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)

REVIEW 1

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

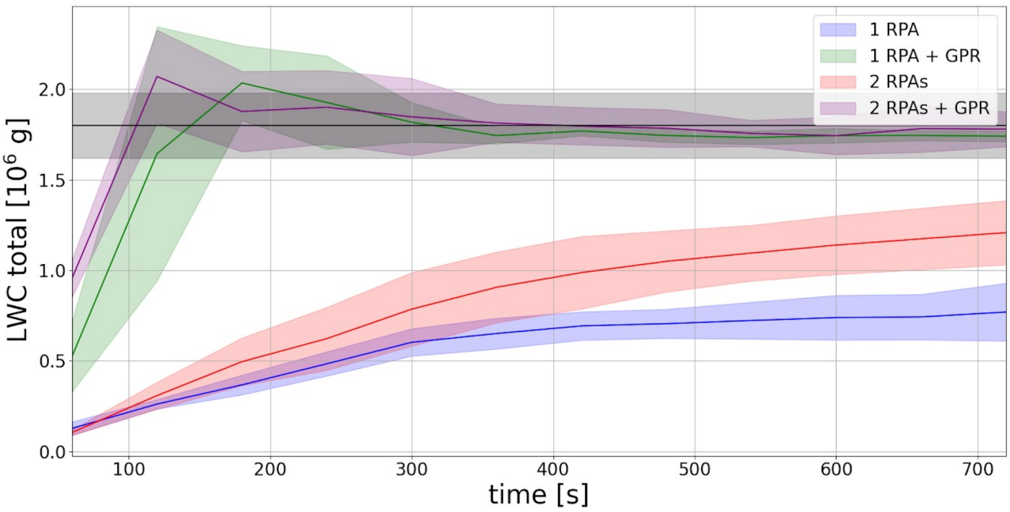
Effective resolution. The authors need to determine an effective resolution of the suggested sampling strategy to assess whether it can measure small-scale heterogeneities in clouds. The mixing timescale □mix= (l^2/□)^(1/3)' might be useful here (Baker et al. 1984). □mix indicates how fast a heterogeneity 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 ~ *w*3 / 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.)

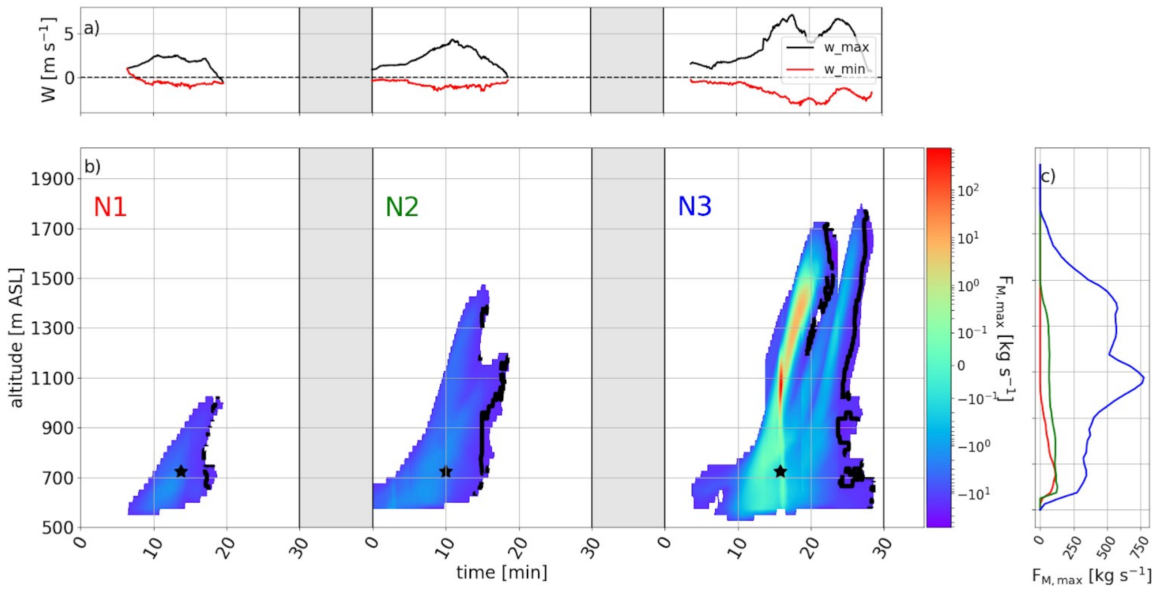
We have homogenized the notation.

L. 150: “RPA” not “RPAS”.

Corrected.

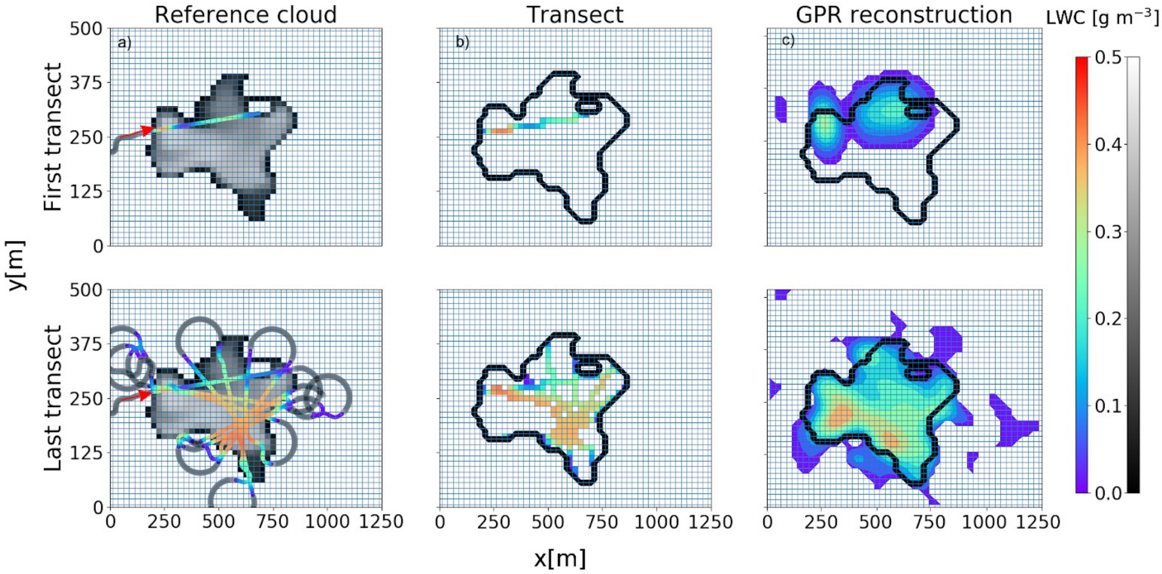
Ll. 221 – 225: Where are the panels a to c in Fig. 6?

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.

REVIEW 2

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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 is our response to the comments (recalled in italic) on a point-by-point basis. The new text in the manuscript is indicated in red.

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 $\tau mix= (l^2/\varepsilon)^{(1/3)}$' might be useful here (Baker et al. 1984). τmix 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 ε = 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.

The mixing time defined by Baker et al.1984, is indeed a good way to judge the adequacy of adaptive UAV sampling. In the Meso-NH model, we have access to the TKE dissipation rate in all model meshes. We decided to take those corresponding to the level of exploration in the clouds as well as to the different times of static exploration. This one is on average at 0.89 for the N2 cloud which allowed us to deduce that a single drone could determine characteristic mixing scales around 150 m (with a good resolution time of 300s). Since it is mentioned in the article of Bodenschatz et al. 2010 that the heterogeneities of the cloud variables are associated with mixing on scales of less than 100m, we continued the study with two UAVs and by associating them the mapping by Gaussian process, which was not the case in the previous version.

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.

According to your comment, computations with the use of two RPAs and GPR mapping was carried on. This is now added in the new version of the manuscript (L301-306; yellow line in Fig.11 and Fig.12).

Adding two RPAs with GPR reduced the time to have a well-defined total field of LWC by almost half (300s for 1 RPA+GPR versus 180s for 2 RPA+GPR). This also allows to quickly reproduce the heterogeneities created by small scale mixing (70-80m). However, the gain is less strong to represent the distribution of LWC in the cloud, since a rapid decrease of the relative error is visible in the first 100 seconds but it still converges to 0.15 as for the exploration with 1 RPA+GPR.

The exploration with two RPA+GPR was then performed on the two other cloud types (N1 and N3). The errors decrease faster for the two clouds but the difference between the N2 cloud and the others remains the same, confirming that the medium size clouds associated with a 75 m scale to perform the mapping remains the most adequate.

Minor Revisions

L. 5: Why are microscopic properties disregarded here?

The article discusses the strategy to sample a cloud at best in order to characterize a horizontal section of a cumulus cloud and the heterogeneities caused by turbulent mixing. Microphysical data, such as droplet size distribution, are currently not measurable with UAVs, the difficulty being to miniaturize such instruments so that they can be embedded. We use a cloud sensor that allows us to calculate the extinction due to the presence of cloud water and by approximation, a liquid water content.

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

We have added the role of cumulus cloud to the radiative budget on Earth.

L. 32: Entrainment and mixing create heterogeneities.

We have complete the two types of heterogeneities causes.

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.

The aim is to understand the variations of the LWC over a few meters, which is complicated to have in LES. It is for this reason that we want to test a new acquisition method in real cumulus cases

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.

The reason for using a one-moment scheme is that no aerosol dimensional spectra were measured during the BOMEX campaign to initialize a two-moment microphysical scheme. Also, since RPAs do not have the capability to measure these spectra, it was chosen to stay with the use of a one-moment scheme.

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 4 in order to have a larger number of clouds (and a more representative cloud population) and also to allow an exploration of RPA without contrainsts 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.

I 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.

The geometric center of the cloud is calculated by combining the shape of the estimated cloud and the measured LWC in the cloud ($\bar{x}=\frac{\sum x_i . LWC(x_i)}{\sum LWC(x_i)}$). Indeed, during the first transects, the geometric center is still badly placed but at the end of the exploration, it is located in a more suitable place.

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

I removed this comment.

L. 204: How do you define microphysical properties?

I removed the "microphysical" term because it is not appropriated 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?

Certain studies concerning the direct observation of cumulus put forward the circular or ellipsoidal shape of the cumulus sections. We want to show that these hypotheses do not always work and that mapping by Gaussian process remains the best way to estimate a total field.

We have change the order of the Figure (Fig.10 becomes Fig. 9)

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.

Corrected

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 and not in number of transects.

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

Corrected

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

We have modified the number of section.

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

Corrected.

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

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

The sentence has been removed.

<u>Technical Corrections</u>

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

Corrected by Earth.

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

Corrected by maritime.

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 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.

REVIEW 2

We wish to thank the reviewer for his/her careful review. Below is our response to the comments (recalled in italic) on a point-by-point basis. The new text in the manuscript is indicated in red.

After providing an access review for this article previously, I have now reread it in some more detail. The approach described here is certainly worth pursuing, but I still think the manuscript would greatly benefit from the inclusion of some exploration of the time-evolving case with multiple RPAs. This could be a proof of principle to show that it is possible to characterise the time-evolution of the cloud.

The intervention of a second drone in static with mapping has been tested in the case of a static cloud. Given the good results of this method, it would indeed be very judicious to apply it in a dynamic case. However, the aim of this article is to focus on the behavior of adaptive exploration in a static cloud (less difficult to sample) and the contribution of GPR mapping to reconstruct cloud cross section. The dynamic case could be treated in a second paper where we would compare those executed in simulation versus applied in real cumulus cloud field.

For the time-evolving case, some of the transects in the mature phase (e.g. transect 4 and 7 in figure 15) might resemble the full PDF, but these could be "lucky" transects. Moreover, since the analysis is on single transects here, there does not seem to be an advantage over using single passes with a traditional approach. The abstract should at least mention that a single RPA isn't enough to accurately reconstruct individual clouds.

During the adaptive exploration in the case of a dynamic cloud, the adaptive exploration was performed with different inputs corresponding to several transects.

These transects were mapped by GPR at the end of each transect in order to map the cross section of the explored cloud and its associated heterogeneities. This mapping was built taking into account the previous transects but attenuating their effects. Indeed, we take into account the temporal length scale which is fixed at 60 s. This has the advantage of reducing the relative error on the PDF of LWC.

Also, this exploration with the Rosette pattern has the advantage of being automatically performed without the help of the operator, unlike a more classical exploration with search planes. The algorithm detects the boundaries and starts the traverses in the cloud by focusing on the geometrical center computed previously and advected by the input data which is the advective wind.

I also think the focus on only 3 clouds (even if these clouds are sampled from multiple starting points) is a weakness of the study. Clouds tend to vary considerably in terms of their shape, especially when they contain multiple updraught cores, so it is hard to see if the results here are generally robust. Showing the LWC convergence for at a few more clouds in the same class size as N2 and N3 would help to establish robustness.

The 3 cloud sampled in this study have not been chosen arbitrarily but after the analysis of the cloud population simulated in the LES. We have indeed shown that the 3 cloud are representative of the cloud population. Indeed, they show also similarities with the clouds sampled in the study of Zhao and Austin (2005). Also, having non-circular cross-sections with fractal edges allows to test the capability of the mapping.

This article is intended to test the adaptive exploration and the coupling with mapping. These explorations have been tested in a real case of cumulus during the BOMEX campaign which will be the subject of an article and has shown the real potential to track clouds in time and space.

The length scales for GPR currently seem to be chosen by trial and error, but will depend on both the cloud scale and how well the cloud has been sampled. Note that 75m seems to give a good PDF of LWC, but the LWC RMSE is relatively high. It would also be worth pointing out that clouds are fractal objects, and that this is one of the reasons an ellipse/circle reconstruction fails (another reason is that a transect may not pass through the actual centre).

The length scales are tested for different types of clouds and the value of 75 m remains the most suitable to reconstruct a LWC field, whatever the size of the cloud. In the future, we plan to deploy conjointly with the RPA two visible cameras with different point-of-view which will allow to reconstruct the geometrical characteristics of the clouds, provide a first value for the length-scale and also help in driving the drone directly to the targeted cloud.

There is another comment on the discussion which mentions the effective resolution of the strategy is 164m. This interpretation does not look right to me, but it would still be good to discuss the practical limitations on resolution that the RPAs may have.

We retested the adaptive exploration with the two UAVs coupled with GPR mapping (L301-306; Fig.11 and Fig.12).

This led to a reduction of the time to have a good restitution of the total LWC and a PDF of lwc below 100 seconds. By applying the formula of Baker et al., 1984, small mixing processes (70-80m) involving LWC heterogeneities in the cross section can be well defined, thus improving these changes in the dynamic case.

Overall, I think some major revisions would really strengthen the article, and make it suitable for publication. Besides these general comments, I have included a list of minor issues below; these are mostly simple to address though.

General notes:

- *Subfigure labels are missing on most plots.* corrected

- *A non-uniform aspect ratio is used in some figures (e.g. figure 9) ==> je suis en train de changer*

- *Some fonts are often too small (e.g Fig 1, 5-6, 8 and 14-15) Fonts have been changed*

- *Figure 6: The black lines in b. are hardly visible The black line has been enlarged*

- *Figure 7: It is hard to compare the LWC in the reconstructed cloud with the LES field here, though figure 9 clarifies this.*

The color palette was chosen to better visualize the measurements made during the first transect and for the entire exploration.

- *I think the "(1-\sigma)" notation for standard deviation is confusing. Is the mean +/- the standard deviation meant?*

The notation «(1-\sigma)» has been changed by ±.

Line-by-line:

- l3: Earth (capitalise) corrected

- l15: "allows to track" → "allows tracking" corrected

- l24" "oceanic surface" → "ocean surface" corrected

- l25: remove "annual" corrected

- l29: "climatic" → "climate" corrected

- l34: "The studies on these processes" → "Studies of these processes" corrected

- l43: "(i.e. the Fast-FSSP (Brenguier et al., 1998) to the HOLODEC" → "(e.g. the Fast-FSSP (Brenguier et al., 1998) and the HOLODEC" corrected

- l47-49: "Some measurement field campaigns have allowed a re-sampling in clouds with aircraft (Burnet and Brenguier, 2007) and with sensors suspended below a helicopter during the CARRIBA campaign (Siebert et al., 2006, Katzwinkel et al., 2014)." → This sentence is not clear.

We have modified the order of this paragraph to better reflect the idea that the sampling is still too limited to reconstruct a horizontal cloud cross section with conventional equipment.

- l52: "in detail" (singular) corrected

- l64: " microphysic" → " microphysical" We have removed the term.

- l68-72: " Section 3 highlights the results of the LES case study with an overview of the cumulus field...We then select one cloud representative of each category and analyze the evolution of their macrophysical and thermodynamical properties, by comparing the exploration strategy and the capacity of the RPAs to reconstruct the microphysical and macrophysical fields for static and dynamic cases." → Both of these sentences are unclear, in particular "an overview of the cumulus field" and "analyze...by comparing the exploration strategy" (which suggests the exploration strategy for static cases is different from that for dynamic cases, it is unclear how "comparing" refers back to "analyze").

- l78: "the period between 22 to 23 June of the Phase 3 of the BOMEX campaign characterized" → "the period 22-23 June of phase 3 of the BOMEX campaign. These days are characterized" corrected

- l81: "LESs" → Rephrase (the plural form is confusing) corrected

- l85: "Well-represented" does this mean the simulations are in line with the intercomparison case? As this is pointed out later, I would leave it out here. *We have removed this sentence.*

- l87: "is initialized... decreases" → make plural corrected

- l89 and elsewhere: asl → ASL *corrected*

- l93: " the piecewise parabolic model" → *I think this has not been introduced. We have simplified the description of simulation set-up.*

- l98: using a single moment scheme may be appropriate in this case, but there is not really a justification given.

We have added a sentence explaining the choice of a microphysical one-moment scheme . Using a two-moment scheme could understand how turbulence affects the distribution of droplets in the cloud, but no aerosol spectra from the BOMEX campaign are available to us.

- l104 "four times" The LES simulation was conducted just one time, at different domain size.

- l108: "outputted" → "stored" corrected

- l109 and elsewhere: "high-resolution" corrected

- l115: It is worth noting the onset of convection is delayed and much more active in Meso-NH.
Added for the 20 minutes delay but convection seems to have the same intensity

- l117: Put the year 2003 in parenthesis. corrected

- l124: "cloud entire life cycle" → "entire cloud life cycle corrected

- l126: "the function of time" → "a function of time" corrected

- l130: "isolates..defines" → "isolate...define" *corrected*

- l132: it is unclear if/where faces, edges, or corners respectively are used in the tracking algorithm

We rephrased by « For each cloudy cell, the method identifies the neighboring cells connecting per face, edge or corner »

- l150: "RPAS" → "RPA" corrected

- l175: It is worth pointing out here that the few clouds in class 3 contribute disproportionally to cloud volume, mass-flux and heat and moisture transport.

We have added a sentence mentioning the importance of these cumulus clouds in the mass transport balance in the boundary layer. « Despite the small number of clouds classified in class 3, they have an important role in the transport of moisture and heat in the boundary layer since their mass flux is an order of magnitude larger than the clouds of class 0 and 1. »

- l180: "the minimum and maximum lifetime...over their lifetime" → rephrase

Rephrased by " For each class, the minimum (maximum) lifetime is calculated by averaging the lowest (large) 10th percentile. The minimum cloud base (top) is calculated by averaging all the minimum bases (tops) of each cloud during their lifetime for each class."

- l184: the smaller clouds may sometimes be remnants where tracking has failed, which would explain their higher cloud base.

⇒ je n'ai toujours pas compris sa phrase et le contexte

- l187: "vertical extension and variations" → what is meant by variations here?

We have remoed this term.

- l193: "The standard deviation is 200 times greater than the average flux for cumulus class 0, while it is only 1.37 times greater than the average mass flux for class 3." → I am a bit sceptical of the first result. Maybe leave this out, as it is not supported with further data or figures. The large standard deviations could be the result of using large bin sizes for the classes.

I agree, we have removed this sentence.

- l205: "are followed" → "is followed" corrected

- l215: "summit" → "top" corrected

- l220 and 344: "maturity" or "its mature phase" corrected

- l226: "has permitted [to describe the→ the description of] heterogeneities [of→ in] the horizontal and vertical structure of cumulus clouds, in particular with respect to LWC" → Horizontal structure only seems to be described later in the article. corrected

- l244 and elsewhere: "the cloud N2" → "cloud N2" corrected

- l249: "and 4% of grids have a LWC near 0.40 g per m^3" → this description is imprecise

We want to justify that only 4 % of cloud grids have an adiabatic value, so we removed the « near ».

- l252: remove parentheses corrected

- l253: Does the LWC really approach the reference distribution (without reconstruction, at this point)? It seems like high LWC is still oversampled. The description also doesn't make it clear the PDFs for the later transects are cumulative.

The PDF distribution of LWC approaches the reference distribution but high values still overestimated at the end of exploration (but less with only one transect).

We have completed the term of PDF by a cumulative reconstructed PDF.

- l255: "and representing 15% of the cloud cross-section" → This is unclear

We wanted to described that 15% of grids of cloud cross section are characterised by a value of vertical wind equal to 0.8 m.s^{-1}, corresponding to the peak of gaussian distribution in the cloud.

- l258: "above-mentioned" corrected

- l267-268: "For following...Gaussian" → "Below...GPR" corrected

- l272: \lambda_t = \infinity: do you simply mean temporal variation is not taken into account?

Yes, \lambda_t = \infinity means that we do not consider time in the GPR mapping. We have added a sentence to explicit that.

- l287: "with Rosette pattern" → "with a Rosette pattern" corrected

- l288: "is compared" → "are compared" corrected

- l289: Since this is at one altitude only, the units of LWC_{tot} seem incorrect (it may be in gram per meter vertical extent).

The lwc_{tot} corresponds to the mass of liquid water contained in the cross section. The volume of each cloud grid, 25 m of side, is multiplied for the LWC of the grid to arrive at a total mass.

Similarly, trying to derive this without GPR or an ellipse/circle fitting method (the "method_transect") seems strange. Looking at figure 7, it may be based on a grid here, but that makes it very dependent on the grid spacing used in that grid.

Indeed the estimation of the area covered by the cloud is dependent on the grid used since the area is equal to a factor multiplicate with the size of the grid but we took clouds that covered an area of at least 4 pixels so not too dependent on the grid. With the resolution used here in the LES, the cumulus clouds are well defined in terms of size leaving the first fractal edges visible (Neggers et al., 2003)

- Equation 1: Use n_{bin} for the number of bins.

The term was modified.

- l312: “Table 2 highlighting a significantly improved mapping the cross section by using the GPR method.” → “Table 2, highlighting a significantly improved mapping of the cross section by using the GPR method.” corrected

- l321: I don’t understand the meaning of “pattern-limited” here. It should still be possible to perform many transects in the smaller cloud and get a good reconstruction, though \lambda may need to be reduced.

The term "pattern-limited" corresponds mainly to the limitation for the U-turn outside the cloud. In order to be completely realistic in the flight plans, this U-turn cannot have a radius of less than 100 m, otherwise it would lead to a stall of the aircraft. If the size of the cloud is small, the turn around would either lead to losing the cloud or to sampling the same area.

- l329: “with time and space” → “with time and in space” corrected

- l329: “and reaches 0.1 by the end of the HFS.” → this is unclear to me corrected by “exploration”

- l331: comma missing before “tracking” I do not see tracking in this line

- l338: “continues” → “continue” corrected

- l345: “resembling to” → “resembling that of” corrected

- l348: “ improve the ability to reconstruction of” → “improves the ability to reconstruct” corrected

- l350: “ either via a better sampling strategy of leg adding a second RPA.” → “either via a better sampling strategy or by adding more RPAs.” corrected

- l354: “non-precipitating” → “weakly precipitating”/“without surface precipitation” corrected

- l356: “derived from the observations in” → “, where the simulations are based on observations during” corrected

- l363: “its growth phase, maturity, and dissipation phases”: remove “phase” corrected

- l366: remove spurious “its” corrected

- l373: “assuming a circular” → “assuming circular” corrected

- l391: “ with a different trajectories RPA” → this is unclear. This sentence mentions both “ To optimize the dynamic exploration of a cloud” and “in improving our ability to observe the cloud life cycle”, which makes it too long.

We have rephrased