

Answers to the comments of the reviewers RC1 and RC2 for the manuscript “Arctic aerosol and meteorological observations using airborne and ground-based systems in spring 2024” (essd-2026-411).

First of all, the authors would like to thank the two reviewers for their detailed comments and suggestions that improve the current version of the manuscript. The revisions done by the authors address in particular the scientific value and utility of the presented data set, which is unique for the community, expand the data availability section, and specify the accuracy, comparability and quality of the performed measurements. Below, the reviewer comments are provided in *italic letters*. Each comment is answered in **blue letters**, and the revised text is provided in **orange letters**. All line numbers given in the text below refer to the revised manuscript. Please find all changes in response to the reviewers including additional changes in the marked-up manuscript enclosed to this reply, with additions in blue and deletions in red.

**RC1:** 'Comment on essd-2026-411', Anonymous Referee #1, 27 Aug 2026

*The manuscript presents a combined observational data set collected during a three-week field campaign (19 May - 8 June 2024) in Ny-Ålesund, Svalbard, using three complementary platforms: the fixed-wing UAS ALADINA and the tethered balloon BELUGA, both profiling aerosol particle number concentration, size distribution and meteorological variables up to 1.3 km, and a near-surface flux-gradient system estimating turbulent sensible heat and particle number fluxes at about 2 m height. The authors describe the instrumentation, calibration and post-processing chain for each platform in detail, provide a campaign-wide overview of data availability and meteorological conditions, and illustrate the combined use of the three data sets with a case study on 3 June 2024, relating vertical and horizontal aerosol variability to boundary-layer stability, advection and surface exchange. The three resulting data sets are archived on PANGAEA with individual DOIs. The paper is intended as a data descriptor for this campaign data set. In its present form, I recommend major revisions according to my comments before the manuscript can be considered for publication in ESSD.*

General comments

*I have a fundamental reservation about the suitability of this manuscript for ESSD rather than for a methods-oriented outlet such as AMT (Copernicus). The dataset covers a single campaign of about three weeks at one site, with rather modest total sampling volumes once post-processing is applied (20 h for ALADINA, 39 h for BELUGA, 214 h for the surface gradient system; Table 1). ESSD's own editorial statement (Carlson and Oda, 2018) is explicit that a data paper must satisfy a dual criterion: data quality and interest/utility to a sufficiently broad user community, and it contrasts a "small data set collected over a short time at a single location" with genuine community-wide, multi-decadal compilations. I do not think this campaign qualifies as the latter. The dataset is scientifically respectable, but I am not convinced it meets the standard the journal itself sets. I would like to see the authors make an explicit case, in the introduction and conclusions, for why this specific combination of platforms and this specific three-week window constitutes a resource of lasting, broad utility rather than assuming this is self-evident.*

The authors would like to thank the reviewer for raising such a fundamental issue as the suitability of the manuscript for ESSD. Sect. 3.8 of Carlson and Oda (2018) identifies data quality and interest to a sufficiently broad user community as the central criteria. They

recognise a range of intermediate products between small data sets collected over short periods at single locations and global long-term compilations. We consider the present data set suitable for ESSD for the following reasons:

- Ny-Ålesund is well equipped with aerosol instrumentation at different sites and altitudes within a highly complex orographic terrain. Therefore, the spatial representativeness of these aerosol measurements obtained at Ny-Ålesund needs to be considered in relation to the prevailing meteorological conditions. In particular, aerosol concentrations close to the fjord and at Zeppelin Mountain can differ. Such differences can arise when atmospheric boundary layer stratification limits the vertical exchange due to stable conditions. In our understanding, the data set described in the manuscript addresses a critical gap by providing comprehensive information on both small-scale vertical and horizontal variability, and allows this variability to be interpreted in the context of the meteorological observations. Therefore, we are confident that the data set will be of highest interest for the community, including for improved process understanding and for validation of numerical simulations. We agree that more measurements or higher total sampling volumes would be useful for a comparison with ground-based data, but these kinds of measurements are limited in operation and funding, and still unique.
- The three-week campaign captured conditions before and during the onset of snow melt, together with changes in meteorological conditions. The observations therefore allow aerosol variability and near-surface exchange to be investigated under changing surface conditions during the transition from spring to summer. This provides a basis for subsequent process studies using the combined aerosol, meteorological and surface flux observations.
- The combined measurements are relevant to researchers studying aerosol processes, atmospheric boundary layer dynamics and surface-atmosphere exchange/interactions, as well as to atmospheric modelers. They provide complementary observations of spatial aerosol distributions and near-surface particle fluxes that can be used to evaluate the representation of transport, mixing and deposition in numerical simulations. The data set contributes to the interpretation of long-term data sets, e.g., at the Zeppelin Observatory or at the Gruebadet Atmosphere Laboratory, particularly with regard to the complex relationship between aerosol and meteorological observations at different altitudes and locations.
- Recent examples for very similar publications of campaign-based data in ESSD are: Dorff et al., 2026 (<https://essd.copernicus.org/articles/18/2799/2026/essd-18-2799-2026.html>), Le et al., 2026 (<https://essd.copernicus.org/preprints/essd-2026-135/>), and Doulgeris et al., 2025 (<https://essd.copernicus.org/articles/17/6497/2025/>)

The main purpose of the manuscript is to document this combined, publicly available data set and facilitate its use in subsequent research. The descriptions of the instrumentation and data processing provide the information needed to assess and use the observations. In the revised manuscript, changes were made to highlight the scientific value of the described data set. For example, this was stated in more detail in the abstract, introduction and conclusions:

Added text in the abstract (L. 14-16): " The data set provides spatial context for interpreting long-term observations in Ny-Ålesund which are strongly influenced by local orography, and a basis for evaluating high-resolution atmospheric simulations of aerosol transport and mixing."

Added text in the introduction (L. 84-87): "This combination provides information about spatial and dynamical context for interpreting long-term measurements in Ny-Ålesund, including the

Zeppelin Observatory (Platt et al., 2022). The campaign captured the onset of snow melt and changing meteorological conditions, allowing aerosol variability to be examined alongside changes in surface conditions and turbulent exchange.”

Revised the conclusions (L. 559-565): “The case study of 3 June 2024 demonstrates this complementarity by showing pronounced variations in the vertical aerosol structure within a stably stratified boundary layer, contrasting aerosol concentrations between land and fjord areas, and periods of net particle deposition. The campaign data set complements long-term measurements in Ny-Ålesund by resolving small-scale vertical and horizontal aerosol variability in relation to atmospheric stratification and near-surface turbulent exchange. Measurements before and during the onset of snow melt allow these relationships to be investigated under changing surface and meteorological conditions. The observed spatial concentration patterns and near-surface particle fluxes can also support the evaluation of numerical simulations of aerosol transport and mixing under the observed conditions.”

*The introduction builds an extensive case around pan-Arctic sources, transport pathways and seasonal aerosol regimes (L. 44-53 and surrounding paragraphs), but it does not engage at all with the substantial body of work already carried out specifically at Ny-Ålesund on ultrafine particles, particle size distribution, ice-nucleating particles, CCN and turbulent particle fluxes. Several groups have published extensively on exactly these topics at this site, and I consider their absence a genuine gap in the literature review. It directly affects the "interest and utility" argument, since the authors need to position their new data against what is already known and available for Ny-Ålesund specifically, not only against the generic Arctic picture. I would ask the authors to add this local context and to clarify how the present data set adds to, rather than duplicates, that existing body of Ny-Ålesund observations.*

We thank the reviewer for the suggestion to include more literature and work that was done in Ny-Ålesund. We have revised the general discussion of Arctic aerosol seasonality and added a paragraph on local studies of particle number size distributions and new particle formation, CCN and cloud droplet formation, and turbulent particle fluxes (L. 45-55). We have also added a paragraph on previous tethered-balloon and UAS observations in Ny-Ålesund, including aerosol profiling and measurements of vertical and horizontal variability (L. 61-72). These studies show that airborne aerosol profiling and near-surface particle flux measurements have previously been carried out in Ny-Ålesund and that further profiles under different atmospheric conditions are needed. The contribution of the present data set is the availability of spatially resolved aerosol and meteorological observations together with near-surface flux estimates from the joint campaign, which covered conditions before and during the onset of snow melt (L. 73-87). We have clarified how this combination provides spatial and meteorological context for interpreting long-term measurements at the site (L. 84-87).

*As currently written, roughly half of the manuscript (Sects. 3.1, 3.2, 3.3) reads as a sensor-development and calibration paper, not a data descriptor. Section 3.1.1 ("Platform and instrumentation", L. 180 onward) is the clearest example: it goes into a level of technical detail - telemetry frequencies, battery-swap logistics, sensor mounting geometry - that in my reading has, in all likelihood, already been published by the same authors elsewhere. The same applies to the derivations in Sect. 3.1.2 (the inverted first-order transfer function and phase-neutral filtering for TSYS01, the Arrhenius-type temperature dependence of the HMP110 time constant in Eq. 1/Fig. 5b, the geometric treatment of wind-direction uncertainty in Fig. 5a, and the Mach-number-based static-temperature correction). This is methodological material of the kind AMT exists for, and in several cases, it is already covered by citable companion papers*

*(Bärfuss et al., 2023; Pilz et al., 2022; Mathes et al., 2025a). Before revising, I would ask the authors to check ESSD's own guidance on what level of instrumental/methodological detail a data descriptor is actually expected to carry (Sect. 3.4 of Carlson and Oda asks for enough detail "to allow readers to replicate the analysis", not a re-derivation of the underlying physics) and compress accordingly, moving material that is not novel to this dataset into a supplement or handling it by citation.*

We agree that the descriptions of the measurement platforms and established processing methods can be shortened, particularly for ALADINA. We have substantially revised Sects. 3.1–3.3 (L. 189-452) by removing selected operational and construction details, reducing repetition of instrumentation and calibration descriptions, and referring to previous publications for established methods. At the same time, the corrections applied to this data set, uncertainties and the quality control criteria are relevant for the use of the data set. These determine the interpretation and comparability of the observations and are consistent with the documentation, validation and uncertainty assessment recommended by Sects. 3.3-3.6 of Carlson and Oda (2018). We have therefore retained concise descriptions of the processing applied during this campaign, including deviations from previously published procedures. Where the relevant methods are already documented, we have replaced detailed descriptions with references. The HMP110 response-time parameterisation, the illustration of wind-direction uncertainty, and examples of the CPC time correction and the exclusion of measurements during turning manoeuvres have been moved to Appendix B. Supporting aerosol measurement comparisons and examples of the flux-gradient processing have been moved to Appendices C and D, respectively.

*According ESSD's explicit open-format requirement (Sect. 3.1 of Carlson and Oda), the data availability section (Sect. 6) must state the file format(s) delivered (netCDF, csv, ...) and be self-sufficient for a user with no other access to the manuscript. As it stands, Sect. 6 gives only the three PANGAEA DOIs and one sentence per data set; it does not state file formats, variable-naming conventions, or whether the three data sets share a common time base/geolocation convention that would let a user combine them (which is, after all, the entire scientific rationale of the paper). I would ask for this to be expanded.*

*David Carlson and Tomohiro Oda. Data publication – ESSD goals, practices and recommendations. Earth Syst. Sci. Data, 10, 2275–2278, 2018. <https://doi.org/10.5194/essd-10-2275-2018>, 2018*

We agree that the data availability section should provide more information to facilitate access to and combined use of the three data sets. We have expanded Sect. 6 (L. 567-585) to specify the tab-delimited text format, the CC BY 4.0 licence, and the organisation of the data into individual flights or separate profile and flux data sets. The section now describes the common UTC time reference and PANGAEA geocode conventions, including geographical coordinates referenced to WGS84 and the distinction between airborne altitudes above sea level and measurement heights above the local surface. Parameter names, units and measurement devices are documented in the PANGAEA metadata. We have clarified aspects relevant to combining the observations, including differences in temporal resolution and measurement location, the separate altitude information for the BELUGA payloads, and the distinction between aerosol concentrations reported at standard and ambient conditions. These additions provide an overview of the archived data and the conventions needed for their use without requiring readers to consult the instrument descriptions.

### Specific comments

240 - 337 (Sect. 3.1.2), Fig. 4, Fig. 5, Fig. 6. In particular, the derivation of the solar-heating bias correction (L. 258 - 271) and the Arrhenius fit for the HMP110 (L. 284 - 298, Eq. 1, Fig. 5b) are original methodological contributions that deserve to be a citable AMT-type reference in their own right, not embedded prose in a data descriptor. If these corrections are indeed novel here (not already described in Bärffuss et al., 2023), that is precisely the argument for publishing them separately with proper methodological peer review, rather than as a paragraph inside a data paper.

We have shortened Sect. 3.1.2 and referred to previous publications for established processing methods. We have retained the processing scheme shown in original Fig. 4 of the submitted manuscript to explain the sequence of processing steps applied to the published data, as described by Bärffuss et al. (2018). The original Fig. 5, showing the wind direction uncertainty and the temperature dependence of the HMP110 response time, has been moved to Appendix B together with the Arrhenius-type equation and fitted parameters. The original Fig. 6 has also been moved to Appendix B, where it illustrates the effect of the CPC time correction and the exclusion of measurements during turning manoeuvres. The purely geometrical assumption used to exclude potentially affected data is not new. To our knowledge, it has not been prominently described in the literature, and we do not consider this assumption alone to justify a separate methodological publication. We have therefore clarified the procedure used to exclude measurements potentially affected by solar heating in the manuscript and revised the text as follows:

L. 237-240: "TSYS01 measurements potentially affected by solar radiative heating are excluded when the angle between the direction towards the sun and the sensor pointing direction, aligned with the airframe's forward vector, is below 45°. Solar radiative heating of the TSYS01 was associated with temperature increases of up to about 0.5 K during the campaign."

A similar consideration applies to the Arrhenius-type fit for the HMP110. The reconstruction of humidity measurements using temperature dependent response times is described in Bärffuss et al. (2023, Appendix A2), while Appendix B describes their estimation by comparing ascent and descent profiles under different temperature conditions. The use of ascent-descent comparisons to determine sensor time constants is also described in Bärffuss et al. (2018). Here, we applied this approach to estimate HMP110 response times under the temperature conditions encountered during the campaign. An Arrhenius-type function was chosen as an assumed model to obtain a physically motivated parameterisation of their temperature dependence. The fitted relationship therefore represents a campaign specific parameterisation within an established reconstruction procedure (e.g., Dirksen et al., 2014; Miloshevich et al., 2004). We consider its documentation necessary to explain the processing of the published humidity data, especially as the retrieved response time for  $(1-1/e)$  - within the text referred as "time constant"  $\tau$  - is counterintuitively high. We have shortened the description in the main text and moved the equation, fitted parameters and corresponding figure to Appendix B. We rewrote the text to:

L. 247-256: "The HMP110 sensor shows a strongly affected response depending on the ambient temperature, therefore a temperature-dependent time constant is applied for reconstruction and filtering, following Bärffuss et al. (2023) and Miloshevich et al. (2004). Valid time constants are estimated by manually varying  $\tau$  until humidity structures in the reconstructed ascent and descent profiles show the best agreement, using seven flights

representative of cold and warm conditions and following the approach described in Bärffuss et al. (2018) and Bärffuss et al. (2023). The median temperature at the top of the vertical profiles is used to associate the estimated time constants with the corresponding temperature conditions. An Arrhenius-type function is fitted to these estimates to parameterise the temperature dependence of the HMP110 response time (Arrhenius, 1889; Laidler, 1984), with the estimated time constants and fitted relationship provided in Appendix B (Fig. B1b). The resulting time constant  $\tau(T)$  is used for reconstruction and filtering of the HMP110 raw sensor readings.”

Dirksen, R. J., Sommer, M., Immler, F. J., Hurst, D. F., Kivi, R., and Vömel, H.: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde, *Atmos. Meas. Tech.*, 7, 4463–4490, <https://doi.org/10.5194/amt-7-4463-2014>, 2014.

150 - 152, “as well as snow height measured at the Bayelva research site” (Boike et al., 2018, 2022). Snow height measured at Bayelva can differ considerably from snow height at the centre of the Ny-Ålesund village itself, given the heterogeneous, patchy melt described by the authors themselves in Sect. 2.1. Other snow-height records for the immediate research area may exist and be more representative of the conditions sampled especially by the gradient system. The authors should clarify exactly how this variable is used in the subsequent analysis (it only appears qualitatively in Fig. 2c) and justify why the Bayelva record, 3 km away, is an adequate proxy for the campaign area rather than just the most convenient one.

We thank the reviewer for pointing this out. We agree that the snow height measured at the Bayelva research site cannot be interpreted as direct representative of local snow conditions at the measurement site, particularly during the spatially heterogeneous melt period. The Bayelva record is not used quantitatively in the analysis and is not treated as a proxy for snow height at the surface flux gradient system site or at the other measurement locations. It is included to provide qualitative temporal context for the onset and progression of snow melt during the campaign period. Local surface conditions at the gradient system site were assessed independently and classified directly as snow, snow and vegetation, or vegetation. We have revised the manuscript accordingly to clarify the spatial limitation of the Bayelva snow height measurement:

L. 162-163: “In addition, snow height measured at the Bayelva research site (adapted from: Boike et al., 2018; Boike et al., 2022) is included as a qualitative indicator of the seasonal onset and progression of snow melt in the wider Ny-Ålesund area”

Sect. 3.2.1 (BELUGA) / Sect. 3.3.1 (gradient system). Same concern as above: the level of detail on box construction (side length, insulation thickness, heating set point), inlet geometry, and flow-rate specifications exceeds what a data user needs and duplicates Pilz et al. (2022) and Mathes et al. (2025a).

We agree and have revised Sects. 3.2.1 and 3.3.1 accordingly. Technical construction and operational details that are not required for interpretation of the data have been removed or replaced by references to the corresponding platform and instrument descriptions in Dorff et al. (2026), Pilz et al. (2022) and Mathes et al. (2025a). This applies in particular to the established TMP and CAMP systems and to the surface gradient system. More technical detail is retained for the mSEMS platform because it was deployed in this configuration for the first time during the presented campaign and is therefore not yet documented in a dedicated previous publication.

Sect. 3.3.2,  $u^* \geq 0.15$  m/s and  $R^2 \geq 0.5$  QC thresholds (L. 553–558). This is exactly the kind of explicit, quantitative QC criterion ESSD wants (cf. Carlson and Oda, Sect. 3.6) - good. Please also report, either here or in Table 1/Sect. 6, how many of the total 20-min flux intervals pass both thresholds, since this determines the effective size of the usable flux data set and is currently not stated anywhere.

Thank you for your suggestions. We have added the information to the manuscript as follows:

L.440-444: “To identify intervals with potentially reduced flux reliability due to weak turbulence or decoupling, a quality-control threshold of  $u_* \geq 0.15$  m s<sup>-1</sup> was applied. Additionally, the regression used to calculate the fluxes was quality checked using a threshold of  $R^2 \geq 0.5$  to identify poorly resolved vertical gradients. Flux estimates that do not meet these criteria should be interpreted with caution rather than being considered invalid. Of all 20-minute intervals, 35% met the  $u_*$  criterion, 27% met the  $R^2$  criterion, and 10% met both criteria simultaneously.”

Fig. 1 caption / L. 100 - 102. The caption states that ground-based stations shown as white dots “include the Zeppelin Observatory, Gruebadet Atmosphere Laboratory, the Bayelva research site and the AWIPEV Research Base.” I checked panels (a) and (b) and the AWIPEV Research Base is not shown/labelled in the figure at all, despite being listed in the caption. Please add the marker or correct the caption.

We thank the reviewer for pointing this out. The AWIPEV Research Base is located within Ny-Ålesund and was therefore initially not indicated by a separate marker in Fig. 1. We have revised Fig. 1b by adding a labelled marker for the AWIPEV Research Base to clarify its exact location.

Fig. 2 caption: “in 2 h median intervals” - please confirm this applies only to the last two panels equally, since panel (a) shows discrete flight bars rather than a continuous median series.

We thank the reviewer for highlighting this. The 2 h median intervals only apply to panels (b) and (c), whereas panel (a) shows the individual measurement periods of the three systems. We have revised the caption accordingly:

Revised caption of Fig. 2: “Data availability of the three measurement systems and time series of selected parameters during the campaign period in May and June 2024. The time series in panels (b) and (c) are shown in 2 h median intervals.”

**RC2:** ‘Comment on essd-2026-411’, Anonymous Referee #2, 30 Aug 2026

Review of “Arctic aerosol and meteorological observations using airborne and ground-based systems in spring 2024” by Schuchard et al. (essd-2026-411)

### General assessment

This manuscript presents an extensive dataset of aerosol and meteorological observations obtained with the fixed-wing UAS ALADINA, the tethered-balloon system BELUGA, and a surface flux-gradient system during spring 2024 in Ny-Ålesund. The manuscript is generally well written and clearly structured. The authors have done a good job describing the platforms, instrumentation, measurement strategy, data processing and quality-control procedures. The combination of repeated vertical profiles, horizontal flight legs, aerosol size distributions and

*near-surface flux measurements represents a valuable dataset for studies of the Arctic atmospheric boundary layer.*

*Nevertheless, I believe that major revision is required before publication. My principal concern is that the quality assessment relies predominantly on laboratory calibrations and internal comparisons, whereas the connection to the extensive reference measurements available around Ny-Ålesund is largely missing. Consequently, the manuscript demonstrates that the airborne systems behave reasonably and produce internally consistent patterns, but it provides limited evidence for the absolute accuracy and comparability of the resulting aerosol and meteorological measurements under field conditions. I will only support the reviewer #1 comments about the data descriptor, but I still think the dataset is of high value and interest within the community.*

We thank the reviewer for the valuable comments and the positive assessment of the data sets. The main purpose of this manuscript is to document the observations, the processing applied, and the information needed for their subsequent use. Comparisons with independent reference measurements have previously been reported for both airborne measurement systems. Altstädter et al. (2015) assessed ALADINA aerosol measurements against ground-based observations at Melpitz, while CAMP was evaluated at Melpitz and during MOSAiC (Pilz et al., 2022, 2023). These studies provide evidence of instrument performance under field conditions and complement the calibration and quality-control procedures described in the present manuscript. At this point, we would like to mention that further studies are currently in progress, which focus on comparison of the campaign data with ground-based measurements (e. g. from the Zeppelin Observatory) and on the spatial representativeness of these observations under different atmospheric conditions. We additionally present meteorological comparisons in this response document and discuss their interpretation and limitations below.

### Major comments

#### *1) Comparison with reference measurements around Ny-Ålesund*

*Ny-Ålesund offers an unusually comprehensive measurement infrastructure, including the AWIPEV meteorological observations, the Zeppelin Observatory, Gruebadet Atmosphere Laboratory and the Bayelva site. These stations are introduced in Sect. 2.1 and shown in Fig. 1, but their measurements are not used for field validation of the new datasets.*

*Laboratory calibration is essential, but it does not fully test the complete measurement chain under flight conditions. This includes inlet aspiration and transmission, tubing losses, flow stability, sensor ventilation, radiative effects, pressure and temperature dependence, response-time corrections and potential platform contamination.*

*I therefore strongly recommend comparing the airborne observations with temporally overlapping reference measurements. For example:*

- Near-surface ALADINA and BELUGA temperature, humidity, pressure and wind measurements could be compared with AWIPEV station or mast observations.*
- Aerosol particle number concentrations and size distributions could be compared with concurrent CPC, SMPS, NAIS or related observations at Gruebadet and, where appropriate, Zeppelin.*

- *Selected periods when ALADINA and BELUGA operated simultaneously could be used for direct comparisons at similar altitudes, even if the platforms were at somewhat different horizontal locations.*
- *Comparisons should preferably include bias, scatter, correlation, number of matched observations and the expected uncertainty or representativeness range.*

*I recognise that differences are expected because the platforms and stations were not collocated and because the complex local topography can generate genuine spatial variability. These limitations should be quantified and discussed rather than used as a reason to omit the comparison. Even comparisons restricted to take-off, landing, near-surface balloon measurements or suitably selected wind sectors would considerably improve confidence in the absolute values.*

*This is particularly important for a data paper. Without such comparisons, much of the interpretation remains based on relative changes within each platform rather than demonstrating traceability and comparability of the reported values.*

We thank the reviewer for highlighting this. A quantitative aerosol comparison with ground-based measurements requires careful consideration of spatial representativeness and differences between the measurement systems. As recognised by the reviewer, the complex terrain, local wind fields and atmospheric stratification in Ny-Ålesund can produce substantial aerosol variability over short distances. Differences in measurement method and sampling conditions as well as spatial separation of the airborne and ground-based measurements further limit direct quantitative comparability. Individual comparisons alone would therefore not allow us to reliably distinguish a systematic instrumental bias from differences caused by boundary-layer processes and spatial aerosol variability. Previous field comparisons at Melpitz assessed ALADINA and CAMP against independent ground-based aerosol measurements (Altstädter et al., 2015; Pilz et al., 2022). We refer to these studies as evidence of instrument performance under field conditions. Comparisons of the present campaign observations with ground-based measurements are currently being pursued in subsequent studies, including a case-by-case assessment of the atmospheric conditions and spatial representativeness. We have therefore not included a quantitative aerosol validation against Gruebadet or Zeppelin in the present manuscript.

The case study in the present manuscript already presents and discusses overlapping ALADINA and BELUGA profiles, illustrating their complementary observations and the spatial variability. We consider this appropriate for demonstrating the combined use of the published data sets, while recognising that it does not serve as independent validation of absolute particle number concentration. We agree that an additional meteorological comparison adds value to the assessment of the observations. We therefore provide this additional meteorological comparison in the publicly accessible response to the reviewer. Figure R1 compares three pairs of temporally overlapping vertical profiles from ALADINA and BELUGA on three different days during the field campaign. For the three profiles, mean differences (ALADINA minus BELUGA;  $\pm$  standard deviation) are  $-0.61 \pm 0.95$  K for temperature,  $+11 \pm 7.3\%$  for relative humidity,  $+7.55 \pm 2.19$  hPa for ambient pressure and  $+0.48 \pm 0.8$  m s<sup>-1</sup> for horizontal wind speed. The comparison is calculated by combining all overlapping 10 m altitude bins of the three profiles and include temporal and spatial distances between the two airborne systems. By comparing AWIPEV mean values with lowest bins of ALADINA profiles (65 or 75 m a.s.l.),

differences up to 0.68 K in temperature, 5.6% in relative humidity and 0.7 m s<sup>-1</sup> in horizontal wind speed are present. Corresponding differences comparing AWIPEV mean values with lowest bins of BELUGA profiles (55 m a.s.l.) reach 1.25 K in temperature, 18.8% in relative humidity and 0.51 m s<sup>-1</sup> in horizontal wind speed. The AWIPEV observations used for the comparison are taken from the same data set as presented in the manuscript (Maturilli, 2020a, b).

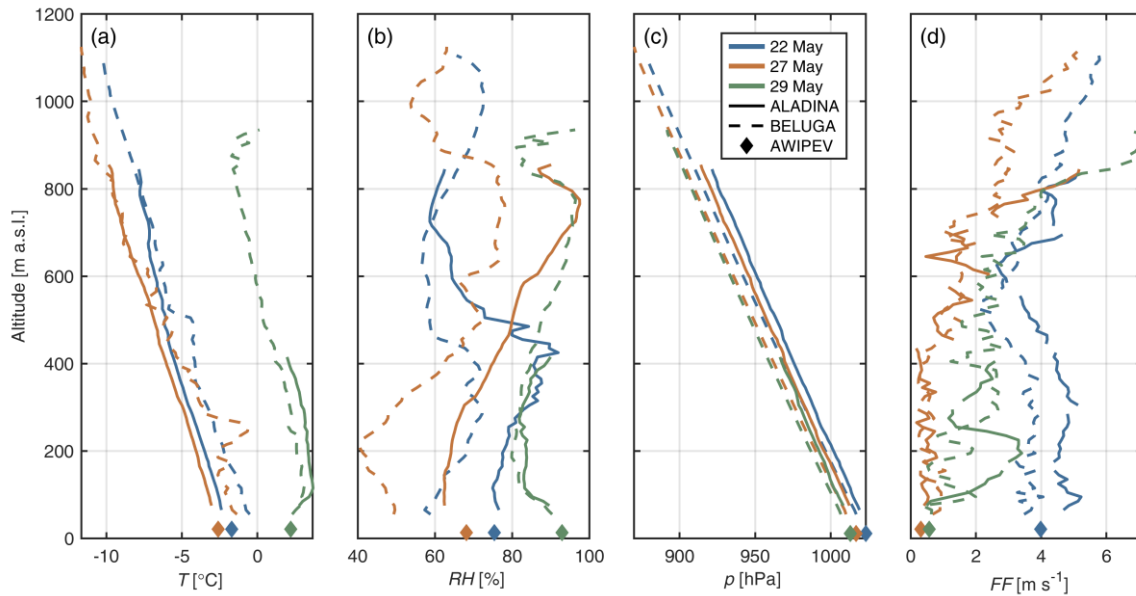


**Figure R1:** Comparison of ALADINA (solid line) and BELUGA (dashed line) profiles of (a) temperature, (b) relative humidity, (c) ambient pressure and (d) horizontal wind speed, averaged in 10 m altitude bins. Diamonds show AWIPEV mean values during the corresponding ALADINA profile. The AWIPEV station is located at 11 m a.s.l. and temperature and wind are measured at 10 m above ground, while relative humidity is measured at 2 m above ground. Profile intervals in UTC from ALADINA/BELUGA on three different measurement days are 10:54-11:01/10:42-11:16 on 22 May 2024, 09:19-09:25/09:07-09:39 on 27 May 2024, and 16:36-16:39/16:11-16:42 on 29 May 2024.

Figure R2 extends the comparison with AWIPEV to all available ALADINA and BELUGA vertical profiles reaching below 100 m a.s.l. For each ascent or descent, temperature, relative humidity and pressure are averaged within the lowest available 10 m. AWIPEV observations are averaged over the corresponding sampling interval or the nearest available value is used, with a maximum time difference of 30 s. The comparison includes 143 vertical profiles from 38 ALADINA flights. For BELUGA, it includes 83 vertical profiles from 20 flights for relative humidity and pressure, and 79 vertical profiles from 19 flights for temperature after excluding measurements flagged for potential radiative influence. The used airborne measurements cover altitudes of 54.3-100 m a.s.l. for ALADINA and 17.7-69.8 m a.s.l. for BELUGA. For ALADINA, mean differences relative to AWIPEV (ALADINA minus AWIPEV;  $\pm$  standard deviation) are  $+0.07 \pm 0.71$  K for temperature,  $-3.42 \pm 4.16$  % RH for relative humidity and  $-4.66 \pm 1.38$  hPa for pressure, with corresponding  $R^2$  values of 0.978, 0.870 and 0.96. For BELUGA, the corresponding differences are  $+0.94 \pm 0.64$  K,  $-9.24 \pm 7.06$  % RH and  $-4.38 \pm 2.34$  hPa, with  $R^2$  values of 0.963, 0.843 and 0.876. These statistics include variable differences in measurement altitude and spatial separation. In particular, the pressure differences include the decrease in pressure with altitude. For this comparison, we decided to use the published post-processed vertical profiles to assess the observations available to subsequent users.

Overall, measurements from both airborne systems show strong correlations with AWIPEV observations despite differences in altitude and location.

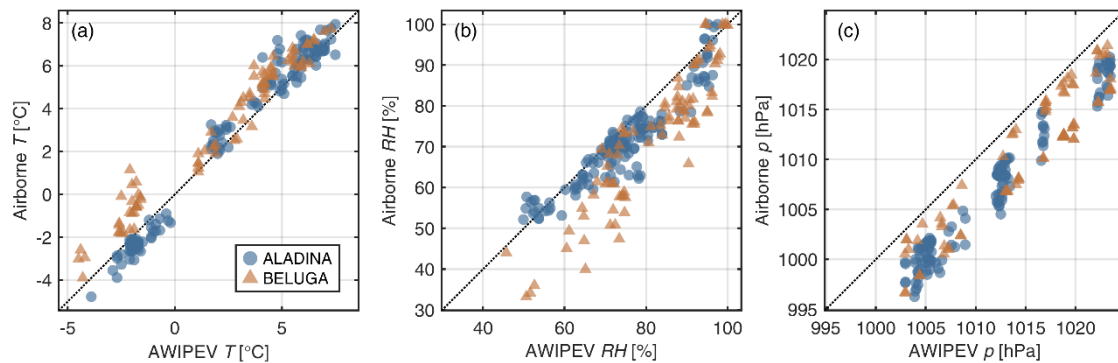


Figure R2: Comparison of AWIPEV observations with mean values from the lowest available 10 m of each ALADINA and BELUGA ascent or descent reaching below 100 m a.s.l.: (a) temperature, (b) relative humidity and (c) pressure. Each point represents one vertical profile. AWIPEV values are averaged over the corresponding sampling interval or matched to the nearest value within 30 s. The dotted lines indicate 1:1 agreement. Pressure values are shown at their respective altitudes without altitude adjustment.

## 2) Aerosol inlet, aspiration and transmission efficiencies

The description of aerosol sampling is not yet sufficient to assess the representativeness of the aerosol data. Please provide, for ALADINA and all BELUGA aerosol payloads:

- inlet geometry, diameter and orientation;
- total and instrument-specific flow rates;
- inlet velocity relative to aircraft or balloon airflow;
- whether sampling is isoaxial and approximately isokinetic;
- lengths, internal diameters and materials of sampling tubes;
- residence times;
- bends, flow splits and bypass flows;
- aerosol drying or other sample conditioning;
- calculated or measured size-dependent aspiration and transmission efficiencies;
- treatment of diffusion, sedimentation, inertial, bend and electrostatic losses; and
- information on whether corrections were applied to the archived data.

We have clarified the aerosol sampling configurations and the corrections applied to the ALADINA and BELUGA data set in the revised manuscript. The descriptions focus on the sampling characteristics, processing steps and limitations needed to assess and use the observations. We kept the information relevant to interpreting the data set within the manuscript, while avoiding repetition of the technical system documentation by providing the relevant references. This also addresses the Referee #1 request to shorten established instrumental and methodological descriptions. Further technical information on the campaign configurations can be provided by the corresponding author upon request.

For ALADINA, Sect. 3.1.1 now specifies the inlet dimensions, material and orientation, the absence of active drying, and the flow distribution through the OPC, CPCs and bypass. The calculated mean inlet velocity is approximately  $3.6 \text{ m s}^{-1}$ , compared with a cruising airspeed of  $28 \text{ m s}^{-1}$ , resulting in sub-isokinetic sampling. The inlet is aligned with the aircraft axis, although this does not ensure strictly isoaxial sampling under all flight conditions. For example, CPC measurements during turning manoeuvres are excluded from the final data set. Revised Sect. 3.1.2 describes the calibration of the assembled aerosol stack, the plateau counting-efficiency and sampling-efficiency corrections, and the applied time shifts. It also specifies that CPC concentrations are converted to standard conditions. OPC concentrations are reported under ambient conditions. For CAMP, the revised Sect. 3.2.1 describes the common vertical funnel inlet, aerosol drying, payload heating and instrument-specific sample flow rates. Further details of the platform design, instrument modifications and flow system are provided by Pilz et al. (2022). For the mSEMS platform, the same section describes the funnel inlet, which has the same geometry as CAMP, the aerosol drying, and the sample monitoring. The measurement size range, scan settings and overall instrumentation are also specified. Revised Sect. 3.2.2 describes the corrections applied to the BELUGA aerosol data. These include the plateau counting-efficiency and sampling corrections applied to the CPCs, the size calibration and channel-specific sampling corrections for the POPS, and the aMCPC plateau counting-efficiency correction, size-distribution inversion and channel-specific sampling corrections for the mSEMS. The corrected aerosol concentrations and size distributions are converted to standard conditions.

To provide additional context for the influence of BELUGA motion on the aerosol sampling, Fig. R3 compares the calculated platform drift speed with the measured wind speed during the campaign. The mean drift speed was  $0.55 \text{ m s}^{-1}$ , compared with a mean measured wind speed of  $2.89 \text{ m s}^{-1}$ . Platform motion was therefore smaller on average, although its contribution may become relevant under low-wind conditions.

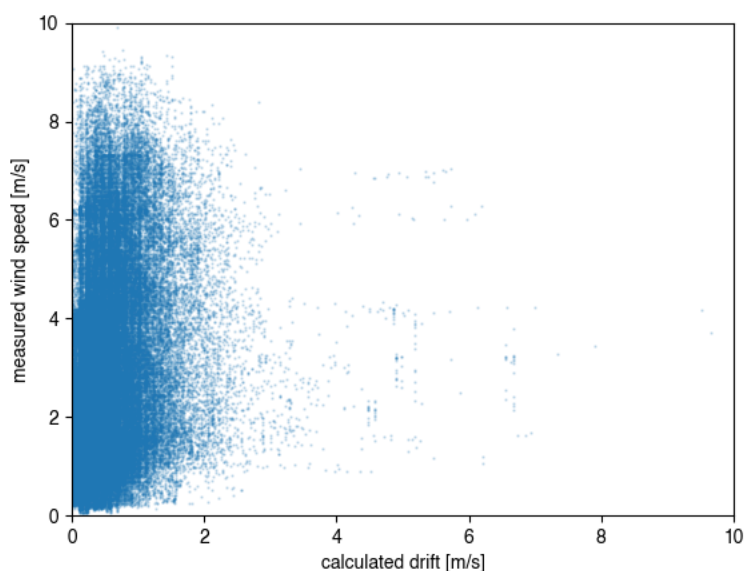


*Figure R3: Comparison of calculated BELUGA platform drift speed and measured wind speed during the campaign.*

*For ALADINA, the reported mean sampling-efficiency factor of 1.05 applies only between 40 and 500 nm. It therefore does not cover the smallest particles measured by the CPCs, whose lower cut-offs are 6 and 19 nm, or the coarse fraction measured by the OPC up to  $10 \mu\text{m}$ . At an aircraft speed of approximately  $28 \text{ m s}^{-1}$ , aspiration and orientation effects may be particularly important for the coarse-particle channels.*

The sampling-efficiency factor of 1.05 represents an average over the particle diameter range of 40-500 nm to account for inlet aspiration efficiency and tubing losses of the CPC measurements. This correction is applied to the CPC concentration in addition to the respective plateau counting-efficiency corrections. We did not consider enhanced particle sampling of the sub-isokinetic inlet above 500 nm for the CPCs, as the particle number concentration in this size range is negligible compared to smaller sizes. Below 40 nm, the CPC counting efficiencies depend on particle size. A size-dependent correction of the integrated CPC concentrations would require assumptions about the particle size distribution at the sampling location. We therefore did not apply an additional sampling correction specifically representing particles below 40 nm. A correction for the difference between the two CPC measurements would likewise require assumptions about the particle size distribution within their overlapping counting-efficiency curves. The manufacturer specified concentration accuracy of  $\pm 20 \%$  for each CPC further limits the quantitative interpretation of  $N_{6-19}$ . The relative uncertainty of the difference can substantially exceed the specified relative uncertainties of each CPC. Accordingly, we use  $N_{6-19}$  as an indicator of ultrafine particles rather than as an exact particle number concentration within a sharply defined size interval. The OPC concentrations are

corrected for the transport delay. We acknowledge that sub-isokinetic sampling can affect the measured concentrations, particularly in the coarse mode.

*The same issue applies to the funnel inlets used by CAMP and mSEMS. The manuscript should state how the inlet geometry and balloon motion affect sampling. The downward-facing inlet of the surface gradient system should also be justified, including its potential effect on sampling larger particles.*

*If a complete inlet characterisation has been published previously, the relevant results should be briefly summarised here and the appropriate references provided. The reader should not have to infer the applicable particle-size range and sampling efficiency from several previous publications.*

For CAMP, the inlet geometry and sampling characterisation are described by Pilz et al. (2022). The vertical funnel inlet permits sampling from different horizontal wind directions. For the configuration used here, the estimated upper particle cut-off is  $2.7\ \mu\text{m}$  at wind speeds up to  $3.5\ \text{m s}^{-1}$ . The published method accounts for inlet aspiration efficiency and tubing losses. The mSEMS platform uses the same inlet geometry, with its own sampling configuration and size depending corrections described in Sects. 3.2.1–3.2.2. The influence of balloon motion is addressed above and illustrated in Fig. R3. For the surface gradient system, the downward-facing inlet prevents precipitation from entering the sampling line and enables measurements close to the surface. These reasons and potential sampling biases for larger particles are now stated in Sect. 3.3.1. Technical details are provided by Mathes et al. (2025), and the corrections applied to the present data are described in Sect. 3.3.2.

### 3) HMP110 response time and humidity reconstruction

*Figure 5b indicates an HMP110 time constant reaching approximately 160 s. This appears very long relative to an ALADINA ascent or descent lasting about 7 min. Based on a 930 m profile completed in approximately 420 s, the mean vertical speed is about  $2.2\ \text{m s}^{-1}$ . A time constant of 160 s would therefore correspond to a characteristic vertical response distance of roughly 350 m before reconstruction. Sharp features such as cloud boundaries, inversion layers or humidity gradients could be strongly displaced and attenuated.*

We agree that a time constant (63% step response time) of approximately 160 s is counter-intuitive and implies substantial smoothing of HMP110 data without recovering measurements with an inverse transfer function of the measurement process. However, strongly increasing response times at low temperatures are well documented for capacitive Vaisala humidity sensors. Miloshevich et al. (2004) report time constants reaching an order of  $10^2\ \text{s}$  under cold conditions and demonstrate that numerical response time correction can recover part of the vertical humidity structure. These findings support the general physical behaviour assumed and the reconstruction applied here.

*The use of an inverse transfer function may partly reconstruct the signal, but it may also amplify noise and cannot necessarily recover atmospheric structure that the sensor did not resolve. Please:*

- *explain more clearly how the temperature-dependent time constants were determined;*

The time constants were estimated by manually varying  $\tau$  until corresponding humidity structures in the reconstructed ascent and descent profiles revealed the best agreement. This follows the ascent-descent comparison approach described by Bärffuss et al. (2018, 2023). We have clarified this selection procedure in the manuscript:

L. 249-253: “Valid time constants are estimated by manually varying  $\tau$  until humidity structures in the reconstructed ascent and descent profiles show the best agreement, using seven flights representative of cold and warm conditions and following the approach described in Bärffuss et al. (2018) and Bärffuss et al. (2023). The median temperature at the top of the vertical profiles is used to associate the estimated time constants with the corresponding temperature conditions.”

- *provide the range of derived time constants and the number of flights used;*

The empirically estimated time constants range from 35.4 s to 159.2 s across the seven flights, with corresponding temperatures between 264.7 and 279.3 K.

- *quantify the resulting effective temporal and vertical resolution;*
- *demonstrate that the reconstructed profiles are stable and not dominated by inversion artefacts;*

The inverse first-order reconstruction is followed by phase-neutral low-pass filtering to reduce amplified noise. The resulting smoothing and the sensitivity to the assumed response time are discussed in Bärffuss et al. (2023, Appendix C). We therefore refer to this methodological assessment for the behaviour and limitations of the reconstruction procedure.

- *validate the reconstructed humidity against the Rapid P14 and, where possible, against surface or radiosonde measurements; and*
- *discuss the uncertainty and usefulness of flights for which only the reconstructed HMP110 measurement is available.*

The reconstruction approach was previously evaluated against radiosonde measurements by Bärffuss et al. (2023, Fig. 6). The uncertainty of the reconstruction, particularly near strong humidity gradients, is discussed in Bärffuss et al. (2023, Fig. 8 and Appendix C2). Similar limitations of time-lag corrections for capacitive humidity sensors are discussed by Dirksen et al. (2014). We refer to these published evaluations of the reconstruction approach and do not include an additional radiosonde comparison for the present campaign. For flights without valid Rapid P14 measurements, the reconstructed HMP110 data are considered suitable for interpreting the broader vertical humidity structure. Sharp humidity gradients should be interpreted with caution because their shape and magnitude are affected by the assumed response time and subsequent filtering. The comparison with AWIPEV observations presented under Major Comment 1 (Fig. R2) provides an additional assessment of the final ALADINA humidity data under campaign conditions.

Dirksen, R. J., Sommer, M., Immler, F. J., Hurst, D. F., Kivi, R., and Vömel, H.: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde, *Atmos. Meas. Tech.*, 7, 4463–4490, <https://doi.org/10.5194/amt-7-4463-2014>, 2014.

#### 4) PANGAEA data and metadata

*I checked the three PANGAEA records listed in the Data availability section:*

- ALADINA: <https://doi.org/10.1594/PANGAEA.988207>
- BELUGA: <https://doi.org/10.1594/PANGAEA.988353>
- Surface flux-gradient system: <https://doi.org/10.1594/PANGAEA.984519>

*The records are accessible and generally well organised. They contain dataset-level citations, temporal and geographical coverage, instruments, variable names, units, events, licences and downloadable tab-delimited data. ALADINA is organised into 38 flight datasets, BELUGA into 23 flight datasets, and the gradient-system record contains processed profile and flux datasets.*

*However, several improvements are needed to make the datasets fully self-describing and independently reusable:*

*a. The ALADINA metadata state that the detailed system and processing description will be provided by “Schuchard et al. (in preparation)”. This should be updated to cite and link the present manuscript.*

[The citation of the manuscript has been updated in PANGAEA.](#)

*b. The gradient-system metadata contain an apparent incorrect reference to “spring 2025”, although the campaign occurred in 2024.*

[The incorrect reference was changed in PANGAEA.](#)

*c. The same gradient-system metadata state in one place that measurements were made at five heights and elsewhere list six heights. This should be made consistent. If at least five of six levels were required for a valid profile, this distinction should be stated explicitly.*

[Thank you very much for pointing this out. The gradient system sampled six distinct height levels in seven consecutive measurement steps. The fourth level was measured once during ascent and again during descent to provide a reference for changes in background particle number concentration. A profile was used when measurements from at least four of the six distinct height levels showed valid measurements. We have corrected the PANGAEA description accordingly and clarified this distinction in the manuscript.](#)

[L. 403-407: “The gradient system was programmed to sequentially sample at six distinct height levels automatically, beginning at 10 cm above the surface and followed by the heights of 14, 22, 38, 69 and 134 cm. The actual sampling heights varied by  \$\pm 1\$  cm, depending on measurement conditions \(e.g. snowfall\) and surface characteristics. During descent from 134 cm, the 38 cm level was sampled a second time, yielding seven measurement steps at six distinct heights per profile.”](#)

L. 432-433: "When evaluating gradients based on ascending stepped profiles, only intervals are considered in which at least four of the six distinct height levels show valid measurements."

*d. Quality-control information is uneven. BELUGA includes a temperature quality flag, but equivalent information describing the validity of aerosol data, wind data, solar-heating effects and other exclusions is not consistently available. ALADINA does not appear to provide explicit quality flags or flight-phase classifications, although substantial filtering and exclusion of manoeuvres are described in the manuscript.*

The quality-control information differs between the measurement systems, as ALADINA and BELUGA use different instrumentation with distinct sensitivities and requirements for quality control and data processing. For BELUGA, temperature measurements are kept in the data set and identified with a quality flag, as the influence of solar heating cannot be reliably corrected. For ALADINA, instrument-specific corrections are applied during post-processing, while measurements identified as invalid are excluded from the final data set as missing values, e.g. during turning manoeuvres. Therefore, no additional quality flag is provided for these measurements. The corresponding quality control and exclusion criteria are described within this manuscript. One of the main purposes of the present data descriptor is to provide this information, allowing users to assess the validity and limitations of the published measurements.

*e. Users should be able to identify vertical profiles, ascents, descents and horizontal flight legs without reconstructing these phases entirely from position and attitude data. I recommend including a measurement-phase or profile identifier, particularly for ALADINA and BELUGA.*

We thank the reviewer for this suggestion. The airborne data are provided as individual flight data sets with UTC time, latitude, longitude and altitude, in accordance with the PANGAEA geocoding conventions. This allows users to distinguish ascents, descents and horizontal flight legs. The corresponding measurement patterns are described in the manuscript. We have retained this flight-based structure without adding separate profile or phase identifiers, allowing users to select and subdivide the observations according to their analysis requirements.

*f. The metadata or an accompanying README should clearly define whether each aerosol concentration is reported at ambient or standard conditions, which corrections have already been applied, the meaning of missing values, applicable uncertainty, lower and upper cut-offs, and whether particle size distributions are expressed as  $dN/d\log D_p$ .*

The requested information has been clarified in the revised manuscript. Sect. 3 and the data availability section describe the applied calibration, corrections, measurement ranges, cut-off diameters, uncertainties and whether aerosol measurements are reported at ambient or standard conditions for the individual instruments. We have also clarified the meaning of missing values and specified that particle number size distributions are expressed as  $dN/d\log D_p$ . Parameter names, units and measurement devices are documented in the accompanying PANGAEA metadata.

*g. For BELUGA, the distinction between the altitude of TMP and the aerosol payload located 10 m below it is documented, but it would be preferable to provide the appropriate altitude explicitly for each measurement stream instead of requiring users to subtract 10 m.*

For BELUGA, the appropriate altitude is already provided separately for the aerosol payload as the parameter "Alt barometric" in the data set. The altitude assigned as the geocode refers

to the TMP, while “Alt barometric” provides the altitude of the aerosol platform. Thus, users do not need to derive the aerosol platform altitude by subtracting 10 m. We have clarified the availability of separate altitude information in the data availability.

*h. Versioning should be checked. The ALADINA datasets refer to different parameter-table versions. The meaning of these versions and any differences among flights should be documented.*

The different parameter-table versions do not represent different processing versions of the ALADINA data. They reflect differences in the parameters available for individual flights. For example, flights without valid wind data do not contain wind parameters in the corresponding table. The parameter content of each individual flight data set was checked during the PANGAEA curation process and is explicitly documented in the respective parameter table.

*Overall, the PANGAEA metadata provide a good foundation, but the identified inconsistencies and missing quality-control details should be corrected before final publication.*

### Specific comments

1. *Lines 55–60: Please provide references supporting the discussion of the extent and limitations of crewed aircraft observations in the Arctic.*

The paragraph has been revised as part of the restructuring of the introduction in response to Referee #1. We have shortened the general discussion of airborne observations and expanded the context of previous measurements at Ny-Ålesund. The previous statement concerning safety-related limitations of crewed aircraft has been replaced by a statement on the potential advantages of UAS and tethered balloons in complex terrain and at low altitudes. The text was revised to:

L. 57-61: “Long-term surface observations provide temporal context, whereas airborne measurements resolve the small-scale variability in aerosol and meteorological properties across the atmospheric boundary layer (ABL). Research aircraft can be equipped with the necessary instrumentation and cover large areas. However, in regions with highly complex topography and at very low altitudes, measurements using uncrewed aerial systems (UAS) and tethered balloons, in parallel to long-term observations on the ground, may be advantageous for resolving small-scale variability.”

2. *Lines 64–68: The combination of UAS, tethered balloons and ground observations is not entirely new. Please cite previous multi-platform studies and clarify the specific novelty of the present campaign and dataset.*

We agree that combining airborne and ground-based observations is not entirely new. The contribution of the present campaign is the joint availability of UAS and tethered-balloon aerosol and meteorological observations together with near-surface flux estimates during the transition from spring to summer in Ny-Ålesund. This is clarified in the revised introduction (L. 73-87). As part of the revision in response to Referee #1, we have expanded the introduction to discuss previous UAS, tethered-balloon and ground-based studies at Ny-Ålesund. We have clarified the remaining observational need and the potential use of this campaign data set in the revised introduction:

L. 61-72: “In Ny-Ålesund, tethered-balloon measurements successfully characterised the vertical distribution of aerosol particle number concentration and size, black carbon, chemical composition, and optical properties, revealing pronounced variability associated with atmospheric stratification and air-mass transport (e.g., Moroni et al., 2015; Ferrero et al., 2016; Mazzola et al., 2016; Markowicz et al., 2017). Measurements using UAS have further shown layers with elevated  $N$  and enhanced aerosol light absorption aloft (Bates et al., 2013), as well as pronounced vertical and horizontal variability of ultrafine particles in relation to ABL properties (Harm-Altstädter et al., 2023). More recent tethered balloon campaigns have examined cloud microphysics, thermal infrared irradiance and the vertical distribution of marine aerosol constituents (Pasquier et al., 2022; Lonardi et al., 2024; Zeppenfeld et al., 2026). Despite these efforts, vertically resolved aerosol observations remain sparse compared with long-term surface measurements, particularly in polar regions and complex terrain. Further profiles and horizontal transects under different atmospheric conditions are required to assess the representativeness of surface observations and to evaluate simulated aerosol distributions (Willis et al., 2018; Creamean et al., 2021; Schmale et al., 2026).”

3. *Figure 1: Panel (b) should include appropriate copyright and attribution information, consistently with panel (a).*

The appropriate copyright and attribution information has been updated in response to the Copernicus editorial support team. The caption was changed to:

Caption of Fig.1: “Map data sources: (a) Earthstar Geographics © 2024. (b) Esri, Vantor, Earthstar Geographics, and the GIS User Community © 2024. GMTED2010 data © U.S. Geological Survey.”

4. *Lines 120–121: Please explain the specific safety risk that required operations to remain outside clouds. Were supercooled clouds and icing expected, or was the restriction mainly intended to protect the instrumentation and maintain visual or operational safety? The present wording is too general.*

The restriction was determined by the operational authorisation, which permitted flights only within visual line of sight (VLOS). Potential effects of cloud exposure on the instrumentation were not the determining reason. We have clarified this in the manuscript:

L. 131-134: “Horizontal legs were not performed during every measurement flight, and the achievable maximum altitude depended on the prevailing cloud base height (CBH), as flight operations were authorised only within visual line of sight (VLOS). Flights into clouds were therefore excluded to maintain visual contact with the aircraft.”

5. *ALADINA should be expanded at its first occurrence, including in the abstract or introduction, rather than only in Sect. 3.1.*

We thank the reviewer for highlighting this issue. We have revised the text accordingly, expanding the ALADINA abbreviation at its first occurrence in the introduction (L. 76–77).

6. *Table 2: Please specify whether the stated CPC and OPC uncertainties refer to particle number concentration, particle sizing, or both. For the OPC, sizing and counting uncertainties should ideally be distinguished.*

We have clarified that the manufacturer uncertainties listed in original Table 2 refer to number concentration for the CPCs and particle sizing for the OPC. The GT-526S manual specifies  $\pm 10\%$  sizing accuracy for factory-calibrated sizes and  $\pm 15\%$  for custom sizes. We therefore conservatively use  $\pm 15\%$  for all OPC channels. The added text reads:

L. 206-207: “The manufacturer uncertainties listed for the CPCs refer to number concentration and for the OPC to particle sizing, conservatively using  $\pm 15\%$  to account for custom size settings.”

7. *Lines 235–239: The wording implies a common controlled flow through all particle counters. Please provide the actual total flow and the flow through each individual CPC and OPC, together with the arrangement of flow splits.*

We have clarified the sampling setup for the aerosol measurements:

L. 220-224: “Aerosols are sampled through a 31 cm long stainless steel inlet tube with an inner diameter of 4.1 mm under sub-isokinetic conditions. The sampled air is not actively dried. The flow through the aerosol instruments is maintained using critical orifices and an external pump (Harm-Altstädter et al., 2023). The total inlet flow of  $2.83 \text{ l min}^{-1}$  passes through the OPC before being split between the two CPCs and a bypass. Each CPC receives  $0.425 \text{ l min}^{-1}$ , comprising an optics flow of  $0.125 \text{ l min}^{-1}$  and an internal bypass flow of  $0.3 \text{ l min}^{-1}$ .”

8. *Lines 281–299 and Fig. 5b: Please address the concern about the HMP110 response time and reconstructed vertical resolution, as discussed in Major Comment 3.*

We have addressed this concern in our response to Major Comment 3. The description of the HMP110 reconstruction has been revised to clarify the determination of the temperature-dependent response times. The limitations associated with response time correction and subsequent filtering are discussed in Bärffuss et al. (2023), with further methodological context provided by Dirksen et al. (2014) and Miloshevich et al. (2004). The original Fig. 5b and the corresponding Arrhenius-type parameterisation have been moved to Appendix B (Fig. B1b).

9. *Lines 325–336: Please expand the description of aerosol sampling efficiency and losses, as discussed in Major Comment 2. A single correction factor for 40–500 nm is insufficient to characterise measurements spanning approximately 6 nm to 10  $\mu\text{m}$ .*

Please see our response to Major Comment 2. The mean sampling-efficiency factor is applied only to the CPC concentrations and does not represent a sampling correction for the full measurement range from 6 nm to 10  $\mu\text{m}$ . We have clarified the CPC and OPC processing separately in Sect. 3.1.2 (L. 270-284). The limitations below 40 nm and the interpretation of the CPC difference as an indicator of ultrafine particles are discussed in our response to Major Comment 2.

10. *BELUGA should also be expanded at its first occurrence in the manuscript.*

We have revised the text accordingly, expanding the BELUGA abbreviation at its first occurrence in the introduction (L. 78).

11. *Lines 428–430: Please retain alphabetical ordering of citations, consistent with the rest of the manuscript; Tuch et al. should precede Wiedensohler et al.*

In the revised manuscript, this statement has been moved to Sect. 3.1.2 in the correct order (L. 272).

*12. Lines 430–435: The CPC flow was strongly modified from the manufacturer’s nominal value of approximately 0.7 L min<sup>-1</sup> to approximately 0.11 L min<sup>-1</sup>. Please explain more rigorously how calibration against the electrometer compensates for this modification. The statement that the calibration includes “additional, unknown corrections” is not sufficiently transparent for a data paper.*

We agree that the previous description was insufficiently precise and have revised the manuscript accordingly (L. 359-363). Calibration against the reference electrometer determines the ratio between the concentration reported by the CPC operated with the modified flow system and the reference concentration. The resulting counting-efficiency curve therefore characterises the behaviour of the modified instrument, including the effect of the changed sample flow. The plateau counting efficiency derived from this curve is used to correct the reported CPC concentrations.

*13. Lines 444–446: Please clarify whether the factors 1.05 and 0.94 were obtained directly from laboratory comparison with an electrometer reference and whether they combine plateau efficiency and sampling losses. The size dependence of these corrections should be given.*

The values 1.05 and 0.94 reported in the submitted manuscript represented combined correction factors of the plateau counting efficiency and the calculated sampling effects in the inlet and tubing. In the revised manuscript, we have replaced these combined numerical factors with an explicit description of the two correction steps: correction using the respective plateau counting efficiency, followed by a sampling-efficiency correction. This distinguishes their contributions more clearly and documents the post-processing applied to the data set.

*14. Lines 457–460: Is the mSEMS correction factor of 0.72 applied uniformly to all scanned size channels? Please distinguish CPC detection efficiency from inlet and transport losses and state how size-dependent sampling losses are treated.*

The factor of 0.72 reported in the submitted manuscript referred to the additional CPC measuring  $N_9$  on the mSEMS platform, not to the scanned size channels of the mSEMS. We have revised Sect. 3.2.2 (L. 371-379) to distinguish the processing of these two instruments. The CPC and the aMCPC, used as the particle detector within the mSEMS, are each corrected using their respective plateau counting efficiencies. For each size channel of the mSEMS, a size-dependent sampling-efficiency correction is applied accounting for inlet and tubing effects.

*15. Lines 475–477 and Fig. 9d: The surface-system inlet appears to point downward. Please explain why this orientation was selected and discuss its potential influence on aspiration and sampling of larger particles.*

Thank you for pointing this out. The inlet was oriented downward to prevent precipitation from entering and contaminating the sampling line and CPC, while also enabling measurements to be taken closer to the surface. Although this orientation may cause wind- and size-dependent aspiration effects, these are expected to be small for ultrafine particles, which closely follow the airflow. The same inlet configuration was used at all measurement heights. However, potential sampling biases for larger particles cannot be ruled out, and this is now acknowledged in the manuscript.

L. 395-398: “The objectives of orienting the aerosol inlet downwards are to prevent precipitation from entering the sampling line and to enable measurements closer to the surface. It is expected that aspiration losses will be small within the relevant particle size range. The inlet configuration was consistent throughout all measurement heights, but potential sampling biases for larger particles cannot be ruled out.”

16. Line 570: “starting at 00 UTC” appears incomplete or inconsistent with the other time notation. Consider “starting at 00:00 UTC”.

We have revised the notation to “starting at 00:00 UTC”.

### Recommendation

*The dataset has clear scientific value, and the manuscript provides a strong description of the three measurement systems. However, field comparison against available reference observations, more complete aerosol-inlet characterisation, clarification of the humidity reconstruction, and correction and expansion of the repository metadata are necessary before the absolute reliability and reusability of the data can be adequately assessed. I therefore recommend major revision.*

We thank the reviewer for recognising the scientific value of the data set and for the constructive recommendations. The revisions and detailed responses above clarify the processing, quality assessment and limitations of the observations. We consider these changes to strengthen the manuscript and facilitate the interpretation and reuse of the data.

# Arctic aerosol and meteorological observations using airborne and ground-based systems in spring 2024

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**Abstract.** A comprehensive observational data set of the vertical and horizontal distribution of aerosol particles and meteorological parameters is presented. Data were obtained from an Arctic field campaign conducted with using three different measurement platforms deployed at distinct locations in close to Ny-Ålesund, Svalbard. The measurements were conducted during the transition period from spring to summer, between 19 May 2024 and 8 June 2024. The An uncrewed aerial system ALADINA was used for vertical and horizontal profiling in the lowermost 930 m above sea level, covering 38 measurement flights including 143 vertical profiles and 62 horizontal flight legs at different constant altitudes. The A tethered balloon system BELUGA performed 90 vertical profiles up to a maximum altitude of 1.3 km above sea level. Together, the airborne platforms provide information on particle number concentrations, including ultrafine particles with diameters below 20 nm, size distribution from the nucleation to coarse mode, and meteorological parameters (i.e. temperature, humidity, pressure, wind direction, wind speed, and downward and upward short-wave irradiance). In addition, a surface flux gradient system was applied for the calculation of turbulent fluxes of sensible heat and vertical motion of particles, covering a sampling time of about 214 h. An illustrative A case study is shown for 3 June 2024, highlighting the spatial variability of aerosol particles, which is strongly influenced by the stability of the polar atmospheric boundary layer. The high-resolution observations enable the study of processes of aerosol-cloud investigations of different processes, including aerosol-cloud interactions, new particle formation and lead to a generally improved understanding of the spatial distribution of Arctic aerosols, and interactions of aerosols with the boundary layer. The data set provides spatial context for interpreting long-term observations in Ny-Ålesund which are strongly influenced by local orography, and a basis for evaluating high-resolution atmospheric simulations of aerosol transport and mixing. The data sets of all three measurement platforms are publicly available on the world data centre PANGAEA as described in the data availability section.

## 1 Introduction

- 20 The Arctic environment is rapidly changing as a result of the phenomenon called Arctic amplification (AA), which causes an increase in surface temperature that is about four times higher than the global average (Rantanen et al., 2022). This effect

is caused by several feedback mechanisms involving the atmosphere, land surfaces, ocean and sea ice, and have led to fast changes in polar regions, especially in recent years (Goosse et al., 2018; Wendisch et al., 2023). These substantial changes are primarily driven by the anthropogenic impact on the Earth's climate system, dominated by a significant and ongoing growth in emissions of greenhouse gases, leading to the most visible consequence in the form of sea ice loss in the central Arctic (Dai et al., 2019; Kim et al., 2023). The decrease in sea ice surface cover implies various changes in the interactions between surface, ocean, and atmosphere, manifested as changes in the Earth's radiation budget (e.g., Huang et al., 2021; Pithan and Mauritsen, 2014), cloud properties (Shupe and Intrieri, 2004), vertical transport of water, temperature and impulse (Chung and Feldl, 2024), bio-geochemical processes (Vancoppenolle et al., 2013; Zitoun et al., 2024), as well as aerosol particles (e.g., Browse et al., 2014; Dall'Osto et al., 2017; Pernov et al., 2022; Wang et al., 2018). **The In particular, the role of aerosol particles remains uncertain, as current . Current** knowledge of their sources and interactions with the Arctic atmosphere during their lifetime is limited (Schmale et al., 2021), as the processes are highly complex and inhomogeneous in space and time. **There are several contributing factors to this phenomenon, some of which can influence each other.** For instance, aerosol particles strongly affect the Earth's surface energy balance through two main different mechanisms. Firstly, the direct effect refers to the scattering and absorption of solar radiation by aerosol particles based on their optical properties, which are **mainly** characterised by their size, chemical and physical composition as well as their mixing state (Charlson et al., 1991). Secondly, the indirect effect relates to aerosol-cloud interactions (ACI), including aerosol particles acting as cloud condensation nuclei (CCN) or **ice nuclei (INice-nucleating particles (INP))**, which influence the formation and characteristics of clouds (Albrecht, 1989; Twomey, 1977). In the high Arctic, the aerosol particle number concentration ( $N$ ) and CCN concentration are generally low. **Especially during summer, clouds cannot always form under supersaturated water vapour conditions due to the low aerosol concentration (Duplessis et al., 2024). Consequently, minor changes in the already low concentration of  $N$  from anthropogenic or natural sources can significantly impact cloud properties (Mauritsen et al., 2011). However, fog events have been observed in the Arctic during late summer that persisted for several hours at particle number concentrations less than  $10\text{ cm}^{-3}$  (Duplessis et al., 2024). Consequently, small changes in  $N$  from anthropogenic or natural sources can strongly affect cloud properties (Mauritsen et al., 2011).** Regarding the Earth's climate and the AA, Arctic clouds can either lead to effects that warm or cool surface temperatures. Their influence depends on the characteristics relating to ACI, but also on seasonal conditions and surface properties (Wendisch et al., 2023). For instance, a two-year study from Ny-Ålesund showed a cooling effect of clouds in summer and a warming effect from September to April/May with an annual positive **cloud radiative forcing radiative forcing due to clouds** (Ebell et al., 2020).

**In general, there are two main seasonal patterns of aerosol size distribution in the Arctic. During winter and spring,  $N$  is dominated by accumulation mode particles. In summer, aerosols are dominated by nucleation and Ny-Ålesund, measurements at the Zeppelin Observatory and the Gruebadet Atmosphere Laboratory have documented pronounced seasonal changes in particle number size distribution, with an enhanced accumulation mode during the spring haze period and a larger contribution of Aitken mode particles , which are predominantly formed locally (e.g., Dall'Osto et al., 2020; Tunved et al., 2013). Previous studies proposed various possible origins for Arctic aerosol particles across different spatial scales. These include marine and continental sources that are advected over long distances by atmospheric transport (e.g., Leck et al., 2002; Stohl, 2006), entrainment from the free troposphere aloft (e.g., Igel et al., 2017; Price et al., 2023), and local processes or sources including blowing snow (e.g., Frey et al., 2020), sea ice melt (e.g., Dall'Osto et al., 2017, 2018), primary marine aerosol emissions from biologically active open water (e.g., Orellana et al., 2011), and secondary aerosol formation from biogenic volatile organic compounds (e.g., Beck et al., 2021; Mungall et al., 2017). However, assessing the actual role of aerosol particles becomes even more challenging when dynamic processes are considered in the atmosphere. in summer (e.g., Tunved**

et al., 2013; Lupi et al., 2016). The seasonal occurrence of new particle formation (NPF) and subsequent particle growth has been characterised by measurements at the Zeppelin Observatory (e.g., Heintzenberg et al., 2017; Lee et al., 2020; Heslin-Rees et al., 2025). Measurements at Gruebadet have further indicated an important contribution of highly oxygenated organic molecules to particle growth during summer (Beck et al., 2021). At the Zeppelin Observatory, long-term CCN measurements show pronounced seasonal variability (Jung et al., 2018), while studies of cloud droplet formation demonstrate the combined influence of aerosol properties and atmospheric dynamics (Motos et al., 2023). Turbulent particle flux measurements have further characterised size-dependent deposition over snow-covered surfaces, during snow melt and over snow-free tundra, showing higher deposition velocities on average during the melting and snow-free periods (Donateo et al., 2023).

Atmospheric dynamics have a significant influence on the spatial distribution of aerosol particles, which often exhibits high temporal variability (e.g., Chen et al., 2021). To date, the majority of field studies have been based on fixed-point, surface-based observatories, including instrumentation installed on vessels navigating through the Arctic ocean. To investigate the spatial distribution of aerosol properties, aircraft-based observations are, in principle, indispensable and have been conducted extensively in the Arctic. Long-term surface observations provide temporal context, whereas airborne measurements resolve the small-scale variability in aerosol and meteorological properties across the atmospheric boundary layer (ABL). Research aircraft can be equipped with the necessary instrumentation and, due to their flight times of several hours, can cover large areas, thereby yielding statistically significant results. However, there are limitations where other observational approaches may be advantageous. In areas in regions with highly complex topography and at very low altitudes, measurements using crewed aircraft are limited in the Arctic for safety reasons. Therefore, to achieve a profound understanding of aerosol processes in the atmospheric boundary layer (ABL) and to improve atmospheric models in the Arctic, high quality data with high spatial and temporal resolution are required (e.g., Matsui and Liu, 2022). This gap can be excellently filled by a combination of uncrewed aerial systems (UAS) and tethered balloons, in parallel to long-term observations on the ground. These observations contribute to a more profound understanding of the small-scale distribution and effects of NPF, CCN, and ACI, may be advantageous for resolving small-scale variability. In Ny-Ålesund, tethered-balloon measurements successfully characterised the vertical distribution of aerosol particle number concentration and size, black carbon, chemical composition, and optical properties, revealing pronounced variability associated with atmospheric stratification and air-mass transport (e.g., Moroni et al., 2015; Ferrero et al., 2016; Mazzola et al., 2016; Markowicz et al., 2017). Measurements using UAS have further shown layers with elevated  $N$  and enhanced aerosol light absorption aloft (Bates et al., 2013), as well as particle growth processes, mixing, and horizontal transport of aerosol particles between the surface and the lower part of the atmosphere for different ABL stability conditions pronounced vertical and horizontal variability of ultrafine particles in relation to ABL properties (Harm-Altstädter et al., 2023). More recent tethered balloon campaigns have examined cloud microphysics, thermal infrared irradiance and the vertical distribution of marine aerosol constituents (Pasquier et al., 2022; Lonardi et al., 2024; Zeppenfeld et al., 2026). Despite these efforts, vertically resolved aerosol observations remain sparse compared with long-term surface measurements, particularly in polar regions and complex terrain. Further profiles and horizontal transects under different atmospheric conditions are required to assess the representativeness of surface observations and to evaluate simulated aerosol distributions (Willis et al., 2018; Creamean et al., 2021; Schmale et al., 2026).

This publication presents an extensive approach combining different observational platforms in a combined observational data set obtained from different measurement platforms during a joint field campaign. Three different measurement systems were deployed at the coastal Arctic site in Ny-Ålesund (Spitsbergen, Norway) during the transition period from spring to summer between 19 May 2024 and 8

June 2024. To study the horizontal and vertical distribution of aerosol particles and interactions with meteorological parameters, the UAS ALADINA (Altstädter et al., 2015)(Application of Light-weight Aircraft for Detecting IN-situ Aerosol), developed by Technische Universität Braunschweig, and the tethered balloon system BELUGA (Egerer et al., 2019)(Balloon-borne Modular Utility for profiling the lower Atmosphere), developed by the Leibniz Institute for Tropospheric Research (TROPOS), were deployed up to an altitude of 930 m and 1.3 km above sea level, respectively. To quantify the turbulent vertical transport of aerosol particles, a surface flux gradient system (Mathes et al., 2025a) was deployed close to the launch point of BELUGA at ground level. The observations of the field campaign consist of aerosol properties ( $N$  of ultrafine aerosol particles (UFPs) with diameters less than 20 nm, size distributions from the nucleation to coarse mode, near-surface particle fluxes), meteorology (temperature, humidity, pressure, wind, irradiance), as well as surface conditions (surface temperature). This combination provides information about spatial and dynamical context for interpreting long-term measurements in Ny-Ålesund, including the Zeppelin Observatory (Platt et al., 2022). The campaign captured the onset of snow melt and changing meteorological conditions, allowing aerosol variability to be examined alongside changes in surface conditions and turbulent exchange.

Herein, this article is structured as follows: Sect. 2 provides an overview of the field campaign in Ny-Ålesund, including an introduction to the measurement site in Sect. 2.1, and information on the observation period and data availability of the individual systems in Sect. 2.2. The three different measurement systems, including instrumentation and data post-processing, are presented in Sect. 3. As an illustrative example, the measurements obtained on 3 June 2024 are presented in Sect. 4. This exemplary case study of the spatial distribution and variability of aerosol particles highlights the potential of this combined measurement approach and serves to advance high-precision ABL parameters and aerosol observations. Finally, Sect. 5 provides a conclusion and the availability of the individual data sets of the three measurement systems is described in Sect. 6.

## 2 Overview of field campaign

### 2.1 Research area

The research village Ny-Ålesund (78.92° N, 11.93° E; 11 m above sea level (a.s.l.)) and its surroundings are characterised by a highly heterogeneous terrain (see Fig. 1a,b), combining tundra, hills, and mountains reaching around 700 m a.s.l., as well as glaciers, fjords, and the adjacent Arctic ocean. Pronounced changes in surface conditions appear over small distances of about a few hundred meters, including snow consisting of different altering stages, ice, soil and open water. The surface wind field is mainly influenced by an orographic channelling effect along the Kongsfjord, resulting in two primary wind regimes that are oriented in the northwest and southeast wind direction (Beine et al., 2001). The prevailing wind directions are combined with multiple local wind regimes, induced by the complex orography that further causes a strong rotation in the wind field above the altitude of 500 m a.s.l. (Graßl et al., 2022; Schön et al., 2022).

The investigation area has a profound history of observatory measurements, covering a multitude of parameters including aerosol properties, chemistry and meteorological parameters. The measurement infrastructure is distributed across various ground-based stations in Ny-Ålesund and its surrounding area, such as the Zeppelin Observatory (e.g., Platt et al., 2022), which is located on Zeppelin Mountain at 472 m a.s.l. (see Fig. 1a,b). Other ground-based stations include the Gruvebadet

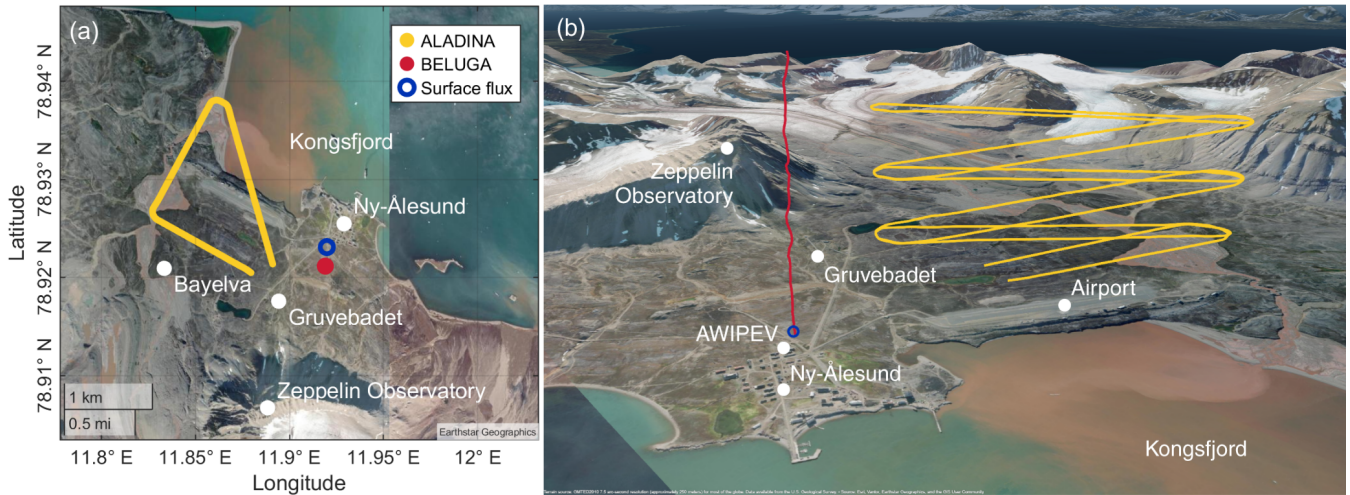


**Figure 1.** Map of the Ny-Ålesund research area shown as a bird's-eye view (a) and side view (b). The figures display the measurement locations of the three different systems used in this study to investigate aerosol and meteorological properties: exemplary horizontal (a) and vertical (b) flight paths of ALADINA (yellow line), a representative BELUGA flight path (red) and the location of the surface flux gradient system (blue circle) at ground level. Ground-based stations (white dots) include the Zeppelin Observatory, Gruvebadet Atmosphere Laboratory, the Bayelva research site and the AWIPEV Research Base in Ny-Ålesund. Map data sources: (a) Earthstar Geographics. © 2024. (b) GMTED2010 7.5 arc-second resolution (approximately 250 meters) for most of the globe, data available from the U.S. Geological Survey; Esri, Vantor, Earthstar Geographics, and the GIS User Community © 2024. GMTED2010 data © U.S. Geological Survey.

125 Atmosphere Laboratory (e.g., Lupi et al., 2016), which is located southwest of Ny-Ålesund at 50 m a.s.l. (see Fig. 1a,b), the Bayelva research site, situated 3 km west from Ny-Ålesund (e.g., Boike et al., 2018), and the French-German AWIPEV (Alfred-Wegener-Institut; Institut polaire français Paul-Émile Victor) Research Base in Ny-Ålesund (e.g., Maturilli et al., 2013).

## 2.2 Research strategy and period

130 The research strategy for the field campaign comprises two main elements. First, the two airborne systems ALADINA and BELUGA are used simultaneously whenever feasible in operation to study the vertical and horizontal distributions of aerosol particles in interaction with meteorological parameters and different ABL stability conditions. Second, continuous ground-based measurements are obtained with the surface flux gradient system to quantify the vertical turbulent transport of aerosol particles.

135 Measurements with the fixed-wing UAS ALADINA (see Sect. 3.1) focus on aerosol properties and meteorological parameters in the vertical distribution from the surface to a maximum altitude of 930 m a.s.l. and in the horizontal distribution within an operation area of approximately 1.5 km<sup>2</sup>. Therefore, ALADINA was operated in two different flight patterns. First, horizontal patterns consisted of straight and level legs flown parallel and perpendicular to the two primary wind regimes (northwest and

southeastdirection) at several fixed altitudes (see Fig. 1a). Second, vertical profiles were performed as steady ascents or descents, interrupted by level 180° turns (see Fig. 1b). A vertical profile up to the maximum altitude typically requires about 7 min per ascent or descent, while a horizontal pattern lasts for approximately 3 min at each constant altitude. The rapid and repeatedly executed vertical profiles provide high temporal resolution of aerosol concentration changes throughout the measurement day, while the horizontal legs capture the spatial heterogeneity and short-term variability of aerosols within the research area. The daily measurement strategy depended on weather conditions and available operation time, as research flights were not possible during temporary air traffic that connects Ny-Ålesund and Longyearbyen. Both flight patterns were repeated during multiple daily ALADINA flights of approximately 40 min, with typical turnaround times a typical turnaround time of about 20 min. If possible, several vertical profiles up to the maximum altitude were combined with horizontal legs at a minimum of three different altitudes. However, horizontal Horizontal legs were not performed during every measurement flight, and the achievable maximum altitude depended on the prevailing cloud base height (CBH), as for safety reasons flight operations are performed out of clouds. The rapid and repeatedly executed vertical profiles provide high temporal resolution of aerosol concentration changes throughout the measurement day, while the horizontal legs capture the spatial heterogeneity and short-term variability of aerosols within the research areaflight operations were authorised only within visual line of sight (VLOS). Flights into clouds were therefore excluded to maintain visual contact with the aircraft. ALADINA was operated from the local airport (see Fig. 1b) between 20 May 2024 and 4 June 2024 on nine measurement days. In total, approximately 20 h of data are available from 38 measurement flights, comprising 143 vertical profiles and 62 horizontal flight legs at multiple constant altitudes, typically at approximately 470 m a.s.l. as well as at altitude levels above and below. The horizontal legs were operated above land and water, including transects that crossed the coastline to the Kongsfjord. Only the two described flight patterns are considered in data post-processing. Other flight segments, such as take-off, landing, and calibration manoeuvres are excluded due to low reduced data quality (see Sect. 3.1.2), thereby reducing the effective flight duration, which is represented in the final data set.

The tethered balloon system BELUGA allows small-scale vertical profiling with interchangeable instruments attached to a tether line. During this field campaign, the balloon was operated with three different payloads to observe meteorological and aerosol microphysical parameters (see Sect. 3.2). The measurement strategy and choice of payload depended on the prevailing meteorological conditions and observed aerosol concentrations. If possible, several vertical profiles with maximum altitudes reaching 1200 m1.3 km a.s.l. were conducted during each BELUGA flight of up to 3 h duration with a mean ascent and descent rate of 0.5 m s<sup>-1</sup>. The system was also maintained at selected constant altitudes to extend the sampling time, for example within pronounced aerosol particle layers or at cloud base and/or cloud top. BELUGA was operated outside of but close to the village of Ny-Ålesund (see Fig. 1a,b), using a temporary ground-based winch and pulley system. On eight days between 19 May 2024 and 7 June 2024, a total of 90 profiles (ascent or descent) were completed during 23 measurement flights, reaching with varying maximum altitudes and collecting approximately 39 h of datasampling time.

The combined use of ALADINA and BELUGA links high temporal resolution, spatially distributed observations obtained from the UAS with quasi-stationary observations, high vertical resolution profiling derived from the tethered balloon, including in-cloud measurements to observe ACI. In turn, the surface flux gradient system (see Sect. 3.3) provides continuous information on near-surface aerosol particle number concentration, as well as wind speed and temperature profiles from 0.1 m above ground

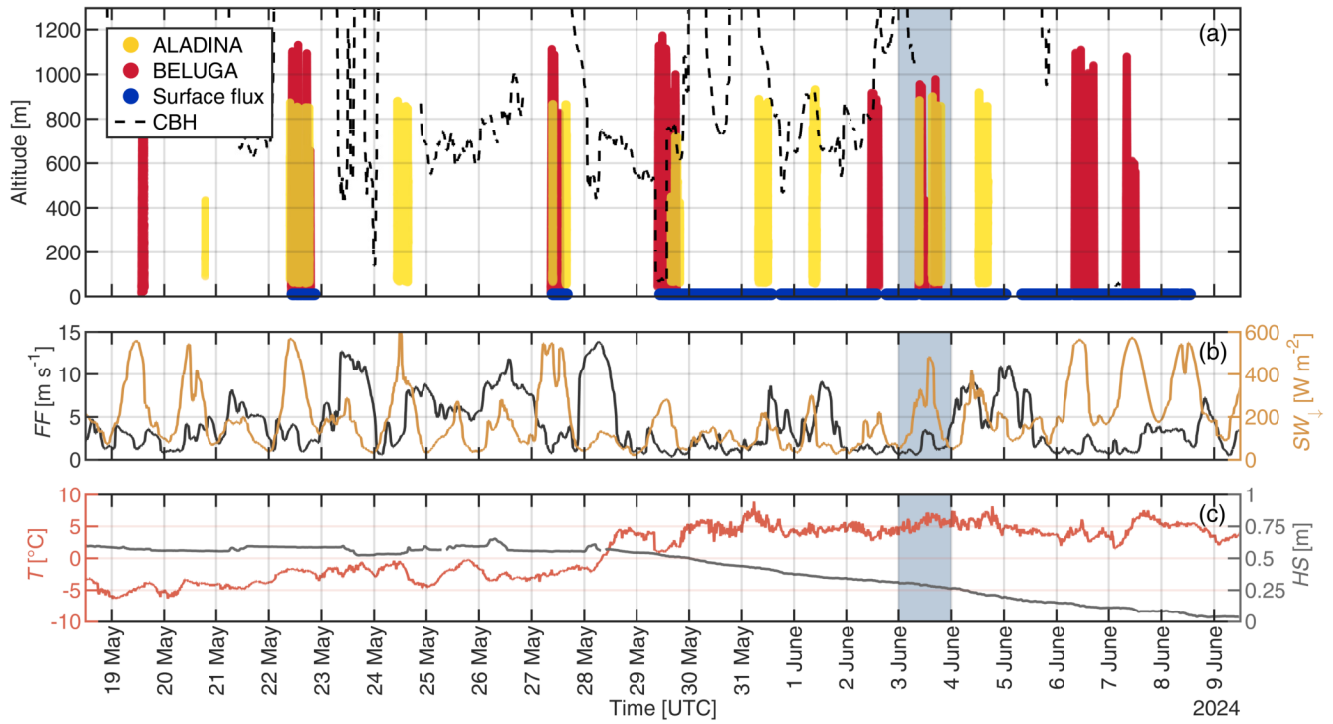


**Figure 2.** Data availability of the three different measurement systems and time series of selected parameters during the research campaign period in May and June 2024, 2024. The time series in panels (b) and (c) are shown in 2 h median intervals. The blue background shading indicates the case study on 3 June 2024 (see Sect. 4). (a) Data availability and altitudes a.s.l. of ALADINA (yellow), BELUGA (red) and surface flux gradient system (blue) together with cloud base height (CBH, m, dashed black line). (b) Wind speed ( $FF$ ,  $\text{m s}^{-1}$ , black line) at 10 m a.g.l. and short-wave downward irradiance ( $SW_{\downarrow}$ ,  $\text{W m}^{-2}$ , amber line). (c) Air temperature ( $T$ ,  $^{\circ}\text{C}$ , red line) at 10 m a.g.l. and snow height ( $HS$ , m, grey line).

level (a.g.l.) up to a height of 1.34 m a.g.l. The vertical particle flux and sensible heat flux are then calculated based on the measured data. The daily runtime of the measurements varied from 6 h to 23 h, depending on the prevailing meteorological conditions. The system was operated at a distance of around 50 m from the ground base of BELUGA on 13 days between 22 May 2024 and 8 June 2024, collecting approximately 214 h of data.

Daily sampling time (h:min) of the three measurement systems after data post-processing, including the number of vertical profiles (V) and horizontal patterns with constant altitude level (H) for ALADINA and the number of vertical profiles (V) for BELUGA. n/o: not operated. **Date ALADINA (V, H) BELUGA (V) Surface flux** 19 May 2024 n/o 1:28 (4) n/o 20 May 2024 0:05 (2, 0) n/o n/o 22 May 2024 3:22 (24, 6) 7:05 (16) 6:40 24 May 2024 2:39 (18, 8) n/o n/o 27 May 2024 1:07 (10, 0) 4:27 (8) 5:40 29 May 2024 2:40 (20, 22) 7:44 (12) 14:00 30 May 2024 n/o n/o 21:40 31 May 2024 2:38 (21, 4) n/o 17:00 1 June 2024 1:19 (11, 0) n/o 22:20 2 June 2024 n/o 3:23 (8) 18:20 **3 June 2024 3:14 (21, 9) 3:53 (8) 20:40** 4 June 2024 2:51 (16, 13) n/o 21:20 5 June 2024 n/o n/o 16:20 6 June 2024 n/o 6:49 (18) 19:40 7 June 2024 n/o 4:16 (16) 21:20 8 June 2024 n/o n/o 8:40 Total 19:55 (143, 62) 39:05 (90) 213:40

Figure 2 provides an overview of the data availability for the three different measurement systems and selected meteorological parameters during the entire **research campaign** period from 19 May 2024 to 8 June 2024, including cloud base height, wind speed, short-wave downward irradiance and air temperature derived from AWIPEV Research Base (adapted from: Maturilli, 2020a, b, 2022), **as well as** . **In addition**, snow height measured at the Bayelva research site (adapted from: Boike et al., 2018; Boike et al., 2022) **is included as a qualitative indicator of the seasonal onset and progression of snow melt in the wider Ny-Ålesund area**. The measurements obtained on 3 June 2024 are presented in Sect. 4 as a representative case study. **Colour schemes employed in** Fig. 2 and in the subsequent figures are based on Crameri (2023). The ALADINA operation is limited by low clouds, fog, precipitation, wind speed and gusts exceeding  $15 \text{ m s}^{-1}$ , also no icing conditions. BELUGA operation is limited to surface wind speed below  $5 \text{ m s}^{-1}$ , but was possible during fog and cloud conditions. Additional constraints in flight time resulted from limited working hours outside the boundaries of Ny-Ålesund and from occasionally required maintenance of the airborne systems. Consequently, no airborne data are available on specific days, **for** . **For** example, on 23 May 2024 and from 25 May 2024 to 26 May 2024 **no flights** **were possible** due to precipitation, appearance of low clouds and high wind speed above  $10 \text{ m s}^{-1}$  (see CBH and wind speed ( $FF$ ) at 10 m a.g.l. in Fig. 2a,b). **A Table A1 in Appendix A provides a** comprehensive overview of data availability **is provided** in Table A1, including the daily sampling time after data post-processing and **the** numbers of flight profiles for the two airborne platforms **respectively**.

The field campaign in Ny-Ålesund was conducted during the transition from spring to summer 2024, coinciding with continuous daylight during the polar day which began on 17 April 2024. In general, this period is characterised by a high frequency of NPF driven by an increase in solar radiation, providing optimal conditions for studying the occurrence of UFPs (Lee et al., 2020). Therefore, the selected **research campaign** period is suitable to address open questions regarding potential sources of NPF and ACI (Dall'Osto et al., 2018). The short-wave downward irradiance ( $SW_{\downarrow}$ ) frequently exceeded  $500 \text{ W m}^{-2}$  under **clear-sky** **clear sky** conditions (see Fig. 2b), thus promoting favourable conditions for photochemical processes. At the beginning of the field campaign, **the** air temperature ( $T$ ) was below  $0^{\circ}\text{C}$  and **the** snow height ( $HS$ ) was constant. From 28 May 2024 onwards, the air temperature increased rapidly, resulting in the onset of snow melt and the progressive exposure of snow-free ground within the **research observation** area (see Fig. 2c). Wind speed **showed pronounced variability** **varied strongly** during the campaign, with episodic **increases** **events** exceeding  $10 \text{ m s}^{-1}$ , indicating changes in synoptic conditions. Several periods were characterised by low CBH below 600 m a.s.l. **or precipitation, occasionally limiting airborne operations**. The observed changes in temperature and wind speed indicate **variable** **a high variability of atmospheric** boundary layer conditions throughout the campaign.

### 3 Measurement systems, instrumentation, and data post-processing

This section presents the configuration of the three different measurement systems **that have been deployed in Ny-Ålesund during the field campaign in 2024** . Furthermore, the **subsequent** **respective** data post-processing and quality control procedures are described. The three resulting data sets from the different measurement systems are publicly available on the world data centre PANGAEA (Felden et al., 2023).

## 3.1 Fixed-wing UAS ALADINA

### 3.1.1 Platform and instrumentation

The fixed-wing UAS ALADINA ([Application of Light-weight Aircraft for Detecting IN-situ Aerosol](#)) is based on the pusher aircraft type Carolo P360, which was designed and developed at Technische Universität (TU) Braunschweig. Since 2013, ALADINA has been deployed in multiple field experiments worldwide, with the main objective of investigating NPF and aerosol properties influenced by varying ABL conditions (e.g., Altstädter et al., 2015; Bärfuss et al., 2018; Harm-Altstädter et al., 2024; Lampert et al., 2020; Platis et al., 2016). For this purpose, it is equipped with a modifiable meteorological and aerosol payload of up to approximately 4.5 kg weight. The system features a wingspan of 3.6 m and a maximum take-off weight of 25 kg. To avoid any possible contamination compared to the use of a combustion engine, and to enable sufficient thrust for agile manoeuvring, the aircraft is powered by an electric engine with 5 kW. The duration of a measurement flight is typically about 40 min, and the cruising speed is kept constant at  $28 \text{ m s}^{-1}$  during automatic flight mode. To facilitate efficient field operations, batteries can be quickly and easily exchanged via a side cargo door, allowing for turnaround times of about 20 min between consecutive measurement flights. Safe operation is possible for wind speed up to  $15 \text{ m s}^{-1}$ , clear visibility and no precipitation. The most recent configuration of ALADINA is described in further detail in Harm-Altstädter et al. (2024), with the exception of a transponder, which was not included during the field campaign described here. Further information regarding sensor installation and validation can be found in Bärfuss et al. (2018). (Altstädter et al., 2015).

In order to meet the high requirements posed by the challenging conditions in the Arctic, ALADINA has undergone several technical adaptations (Lampert et al., 2020) in preparation for a previous study in Ny-Ålesund in 2018 (Harm-Altstädter et al., 2023). A key modification is the insulation and active heating of the front payload compartment, which houses the meteorological instrumentation, and, in particular, the aerosol sensors that are sensitive to fluctuations in ambient temperature and humidity. The compartment is preheated and temperature-controlled prior to take-off and during flight to maintain an internal temperature of about  $25^\circ\text{C}$ . As Ny-Ålesund is a radio-silent zone that prohibits the use of frequencies above 2 GHz, all telemetry links are configured to operate exclusively at 433 MHz and 868 MHz. The aircraft is remotely controlled during take-off and landing, using a Horus X12S (FrSky, China) and the redundant telemetry links EzUHF Rx at 433 MHz (ImmersionRC, Switzerland) and Archer RS at 868 MHz (FrSky, China), while a Pixhawk 2.1 Cube autopilot (CubePilot, Australia) is used during flight missions. Telemetry data are monitored at the ground control station using a RFD868s modem (RFDesign, Australia) and the MissionPlanner software. In addition, ALADINA is equipped with an inertial measurement unit (IMU) of type ADIS16488 (Analog Devices, USA) and a Global Navigation Satellite System (GNSS) module GPS16481 (Sparkfun, USA) with a receiver of type uBlox ZED-F9P (u-blox, Switzerland) to determine the attitude/orientation and position/altitude of the UAS. The GNSS data are also used to generate an accurate time standard for the measurement system. Both devices (IMU and GNSS) operate independently of the autopilot system, thereby providing redundant information on the aircraft's position and attitude during flight operations.

Figure 3 shows ALADINA during flight operation, as well as the meteorological sensors and the payload compartment. A more comprehensive overview of the measurement instrumentation deployed, including the calculated parameters and uncertainties provided by the manufacturers, is provided in Table 1. To sample the undisturbed airflow, the meteorological sensors and the aerosol inlet are mounted at the tip of the nose of ALADINA (see Fig. 3d). Three temperature sensors are installed, consisting of a platinum Finewire (FW) resistance thermometer with two measurement channels (Bärfuss et al., 2018), manufactured at the Institute of Flight Guidance (TU Braunschweig, Germany), a TSYS01 (Measurement Specialties, Ireland), both measuring at a fast temporal resolution of 100 Hz, as well as a HMP110 (Vaisala, Finland) with 1.7 Hz temporal resolution. Two distinct humidity sensors are integrated, covering a HMP110 (Vaisala, Finland) with 1.7 Hz temporal resolution, and a Rapid P14 (Innovative Sensor Technology, Switzerland) with  $< 1.5$  s response time from 50 % to 0 % relative humidity at  $23^\circ\text{C}$ . Two pyranometers of model ML-01 Si (Eko Instruments, Japan) are installed at the top and bottom of the fuselage to measure the up- and downwelling short-wave irradiance with a fast response time of less than 1 ms. In addition, a surface temperature sensor (MLX90614, Melexis, Belgium) is installed at the bottom of the fuselage with a field of view fixed to the aircraft body and temporal resolution of 100 Hz. A first calculation of wind speed ( $FF$ ) and wind direction

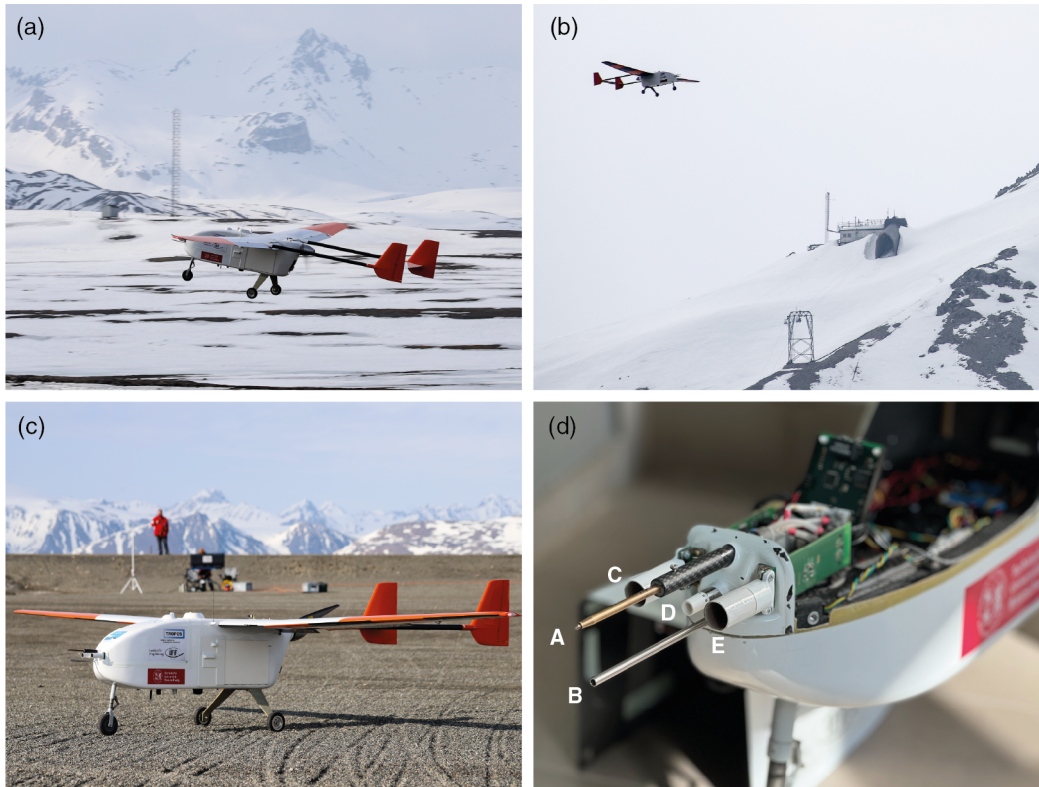


**Figure 3.** The fixed-wing UAS ALADINA during the field campaign in Ny-Ålesund in 2024. (a) ALADINA during take-off at the local airport on 1 June 2024, (b) during a measurement flight near the Zeppelin Observatory on 1 June 2024, (c) after landing, with the ground control station in the background on 3 June 2024, and (d) a picture showing the payload compartment and instrumentation mounted at the aircraft nose, including a multi-hole probe (A), the aerosol inlet (B), Finewire temperature sensor (C), HMP110 (D) and TSYS01/Rapid P14 (E) temperature and humidity sensors. (Pictures: TU Braunschweig)

(DD) is determined from a multi-hole probe (TU Braunschweig, Germany) with AMS 5812 pressure sensors (Analog Microelectronics, Germany) and attitude information covering roll angle, pitch angle and heading of ALADINA from the Pixhawk 2.1 Cube autopilot system (see Sect. 3.1.2).

ALADINA can be equipped with modifiable meteorological and aerosol payload of up to approximately 4.5 kg (e.g., Altstädter et al., 2015; Bärfuss et al., 2018; Harm-Altstädter et al., 2024; Lampert et al., 2020). During this field campaign, the electrically powered UAS was operated at  $28 \text{ m s}^{-1}$  cruising speed with a typical flight duration of about 40 min. The most recent configuration of ALADINA is described in Harm-Altstädter et al. (2024). Further information regarding sensor installation and measurement validation methods can be found in Bärfuss et al. (2018). To meet the high requirements posed by the challenging conditions in the Arctic, ALADINA has undergone several technical adaptations (Lampert et al., 2020) in preparation for a previous study in Ny-Ålesund in 2018 (Harm-Altstädter et al., 2023). The front payload compartment is insulated and actively heated to maintain an internal temperature of about  $25^\circ\text{C}$ . All telemetry links operate at 433 MHz and 868 MHz to meet the radio frequency restrictions in Ny-Ålesund. An Inertial Measurement Unit (IMU) and a Global Navigation Satellite

**Table 1.** Meteorological and aerosol instrumentation integrated in the UAS ALADINA for measurements of static temperature ( $T$ ), relative humidity ( $RH$ ), static pressure ( $p$ ), wind speed ( $FF$ ) and wind direction ( $DD$ ), short-wave downwelling irradiance ( $SW_{\downarrow}$ ) and upwelling irradiance ( $SW_{\uparrow}$ ), surface temperature ( $T_S$ ), and aerosol particle number concentration ( $N$ ) in different size ranges from 6 nm to 10  $\mu\text{m}$ .

| Variable          | Sensor (Manufacturer)                    | Sampling frequency | Measuring range                                                       | Uncertainty                 |
|-------------------|------------------------------------------|--------------------|-----------------------------------------------------------------------|-----------------------------|
| $T$               | Finewire (TU Braunschweig)               | 100 Hz             | –                                                                     | $\pm 0.1$ K                 |
|                   | TSYS01 (Measurement Specialties)         | 100 Hz             | $-20$ $^{\circ}\text{C}$ to $+70$ $^{\circ}\text{C}$                  | $\pm 0.1$ K                 |
|                   | HMP110 (Vaisala)                         | 1.7 Hz             | $-40$ $^{\circ}\text{C}$ to $+80$ $^{\circ}\text{C}$                  | $\pm 0.4$ K                 |
| $RH$              | Rapid P14 (Innovative Sensor Technology) | 100 Hz             | 0 % to 100 %                                                          | $\pm 1.5$ %                 |
|                   | HMP110 (Vaisala)                         | 1.7 Hz             | 0 % to 90 %<br>( $-40$ $^{\circ}\text{C}$ to $0$ $^{\circ}\text{C}$ ) | $\pm 3$ %                   |
|                   |                                          |                    | 90 % to 100 %                                                         | $\pm 4$ %                   |
|                   |                                          |                    | 0 % to 90 %<br>( $0$ $^{\circ}\text{C}$ to $+40$ $^{\circ}\text{C}$ ) | $\pm 1.5$ %                 |
|                   |                                          |                    | 90 % to 100 %                                                         | $\pm 2.5$ %                 |
| $p$               | AMS 5812 (Analog Microelectronics)       | 100 Hz             | 758 hPa to 1207 hPa                                                   | $\pm 1$ %                   |
| $FF$              | AMS 5812 (Analog Microelectronics),      | 100 Hz, 25 Hz      | –                                                                     | $\pm 0.2$ $\text{m s}^{-1}$ |
| $DD$              | Pixhawk 2.1 Cube (CubePilot)             |                    | –                                                                     | depending on $FF$           |
| $SW_{\downarrow}$ | ML-01 Si (EKO Instruments)               | 100 Hz             | $0$ $\text{W m}^{-2}$ to $2000$ $\text{W m}^{-2}$                     | $\pm 50$ $\text{W m}^{-2}$  |
| $SW_{\uparrow}$   | ML-01 Si (EKO Instruments)               | 100 Hz             | $0$ $\text{W m}^{-2}$ to $2000$ $\text{W m}^{-2}$                     | $\pm 50$ $\text{W m}^{-2}$  |
| $T_S$             | MLX90614 (Melexis)                       | 100 Hz             | $-70$ $^{\circ}\text{C}$ to $+380$ $^{\circ}\text{C}$                 | $\pm 0.5$ K                 |
| $N_6$             | CPC 3007 (TSI)                           | 1 Hz               | 6 nm to 1 $\mu\text{m}$                                               | $\pm 20$ %                  |
| $N_{19}$          | CPC 3007 (TSI)                           | 1 Hz               | 19 nm to 1 $\mu\text{m}$                                              | $\pm 20$ %                  |
| $N_{300}$         | OPC GT-526S (Met One Instruments)        | 1 Hz               | 0.3 $\mu\text{m}$ to 0.5 $\mu\text{m}$                                | $\pm 15$ %                  |
| $N_{500}$         | OPC GT-526S (Met One Instruments)        | 1 Hz               | 0.5 $\mu\text{m}$ to 0.7 $\mu\text{m}$                                | $\pm 15$ %                  |
| $N_{700}$         | OPC GT-526S (Met One Instruments)        | 1 Hz               | 0.7 $\mu\text{m}$ to 1 $\mu\text{m}$                                  | $\pm 15$ %                  |
| $N_{1000}$        | OPC GT-526S (Met One Instruments)        | 1 Hz               | 1 $\mu\text{m}$ to 2.5 $\mu\text{m}$                                  | $\pm 15$ %                  |
| $N_{2500}$        | OPC GT-526S (Met One Instruments)        | 1 Hz               | 2.5 $\mu\text{m}$ to 5 $\mu\text{m}$                                  | $\pm 15$ %                  |
| $N_{5000}$        | OPC GT-526S (Met One Instruments)        | 1 Hz               | 5 $\mu\text{m}$ to 10 $\mu\text{m}$                                   | $\pm 15$ %                  |

260 System (GNSS) provide aircraft attitude and position information, respectively. The GNSS data are also used to generate an accurate time standard for the measurement system.

Figure 3 shows ALADINA during flight operation, as well as the meteorological sensors and the payload compartment. A more comprehensive overview of the measurement instrumentation deployed, including the calculated parameters and measurement uncertainties, is provided in Table 1. The manufacturer uncertainties listed for the CPCs refer to number concentration and for the OPC to particle sizing, conservatively using  $\pm 15$  % to account for custom size settings. To sample an undisturbed incoming airflow, the meteorological sensors and the aerosol inlet are mounted at the tip of the nose of ALADINA (see Fig. 3d). Air temperature is measured using a two-channel platinum Finewire (FW) resistance thermometer (Bärfuss et al., 2018), a

265

TSYS01 and an HMP110. Relative humidity is measured using an HMP110 and a Rapid P14. Two ML-01 Si pyranometers are mounted on the upper and lower sides of the fuselage and are used to measure downwelling and upwelling short-wave irradiance, respectively. An infrared sensor mounted beneath the fuselage measures surface temperature with a field of view fixed relative to the aircraft. Horizontal wind speed ( $FF$ ) and wind direction ( $DD$ ) are derived from multi-hole probe pressure measurements and aircraft velocity and attitude information from the autopilot system (see Sect. 3.1.2).

Furthermore, two condensation particle counters (CPC) of the same model 3007 (TSI, USA) are integrated in the payload compartment of ALADINA. The instruments were tuned in the laboratory of TROPOS by modifying the are modified with respect to the temperature difference between the saturator and the condenser, resulting in different lower cut-off sizes of 6 nm ( $N_6$ ) and 19 nm ( $N_{19}$ ), respectively. The calibration of both CPC instruments at TROPOS is applied in accordance with the procedures described in Tuch et al. (2016) and Wiedensohler et al. (2018). The difference in the measured particle number concentrations between both sensors provides an identification indication of UFP for the size between 6 nm and 19 nm, hereafter named ( $N_{6-19}$ ). The uncertainty of  $N$  measured with both CPCs is given by the manufacturer with  $\pm 20\%$ . Additionally, an optical particle counter (OPC) of type GT-526S (Met One Instruments, USA) is integrated below the two CPCs is integrated, measuring  $N$  for six different size channels between 300 nm and 10  $\mu\text{m}$ , with a measurement uncertainty of  $\pm 15\%$ . The two CPCs and OPC use a critical orifice with a single pump to ensure a controlled airflow from the aerosol inlet towards the instruments. Aerosols are sampled through a 31 cm long stainless steel inlet tube with an inner diameter of 4.1 mm under sub-isokinetic conditions. The sampled air is not actively dried. The flow through the aerosol instruments is maintained using critical orifices and an external pump (Harm-Altstädter et al., 2023). At a sufficient pressure difference between the pressure behind and in front of the orifice, the mass flow reaches a maximum and remains constant during measurement flights. The temporal resolution of both CPCs and OPC is 1 Hz. The total inlet flow of  $2.83 \text{ l min}^{-1}$  passes through the OPC before being split between the two CPCs and a bypass. Each CPC receives  $0.425 \text{ l min}^{-1}$ , comprising an optics flow of  $0.125 \text{ l min}^{-1}$  and an internal bypass flow of  $0.3 \text{ l min}^{-1}$ .

### 3.1.2 Data processing and quality control

The data post-processing of ALADINA measurements is conducted individually for each flight. In general, data acquisition and time synchronisation of the overall measurement data from numerous sensors are achieved through a central bus system, operating at a sampling rate of 100 Hz, as shown in Bretschneider et al. (2022). To create a joint data set, including all measured variables, a common time axis of 100 Hz is defined with reference to Coordinated Universal Time (UTC), and used for synchronisation. The raw data readings are post-processed in several ways, as described below. Although there are multiple sources for sensors for measuring identical atmospheric parameters, such as temperature and humidity, data are combined or validated by comparing individual sensor values, as shown in Bärffuss et al. (2018). Signal reconstruction and corrections are applied when necessary, as also demonstrated in Bärffuss et al. (2023). Measurements recorded at lower temporal resolution are included when available a temporal resolution lower than 100 Hz are included, when available, and gaps are retained as missing values. In addition to meteorological and aerosol variables, the final data set includes GNSS geolocation (latitude, longitude, altitude a.s.l., referenced to WGS84) and attitude information from the autopilot system (roll, pitch, heading).

Temperature is derived from the two fast-response fast response sensors TSYS01 and Finewire. The additional temperature measurements from HMP110 are not applied to the further processing of temperature data. To recover spectral errors and time lag in the raw sensor readings, several processing steps are applied to the raw measurements. Raw TSYS01 signal is reconstructed using an inverted first-order transfer function followed by phase-neutral

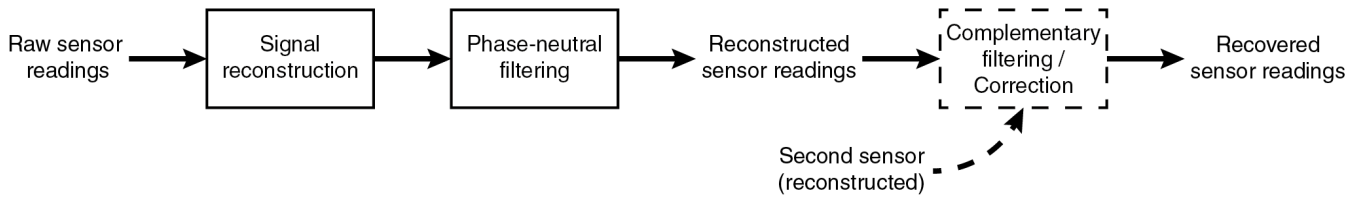


**Figure 4.** Generic data post-processing scheme applied to ALADINA raw sensor readings (e.g. temperature, humidity): signal reconstruction via inverted transfer function of first order, phase-neutral filtering, and optional individual correction and/or complementary fusion with a second sensor stream to obtain a recovered time series. Adapted from Bärffuss et al. (2018).

low-pass filtering to reduce amplified noise, as described in Bärffuss et al. (2023) and Bärffuss et al. (2018, 2023) and as demonstrated in the block diagram in Fig. 4. First, the raw TSYS01 signal is reconstructed by applying an inverted transfer function of first order to the measured output. To identify a suitable The time constant  $\tau$ , representing the response time of TSYS01 during signal reconstruction, ascents and descents of is determined by comparing ascent and descent profiles from different measurement flights are compared. Second, to reduce amplified noise during the first step, the reconstructed signal is phase-neutrally low-pass filtered forwards and backwards (Bärffuss et al., 2018). As a third step, and depending on the individual sensor, additional corrections or complementary filtering can be applied to the reconstructed sensor readings. Here, the potential bias from . TSYS01 measurements potentially affected by solar radiative heating on the TSYS01 measurements is identified when the angular separation between the sun direction (azimuth and elevation) and the ALADINA attitude (heading and pitch) are excluded when the angle between the direction towards the sun and the sensor pointing direction, aligned with the airframe's forward vector, is below  $45^\circ$ . Solar azimuth and elevation angles are derived from UTC time and the sun–earth geometry retrieved from the JPL Development Ephemeris DE405/LE405 (Standish, 1998). The resulting earth-centred inertial sun vector is transformed to local azimuth and elevation at the ALADINA GNSS position. The identified bias from solar radiative heating show maximum radiative heating of the TSYS01 was associated with temperature increases of around up to about 0.5 K in the TSYS01 measurements, depending on the weather conditions during measurement flights during the campaign. No complementary filtering is applied for temperature, as the Finewire sensors demonstrate show a stable fast response and no detectable bias from solar radiation through their design of two 0.0125 mm platinum wires. Instead of complementary filtering, the TSYS01 measurements are used as corresponding reference to validate and convert the raw sensor readings from the two Finewire channels into corrected temperature time series. A linear relationship is assumed and fitted between the raw Finewire sensor solar radiative bias during the campaign. Instead, both Finewire channels are calibrated by fitting a linear relationship between their raw readings and the reconstructed temperature of TSYS01 temperature during airborne conditions. Samples flagged for solar radiative heating are excluded during the calculations. The resulting Finewire temperature is quality checked by calculating the residual standard deviation If the standard deviation of the temperature difference relative to the reconstructed TSYS01 reference . If both channels fail quality check exceeds 0.6 K for both Finewire channels, the reconstructed temperature of TSYS01 temperature is used instead.

The The total air temperatures measured by TSYS01 and the Finewire sensors represent the total air temperature at the stagnation point of ALADINA. The Finewire are converted to static air temperature is calculated using a simplified Mach number  $Ma$  based on the true airspeed and the total air temperature, following the procedure described in following Bärffuss et al. (2023). The true airspeed is derived from the corrected dynamic pressure and dry-air density. The dry-air density is computed from the measured static pressure, the total air temperature, and the specific gas constant for dry air. Low-dynamic-pressure phases are excluded prior to the true airspeed calculation. The Mach number and the corresponding static air temperature are then calculated using the heat capacity ratio of air ( $\kappa = 1.4$ ). This approximation introduces only a negligible error ( $\ll 0.01$  K) within the operating range of ALADINA, with cruising speed below  $30 \text{ m s}^{-1}$  ( $Ma < 0.1$ ).

Humidity is based primarily on the Rapid P14 sensor and complemented by the HMP110 sensor. Analogous to the temperature processing, spectral errors and time lag in the Rapid P14 and HMP110 The raw sensor readings are reconstructed by applying an inverted transfer function of first order followed by a phase-neutral low-pass filter and filtered using the same procedure as for temperature (see Fig. 4). The time constant  $\tau$  for the Rapid P14 sensor is determined by comparing ascents and descents of different measurement flights. In contrast, the HMP110 sensor shows a strongly affected response depending on the ambient temperature. Therefore, , therefore a temperature-dependent time constant is applied for the HMP110 reconstruction . First, suitable values of  $\tau$  are identified by comparing ascents and descents of selected flights during measurement days with reconstruction and filtering, following Bärffuss et al. (2023) and Miloshevich et al. (2004). Valid time constants are estimated by manually varying  $\tau$  until humidity structures in the reconstructed ascent and descent profiles show the best agreement, using seven flights representative of cold and warm ambient conditions conditions and following the approach described in Bärffuss et al. (2018) and Bärffuss et al. (2023). The median temperature at the top of the vertical profiles is used to establish a relationship between the identified time constants and the corresponding temperatures. Second, the Arrhenius equation is adapted to describe this relation between the associate the estimated time constants with the corresponding temperature conditions. An Arrhenius-type function is fitted to these estimates to parameterise the temperature dependence of the HMP110 response time, represented by  $\tau$ , and the temperature  $T$  (Arrhenius, 1889; Laidler, 1984):

$$\tau(T) = \tau_0 \exp\left(\frac{E_a}{RT}\right)$$

where  $\tau_0$  is a reference time constant,  $E_a$  the activation energy,  $R$  the universal gas constant, and  $T$  the measured temperature. The empirically determined HMP110 time constant and the fitted Arrhenius relationship are shown in (Arrhenius, 1889; Laidler, 1984), with the estimated time constants and fitted relationship provided in Appendix B (Fig. B1b). The resulting time constant  $\tau(T)$  is used for both, the first-order reconstruction , and the subsequent phase-neutral low-pass reconstruction and filtering of the HMP110 raw sensor readings. Prior to reconstruction, the HMP110 measurements are calibrated using a two-point salt-chamber calibration, while the Rapid P14 measurements are offset-calibrated against the calibrated HMP110 measurements using median values under non-saturated conditions. Finally, the relative humidity is obtained by complementary filtering of the calibrated and reconstructed Rapid P14 and HMP110 sensor readings, as described in detail in, as shown in Bärffuss et al. (2018). For flights without valid Rapid P14 data, only the reconstructed humidity of HMP110 is used.

The horizontal wind vector is derived from the differential pressure measurements at the is calculated from multi-hole probe together with the inertial navigation data of measurements and navigation data from the autopilot system. The calculation is based on the vector difference between the velocity of the aircraft relative to the ground and the true airspeed vector relative to the moving air (Lenschow, 1972; Bärffuss et al., 2018, 2023). To reduce noise, the horizontal (Bärffuss et al., 2018, 2023; Lenschow, 1972), and the wind components are subsequently phase-neutrally low-pass filtered with a phase-neutral using a 20 Hz Butterworth filter , and wind direction ( $DD$  before calculating wind speed ( $FF$ ) and wind speed ( $FF$ ) are recalculated from the filtered wind components. For direction ( $DD$ ). Wind data are discarded for flights with unstable autopilot attitude information, wind data are discarded for the entire measurement flight. The uncertainty of the calculated horizontal wind vector is  $\pm 0.2 \text{ m s}^{-1}$  in the horizontal plane. Consequently, the uncertainty of the wind direction  $DD$  depends on the wind speed  $FF$ , as shown in (see Fig. B1a . The two exemplary wind vectors illustrate the influence of wind speed on the uncertainty of the derived wind direction. At low and Bärffuss et al. (2023) Appendix C). At wind speed below  $0.5 \text{ m s}^{-1}$ , the uncertainty of  $DD$  becomes increasingly dominated by the overall uncertainty of the horizontal wind vector, resulting in a strongly reduced significance of the derived wind direction.

(a) Two exemplary horizontal wind vectors showing the dependence of the uncertainty in wind direction  $DD$  on the wind speed  $FF$ . The orange circles indicate the wind vector uncertainty of  $\pm 0.2 \text{ m s}^{-1}$  in any direction. The blue arrows indicate possible horizontal wind vectors within this uncertainty range. (b) Temperature dependence of the HMP110 response time constant  $\tau$ . Black dots show empirically determined HMP110 time constants from selected cold and warm measurement flights, derived from ascent–descent comparisons. The red line shows the fitted Arrhenius function used for the HMP110 humidity reconstruction.

365 Short-wave downwelling and reflected irradiance are derived from the two ML01 sensors using fixed conversion factors based on the manufacturer’s specifications. The resulting short-wave irradiance is provided in  $\text{W m}^{-2}$ . The static pressure surface temperature is measured by the AMS5812 pressure sensor and used to calculate the dry-air density and the static air temperature. The surface temperature is measured directly by the infrared sensor and is not subjected to further post-processing.

The aerosol particle number concentration  $N$  is post-processed by applying instrument-specific corrections. Both CPCs were  
370 calibrated at TROPOS as assembled aerosol stack, excluding the stainless steel inlet tube, using monodisperse silver particles with diameters below 40 nm. The calibration method is described in detail in Tuch et al. (2016) and Wiedensohler et al. (2018). A size-dependent counting-efficiency function was fitted to determine the lower cut-off diameter  $D_{p50}$  and plateau counting efficiency  $E_\infty$  of each CPC, as presented in Pilz et al. (2022). The raw concentrations are corrected using the respective  $E_\infty$ . A mean sampling-efficiency factor for the particle size range from 40 nm to 500 nm is applied to account for inlet aspiration  
375 efficiency and tubing losses. We did not consider enhanced particle sampling of the sub-isokinetic inlet above 500 nm for the CPCs, as the particle number concentration in this size range is negligible compared to smaller sizes. Furthermore, the CPC concentration time series are corrected for the measurement delay by applying a fixed negative time shift of 1.5 s. This shift is based on the transport delay estimated from the flow velocity and tubing volume and on comparisons of ascent and descent profiles of different measurement flights, consistent with the findings of Altstädter et al. (2015). An example illustrating the  
380 effect of the CPC time correction is provided in Appendix B in Fig. B2a. Finally, the calibrated CPC number concentrations are converted to standard conditions (1013.25 hPa and 273.15 K). For the OPC, a fixed negative time shift of 0.14 s is applied to account for the transport delay estimated from flow velocity and tubing volume. The OPC data are provided as particle number concentrations  $N$  in six size channels under ambient conditions.

For the final data set, each measurement flight is cropped to the periods covering the two scientifically relevant flight patterns  
385 in their vertical and horizontal extents (see Sect. 2.2). Flight phases in remote control flown manually, as well as calibration patterns before and after the measurement section are excluded. In addition, selected variables are discarded during turning manoeuvres, including curves within the vertical profiles. In particular, the aerosol particle number concentration  $N$  measured by the two CPCs 3007 shows enhanced variability during curve phases, possibly caused by effects of aircraft acceleration or sampling under side-slip conditions. Figure B2b demonstrates the affected measurement of An example of the affected  $N_6$  during an exemplary vertical profile . measurements  
390 during a vertical profile is provided in Appendix B in Fig. B2b. The particle number concentration measured during turning manoeuvres (red line) exhibits substantially higher variability and is therefore treated as non-representative of the ambient aerosol field. Other variables excluded during turning manoeuvres are wind ( $FF$  and  $DD$ ), short-wave irradiance  $SW_\downarrow$  and  $SW_\uparrow$ , and surface temperature  $T_S$ , as the rapidly changing attitude of ALADINA during these phases may cause substantial variability and bias.

395 (a) Exemplary vertical profile of the particle number concentration  $N_6$  during ascent and descent before (left) and after (right) application of the CPC time correction. (b)  
Exemplary vertical profile of  $N_6$  with sections measured during turning manoeuvres highlighted in red. These curve phases show enhanced variability and are excluded from the  
final data set.

The aerosol particle number concentration  $N$  is post-processed by applying instrument-specific corrections. First, the raw data of the CPC sensors are calibrated using laboratory-  
determined detection efficiencies together with an additional mean sampling-efficiency factor of 1.05, determined for the particle size range from 40 nm to 500 nm. Second, the CPC  
400 concentration time series are corrected for the instrumental response time by applying a fixed negative time shift of 1.5 s, consistent with the findings of Altstädter et al. (2015). The  
response time correction is derived from the delay caused by flow velocity and tubing volume and by comparing ascents and descents from different measurement flights. Figure B2a  
shows an example of the measurement of  $N_6$  before and after time correction. The uncorrected data show an ascent–descent offset in the vertical aerosol structure, consistent with  
the instrumental response delay. After time correction, the prominent concentration peak at approximately 770 m a.s.l. is aligned more closely between both profiles. Third, the  
calibrated aerosol number concentrations are converted to standard conditions (1013.25 hPa and 273.15 K), using the measured static pressure and the derived static air temperature.  
405 The OPC raw sensor readings are corrected for residence time and latency by applying a fixed negative time shift of 0.14 s, representing the response time induced by flow velocity  
and tubing volume. The resulting final data set provides synchronised meteorological, aerosol, and attitude-related variables for each measurement flight on a common UTC time  
axis.

## 3.2 Tethered balloon BELUGA

### 3.2.1 Platform and instrumentation

410 The BELUGA (Balloon-bornE moduLar Utility for profilinG the lower Atmosphere) system BELUGA consists of a helium-filled tethered balloon with  
a volume of 90 m<sup>3</sup> that is operated by an electrical winch system and a tether-guiding pulley. It is capable of lifting different  
platforms with a total payload of up to 15 kg attached to the tether. BELUGA has been operated in the Arctic before, e.g.,  
during the PASCAL (Physical Feedbacks of Arctic Boundary Layer, Sea Ice, Cloud and AerosoL) 2017 (Egerer et al., 2019)  
and MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) 2020 (Pilz et al., 2023) campaigns.  
415 It consists of a 90 m<sup>3</sup> helium-filled tethered balloon operated by an electrical winch system and a tether-guiding pulley up to an altitude of 1.5 km. Different platforms with a  
total payload of up to 15 kg can be attached to the tether. During the field campaign in Ny-Ålesund presented here, BELUGA was operated  
with three different payloads were used to measure vertical profiles of aerosol and meteorological parameters. Safe operation is  
possible for wind speed up to 5 m s<sup>-1</sup> at ground and overall up to 15 m s<sup>-1</sup>. The Turbulence Meteorological Probe (TMP)  
was used during all measurement flights in conjunction with one of the aerosol measuring platforms, either the Cubic Aerosol  
420 Measurement Platform (CAMP) or the miniaturized Scanning Electrical Mobility Sizer (mSEMS) box. The instrumentation  
of the three payloads is and the corresponding measurement uncertainties are listed in Table 2. The mSEMS was used for the  
first time during this field campaign for potential further application as a balloon borne platform in cold environments. It was  
operated on four measurement flights conducted on 22 May 2024, 29 May 2024, 3 June 2024, and 6 June 2024. A detailed  
overview of the measurement days and sampling time is presented in Table A1. Here, a profile is defined as one ascent and one descent, while  
425 an entire flight is a measurement period with continuous data collection and no significant break, such as needed for battery exchange. The operation of the balloon depends on  
the meteorological conditions. The surface wind speed should not exceed 5 m s<sup>-1</sup>, and wind speed throughout the vertical profile should remain below 15 m s<sup>-1</sup>. The measured

variables are monitored during flight operation. When prominent aerosol layers are detected, especially enhanced particle number concentrations in the UFP range, the focus of the flight is adjusted towards the corresponding altitude range to best characterise the level.

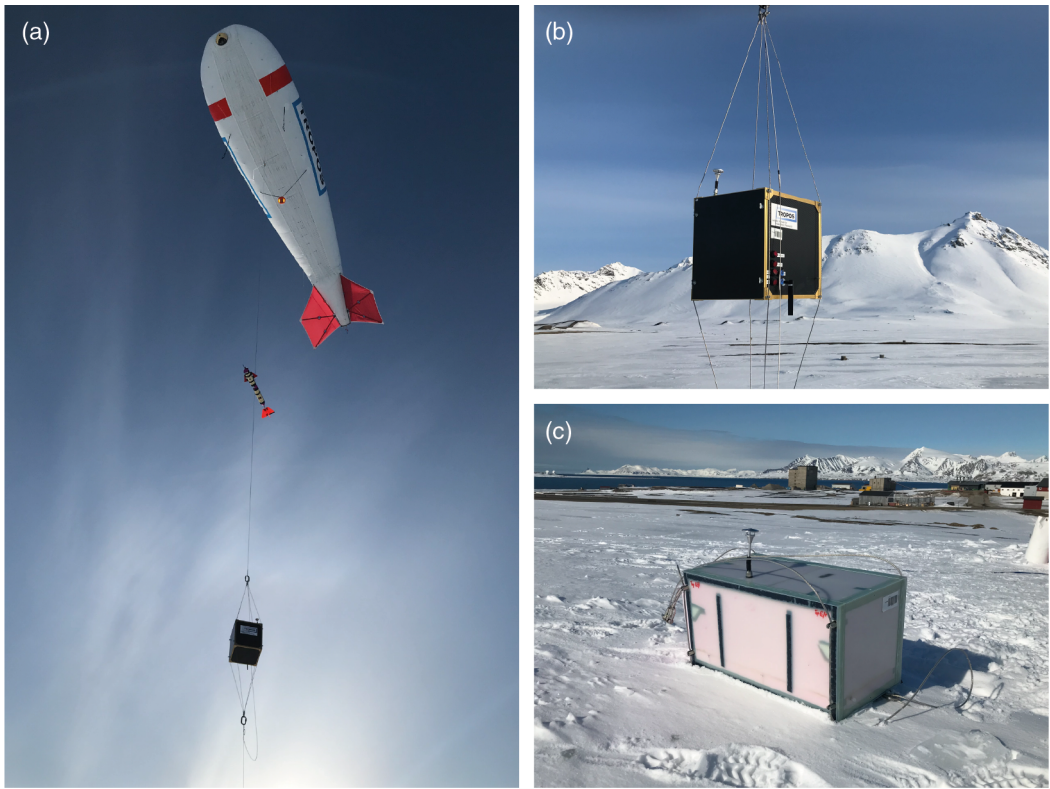


**Figure 5.** BELUGA measurement systems on 22 May 2024 during the field campaign in Ny-Ålesund. (a) TMP and CAMP attached to the tether line, (b) close-up picture of the CAMP system and (c) mSEMS box platform on ground on 22 May 2024. (Pictures: Christian Pilz, TROPOS)

The Turbulence Meteorological Probe (TMP) is a development of TROPOS that is constantly being refined and adapted to specific requirements (, see Fig. 5a) . The TMP is a development of TROPOS and was previously used in an identical configuration during an expedition to Villum Research Station at Station Nord in northeast Greenland (Dorff et al., 2026). This version is designed to monitor standard meteorological parameters, such as wind speed , wind direction, temperature, humidity, and static pressure from which the barometric altitude is primarily determined. The aim of the TMP is to determine the meteorological parameters for scientific analysis and also to continuously monitor meteorological conditions to ensure flight safety. A Wind speed is measured using a small ultrasonic anemometer/thermometer(Trisonica mini, Li-Cor, USA) measures the . Wind direction and probe attitude are derived from a three-dimensional wind vector and virtual temperature. According to the specifications provided by the manufacturer, the design of the Trisonica mini enables a horizontal inflow of  $\pm 15^\circ$  . Due to the geometry of the instrument, it is not possible to accurately determine the vertical wind component. Therefore, only the absolute wind speed is used and it is assumed compass, assuming that the TMP’s wind vane allows the system to be aligned with the mean wind. Alignment and attitude are determined using a three-dimensional compass (HMC6343, Honeywell, USA). The yaw angle then represents a measurement of the mean wind direction. Roll and pitch angles are only used to determine whether the probe and thus the Trisonica mini are still within the manufacturer’s attitude range. Temperature, relative

440 humidity, and static pressure are measured using a Graw radiosonde (DFM-17, Graw Radiosondes, Germany). The data structure of the DFM-17 is used to integrate wind speed and direction from the Trisonica mini and the three-dimensional compass into the radiosonde's transmission protocol, thus enabling monitoring the flight operation from the ground. The meteorological observations are available with a temporal resolution of 1 Hz, which corresponds to an altitude resolution of about 0.5 m, valid for typical ascent rates of around  $0.5 \text{ m s}^{-1}$ . In addition, a . Additional one-dimensional hot-wire anemometer (Dantec Dynamics, Denmark) has been implemented measurements were recorded during selected flights for high-resolution turbulence measurements. The hot-wire anemometer is sampled at a rate between 50 Hz and 250 Hz. However, a malfunction in the data acquisition system has thus far prevented routine post-processing of the data, meaning that it can only be provided for a limited number of flights on request . Therefore, the hot-wire data and is not included in the first release of the data set uploaded data set on PANGAEA.

**Table 2.** Instrumentation of the TMP and the aerosol platforms CAMP and mSEMS used with BELUGA for measurements of static pressure ( $p$ ), temperature ( $T$ ), relative humidity ( $RH$ ), wind direction ( $DD$ ) and wind speed ( $FF$ ), aerosol particle number concentration ( $N$ ) with different lower cut-off sizes, and the aerosol particle number size distribution ( $PNSD$ ) in different size ranges. For the TMP system, the measuring range and accuracy are based on the manufacturer's specifications.

| Measurement system | Variable | Sensor (Manufacturer)         | Sampling frequency | Measuring range                                                   | Uncertainty                        |
|--------------------|----------|-------------------------------|--------------------|-------------------------------------------------------------------|------------------------------------|
| TMP                | $p$      | DFM-17 (Graw)                 | 1 Hz               | 1 hPa to 1100 hPa                                                 | $\pm 1 \text{ hPa}$                |
|                    | $T$      | DFM-17 (Graw)                 | 1 Hz               | $-90 \text{ }^{\circ}\text{C}$ to $+ 60 \text{ }^{\circ}\text{C}$ | $\pm 0.2 \text{ }^{\circ}\text{C}$ |
|                    | $RH$     | DFM-17 (Graw)                 | 1 Hz               | 0 % to 100 %                                                      | $\pm 3 \text{ } \%$                |
|                    | $DD$     | HMC6343 (Honeywell)           | 1 Hz               | $0^{\circ}$ to $360^{\circ}$                                      | $\pm 5^{\circ}$                    |
|                    | $FF$     | Trisonica mini (Li-Cor)       | 1 Hz               | 0 to $50 \text{ m s}^{-1}$                                        | $\pm 0.2 \text{ m s}^{-1}$         |
| CAMP               | $N_{11}$ | CPC 3007 (TSI)                | 1 Hz               | 11 nm to $1 \text{ }\mu\text{m}$                                  | $\pm 20 \text{ } \%$               |
|                    | $N_{15}$ | CPC 3007 (TSI)                | 1 Hz               | 15 nm to $1 \text{ }\mu\text{m}$                                  | $\pm 20 \text{ } \%$               |
|                    | $PNSD$   | POPS 3100 (Handix Scientific) | 1 Hz               | $0.15 \text{ }\mu\text{m}$ to $3 \text{ }\mu\text{m}$             | $\pm 20 \text{ } \%$               |
| mSEMS platform     | $N_9$    | CPC 3007 (TSI)                | 1 Hz               | 9 nm to $1 \text{ }\mu\text{m}$                                   | $\pm 20 \text{ } \%$               |
|                    | $PNSD$   | mSEMS 9404 (Brechtel)         | 1 min scan time    | 8 nm to 350 nm                                                    | $\pm 20 \text{ } \%$               |

The Cubic Aerosol Measurement Platform (CAMP) (Pilz et al., 2022) was developed for the operation on a balloon tether in cold atmospheric conditions (see Fig. 5b). The cubic box, which has a side length of 35 cm, is connected to carabiners via steel ropes at eight corners. This allows the system to be mounted on the tether line. The exterior walls are insulated and an internal heating system maintains the box temperature at platform design, instrument modifications and flow system are described in detail in Pilz et al. (2022). The insulated payload compartment is actively heated to maintain an internal temperature of about  $25 \text{ }^{\circ}\text{C}$  to ensure stable measurement conditions. All instruments used in the CAMP sample from the identical steel vertical sample through a common vertical steel funnel inlet at the top of the box. The design of the inlet in combination with an overall flow rate of  $1.4 \text{ m s}^{-1}$  determines an upper particle cut-off of  $2.7 \text{ }\mu\text{m}$  at a wind speed of up to  $3.5 \text{ m s}^{-1}$ . The platform , followed by a custom silica-based diffusion dryer (Pilz et al., 2022). CAMP is equipped with two CPCs (model3007, TSI, USA) with two of the same model. The instruments are modified with respect to the temperature difference between the saturator and the condenser, resulting in different lower cut-off

sizes of 11 nm ( $N_{11}$ ) and 15 nm ( $N_{15}$ ), measuring at a counting frequency of 1 Hz. The calculation of the counting efficiency of the CPCs is shown in Sect. 3.2.2. The initial flow system was replaced with an external vacuum pump and a customised critical orifice to set a constant sample flow rate of  $0.11 \text{ l min}^{-1}$ , reducing measurement uncertainty of the CPCs from  $\pm 20 \%$  to  $\pm 5 \%$ . A more detailed description of the CPC modification is presented by Pilz et al. (2022). . Thus, the difference between both CPC measurements provides an indication of particles in the size range from 11 nm to 15 nm ( $N_{11-15}$ ). Furthermore, a Portable Optical Particle Spectrometer (POPS, model 3100, Handix Scientific, USA) is integrated for measurements of the aerosol particle number size distribution ( $PNSD$ ) (Gao et al., 2016). The POPS is a small and lightweight instrument that measures the single particle backscatter of a 405 nm diode laser, focused by a  $38^\circ$ – $142^\circ$  collection angle by a photomultiplier. The backscatter intensity is translated into an OPC particle number size distribution between 130 nm and  $3 \mu\text{m}$  with a 1 Hz sampling frequency. For operation in the field, the sample flow of (Gao et al., 2016). The sample flow rates are maintained at  $0.11 \text{ l min}^{-1}$  for each CPC and  $0.46 \text{ l min}^{-1}$  is controlled using a critical orifice for the POPS using critical orifices and an external pump.

The second aerosol measuring platform mSEMS (see Fig. 5c) is designed similarly to the CAMP system and contains a CPC with a lower cut-off size of 9 nm ( $N_9$ ) and the miniaturised Scanning Electrical Mobility Sizer (mSEMS, Model 9404, Brechtel Manufacturing Inc., USA). The instruments are housed in an insulated enclosure mounted on the balloon tether. The mSEMS measures the mobility particle number size distribution in the range of 8 nm to 350 nm. A soft X-ray neutraliser (Model 5525-X, Grimm Aerosol Technik, Germany) is used to establish a defined charge distribution before selecting the particles for electrical mobility with the differential mobility analyser (DMA). The particles are counted with an advanced Mixing Condensation Particle Counter (aMCPC, Model 9403, Brechtel Manufacturing Inc., USA). The mSEMS was used with 30 size bins and a bin time of 2 s, resulting in a full up- or down-scan time of approximately 1 min through all channels. The mSEMS box has a size of 50 cm x 26 cm x 22 cm and weighs about 11.5 kg. Four steel cables, fixed to the aluminium framework, are used to attach the box to the tether, with two carabiners above and below. The instrument enclosure is formed by glass fibre composite plates of 0.5 mm thickness and 20 mm thick polystyrene foam insulation. Aerosols are sampled with a funnel inlet of the same geometry as used in CAMP and are dried with a custom silica-bead dryer. The inlet flow rate is  $1.08 \text{ l min}^{-1}$ , the mSEMS sample flow rate is  $0.36 \text{ l min}^{-1}$  and the CPC sample flow rate is  $0.11 \text{ l min}^{-1}$ . The residual sample flow is used by a POPS, which is not included in this data set due to a malfunction during the field campaign. The barometric pressure, internal temperature, and relative humidity are recorded with a BME280 sensor (Bosch Sensortec GmbH, Germany). The sampled air temperature and relative humidity downstream of the dryer are monitored with a HYT221 sensor (B+B Thermo-Technik GmbH, Germany).

### 3.2.2 Data processing and quality control

The BELUGA measurements are divided into post-processed as individual flights, whereby one flight describes a continuous measurement period with a specific instrument setup and without long interruptions above interruptions longer than 5 min. Measurement flights can include several ascents and descents. The altitude of the measurement systems meteorological observations and additionally of the aerosol measurements is calculated using the isothermal hypsometric equation with the measured pressure values, respectively, as well as the ground pressure and temperature. In addition to meteorological and aerosol variables, the final data set includes geolocation.

For the data post-processing The meteorological observations of the TMP measurements, a are available at a sampling rate of 1 Hz, corresponding to a vertical sampling interval of about 0.5 m at typical ascent rates of around  $0.5 \text{ m s}^{-1}$ . For the data post-

processing, a rolling median is applied on five data points. Temperature measurements are additionally low-pass filtered to remove artificial spikes. It has been shown that the radiation protection of the integrated radiosonde sensors does not function optimally with certain orientations of the probe. Increased temperatures in the range of Solar radiative heating of the radiosonde temperature sensor was associated with temperature increases of 2-5 K were measured due to direct sunlight. Consequently, all angles at which a temperature increase due to sunlight can occur are flagged, and the quality of the temperature measurements must be carefully considered on a for certain probe orientations. Potentially affected temperature measurements are flagged according to the probe orientation relative to the sun and require case-by-case basis assessment. This is relevant when the sonde exceeds a pitch value of more than 5° and the sonde's pointing direction is within ±45° of the sun's azimuth angle. Similarly, this is applied when the sonde's pitch angle exceeds -15° when pointing in the opposite direction within ±45° of the azimuth angle. This is not applied for cloudy measurement days or days with low solar radiation. Regarding wind speed measurements from the Trisonica mini, it is assumed that within a horizontal inflow of ±15° a proper functionality is guaranteed and that the calculated virtual temperature is valid within this range. The wind direction derived from the three-dimensional compass may contain increased uncertainties at low wind speed, as it is assumed that the TMP's wind vane aligns with mean wind direction.

(a) All measurement point pairs of  $N_{11}$  and  $N_{15}$  obtained from the CAMP platform during the field campaign, showing the relation between the measurements of both CPCs with different lower cut-off size. (b) Integrated values of mSEMS measurements (9 nm to 350 nm) in comparison with 2 min mean of ( $N_9$ ) used in the mSEMS box.

In For the CAMP platform, two CPCs are modified with respect to the temperature difference between the saturator and the condenser. Both instruments are calibrated using a reference electrometer with monodisperse silver aerosol particles of different sizes from 7 nm to 40 nm selected by a Differential Mobility Analyzer (DMA). The calibration method used is described in detail in Wiedensohler et al. (2018) and Tuch et al. (2016). As the CPCs internally calculate particle concentration from counts, the calibration includes additional, unknown corrections. The calibration process is thus able to compensate for any differences in the original flow rate. Consequently, the resulting calibration factors account for both the modified flow and the instrument's detection efficiency. Due to these corrections, the calculated counting efficiencies can exceed 100 %. The modified flow rates, measured during the campaign and laboratory volumetric flow values, demonstrate a strong correlation, with a mean discrepancy of ±6 %. A curve fit of the counting efficiency  $E$ , depending on the particle diameter  $D_p$  is estimated according to

$$E = E_{\infty} \left( 1 - \exp \left( - \frac{D_p - D_{p0}}{D_{p50} - D_{p0}} \cdot \ln(2) \right) \right),$$

with  $D_{p50}$ , the particle diameter at which a 50 % efficiency is reached, which is the typical definition of the both CPCs were calibrated at TROPOS using the calibration method as described for ALADINA in Sect. 3.1.2. A size-dependent counting-efficiency function was fitted following Pilz et al. (2022) to determine the lower cut-off of the instrument (Tuch et al., 2016), and  $D_{p0}$  as the diameter with zero counting efficiency. The temperature difference between the saturator and the condenser of 15.1 K used in the first CPC led to a diameter  $D_{p50}$  of 11 nm and the temperature difference of 9.5 K used in the second CPC led to a  $D_{p50}$  of 15 nm. Thus, the difference between both CPC measurements represents the particle number concentration from 11 nm to 15 nm ( $N_{11-15}$ ). The values of  $N$  from both CPCs are additionally corrected for their respective plateau efficiency  $E_{oo}$ . The manufacturer specifies an upper limit of 1 and plateau counting efficiency  $E_{\infty}$  of each CPC. The raw concentrations are corrected using the respective plateau counting efficiencies. Additionally, a mean sampling-efficiency factor is applied to account for inlet aspiration efficiency and tubing losses. A comparison of the two CPC measurements is presented in Appendix C to assess their consistency (see Fig.  $\mu m$ , which is assumed here to define the upper cut-off for all CPC measurements. In combination with sampling losses at the inlet and in the tubing system, the CPC measuring  $N_{15}$  is corrected

by a factor of 1.05 while the CPC measuring  $N_{11}$  is corrected by a factor of 0.94. As a last step, the corrected  $N$  from both CPCs is converted to standard conditions (1013.25 hPa and 273.15 K). For both CPCs, the manufacturer specifies an uncertainty range of  $\pm 20\%$ , which is reduced to  $\pm 5\%$  by flow stabilisation.

Figure C1a shows the relationship between  $N_{11}$  and  $N_{15}$ , measured with the two CPCs during the field campaign. Due to their different cut-off sizes,  $N_{15}$  measurements should not exceed  $N_{11}$ , which is observed to apply for 90.3 % of the measurement data. This verifies the reliability of the measurements in estimating  $N_{11-15}$  in the ultrafine particle regime. In addition to the two CPCs installed in the CAMP platform, a POPS provides measurements of the  $PNSD$ . Size calibrations for the different channels of the POPS are C1a). For the POPS, a size calibration is applied using spherical polystyrene latex (PSL) particles following the procedure described in 13 sizes ranging from 0.125  $\mu\text{m}$  to 3  $\mu\text{m}$ . The calibration procedure is described in detail by Pilz et al. (2022). It has been shown that the Additionally, a size-dependent sampling-efficiency factor for each measurement channel of the POPS is applied to account for inlet aspiration efficiency and tubing losses. Due to background noise below 150 nm is relevant under clean conditions. Therefore, only size channels larger than above 150 nm are used considered for further analysis. The integration over all size channels above 150 nm results in a and the data set. Finally, the corrected CPC number concentrations and the  $PNSD$  from the POPS are converted to standard conditions (1013.25 hPa and 273.15 K). The POPS data are provided on PANGAEA as particle number size distributions ( $dN/d\log D_p$ ) in 14 size channels and as integrated particle number concentration hereafter named over the retained size channels ( $N_{150}$  (Pilz et al., 2022)).

For the mSEMS box, the size-resolved sampling efficiency is determined for the aMCPC in a laboratory calibration, and correction factors are applied accordingly. Similarly to the previously described post-processing of CPC measurements, corrections are applied to the CPC used in the mSEMS box (correction factor 0.72 and a  $D_{p50}$  of 9 nm) and the corrected  $N$  is converted to standard conditions. Data inversion on platform, the CPC measuring  $N_9$  is corrected using the respective plateau counting efficiency and a mean sampling-efficiency factor following the identical procedure as described for ALADINA and CAMP. For the mSEMS, data inversion of the  $PNSD$  is performed using the manufacturer's script's software to account for doubly charged particles. Up- and down-scans are then averaged over concentration, resulting in an effective scan frequency temporal resolution of 2 min for the final data set. Figure C1b presents a The aMCPC is corrected using its plateau counting efficiency determined by laboratory calibration at TROPOS. Additionally, a size-dependent sampling-efficiency factor for each measurement channel of the mSEMS is applied to account for effects at the inlet and in the tubing system. The corrected CPC number concentrations and the  $PNSD$  from the mSEMS are converted to standard conditions (1013.25 hPa and 273.15 K). The mSEMS data are provided as particle number size distributions ( $dN/d\log D_p$ ) in 30 size channels. A comparison of the integrated  $PNSD$  from the mSEMS with  $N_9$  obtained from the CPC of the mSEMS box platform is presented in Appendix C to assess their consistency (see Fig. C1b). Both measurement data demonstrate a strong correlation ( $R^2$  of 0.915), with 80 % of the measurements falling within a range of  $\pm 20\%$  of each other.

### 3.3 Surface flux gradient system

#### 3.3.1 Platform and instrumentation

Profile measurements with the surface flux gradient system (Mathes et al., 2025a), hereafter referred to as the gradient system, were carried out on 13 different days (see Table A1). The system design and measurement method are described in detail in Mathes et al. (2025a). The sampling time per day varied from 6 h to 23 h. The derived data are divided into three categories based on

the surface coverage with snow:

1) Snow: surface is fully covered with snow or ice (see Fig. 6a).

2) Snow and vegetation: snow patches and patches with open tundra vegetation (see Fig. 6b).

560 3) Vegetation: snow is fully melted, tundra vegetation is dominant (see Fig. 6c).

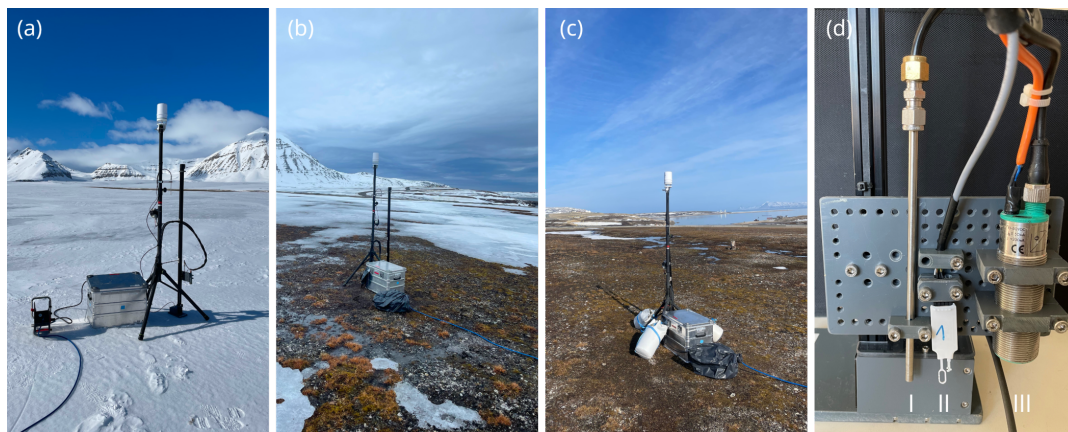


**Figure 6.** Three pictures of the studied surface types during the field campaign in Ny-Ålesund. (a) Snow on 22 May 2024, (b) Snow and vegetation on 30 May 2024, (c) Vegetation on 5 June 2024, and the (d) sensor board of the gradient system: (I) aerosol inlet, (II) hot wire anemometer and the (III) distance sensor. The sensor board was attached to the linear actuator. (Pictures: Theresa Mathes, TU Berlin)

To measure near-surface aerosol particle number concentration profiles, a 1.5 m high linear actuator is used with a sensor board (see Fig. 6d). A 20 cm long, The sensor board carries a downward-facing stainless steel inlet with an inner diameter of 3 mm is mounted on the sensor board. The inlet is aerosol inlet connected to a CPC (model 3007, TSI, USA) via a 205 cm long conductive silicon tube with an inner diameter of 4.2 mm. The CPC measures  $N$  with a lower cut-off diameter of 10 nm at a sampling frequency of 1 Hz and with a sample volume flow rate of  $0.7 \text{ l min}^{-1}$  (see Table 3). In addition to the aerosol inlet (I) shown in Fig. 6d, the sensor board contains a simple hot wire anemometer (Rev. P., Modern Device, USA) to measure measuring  $N_{10}$ , a hot-wire anemometer for wind speed and temperature (Fig. 6d, II), and an ultrasonic distance sensor (UC2000-30GM-E6R2-V15, Pepperl and Fuchs, Germany) to measure the distance to the surface (Fig. 6d, III). These sensors are operated with a sampling frequency of 1 Hz (see Table 3). The linear actuator and all sensors are operated via a 24 V power connection. A laptop for system control and data recording, and the CPC were placed downwind of the gradient system in an aluminium box for weather protection during the field campaign to determine the height above the surface. The inlet design, tubing and sample flows are described in detail in Mathes et al. (2025a). The objectives of orienting the aerosol inlet downwards are to prevent precipitation from entering the sampling line and to enable measurements closer to the surface. It is expected that aspiration losses will be small within the relevant particle size range. The inlet configuration was consistent throughout all measurement heights, but potential sampling biases for larger particles cannot be ruled out. An overview of the instrumentation, sampling frequencies and measurement uncertainties is provided in Table 3. The gradient system was realigned into the wind when the wind direction changed, and was predominantly located upwind of the BELUGA ground station due to the prevailing northwest and southeast

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main wind directions. A tripod was used to stabilise the system and was positioned downwind of the gradient system. During periods of high wind speed, exceeding  $6 \text{ m s}^{-1}$ , the gradient system was stabilised using sandbags.

Meteorological parameters, including wind direction and wind speed, temperature, relative humidity, precipitation and solar irradiance, were are measured using a weather station (Atmos 41, METER, USA) installed at the top of the tripod (at 2 m height, (see Fig. 3). The gradient system was programmed to sequentially sample at six distinct height levels automatically, beginning at 10 cm above the surface and followed by the heights of 14, 22, 38, 69 and 134 cm. The actual sampling heights varied by  $\pm 1 \text{ cm}$ , depending on measurement conditions (e.g. snowfall) and surface characteristics. During the downward movement descent from 134 cm back to 10 cm, an additional measurement was taken at the height of cm, the 38 cm. This served as a reference point to monitor potential changes in background particle number concentration but is not included in the gradient calculation. Each height cm level was sampled for 50 s, resulting in a complete vertical profile every 350 s a second time, yielding seven measurement steps at six distinct heights per profile.

**Table 3.** Instrumentation used at of the near-surface gradient system used for measurements of temperature ( $T$ ), relative humidity ( $RH$ ), short-wave irradiance ( $ISW$ ), precipitation ( $P$ ), wind direction and speed ( $DD$ ,  $FF$ ), aerosol number concentration ( $N_{10}$ ), and distance to the surface ( $d$ ).

| Variable    | Sensor (Manufacturer)                       | Sampling frequency | Measuring range                                                 | Uncertainty                           |
|-------------|---------------------------------------------|--------------------|-----------------------------------------------------------------|---------------------------------------|
| $T$         | Hot Wire Anemometer (Rev. P, Modern Device) | 1 Hz               | –                                                               | –                                     |
|             | ATMOS 41 (METER)                            | 0.1 Hz             | $-50 \text{ }^{\circ}\text{C}$ to $60 \text{ }^{\circ}\text{C}$ | $\pm 0.6 \text{ }^{\circ}\text{C}$    |
| $RH$        | ATMOS 41 (METER)                            | 0.1 Hz             | 0 % to 100 %                                                    | $\pm 3 \text{ } \%$                   |
| $ISW$       | ATMOS 41 (METER)                            | 0.1 Hz             | 0 to $1750 \text{ W m}^{-2}$                                    | $\pm 5 \text{ } \%$                   |
| $P$         | ATMOS 41 (METER)                            | 0.1 Hz             | 0 to $1500 \text{ mm h}^{-1}$                                   | $\pm 5 \text{ } \%$                   |
| $FF$ , $DD$ | ATMOS 41 (METER)                            | 0.1 Hz             | 0 to $30 \text{ m s}^{-1}$ , $0^{\circ}$ – $360^{\circ}$        | $\pm 3 \text{ } \%$ , $\pm 5^{\circ}$ |
|             | Hot Wire Anemometer (Rev. P, Modern Device) | 1 Hz               | –                                                               | –                                     |
| $N_{10}$    | CPC 3007 (TSI)                              | 1 Hz               | $> 1010 \text{ nm}$ to $1 \text{ } \mu\text{m}$                 | 20 %                                  |
| $d$         | UC2000-30GM-E6R2-V15 (Pepperl & Fuchs)      | 1 Hz               | 80 mm to 2000 mm                                                | –                                     |

### 3.3.2 Data processing and quality control

The data post-processing and data analysis of the gradient system proceed in a series of steps. Firstly, the follows the procedure described in Mathes et al. (2025a). The height level of the gradient system is verified using data from the distance sensor. A measured profile is included in the subsequent analysis if more than 80 % of the height measurements at each level are within  $\pm 20 \text{ } \%$  of the respective set point. The CPC required up to 9 s to fully adjust to a change in particle number concentration, and the vertical movement between levels required up to 10 s. Therefore, the Only the final 30 s of each 50 s measurement interval, during which the CPC has reached a stable response and the system was no longer moving, are used for further analysis. Secondly, outliers are removed if values are are used to account for sensor response times and movement between height levels. Outliers outside 1.5 times the interquartile range within a moving window of 20 min. This specific time period is selected to mitigate the impact of short-term fluctuations while still capturing long-term trends. The arithmetic mean over the 30 s measurement interval is then calculated window are

removed, and the remaining measurements are averaged for each height level. Thirdly, wind speed and temperature from the hot-wire anemometer are compared to measurements from the weather station, which is located at the top of the gradient system at 200 cm a.g.l. To avoid flow distortion caused by obstacles, data from a 90° wind sector centred on the instrument tripod and the equipment box containing the logging system are excluded from the analysis. Furthermore, time periods that have potentially been influenced by local pollution, characterised by a rapid increase in particle number concentration, are excluded from the analysis. A logarithmic wind profile with height is assumed, as all measurement levels are within the surface (Prandtl) layer. Based on a linear regression of wind speed against the logarithm of height, Wind speed and temperature from the hot-wire anemometer data are extrapolated to the are compared against the weather station measurements at the top of the gradient system at 200 cm reference height. A correction factor is derived based on the calculated offsets, and all data are adjusted accordingly. Consequently, the a.g.l. The hot-wire wind speed measurements are extrapolated to this reference height by linear regression against the logarithm of height. The corrected hot-wire anemometer data are used in wind speed measurements are used together with the hot-wire temperature in the further analyses.

The measured  $N$  is calibrated by applying detection efficiencies derived from a reference electrometer with monodisperse silver aerosol of different sizes from 5 nm to 40 nm. Additionally, the measured particle number concentration is adjusted for losses that occurred measured with the CPC is corrected by applying the plateau counting-efficiency derived from calibration at TROPOS, following the procedure described for ALADINA and BELUGA. Diffusional losses in the inlet system and sampling lines, particularly diffusional losses of small particles to the inner walls of the tubing and inlet surfaces (Kulkarni et al., 2011). These losses are estimated as described by Gormley and Kennedy (1949). To determine the particle penetration efficiency as a function of particle size,  $N$  in the are corrected using a particle-number-weighted penetration efficiency calculated from the measured  $PNSD$  over the size range from 12 nm to 573 nm is used, following Mathes et al. (2025a). Measurements of the  $PNSD$  from a Neutral Cluster and Air Ion Spectrometer (NAIS, Airel, Estonia) are used for the size range from 12 nm to 37 nm (Boyer, 2025), and for the size range from 37 nm to 573 nm, measurements from a scanning mobility particle sizer (SMPS model 3034, TSI, USA) are used. Both instruments are located at the Gruvebadet Atmosphere Laboratory. The obtained particle concentration in the positive and negative charging mode from the NAIS are averaged. It is assumed that the measured  $PNSD$  from the NAIS and SMPS are representative of the measurements of the gradient system, as direct measurements of the particle size distribution at the location of the gradient system are not available. The corresponding sampling loss rate is calculated for each size bin of the NAIS and SMPS based on the inlet characteristics described in Sect. 3.3.1. The size dependent loss rates are then multiplied by the normalised  $PNSD$  from the NAIS and SMPS, and the total particle penetration efficiency is estimated by summing up the number-weighted particle penetration efficiencies in the considered size range. When  $PNSD$  data from the NAIS or SMPS are unavailable, the daily mean penetration efficiency is used instead. The median particle penetration efficiency for one hour intervals ranged from 85 % to 99 %, with an overall median of 98 %. This variability reflects the strong dependence of particle losses on size (Kulkarni et al., 2011).

Illustrative example of vertical profiles of (a) particle concentration  $N \text{ cm}^{-3}$  and (b) wind speed  $FF \text{ m s}^{-1}$ . The beige line shows the linear regression fit, with  $R^2$  of 0.99 for the particle concentration gradient and  $R^2$  of 0.97 for the wind speed gradient.

When evaluating gradients based on ascending stepped profiles, only intervals are considered in which at least four of the six distinct height levels show valid measurements. Figure D1 provides an illustrative example of the measurements of the gradient system used in the subsequent data analysis, showing exemplary profiles of  $N$  and wind speed  $FF$ , as well as linear regression fits. In the surface layer, turbulent fluxes, such as momentum flux ( $\overline{U'w'}$ ), The friction velocity  $u_*$ , sensible heat flux ( $H = \overline{w'T'}$ ),  $H$  and particle number flux ( $P = \overline{w'C'}$ ) are often related to vertical gradients

of particle number concentration  $N$ , horizontal wind speed  $FF$ , and temperature  $T$  (Holton and Hakim, 2013; Foken and Mauder, 2024). A comprehensive description of this relationship is presented in the study of  $P$  are derived from linear regressions of wind speed, temperature and particle number concentration against the logarithm of height, following Mathes et al. (2025a). Assuming The calculation assumes equal eddy diffusivities ( $K_m = K_H = K_P$ ) under neutral stratification (e.g., Wieringa, 1980; Held et al., 2011), and with the von Karman constant  $\kappa = 0.4$ , the friction velocity  $u_*$  is used to express:

$$u_* = \kappa \frac{\partial U}{\partial \ln z} \quad [\text{m s}^{-1}]$$

The friction velocity  $u_*$  is determined according to Eq. (??) from the measured vertical gradient of the horizontal wind speed  $FF$  using a linear regression of five wind speed measurements against the logarithm of the respective heights. In the same way, vertical gradients of air temperature  $T$  and particle number concentration  $N_{10}$  are obtained from linear regressions and used to estimate the corresponding sensible heat flux  $H$  (Eq. (??)) and particle flux  $P$  (Eq. (??)).

$$H = -\kappa \cdot u_* \cdot \frac{\partial T}{\partial \ln z} \quad [\text{W m}^{-2}]$$

$$P = -\kappa \cdot u_* \cdot \frac{\partial N_{10}}{\partial \ln z} \quad [10^6 \text{ m}^{-2} \text{ s}^{-1}]$$

Positive values of  $H$  indicate an upward flux, i.e. when the calculated temperature decreases with height. Similarly, a positive  $P$  denotes an upward flux of particles, when particle concentration decreases with height. . Positive fluxes indicate upward transport. The particle and sensible heat fluxes are evaluated in 20 min intervals (see Eqs. (??) and (??)). . A temporal linear regression is applied to obtain corresponding values of particle number concentration, wind speed, and temperature at the median timestamp for each interval. Figure D2 shows a 20 min interval with four profiles of particle concentration and wind speed. In this example, the interval starts at 12:09 UTC on 8 June 2024 and ends at 12:31 UTC on 8 June 2024 with four to six different height levels per profile. All heights are interpolated for a median timestamp at 12:20 UTC. The calculated  $u_*$  is  $0.14 \text{ m s}^{-1}$ , with a net  $P$  of  $0.98$ . Examples of the vertical profiles and their temporal interpolation are provided in Fig. D1 and Fig. D2 in Appendix D.

To exclude intervals with weak turbulence and potential decoupling, especially relevant under stable conditions or above snow and ice surfaces, fluxes are only calculated for profiles with friction velocity identify intervals with potentially reduced flux reliability due to weak turbulence or decoupling, a quality-control threshold of  $u_* \geq 0.15 \text{ m s}^{-1}$  was applied. Additionally, data were quality checked during the regression analysis for the flux calculation to ensure that only values based on an R-squared  $\geq 0.5$  are included. the regression used to calculate the fluxes was quality checked using a threshold of  $R^2 \geq 0.5$  to identify poorly resolved vertical gradients. Flux estimates that do not meet these criteria should be interpreted with caution rather than being considered invalid. Of all 20-minute intervals, 35 % met the  $u_*$  criterion, 27 % met the  $R^2$  criterion, and 10 % met both criteria simultaneously. The majority of measurements were taken under near-neutral stratification conditions, with interquartile range values of  $-0.235 < z/L < 0.005$ . Therefore, stability corrections are neglected, with a maximum estimated error below 11 % (Businger et al., 1971). Uncertainties in flux estimates due to measurement uncertainty are assessed using Monte Carlo simulations. For each profile, 10,000 iterations are generated using Gaussian-distributed noise. The assumed standard deviations are 20 % for particle concentration according to the manufacturer, 5 % for temperature, and  $0.5 \text{ m s}^{-1}$  for wind speed (Prohasky and Watkins, 2014). Fluxes are recalculated for each ensemble, and the 90<sup>th</sup> percentile

is taken as the uncertainty range (Watanabe and Pfeiffer, 2022). The resulting absolute median uncertainties are  $17 \text{ W m}^{-2}$  (standard deviation (SD)  $\pm 38$ ) for  $H$  and  $0.70 \times 10^6 \text{ m}^{-2} \text{ s}^{-1}$  (SD  $\pm 7.21$ ) for  $P$ . A more detailed description of the applied method and its validation is provided in Mathes et al. (2025a).

665 Time series of (a) particle concentration  $N \text{ cm}^{-3}$  and (b) wind speed  $FF \text{ m s}^{-1}$  derived from multiple profiles of the gradient system in a 20 min interval on 8 June 2024. The different colours show the height of the measurement.

#### 4 Combined airborne and surface-based observations on 3 June 2024

In this section, the measurements obtained from all three systems on 3 June 2024 are presented as a representative case study , demonstrating on 3 June 2024. The observations show the potential of the combined observations systems to investigate aerosol variability in interaction with boundary-layer and interactions with atmospheric boundary layer and surface exchange processes. Throughout the measurement day, ALADINA was operated between 09:15 UTC and 19:34 UTC, conducted 21 vertical profiles and nine horizontal patterns. BELUGA was operated between 09:12 UTC and 18:11 UTC, resulting in eight vertical profiles. The surface flux gradient system was in operation starting at 00:00 UTC, with the exception of a time period between 08:50 UTC and 12:00 UTC.

675 To provide a broader campaign context for the observations from on 3 June 2024, Fig. 7 presents overall campaign vertical statistics of potential temperature  $\theta$ , specific humidity  $q$  and aerosol particle number concentration  $N$ , derived from all available ALADINA and BELUGA vertical profiles. The median profiles illustrate the range of thermodynamic and aerosol conditions observed during the field campaign, and are not intended as a direct platform comparison. This is important because ALADINA and BELUGA were not always operated simultaneously or on the same day due to operational limitations (see Sect. 2.2). In addition, the two systems covered different altitude ranges, operated at different locations in the vicinity of Ny-Ålesund, and thus sampled different meteorological regimes during the campaign, including cold conditions and periods affected by snow melt (see Sect. 2.2). For all three parameters shown in Fig. 7, the interquartile ranges underline the variability of the meteorological conditions observed during the field campaign.

Both airborne systems demonstrate show an increase in potential temperature  $\theta$  with growing altitude, indicating a predominantly stable stratification in the measured lower atmosphere. The specific humidity  $q$  either decreased with altitude (BELUGA) or remained nearly constant within the altitude range (ALADINA), indicating that vertical humidity gradients were not uniform across the campaign period. The increased median values in the BELUGA profile of  $q$  near the surface suggest that enhanced moisture content was confined to lower altitudes, was confined at lower altitudes. This phenomenon is likely due to stable stratification and periods affected by snow melt during measurement days after 28 May 2024, while drier conditions occurred at higher altitudes. Furthermore, elevated values of  $q$  between 600 m and 900 m a.s.l. in the BELUGA profile may correspond to cloud-influenced layers aloft. Observations over a period of 25 years in Ny-Ålesund demonstrated that the median cloud base height during the spring and summer seasons frequently remained at altitudes below 1 km (Maturilli and Ebell, 2018). This is not captured by the ALADINA measurements due to the operation under solely cloud-free conditions. The aerosol particle number concentrations show a pronounced vertical variability, with differences between the two airborne systems partly related to the different lower

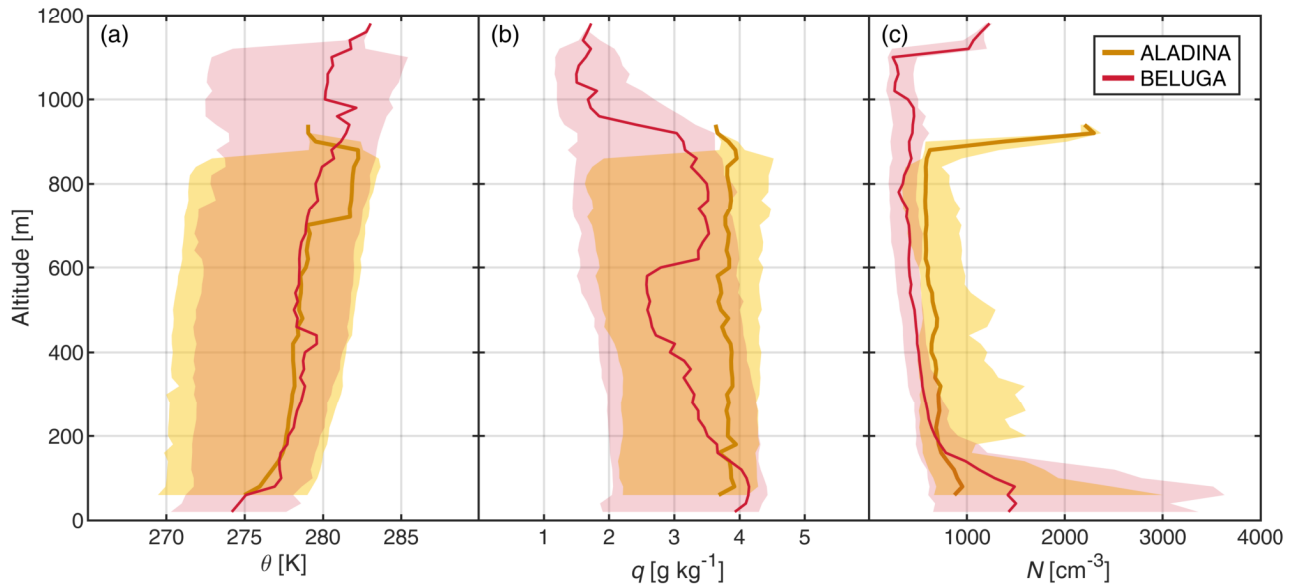


**Figure 7.** Median profiles derived from all available ALADINA and BELUGA vertical profiles during the field campaign: (a) potential temperature  $\theta$ , (b) specific humidity  $q$  and (c) aerosol particle number concentration  $N$ . The profiles were calculated for each airborne system in 20 m altitude bins, with shaded areas indicating the interquartile range between the 25th and 75th percentiles of the measured values. For the aerosol profiles,  $N_6$  was used for ALADINA and  $N_{11}$  for BELUGA where available.

695 cut-off diameters used for  $N$  and to the variability of aerosol conditions observed on different measurement days. The enhanced concentrations observed at elevated altitudes may be influenced by differences in altitude coverage among the individual measurement flights, as not every profile reached the maximum altitude. At the same time, increased  $N$  below 180 m a.s.l. coincides with a pronounced surface-based inversion layer visible in the median profiles of  $\theta$ . Observations during a previous field campaign in Ny-Ålesund in 2018 similarly showed increased values of  $N$  below 300 m a.s.l. (Harm-Altstädter et al., 700 2023). Overall, the campaign-wide profiles provide a reference for interpreting the thermodynamic and aerosol observations obtained on 3 June 2024.

The prevailing meteorological surface conditions near the surface during the selected case study day are shown in Fig. 8 and include wind speed and direction, temperature and short-wave downward irradiance (adapted from: Maturilli, 2020a, b). During the measurement period, near-surface wind speed increased notably after 10:00 UTC and remained elevated until approximately 16:00 UTC, reaching up to approximately 6 m s<sup>-1</sup>. At the same time, the wind direction changed from variable conditions at low wind speed to a more persistent wind direction with increasing wind speed, ranging from East to Southeast as the wind speed increased. The air east to southeast. Air temperature remained consistently above 4 °C throughout the day. The pronounced temporal variability in downward short-wave irradiance indicates the occurrence of alternating periods of clear sky conditions and cloud cover.

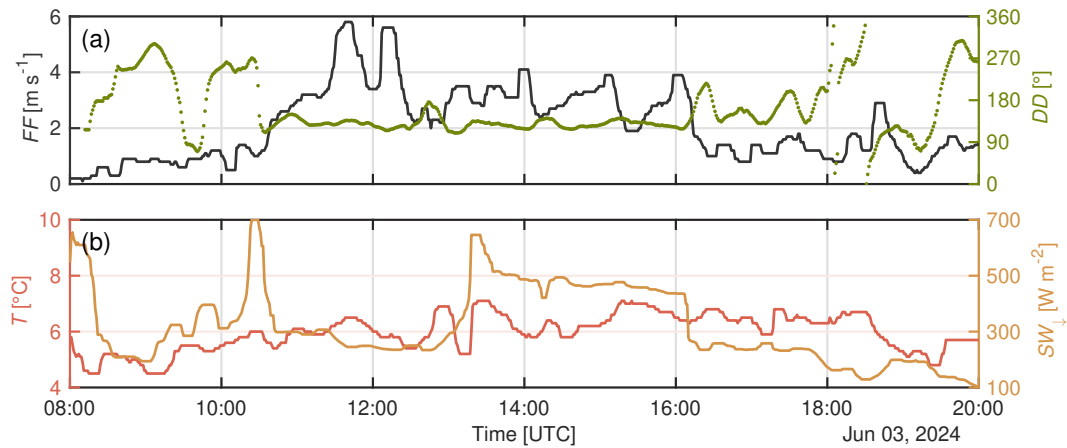


**Figure 8.** Time series of selected surface meteorological parameters in 15 min intervals, derived from AWIPEV Research Base during the measurement period on 3 June 2024. (a) Wind speed ( $FF$ ,  $\text{m s}^{-1}$ , black line) and wind direction ( $DD$ ,  $^{\circ}$ , green dots) both at 10 m a.g.l. (b) air temperature ( $T$ ,  $^{\circ}\text{C}$ , red line) at 10 m a.g.l. and short-wave downward irradiance ( $SW_{\downarrow}$ ,  $\text{W m}^{-2}$ , amber line).

710 The sensible heat flux  $H$  and particle flux  $P$  on 3 June 2024, derived from the measurements of the surface flux gradient system, are presented in Fig. 9. The surface area around the measurement site was clear of snow, although a small snowfield was present at a distance of approximately 10 m, orientated upwind in the main wind direction (see Fig. 6b). The results show a net upward  $H$  during 75 % of the day (see Fig. 9a), with an average flux of  $25 \text{ W m}^{-2}$  for the net positive flux intervals. Taking the potential uncertainties represented by the grey error bars into account the maximum error in Fig. 9 into account, the sensible heat fluxes are were mostly positive.  $H$  reached an average flux of  $53 \text{ W m}^{-2}$  between 12:00 UTC and 18:00 UTC. The positive  $H$  coincides with a clearing of cloud cover and an increase in short-wave downward irradiance, which increased from approximately  $250 \text{ W m}^{-2}$  to over  $500 \text{ W m}^{-2}$  during this measurement interval. In addition, an increase in temperature was observed during this period, reaching a daily maximum of  $6.9 \text{ }^{\circ}\text{C}$  at 18:00 UTC at the gradient system measurement site. Concurrently, increasing wind speed during this period wind speed increased, which further resulted in an increase of friction velocity to  $0.2 \text{ m s}^{-1}$ . With regard to particle flux (see Fig. 9b), deposition intervals predominated for 61 % of the day. The most pronounced flux occurred between 13:00 UTC and 17:00 UTC, with a net particle deposition flux of  $-1.04 \cdot 10^6 \text{ m}^{-2} \text{ s}^{-1}$ . During this interval, the aerosol number concentration  $N_{10}$  increased to  $1,040 \text{ cm}^{-3}$  at the gradient system measurement site, compared to an average of  $940 \text{ cm}^{-3}$  for the rest of the day. It is possible that the shift in wind direction after 10 UTC from variable conditions to Southeast along with increasing wind speed led to a change in air masses, which may have contributed to the observed net particle deposition. This transition was accompanied by an increase in friction velocity ( $u_*$ ), potentially enhancing deposition processes. Conversely, the melting of the snow or drying of the tundra due to higher solar irradiance and higher temperature probably leads to an increase in sensible heat flux.

Observations from the two airborne systems ALADINA and BELUGA on 3 June 2024. Given times indicate the start of a respective vertical profile or a horizontal pattern in UTC. Panels (a) and (b) show  $N_6$  and potential temperature  $\theta$ , respectively, from the first vertical profile during all ALADINA flights performed on 3 June 2024. Panel (c) shows

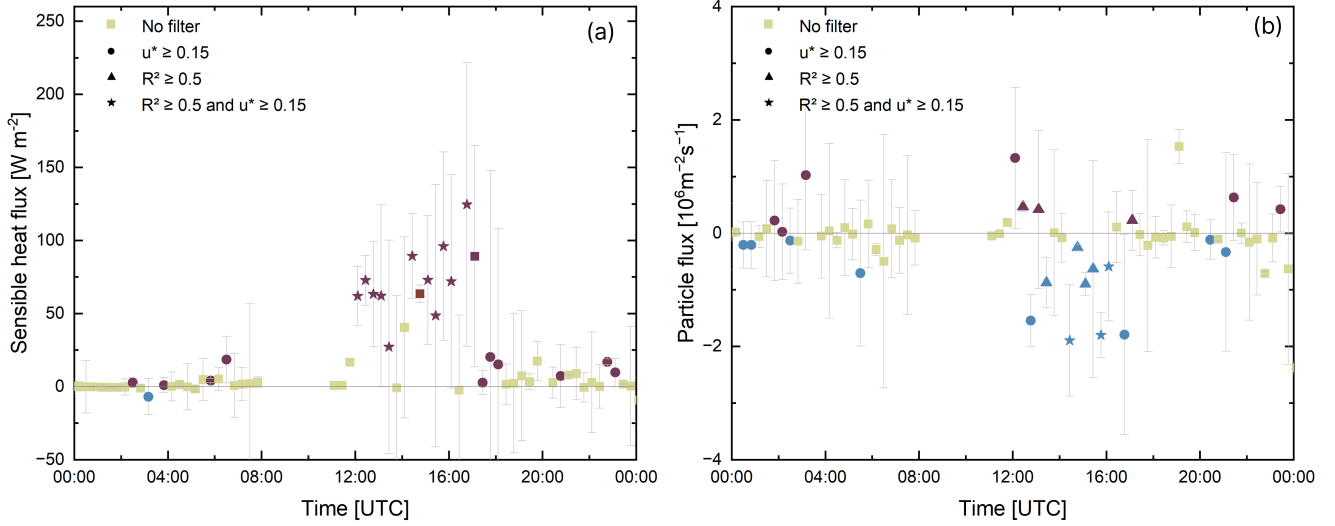


**Figure 9.** (a) Sensible heat flux ( $H$ ,  $\text{W m}^{-2}$ ) and (b) particle flux ( $P$ ,  $10^6 \text{ m}^{-2} \text{ s}^{-1}$ ) calculated from measurements of the surface flux gradient system on 3 June 2024 with surface type Snow and Vegetation. The brown colour indicates net positive flux intervals, and the blue colour indicates net negative flux intervals. The beige colour indicates intervals with  $u_* < 0.15 \text{ m s}^{-1}$  or  $R^2 < 0.5$ . The circle shows intervals with  $u_* \geq 0.15 \text{ m s}^{-1}$ , the triangle when  $R^2 \geq 0.5$ , and the star when both conditions are met. The grey bars illustrate the maximum error, as estimated by Monte Carlo simulations.

730  $N_{11}$  from all ascending BELUGA profiles obtained with the CAMP platform on 3 June 2024, while panel (d) presents an exemplary ascending BELUGA profile of the  $PNSD$  measured by the POPS on CAMP at 09:12 UTC. Panel (e) shows  $N_6$  and arrows indicating a 3 s rolling median of  $DD$  during an exemplary horizontal ALADINA pattern flown at constant altitude of 430 m a.s.l. at 19:15 UTC. Panel (f) presents an exemplary ascending BELUGA profile of the  $PNSD$  derived from the mSEMS at 11:32 UTC. Map data source panel (e): Earthstar Geographics.

Observations from the two airborne systems ALADINA and BELUGA are presented in Fig. 10. To provide a broader  
 735 overview of the meteorological and aerosol conditions during the measurement day, data from the first vertical ascending profiles of each flight of both systems are presented. The potential temperature  $\theta$  derived from ALADINA measurements (see Fig. 10b) indicates a stably stratified ABL throughout the day, with  $\theta$  increasing with altitude in all profiles. The strongest vertical gradients occur in the lowest few hundred meters, with a pronounced stable layer near the surface and a transition layer around 250–400 m characterised by a smaller vertical gradient. Above this layer,  $\theta$  continues to increase more gradually  
 740 with altitude, while profiles after 17:00 UTC show additional enhanced gradients at higher altitudes, indicating further stable layering aloft in the later part of the measurement period. Vertical profiles of  $N_6$  from ALADINA (see Fig. 10a) show substantial variability between the individual profiles. The first profile at 09:15 UTC demonstrates elevated  $N_6$  reaching  $1,900 \text{ cm}^{-3}$  observed at altitudes below 200 m a.s.l., indicating an enhanced aerosol layer near the surface. This layer coincides with pronounced stable stratification in the potential temperature profile, suggesting limited vertical exchange in the lower ABL in the  
 745 morning. In contrast, the profiles at 15:15 UTC and 16:08 UTC show a more vertically homogeneous distribution of  $N_6$  of

approximately  $500 \text{ cm}^{-3}$  increasing to  $600 \text{ cm}^{-3}$ . After 17:00 UTC, profiles of  $N_6$  show a gradual decrease in the overall concentration level below  $500 \text{ cm}^{-3}$ , while remaining relatively homogeneous within the lowest 300 m. The observed decrease in particle concentration may be consistent with deposition processes, as indicated by the negative particle flux between 13:00 UTC and 17:00 UTC measured from the gradient system. Above 300 m,  $N_6$  decreases with altitude reaching a minimum of about  $250 \text{ cm}^{-3}$ . This vertical structure coincides with stronger gradients in  $\theta$ , suggesting reduced vertical mixing. Vertical profiles of  $N_{11}$  from BELUGA (see Fig. 10c) generally align with the observations from ALADINA, showing a similar layer of increased particle concentration at 09:12 UTC at low altitudes below 100 m. The reduced vertical extent of this pronounced aerosol layer compared to ALADINA, where enhanced concentrations were observed up to about 200 m a.s.l., may be related to the different measurement locations of the two systems with different terrain elevation and local variability in the ABL. Furthermore, profiles of  $N_{11}$  after 10 UTC similarly demonstrate a more vertically homogeneous distribution. During the first two BELUGA profiles,  $N_{11}$  increases with altitude, reaching values of up to approximately  $800 \text{ cm}^{-3}$ , whereas after 16:00 UTC, it decreases with altitude, reaching a minimum below  $500 \text{ cm}^{-3}$ .

The vertical profile of  $PNSD$  at 09:12 UTC (see Fig. 10d), derived from the CAMP platform of BELUGA, demonstrates a predominant aerosol particle size in the accumulation mode between 150 nm and 300 nm and an absence of particles larger than 400 nm. This observation is complemented by an additional vertical profile of  $PNSD$  at 11:32 UTC (see Fig. 10f), derived from the mSEMS platform of BELUGA. This profile demonstrates an additional aerosol particle mode in the Aitken mode between 30 nm and 50 nm, and the absence of smaller particles below 30 nm. Consequently, observations of  $N_6$  from ALADINA and  $N_{11}$  from BELUGA (see Fig. 10a,c) show similar particle concentrations, despite the varying lower cut-off sizes. Finally, the horizontal distribution of  $N_6$  is presented in Fig. 10e, showing an exemplary horizontal ALADINA flight pattern at constant altitude of 430 m a.s.l. at 19:15 UTC. The horizontal pattern indicates a higher aerosol particle concentration above land, reaching values above  $450 \text{ cm}^{-3}$  and a lower concentration around  $350 \text{ cm}^{-3}$  to  $400 \text{ cm}^{-3}$  above the Kongsfjord in the transect by crossing the coastline. The wind direction along the horizontal flight path (see Fig. 10e) was predominantly homogeneous, with  $DD$  around  $120^\circ$ . A moderate alteration in wind direction in the southern part of the pattern indicates local variations, potentially influenced by the orography surrounding Zeppelin Mountain, which may have contributed to the observed horizontal variability in  $N_6$ .

Overall, the observations on 3 June 2024 indicate that the spatial distribution of aerosol particles on 3 June 2024 was influenced by the combined effects of changing advection, surface exchange and stable stratification. The transition of wind direction to EastEast, together with increasing wind speed, enhanced short-wave irradiance, positive sensible heat flux and net particle deposition, is consistent with the observed vertical and horizontal variability in aerosol properties and the stable stratification of the ABL observed by ALADINA and BELUGA.

## 5 Conclusions

This publication presents a combined data set of airborne and surface-based observations obtained during a field campaign in Ny-Ålesund in spring 2024. The three measurement systems provide complementary information on aerosol and meteorologi-

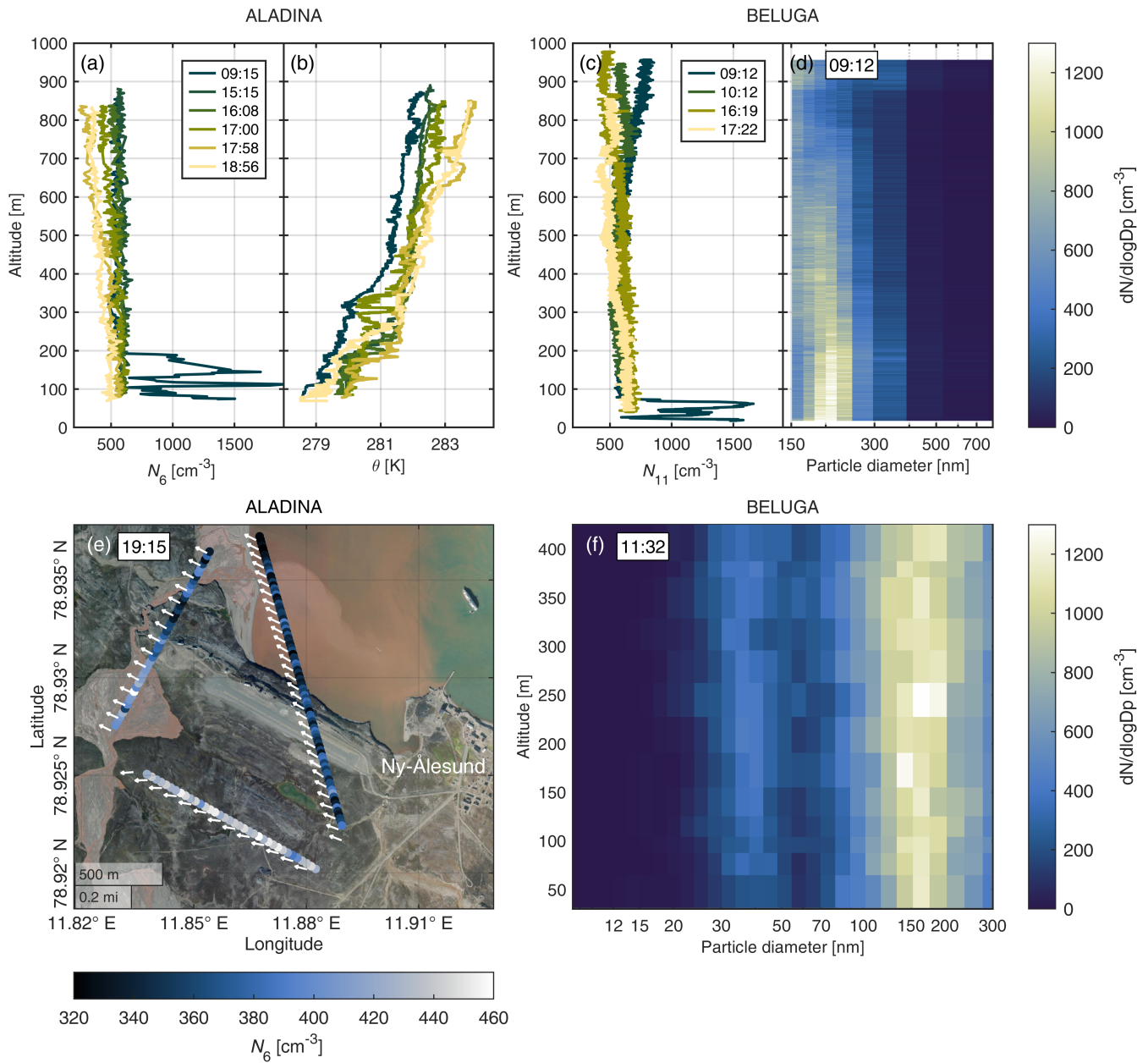


**Figure 10.** Observations from the two airborne systems ALADINA and BELUGA on 3 June 2024. Given times indicate the start of a respective vertical profile or a horizontal pattern in UTC. Panels (a) and (b) show  $N_6$  and potential temperature  $\theta$ , respectively, from the first vertical profile during all ALADINA flights performed on 3 June 2024. Panel (c) shows  $N_{11}$  from all ascending BELUGA profiles obtained with the CAMP platform on 3 June 2024, while panel (d) presents an exemplary ascending BELUGA profile of the  $PNSD$  measured by the POPS on CAMP at 09:12 UTC. Panel (e) shows  $N_6$  and arrows indicating a 3 s rolling median of  $DD$  during an exemplary horizontal ALADINA pattern flown at constant altitude of 430 m a.s.l. at 19:15 UTC. Panel (f) presents an exemplary ascending BELUGA profile of the  $PNSD$  derived from the mSEMS at 11:32 UTC. Map data source panel (e): Earthstar Geographics.

cal conditions in the lower Arctic atmosphere. The UAS ALADINA resolves the spatial variability of aerosol particle number concentration and thermodynamic properties through repeated vertical profiles and horizontal flight patterns, while the tethered balloon system BELUGA extends the vertical profiling capability and provides additional aerosol size distribution. The surface flux-gradient system adds continuous near-surface measurements and enables estimates of sensible heat and particle fluxes. The case study on 3 June 2024 demonstrates how the combined observations can be used to relate aerosol variability to boundary-layer structure, meteorological conditions and surface exchange processes. The combined use of UAS, tethered balloon and surface flux measurements therefore provides a valuable observational basis for investigating aerosol processes and their interaction with atmospheric dynamics in the Arctic boundary layer. This complementarity is shown by pronounced variations in the vertical aerosol structure within a stably stratified boundary layer, contrasting aerosol concentrations between land and fjord areas, and periods of net particle deposition. The campaign data set complements long-term measurements in Ny-Ålesund by resolving small-scale vertical and horizontal aerosol variability in relation to atmospheric stratification and near-surface turbulent exchange. Measurements before and during the onset of snow melt allow these relationships to be investigated under changing surface and meteorological conditions. The observed spatial concentration patterns and near-surface particle fluxes can also support the evaluation of numerical simulations of aerosol transport and mixing under the observed conditions.

## 6 Data availability

The ALADINA data are processed data of all three measurement systems are publicly available on PANGAEA at <https://doi.org/10.1594/PANGAEA.988207> (Schuchard et al., 2026). In addition to as tab-delimited text files under the Creative Commons Attribution 4.0 International licence (CC BY 4.0). The data follow PANGAEA's geocode conventions, with timestamps in UTC and geographical coordinates given as latitude and longitude in decimal degrees referenced to WGS84. The altitudes of the airborne observations are reported above sea level, while the heights of the surface flux gradient system are reported above ground. Parameter names, units and measurement instrumentation are documented in the accompanying metadata. The post-processed data and metadata underwent editorial checks and standardisation during the PANGAEA curation process (Felden et al., 2023).

The ALADINA data are available at <https://doi.org/10.1594/PANGAEA.988207> (Schuchard et al., 2026), grouped into 38 individual flight data sets. They include meteorological observations, aerosol particle number concentrations, the data presented in Table 1, the final data set includes the aircraft's position (latitude, longitude, and altitude a.s.l. referenced to WGS84) altitude), and attitude information (roll, pitch, heading). BELUGA data are published on PANGAEA at <https://doi.org/10.1594/PANGAEA.988353> (Kellermann et al., 2026), including data available at <https://doi.org/10.1594/PANGAEA.988353> (Kellermann et al., 2026), grouped into 23 individual flight data sets containing observations from the TMP and the aerosol platforms CAMP and mSEMS. or mSEMS. These include meteorological observations, particle number concentrations, and particle number size distributions expressed as  $dN/d\log D_p$ . Data of the surface flux gradient system are available at <https://doi.org/10.1594/PANGAEA.984519> on PANGAEA (Mathes et al., 2025b). <https://doi.org/10.1594/PANGAEA.984519> (Mathes et al., 2025b), with separate data sets for the processed profile measurements and the derived particle and sensible heat fluxes. When combining the data sets, their different temporal resolutions and measurement locations must be considered. For BELUGA, separate altitude information is provided for the TMP and the

aerosol platform. ALADINA OPC and surface flux gradient system concentrations refer to ambient conditions. ALADINA CPC concentrations as well as BELUGA concentrations and size distribution are reported at standard conditions (1013.25 hPa and 273.15 K).

- 815 *Video supplement.* A short video illustrates the operation of the UAS ALADINA from take-off to landing using different camera perspectives. Most sequences were recorded during measurement days in June 2024, after the onset of snow melt. The video is available at the German National Library of Science and Technology (TIB) under <https://doi.org/10.5446/73086>.

Appendix A: Overview of data availability and sampling time

**Table A1.** Daily sampling time (h:min) of the three measurement systems after data post-processing, including the number of vertical profiles (V) and horizontal patterns with constant altitude (H) for ALADINA and the number of vertical profiles (V) for BELUGA. n/o: not operated.

| Date               | ALADINA (V, H)      | BELUGA (V)      | Surface flux |
|--------------------|---------------------|-----------------|--------------|
| 19 May 2024        | n/o                 | 1:28 (4)        | n/o          |
| 20 May 2024        | 0:05 (2, 0)         | n/o             | n/o          |
| 22 May 2024        | 3:22 (24, 6)        | 7:05 (16)       | 6:40         |
| 24 May 2024        | 2:39 (18, 8)        | n/o             | n/o          |
| 27 May 2024        | 1:07 (10, 0)        | 4:27 (8)        | 5:40         |
| 29 May 2024        | 2:40 (20, 22)       | 7:44 (12)       | 14:00        |
| 30 May 2024        | n/o                 | n/o             | 21:40        |
| 31 May 2024        | 2:38 (21, 4)        | n/o             | 17:00        |
| 1 June 2024        | 1:19 (11, 0)        | n/o             | 22:20        |
| 2 June 2024        | n/o                 | 3:23 (8)        | 18:20        |
| <b>3 June 2024</b> | <b>3:14 (21, 9)</b> | <b>3:53 (8)</b> | <b>20:40</b> |
| 4 June 2024        | 2:51 (16, 13)       | n/o             | 21:20        |
| 5 June 2024        | n/o                 | n/o             | 16:20        |
| 6 June 2024        | n/o                 | 6:49 (18)       | 19:40        |
| 7 June 2024        | n/o                 | 4:16 (16)       | 21:20        |
| 8 June 2024        | n/o                 | n/o             | 8:40         |
| Total              | 19:55 (143, 62)     | 39:05 (90)      | 213:40       |

Appendix B: Additional information on ALADINA data processing

820 Figure B1a illustrates the dependence of wind direction uncertainty on horizontal wind speed. Figure B1b shows the temperature dependence of the HMP110 response time parameterised using an Arrhenius-type function:

$$\tau(T) = \tau_0 \exp\left(\frac{E_a}{RT}\right)$$
 (B1)

where  $\tau_0$  and  $E_a$  are fitted parameters,  $R$  is the universal gas constant, and  $T$  is the measured temperature in K. Here,  $\tau_0$  is a factor with units of seconds, and  $E_a$  represents an effective activation energy in the assumed Arrhenius-type model. The fitted parameters are  $\tau_0 = 1.832 \times 10^{-10}$  s and  $E_a = 60199$  J mol<sup>-1</sup>

825 Figure B2a illustrates how the CPC time correction improves the alignment of aerosol structures between ascent and descent profiles. After correction, the prominent concentration peak at approximately 770 m a.s.l. is aligned more closely between both profiles. Figure B2b shows enhanced variability during turning manoeuvres, for which aerosol measurements are excluded from the final data set.

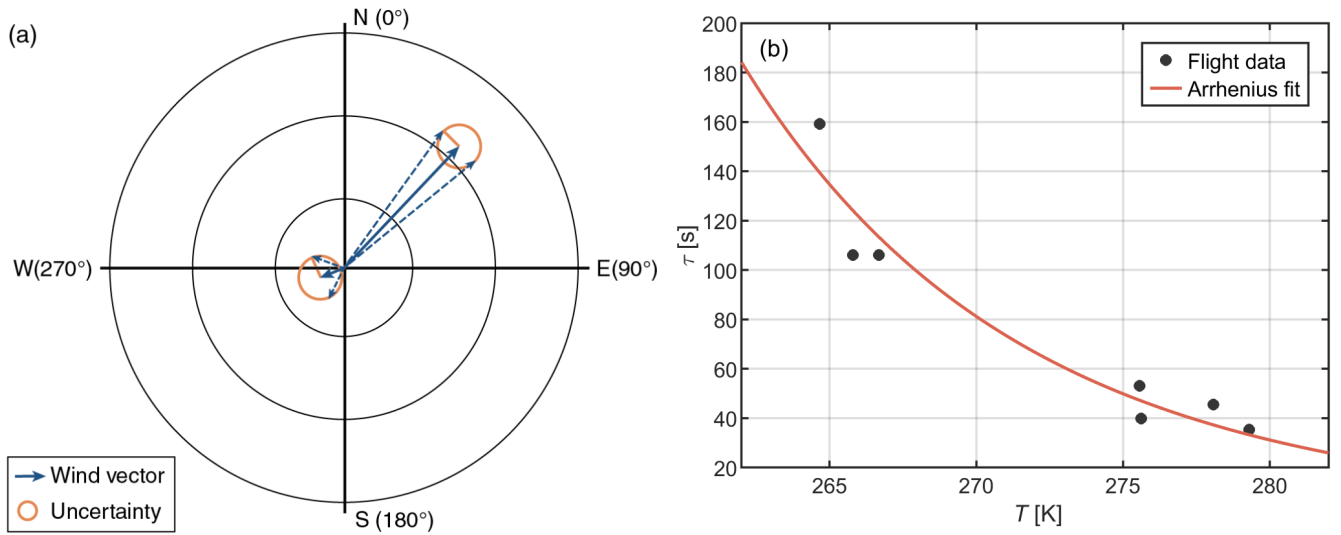


**Figure B1.** (a) Two exemplary horizontal wind vectors showing the dependence of the uncertainty in wind direction  $DD$  on the wind speed  $FF$ . The orange circles indicate the wind vector uncertainty of  $\pm 0.2 \text{ m s}^{-1}$  in any direction. The blue arrows indicate possible horizontal wind vectors within this uncertainty range. (b) Temperature dependence of the HMP110 response time constant  $\tau$ . Black dots show empirically determined HMP110 time constants from seven cold and warm measurement flights, derived from ascent–descent comparisons. The red line shows the fitted Arrhenius function used for the HMP110 humidity reconstruction.

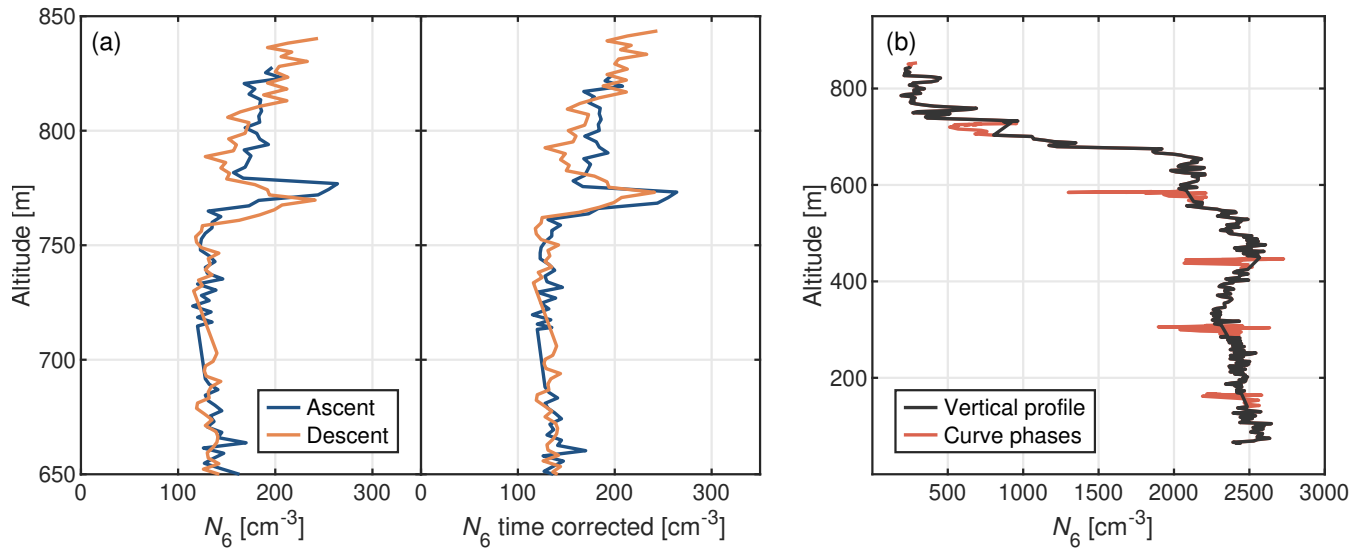


**Figure B2.** (a) Exemplary vertical profile of the particle number concentration  $N_6$  during ascent and descent before (left) and after (right) application of the CPC time correction. (b) Exemplary vertical profile of  $N_6$  with sections measured during turning manoeuvres highlighted in red. These curve phases show enhanced variability and are excluded from the final data set.

Figure C1a shows the relationship between  $N_{11}$  and  $N_{15}$ , measured with the two CPCs during the field campaign. Due to their different cut-off sizes,  $N_{15}$  measurements should not exceed  $N_{11}$ , which is observed to apply for 90.3 % of the measurement data. This provides a consistency check of the two CPC measurements in estimating  $N_{11-15}$  in the ultrafine particle regime. Figure C1b compares the integrated mSEMS  $PNSD$  with the corresponding 2 min mean CPC number concentrations  $N_9$ . The measurements show a strong correlation ( $R^2 = 0.915$ ), with 80 % of the paired measurements agreeing within  $\pm 20$  %.

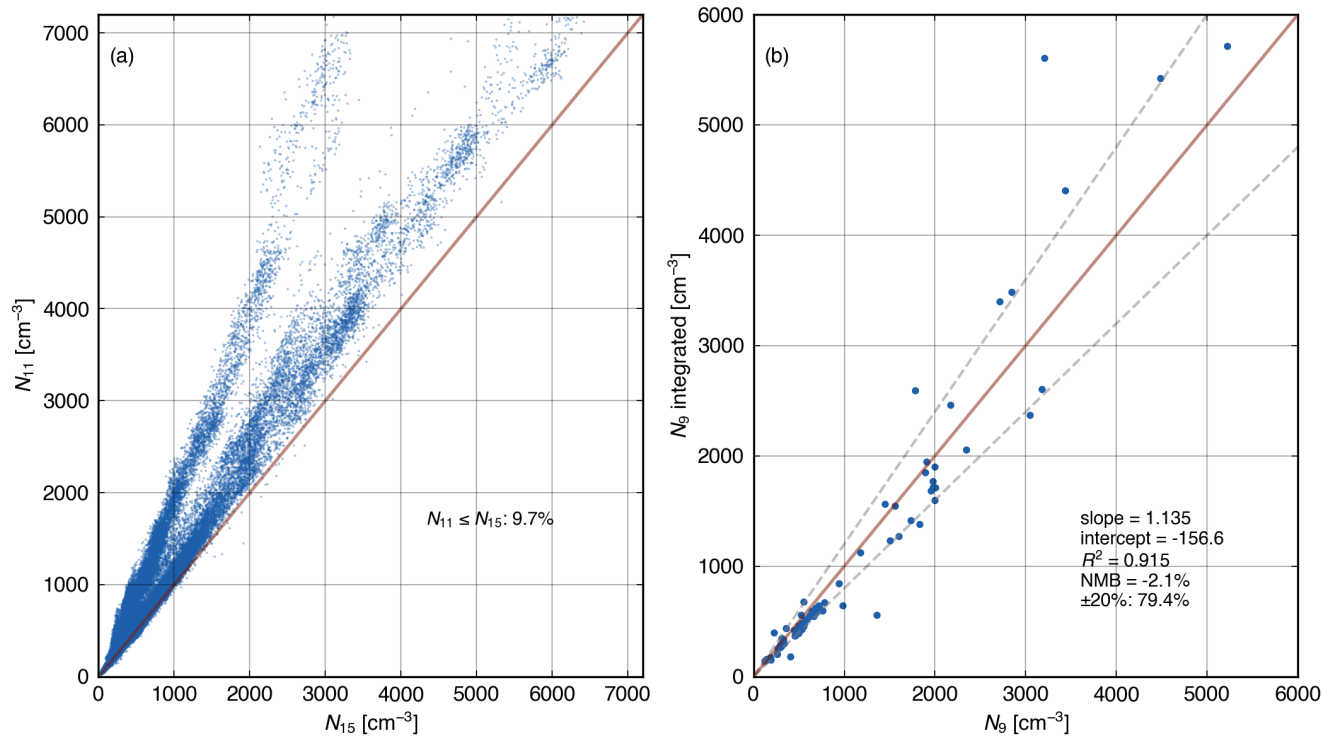


**Figure C1.** (a) All measurement point pairs of  $N_{11}$  and  $N_{15}$  obtained from the CAMP platform during the field campaign, showing the relation between the measurements of both CPCs with different lower cut-off size. (b) Integrated values of mSEMS measurements (9 nm to 350 nm) in comparison with 2 min mean of ( $N_9$ ) used in the mSEMS platform.

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**Appendix D: Additional information on surface flux gradient system data processing**

Figure D1 shows exemplary vertical profiles of particle number concentration  $N$  and wind speed  $FF$ , together with the corresponding linear regression fits against the logarithm of height. These gradients are used to determine the friction velocity and particle number flux following Mathes et al. (2025a). Figure D2 shows a 20 min interval with four profiles of particle concentration and wind speed. In this example, the interval starts at 12:09 UTC on 8 June 2024 and ends at 12:31 UTC on 8

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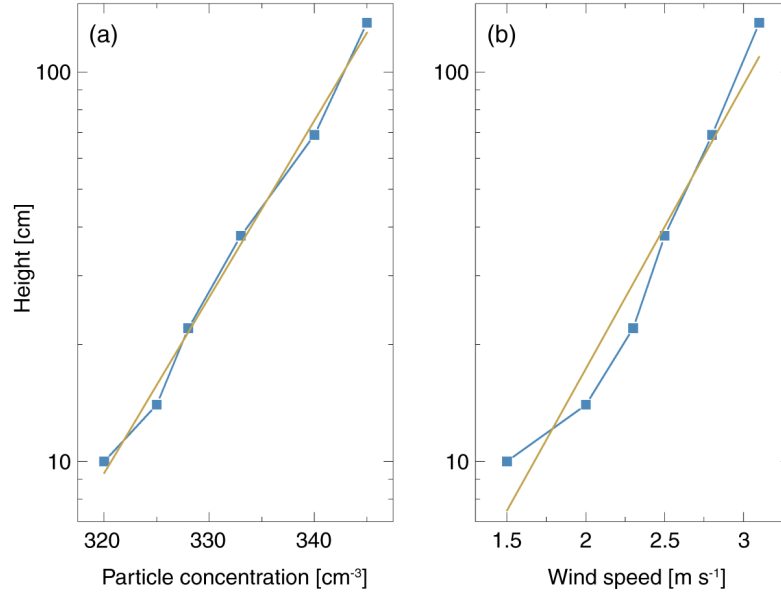


**Figure D1.** Illustrative example of vertical profiles of (a) particle concentration  $N$  [ $\text{cm}^{-3}$ ] and (b) wind speed  $FF$  [ $\text{m s}^{-1}$ ]. The beige line shows the linear regression fit, with  $R^2$  of 0.99 for the particle concentration gradient and  $R^2$  of 0.97 for the wind speed gradient. Adapted from Mathes et al. (2025a).

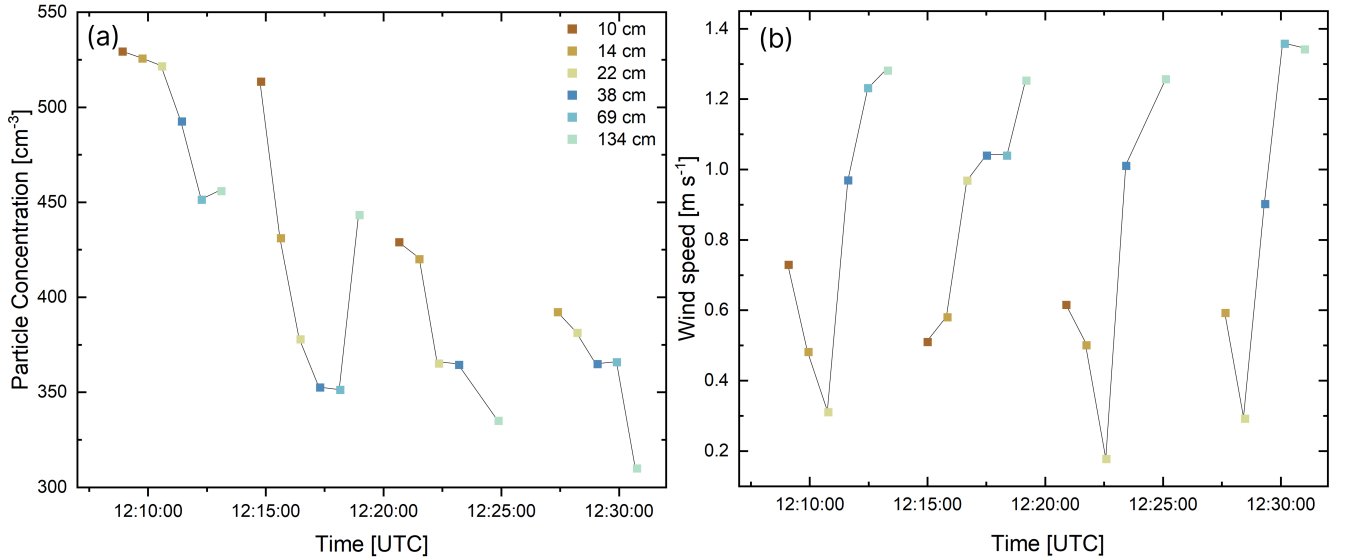


**Figure D2.** Time series of (a) particle concentration  $N$  [ $\text{cm}^{-3}$ ] and (b) wind speed  $FF$  [ $\text{m s}^{-1}$ ] derived from multiple profiles of the gradient system in a 20 min interval on 8 June 2024. The different colours show the height of the measurement.

June 2024 with four to six different height levels per profile. All heights are interpolated for a median timestamp at 12:20 UTC. The calculated  $u_*$  is  $0.14 \text{ m s}^{-1}$ , with a net  $P$  of  $0.98 \cdot 10^6 \text{ m}^{-2} \text{ s}^{-1}$ .

*Author contributions.* The contact author MS wrote the main text and contributed to the figures. MS, KB, LB, TC, MK, TM, JM, CP, AS, BW, BH participated in the field campaign. MS, KB, MK, TM, CP, AH, AS, HS were responsible for data post-processing. BW, AL acquired  
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*Competing interests.* The authors declare that they have no conflict of interest.

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