Review of "*The Arctic Low-Level Mixed-Phase Haze Regime and its Microphysical Differences to Mixed-Phase Clouds*", by Manuel Moser, Christiane Voigt, Oliver Eppers, Johannes Lucke, Elena De La Torre Castro, Johanna Mayer, Regis Dupuy, Guillaume Mioche, Olivier Jourdan, Hans-Christian Clemen, Johannes Schneider, Philipp Joppe, Stephan Mertes, Bruno Wetzel, Stephan Borrmann, Marcus Klingebiel, Mario Mech, Christof Lüpkes, Susanne Crewell, André Ehrlich, Andreas Herber, and Manfred Wendisch, egusphere-2025-3876.

# Response to reviewer 2

Dear reviewer,
We are very grateful for your valuable feedback and suggestions which helped us to improve the manuscript. The manuscript has been thoroughly revised and point-by-point responses have been prepared. Please find below our replies, highlighted in blue, along with changes made in the manuscript, highlighted in orange. The revised manuscript is also provided with tracked-changes for clarity.

Major comments

**1: Clustering and Physical Interpretation**

The authors employ clustering and statistical analysis to interpret the underlying mechanisms of the observed phenomena. However, observational data alone do not directly confirm physical processes (e.g., during HALO-(AC)³, the synoptic situation primarily controls the ABL top temperature, while surface-driven processes determine its vertical extent). The logical connections could be strengthened by incorporating back-trajectory analyses—especially in Section 2.3, and at Lines 183 and 207 in Section 3.1.1.

Reply: We thank the reviewer for this comment. It is not entirely clear whether the reviewer refers to the clustering of meteorological parameters shown in Figure 3, or the clustering of microphysical parameters distinguishing regimes 2a and 2b in Section 3.1.1.
In both cases, backward trajectory analyses were already applied to interpret the differences between the identified clusters.
For the meteorological classification in Figure 3b, the color coding is directly based on 24-h backward trajectories, as described in Line 143: "Backward trajectory analyses were conducted to determine the dominant surface type over which the low-level air masses had resided during the 24 h prior to their in-situ measurement by Polar 6." Hence, each meteorological cluster in Fig. 3b implicitly contains the information on air-mass origin and synoptic conditions.
For the microphysical regimes 2a and 2b, the hypothesis that their differences are primarily driven by surface type and corresponding air-mass history is discussed in detail in Moser et al. (2023b), which also relied on backward trajectories to support this interpretation.
If the reviewer referred to a different aspect of clustering, we would be happy to clarify this further in a revised version of the manuscript.

**2: Clustering Justification and Consistency**

(i): In Table 1, MPH is divided into sub-clusters 2a and 2b, which are later recombined for microphysical comparisons with MPC. The rationale for creating sub-clusters (e.g., 2a vs. 2b, or 1a vs. 1c) is unclear.

Line 136 mentions that Table 1 lists the thresholds defining each regime, but the basis for these choices isn't fully explained.

(ii): Additionally, there's no figure provided to support Lines 288–289.

(iii): It appears that in many sections, sub-clusters are merged (e.g., 2a+2b → 2), raising the question of whether the initial subdivision is necessary. While Lines 200–221 are logically structured, please clarify the importance of including these sub-clusters in the context of the central narrative. Why are these regime details crucial for the main scientific conclusions?

Reply:

We thank the reviewer for raising these constructive questions. They can be divided into three main aspects, addressed below as (i)–(iii).

(i) and (iii)

We appreciate the reviewer's remark that the physical reasoning behind the applied classification was not sufficiently clear in the manuscript. The classification scheme used in this study builds directly on the work of Moser et al., 2023b, where a clustering of all AFLUX and MOSAiC-ACA data revealed seven local maxima in the N-Deff space. These maxima define the regimes 1a, 1b, 2a, 2b, 2c, 3, and 4.

The same cluster structures are reproduced in the HALO-(AC)3 dataset, which allows the regimes in the current study to be assigned consistently to those defined in Moser et al., 2023b. The boundaries were slightly adjusted to match the maxima of the new dataset, but the classification algorithm remains identical.

The naming convention (1a - 4) follows the microphysical regime type: ice (1a, 1b), mixed-phase (2a, 2b, 2c), liquid (3), and aerosol (4). In the present study, which extends the work of Moser et al., 2023b, the mixed-phase regime (2a, 2b, 2c) is reexamined in greater detail. The results show that a further differentiation within this regime is physically meaningful, specifically between mixed-phase haze (2a, 2b) and mixed-phase cloud (2c). A new naming scheme was intentionally avoided to maintain consistency with the previous study.

We acknowledge that the basis for this decision was not explained clearly enough in the original version and have therefore added the following clarification at the end of Section 2.2 (Line 139):

"Please note that the classification into regimes 1a, 1b, 2a, 2b, 2c, 3, and 4 originates from Moser et al. (2023b). The present study builds upon these findings and focuses specifically on the mixed-phase regime. The results suggest that refining this classification would be appropriate, as the mixed-phase regime can be subdivided further based on its distinct microphysical characteristics. However, to ensure consistency with the previous work and to avoid unnecessary complexity, the original nomenclature is retained. Accordingly, regimes 1a and 1b (hereafter referred to as the ice regime) represent ice clouds, regimes 2a and 2b (the MPH regime) represent the mixed-phase haze conditions, regime 2c (the MPC regime) represents classic mixed-phase clouds, regime 3 (the liquid regime) represents liquid clouds, and regime 4 (the aerosol regime) corresponds to aerosol measurements."

(ii):

We believe that the information supporting Lines 288-289 is already clearly presented in the manuscript. The haze droplet sizes (3-6 µm) are shown and discussed in Section 3.1.1. The corresponding dry diameters (1-3 µm) were derived from the hygroscopic growth factor (median = 2.2; 25th/75th percentiles = 2.1/2.6) using the relations 3µm/2.6≈1µm and 6µm/2.1≈3µm.

The statement that the observed droplets exist above the deliquescence point of NaCl is evident in Figure 5b. Therefore, no additional figure is required. To make this more transparent, we replaced the sentence at Line 288 with the following:

"Based on this hygroscopic growth factor and the observed haze droplet sizes ranging from 3 µm to 6µm, the estimated dry diameters of the solute particles are between 1µm and 3µm, calculated from the observed wet diameter range (3–6µm) divided by the 25th and 75th percentile of the hygroscopic growth factor."

**3: Suggestions for Figure 2**

Figure 2 shows large variability, and the gray lines do not provide as much value as intended. I suggest replotting the three profile types in separate panels with a shared axis range, using the color scheme from Figure 3. Each panel can include all dropsondes of that type along with an averaged profile. This restructuring would facilitate cross-comparison with Figure 3, support the discussion on "exceptions and normals" (p. 8), and better illustrate inversion frequency.

Reply: Figure 2 has been revised accordingly. The three profile types are now displayed in separate panels with a consistent axis range, following the color scheme used in Figure 3. This restructuring enables a direct comparison between Fig. 2 and 3 and allows the reader to easily identify the air mass origin and surface type for each individual temperature profile.

Adapted figure caption: Temperature profiles measured by dropsondes from HALO and Polar 5. The data are used for the analysis in Sect. 3.1.2 and Sect. 3.2. The dropsondes are separated by the underlying surface conditions: (a) over sea ice, (b) within the marginal sea ice zone (MIZ), and (c) over the open ocean. The color of each individual dropsonde represents the air mass origin. For each surface condition, an averaged temperature profile is additionally shown. All dropsondes used in this figure are listed in Table A1.

We have added the following in line 167:

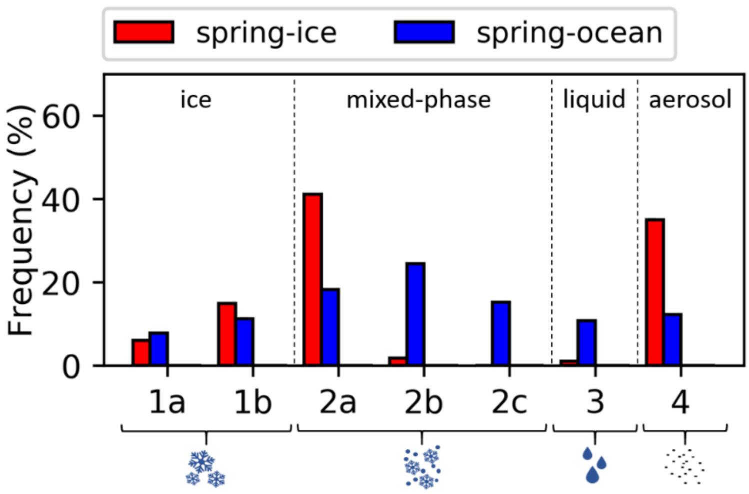
The color of each individual dropsonde indicate the air mass origin. Additionally, the dropsondes were classified based on satellite data to determine whether they were deployed over sea ice (Fig. 2 (a); SIC > 80 %), the open ocean (Fig. 2 (c); SIC < 20 %), or the MIZ (Fig. 2 (b); 20 % ≤ SIC ≤ 80 %).

**4: Further Analysis of Figure 4 by Environment Type**

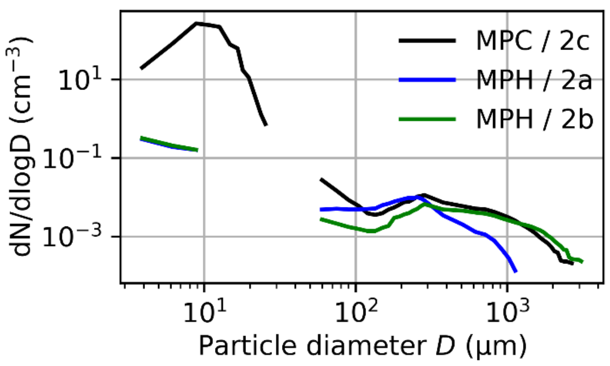
Figure 4 is already informative, but the analysis could be enhanced by breaking it down by environment—such as marginal ice zone (MIZ), open ocean, and sea ice. Including additional subplots by surface type would provide valuable insights for readers and future studies.

Reply: We thank the reviewer for this valuable suggestion to further enhance the information content of Figure 4. However, the intention of this figure is to explicitly highlight the microphysical differences between the mixed-phase haze (MPH; regimes 2a+2b) and the mixed-phase cloud (MPC; regime 2c), emphasizing the necessity of distinguishing these two regimes.
A subdivision by surface type (sea ice, MIZ, open ocean) would go beyond the scope and purpose of this particular figure and cannot be meaningfully implemented with the available dataset. In contrast to AFLUX (see Moser et al., 2023b), only very few MPCs were observed over sea ice during the HALO-(AC)[3] campaign (see R_Fig. 1). Therefore, a statistically robust comparison of PSDs by surface type is not feasible.

Nevertheless, R_Fig. 2 illustrates the particle size distributions of regimes 2a, 2b, and 2c. The largest differences between regimes 2a and 2b occur in the ice-crystal size range. Since regime 2a is more frequently observed over sea ice and regime 2b over open ocean, these differences can be attributed to surface influence, consistent with the findings of Moser et al. (2023b). Moreover, detailed PSDs of these regimes are already published in Fig. 7 in Moser et al. (2023b).
For clarity and focus, Fig. 4 in the current manuscript is therefore kept in its present form, as it aims to illustrate specifically the microphysical distinction between MPH and MPC.




R_Figure 1: Frequency of occurrence for each particle regime (1a, 1b: Ice particles; 2a, 2b, 2c: Mixed-phase particles; 3: Liquid particles; 4: Aerosol particles), separated by surface conditions for the HALO-(AC)[3] low-level cloud data (< 1000 m). The values are normalized by the respective surface condition. This figure is taken from the PhD thesis Moser (2024) (Fig. 55 in http://doi.org/10.25358/openscience-11192).




R_Figure 2: Particle size distribution of classic mixed-phase cloud (2c) and the mixed-phase haze sub-regimes 2a and 2b. The PSD lines give the median value, calculated the same way as stated in the manuscript.

**5: Clarity in Figure 5**

Figure 5 is the most difficult to interpret due to the complexity of the color-coded “step” histograms. Would it be possible to separate Ice and MPH into an additional column or panel to reduce visual clutter?

Reply: We agree that Fig. 5 is an important but visually complex plot, and that a separation of the regimes substantially improves its readability. Therefore, we have added a second column with three additional panels in which the mixed-phase haze (MPH) and mixed-phase cloud (MPC) regimes are displayed side by side (panels d–f). Panels (a–c) now show the ice, aerosol, and liquid regimes. This new layout allows for a direct comparison between MPH and MPC while maintaining the possibility to contrast them with the other cloud regimes.

Changes is the manuscript (Line 249):

The meteorological parameters T , RHw, and RHice measured within the different cloud regimes are shown in Fig. 5. The regimes ice, liquid, and aerosol are presented in panels (a–c), while the corresponding distributions for the MPH and MPC regimes are shown in panels (d–f).

Revised figure caption (Fig. 5):

Normalized frequency distribution of the different cloud regimes as a function of environmental conditions such as temperature (a, d), relative humidity over water (b, e) and relative humidity over ice (c, f).

**6: Clarify Novelty and Contribution in Introduction**

Please clearly state the novelty of this study in the Introduction, ideally around Line 50. For example: "In this study, we conduct a detailed investigation of a previously unclassified cloud regime, which we refer to as the mixed-phase haze (MPH)." Is this the first study to define MPH as a unique regime? Does the novelty stem from high-resolution in-situ observations? How does this work advance beyond previous research? These elements are hinted at throughout the Introduction, but an explicit statement would help readers better understand the contribution.

Reply:
We have adopted this suggestion. We have replaced the sentence in line 50 with the following:
“In this study, thin cloud layers are explicitly included in the analysis. Their occurrence frequency is found to be remarkably high, which motivates the definition of a new cloud regime. Based on microphysical properties measured with high resolution in-situ cloud instruments, this regime is referred to as mixed-phase haze. It is characterized by relatively low particle number concentrations compared to classic mixed-phase clouds. The detailed investigation and characterization of this mixed-phase haze regime form the main focus and novelty of this study.”

**7: Line 340–341: Secondary Ice Production?**
The statement that NINP is lower than the haze droplet number (Line 340) might also suggest the influence of secondary ice production. If so, the "Therefore" at Line 341 feels misleading. Please clarify the logical flow here.

Reply:
We greatly appreciate the reviewer’s thoughtful consideration that remnants of secondary ice production (SIP) could contribute to the haze particles number concentration observed in the MPH regime. Based on our data, we cannot entirely rule out this possibility, and it is conceivable that a small fraction of particles within the MPH may originate from SIP. However, this fraction is likely minor, since particles generated by SIP are typically expected to exhibit irregular or non-spherical shapes. In contrast, the optical properties measured by the Polar Nephelometer show angular scattering patterns consistent with predominantly spherical particles. We therefore conclude that while a minor contribution of SIP-origin ice particles to the haze number concentration cannot be excluded, the population is clearly dominated by liquid or near-spherical particles.

To acknowledge the possibility of SIP and to phrase our conclusion more cautiously, we have revised Line 341 in the manuscript as follows:
“We therefore consider it most likely that the contribution of ice particles to the haze droplet number concentration is negligible.”

Minor comments

- Line 6: "The particle number concentration" — specify what kind of particles (e.g., hydrometeors?).
  We have changed to (line 6)“number concentration of cloud particles”

- Line 17–24: Consider shortening this part of the Introduction. The discussion begins focusing on clouds at Line 25, so the earlier text may be unnecessarily long.

  We thank the reviewer for this suggestion and understand the concern. However, we decided to keep this introductory part unchanged. The in-situ dataset used in this study was collected within the framework of the $(AC)^3$ project (ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms; https://ac3-tr.de/ ), and this introductory section serves to provide the scientific context of the study within the overall project objectives. Therefore, we consider this background information essential for the motivation of our work.

- Line 49: Add citation for the Wegener–Bergeron–Findeisen (WBF) process.
  The original works by Wegener (1912), Bergeron (1935), and Findeisen (1938) describe a physical mechanism of precipitation formation. In cloud physics, however, the term WBF-process is commonly used in a more specific sense to denote the rapid growth of ice crystals at the expense of surrounding supercooled droplets due to differences in saturation vapor pressure over ice and water. To provide concise and accessible references for this commonly used concept, we added the following citations in the revised manuscript:
  "They have hypothesised that these clouds may have been formed by the drying of mixed-phase clouds via the Wegener-Bergeron-Findeisen process (Pruppacher and Klett, 2010; Storelvmo and Tan, 2015)."

- Line 63: "Three research aircrafts" → should be "three research aircraft".
  The word aircraft is already in its correct plural form, so no modification was needed.

- Abstract: Consider combining the two paragraphs into one for better flow.
  This change has been adopted in the revised version.

- Lines 90–100: The description of instruments could benefit from a summary chart. This could include size ranges, acronyms, uncertainties, transmission efficiency, and lower/upper limits.
  In this study, we intentionally kept the instrument description concise, as the same measurement systems and processing methods were already described in detail in Moser et al. (2023b) and Mech et al. (2022). Additional information specific to the HALO-$(AC)^3$ campaign is provided in Ehrlich et al. (2025), to which we refer throughout the manuscript.

- Indentation inconsistencies: e.g., Lines 280–281. Please ensure consistent formatting throughout the manuscript.
  We thank the reviewer for this remark. The formatting issue resulted from different methods used for line breaks in LaTeX. This has now been unified to ensure consistency throughout the manuscript.

References: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*Moser, M.: Microphysical properties and thermodynamic phase of Arctic low-level clouds from in-situ aircraft measurements, PhD thesis, Johannes Gutenberg University Mainz, Mainz, Germany, https://doi.org/10.25358/openscience-11192, 2024*

*Wegener, A. (1912). "Thermodynamik der Atmosphäre". In: Nature 90.2237, pp. 31–31. DOI:10.1038/090031a0*

*Bergeron, T. (1935). "On the physics of clouds and precipitation." In: International Union of Geodesy and Geophysics.*

*Findeisen, F. (1938). "Kolloid-meteorologische Vorgänge bei Niederschlagsbildung". In: Meteor.*

*Pruppacher, H. and Klett, J.: Microphysics of Clouds and Precipitation, Atmospheric and Oceanographic Sciences Library, Springer Netherlands, ISBN 9780306481000, https://doi.org/10.1007/978-0-306-48100-0, 2010.*

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