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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Small-scale mixing processes enhancing troposphere-to-stratosphere transport by pyro-cumulonimbus storms" *by* G. Luderer et al.

G. Luderer et al.

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Reply to referee #1 (The Reviewers comments are contained in brackets):

[This article presents a compelling new simulation of pyro-Cumulonimbus convection that both well describes a previously unexplained observed phenomenon (cold U/warm center) and also provides insight into the role of gravity wave breaking in tropospheric-stratospheric exchange.]

We would like to thank the anonymous referee for her/his review and the constructive comments. Replies to the general and specific comments are given below.

[This particular simulation shows strong evidence of gravity wave breaking (Figure 9).

The increase of aerosol mass in a given potential temperature range with time (Figure 10) is a convincing way to show that transport is occurring via mixing. However, I wonder if much of the mixing is in fact due local turbulence (e.g., see "turbulence local to the cloud top" in Lane et al., 2003), as opposed to break-down of the main stationary gravity wave caused by the overshoot. The mixing bullseye in figure 9h that is centered at x=-28 seems responsible for a greater increase in aerosol concentration than the bullseye at x=-17 and is not clearly associated with steep or overturning isentropes. This x=-28 bullseye also doesn't appear to be turbulence advected from the breakdown region, as it actually starts to form prior to the wave-breaking event. I would agree, however, that the breakdown of the main gravity wave (at x=-17) is probably very important for the highest potential temperature bins in figure 10b, as that mixing zone brings in the highest stratospheric temperatures. I would like the authors to address the issue of the different mixing zones, but otherwise strongly support publication of this informative and well-written article.]

The issue of different mixing zones raised here is indeed very important. We agree that the local turbulence at the cloud top is responsible for much of the mixing of aerosol into the lower stratosphere. A closer analysis shows that the turbulence bullseye at x=-28km is mostly due to a strong vertical shear of the horizontal wind field at the cloud top on the downwind side of the overshoot. This is evident from the newly inserted Figure 8e in the manuscript, which shows the horizontal wind field. Since the overshoot establishes an obstacle for the background flow, wind speeds above the cloud top downwind of the overshoot are close to zero. Air masses outflowing from the convection into the anvil, by contrast, are characterized by horizontal wind speeds of up to 45 m/s. In response to this comment, the descriptions in Sections 4.2 and 4.3 have been extended and now discusses the formation of the second turbulence bullseye in detail. For better illustration, Fig. 8e has been added.

SPECIFIC COMMENTS

[-page 10374, line 17: How is the air mass 'exposed'? Do you just mean to convey

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that the cold U region is due to air masses that have ascended past the level of neutral buoyancy? If so, "– cold U region is due to air masses that have –" would be clearer.]

The intention was to convey that cold U is caused by those cool air masses of the overshoot that become exposed to the view of the satellite radiometer. The text has been adjusted accordingly.

[-page 10375, lines 20-22: A cold front in the vicinity may have meant the pyroCb actually developed in an air mass with a lower tropopause and a different buoyancy profile than shown in the Edmonton sounding, which might have significant bearing on the TST. Was this considered? Did the ECMWF reanalysis show a sloping tropopause in the region?]

The role of the background meteorological conditions was explored by Luderer et. al, 2006. They found that different profiles of buoyancy and moisture have a strong impact on the dynamic development and the amount of aerosol TST. The ECMWF reanalysis shows that the tropopause is sloping and significantly lower to the west of the fire location due to the upper level trough associated with the frontal system. Since the Edmonton sounding was recorded in reasonable spatial proximity and only shortly before the arrival of the cold front, it seems to provide a good (and likely the best available) representation of the conditions that were present during the Chisholm pyroCb formation.

[-page 10386, lines 14-15: You have calculated the equivalent potential temperature from the boundary layer to 8 km to be 320-322 K, which, when the fire heating is added, is not enough to reach tropopause temperatures. However, estimating from the sounding (figure 2), the equivalent potential temperature in the boundary layer looks to be at least 325 K. Did you include the boundary layer air mass (it was not clear from your wording if you only calculated from the top of the boundary layer, or from within the boundary layer)? If you are not considering the boundary layer air, why not? If, on the other hand, you are considering boundary layer air, the addition of a lifted parcel

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on figure 2 would help clarify the failure of parcel theory to explain the transport.]

Indeed there was an error in the calculation of the equivalent potential temperature. With the exception of few outliers with lower Teq, the equivalent potential temperature is 324-326 K from the ground to a level of about 7.5 km. Boundary layer air was considered in this analysis. This results in slight changes of the quantitative assessment, the conclusion that the combined effect of latent heat release from condensation of moisture and fire heating is not sufficient to explain mixing of aerosol above the 332 K tropopause level. The text in the manuscript was changed accordingly. We decided against adding the profile of a lifted parcel to Fig. 2. Fig. 2 is already rather busy, and the version with a lifted parcel profile added seems to make it quite confusing. Moreover, we feel that the to the argument made in Section 4.4 is more straight forward than such a graphical illustration.

[-page 10394, figure 1: The structure in the visible channel that is mentioned in the text (page 10376, lines 21-22) is hard to discern. Could this figure be made larger to show higher resolution?]

The figure will be printed larger in order to make the structure easier to discern.

[Technical corrections

-page 10372, lines 21-23: This sentence is difficult to read. A suggested rewrite: "In its most extreme form, this fire-induced convection is called pyro-Cumulonimbus (pyroCb), a phenomenon shown by both observational and modeling studies to result in direct –"]

-page 10380, line 29:

"In the case of water droplets –"

-page 10381, line 10:

overshooting top is centered at x=-15 km (minus sign omitted)

-page 10386, line 17:

"air masses" (space omitted)

-page 10394, figure 2:

"diagram"

-pages 10401-10402, figure 9:

"vertical"

Also, could this figure me made larger so that the potential temperature values could be read? Perhaps break into two four-panel figures.]

All technical corrections were performed as suggested by the reviewer. Fig. 9 will be expanded to a full A4 page in the final ACP paper, therefore it does not seem necessary to break it into two figures.

Interactive comment on Atmos. Chem. Phys. Discuss., 7, 10371, 2007.