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Interactive Comment

Interactive comment on "Contribution of mixing to the upward transport across the TTL" *by* P. Konopka et al.

P. Konopka et al.

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Response to reviewer 2

We would like to thank the reviewer for a very thoughtful and detailed review of our manuscript. In the following we address, the major points raised in the review.

1. *"Figure 7 is incorrectly referred, splitting should be omitted..."*
   The figures 3, 5, and 7 were split (each panel of these figures as a separate figure) in order to avoid too small figures in the print version of the ACPD version of this manuscript. The consequence was that some of the links to these figures in the text were not correctly set. In the revised version of the manuscript we will certainly correct this error problem.

2. *The arrow in Fig 3a points to a point that does not lie within the ITCZ...*
   This point was also criticized by reviewer 1 who believes that the example denoted by the black arrow (Figs. 3a and 5a) is probably due to the warm conveyor belt rather than due to a MCS. We plan to look more into the details of this example even if a significantly increased density of high clouds can be seen in the GOES satellite data in the region denoted by the black arrow (not shown in the paper).

   However, over south Brazil and north Argentina, strong convection was reported by the Brazilian met. office for the same day (a MCS that also manifests in enhanced ECMWF 2̋O even if this structure is not so pronounced as the signature denoted by the black arrow). We plan to discuss this point more carefully, in particular motivated by the additional recommendation of the reviewer 3 to demonstrate more explicitely how shear-induced mixing in the outflow region of large-scale convection contributes to an uplift of the air masses. Here we plan to add an additional figure to the manuscript discussing the impact of convection on vertical mixing and on the observed tracer distributions on February, 8, 2005.

3. *“spatial distribution of the vertical velocities in the vicinity of convective cells, how $\dot{\zeta}$ is validated ?"*
   We agree with the reviewer that the convection represented in the analyzed vertical winds can only be understood as the mean vertical motion averaged over the ECMWF grid box smearing out the “real" up- and downdrafts within a convective cell. We will include this point into the revised version.

   We also agree that our “validation" of $\dot{\zeta}$ in the tropics is incomplete. By comparing the vertical displacements of trajectories with, to some extent, independent ECMWF-H_2O fields in Fig. 3 we only show that a good correlation between these field indicates some consistency between $\dot{\zeta}$ and ECMWF-H_2O distributions. Independent validation of $\dot{\zeta}$ in the TTL would require a Lagrangian tracer experiment with subsequent trajectory calculations (analog to the Match technique) even if

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for such an idealized case mixing cannot be completely switched off.

4. *"why* $\eta = p/p_0$ *rather than* $\eta = p/p_{surf} = \sigma$ *?"*
The use of the pressure-like coordinate below the tropopause ($\eta = p/p_0$ instead of $\eta = p/p_{surf}$ (i.e. terrain following, the so-called η-coordinates) is motivated solely by the simpleness of this coordinate. We use the ECMWF analyzed fields on pressure levels (even if these fields were originally determined in $\eta-$coordinates) and calculate with the radiation module (that works only on pressure and not η-coordinates) the radiative heating/cooling rates $\dot{T}$ and $\dot{\theta}$. The calculated values of $\dot{\theta}$ are used in eq. (4) for the calculation of $\dot{\zeta}$. In the Eulerian models, the use of the η-coordinate allows to define a compact, terrain following surface as the lower boundary of the model on which boundary conditions can be formulated.

In a Lagrangian approach and in particular within the framework of the CLaMS hybrid ζ coordinate, we define the boundary conditions within a layer $\Delta\zeta$ following the orography (defined by the highest levels with missing values in ECMWF pressure). Here, the mixing ratios of the air parcels are redefined according to prescribed boundary conditions (every 24 hours). Other tropospheric CLaMS layers can intersect this terrain following layer. If the ECMWF velocities are correct, the trajectories of the air parcels should overcome all possible orographic obstacles. But it is not a problem for the CLaMS model if an air parcel would "crash" with an orographic obstacle. In such a case this air parcel will be removed from the model domain. The mixing algorithm creates a new one by filling the resulting hole. The mixing ratio of this air parcel is interpolated from the next available neighbors.

Thus, in contrast to the Eulerian approach, it is not necessary to have a single, terrain-following surface as the lowest boundary of the model. Nevertheless, some studies comparing the positions of trajectories calculated in $\eta-$coordinates (FLEXPART) with the corresponding positions in p-coordinates (LAGRANTO)

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show some advantages of using the terrain following coordinates (mainly due to an improved interpolation technique in $\eta-$ coordinates Stohl2001).

In summary, while our method might possible cause problems in a simulation of mixing ratios in the boundary layer, it will have no impact on the CLaMS simulations of the TTL.

5. *“vertical discretization based on (total) entropy has the undesirable property to modulate the vertical mixing per event..."*
Here, we have to contradict. This is one of the main *desirable* properties of our choice of the vertical discretization. Note that according to our choice, the vertical grid with the thinnest layer can be found around the tropical tropopause. This implies also the lowest vertical diffusivity per mixing event within this layer and that this diffusivity increases both above and below this level (red line on the right side of Fig. 2). The upward increase by about a factor of 10 near 30 km is in a qualitative agreement with the expected relative increase of the vertical diffusivity as derived from the investigations of the age of air and of (one-dimensional) eddy diffusion coefficients Ehhalt2004

   Furthermore, the mixing-driven vertical transport across the TTL occurs in spite of the fact that the mixing intensity per interpolation event in the TTL is the smallest! We believe that this property supports our main hypothesis on the relevance of mixing for the vertical transport.

6. *“cooling layer near $\zeta = 350$ K"*
This cooling layer is the consequence of our calculation of $\dot{\zeta}$ based on clear-sky radiation derived from the Morcrette scheme. Thus, as shown in many papers on this topic (see e.g. [Gettelman et al.(2004)]), the $Q = 0$ level can be found around 360 K. Below this level cooling occurs with higher cooling rates even in the presence of clouds Gettelman2004. An additional sentence explaining this fact will be included into the revised version.

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7. *“the case study based on Figs. 3 and 5 is not easy to understood..."*
We agree and as also recommended by reviewer 3, we plan to give a more detailed explanation how CLaMS does couple deformations, in particular the vertical shear, with mixing. We plan to show this point more explicitely and will add an additional figure to the manuscript discussing the impact of convection on vertical mixing and on the observed tracer distributions on February, 8, 2005.

8. *“jet split versus Rossby wave breaking..."*
This point was also raised by reviewer 1. Here, we will explain the observed stratospheric intrusion using the terminus “Rossby wave breaking" rather than “jet split".

9. “quality of ozone assimilated by ECMWF compared with FOZAN observations..."
Our statement: “Ozone assimilated by ECMWF overestimates the FOZAN observations above $\theta = 380$ K, with a linearly increasing error up to 40% at $\theta = 450$ K." was derived from all local flights. We share the opinion of the reviewer that this is “surprisingly good". We will mention both points in the revised version.

10. *“why is between 17.30 and 18.00 (Fig. 7), the comparison between the simulated (CLaMS) and the observed ozone fairly poor ?"*
It seems, that during this period, the real atmospheric mixing homogenizes ozone distribution more effective than the mixing parameterization in CLaMS. We will mention this point in the revised version.

11. *“mixing as a procedure smearing out filaments and another small-scale structure..."*
This property of mixing was observed mainly during the pure stratospheric studies (see e.g. Konopka2004). Here, the transport within and across the TTL is not only (weakly) influenced by rather dominated by mixing. As can be seen in Fig. 7 and 8, the transport without mixing strongly overestimates stratospheric

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properties of the observed air masses. On the other side, the CLaMS simulations with mixing “restore" a balance between the tropospheric and stratospheric properties. Of course, we cannot argue that only due to mixing such a balance is possible but we believe that these are strong indications that mixing must be taken into account.

12. *“color bar is missing in Fig. 7b..."*
    This is the consequence of splitting of Figure 7 into 3 panels. The missed color bar is in Fig. 7a. Sorry, we can only do it better in the revised version.

13. *“objective definition of the boundary between the tropospheric and stratospheric branch in Fig. 8"*
    It is difficult to find a clear boundary between these air masses. We will try to find it as also recommended by reviewer 3 using the observed correlations and include this discussion into the revised version.

14. *“mixing-driven upward transport across the TTL versus cooling-induced downward transport between 340 and 360 K versus violation of the continuity equation"*
    The violation of the continuity equation is the consequence of the use of the vertical velocities derived from a radiation module which do not match (in the sense of the continuity equation) the ECMWF horizontal winds. Thus, assuming that the vertical velocities as derived from radiation approach are correct (as we do), we deduce from our zonal mean calculation of the mass conservation (Fig. 13, bottom) that the horizontal velocities, in particular the meridional velocity v has to be slightly modified. In particular these (zonally averaged) velocities are too strong, with too much poleward divergence that can also be seen from the transport at 360 K where the air parcels slowly move away from the tropics, poleward, even if $\dot{\theta} \approx 0$ is valid at this surface.

    A correction of the horizontal winds that does restore the validity of the contin-

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uum equation can be done (B. Legras, personal communication). In addition, the necessary corrections in order to achieve mass conservation are very small in comparison with the real horizontal winds. By applying of such a correction, we would avoid the formation of the white, air parcels free, gaps shown in Fig. 11.

But, as we will describe more precisely in the revised version of our manuscript, this correction will not produce an additional vertical transport across the TTL (in a CLaMS configuration without mixing). Furthermore, the intensity of mixing will not significantly change if the white gaps would be filled with air parcels. We discussed it in the previous version of our manuscript in the following way:
“The high rates of the strain and mainly shear-induced deformations within the TTL, in particular in the outflow of the large-scale convection and in the vicinity of the STJ, enhance the diffusive flux across the TTL. This occurs even if the continuity equation would be satisfied because the number of mixing events which are necessary to close the white gaps in the left top panel of Fig. 11 is only a small fraction ($\approx$5%) of all the mixing events induced by the flow deformations."

The question that still arises is what is the mechanisms the push the trajectories across the TTL if only 3D ECMWF velocities (which are mass conserving) are used (as done e.g. in Fueglistaler2004). Considering our previous discussion, we think the probably slightly too high meridional, poleward velocities “pump", via the vertical velocities derived from the continuity equation, the air parcels upwards across the TTL. It can occur at the same places where the upward transport is diagnosed by CLaMS but we can also expect some differences. These differences, if present, would help to find out which transport mechanism is correct. We will analyze this point in the future.

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