

Response to EGU_{sphere}-2026-2699 reviews for RC1

We thank Reviewer #1 for their effort and feedback on our manuscript EGU_{sphere}-2026-2699. In response to their suggestions and questions, please find our answers and corrections listed below: **Reviewer #1 comments are extracted in bold from original review supplement**; our responses are given directly below in normal font; *the original text in previous manuscript is repeated in red italic* and *revised text is typed in blue italic*. We also list our revisions after proof-reading but not commented by reviewers at the end of our response document.

General comments:

The authors present a field study conducted in Payerne, Switzerland, during which they collected an extensive dataset of ice nucleating particles (INPs), fluorescent particles, pollen grains, other aerosol properties, and remote-sensing measurements. Based on a careful analysis of these data, they conclude that biological aerosol particles are more important immersion-mode INPs than dust across a wide temperature range. They compare established INP parameterizations with newly developed parameterizations that incorporate the ratio and/or the concentration of fluorescent particles to account for the biological component of INPs. These new parameterizations perform better and reproduce measured INP concentrations from independent datasets very well.

I would like to congratulate the authors on this highly relevant and very well-executed study. I only have two “major” comments, which I am confident can be addressed relatively quickly.

About the HIRST data... Not all detected pollen taxa are expected to exhibit ice nucleating activity at the same temperatures, or even at all, so this information would be highly valuable.

R: We thank Reviewer #1 for their overall positive comments and constructive suggestions! Fungal spores were recognized during the data analysis (see Figure S6 in the Supplement) and they were not counted, so they were not included in $H_{\text{irstTotal}}$ particles defined in this study. The main purpose of using Hirst data was to evaluate the abundance of pollen particles. We now revised the manuscript accordingly to reflect this.

a. The text in Line 246 in the original manuscript was revised as below:

“... ABC_{WIBS} numbers are much larger than $H_{\text{irstTotal}}$ (pollen particles measured by a Hirst)...”

The original text was as below:

“... ABC_{WIBS} numbers are much larger than $H_{\text{irstTotal}}$ (including pollen, fungi and fungal spores measured by a Hirst) ...”

We keep the text in Line 359-360 in the original manuscript since we also referred the text to Figure S6 which clearly presents fungal spores in the images. This demonstrates the presence of fungal spores and suggests their potential contribution to the observed ice nucleating particles (INPs). We agree with the reviewers that it would be great to investigate the contribution of specific pollen taxa to the observed INPs but is something that will be investigated in an upcoming publication.

Interpretation of WIBS data:

Line 356: You cite Tang et al. (2022) after stating that A particles are representative of bacteria and fungal spores. However, Tang et al. did not directly measure this. Instead, they refer to chamber studies conducted with the older WIBS-4 instrument, which uses different detector gain settings and is therefore not directly comparable to the instrument used here.

I believe it is important to discuss direct in situ comparison studies (e.g., WIBS versus HIRST measurements or biological tracers), particularly regarding ABC particles, since these show the strongest correlation with INPs and may therefore contribute most substantially to the observed INP population.

Since you deployed both a WIBS and a HIRST instrument, as well as a Rapid-E, such an analysis could potentially be performed using your own dataset. However, I understand from the manuscript that a future publication based on these data is planned where this might be examined in detail. If such an analysis is not planned, I would strongly encourage the authors to include it here, as it would be a missed opportunity. If it is planned for future work, then the present manuscript should at least provide a more comprehensive discussion of the relevant literature.

In that case, the literature suggests that ABC particles, rather than A particles, are generally more representative of fungal spores (e.g., Clancy et al., 2025; Gratzl et al., 2025; Sarangi et al., 2022). This should be discussed in detail, including how it might affect the interpretation of which particle types are acting as INPs in this study. Similarly, it would be useful to discuss which WIBS fluorescence classes are most representative of pollen grains. For example, Clancy et al. (2025) report that BC particles, rather than ABC particles, are most strongly associated with pollen.

I would also suggest adding a brief discussion of what is currently known about the ice nucleating activity of the detected PBAPs, particularly pollen grains and, if relevant, fungal spores.

For example, in line 360, I would expect that most pollen taxa detected by the Rapid-E have previously been tested for ice nucleating activity and that many exhibit at least some degree of activity. How much do the remaining taxa detected only by the Hirst instrument contribute to the overall pollen concentration? Can this difference alone explain the observed difference in correlation coefficients?

Or could the discrepancy instead arise because fungal spores are included in the Hirst measurements?

R: We agree with Reviewer #1 regarding the complex links between WIBS sub-type particles and specific biological particles. Identifying these biological types and correlating them to INPs is particularly challenging due to biological overlaps, non-biological interferences, instrument detection limits, and data scarcity. Nevertheless, this study aims to discuss the significant correlations between WIBS sub-type particles (e.g., A_{WIBS}) and INPs in Figure 4, as it can also be used as a parameterization for models. This is the main research focus of this study. We agree that more detailed intercomparisons between WIBS, HIRST, and Rapid-E data will contribute to further understanding of biological particle detection but not substantially help their contribution to INPs of interests. It is reported that bacteria (Hernandez et al., 2016; Savage et al., 2017), fungal spores (Gratzl et al., 2025; Savage et al., 2017; Hernandez et al., 2016) and pollen fragments (Savage et al., 2017) can contribute to the fluorescence of A_{WIBS} . We now list our revisions as below:

a. The original statement in Line 359–361 was as below:

“In addition, A_{WIBS} particles, representatives for bacteria and fungal spores (Tang et al., 2022), exhibit significant correlations ($\rho_{Pearson}$ and $\rho_{Spearman} \sim 0.4$) with N_{INP} between -13°C and -17°C .”

And now it is revised as below:

“In addition, A_{WIBS} particles, representatives for bacteria (Hernandez et al., 2016; Savage et al., 2017), fungal spores (Gratzl et al., 2025; Savage et al., 2017; Hernandez et al., 2016) and pollen fragments (Savage et al., 2017), exhibit significant correlations ($\rho_{Pearson}$ and $\rho_{Spearman} \sim 0.4$) with N_{INP} between -13°C and -17°C .”

b. We added a new sentence to the revised manuscript as below:

“The effective ice nucleation ability of birch pollen, which is one of the most abundant pollen taxa at the beginning of the campaign, was reported in Pummer et al. (2012) and Augustin et al. (2013).”

Minor comments

1. **Line 78:** After mentioning Cornwell et al., who identified bioaerosols as the primary source of INPs, you could also cite Gratzl et al. (2025), who specifically identified fungal spores as the dominant source in northern Finland.

R: Agreed. We now add a new sentence in the revised manuscript as below:

“... and Gratzl et al. (2025) reported that fungal spores are important INP contributors in the northern boreal forests.”

2. **Line 99:** What type of forest?

R: We clarified it as below:

*“The site is located at a semi-rural area surrounded by grassland and several farmlands and is close to a forest ecosystem (highly dominated by Oak (*Quercus*), Beech (*Fagus sylvatica*), Birch (*Betula*), Hornbeam (*Carpinus*), and Ash (*Fraxinus*), ~1.6 km south-east from the station, Fig. 1b).”*

3. **Section 2.2 DRINCZS:** How many droplets were analyzed per sample? What was the droplet volume? How were atmospheric INP concentrations calculated from the measurements?

R: We now add the information and revise the relevant text as below:

“Thus, DRINCZ analyzed 288 droplets (50 μ L) distributed across three 96-well PCR plates for each sample.”.

For the calculation of INP concentration, we referred to DRINCZ data processing protocol reported in Wieder et al. (2022) (see Line 130-131 in the original manuscript).

- 4. Line 142: Please explain what the Forced Trigger mode is, or at least its purpose. This becomes clearer in line 148, but it is not immediately obvious that the threshold is derived from the Forced Trigger measurements.**

R: Agree. Now, the sentence is revised to make it clear:

“The instrument was operated in forced trigger mode every twelve hours for one minute to detect the background signal level.”

- 5. Line 143: Do you mean any of the three fluorescence channels rather than detectors, since there are only two detectors measuring fluorescence intensity?**

R: Agreed. Now, the sentence is revised for clarity as follows:

“Particles detected by any one of three ~~detectors~~ channels are termed $Fluo_{WIBS}$; ...”

- 6. Line 144–145: Please briefly explain which particle classes (A, B, AB, etc.) fluoresce in which channels. This may not be obvious to readers unfamiliar with the WIBS instrument.**

R: Agreed. Now, the sentence is revised for clarity as follows:

“... particles that show fluorescence in only one of three channels are denoted as types A_{WIBS} (FL1), B_{WIBS} (FL2) and C_{WIBS} (FL3), respectively; ...”

- 7. Line 151–156: This is only a suggestion, but it may be useful to include a table summarizing all concentration metrics derived from the WIBS and the other instruments. A large number of concentration types are introduced throughout the manuscript, and a summary table would improve readability.**

R: Thank you for this helpful suggestion. We previously considered including a summary table; however, to maintain a concise manuscript and avoid redundancy, we opted to provide detailed definitions and explanations of these concentration metrics directly within the relevant figure captions (e.g., Figure 2). We believe this allows readers to easily reference the metrics while interacting with the data.

- 8. Line 262: I suggest adding "that are not detected as ABC particles" after "including large FBAPs" or a similar clarification.**

R: Agreed. Now, the sentence is revised as follows:

“The difference between $ABC_{WIBS>2.5\mu m}$ and $Total_{WIBS>2.5\mu m}$ (i.e., total particles between 2.5 and 30 μm detected by WIBS) is calculated as $\Delta_{Coarse>2.5\mu m}$ to represent the upper number concentration estimation of coarse dust (Gao et al., 2024) including large FBAPs that are not detected as ABC_{WIBS} particles (Error! Reference source not found.d).”

- 9. Section 3.2: Why is this particular case study discussed in the main text, whereas the others are included only in the Supplement? Is there a specific reason for highlighting this case.**

R: It is the first sample which has both aerosol range-corrected lidar signals at 355 nm and range-corrected aerosol fluorescent lidar signal at 470 nm. In addition, this case study is representative to all case studies as discussed in the Supplement, which shows different types of aerosol sources of interests in this study.

- 10. Figure 3: The rainbow color scale used in panels k and l is outdated. Does the blue stripe near the bottom of the panels (~500 m) indicate that no data were available below that height? The unit "a.u." should also be included directly in the plots.**

R: Because these values depend entirely on the specific lidar's laser power, telescope size, and detector efficiency, they don't mean much on their own. Therefore, the axis can be labelled as Arbitrary Units (a.u.) or usually it is labelled unitless in literature.

- 11. Lines 335: You write: "Total WIBS (i.e., total particles between 0.5 and 30 μm detected by WIBS) generally shows a weak correlation with N_INP (ρ_{Pearson} and $\rho_{\text{Spearman}} < 0.2$), reflecting the scarcity of INPs relative to the total abundance of even coarse particles for warm MPCs.". Based on**

Total_WIBS alone you cannot conclude that this is true for coarse particles, since I guess they are only a minor fraction of Total_WIBS. You should refer to DELTA_coarse here.

R: Now, the sentence is revised as below:

“Total_{WIBS} (i.e., total particles between 0.5 and 30 μm detected by WIBS) generally shows a weak correlation with N_{INP} (ρ_{Pearson} and $\rho_{\text{Spearman}} < 0.2$), reflecting the scarcity of INPs relative to ~~the total~~ ~~even coarse~~ particles.”

12. Line 350: Why are fungal spores excluded here? Most fungal spores are larger than 2.5 μm

R: Agree. Now, the sentence is revised as below:

“This is because the largest particles that fluoresce are associated with coarse-sized PBAPs, like fungal spores, pollen or pollen fragments, some of which are known to be effective INPs (Augustin et al., 2013).”

13. Figure 5: I do not fully understand the added value of Fig. 5b relative to Fig. 5a. Could the authors clarify this point? Furthermore, how can all INPs active above -12°C be heat-labile in panel c if this is not apparent in panel a? Please elaborate

R: First, panel b shows N_{INP} violin plots of all samples ($n=66$) whose N_{INP} values of both untreated and T90 (heated at 90°C) samples at the same T are available, which means heating treatment does not deactivate all INPs at the T for the sample. This is different from panel a which shows collectively N_{INP} values of all untreated and T90 samples. Because of the heat treatment, the N_{INP} of untreated samples may be detectable at warm temperatures whereas heating at 90°C may deactivate the sample and decrease the N_{INP} below the detection limit (thus is unavailable). Such a data inconsistency may lead to bias for the calculation of deactivated fraction in panel c. Secondly, panel a presents the active INPs above -12°C for some untreated samples but it is not seen in panel b because of complete deactivation. This clearly shows that heating has completely deactivated INPs in some samples (13) above -12°C .

14. Line 397: Change “and” soil dust to “or” soil dust (since just with heating you cannot be sure of either)

R: Changed. Now, the sentence is revised as follows:

“For $T \geq -8^{\circ}\text{C}$, INPs of 18 T90 samples are completely degraded or below the detection limit (Error! Reference source not found.a), clearly suggesting the contribution to INPs of heat-labile bacteria (Lukas et al., 2022; Stopelli et al., 2017), fungi or fungal spores (Fröhlich-Nowoisky et al., 2015), or soil dust particles carrying active ice nucleating proteins (O'sullivan et al., 2013)”

15. Line 410–412: This sentence is very long and could be split into two shorter sentences to improve readability

R: Agree. Now, the sentence is revised now.

The original sentence in Line 410–412 was as below:

“To further access the role of dust in the observed INPs, we first examine air-mass back trajectories arriving at a height of 500 m and 1000 m above the ground level (a.g.l.) for INP samples collected during and outside the dust-event period (Error! Reference source not found.d) in Error! Reference source not found. to identify dust plumes, and then quantify dust contribution to immersion-mode INPs (Error! Reference source not found.).”

Now it is revised as follows:

“We first examined air-mass back trajectories arriving at 500 m and 1000 m a.g.l. to identify dust plumes during and outside the dust event (Figs. 2d and 6). Based on these trajectories, we then quantified the dust contribution to immersion-mode INPs (Fig. 7).”

16. Line 464–465: Is there a reference supporting the statements regarding more intense aging and reduced ice-nucleating activity? If not, please reformulate this as a possible explanation rather than a conclusion

R: The original text was developed as a possible explanation but not a solid conclusion. It is stated that *“This is likely attributable to the relatively lower altitude of the observation site in this study (491 m a.s.l.), where transported dust particles could undergo more intensive atmospheric aging within the planetary boundary layer (Fig. 3k), leading to somewhat reduced IN activity.”*

17. Line 471 (and also line 302): Must heat-labile INPs at low temperatures necessarily be FBAPs (or PBAPs)? Other possibilities should also be considered and discussed.

R: Agree. We respond the same as for Reviewer #2 comment #1. We list our revisions as below:

(a) We added the following sentences in the Methodology section:

“While heat treatment is a widely used diagnostic tool for biological INPs, Daily et al. (2022) observed that boiling (~96°C) only slightly deactivated birch pollen (Betula pendula) washing water, while suppressing the median freezing temperature of highly concentrated quartz by 4°C. However, more recent work by Wieland et al. (2025) demonstrated that heat treatments exceeding 40°C, 78°C, and 98°C disrupt the aggregation of ice-nucleating macromolecules, significantly suppressing pollen ice nucleation at $T > -15^{\circ}\text{C}$. Consequently, heat sensitivity remains a valid indicator for identifying biological INPs for $T > -15^{\circ}\text{C}$, whereas it may affect minerals like quartz or plagioclase forming ice at lower temperatures.”

(b) We revised the following sentences in the Discussion section as follows:

“This may indicate important contributions of PBAPs to INPs (Murray et al., 2012; Kanji et al., 2017) and heat-sensitive dust like quartz or plagioclase (Daily et al., 2022).”

The original sentence was as below in the original manuscript (Line 301-302):

“This indicates important contributions from PBAPs to INPs (Murray et al., 2012; Kanji et al., 2017).”

(c) We revised the following sentences in the Discussion section:

“The reduction may result from deactivation of soil dust containing heat-labile biological material (O'sullivan et al., 2013) or dust samples containing quartz or plagioclase (Daily et al., 2022).”

The original sentence was as below in the original manuscript (Line 310-311):

“The reduction may result from deactivation of soil dust containing heat-labile biological material (O'sullivan et al., 2013).”

(d) We revised the following sentences in the Discussion section:

“For $T < -12^{\circ}\text{C}$, the dN_{INP} fractions of T90 samples are consistently more than 85% (Error! Reference source not found.c), suggesting the contribution of heat-sensitive INPs of biological origin and/or IN active but heat-sensitive quartz or plagioclase (Daily et al., 2022).”

The original sentence was as below in the original manuscript (Line 403):

“For $T < -12^{\circ}\text{C}$, the dN_{INP} fraction of T90 samples are consistently more than 85% (Error! Reference source not found.c).”

(e) We revised the following sentences in the Discussion section:

“Error! Reference source not found.i compares the fraction of heat-resistant INPs in dust and non-dust influenced groups. Overall, heat-resistant INPs constitute $<10\%$ in both groups. It also shows that dust events only slightly enrich heat-resistant INPs for $T \leq -20^{\circ}\text{C}$ but not for warm Ts. This minimal impact of dust events eliminates minerals like quartz or plagioclase as major contributors to the observed IN activity, thereby supporting the discussion on heat sensitive tests in Section 3.4 and highlighting the importance of PBAPs. Therefore, our results demonstrate that heat-labile FBAPs are the dominant source of INPs, irrespective of dust presence.”

The original sentence was as below in the original manuscript (Line 469-472):

“Error! Reference source not found.i compares the fraction of heat-resistant INPs in dust and non-dust influenced groups. Overall, heat-resistant INPs constitute $<10\%$ in both groups. It also shows that dust events only slightly enrich heat-resistant INPs for $T \leq -20^{\circ}\text{C}$ but not for warm Ts. In other words, our results demonstrate that heat-labile FBAPs are the dominant source of INPs, irrespective of dust presence.”

18. Table 1 (line 477): WIBS_ratio is not equal to the difference between Fluo_WIBS and Total_WIBS. That quantity would correspond to NonFluo_WIBS.

R: It was correct. Here we mean NonFluo_{WIBS} is the difference between Fluo_{WIBS} and Total_{WIBS}, and WIBS_ratio is the ratio of Fluo_{WIBS} to NonFluo_{WIBS}. We now revised the text as follows:

“WIBS_ratio is the ratio of Fluo_{WIBS} to NonFluo_{WIBS} (which is the difference between Fluo_{WIBS} and Total_{WIBS}) particle concentration.”

Supplement

1. Figure S12: Data appear to be missing for panels b, c, and f.

R: Thanks. WIBS data was not available on that day because of instrument maintenance. We revised the figure caption and noted that *‘Blank panels are because of data unavailability due to instrument maintenance.’*.

2. Case studies in general: If the authors wish to retain all case studies in the Supplement, it would be very helpful to include a brief explanatory paragraph for each one, similar to the descriptions provided in the main text. Otherwise, it is difficult for readers to interpret their significance.

R: Thank you for this guidance. While we have provided the comprehensive methodology and analysis framework in the main text, we recognize that the supplementary figures could benefit from clearer context. Instead of adding lengthy text for each individual case, we have added a brief, overarching introductory paragraph at the beginning of the Supplement section to clearly outline the significance and interpretation of these additional cases.

3. S10: Are Groups 1, 2, and 3 simply different dates, or are they referred to as groups for a specific reason?

R: These were indicated in the Text S10. Three groups of samples before and during precipitation (time gap <4 hours in each group, see Table S1) were collected between 21 and 23 June 2023 (Fig. S10).

4. Middle of paragraph: "In contrast" instead of "B contrast".

R: Corrected.

5. Microscopy images: I personally appreciate that the authors included these images. If possible, I would suggest increasing both their size and image quality.

R: We now changed the arrangement of subpanels to zoom in each panel and replaced the images with the best resolution we have.

6. Figure S6c: Does "Spores" refer to unidentified fungal spores? Were all observed spores marked in the images? This relates again to the question of whether fungal spores were included in the analysis and, if not, why they were excluded. It may also be worth noting that only one dust particle is marked, although several more appear to be present in the images, which is somewhat difficult to assess given the current image quality.

R: Thank you for pointing this out. We have updated Figure S6c with a higher-quality image to improve clarity. To clarify, "Spores" indeed refers to unidentified fungal spores. Because the primary objective of using the Hirst data in this study was to calculate total pollen concentrations for comparison with the Rapid-E monitor, a comprehensive identification and count of all fungal spores and dust particles was outside our operational scope.

Technical corrections

1. Line 119: "For" instead of "Fpr".

R: Corrected.

2. Line 174: Change "will be replaced" to "were replaced".

R: Changed.

3. Line 256: Add "of" after "(mostly >0.05)"

R: Added.

4. Figure 6, line 428: "n =" is missing before "16"

R: Added.

Revisions after proof-reading (but not suggested by reviewers):

In addition to revising the text in the manuscript, we did a double check for our dataset used in this paper given that many measurements were included. We listed these extra revisions as below.

1. The original statement about the filter sampling in Line 37–39 was as below:

“We synergically use the results of in-situ and offline measurements to identify INPs originated from different sources, including biological aerosols, dust, and biomass burning aerosols, and to quantify their abundance and relative contributions to total INPs.”

Now, it is revised as:

“By combining in-situ and offline measurements, we identify INPs from biological, dust, and biomass burning sources, and quantify their relative contributions to the total INP population.”

2. The original statement about the filter sampling in Line 66–68 was as below:

“Georgakaki et al. (2024) reported that primary ice formation induced by active INPs from PBAPs (Gao et al., 2024) prolifically catalysed secondary ice production through ice-ice collisional break-up (Phillips et al., 2017) ultimately leading to enhanced precipitation.”

Now, it is revised as:

“Georgakaki et al. (2024) reported that primary ice formation induced by active INPs from PBAPs (Gao et al., 2024) prolifically catalysed secondary ice production through ice-ice collisional break-up (Phillips et al., 2017), ultimately leading to enhanced precipitation.”

3. The original statement about the filter sampling in Line 76–77 was as below:

“Schneider et al. (2021) found the seasonal cycle of INPs is linked to the abundance of PBAPs in boreal forests.”

Now, it is revised as:

“Schneider et al. (2021) found the seasonal cycle of INPs is linked to the varying abundance of PBAPs in boreal forests.”

4. The original statement about the filter sampling in Line 96–98 was as below:

“A field campaign, called Payerne lidaR Insitu detection of fluorescent biomass burning, bioaerosol and dust particLES and their cloud impacts (PERICLES), was conducted at the Payerne MeteoSwiss station (46.822° N, 6.941° E, 491 m a.s.l.) on the Swiss Plateau, from 8 May to 8 December 2023.”

Now, it is revised as:

“A field campaign, called Payerne lidaR Insitu detection of fluorescent biomass burning, bioaerosol and dust particLES and their cloud impacts (PERICLES), was conducted at the MeteoSwiss station (46.822° N, 6.941° E, 491 m a.s.l.) in Payerne on the Swiss Plateau, from 8 May to 8 December 2023.”

5. The original statement about the filter sampling in Line 104–106 was as below:

“An aethalometer (E) ~~used~~ for elemental carbon analysis and a total carbon analyser (F) were installed at Site 2 ~~which is~~ approximately 70 m south-west from Site 1.”

Now, it is revised as:

“An aethalometer (E) for elemental carbon analysis and a total carbon analyser (F) were installed at Site 2, approximately 70 m south-west from Site 1.”

6. The original statement about the filter sampling in Line 106–107 was as below:

“Additionally, a UV-Fluorescent-Mie lidar system (G) was set up at Site 3 to obtain the vertical distribution of aerosol elastic and fluorescent backscatter coefficients (Gidarakou et al., 2026).”

Now, it is revised as:

“Additionally, a UV-Fluorescent-Mie lidar system (G) was set up at Site 3 to retrieve the vertical profile of aerosol elastic and fluorescent backscatter coefficients (Gidarakou et al., 2026).”

7. The original statement about the filter sampling in Line 119–121 was as below:

“For each sample, three DRINCZ experiments were conducted at three different dilutions with a dilution ratio from a factor of 10 to 100, to ensure more accurate detection of low concentration INPs.”

Now, it is revised as follows:

“For each sample, three DRINCZ experiments in total were conducted using three different dilution ratios between 10 and 100, to ensure more accurate detection of INPs with different concentrations.”

8. The original statement about the filter sampling in Line 137–138 was as below:

“WIBS utilizes pulsed ultraviolet light to excite fluorescence from individual particles and then detects the fluorescence emissions at two wavebands, resulting in three fluorescence detectors ...”

Now, it is revised as follows:

“WIBS utilizes pulsed ultraviolet light to excite fluorescence from individual particles and then detects the fluorescence emissions at two wavebands, resulting in three fluorescence channels ...”

9. The original statement about the filter sampling in Line 140–141 was as below:

“The three fluorescence detectors are sensitive to tryptophan-containing proteins, NAD(P)H co-enzymes and riboflavin respectively ...”

Now, it is revised as follows:

“The three fluorescence channels are sensitive to tryptophan-containing proteins, NAD(P)H co-enzymes and riboflavin respectively ...”

10. The original statement about the filter sampling in Line 165–167 was as below:

“On the basis of the size, morphology and fluorescent property of the particles, the instrument can recognize the type of single pollen particles Using automatic recognition algorithms (Šaulienė et al., 2019; Chappuis et al., 2019; Crouzy et al., 2016).”

Now, it is revised as follows:

“Using automatic recognition algorithms (Šaulienė et al., 2019; Chappuis et al., 2019; Crouzy et al., 2016), the instrument identifies individual pollen types based on particle size, morphology, and fluorescence properties.”

11. The original statement about the filter sampling in Line 169–171 was as below:

“... we use pollen classification algorithm based on a convolutional neural network to allow automatic feature extraction from scattering light fluorescence spectrum and life time of fluorescence measurements of each particle sampled by Rapid-E.”

Now, it is revised as follows:

“... we use a convolutional neural network algorithm to classify pollen and automatically extract features from the scattering light, fluorescence spectra, and fluorescence lifetime measurements of each particle sampled by Rapid-E.”

12. The original statement about the filter sampling in Line 189–190 was as below:

“During the PERICLES campaign, lidar measurements were performed using a UV Fluorescence-Mie lidar to obtain the vertical profile of the aerosol backscatter coefficients ...”

Now, it is revised to:

“During the PERICLES campaign, lidar measurements were performed using a UV Fluorescence-Mie lidar to retrieve the vertical profile of the aerosol backscatter coefficients ...”

13. The original statement about the filter sampling in Line 190–191 was as below:

“The lidar system is based on a pulsed Nd:YAG laser emitting pulses at 355 nm with energy of 130 mJ at 10 Hz repetition frequency.”

Now, it is revised to:

“The lidar system is based on a pulsed Nd:YAG laser emitting pulses at 355 nm with energy of 130 mJ at 10 Hz repetition frequency.”

14. The original statement about the filter sampling in Line 192–194 was as below:

“A set of dichroic mirrors with high reflectivity (>99%) at 355 nm followed by a Pellin-Broca prism ensure the emission of the laser beam only at 355 nm.”

Now, it is revised to:

“A set of dichroic mirrors with high reflectivity (>99%) at 355 nm followed by a Pellin-Broca prism was deployed to ensure the emission of the laser beam only at 355 nm.”

15. The original statement about the filter sampling in Line 213–215 was as below:

“Three samples (Fig. 2b) on 20 June, 21 June and 22 June 2023 during the dust event period defined in Fig. 2d were analysed to provide visual evidence for the presence of dust and biological particles.”

Now, it is revised to:

“Three samples (Fig. 2b) on 20 June, 21 June and 22 June 2023 during the dust event period defined in Fig. 2d were analysed to provide visual evidence for the presence of dust and biological particles.”

16. The original statement about the filter sampling in Line 218–220 was as below:

“We combined the in-situ, remote sensing and simulation results to identify INP sources, quantified the abundance of INPs of biological origin and linked them to different PBAP types and pollen.”

Now, it is revised to:

“We combined the in-situ, remote sensing and simulation results to identify INP sources, quantified the abundance of INPs of biological origin and linked them to different PBAP types and pollen.”

17. The original statement about the filter sampling in Line 306–307 was as below:

“Notably, constant N_{INP} levels between -16 and -20°C for the T90 sample (Fig. 3a) suggests complete deactivation of INP subgroups found in the untreated sample.”

Now, it is revised to:

“Notably, constant N_{INP} levels between -16 and -20°C for the T90 sample (Fig. 3a) suggest complete deactivation of INP subgroups found in the untreated sample.”

18. The original statement about the filter sampling in Line 506–507 was as below:

“Both DeMott2010 and Tobo2013 are adapted by fitting the formula to the combined dataset to calculate a new set of parameters.”

Now, it is revised to:

“Both DeMott2010 and Tobo2013 are adapted (termed Adapted DeMott2010 and Adapted Tobo2013) by fitting the formula to the combined dataset to calculate a new set of fitting parameters.”

19. The original statement about the filter sampling in Line 517–518 was as below:

“...suggesting that particle fluorescence can enhance N_{INP} predictability.”

Now, it is revised as follows:

“...suggesting that the application of particle fluorescent properties can improve N_{INP} predictability.”

20. The original statement about the filter sampling in Line 520–522 was as below:

“Higher WIBS_{ratio} values indicate a larger fraction of fluorescent particles, likely more PBAPs with enhanced IN activity compared to dust.”

It is now revised as follows:

*“Higher WIBS_{ratio} values indicate a larger fraction of fluorescent particles, likely more PBAPs with **more active** IN activity compared to dust.”*

References:

- Augustin, S., Wex, H., Niedermeier, D., Pummer, B., Grothe, H., Hartmann, S., Tomsche, L., Clauss, T., Voigtländer, J., Ignatius, K., and Stratmann, F.: Immersion freezing of birch pollen washing water, *Atmos. Chem. Phys.*, 13, 10989-11003, <https://doi.org/10.5194/acp-13-10989-2013>, 2013.
- Chappuis, C., Tummon, F., Clot, B., Konzelmann, T., Calpini, B., and Crouzy, B.: Automatic pollen monitoring: first insights from hourly data, *Aerobiologia*, 36, 159-170, <https://doi.org/10.1007/s10453-019-09619-6>, 2019.
- Crouzy, B., Stella, M., Konzelmann, T., Calpini, B., and Clot, B.: All-optical automatic pollen identification: Towards an operational system, *Atmos. Environ.*, 140, 202-212, <https://doi.org/10.1016/j.atmosenv.2016.05.062>, 2016.
- Daily, M. I., Tarn, M. D., Whale, T. F., and Murray, B. J.: An evaluation of the heat test for the ice-nucleating ability of minerals and biological material, *Atmos. Meas. Tech.*, 15, 2635-2665, [10.5194/amt-15-2635-2022](https://doi.org/10.5194/amt-15-2635-2022), 2022.
- Fröhlich-Nowoisky, J., Hill, T. C. J., Pummer, B. G., Yordanova, P., Franc, G. D., and Pöschl, U.: Ice nucleation activity in the widespread soil fungus *Mortierella alpina*, *Biogeosciences*, 12, 1057-1071, <https://doi.org/10.5194/bg-12-1057-2015>, 2015.
- Gao, K., Vogel, F., Foskinis, R., Vratolis, S., Gini, M. I., Granakis, K., Billault-Roux, A.-C., Georgakaki, P., Zografou, O., Fetfatzis, P., Berne, A., Papagiannis, A., Eleftheriadis, K., Möhler, O., and Nenes, A.: Biological and dust aerosol as sources of ice nucleating particles in the Eastern Mediterranean: source apportionment, atmospheric processing and parameterization, *Atmos. Chem. Phys.*, 24, 9939-9974, <https://doi.org/10.5194/acp-24-9939-2024>, 2024.
- Georgakaki, P., Billault-Roux, A.-C., Foskinis, R., Gao, K., Sotiropoulou, G., Gini, M., Takahama, S., Eleftheriadis, K., Papayannis, A., Berne, A., and Nenes, A.: Unraveling secondary ice production in winter orographic clouds through a synergy of in-situ observations, remote sensing and modeling, *npj Clim. Atmos. Sci.*, 7, <https://doi.org/10.1038/s41612-024-00671-9>, 2024.
- Gidarakou, M., Papayannis, A., Gao, K., Gidarakos, P., Crouzy, B., Foskinis, R., Erb, S., Zhang, C., Lieberherr, G., Coen, M. C., Branko, S., Kanji, Z. A., Clot, B., Calpini, B., Giagka, E., and Nenes, A.: Profiling pollen and biomass burning particles over Payerne, Switzerland using laser-induced fluorescence lidar and in situ techniques during the 2023 PERICLES campaign, *Atmos. Chem. Phys.*, 26, 923-945, <https://doi.org/10.5194/acp-26-923-2026>, 2026.
- Gratzl, J., Brus, D., Douglis, K., Böhmländer, A., Möhler, O., and Grothe, H.: Fluorescent aerosol particles in the Finnish sub-Arctic during the Pallas Cloud Experiment 2022 campaign, *Earth System Science Data*, 17, 3975-3985, <https://doi.org/10.5194/essd-17-3975-2025>, 2025.
- Hernandez, M., Perring, A. E., McCabe, K., Kok, G., Granger, G., and Baumgardner, D.: Chamber catalogues of optical and fluorescent signatures distinguish bioaerosol classes, *Atmos. Meas. Tech.*, 9, 3283-3292, <https://doi.org/10.5194/amt-9-3283-2016>, 2016.
- Kanji, Z. A., Ladino, L. A., Wex, H., Boose, Y., Burkert-Kohn, M., Cziczo, D. J., and Krämer, M.: Overview of ice nucleating particles, in: *Meteorological Monographs*, 1.1-1.33, <https://doi.org/10.1175/amsmonographs-d-16-0006.1>, 2017.
- Lukas, M., Schwidetzky, R., Eufemio, R. J., Bonn, M., and Meister, K.: Toward Understanding Bacterial Ice Nucleation, *J. Phys. Chem. B*, 126, 1861-1867, <https://doi.org/10.1021/acs.jpcc.1c09342>, 2022.
- Murray, B. J., O'Sullivan, D., Atkinson, J. D., and Webb, M. E.: Ice Nucleation by Particles Immersed in Supercooled Cloud Droplets, *Chem. Soc. Rev.*, 41, 6519-6554, <https://doi.org/10.1039/c2cs35200a>, 2012.
- O'Sullivan, D., Murray, B. J., Malkin, T. L., Webb, M. E., Whale, T. F., Atkinson, J. D., and Baustian, K. J.: Atmospheric ice nucleation by fertile soil dusts particles: Relative importance of mineral and biological components, <https://doi.org/10.1063/1.4803409>, 2013.
- Phillips, V. T. J., Yano, J.-I., and Khain, A.: Ice Multiplication by Breakup in Ice-Ice Collisions. Part I: Theoretical Formulation, *J. Atmos. Sci.*, 74, 1705-1719, <https://doi.org/10.1175/jas-d-16-0224.1>, 2017.

Pummer, B. G., Bauer, H., Bernardi, J., Bleicher, S., and Grothe, H.: Suspendable Macromolecules Are Responsible for Ice Nucleation Activity of Birch and Conifer Pollen, *Atmos. Chem. Phys.*, 12, 2541-2550, <https://doi.org/10.5194/acp-12-2541-2012>, 2012.

Šaulienė, I., Šukienė, L., Daunys, G., Valiulis, G., Vaitkevičius, L., Matavulj, P., Brdar, S., Panic, M., Sikoparija, B., Clot, B., Crouzy, B., and Sofiev, M.: Automatic pollen recognition with the Rapid-E particle counter: the first-level procedure, experience and next steps, *Atmos. Meas. Tech.*, 12, 3435-3452, <https://doi.org/10.5194/amt-12-3435-2019>, 2019.

Savage, N. J., Krentz, C. E., Könemann, T., Han, T. T., Mainelis, G., Pöhlker, C., and Huffman, J. A.: Systematic characterization and fluorescence threshold strategies for the wideband integrated bioaerosol sensor (WIBS) using size-resolved biological and interfering particles, *Atmos. Meas. Tech.*, 10, 4279-4302, <https://doi.org/10.5194/amt-10-4279-2017>, 2017.

Schneider, J., Höhler, K., Heikkilä, P., Keskinen, J., Bertozzi, B., Bogert, P., Schorr, T., Umo, N. S., Vogel, F., Brasseur, Z., Wu, Y., Hakala, S., Duplissy, J., Moiseev, D., Kulmala, M., Adams, M. P., Murray, B. J., Korhonen, K., Hao, L., Thomson, E. S., Castarède, D., Leisner, T., Petäjä, T., and Möhler, O.: The seasonal cycle of ice-nucleating particles linked to the abundance of biogenic aerosol in boreal forests, *Atmos. Chem. Phys.*, 21, 3899-3918, <https://doi.org/10.5194/acp-21-3899-2021>, 2021.

Stopelli, E., Conen, F., Guilbaud, C., Zopfi, J., Alewell, C., and Morris, C. E.: Ice nucleators, bacterial cells and *Pseudomonas syringae* in precipitation at Jungfraujoch, *Biogeosciences*, 14, 1189-1196, <https://doi.org/10.5194/bg-14-1189-2017>, 2017.

Tang, D., Wei, T., Yuan, J., Xia, H., and Dou, X.: Observation of bioaerosol transport using wideband integrated bioaerosol sensor and coherent Doppler lidar, *Atmos. Meas. Tech.*, 15, 2819-2838, <https://doi.org/10.5194/amt-15-2819-2022>, 2022.

Wieder, J., Mignani, C., Schär, M., Roth, L., Sprenger, M., Henneberger, J., Lohmann, U., Brunner, C., and Kanji, Z. A.: Unveiling atmospheric transport and mixing mechanisms of ice-nucleating particles over the Alps, *Atmos. Chem. Phys.*, 22, 3111-3130, <https://doi.org/10.5194/acp-22-3111-2022>, 2022.

Wieland, F., Bothen, N., Schwidetzky, R., Seifried, T. M., Bieber, P., Pöschl, U., Meister, K., Bonn, M., Fröhlich-Nowoisky, J., and Grothe, H.: Aggregation of ice-nucleating macromolecules from *Betula pendula* pollen determines ice nucleation efficiency, *Biogeosciences*, 22, 103-115, <https://doi.org/10.5194/bg-22-103-2025>, 2025.