Review 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 manuscript assesses how Remotely Piloted Aircrafts (RPAs) could be applied to measure the spatial and temporal distribution of liquid water in shallow cumulus clouds. Within high-resolution large-eddy simulations (LESs), virtual RPAs mimic measurement patterns, which allow the authors to evaluate the potential of this promising measurement approach for static and a temporally developing cloud. Overall, the study is very interesting, and the presented approach could be beneficial to measure small-scale heterogeneities in clouds. However, the manuscript requires substantial major revisions to present a convincing sampling strategy and to reach a state acceptable for publication in Atmospheric Measurement Techniques. More details follow below.

We wish to 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.

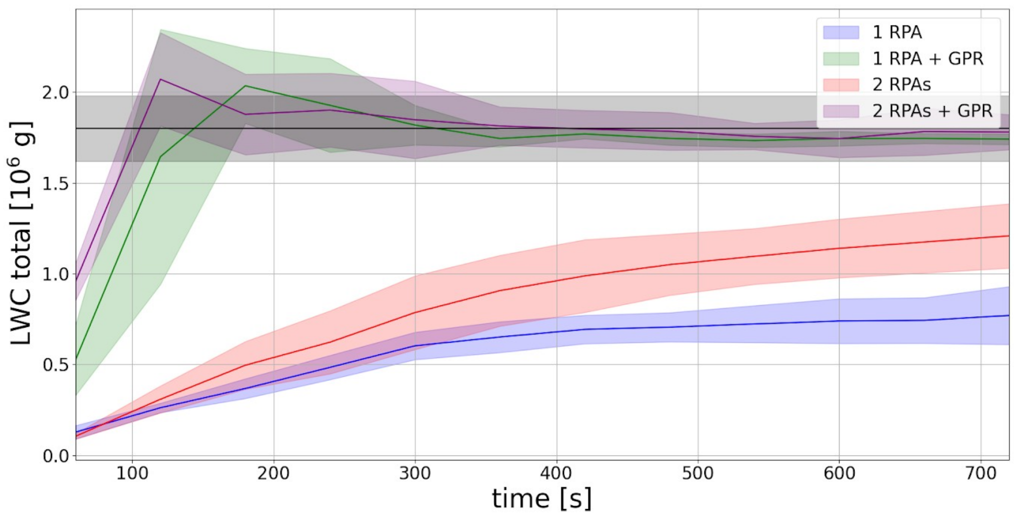
Major Revisions

Effective resolution. The authors need to determine an effective resolution of the suggested sampling strategy to assess whether it can measure small-scale heterogeneities in clouds. The mixing timescale □mix= (l^2/□)^(1/3)' might be useful here (Baker et al. 1984). □mix indicates how fast a heterogeneity with a typical lengthscale l decays to the Kolmogorov lengthscale for a turbulence kinetic energy dissipation rate ε. Figure 11 shows that for estimating the total LWC, at least 300 s of measurements are necessary (1 RPA + GPR). If you equate this to the mixing timescale and solve for l, one yields an effective resolution of 164 m. (I used □ = 10 cm^2 s-3, which is a low but typical value for shallow cumulus; more accurate estimates of ε might be available from the LES model’s subgrid scheme.) Accordingly, only heterogeneities larger than 164 m can be assessed reasonably, which is probably too large to investigate the dynamics of entrainment and mixing, which are associated with lengthscales ≤ 100 m (e.g., Bodenschatz et al. 2010). This quick calculation indicates that several RPAs, which can shorten the time to measure the cloud, are necessary to gain reasonable insights into the small-scale dynamics of clouds, and the authors have missed the opportunity to include more RPAs in their analysis.

We appreciate the reviewer’s insight and fully agree that a scale analysis establishes criteria for a sampling strategy. The mixing time stated Baker et al.1984, provides a target temporal resolution for assessing the evolution within the cloud. As noted by the reviewers, for the simulations shown in Figure 11, this scale analysis suggests that total LWC needs to be measured within temporal scales of ca. 200 sec (using a 100 m length scale defined in Bodenschatz et al., 2010).

We can also assess mixing length scales (L) using the follow expression (Taylor, 1935), L ~ $w3$ / ε

Updrafts (w) in trade wind cumuli are typically > 1 m/s (Katzwinkel et al., 2014), resulting in length scales > 1000 m (which are often larger than the cloud itself). This scale analysis suggests that spatial scales in clouds are driven by gradients in updraft, which mostly occur at the cloud edges. Therefore, to estimate total LWC, the identification of cloud edge and fractal morphology of the cloud is most important. This is consistent with the analysis presented in Figure 9 that reconstructing clouds using circles or ellipses are inadequate -- and that using GPR to map horizontal cross sections of a cloud to estimate total LWC is a viable approach.



Improvements in the sampling strategy can be accomplished in multiple ways, including by adding RPAs, improving the trajectory paths associated with the autonomous sampling, and optimizing the GPR length scales. We have since added the results from the simulation of two RPAs (Fig. 11) and show that the time to estimate the total LWC approaches 200 sec -- a temporal resolution that is sufficient for following the evolution of a cloud. We expect optimization of GPR length scales and using coordinated trajectories will improve the mapping of the cloud cross section and reduce the time to estimate the total LWC.

The use of multiple RPAs. The number of RPAs is probably insufficient to resolve the cloud at spatial scales relevant to entrainment and mixing, as indicated above. Furthermore, the authors also conclude that one RPA is insufficient for assessing a developing cloud (ll. 348 – 351). Accordingly, why do the authors not investigate the impact of a potentially much larger number of RPAs? The presented workflow for determining the virtual RPA measurements could be repeated several times with different initial locations without too much additional work. The results would probably assess how the results improve as a function of the number of RPAs, and how many RPAs are at least required to sample a developing cloud. This information is highly relevant for planning real applications of RPA sampling, and need to be included in this manuscript.

The GPR mapping with the use of two RPAs was carried out, and has been added to the new version of the manuscript (L301-306; purple line in Fig.11 and Fig.12). As mentioned in the previous response, adding two RPAs with GPR reduced the time to estimate total LWC from 300 seconds for 1 RPA+GPR to ca. 200 seconds.

We intend to investigate GPR mapping using a much larger number of RPAs; however, exponentially more computer resources were needed and, unfortunately, we were not able to go beyond two RPAs for this study. We are currently optimizing the simulations to conduct the cloud mapping with several (up to 6) RPAs to define temporal scales as a function of the number of RPAs.

Minor Revisions

L. 5: Why are microscopic properties disregarded here?

We include a reference to microphysical properties. The text now reads "… thermodynamic, microphysical, and macroscopic … "

Ll. 30 – 31: Clarify "climate responses".

We have contributed the role of cumulus clouds to the radiative budget on Earth.

The text now reads "... the impacts of such clouds on the climate radiation budget."

L. 32: Entrainment and mixing create heterogeneities.

We have specified the two types of heterogeneities to the text. The text now read "Mixing process and entrainment impact cloud microphysical properties…"

Ll. 36 – 39: Sub-grid scale liquid water content is not a quantity that is predicted in most LES models. L.54: As above, sub-grid scale variations in the cloud droplet number are rarely predicted in LES.

We agree and we had already acknowledged in the text that LES do not reproduce sub-grid heterogeneities.

"However such models, with a horizontal resolution of a few tens of meters, still use parameterizations to represent cloud microphysics and small-scale turbulence to correctly reproduce sub-grid heterogeneities inside cumulus clouds such as sub-grid scale liquid water content (LWC) variability resulting from mixing processes at the cloud-air interface."

L. 42: A more appropriate reference for CARRIBA is Siebert et al. (2013).

Corrected

L. 47: Regarding the oversampling of the cloud core, you should cite Hoffmann et al. (2014) here. Corrected

L. 98: Why did you use only a one-moment microphysics scheme? Turbulent mixing, which is a potential subject to be addressed within the presented framework (l. 32), is known to droplet number significantly (e.g., Baker and Latham 1979), which requires a two-moment microphysics scheme to be represented correctly.

We agree, but the reason for using a one-moment scheme is that no aerosol size distributions were measured during the BOMEX campaign to initialize a two-moment microphysical scheme.

In addition, since these RPAs did not measure aerosol size distribution, we chose to stay with the use of a one-moment scheme to compare with previous BOMEX simulations (Siebesma et al., 2003).

L. 100: In the literature, the term "saturation adjustment" is more frequently used than "all-or- nothing". Please consider changing.

Corrected

Ll. 104 – 107: What do you expect from the larger domain? Why do you introduce that smaller domain at all?

The Siebesma et al., 2003 intercomparison exercise was based on a 6.4 km square domain. We first used this domain to validate our model and then we enlarged the domain by (2 x 2 -- a factor of four) to have a larger number of clouds and a more representative cloud population for subsequent analysis. The larger domain facilitates exploration by the RPAs without constraints from domain boundaries.

L. 109: The term "High Frequency Simulation" is misleading. The simulation is not high frequent; the output of data is. I suggest "High Frequency Sampling" as an alternative.

Corrected

Ll. 116 – 117: It is well known that the TCC increases for higher resolutions. I suggest citing Matheou et al. (2011) here.

We thank the reviewers for pointing this out. We have added the citation.

L. 158: How do you calculate the geometric center? The red dot in Fig. 3 does not look very much in the geometric center. In the conclusions, you state that the geometric center is weighted by the LWC, which is relevant information but should be stated here already.

Yes, the geometric center is weighted by the LWC from the cloud mapping. We have included this in the manuscript "using a weighted sum of the LWC".

Indeed, during the first transects, the geometric center is still incorrectly placed but at the end of the exploration, the geometric center is located in the correct place. This has been clarified in the text as well.

Ll. 192 – 193: Clarify how the large standard deviation highlights the role of clouds in the transport of water in the atmosphere.

We had not intended to relate the large standard deviation to the role of clouds in the transport of water in the atmosphere, but to the positive mass flux. This phrase is not needed and has been removed.

L. 204: How do you define microphysical properties?

We have removed the term “microphysical”, because it is not appropriate here.

Ll. 258 – 268, 373 – 376: Is the discussion of simple geometric forms necessary? I would omit these lines in the revised manuscript. Why do you address Fig. 10 before Fig. 9?

We feel that the discussion of simple geometric forms is necessary. Certain studies as Rodts et al., 2003 made the direct observation of cumulus, and proposed the circular or ellipsoidal shape of the cumulus sections. Figure 10 (previously Figure 9) clearly shows that mapping by GPR improves the estimate of a total LWC.

Also, we have changed the order of the figures.

Fig. 10: The colors stated in the caption do not correspond to the colors assigned in the line labels.

Corrected

L. 290: Clarify what do you mean by 1-RPA and 2-RPA. I assume that the latter describes the

investigation with two RPAs, but it is not stated explicitly.

We clarified this point by adding the following text to the manuscript: “Four sampling strategies are compared: single RPA exploration just using observations along the trajectory (1-RPA) and with GPR mapping (1-RPA + GPR). Similar notation is used for the 2-RPA exploration.”

Fig. 11: It might be helpful to add the number of transects on the x-axis, in addition to time.

The transects for each of the different explorations do not have the same duration, which led us to express the x-axis in time rather than the number of transects.

Ll. 324 – 325: Does this statement refer to N2? This is, however, already shown in Fig. 12. Please

clarify.

Corrected

The manuscript now reads: " Finally, Fig.13 shows that when using GPR for a middle cloud (cloud N2), the relative error is below 0.2 midway through the exploration."

L. 333: The static cloud has been discussed in the Sections 3.3.1 to 3.3.4.

We have corrected the section numbers.

L. 340: For clarity, consider calling the four "instances" "timeframes".

We agree and have changed the text in the manuscript.

Fig. 14b: Why is this panel not discussed in the text? And why are there two sets of starting and

ending points?

We have added the description for Fig 14b.

"Figure 14b represents the RPA transects in a fixed frame where advection has been removed (in a Langrangian reference frame). The cloud transects are 500-600 m long, and map the evolution of the cloud's boundary."

The flights of RPAs took place at a simulated altitude of 700 m above the ground. If the altitude of the drone exceeded an altitude range of +/- 10 m, the simulated measurements were from an overlying or underlying mesh and not recorded. This means that in some places, the points are not plotted, especially during the turns of the RPAs.

Ll. 350 – 351: A potentially better sampling strategy has not been discussed. Omit this sentence.

Indeed. The sentence has been removed.

<u>Technical Corrections</u>

Ll. 2 and 26: Decide on "earth" or "Earth".

Corrected. We use "Earth".

L. 14: "maritime" instead of "oceanic".

Corrected.

L. 19: “distribution”, not “distributions”.

Corrected.

Ll. 133 – 142: The figure uses a slightly different notation for the points in time. (E.g., t=0 and not t0.)

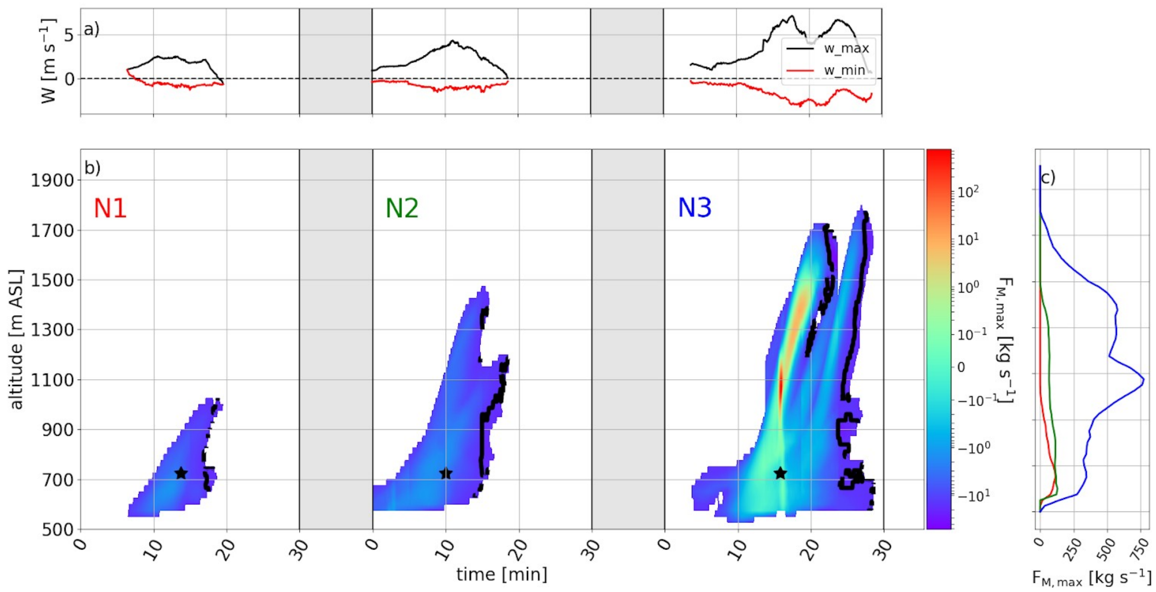
We have homogenized the notation.

L. 150: “RPA” not “RPAS”.

Corrected.

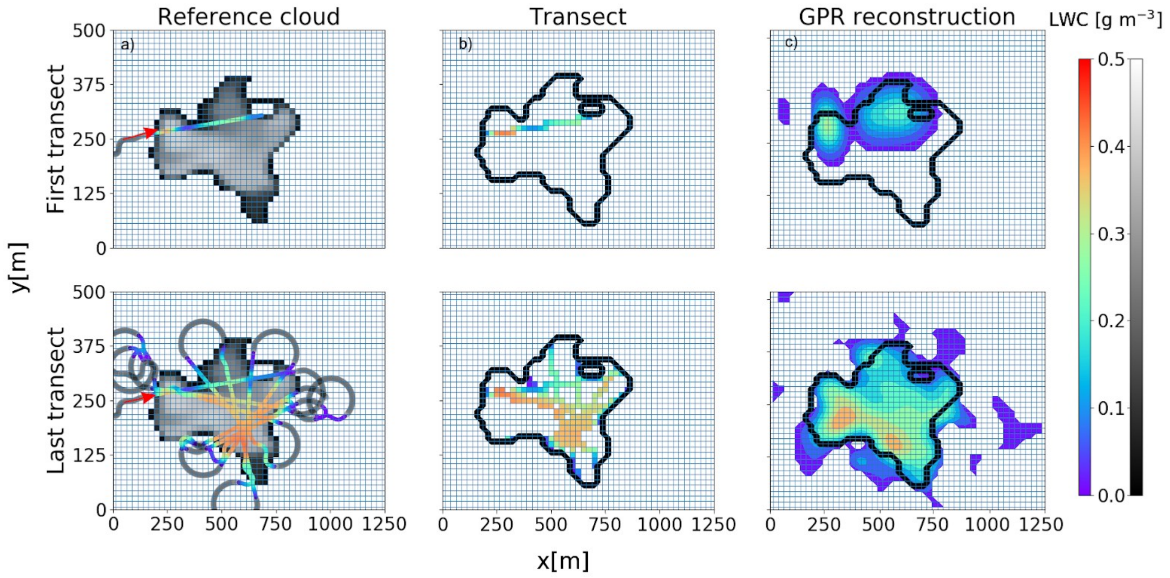
Ll. 221 – 225: Where are the panels a to c in Fig. 6?

We have added the panels in the figure.



L. 241: Where is the red arrow in Fig. 7a? And where is Fig. 7a?

We have added the panels and red arrows in the figure.



L. 252: Check the citation style: “Hoffmann et al. (2014)” instead of “(Hoffmann et al. 2014)”. Corrected.

L. 271: Add a blank after “profile.”

Corrected.

L. 278: There is one parenthesis “)” too many.

Corrected.