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Atmospheric
Chemistry
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Discussions

Interactive comment on "On interpreting studies of tracer transport by deep cumulus convection and its effects on atmospheric chemistry" *by* M. G. Lawrence and M. Salzmann

M. G. Lawrence and M. Salzmann

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We are very thankful to the two anonymous referees and the editor Owen Cooper for their positive reviews and helpful suggestions for our manuscript. We have revised the manuscript accordingly for resubmission. Below are our replies to the individual points which have been raised and an indication of the changes which have been made to the manuscript.

Note that in addition to the changes listed below, in the introduction we have added a brief reference to thesis of B. Lintner (2003), which includes simulations with and without tracer transport by the DCC parameterization that were used to examine processes influencing interhemispheric transport (we were alerted to this during the discussion

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phase).

Anonymous Referee 1:

$>$ However, what is the justification for assuming values of 0 to 0.5 for flad?

Our objective here is to establish the relationship between the large scale mean fluxes and the deep cumulus convective fluxes. Determining this relationship directly suffers the major uncertainty that some unknown amount of the large scale mean flux is ascending due to "ladder-like" processes outside of deep cumulus convection. Due to this, we can only establish upper and lower bounds for the relationship. Our reasoning in choosing these extremes for f_{lad} (the fraction occurring due to "ladder-like" non-convective processes) is as follows. If all the flux were to occur through deep cumulus convective towers, and no other processes contributed to transporting airmasses to the upper troposphere, then we would have the lower bound extreme of $f_{lad} = 0$. On the other hand, it is likely that other processes do contribute at least some to the vertical mass flux. However, previous studies dating back to Riehl and Malkus (1958) indicate that the non-convective processes (i.e., slow vertical advection) cannot account for most of the vertical mixing in the tropics. If we take a literal interpretation of the term "most", it would mean that these processes are not more than half of the total flux, and thus we choose the upper bound extreme of f_{lad} to be 0.5.

To make this clearer in the manuscript, we have replaced the text following the sentence on the assertion of Riehl and Malkus (1958) and subsequent studies with the following:

"In turn, this means that at least half of the vertical mixing must be due to DCC, i.e., $f_{\text{dcc}} \geq 0.5$, and based on Equation (1), $f_{\text{lad}} \leq 0.5$. This has two implications for our discussion. First, for question 2 from above, we can thus assume that $f_{\text{dcc}}>f_{\text{lad}}$, i.e., f_{dcc} is not small. Second, we can also use this to establish bounds on the relative magnitudes of the fluxes: using $f_{\text{lad}}=0.5$ will yield an approximate lower bound for the DCC component of the flux, while setting $f_{\text{lad}}=0.0$ (i.e., assuming that non-convective processes are non-existent or negligible) will provide an upper bound for the DCC

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component.

With these upper and lower bounds as a basis, we can then directly address questions 1 and 3..."

$>$ Comparison of NCEP and MATCH convective mass fluxes.

Thanks for noting this; this is a very good point to bring out more clearly in the manuscript. We agree completely that for a more comprehensive study focusing on the physical relationship between deep convective mass fluxes and the large scale mean fluxes, it would be best to use an online GCM, where the fluxes are more internally consistent with each other. The NCEP and ECMWF models would be possible sources for doing this. An especially appropriate tool, which we mentioned in this regard in the conclusions, would be the model EMAC (ECHAM5/MESSy Atmospheric Chemistry) (Jöckel et al., 2006), which is capable of employing several different deep convection parameterizations in stable, consistent simulations, which all reproduce the main features of the observed global precipitation distribution, as discussed in Tost et al. (2006). We have begun to look at these fluxes as computed by EMAC, though this will be the basis of a follow-up study which will go considerably beyond the main point which is brought out in the present paper.

For the present paper, we decided it would actually be best to show the comparison between the NCEP large scale mean advective fluxes and the convective mass fluxed diagnosed by MATCH (rather than comparing to the NCEP convective mass fluxes). The reason for this is that our main objective here is to examine the relationship between the mass fluxes from the perspective of interpreting previous studies which have considered the effects of deep convective transport by turning the transport off for one or more tracers. Most of these studies have been done with offline models like MATCH, using their own re-diagnosed deep convective mass fluxes. Thus, the setup we are using here and the comparison of fluxes that we show should be most directly representative of what was being used in those studies.

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We have modified the text as follows to reflect this:

In section 3.2, at the end of the first paragraph we have added:

"We have chosen to compare the diagnosed advective and convective mass fluxes exactly as they are used in MATCH since these fluxes are representative for one of the previous studies of the effects of DCC transport mentioned in the introduction (Lawrence et al., 2003b, with the exception of being at a higher resolution, T62 vs. T21, and without chemistry). Most of the other previous studies examining the effects of DCC transport have also been done with offline models like MATCH-MPIC, using their own re-diagnosed deep convective mass fluxes, so that the comparison we show in this section should be generally representative of what was being used in those studies. However, it is worth noting that for a comprehensive, quantitative study focusing on a more fundamental understanding of the relationship between DCC mass fluxes and large scale circulation (e.g., the Hadley and Walker cells), it would be better to use the advective and convective mass fluxes directly from an NWP model like NCEP or ECMWF, or from a GCM. We return to this point briefly in the conclusions section."

Also, in the conclusions, we modified the paragraph on this topic to now read:

"As noted above, further analysis of the fundamental relationship between parameterized deep cumulus convection and large-scale circulations, as well as of the present uncertainty due to differences in convection parameterizations, would best be done using the output from an NWP model or a GCM, rather than a CTM. An especially appropriate tool which we have begun to make use of for this purpose is the EMAC (ECHAM5/MESSy Atmospheric Chemistry) model (Jöckel et al., 2006), which is capable of employing several different deep convection parameterizations in stable, consistent simulations, all of which reproduce the main features of the observed global precipitation distribution, as discussed in Tost et al. (2006)."

Anonymous Referee 2:

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No changes were requested, the manuscript was considered acceptable as is.

Editor Owen Cooper:

The main comment from the editor unfortunately got mis-formatted during the latex conversion for the ACPD website; for clarity, with the editor's permission, we repeat his entire comment here:

*****

There is one issue that I would like to see addressed, if only briefly: If some 30% (or more) of the FCU is non-local and should be feeding into the Hadley Cell, but is instead being artificially returned to the surface then this will lead to errors in tracer transport, a specific issue which I don't think is addressed in this paper, but one that deserves a paragraph or two. For example, assume a polluted air parcel in the tropical boundary layer is lofted to the upper troposphere due to the DCC parameterization. Approximately 30% of this lofted mass should subsequently leave the tropics in the upper branch of the Hadley Cell. But when this polluted parcel is advected to the next tropical grid cell where the DCC parameterization is applied, then a significant proportion will be transported downward due to f-artificial. So the net effect is that too much of the pollution lofted to the upper troposphere is being transported back down to the surface and in effect the DCC parameterization is retaining a fraction of the pollutants in the tropics instead of allowing it to exit the tropics in the upper branch of the Hadley Cell.

*****

This is an interesting alternate perspective on what we mention in the discussions section (p. 12183) about how the separate treatment of convective and advective mass fluxes can affect tracer simulations. In general, there are two fluxes (or fractions of the total modeled fluxes) to consider: the artificial subsidence in the deep convection parameterization, and the mean ascent due to deep convective processes which

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is present in the large scale mean winds used for the advection routine. These two will tend to cancel each other out, as shown in Figure 1. So in principle, if the transport were done "perfectly" (what we call "shape preserving") in both the advection and deep convection algorithms, then this would end up not leading to any net downward transport.

Considering the specific example brought up here, if a tracer in an airmass is transported to the UT in the ITCZ, then in the columns where the main upward transport through the DCC parameterization occurs, there will also be an upward flux in the large scale wind fields that are used for the model's advection routine. Furthermore, the downward transport due to the artificial mass balancing subsidence term in the DCC parameterization will be exactly balanced by the residual upward transport in the advection term (this can be seen by combining equations 3 and 4, with the exception that although the fluxes as defined in the paper are balanced, the transport may not be balanced due to numerical diffusion, see below). If this airmass is then advected poleward, then when it enters another model column in which the DCC parameterization is active and extends vertically beyond the altitude where the airmass resides, it will again be forced downward by the subsidence term in the DCC parameterization, F_{CS}, (note that part of the tracer can also be entrained and transported further upward, but this is a separate issue). Some part of this can be seen as "real" subsidence which should indeed be locally balancing the convective updrafts; this part is pictured as f_{ms} in Figure 1. This will lead to a partial retention of the tracer by DCC in the tropics, as indicated in the comment, but this part represents a real physical process. The other component, represented as f_{art}, which is the additional subsidence required to balance the mass that should be leaving the tropics due to horizontal poleward advection, will be principally balanced by the upward transport in the advection scheme, just like in the ITCZ, with one important exception: this only works if the transport is perfectly shape preserving in both the advection and deep convection algorithms. If this is not the case, then for this particular example the numerical diffusion will end up resulting in vertically smearing out the tracer signal, and the component which is articially

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transported downward will be retained more effectively in the tropics than it should be. This is a nice practical example of what we discuss theoretically in Section 4, so we've added a short description of it to the text (after "highly numerically diffusive"):

"An example of the kinds of consequences this can lead to can be seen by considering tracer transport in the Hadley Cell. An airmass containing a pollutant tracer emitted at the surface is transported upward through the DCC parameterization in the ITCZ, and then advected poleward. If, while still in the upward branch of the Hadley Cell, it encounters another column in which deep convection is active, then the airmass will be forced downward somewhat due to the artificial mass-balancing subsidence present in the DCC parameterization. However, as seen in Figure 1, it will also be transported back upward a compensating amount by the mean vertical winds used in the advection algorithm. Since in most models this transport is not perfectly shape preserving, numerical diffusion will result in the tracer signal being smeared out vertically, and the component which is articially transported downward in this way will be retained more effectively in the tropics than it should be."

Minor Comments:

$>$ The big black "X":

Thanks, we forgot to include the explanation of this. We added the following text in the manuscript prior to "One of the most important relationships..." (p. 12172, bottom):

"One of the key features of the figure is the large black “X” that crosses out the arrow at the top of the figure. As discussed above, in nature, some part of the airmass which is transported upward in DCC updrafts will then be horizontally advected away (e.g., poleward in the Hadley Cell). Since this connection is not explicitly present in models with a split operator treatment of DCC and advection, this connecting arrow is crossed out. Mathematically, this results in one of the most important relationships..."

Also, at the end of the figure caption we added:

"See the text for further explanations, e.g., the large black “X” at the top of the figure."

$>$ "Contiguous":

Good point, reworded as follows:

"...the fraction of F_{LS} which represents the contribution to the resolved mean upwelling which is not occurring through DCC, i.e., the component of the airmass which is transported from the surface to the upper troposphere by processes other than single deep convective updrafts which accomplish the transport in one step; this non-DCC transport is depicted here as a “ladder” of sequential upwelling through disconnected layers of shallow cumulus or stratus clouds."

$>$ "from the BL":

Fixed

$>$ "Large scale mass fluxes without convection:"

Actually, since MATCH is an offline model, the large scale mass fluxes do not really change whether the DCC parameterization is turned on or off (in MATCH there is a small connection, since we have an online hydrological cycle that is influenced by the DCC parameterization, which in turn influences the air density and the flux computation, but this is negligible). In a GCM or NWP model, turning off the DCC parameterization would have a much larger effect on the vertical wind field and advective mass fluxes, due to its influence on the horizontal pressure gradients. We hope some of this will be clearer now through the extended explanation of our motivation for the choice of fluxes to compare (comment 2 from Referee 1), and we have also made the following change in the text to relate this better to the figures:

Where we discuss the pressure velocity (p. 12178), we changed "shown here" to "shown in the figures discussed in this section", and we reworded the overall sentence to make it somewhat more complete and simpler to understand:

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"The pressure velocity (Ω) fields used to compute the vertical large-scale mass fluxes shown in the figures discussed in this section are based on the NCEP horizontal wind fields; the divergence in these fields are used in MATCH to diagnose the vertical wind field, assuming zero fluxes at the upper and lower model boundaries, and applying small corrections to the horizontal wind fields to guarantee mass-wind consistency (see von Kuhlmann et al. (2003) for details). The fluxes shown here thus correspond to those used for tracer transport by the advection routine in MATCH."

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 12163, 2008.

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