Author response to RC2

December 22, 2024

We are grateful for the helpful comments and suggestions from the reviewer. Below the reviewers comments are in blue with our responses in black directly below.

The authors report the development and application of an aerosol filter sampler that fits onboard fixed-wing UAVs. This technique paper will be worth publishing if it includes the discussion & implication of ground INP vs. UAV-collected INP results in Sect. 3. This reviewer wishes to see what the authors learned and what readers should be aware of in Sect. 3. Also, any INP data from Campaigns 1 and 3? If there are any, it would be worth reporting the change/improvement in INP results from the 1st setup to the 3rd one.

Unfortunately, we are unable to directly report an improvement in the quality of the INP conentration measurements from the setup improvements. This is - in part - because we do not have an INP concentration reference instrument, that we could compare our data to. Neither did we have the opportunity to measure the aerosol size distribution for the different setups directly, but had to on well-established theoretical estimations of the collection efficiency as presented in Appendix B. This paper focuses on the scientific feasibility of the described setup. The authors would hesitate to draw any conclusion from the data obtained during campaign 1 to 3, as not enough experiments were conducted. In addition, we want to add that an intensive field campaign (Pallas Cloud Experiment 2022) was conducted during autumn 2022 at the same location, featuring INP reference instrumentation on the nearby Sammaltunturi station for a longer time period of one month. Data from this campaign will be published in a special issue from Earth System Science Data.

L1: for the collection of –> for collecting. L2: deployed –> tested

We have corrected this part.

old A mobile sampler for the collection of aerosol particles on an uncrewed aerial vehicle (UAV) was developed and deployed during three consecutive Pallas Cloud Experiment campaigns in the vicinity of the Sammaltunturi Global Atmosphere Watch site (67°58' N, 24°7' E, 565 m above sea level).

new A mobile sampler for collecting aerosol particles on an uncrewed aerial vehicle (UAV) was developed and tested during three consecutive Pallas Cloud Experiment campaigns in the vicinity of the Sammaltunturi Global Atmosphere Watch site (67°58' N, 24°7' E, 565 m above sea level) *in Finland*.

Note that the part in *italic* was changed due to comments from reviewer 1.

L3-5: The sentence is running long. Maybe "The sampler is composed of Nuclepore ... analyzed for INP abundance offline as a function of temperature using a cold stage assay." Abstract does not need to provide the full name of a developed technique, such as INSEKT. It can be mentioned in the main manuscript.

Changed the sentence to:

old The sampler is designed to collect aerosol particles onto Nuclepore filters, which are subsequently analysed for the temperature-dependent number concentration of ice-nucleating particles of the sampled aerosol with the Ice Nucleation Spectrometer of the Karlsruhe Institute of Technology (INSEKT).

new The sampler is designed to collect aerosol particles onto Nuclepore filters, which are subsequently analysed for the temperature-dependent number concentration of ice-nucleating particles of the sampled aerosol using a freezing assay.

We would like to use freezing assay instead of cold stage assay to separate INSEKT from a cold stage.

L5-6: This setup is… This sentence is not adding much value – sounds like a sales brochure statement. This review suggests the authors exclude this sentence.

We have removed this sentence.

old This setup is an easy and flexible way to connect INP concentration measurements with cloud microphysics.

new

L7-8: 1 hour to what upper limit time? More than 1.5 hours means? Please define it in L7-8 in a simple manner.

The upper limit for the sampling time is defined by the flight time at the designated altitude of the UAV. This flight time depends on the ambient conditions and also on the designated height. We performed flights that lasted more than 100 minutes, but these were ideal conditions and a more typical upper limit is 90 minutes. We have changed our statement accordingly:

old The total flight time ranges from 1 hour to more than 1.5 hours, depending on environmental conditions.

new The total flight time ranges from 60 min to around 100 min, depending on environmental conditions.

L9-10: The authors complement a shorter flight with a relatively large air sampling flow rate, which is good. But how did the author make sure the sampling flow is laminar? Any simulation done?

The flow regime was estimated by calculating the Reynolds number taking into account a flow of $10\,\mathrm{l\,min^{-1}}$ and a tube diameter of $4 \times 10^{-3}\,\mathrm{m}$, resulting in a Reynolds number of roughly 4100, resulting in a turbulent regime. The transport efficiency was calculated with this in consideration as well. No simulation were done apart from the ones described in the paper and in the Appendix. The following is the relevant section of the Appendix:

The theoretical calculations of the transport efficiency are dependent on a multitude of factors, one of them the flow regime. The Reynolds number, Re, is given as

$$\mathrm{Re} = \frac{v_\mathrm{m} d}{\nu} \approx 4100\ , \tag{B1}$$

where the mean velocity, v_m, is calculated with a flow of $10\,\mathrm{l\,min^{-1}}$ and a tube diameter, $d = 4 \times 10^{-3}\,\mathrm{m}$.

L35: … have become one of the focuses for airborne aerosol measurements …

We want to highlight here that UAV are also of focus for ambient measurements, for example measuring similar parameters as on radiosondes. We changed the sentence accordingly:

old Recently, uncrewed aerial vehicles (UAVs) have become a focus for atmospheric measurements (e.g., Bärfuss et al. 2018; Lampert et al. 2020; Marinou et al. 2019; Villa et al. 2016; Yu et al. 2017).

new Recently, uncrewed aerial vehicles (UAVs) have become one of the focuses for atmospheric measurements (e.g., Bärfuss et al. 2018; Lampert et al. 2020; Marinou et al. 2019; Villa et al. 2016; Yu et al. 2017).

L74-75: Right now this sentence sounds like a KNF pump was only employed for your final (3rd) setup in fall 2021. Is that the case? Then, how were aerosol particles collected on a filter without a pump in the 1st and 2nd setup?

The same pump was used for all three setups. To reflect this in the manuscript, we have changed the sentence:

old In our final setup, the payload contains a micro-diaphragm pump (NMP850.1.2KPDC-B HP, KNF), which provides a flow of 15 l min^{-1} at standard conditions (KNF).

new In each setup, the payload contains a micro-diaphragm pump (NMP850.1.2KPDC-B HP, KNF), which provides a flow of 15 l min^{-1} at standard conditions (KNF).

Figure 2: Not sure if this figure needs to be on a main manuscript. The point here is an easy and quick connection, which is said in L82, but not well represented by this image. This reviewer thinks a photo of the actual deployed filter holder with a connector would be more representative than this figure.

We agree and have changed this figure to an actual picture of the mounted filter holder with the individual components.

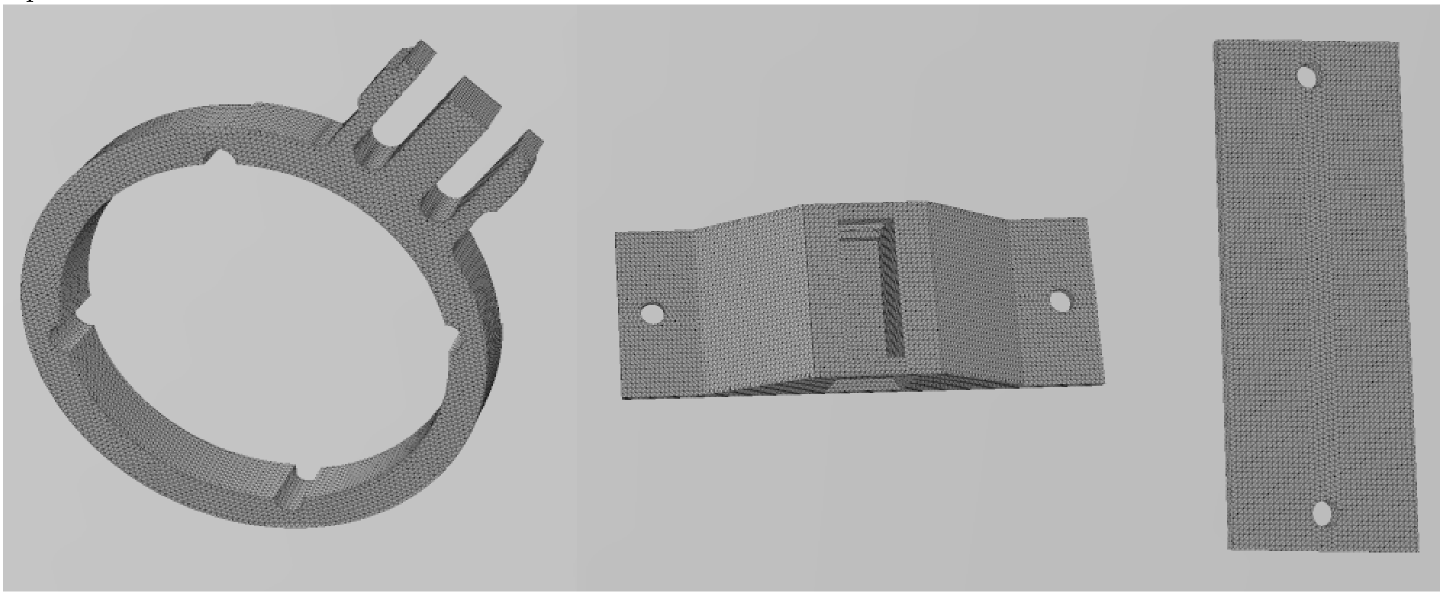

Figure 1: 3D printed parts for the filter holder mounting to the plane. From left to right: filter holder mount, mount base, mount backplate. The mount base is connected to the wing by the backplate, while the filter holder snaps into the base and secures the position of the filter holder.

Figure 2: 3D printed parts for the filter holder mounting to the plane. From left to right: mount base, mount backplate, filter holder mount and final setup. The mount base is connected to the wing by the backplate, while the filter holder snaps into the base and secures the position of the filter holder.

L98: What does this imply? It takes longer than 10 min at a certain high altitude?

We agree that this sentence was not clear. Under start-up procedure we also included the time needed for the UAV to reach the targeted sampling altitude. We have changed this sentence therefore:

old The start-up procedure typically takes less than 10 minutes, depending on the targeted sampling altitude.

new The start-up procedure, including the ascend time, typically takes less than 10 minutes, depending on the targeted sampling altitude.

L102-103: So the pressure data is from which sensor (SHT40 or BME280)?

The pressure data is taken from the BME280, by averaging over the flight duration. We have changed the sentence to accurately reflect this:

old The pressure data is important for the setup since it is used to calculate the sampling flow.

new The pressure data from the BME280 is important for the setup since it is used to calculate the sampling flow.

L110: "until analyzed" – define how long in L110.

The time between filter sampling and analysis with INSEKT does depend on some factors, i.e. shipping and availability of the instrument. We understand that this comment asks in regard to the results shown in this paper. The data sets available at `https://radar.kit.edu/radar/en/dataset/ecljSTKjCuIoqEkr?token=sSJKlzwZKHYlpepdBzaK` contain the complete list of all samples shown with the start and stop time of the experiment (at INSEKT) as well as the start and stop time of the filter sample. The frozen fractions of the aerosol suspensions shown in Figures 6 and 7 were analysed with INSEKT between 2021-06-01 and 2021-06-09, while the filters were taken between 2021-04-19 and 2021-04-21. The filters were therefore stored before analysis for around 45 days. We have added a sentence in the section "Filter handling and subsequent offline INP analysis" to highlight this:

old

new The results shown in this paper are obtained from filters stored for around 45 days at −20 °C before analysis.

L120-130: This part can be much shorter by citing Schneider et al. INSEKT is a developed technique and does not need this much description in the current manuscript.

The configuration of INSEKT described by Schneider et al. 2021 is very similar to the described configuration in this paper, but there are some smaller differences. We have found the need to specify the used equipment in more detail to increase repeatability of the results after the published results from Barry et al. 2021 (e.g., differences between PCR plates). In addition, a cooling rate of 0.33 K/min was used for the analysis in this paper compared to 0.25 K/min in Schneider et al. 2021.

L147: Why 500L? A list of sampling conditions for all filters presented in this paper (starting – ending time, sampled air volume, and used suspension water volume at least) should be included in Appendix or SI.

We have added a table with this information to the Appendix. The 500 l was just a typical value to demonstrate the principle of the freezing assay and its lower detection limit, which is based on the amount of air sampled.

L168: ... feasibility, the frozen fraction of aerosol particles collected on the UAV and ...

We have changed the sentence:

old To demonstrate the scientific feasibility, the inverse of the liquid fraction, the frozen fraction, of the UAV and ground filters are compared to their respective handling blank filters taken during campaign 2.

new To demonstrate the scientific feasibility, the frozen fraction of the UAV and ground filters are compared to their respective handling blank filters taken during campaign 2.

Figures 5 & 6 & 7: AMT submission guide (Figs & Tables) states that labels of panels must be included with brackets around letters by lowercase. Also, state what vertical errors represent in the caption of Fig. 6 & 7.

We have updated the figures and added labels for the different panels. For Figures 6 and 7 we also changed the figure caption.

For Figure 6:

old The frozen fraction as a function of the freezing temperature T is shown for the UAV filter suspensions from campaign 2 in comparison to its blank filter suspension and the Nanopure water background (left panel). The right panel shows the equivalent for the ground filters. The blanks were handled the same way as the filter, but the pump was not turned on, and the UAV was not flying (see Sect. 2.4).

new The frozen fraction as a function of the freezing temperature T is shown for the UAV filter suspensions from campaign 2 in comparison to its blank filter suspension and the Nanopure water background (panel (a)). Panel (b) shows the equivalent for the ground filters. The blanks were handled the same way as the filter, but the pump was not turned on, and the UAV was not flying (see Sect. 2.4). The errorbars represent the 95 % confidence interval.

For Figure 7:

old The left panel shows the INP concentration in air, $c_{\mathrm{INP}}^{\mathrm{air}}$, at 400 m agl as a function of the freezing temperature, T, for a UAV and a ground (GR) filter during campaign 2. Both filters agree very well with each other. On the right panel, the same is shown for two filters one day after at 500 m agl. This filter was flown two times, doubling its sampling time and therefore increasing the amount of air sampled (note also the decreased lower detection limit as a red horizontal line, Eq. (3)). It can be seen that lower INP concentrations can be detected*, as well as a steeper freezing curve*. The freezing curve does not reach the water background on the right panel. This is due to the fact that no dilution was prepared, and therefore the water background was not reached with the higher amount of INPs that can freeze a well.

new Panel (a) shows the INP concentration in air, $c_{\mathrm{INP}}^{\mathrm{air}}$, at 400 m agl as a function of the freezing temperature, T, for a UAV and a ground (GR) filter during campaign 2. Both filters agree very well with each other. On panel (b), the same is shown for two filters one day after at 500 m agl. This filter was flown two times, doubling its sampling time and therefore increasing the amount of air sampled (note also the decreased lower detection limit as a red horizontal line, Eq. (3)). It can be seen that lower INP concentrations can be detected *due to the increased sampling time.* The freezing curve does not reach the water background on panel (b). This is due to the fact that no dilution was prepared, and therefore the water background was not reached with the higher amount of INPs that can freeze a well. The errorbars represent the 95 % confidence interval.

Note that the part in *italic* was changed due to comments from reviewer 1.

L187-188: This does not fit here. All of a sudden, the Arctic sampling with many citations kicks in here. Remote locations are not limited to the Arctic. Maybe it fits better as an outlook.

We have moved this sentence to the outlook.

Fig. 7 @ 400 m agl, why UAV INP conc. is higher than the ground-level INP conc.?

We are unable to give a definitive answer to this question. For this paper we focused on the scientific feasibility of the presented setup. More flights over a longer time period are needed to obtain a statistic on the actual difference between ground-based and UAV-based INP concentrations. As mentioned above we conducted a follow-up study during autumn 2022 (Pallas Cloud Experiment 2022) and the results of this study will be published in a special issue from Earth System Science Data.

L218: ... will include aerosol particle size distribution ...

We have adjust the wording:

old Future *improvements* will include size distribution measurements in addition to INP measurements via small, lightweight optical particle counters.

new Future *experiments* will include aerosol particle size distribution measurements in addition to INP measurements via small, lightweight optical particle counters.

Note that the part in *italic* was changed due to comments from reviewer 1.

References

Bärfuss, K. et al. (2018). "New Setup of the UAS ALADINA for Measuring Boundary Layer Properties, Atmospheric Particles and Solar Radiation". In: *Atmosphere* 9.1. ISSN: 2073-4433. DOI: 10.3390/atmos9010028.

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