Author comments on "Vertical transport of pollutants by shallow cumuli from large eddy simulations" by G. Chen et al.

We thank the referees for their useful comments. Below are our point-by-point responses.

T. Heus (the referee)

The authors use Large Eddy Simulations to study how passive scalars can be transported in a cumulus topped boundary layer. The topic is definitely interesting, and while cumulus transport is quite commonly studied, and dispersion is done very often for the dry convective boundary layer, there is definitely room for improvement in our understanding of dispersion in a cumulus layer. Unfortunately, this paper has a number of fundamental flaws that make it impossible to recommend acceptance of this paper. I will list my biggest concerns here.

1) **The LES simulation is run at a 100 x 100 x 40m resolution. While the eventual outcome that the subsiding shell is responsible for significant downward transport is in line with my personal view, Heus et al (QJ, 2009) showed that we need at least 25 m in the horizontal to even begin to resolve this shell. 100 m resolution is in my opinion not enough to resolve the clouds reliably (see, e.g. Matheou et al, MWR 2011) but when we're talking about the detailed structure of the cloud, like here, I believe 25 m is the maximum acceptable resolution.**

Our reply:

The biggest concern raised by both referees was the resolution of our simulations (100 m × 100 m × 25 m). We now run the simulations with a higher resolution (25 m × 25 m × 10 m to maintain the same aspect ratio), and the results do not show much change. Figs. 1 – 6 in the old version of the manuscript are now all plotted with the new simulation data (see Figs. 1 – 6 at the end of the reply here). It should be mentioned that, as the grid size becomes smaller, more sub-grid saturation in the old simulation is resolved in the new simulation. The cloud fraction averaged over the last 22 hours is 8.4%, larger than that in the old simulation, 5.2%. Results show that the boundary layer grows a little slower, but cumulus clouds are still able to transport tracers from the surface to the cloud layer, and fumigate tracers in the inversion layer downward to the lower boundary layer. Cloudy regions contribute to the upward transport, while cloud-free regions contribute to the downward transport. At 6 h and 12 h of case 2 (tracers are released in the inversion layer), it can be seen in the vertical cross sections (Fig. 6) that regions near cloud edges dominate the downward transport, while regions far from clouds show negligible downward transport. Therefore it is not necessary to plot a new Fig. 7 as in the old manuscript.

2) **The comparison with the dry boundary layer does not make sense at all to me.**

Of course, when the dry inversion never reaches the pollutants, the pollutants will not be entrained into the layer. But this cannot be a reason to conclude that cumulus clouds are much more efficient in transport: Such a conclusion can only be arrived by a different dry setup, that is well scaled, both in boundary layer depth, surface flux as well as with the resultant typical time scale. This however would be quite close to what has already been done by Verzijlbergh et al, including a discussion of autocorrelation time scales etc. A more extensive discussion of the dry cbl can be found in the works of Dosio (e.g. JAS 2005). I am not sure that the current work can add to that base of knowledge, and I therefore suggest to leave this out altogether.

Our reply:

Based on the referee's suggestion, we have removed the results of dry convection from the figures. We also removed the discussion on dry convection in the revised manuscript.

3) **The figures 2 and 5 only show the resolved transport, not the unresolved, which is large by definition at the surface, and probably significant elsewhere as well given the resolution of the simulations.**

Our reply:

We agree with the referee that sub-grid scale transport is significant at the surface. Figs. 7 and 8 include both resolvable and sub-grid scale transport of the high resolution simulation (Panels a and b). It is seen that the sub-grid scale transport is indeed significant near the surface, and much smaller than the resolvable scale transport in the cloud layer, compared with Figs. 2 and 5. Figs. 7 and 8 are now used in the revised manuscript (to replace the old Figs. 2 and 5).

4) **Without an accurate description of the case, and especially the maximum cloud top height evolving over time, it is hard to interpret the results. If the data would be non-dimensionalized, the results would be even clearer.**

Our reply:

The non-dimensionalized vertical transport is shown in Figs. 7 and 8 (Panels c and d) for cloudy grids, and cloud-free grids within 200 m and 600 m from cloud edges. Transport over cloudy grids is non-dimensionalized with the depth of that cloud. Transport over cloud-free grids is non-dimensionalized using the depth of the nearest cloud to it. As the referee pointed out, the results are even clearer. Cloudy regions contribute to the upward transport, while cloud-free regions contribute to the downward transport. Cloud-free grids within 200 m from cloud edges contribute quite a large fraction of total downward transport, in spite of their relatively small coverage. This confirms that the downward transport outside clouds is also induced by the cumulus clouds. The discussion related to non-dimensionalized vertical transport is added in the revised manuscript.

On a brighter note, I do believe that the authors have an interesting topic with the notion that much of the downward transport is related to clouds. I also do like the elegance of the decomposition between near-cloud and remote air in figures 2 and 5. A related notion that only seems to be implicit in this study becomes clear from figures 4 and 5 at 12 hours: Despite the lack of tracer in the sub cloud layer, the clouds already have a significant upward transport of tracer. This suggests that a) the cloud layer has been mixed reasonably well within 12hrs, b) a significant amount of air is laterally mixed into the clouds at lower levels and c) in cloud downdrafts do not show. If the authors would be able to further our knowledge in this respect, I would be very interested and enthousiastic about it.

Our reply:

We thank the referee for pointing out the interesting feature in Figs. 4 and 5. This feature was not discussed in the old version of the manuscript. We therefore added some discussion in the revised version: At 12 h, despite the lake of tracers in the subcloud layer, cloudy grids already have a significant upward transport. This indicates that tracers are laterally mixed into clouds through the lower part of the cloud layer. This is consistent with the results of Zhao and Austin (2005), which confirms toroidal circulations associated with cumulus clouds. With such circulation, tracers can be entrained into clouds through the lower part of the clouds and detrained through the upper part. Therefore the shallow cumulus clouds have net convergence in the lower part and net divergence in the upper part, as presented in Chen et al. (2012).

In the old version of the manuscript, we only showed the total transport by cloudy regions in Figs. 2 and 5. It is seen that cloudy regions are responsible for upward transport. In fact, downdrafts exist in cloudy regions. Fig. 9 presents the distribution of vertical velocity in cloudy grids. It shows that downdrafts occur in clouds, but are much weaker and less frequent than updrafts.

Anonymous Referee #2

General comment:

In this paper, an analysis of vertical transport of a passive tracer (signifying pollutants) in shallow cumuli is presented using large eddy simulations (LES). The tracer source is uniformly distributed at the surface and in the inversion layer, respectively, to study the upward and downward transport. As convective clouds can enhance vertical mixing of aerosol and gaseous matter, investigating the transport mechanism can improve our understanding on dispersing local pollutants. Thus this subject is worthy to study in detail. However, some major points need to be addressed:

- **Resolution: I agree with the first referee's comment that the coarse horizontal resolution (100 m) applied in this study may not be able to adequately resolve the cloud structure. Moreover, the vertical resolution (40**

m) may also be insufficient in analyzing the entrainment/detrainment on the top of boundary layer. The boundary layer entrainment is sensitive to the vertical grid spacing (e.g., Lewellen and Lewellen, 1998; vanZanten et al., 1999). Since the main subject in this paper is to understand the vertical transport through boundaries, the finer vertical resolution is needed to properly represent processes at the entrainment interface.

Our reply:

As we replied to the other referee, we run the simulations with a higher resolution of 25 m × 25 m × 10 m (to maintain the same aspect ratio with our old simulation). The results do not show much change. Figs. 1 – 6 in the old version of the manuscript are now all plotted with the new simulation data (see Figs. 1 – 6 at the end of the reply here). It should be mentioned that, as the grid size becomes smaller, more sub-grid saturation in the old simulation is resolved in the new simulation. The cloud fraction averaged over the last 22 hours is 8.4%, larger than that in the old simulation, 5.2%. We agree with the referee that boundary layer entrainment is sensitive to the vertical grid spacing. The higher resolution run does show that boundary layer grows a little slower. But cumulus clouds are still able to transport tracers from the surface to the cloud layer, and fumigate tracers in the inversion layer downward to the lower boundary layer. Cloudy regions contribute to the upward transport, while cloud-free regions contribute to the downward transport. At 6 h and 12 h of case 2 (tracers are released in the inversion layer), it can be seen in the vertical cross sections (Fig. 6) that regions near cloud edges dominate the downward transport, while regions far from clouds show negligible downward transport. We now removed Fig. 7 in the revised manuscript.

- **The interpretation of the results should be revised as it is often not clear and can lead to confusion. See specific comments below.**

Specific comment:

P11396, L3-4: Only the condensation scheme is described here. What about other processes? Is sedimentation/precipitation included in the simulation? It is commented in the introduction concerning the difference in dispersion efficiency between non-precipitating and precipitating cumuli. Are the shallow cumuli precipitating in these simulations?

Our reply:

We thank the referee for pointing out this. We added more detailed description of model setup in the revised manuscript. The cumulus case simulated in this study is a typical non-precipitating shallow cumulus case. Therefore sedimentation/precipitation is not included in the simulation. The tracers added in the simulation are totally passive and inert (and insoluble to water). We study the transport of these tracers in the dynamical field associated with non-precipitating shallow cumulus. Transport of pollutants in a precipitating cumulus environment is beyond the scope of this study.

P11396, L15-16: What does the sentence "BOMEX has the practical advantage of a lack of diurnal cycle" really mean? Also, is radiation included in these simulations? If so, are both longwave and shortwave radiation included? As radiation affects the cloud formation, more description is needed for the model setup.

Our reply:

The diurnal cycle influences the statistical properties of the cloud field a lot. For example, the morning cumuli over the continents are usually boundary-layer confined cumuli, while the cloud population in the afternoon is a mixture of boundary layer cumuli, towering cumuli and cumulonimbi. Because BOMEX is a typical marine shallow cumulus case, the diurnal cycle is not significant in it. This will ensure a statistically identical cloud field during a relatively long simulating time.

We set up the simulation according to the intercomparison of Siebesma et al. (2003), in which the radiation is parameterized by prescribing a fixed radiative cooling rate. No interactive radiation scheme is used. We added more detailed description of the model setup in the revised manuscript to avoid misunderstanding.

P11397, L23-26; P11398, L12-14: It is stated that "the higher tracer mixing ratio over cloud-free columns results from clouds that were higher and transported tracers upward at previous moments but have evaporated and left tracers in the cloud-free columns at this moment." What is the approximate life time or time scale of each shallow cumulus cloud? It is not clear to readers concerning the evolving of the cloud with time. More details are needed to support these statements.

Our reply:

Cumulus clouds in the case simulated in this study have lifetime of about 20 – 30 minutes, as can be seen in Jiang et al. (2006). At any moment, clouds in the simulated domain can be at different stages: forming, developing and decaying. The statement "the higher tracer mixing ratio over cloud-free columns results from clouds that were higher and transported tracers upward at previous moments but have evaporated and left tracers in the cloud-free columns at this moment." is for 6 h in the old version of Fig. 1 (100 m × 100 m × 40 m). Cloud fraction is a minimum at 6 h, so is cloud top height, as seen in the time series (not shown in the manuscript). This indicates that some clouds at previous moments evaporated. In the new simulation with a high resolution, this phenomenon is not shown in Fig. 1 at 6 h, but can still be seen in the vertical cross section (Panel c in Fig. 3, x = -1.0 – 1.0 km, z = 1.0 – 1.5 km), where no clouds are present but tracer mixing ratio is high. We now used the statement to explain the phenomenon in Fig. 3.

P11398, L14-18: It is mentioned that the clouds penetrate into the inversion layer,

evaporate, and release tracers above the boundary layer. How often does the cloud penetrate the inversion? The variation of cloud top heights with time can help readers understand this matter.

Our reply:

The inversion layer height is about 1.56 km at 6 h and 1.65 km at 12 h. From Fig. 9 in this reply, it can be seen that many cloudy grids exist in the inversion layer at 6 h and 12 h. The clouds at x = 1.0 – 2.0 km at both 6 h and 12 h (Panels c and d in Fig. 3) are examples for this. These clouds penetrate into the inversion layer, and will leave tracers there when they evaporate. In Fig. 1, it can also be seen that some tracers are transported into the inversion layer.

P11399, L6-9: Based on the description "the maximum vertical transport at about 0.2 km at 6 h (Fig. 2) is due to higher tracer mixing ratio in cloudy columns (associated with updrafts) than in cloud-free columns (associated with downdrafts) and intense vertical air motion", it seems the maximum transport at 0.2 km is due to the convective cloud. In that case, why does the dry convection have even stronger vertical transport at 0.2 km at 6 h? The explanation is confusing.

Our reply:

We agree with the referee that the dry convection has even stronger vertical transport at 0.2 km at 6 h. In the dry convection, tracer mixing ratio was also higher in the updraft regions than in the downdraft regions, leading to a strong vertical transport at 0.2 km at 6 h. By comparison of dry convection and shallow cumulus convection, we speculate that latent heat released by cumulus clouds makes the air below clouds more stable, and hence less vertical transport than dry convection. This needs further research to confirm. However, from cloud layer and above, vertical transport by cumulus convection is stronger and to a higher height compared to dry convection. Based on suggestions of the other referee, we removed discussion about dry convection in the revised manuscript. The profiles of dry convection are no longer in the revised figures.

P11401, L21-22: It is mentioned that the great values of vertical transport in the inversion layer (Fig. 5) are induced by oscillating movement of air and high tracer mixing ratio. According to this explanation, why it is not seen in the corresponding dry convection case?

Our reply:

As explained in the reply to referee's last comment, dry convection cannot get as high as cumulus convection. Therefore the oscillating movement of air in the pollutant layer of dry convection is relatively weak, leading to nearly no vertical transport. Based on suggestions of the other referee, we removed the discussion about dry convection in the revised manuscript.

P11403, L7-9: It is stated that shallow cumuli are efficient in venting pollutants from the surface upward to the cloud layer. However, the overall effect (for the whole domain) with and without cumulus convection does not seem to make a big difference according to Fig. 1. It is shown the dry convection has very efficient vertical mixing within the boundary layer as well (though it does not cross the inversion). Doesn't this indicate that without convective cloud the pollutants can still be transported efficiently within the boundary layer?

Our reply:

We agree with the referee that dry convection can efficiently mix pollutants within the boundary layer. However, dry convection does not transport pollutants to higher heights as the cumulus convection does (as can be seen in the old version of Fig. 1). In the case of having pollutants at the top of the boundary layer, cumulus convection is more efficient to transport pollutants downward because cumulus convection are easier to get to higher heights.

Because the other referee suggested we remove the discussion on dry convection, this part now has been removed from the manuscript.

Typing errors:
P11392, L11: preformed → performed.
P11392, L22: in the boundary.→ in the boundary layer.
Caption in Fig. 2.: The black, red, and blue lines represent ….. cloudy grids, and cloud-free grids. → add ", respectively" in the end.

Our reply:

All these errors are corrected in the revised manuscript.

Reference

Chen, G., Xue, H., Zhang, W., and Zhou, X.: The three-dimensional structure of precipitating shallow cumuli. Part one: The kinematics, Atmos Res, 112, 70-78, 10.1016/j.atmosres.2012.04.007, 2012.

Jiang, H. L., Xue, H. W., Teller, A., Feingold, G., and Levin, Z.: Aerosol effects on the lifetime of shallow cumulus, Geophys Res Lett, 33, Artn L14806 Doi 10.1029/2006gl026024, 2006.

Siebesma, A. P., Bretherton, C. S., Brown, A., Chlond, A., Cuxart, J., Duynkerke, P. G., Jiang, H. L., Khairoutdinov, M., Lewellen, D., Moeng, C. H., Sanchez, E., Stevens, B., and Stevens, D. E.: A large eddy simulation intercomparison study of shallow cumulus convection, J. Atmos. Sci., 60, 1201-1219, 2003.

Zhao, M., and Austin, P. H.: Life cycle of numerically simulated shallow cumulus clouds. Part II: Mixing dynamics, J. Atmos. Sci., 62, 1291-1310, 2005.

Figures

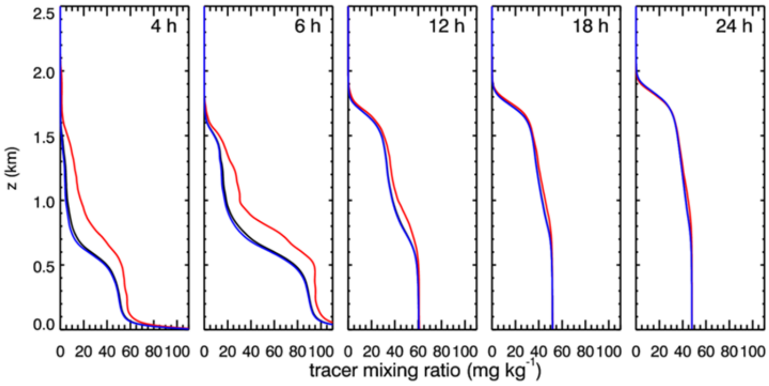

Fig. 1. Sampled profiles of tracer mixing ratio for case 1 at various moments. The black, red and blue lines represent profiles sampled over the whole domain, cloudy column (liquid water path > 10 g m^{-2}), and cloud-free columns, respectively in case 1.

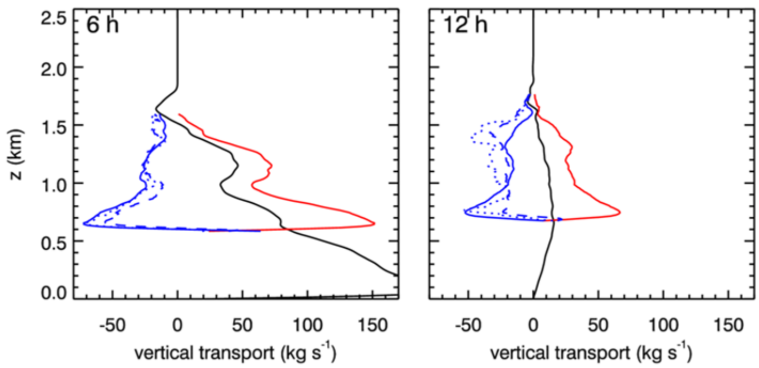

Fig. 2. Sampled profiles of tracer vertical transport at 6 h and 12 h from case 1. To better illustrate the effect of clouds on the vertical transport, we concentrated on cloudy grids (liquid water mixing ratio < 0.01 g kg^{-1}) and cloud-free grids here. The black, red, and blue solid lines represent profiles over the whole domain, cloudy grids, and cloud-free grids, respectively. The blue-dotted and blue-dashed lines represent profiles sample over cloud-free grids within 600 m from cloud edges and cloud-free grids within 200 m from cloud edges.

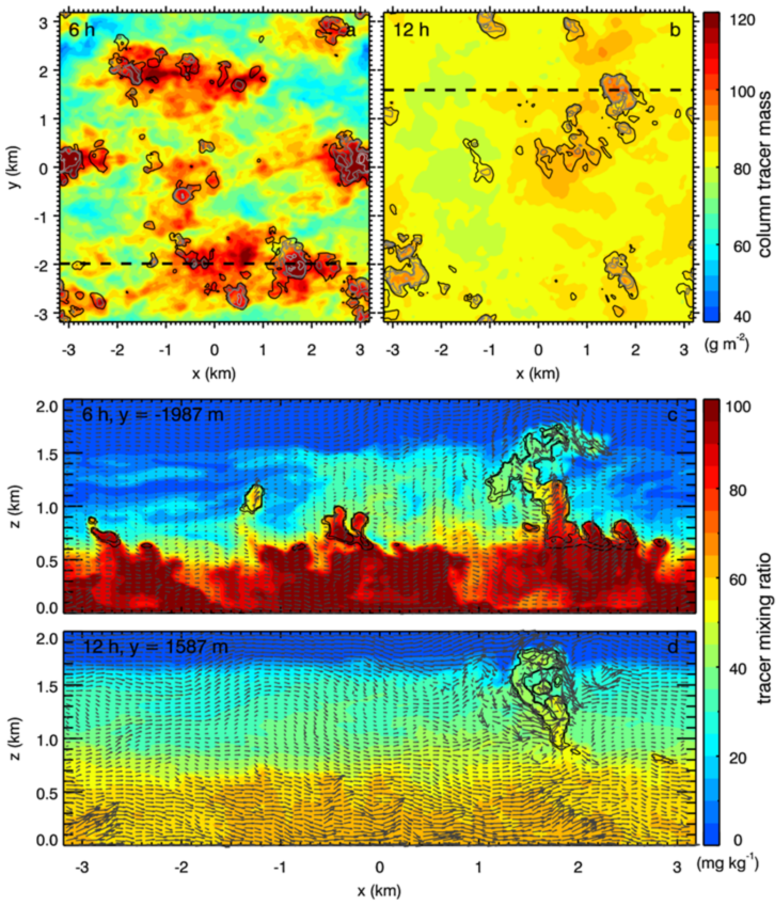

Fig. 3. Snapshots of column integral tracer mass (a and b) and two selected vertical cross sections (c and d). In (a) and (b), the contours from dark to light indicate liquid water path with increasing values of 10, 50, 100, 300 and 500 g m^{-2}. It is shown that cloudy columns usually have higher tracer mixing ratio than cloud-free columns. In (c) and (d), the contours indicate liquid water mixing ratio with increasing values of 0.01, 0.1 and 1 g kg^{-1}, and the arrows indicate u-w wind components.

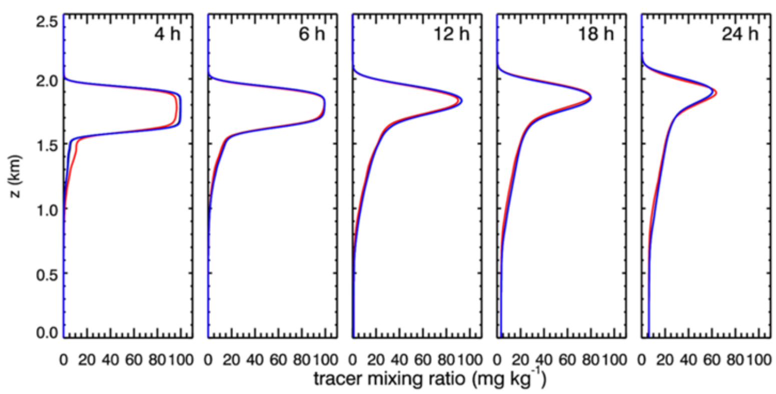

Fig. 4. As in Fig. 1, but for case 2, where tracers are released into the inversion layer at 2 h 0 min. The cumulus convection is able to transport tracers from the inversion layer downward into the cloud and subcloud layers.

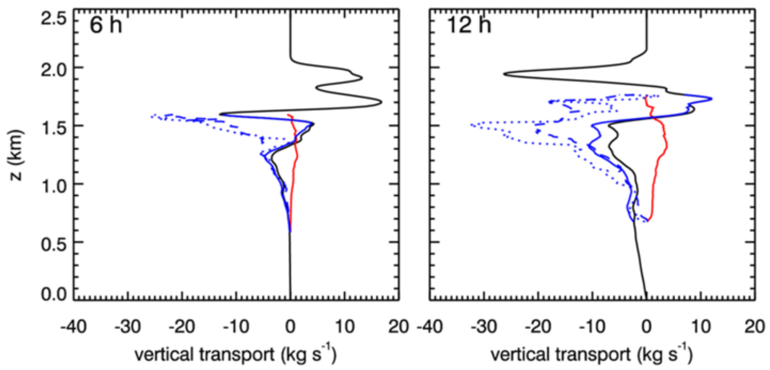

Fig. 5. As Fig.2, but for case 2. Cloud-free grids are responsible for downward transport, which mainly occurs in thin regions around clouds, indicating that the downward transport is also induced by cumulus clouds.

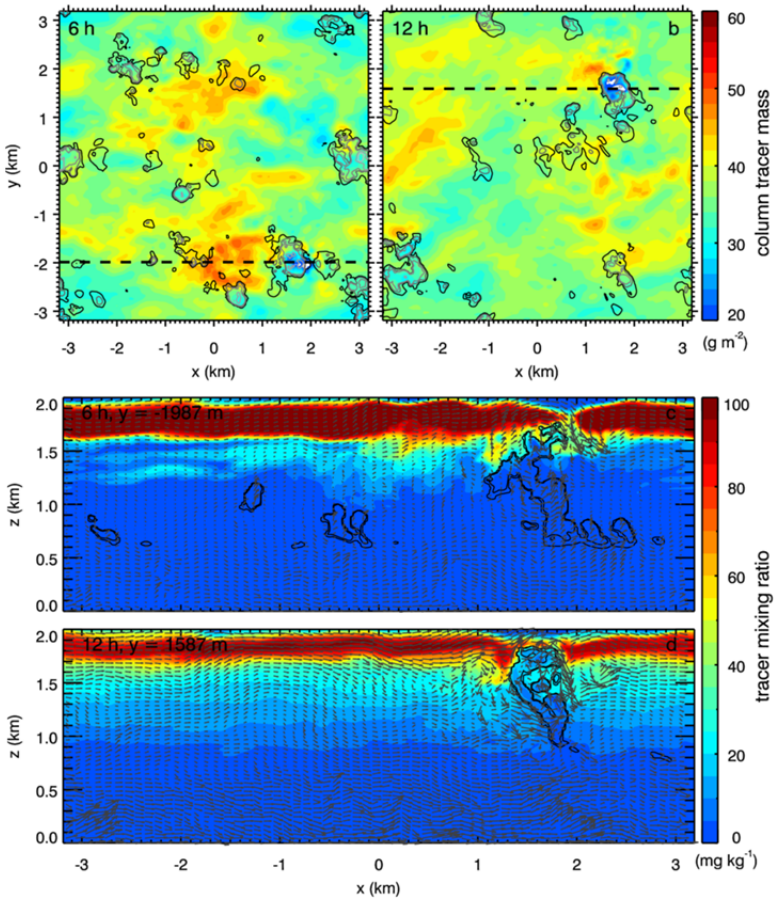

Fig. 6. As Fig. 3, but for case 2. In Panels (a) and (b), cloud columns usually have lower tracer mixing ratio. Panels (c) and (d) confirms this, and shows that Cloud-free grids are responsible for downward transport, which mainly occurs in thin regions around clouds, indicating that the downward transport is also induced by cumulus clouds.

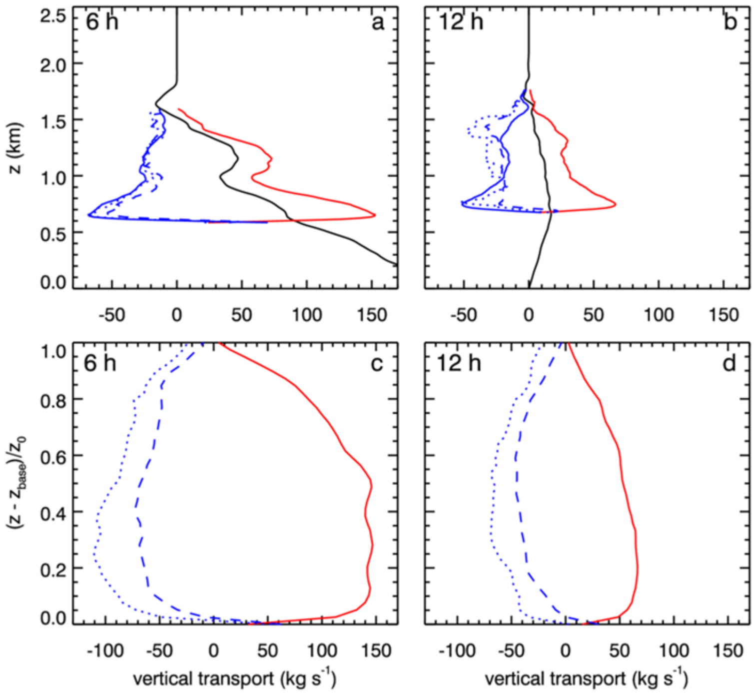

Fig. 7. Sampled profiles of tracer vertical transport at 6 h and 12 h from case 1. To better illustrate the effect of clouds on the vertical transport, we concentrated on cloudy grids (liquid water mixing ratio < 0.01 g kg^{-1}) and cloud-free grids here. The black, red, and blue solid lines represent profiles over the whole domain, cloudy grids, and cloud-free grids, respectively. The blue-dotted and blue-dashed lines represent profiles sample over cloud-free grids within 600 m from cloud edges and cloud-free grids within 200 m from cloud edges. In Panels a and b, profiles are plotted with respect to height. In Panels c and d, transport related to each cloud is non-dimensionalized with respect to the depth (z_0) of that cloud. Note that clouds with cloud base higher than 1400 m is not included in the non-dimensionalized profiles. This figure will replace Fig. 2 in the revised manuscript.

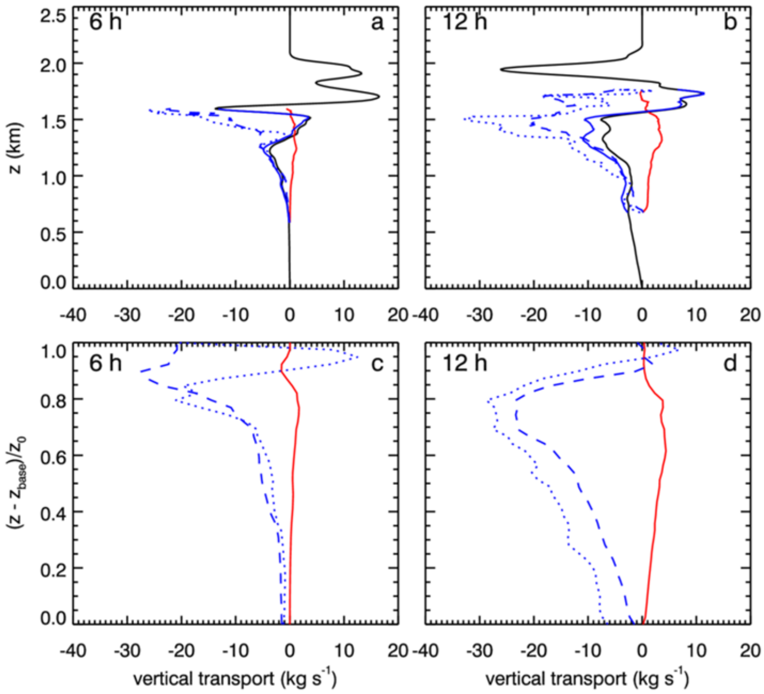

Fig. 8. As Fig. 7, but for case 2, where tracers are released into the initial inversion layer at 2 h 0 min. This figure will replace Fig. 5 in the revised manuscript.

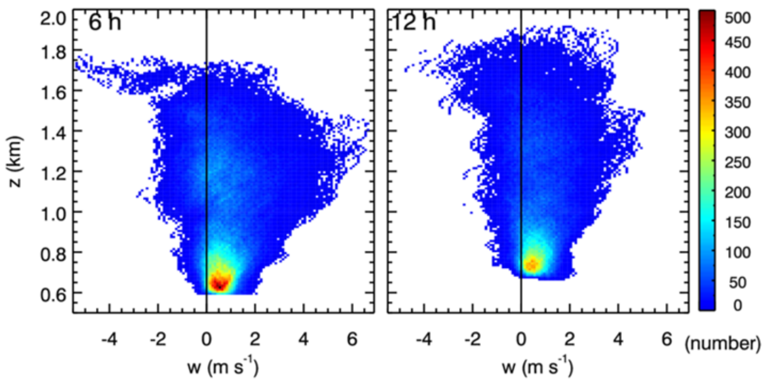

Fig. 9. Distribution of vertical velocity in cloudy grids. The bin width is 0.1 m s^{-1}. The black lines indicate the zero vertical velocity. Downdrafts occur in clouds, but are much weaker and less frequent than updrafts.