We would like to express our sincere gratitude to the editor and the reviewer for their careful evaluation of our revised manuscript and for the valuable comments and suggestions, which have further contributed to improving the clarity and scientific rigor of our work. Below, we provide a detailed, point-by-point response to each of the reviewer's comments. The reviewer's comments are presented in blue text, our responses are written in black text, and quotations from the revised manuscript are presented in italic type.

Referee #1

All line numbers refer to the tracked-changes manuscript!

Thank you very much for putting the efforts in the revision, thereby widely acknowledging the review suggestion. I see little need for a second round of revision, except for one major point. This is, that the result of the comparisons between the different model runs changed partly considerable. E.g., in Sections 3.2.2 (lines 765-776) or 3.2.4. I'm also puzzled by the values given in the conclusions section (lines 996-997), because neither the change of IWP from 29.1 to 41.1% nor the change of LWP from 9.5 to 8.6% seem to affect the radiative effects that are reported just 2 lines below. Is this really valid or were the radiative simulations not updated appropriately?

Response: We thank the reviewer for raising this important concern. We apologize that the reason for the changes in the reported cloud-related variables was not sufficiently explained in our previous response.

The changes in ice water path (IWP), liquid water path (LWP), and the other cloud-related variables do not result from modifications to the model simulations or the radiation calculations. Instead, they result from the revised statistical post-processing introduced in response to the first-round comment concerning the treatment of non-cloud grid cells.

For cloud-related variables, such as ice crystal number concentration, cloud droplet number concentration, ice crystal effective radius, cloud droplet effective radius, ice and liquid water content, IWP, and LWP, grid cells without clouds should be excluded because the corresponding cloud microphysical properties are either zero or physically undefined in these grid cells. Including a large number of non-cloud grid cells would dilute the cloud-property averages and make them strongly dependent on the regional cloud fraction rather than on the microphysical properties of the clouds themselves. Therefore, in the revised analysis, cloud-related variables were calculated only for cloud grid cells, defined as grid cells in which the sum of the ice and liquid water mixing ratios exceeds 10^{-6} kg kg^{-1}, following Hines et al. (2019). The application of this criterion changed the grid cells included in the calculation and consequently changed some of the reported differences among the simulations, including the IWP and LWP changes discussed by the reviewer.

In contrast, no cloud-grid threshold was applied to the radiative variables because the reported radiative effects were intended to represent the overall radiative effects of dust INPs on the regional top-of-atmosphere energy balance. These effects were therefore calculated as all-sky, domain-mean differences in radiative fluxes over the entire simulation domain. Radiative fluxes are defined over both cloudy and cloud-free grid cells, and a grid cell may be cloudy in one simulation scenario but cloud-free in another. Restricting each simulation scenario to its own cloudy grid cells would therefore result in comparisons between different spatial samples and would exclude radiative changes associated with the formation, dissipation, or displacement of clouds. All grid cells were consequently retained to ensure that the same spatial domain was compared among the simulations and that both changes in cloud properties and changes in cloud occurrence were included, thereby providing a complete representation of the overall radiative effects of dust INPs.

Therefore, the revised cloud-grid filtering affected the reported cloud-property statistics but did not affect the radiative effects, which were calculated independently over all model grid cells to represent the overall radiative effects of dust INPs. The radiative outputs and their post-processing were treated appropriately, and no recalculation of the radiative effects was required because the revision concerned only the statistical selection of grid cells for cloud-related variables. We have carefully rechecked the corresponding model outputs and post-processing procedures and confirmed that this treatment is consistent.

To clarify the different statistical treatments of cloud-related and radiative variables, we have revised Sect. 2.6, *Statistical methods*. The revised text in the revised manuscript (471–506) is shown below:

"To ensure a physically meaningful analysis of cloud-related variables, we applied a threshold to select grid cells within clouds. Specifically, a grid cell was considered to be inside a cloud if the sum of the ice water mixing ratio and liquid water mixing ratio exceeded 10^{-6} kg kg^{-1}, as suggested by Hines et al. (2019). For cloud-related variables, including ice crystal number concentration, ice crystal effective radius, ice water content, cloud droplet number concentration, cloud droplet effective radius, liquid water content, IWP, and LWP, only cloud grid cells were included in the statistical analysis. This criterion excludes non-cloud grid cells in which cloud microphysical variables are zero or, for some variables, not physically meaningful, and prevents the calculated cloud-property averages from being diluted by cloud-free conditions."

"For PM_{10} concentration, dust number concentration, dust INP concentration, and radiative variables, no threshold was applied because these variables are relevant across all grid cells. In particular, the shortwave, longwave, and net radiative effects were calculated as all-sky, domain-mean differences in top-of-atmosphere radiative fluxes over the entire simulation domain to represent the overall radiative effects of dust INPs on the regional energy balance. Radiative fluxes are defined over both cloudy and cloud-free grid cells, and a grid cell may be cloudy in one simulation scenario but cloud-free in another. Applying the cloud threshold separately to each

simulation scenario would therefore result in comparisons between different spatial samples and would exclude radiative changes associated with the formation, dissipation, or displacement of clouds. All grid cells were consequently retained to ensure that the same spatial domain was compared among the simulations and that both changes in cloud properties and changes in cloud occurrence were included in the overall radiative effects of dust INPs."

"We compared the mean values of cloud-related variables with and without threshold filtering applied to cloud grids. This comparison, presented in Tables S3 and S4, showed that filtering the data generally resulted in higher average values for cloud-related variables because non-cloud grid cells were excluded. However, the responses of cloud properties to dust INPs were generally consistent with and without threshold filtering, confirming that the central conclusions regarding dust-cloud interactions were not substantially affected by the threshold."

"We focused on analyzing mean values in this study because they provide a comprehensive overview of model performance and aerosol-cloud interactions. Median values were not analyzed because they may not adequately represent domain-integrated responses in large-scale simulations, particularly for variables with many zero values or strong spatial heterogeneity."

We thank the reviewer again for identifying this ambiguity. The revised *Statistical methods* section now clearly explains why the reported cloud-related variables changed following the updated statistical treatment, whereas the all-sky regional radiative effects remained unchanged.

minor comments:

1) lines 75-78: Recently more insights into the role of smoke on cirrus formation were published. E.g., https://doi.org/10.5194/acp-25-4847-2025 or https://doi.org/10.5194/acp-25-4867-2025

Response: We thank the reviewer for bringing these recent studies to our attention. We agree that the coordinated observational and modeling studies of Ansmann et al. (2025a, b) provide important new insights into the potential role of aged wildfire smoke in cirrus formation.

Following the reviewer's suggestion, we have added these studies to the Introduction to strengthen the discussion of observational and process-level evidence for the influence of smoke particles on cirrus formation.

The following sentence has been added to the revised manuscript (Lines 97–100):

"Recent coordinated lidar-radar observations and process simulations during the MOSAiC expedition further suggest that aged Siberian wildfire smoke substantially influenced Arctic cirrus formation and may have suppressed homogeneous freezing under smoke-polluted upper-tropospheric conditions (Ansmann et al., 2025a, b)."

2) line 352: Which values can K take? It is a generally fixed value or is it a simulated variable?

Response: We thank the reviewer for requesting this clarification. K is not a fixed or prescribed constant. It is the vertical turbulent eddy diffusivity calculated online by the planetary boundary layer scheme and varies spatially and temporally according to the simulated turbulence and atmospheric stability.

We have revised the description following Eq. (11) to clarify the meaning and variability of K. The revised text in the revised manuscript (Lines 342–346) is shown below:

"where K (in m^2 s^{-1}) is the vertical turbulent eddy diffusivity calculated online by the planetary boundary layer scheme, and Δz *is the model layer thickness. Thus, K is not a fixed constant but varies spatially and temporally according to the simulated turbulence and atmospheric stability. Here,* w' *represents the magnitude of turbulence-induced vertical velocity fluctuations."*

3) line 1018: "...particles, biomass-burning..." --> "particles or biomass-burning"

Response: We thank the reviewer for pointing out this unclear wording. We have revised the sentence by replacing the comma with "or" as suggested.

The revised text in the revised manuscript (Lines 1021–1024) is shown below:

"Nevertheless, other aerosol types such as biological particles or biomass-burning smoke may also contribute to ice nucleation under different environmental conditions or during other seasons."

4) Discussion of Fig. 10: Just would like to refer to the study of Omanovic et al., 2024, who found indications that ICON even underestimates the role of the WBF process in presence of high ice crystal concentrations. I cannot estimate to which extent this applies to the study discussed in here, but maybe it's worth mentioning.

Response: We thank the reviewer for suggesting this relevant study. We agree that the findings of Omanovic et al. (2024) provide an important perspective on uncertainties in the representation of the WBF process in numerical models.

Using ICON in large-eddy mode and in situ measurements from the CLOUDLAB project, Omanovic et al. (2024) found that the model reproduced the observed reduction in cloud droplet number concentration only when ice crystal number concentrations were substantially overestimated. Their results therefore indicate that the WBF process, or the diffusional growth of ice crystals associated with it, may be too slow or inefficient in ICON.

We agree that this result cannot be transferred quantitatively to the present WRF-Chem simulations because the models differ in their spatial resolution, microphysics schemes, turbulence treatments, and experimental configurations. Nevertheless, it highlights an important structural uncertainty in the modeled strength of liquid-to-ice conversion.

Our process-rate diagnostics in Fig. S19 demonstrate that cloud droplet evaporation and vapor deposition increase under WBF-favorable conditions, supporting the occurrence and relative enhancement of the WBF process in our simulations. However, these diagnostics do not constitute a direct observational evaluation of the absolute efficiency of the WBF process. We have therefore added a discussion to Sect. 3.2.6 (*Microphysical process analysis*) acknowledging that the quantitative magnitude of the simulated WBF response remains uncertain and requires further observational constraints.

The added text in the revised manuscript (Lines 951–953) is shown below:

"Nevertheless, the quantitative strength of the simulated WBF process remains subject to uncertainties in cloud microphysics parameterizations (Omanovic et al., 2024). These process-rate diagnostics support the occurrence and relative strengthening of the WBF process among the simulations, but observational constraints are still required to evaluate the absolute magnitude of this response."

Reference

Ansmann, A., Jimenez, C., Roschke, J., Bühl, J., Ohneiser, K., Engelmann, R., Radenz, M., Griesche, H., Hofer, J., Althausen, D., Knopf, D. A., Dahlke, S., Gaudek, T., Seifert, P., and Wandinger, U.: Impact of wildfire smoke on arctic cirrus formation – part 1: analysis of MOSAiC 2019–2020 observations, Atmos. Chem. Phys., 25, 4847–4866, https://doi.org/10.5194/acp-25-4847-2025, 2025a.

Ansmann, A., Jimenez, C., Knopf, D. A., Roschke, J., Bühl, J., Ohneiser, K., and Engelmann, R.: Impact of wildfire smoke on arctic cirrus formation – part 2: simulation of MOSAiC 2019–2020 cases, Atmos. Chem. Phys., 25, 4867–4884, https://doi.org/10.5194/acp-25-4867-2025, 2025b.

Hines, K. M., Bromwich, D. H., Wang, S.-H., Silber, I., Verlinde, J., and Lubin, D.: Microphysics of summer clouds in central west Antarctica simulated by the polar weather research and forecasting model (WRF) and the antarctic mesoscale prediction system (AMPS), Atmos. Chem. Phys., 19, 12431–12454, https://doi.org/10.5194/acp-19-12431-2019, 2019.

Omanovic, N., Ferrachat, S., Fuchs, C., Henneberger, J., Miller, A. J., Ohneiser, K., Ramelli, F., Seifert, P., Spirig, R., Zhang, H., and Lohmann, U.: Evaluating the wegener–bergeron–findeisen process in ICON in large-eddy mode with in situ observations from the CLOUDLAB project, Atmos. Chem. Phys., 24, 6825–6844, https://doi.org/10.5194/acp-24-6825-2024, 2024.

Additional Manuscript Revisions

In addition to the revisions made in response to the editor and reviewer comments, we carefully checked the manuscript for author information, affiliations, terminology, cross-references, numerical values, figure consistency, and reference formatting. The additional corrections and updates are listed below. All line numbers refer to the manuscript with tracked changes. The original manuscript text is presented in red, and the revised text is presented in blue.

1. **Lines 28–30:** The affiliation of co-author Jonathan H. Jiang was updated from "Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91125, USA" to "Joint Institute for Regional Earth System Science & Engineering, University of California, Los Angeles, Los Angeles, California, 90095, USA." **Reason:** This change reflects his change of position during the review period.

2. **Lines 136–138:** "Event-based simulations also show similar behavior." was revised to "However, event-based simulations have reported different microphysical responses." **Reason:** The original wording was inconsistent with the following description. The preceding studies reported a negative Twomey effect, with fewer and larger ice crystals, whereas the cited event-based simulations reported a Twomey-like response, with more and smaller ice crystals.

3. **Line 220:** "Sect. 2.3.1" was corrected to "Sect. 2.2.1", and "Sect. 2.3.2" was corrected to "Sect. 2.2.2". **Reason:** The mixed-phase-cloud and ice-cloud INP parameterizations are described in Sects. 2.2.1 and 2.2.2, respectively.

4. **Lines 568–569:** "between −6°C and −12°C and near −18°C" was revised to "between −12 °Cand −18°C", and "in the −12°C to −18°C range" was revised to "above −12°C and below −18°C". **Reason:** The revised temperature ranges are consistent with the results shown in Fig. 2a.

5. **Line 584:** "overestimation" was corrected to "underestimation". **Reason:** The corrected wording is consistent with the results shown in Fig. 2a.

6. **Line 599:** "3.2" was corrected to "5.6". **Reason:** According to Fig. S4, dust particles with diameters of 0.18–5.6 μm contribute more than 95% of the total dust surface area.

7. **Lines 789–791:** "20.4%", "3.2%", and "9.3%" were corrected to "19.1%", "3.1%", and "8.6%", respectively. **Reason:** The previous values were inadvertently taken from the filtered "(MixIceINPs − NoINPs) / NoINPs" row of Table S4. The text describes the IceINPs scenario and should therefore use the filtered "(IceINPs − NoINPs) / NoINPs" row.

8. **Line 863:** "3.2" was corrected to "2.3". **Reason:** This value represents the ratio of the dust INP concentration simulated with DeMott2015 to that simulated with Chen2021. The meridionally averaged vertical-cross-section mean for Chen2021 is 1.8×10^{-3} L^{-1} (Fig. 3j), and the DeMott2015–Chen2021 difference is 2.3×10^{-3} L^{-1} (Fig. 8a), giving $(1.8 + 2.3) / 1.8 \approx 2.3$.

9. **Lines 911 and 944:** The headings "3.2.5 Sensitivity to subgrid vertical velocity parameterization" and "3.2.6 Microphysical process analysis" were changed to bold. **Reason:** This change makes their formatting consistent with the other subsection headings.

10. **Line 950:** "sublimation" was corrected to "deposition". **Reason:** The two subprocesses associated with the WBF process discussed here are cloud droplet evaporation and vapor deposition, not sublimation.

11. **Line 992:** "3.2" was corrected to "5.6". **Reason:** This correction is consistent with the particle-size range described in Item 6 and Fig. S4.

12. **Lines 1047–1052:** The unpublished Zenodo preview link was replaced with the published DOI citation "https://doi.org/10.5281/zenodo.19113407 (Zhang et al., 2026)". **Reason:** The repository has now been published, so the persistent DOI should be cited instead of the temporary preview link.

13. **Line 1064:** "PM" was corrected to "MP". **Reason:** The initials refer to co-author Muyan Peng.

14. **Lines 1115 and 1221:** The journal names "Reviews of Geophysics" and "JGR Atmospheres" were revised to "Rev. Geophys." and "J. Geophys. Res.: Atmos.", respectively. **Reason:** The journal abbreviations were corrected to comply with the ACP reference-formatting requirements. The previous forms resulted from reference-management software.

15. **Lines 1120–1123:** The capitalization of the reference title was corrected to match the source and the formatting of the other references. The reference entry for the report was also reformatted according to the ACP requirements for reports. **Reason:** The previous formatting resulted from reference-management software.

16. **Lines 1157–1158, 1178–1179, 1182–1184, 1255, 1263, 1329, 1339–1340, 1356, and 1406:** The initial letters of proper nouns in reference titles were capitalized. **Reason:** These capitalization errors resulted from reference-management software.

17. **Lines 1186 and 1395–1397:** The capitalization of the reference titles was corrected to match the source and the formatting of the other references. **Reason:** The previous formatting resulted from reference-management software.

18. **Lines 1248–1249 and 1325:** The journal abbreviation "J. Geophys. Res." was corrected to "J. Geophys. Res.: Atmos.". **Reason:** Both articles were published in Journal of Geophysical Research: Atmospheres. The previous abbreviation resulted from reference-management software.

No other changes were made beyond those listed above and the revisions made in direct response to the editor and reviewer comments.