Review 1 of “Use of Large-Eddy simulations to design an adaptive sampling strategy to assess cumulus cloud heterogeneities by Remotely Piloted Aircrafts” by Maury et al. (amt-2021-20)

The revised version of the manuscript addresses most of my concerns with great care, and I have
only very minor and technical comments left. I can now fully support the manuscripts publication in
Atmospheric Measurement Techniques. I do not need to see the manuscript again.
Please note that line numbers refer to the tracked changes version of the manuscript.
The authors thank you for your feedback and your acceptance for this article to be published. The authors have taken into account your technical comments

Minor Revisions

L. 14: It might be necessary to state that the study is targeted toward “shallow” cumulus clouds.
We have added the term “shallow” in the abstract.
Ll. 22 – 24: It might better fit the scope of the study if the last sentence of the abstract ends with “[...] on scales small enough to quantify the variability of important parameters such as the LWC.”
We have replaced the end of the sentence with your proposition.
L. 84: Why did the authors remove the year of the BOMEX campaign?
We have added again.
Ll. 105 – 105: Did the authors use the radiative tendency prescribed in Siebesma et al. (2003), or used a model to determine the longwave cooling rates?
We used the prescribed radiative tendency defined in Siebesma et al., 2003. We have added in text a sentence to clarify: “The radiative tendency was prescribed for each hour following the values presented in Siebesma et al., 2003.”
Ll. 236 – 238: While I agree with the statement, how do the authors distinguish between cloud core and cloud edge in Fig. 6?
A cross section is observed for each vertical level in the cloud and allows us to determine a core associated with positive velocities (updrafts) and positive buoyancy. The edges are associated with negative velocities (downdrafts) and negative buoyancy. We have added this information as “(studied for each cloud cross section)”.
Ll. 319 – 322: The units for the dissipation rate seem to be incorrect. I assume that a minus is missing in the exponent (10 -3 instead of 10 3). The stated value is unrealistically high!

Thank you for catching this mistake. Indeed the minus is missing. We have corrected this value.

Technical Corrections

L. 8: Use the plural for Remotely Piloted Aircrafts here: “Remotely Piloted Aircrafts (RPAs)”
Corrected.
L. 26: “oceans” instead of “ocean regions”
Corrected.
L. 67: “maritime” instead of “marine”
Corrected.
L. 88: “LESs” instead of “Large-Eddy simulations”
Corrected.
L. 93: “LESs” instead of “LES”
Corrected.
L. 95: Remove the period between “m” and “ASL”
Corrected.
L. 116: Add “data” after “high-resolution”
Corrected.
L. 120: The accent aigu is used inconsistently in naming Meso-NH.
Corrected.
L. 269: Add a blank between “and” and “15 %”
Corrected.
L. 274: No comma before “provide”
Corrected.
Ll. 319 ff.: Please rephrase the beginning of this sentence, e.g., “Using equation (5) of Baker et al
(1984) allows [...]”
Corrected.

Review 2 of "Use of Large-Eddy simulations to design an adaptive sampling strategy to assess cumulus cloud heterogeneities by Remotely Piloted Aircrafts" by Maury et al. (amt-2021-20)

Though I think the work would be a worthwhile addition to the literature if some more material is added, I am not yet entirely happy with the draft as it currently stands. The authors have addressed almost all of the minor points I raised, but the larger weaknesses of the study remain. I would encourage the authors to do more work on the draft and resubmit, as I think the topic is important.

We thank the reviewer for his/her careful review. Below are our responses (in red) to the comments (in black) on a point-by-point basis. The text that has changed in the manuscript is indicated in quotation marks.

I still think that the main weakness of the study is that it almost exclusively uses exploration with a single RPA, rather than multiple RPAs. In their reply, the authors acknowledge that for practical applications, the use of multiple RPAs is one of the main advantages over traditional methods.
The authors mention that using multiple RPAs exponentially increases computing resources required, but I find it hard to see why these computations would be prohibitively expensive and the cost would grow in a non-linear way, especially for the time-independent case at a single level. I can imagine that a time-dependent GPR with multiple RPAs would require substantial resources, although I think this may be possible provided the algorithm has been coded in an efficiently way. In the abstract, the authors now mention that two RPAs are appropriate, but the draft only demonstrates this for a non-evolving cloud of a certain size class, and it may not work for larger clouds or an evolving cloud.

At the writing of this manuscript, the exploration routines were indeed not efficient and exploration with multiple RPAs in a dynamic environment was prohibitive. We entirely agree with the reviewer that more analysis using multiple RPAs in a dynamic environment is merited -- and is the target for future studies. Nonetheless, the answer to the reviewer's concerns is addressed by averaging individual explorations as there is not (yet) inter-fleet coordination.

Figure 15 extends the exploration to a dynamic case using a single RPA with GPR, which captures the salient features during the cloud's mature phase when its evolution is slower (Figure 15b; 300 and 500 seconds). For the development and dissipation phases (Figure 15b; 50 and 600 seconds) , the multiple explorations on average reproduce the reference PDFs (black line) for LWC between 0.1 and 0.3 g m-3. Averaging the multiple explorations (individual lines in Figure 15b) yields essentially the same results as a dynamic exploration with multiple, uncoordinated RPA. These results show that the ‘noise’ associated with the reconstructed probability function of LWC is greater during phases with more rapid evolution -- therefore, to reduce the uncertainty, one needs to add RPA. In addition, Figure 15b; 50 and 600 seconds show that the RPA does not capture the higher LWC values associated with the core of the cloud when the cloud element is small, which is a result of a less efficient choice of exploration strategy. In this case, the exploration of small clouds is ‘pattern-limited’, whereby the Rosette strategy, implemented in Figure 15, is limited by the turn-radius of the RPA relative to the size of the cloud. Other patterns for exploration are currently being studied to address this issue.

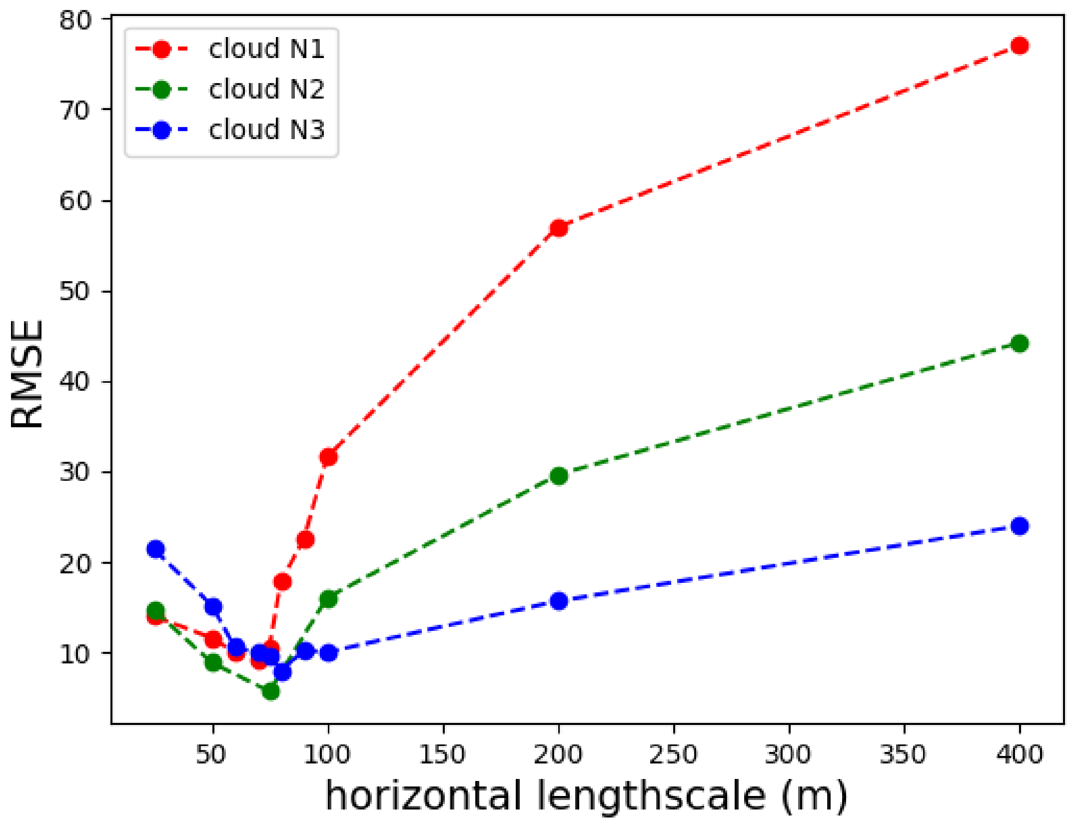
To reiterate, we have made significant progress in developing strategies for exploring clouds in this study. In the current manuscript, we show that exploration of a cloud with a single RPA using GPR is far more effective than multiple RPAs without GPR (Figures 11 and 12).

In the text, we have added the following lines in section 3.3.5:

“Averaging the multiple explorations (individual lines in Figure 15b) yields similar results as a dynamic exploration with multiple, uncoordinated RPA. These results show that the ‘noise’ associated with the reconstructed probability function of LWC is greater during phases with more rapid evolution -- therefore, to reduce the uncertainty, one needs to add RPA. In addition, Figure 15b; 50 and 600 seconds show that the RPA does not capture the higher LWC values associated with the core of the cloud when the cloud element is small, which is a result of a less efficient choice of exploration strategy. “

I am also not convinced that the constant length scale used in the reconstruction is appropriate in every situation. If the cloud would be much larger than N3 in the horizontal dimensions (e.g. a congestus cloud) but would have a similar shape and fractal structure, one would expect the length scale needs to increase as well. There may be reasons to expect that e.g. the scale of the shell does not increase proportionally to cloud scale, but I would still expect that for large clouds, there will at some points be “gaps” when a reconstruction scale of 75m is used. For small cumulus clouds, 75m may be an appropriate choice, but it is good to keep in mind that the scale of 75m is probably close to the effective/actual resolution of the LES (which tends to be a few times larger than the grid spacing) and may also relate to the scale of the gaps between sampled transects.

The sensitivity test to the length scale was first applied on the N2 cloud (equivalent diameter=597 m), which shows that the most efficient length scale is 75 m. The same tests were carried out for the other two clouds, one smaller (Cloud N1, equivalent diameter=240 m) and one larger (Cloud N3, equivalent diameter=1161 m), which resulted in similar length scales averaging 75 +/- 5 m for the three cases (see figure below). The optimum length scale is independent of the cloud size (i.e., N1, N2, N3) suggesting the length scale defined for GPR is related to the length scales of the strongest gradient of the parameter being explored (i.e., LWC in this case). The strongest gradient in LWC occurs in the cloud shell, which is generally two to three grid sizes (i.e., 50 to 75 m) of the LES simulation. The figure below also shows that small length scales (i.e., 25 m) create ‘gaps’ in the exploration, particularly for large clouds, while large length scales blend the cloud shell and cloud core, which is relatively more important for small clouds.



We have added a paragraph in the manuscript discussing this topic below: “Length scales between 25 m and 400 m were used to find an optimal length scale for Clouds N1, N2, and N3. The sensitivity test was first applied on the Cloud N2 (equivalent diameter=597 m), and the most efficient length scale was found to be 75 m. The same tests were performed for the other two clouds (Cloud N1, equivalent diameter=240 m); Cloud N3, equivalent diameter=1161 m), which resulted in similar length scales, averaging 75 +/- 5 m for the three cases. The optimum length scale is independent of the cloud size (e.g., N1, N2, N3) suggesting the length scale defined for GPR is related to the length scales of the strongest gradient of the parameter being explored (i.e., LWC in this case). The strongest gradient in LWC occurs in the cloud shell, which is generally two to three grid sizes (i.e., 50 to 75 m) of the LES simulation. Length scales that are too small (i.e., 25 m) create ‘gaps’ in the exploration, particularly for large clouds; while length scales that are too large blend the cloud shell and cloud core, which is relatively more important for small clouds.”

The title of section 3.3.4 has also been changed to reflect the analysis: ‘3.3.4 Exploring clouds of different sizes’

Minor points:

- The authors mention that random sampling of entry points has a similar effect as using multiple clouds. Especially if the clouds have been selected by hand, there is a chance that robustness for some edge cases (like clouds that are broken up at a certain level, or clouds that have a more line-like shape) is not tested for. This may be a small limitation in practice if other information (e.g. radar) is available, but it would be worth mentioning.

We agree and already briefly mention in the conclusion that improvements in a priori information, such as a camera (or as the reviewer has mentioned, a radar) would significantly enhance the cloud exploration. The sentence now reads:

“In order to improve the observational capacity of airborne measurements, various methods are currently being explored, including the use of a camera system or radar to improve the cloud exploration, particularly for conditions when the cloud boundaries are broken or not well defined (e.g., a dissipating cloud).”

- I think the way the GPR works could be described more clearly. In particular, any differences between the way the edge and the interior (cells that fall between different transects) of the cloud are handled are unclear. Note that in Figure 10, there is a large amount of spurious cloud at the outer boundary.

GPR estimates a value and associated uncertainty using the assigned length scales for a given observation (see above response for the length scale analysis). Along the RPA trajectory the values are known, while the prescribed values that extend beyond the RPA trajectory are the results of a weighted ensemble from each of the observed points. The large amounts of spurious clouds result from the extension of the GPR estimates leading to non-zero values outside the cloud -- especially for longer length scales. Note that a small increase in the threshold (to 0.05 g m-3) would eliminate much of the spurious clouds in Figure 10.

- Another minor point is that it is remarkable that two RPAs+GPR eventually give a larger relative error as compared to one (Fig. 12). Do the authors have an explanation for this (it could relate to the previous point)?

The slightly higher relative error at the end of the exploration for two RPAs+GPR with respect to the LWC distribution comes from the spurious points outside the cloud (see response above). These low values of LWC outside the cloud do not impact the total LWC (Figure 11), but do add a small error for low LWC values when comparing to the LWC distribution (Figure 12 and Figure 15). The message from Figure 12 is that two RPAs+GPR yield better results as the cloud is initially being explored -- which is most important, especially in a dynamic environment.

Minor comments :

- Some examples of e.g. “the N2 cloud”/“the clouds N1 and N3” (with article) appear in the manuscript.

We have rewritten “ Cloud N2 “ to be coherent with figures and throughout the manuscript.

- Multiple occurrences: “cloud grids” → “cloudy grid cells”

We have replaced ‘cloud grids’ with ‘cloudy grid cells’.

- At places where volumes are calculated, it is still not clear that a 25m thick layer is used (e.g. Figure 9). This needs to be made very explicit (and in fact it would be better to use per area quantities). For the transect method, the 25m grid used to calculate the total LWC also needs to be mentioned explicitly.

We have added a statement to specify how the volume is calculated.

“The transect method systematically underestimates the cloud volume section (area of the section multiplied by the 25 m thickness of the grid cell)”.

- Line 53-55: “These campaigns”/”These LES” needs to be expanded (as “these” does not refer back to the previous sentence).

We have replaced ‘these’ with “the “.

- Line 74: “in static case” → “in a static case”

Corrected

- Line 75: “field” → “fields”

Corrected

- Line 101: “is not” → “are not”... “a two-moment microphysics scheme” (article and plural needed, also in other places)
We replaced ‘is’ with ‘are’ and “a two-moment microphysic scheme” by a two-moment microphysical scheme”.

- Line 109 etc.: meshes → grid points
Corrected

- Line 121: replace second “of” by e.g. “who argued”
Corrected
- Line 125: change word order “varies between...”
We have changed the word order.

- Line 135; “for the first time” → not sure what is meant here.
We have deleted this term.

- Line 155: a RPA airspeed → an RPA airspeed (similarly “an RPA in line 159 and 322)
Corrected

- Line 258: “ PDF distribution” → “PDF”, “and15” → add space
Corrected

- Line 259: equal to → between X ...and Y. (indicate range, rather than single value)
Corrected. “between 0.7 to 0.9 m.s-1.”

- Line 270: a space is missing in this line.
Corrected

- Line 306: reword to “the formula of Baker et al. “ → This needs explanation: it would be good to repeat the formula of Baker et al.
We have reformulated by: “Using equation (5) of Baker et al. (1984) allows relating the time needed for”.

- Line 308: “allow us to”
Corrected.

- Line 310: “in the hypothesis of a dynamic cloud” → I am not sure what is meant here.
We have replaced this phrase by “in the case of a dynamic cloud.”

- Line 334: “pattern-limited”: explain in text.
We have added: “in that the RPA cannot turn around and re-enter the cloud if the cloud itself is smaller than the RPA’s turning radius. “

- Line 350: note how the reference frame might be derived in practical applications.
We have added “which is redefined at each time step by accounting for the advective wind.”

- Line 374: “intercomparison” (for consistency)
Corrected.
- Line 375 “high-frequency”
Corrected
- Line 403: “allows us to”
Corrected
- Figure 8 caption: replace “alt= 700 m” by “a height of 700 m ASL”.
Corrected