Author's comment for the editor: Overview of changes made in the revised manuscript

We thank the reviewers for the valuable feedback on our manuscript. We've implemented many changes, as described in detail in the responses to the reviewers, as well as a few additional changes. We present here a brief overview of the major changes to the revised manuscript:

- New section (Appendix A) presents estimates of POPS inlet sampling efficiencies, including new figure (Fig. A1)
- New section (Section 3.1) to illustrate POPS measurement uncertainties, which refers to Appendix B:
    - New figure (Fig. B1) with data from a comparison between $POPS_{TBS}$ and $POPS_{UAV}$ under ambient air
    - New subplot (Fig. B2c) showing POPS measurements of 3 µm particles
    - New subplot (Fig. B3b) showing the quantification of the differences between POPS, APS, and SMPS measurements
- Section 3.2 has been extended to include quantitative comparisons of the effect of rotors, including an updated Figure 4c with lines that show the difference between the size distributions.
- Section 3.3 has been updated to include a discussion of the coarse mode particle measurements during ascent and descent (corresponds to new Figure C2).
- Figure 5 has been updated – the particle number concentrations are now binned in altitude intervals of 20 m instead of 100 m.
- The previous appendix on the data filter for high concentration POPS data is now in the main text (Section 3.4)
- Section 4 has been restructured to present the POPS estimates of PBL height before the ceilometer PBL height
- Figure 11 has been updated to include subpanel (c), which shows timeseries of cloud droplet number concentration and ice particle number concentration from the holographic imager, taken at the same time as the POPS measurements

Author's response to review of "Two new multirotor UAVs for glaciogenic cloud seeding and aerosol measurements within the CLOUDLAB project"

We thank the referee for carefully reviewing our manuscript. We will address the reviewer's comments (black), present our responses (red), and highlight the changes that were made to the revised manuscript (blue). All line numbers in the author's response refer to the revised manuscript.

Referee #2

General Comments:

In the presented manuscript, Miller et al. describe two Uncrewed Aerial Vehicles (UAVs) for cloud research: (i) the "measurement" UAV equipped with an optical particle counter for measuring particle size between 0.1 and 3.4 µm (in diameter) and met sensors, and (ii) the "seeding" UAV equipped with seeding flares, initiating ice particles in supercooled clouds. There is a comprehensive description of the cloud seeding procedure. Tests were made to validate the POPS measurements on-board the multi-rotor, by (i) comparing the ascent and descent profiles, and (ii) assessing the observations with and without the rotors. Characterization of a dispersion of an out-of-cloud seeding plume produced by the flares on-board the UAV was made successfully through the experiment. Results are also shown from an in-cloud seeding experiment, where the seeding UAV was inside a supercooled cloud and the TBS system was downstream. This study successfully demonstrates the capabilities of the measurement UAV and the TBS system to capture the plume produced by the seeding UAV inside and outside the clouds. This work adds a valuable contribution to the atmospheric measurement community and is suitable for publication in AMT with minor revisions.
We sincerely thank the reviewer for the time and care taken for reviewing this manuscript, and for the positive and constructive feedback provided. We are glad that you see the value in our work.

Although, there are some specific areas in the manuscript that need further elaboration/clarification. Here are the main parts that should be revised.

- First of all, the scope of each experiment should be clearly described in the beginning of each related section. There is no clear distinction between the technical purpose and the scientific aim of each experiment.

Thanks for this feedback. We have added three sentences to the beginning of Section 5 to explain better the purpose of the seeding experiments: "Next, we demonstrate how the seeding and measurement UAV are deployed within the CLOUDLAB project (Henneberger et al, 2023). First, we show how the measurement UAV with POPSUAV can be used to characterize the dispersion of an out-of-cloud seeding plume (Section 5.1 and Fig. 8a). The purpose of the out-of-cloud seeding experiment was to estimate the concentration and dispersion of the particles produced from the flares onboard the seeding UAV. Second, we present an in-cloud seeding experiment in a supercooled stratus cloud where the changes in the aerosol and microphysical properties induced by the seeding UAV were measured downstream by the TBS (Section 5.2 and Fig. 8b). The in-cloud seeding experiment was designed to induce ice nucleation and observe ice crystal growth in supercooled clouds. The examples presented here demonstrate the capabilities of the UAVs and other instrumentation, and further results will come in future publications." (lines 378-386)
We also added a sentence to Section 3.3 to give more context to our vertical profile flights with the measurement UAV: "The flights were performed to measure temperature, humidity, wind, and aerosol to plan our seeding experiments (see Section 5), but the flight data can also be used to assess the effect of flight on particle sampling." (line 251-253).

- The authors did not use the UAV observations to estimate the PBL height, but the UAV data were only used for validating the PBL height retrieved by the ceilometer measurements. I would suggest that the authors describe the method of how the PBL height can retrieve only using the met profiles from the UAV, and then validating it with the results from the ceilometer.

Thanks for this suggestion – we agree that reordering the section is sensible. We have adapted the section so that it starts with deriving the PBL from the RH and particle measurements from the UAV, and then comparing those PBL estimates to those from the ceilometer. Please see Section 4 for the updated text.

- In addition, as there was a holographic imager on-board the UAV, it would be good to show some results from it.

The holographic imager was onboard the TBS. We agree that showing these data strengthens the paper and added the cloud droplet and ice crystal number concentrations from the holographic imager to Figure 11c.

- It would be good to show an in-depth characterization of inlet sampling efficiencies for a range of particle sizes and how the 3-D wind affects its efficiency, as well as whether this efficiency differs between ascent and descent profiles.

We have added a new section to discuss the inlet sampling efficiencies, Appendix A: Sampling efficiency of POPS inlet, as also suggested by Reviewer 1.

Specific Comments:

Lines 98, 99: It would be good to stick on the same metric system. Ms^{-1}, and kmh^{-1} are both used.

90 km h^{-1} was replaced with 25 m s^{-1}: “They can fly for approximately 20 minutes at a maximum speed of 10 m s^{-1} and can withstand wind speeds up to 25 m s^{-1}” (lines 99-100)

Lines 100-105: Which met sensors are used on-board? Are they custom-made or commercial? Provide details.

The company manufacturer of the met sensors is considered intellectual property of Meteomatics and thus cannot be disclosed. However, we have added details about the types of sensors: “The standard version of the Meteodrone is equipped with sensors to measure temperature (±0.1 K; Integrated Circuit temperature sensor), relative humidity (±1.8% at 23 °C between 0-90% RH; capacitive sensor with humidity-permeable cover layer), and pressure (±1.5 hPa; Piezo-resistive sensor), as well as a calibrated system for measuring wind speed (± 1 m s^{-1}) and wind direction (± 10°), each at 10 Hz sampling frequency (Meteomatics, personal communication; Hervo et al., 2023).” (lines 102-106)

Line 128: Is it isokinetic inlet? Elaborate if yes, or not.

No, our inlet is not isokinetic. We have added that to the text here: “An inlet extension was designed so that the inlet (2 mm inner diameter, not isokinetic) extends out of the housing,…” (line 133). Furthermore, we have added a new section Appendix A: Sampling efficiency of POPS inlet to discuss inlet sampling efficiencies.

Lines 151-155: Needs elaboration here – provide details on how you decide the ideal seeding altitude, which parameters/conditions are important for this?

We do already list the variables which are important for us: wind, temperature, cloud altitude, temperature, and cloud structure. We have added an additional sentence to provide an example of what we look for specifically when we are going for an in-cloud seeding experiment to produce ice: “For example, when we plan an in-cloud seeding mission, during which we expect to nucleate and measure ice crystals, we target stable low stratus clouds with cloud temperatures below -5 °C (cold enough for ice nucleation to occur with silver iodide particles), low radar reflectivity (i.e., low background ice content), cloud base between 1100 and 1600 m amsl (low enough to be reached with our UAVs and tethered balloon), and wind speeds of 3-15 m s^{-1} (high enough to get advection of the seeding plume, and low enough to have safe conditions for flight of UAV and balloon)." (lines 159-164)

Line 187: Why only those 2 "small" sizes were chosen for the calibration? How about the accuracy for larger sizes than these (i.e. for 2 µm, 3 µm)?
We only showed these two measurements because they were done with both POPS, allowing for direct comparison. We also had an experiment of $POPS_{TBS}$ with the APS measuring 3 µm polyethylene glycol aerosol particles, produced using a Vibrating Orifice Aerosol Generator (VOAG, TSI), now added as a subplot Figure A1. Unfortunately, the $POPS_{UAV}$ was not available at that time to be included in the comparison. However, we do expect that the two POPS would measure similarly to each other, as they do for ambient air (also added, see Figure A1) and for the 246 and 522 nm particles. The following text was added, in addition to the new Figure A2: "To measure supermicron particles, 3 µm polyethylene glycol (PEG) particles were generated using a Vibrating Orifice Aerosol Generator (VOAG 3450, TSI). Measurements from $POPS_{TBS}$ were compared to an Aerodynamic Particle Sizer (APS540 3221, TSI), as shown in Figure B2c. The APS aerodynamic diameters were converted to volume equivalent diameters using the density of PEG of 1.125 g cm^{-3} and a shape factor of 1. Furthermore, the APS data was rebinned and renormalized to match the bin widths of the POPS instrument, to make the size counts more comparable. $POPS_{TBS}$ correctly sized the 3 µm PEG particles, and the concentrations in the 2585-3370 nm size bin agree with the APS concentrations within 44%, similar to the APS and POPS differences under polydisperse ambient air. At this time, $POPS_{UAV}$ was not available for experiments, but based on the previous comparisons of $POPS_{UAV}$ and $POPS_{TBS}$, we expect that they would perform similarly here." (lines 588-596).

Line 217: Have you checked this in lower ascending/descending speeds than 10ms^{-1}? It would be interesting to see whether similar results are derived.
Early on in the development of the measurement UAV, we tested profiling speeds of 1, 3, and 10 m s^{-1}, though we were only allowed to fly to 100 m at that time. In those very preliminary tests, no differences were found between flight speeds. To optimize time and the limited use of battery, we decided to follow the Meteomatics operational flight speed of 10 m s^{1} for our vertical flying speed, especially because the meteorological measurements are validated and calibrated for this flight speed (corresponding information was added: "… and all meteorological measurements are validated and calibrated by the manufacturer for the operational profiling flight speed of 10 m s^{-1}" lines 107-108). Therefore, we did not perform further profiling with other flight speeds. However, we do agree that it would be interesting to see whether similar results to our ascent/descent analysis would be found with other flight speeds.

Line 234: The ascent/descent speed for the experiment were 10ms^{-1}?
Yes, exactly.

Line 246-248: There are many more ways to calculate the vertical profiles of aerosol concentrations. The sentence needs rephrasing, to be completely valid.
That is true. However, in restructuring the section, as suggested in your general comment above, this sentence is now omitted.

Line 251: Text needs to be ahead the figure (i.e. Fig. 6).
We have moved the figure to be after the text. The final formatting will be done by the journal.

Line 253: How the blue line was derived by the RH minimum gradient? Provide justification.
The gradient of the relative humidity curve was calculated, and the point at which this gradient was smallest, i.e. the most negative, was taken as the height of the PBL. This is a common method for

determining PBL height, described for example in Seidel et al (2010) or Collaud Coen et al (2014). We have adapted the text to read: "The height of the PBL using this RH profile can be estimated by finding the minimum (i.e., most negative) in the gradient of RH with respect to altitude (Seidel, et al.., 2010; Collaud Coen, et al., 2014), which results in a PBL height of 1421 m amsl." (lines 357-359)

Line 302-304: Not clear aim of this experiment (Sec. 5.2). Which was the main purpose of this specific experiment? Why not using a sensor for measuring the large particles in the plume too, so as to measure the supercooled cloud droplets and ice crystals there? Was the sole scope to measure only the remaining inactivated seeding particles?
We can see how this may be confusing. The overall goal of the in-cloud seeding experiment was to produce ice crystals. We have done many of these experiments in the course of our CLOUDLAB project, and the results in terms of ice crystal production are discussed in the CLOUDLAB introduction paper by Henneberger et al. (2023). We did decide to additionally add data from the holographic imager to show cloud droplets and ice crystals in Figure 11c. We've added two sentences at the beginning of Section 5 to explain better our goals for these experiments: "Second, we present an in-cloud seeding experiment in a supercooled stratus cloud where the changes in the aerosol and microphysical properties induced by the seeding UAV were measured downstream by the TBS (Section 5.2 and Fig. 8b). The in-cloud seeding experiment was designed to induce ice nucleation and observe ice crystal growth in supercooled clouds. The examples presented here demonstrate the capabilities of the UAVs and other instrumentation, and further results will come in future publications." (lines 382-386)

Line 305: It would be good to show some results from the holographic imager.
We agree! We have added to Figure 11c timeseries of cloud droplet number concentration and ice crystal number concentration and included some mentions of it in the text:
"The seeding signal is also visible in the ice crystal number concentrations, which increase from 0 up to 500 L^{-1} (Fig. 11c) at the same time as the particle number concentration increases." (lines 440-442)
"Therefore, we believe the elevated concentrations that $POPS_{TBS}$ and HOLIMO measured are the seeding plume passing by, and not natural variation in the cloud" (lines 446-447).
"We have shown that not only can we produce a cloud seeding plume from a multirotor UAV, but we can also detect seeding particles and ice crystals up to 3000 m downstream (Sect 5.2),.." (lines 502-503)

Line 311: Are there specific criteria to choose the seeding altitude?
We choose the seeding altitude based on the criteria mentioned in Section 2.4. If we have access to the whole cloud, as was the case in this experiment, then we tended to choose based on temperature. It is also a matter of logistics such as how high the TBS can fly, how bad the icing conditions are for the UAV and the TBS, etc.

Lines 337-339: Good thinking and reasoning, are there any relevant references from literature?
Thanks, and yes we have now added two references, Flossmann and Wobrock (2010) and Ohata et al. (2016) to the sentence: "..showing the effects of particle activation into cloud droplets as well as scavenging of aerosol particles by cloud droplets, as previously documented by others (e.g., Flossmann and Wobrock, 2010; Ohata et al., 2016)" (lines 561-462). The first is a review of theoretical and modeling concepts regarding wet scavenging of aerosol, and the second is recent experimental evidence for wet scavenging.

Line 341-344: Additional information is needed for the inlet of POPS. Also, could you also use any "drying and/or heating mechanism" to tackle the tackle the built-up moisture in the inlet?

Additional information on the POPS inlet was added to Section 2.2: "The sampled particles are not dried prior to measurement, thus $POPS_{UAV}$ reports particle diameters that are humidity-dependent and have to be interpreted along with the relative humidity measured by the Meteodrone sensor." (lines 136-137), and reference that in Section 2.5: "$POPS_{TBS}$ has an inlet design identical to that of $POPS_{UAV}$ (see Section 2.2)." (line 192). Further information on the inlet sampling efficiencies is added in the new section Appendix A: Sampling efficiency of POPS inlet.
Regarding a drying or heating mechanism, that would be something that could be added in the future which would help to overcome this problem. A sentence has been added for that: "For future projects, it could be worthwhile to build an inline drying or heating mechanism in the inlet, with the consequent exclusion of cloud droplets measurements due to their evaporation." (lines 469-470).

Line 350: "comparable to other aerosol instrument measurements": add some quantitative results here, e.g. XX% deviation, etc.
We added a quantification to the text: "We then showed that the POPS data are comparable to other aerosol instrument measurements (particle number concentrations within 50%; Sect. 3.1) and that there is a minimal effect of rotor-induced turbulence from the UAV on particle number concentration (Sect. 3.2 and 3.3)." (lines 474-476)

Line 355: Not correct wording. The concentration of the UAV profile was not compared to the backscatter signal from the ceilometer; as the parameter shown was not the same to be able to compare them. The sentence needs rephrasing.
Since we have restructured the section about the use case for determining the PBL, we feel that this sentence in the conclusions is now appropriate as written.

Line 376: There was not robust assessment of the microphysical properties/changes.
It is true we have not shown that in this work. We intended it to mean that it would be possible in the future. We've clarified the sentence as follows:
"We have shown that not only can we produce a cloud seeding plume from a multirotor UAV, but we can also detect it up to 3000 m downstream (Sect. 5), and in future work we can therefore assess the microphysical changes within the plume." (lines 502-503)

Line 473: XX needs to be replaced with the corresponding text.
Yes, thanks for the reminder. The data and scripts are now available at
https://doi.org/20.500.11850/640942

Figures:
General comment: Text introducing figures should always be ahead the figures
We did this where it was possible, but we also wanted to optimize the space in the document. We trust that the final formatting will be done by the journal accordingly.

Figure 2: Not very clear image
We would like to have a higher-resolution image of the seeding UAV in-action, but this was limited given that the UAV must be at least 100 meters above us for seeding.

Figure A1: Not very clear. It would be better to visualise the two sizes in 2 different figures, one next to the other.
Thanks for this comment. We have split up the two sizes into two subplots, and added a third subplot to include measurements of 3 µm particles, as mentioned above.

References

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