Of course, the shallow branch consists not only of two-way eddy mixing but also advection by the residual circulation.

We changed the text here as follows also taking into account the comments of reviewer #2:

"The stratospheric circulation contributes with two distinct branches distinguished based on the transit time between the major entry point of air into the stratosphere, i.e., the tropical tropopause, and the extratropics. The so called deep branch, i.e., associated with long transit times affects the ExTL through the descent of old stratospheric ozone rich air into the UTLS. In contrast, the shallow branch with significantly shorter transit times introduces relatively young air from the tropical and subtropical UTLS into the extratropical UTLS (Birner and Bönisch, 2011). A recent study based on airborne measurements showed the effect of these two transport pathways on the changing abundance of carbon monoxide (CO) over the course of the Arctic winter in the ExTL (Krause et al., 2018)."

P6 L13. The description of the COSMO model could use just a little more detail. It's a regional model, right? Where do the boundary conditions come from? Also, define the acronym (I believe, Consortium for Small-scale

Modeling)

We initially kept this description brief, because it is a repetition of Kunkel et al. (2014, 2016) and we wanted only to provide the most necessary details to follow the discussion later in the manuscript. However, since both reviewers ask for more details, we extended the description of the COSMO model setup in the revised version and added more details to the new Appendix A.

P16 L15. I think it should be stated explicitly what this classical meaning is. This comes up again below in Section 3.3.

At this point the classical meaning of TST is exactly what the reviewer suggests in the next comment, i.e., an air parcel irreversibly crossing the tropopause from the troposphere into the stratosphere (as indicated by changing PV). However, although we think that our measurements show that air parcels from the troposphere must have entered the stratosphere, the trajectories are not that clear. In our trajectory analysis we do not find a coherent ensemble of trajectories entering the stratosphere just once and then staying there. We rather find trajectories coming from the troposphere, thus carrying a tropospheric chemical signature, which cross the tropopause multiple times. Note, that Wernli and Bourqui (2002, their Figure 1) introduced a residence time criterion which accounts for such multiple changes. The question remains whether this back and forth is something that happens as such in nature or whether this is potentially indicative for a gradual transition between the troposphere and stratosphere. Another option is of course that this behavior is rather an artifact due to the inability of the model to represent this situation entirely correct. For further clarification we rephrase this paragraph as follows:

“Thus, for further discussion we rather omit the terminology of TST and STT trajectories in a sense of coherent ensembles of trajectories which cross the tropopause only once from the troposphere (stratosphere) to the stratosphere (troposphere) (Wernli and Davies, 1997; Stohl et al., 2003). We rather think of trajectories which show the potential of mixing around the tropopause by encountering low Richardson numbers and having PV values changing between tropospheric and stratospheric values, nevertheless leading to a subsequent exchange across the tropopause.”

P19. L14-17. Again, I'm confused about the “classical” STE and how it's opposed to what we have here. Isn't “an air parcel crossing the dynamic tropopause” the one and only meaning of TST? Does this sentence simply mean to say that we can't tell, based on the trajectory analysis, whether a STE event has occurred or not but the analysis provides evidence that it has? Maybe it's just a matter of defining things more clearly. Also, I would say “classical sense” instead of “classical meaning”; just a preference.

Here and according to the comments above we change parts of the paragraph to:

“However, based on the trajectory analysis it is difficult to estimate whether STE and in particular TST occurs in a way that air parcels cross the dynamic tropopause

only once from the troposphere into the stratosphere and stay there afterwards. We also performed longer trajectory calculations which, however, also provide no further evidence of TST trajectories which then stay in the stratosphere. We rather find trajectories which, based on PV, alternate back and forth between troposphere and stratosphere and which encounter low Richardson numbers along their paths. One potential reason why no TST trajectories are found which stay in the stratosphere is that the model fails to correctly resolve the process. “

Technical corrections

P4 L11. The acronym ‘TIL’ is introduced here but later “tropopause inversion layer” it is almost always spelled out throughout the paper. It should just be “TIL” from now on.

We changed tropopause inversion layer to TIL on the following pages.

P3 L17. “All processes which lead to cross tropopause transport of air parcels have one common impact on this air parcel,” There’s something grammatically wrong with this sentence

We changed this sentence to:

“An air parcel crossing the tropopause has to be affected by processes which can modify its potential vorticity (Hoskins et al., 1985). Only then the air parcel can enter from a region with generally low PV, i.e., the troposphere, into a region of high PV, i.e., the stratosphere or vice versa.”

P4 L14 initial → initially

Changed as suggested.

P6 L4. forecast →forecasts

Changed as suggest.

P7 L13, “in this study we use the 2 pvu isosurface as dynamic tropopause” this was already stated in the first paragraph of section 2.3. I suggest deleting this sentence.

We deleted this sentence.

P9 L5. “(Figures 1c,d)” Should it be 1c,e?

Correct. However, since we modified Figure 1, this part refers now to Figures 1b,c.

P10 L14-L16 This sentence a little awkward. It talks about crossing the tropopause above the tropopause, which doesn’t make sense to me!

We changed this sentence to:

“At FL 380 HALO was initially flying in the lowermost stratosphere, then gradually approaching and finally crossing the dynamic tropopause which was slightly tilted according to the ECMWF analysis (Figure 3a).“

Fig 3a caption. Richardson number contour is not mentioned in the caption.

We added the description to the caption.

P10 L33. “defincies” → deficiencies(?)

Correct. We changed it accordingly.

P12 L5. “seek for” → seek (or search for)

Correct. We changed it accordingly.

Figure 4 Caption. I think the symbols Q M and Q should be swapped. Also, lrt1 (first lapse rate tropopause) is not described in the caption or discussed in the text.

Thanks for pointing this out. We corrected the symbols and we included the description of lrt1 to the figure caption. In the text it is now also referred to the lrt1. We also note that we kept the lrt1 because in this figure it nicely shows how close the lrt1 and dynamic tropopause are in this case.

P20 L9. 240.000. I think you want a comma there: 240,000

True. Changed it accordingly.

P20 L13. Propability → probability.

Correct. We changed it accordingly.

P23 L 10 passoing → passing

Correct. We changed it accordingly.

References:

Wernli, H. and Bourqui, M.: A Lagrangian “1-year climatology” of (deep) cross-tropopause exchange in the extratropical Northern Hemisphere, *J. Geophys. Res.*, 107(D2), 4021, doi:10.1029/2001JD000812, 2002.