

## Referee #1

This review concerns the ACP manuscript of Hua Zhang et al. entitled “Contrasting Impacts of Dust Ice-Nucleating Particles on the Evolution and Radiative Effects of Mixed-Phase and Ice Clouds”.

The authors use a customized version of WRF-Chem to investigate the impact of variable INP setups on the cloud evolution and radiation budget over China and associated regions of Asia. The conclusions which the authors draw from their study are generally sound and of certain relevance to the community. Nevertheless, one has to consider that the study is kind of a synthesis report which deploys a range of existing methods and techniques to investigate the subject of dust impacts on the evolution of the tropospheric ice phase and the radiation budget. This was, however, done before by others, which is also acknowledged by the authors in the manuscript.

Given that the study is not a big leap forward for fundamental research (while it is certainly of some interest and impact for the community), there is no new technique that would require careful evaluation. After having read the study in the framework of this review I thus only identified mostly minor issues. The identification of these minor issues was happily possible rather easy as the quality of the English text is already in the current state pretty advanced.

Find below the listing of the comments. Only general minor (or rather semi-major) comments are listed here. I’m strongly in favor for a second round of reviews, as the implementation of some of my comments might have some impact on the study.

**Response:** We thank the reviewer for the careful and constructive evaluation of our manuscript, as well as for recognizing its clarity and overall quality. We appreciate the reviewer’s assessment that the study is relevant to the community and that the identified issues are mostly minor.

We acknowledge the reviewer’s concern that the study builds on existing methods and does not introduce a fundamentally new technique. We would like to clarify that the primary contribution of this work lies not in methodological novelty, but in providing a more comprehensive and process-based assessment of dust INP effects across both mixed-phase and ice clouds within a unified modeling framework. Previous studies have typically focused on either mixed-phase or ice clouds separately, or have treated their impacts independently. In contrast, our study explicitly represents dust INPs in both cloud regimes simultaneously and demonstrates that their effects cannot be understood as a simple sum of the two, due to interactions between cloud phases and microphysical processes.

Specifically, by implementing improved INP parameterizations (including both non-size-resolved and size-resolved schemes) and evaluating them against observations, we provide a more complete representation of atmospheric dust INPs. This enables us to quantify the contrasting yet coupled impacts of dust INPs on cloud microphysics and radiation. Our results show that dust INPs enhance ice formation in both cloud types but through different pathways, leading to distinct radiative effects. These

findings highlight the importance of jointly considering mixed-phase and ice cloud responses when assessing dust–cloud–radiation interactions.

In addition, following the reviewer’s suggestions, we have strengthened the manuscript by clarifying the statistical methodology, expanding the discussion of other INP types, incorporating additional observational constraints, and improving figure readability. We have also revised the title to better reflect the modeling nature of the study.

We appreciate the reviewer’s recommendation for a second round of review and believe that the revisions have improved the clarity, robustness, and scientific contribution of the manuscript.

The reviewer’s comments are presented in blue text, our responses are written in black text, and quotations from our manuscript are presented in italic type.

#### General comments:

**Title:** The title is misleading. I was only triggered to accept the review because I was hoping for an observational study. I kindly ask the authors to modify the title of the study in such a way that it is clear to everybody that simulations are used. Suggestion: Simulations of the impacts of contrasts in dust ice-nucleating particles on the evolution and radiative effects of mixed-phase and ice clouds.

**Response:** We thank the reviewer for this helpful suggestion. We agree that the original title did not clearly indicate that the study is based on numerical simulations, which could potentially lead to confusion for readers expecting an observational study. Following the reviewer’s recommendation, we have revised the title to explicitly highlight the modeling approach used in this work.

The title has been changed to: “*Simulation of Contrasting Impacts of Dust Ice-Nucleating Particles on the Evolution and Radiative Effects of Mixed-Phase and Ice Clouds.*”

This revised title clearly communicates that the study is based on simulations while also emphasizing the contrasting impacts of dust ice-nucleating particles investigated in our work.

**Fundamentals of the statistical analysis:** The authors provide a lot of statistical analyses, including many mean values. But the theory behind the acquisition of these statistics is not outlined in the manuscript. The output of any model, especially with respect to aerosol and cloud microphysics yields usually output values in every grid box. The evaluation of statistics thus requires a custom decision of the authors about the applied thresholds, below which values are neglected and set to zero. Thus, which thresholds did the authors apply to define the ‘background’ or zero values? This of course addresses all parameters the authors analysed statistically.

I kindly ask the authors to elaborate a bit how the selected minimum realistic data values affected the derived statistics. How do mean and median values behave and which conclusions can be drawn from this comparison?

If there was no threshold applied to filter out the background/simulation noise, the authors must explain/describe what the impact of the background/simulation noise is on the mean/median values.

I see need that the authors add a new section to the manuscript where they describe the statistical approach and where they discuss the decisions for the thresholds and how the impact mean/median values. Perhaps that can be done by means of a table and a new section 2.5: Statistical methods.

**Response:** We thank the reviewer for their thoughtful comments regarding the statistical analysis and the application of thresholds in our study. In response, we have added a new section to the manuscript (Section 2.6: Statistical methods) to describe our statistical approach and the reason behind the thresholds used for various variables.

For most of the variables analyzed in the study, including PM<sub>10</sub> concentration, dust number concentration, dust INP concentration, and radiative variables, we did not apply any thresholds. These variables are relevant across all grid cells, and background noise is not a significant concern for their evaluation. In particular, we did not filter these variables because they provide important model output values that contribute to the overall assessment of aerosol-cloud interactions and radiation effects, which are critical for understanding large-scale processes.

However, for cloud-related variables (e.g., ice crystal number concentration, ice crystal effective radius, ice water content, cloud droplet number concentration, cloud droplet effective radius, and liquid water content), we did apply a threshold to filter out non-cloud grid cells. The criterion used for defining “cloud” grids was based on the sum of the ice water mixing ratio and liquid water mixing ratio exceeding  $10^{-6}$  kg kg<sup>-1</sup>, as suggested by (Hines et al., 2019). This threshold ensures that only grids with significant cloud water content are considered, which is essential for accurately analyzing aerosol-cloud interactions. We have clarified this methodology in the revised manuscript.

We also compared the mean values of cloud-related variables with and without the threshold applied (Table S3 and Table S4). Specifically, Table S3 (shown below) corresponds to the mean values shown in Fig. 5, while Table S4 (shown below) corresponds to the mean values in Fig. 6. This comparison showed that, while the average values increased when filtering for cloud grids, the core relationships between dust INP concentrations and cloud responses remained almost identical. This indicates that the dust-cloud interactions, which are central to our study, were not significantly affected by the thresholding approach. The filtering simply helped focus the analysis on the grid cells where dust impacts on cloud properties are most relevant, without substantially altering the conclusions about the effects of dust INPs on cloud

microphysics. We have updated Fig. 5 and 6 to show the results with threshold filtering applied to cloud grids, which we believe offers a more accurate representation of the data.

Regarding the use of median values, we primarily focused on mean values in our analysis, as they provide a comprehensive overview of model performance and dust-cloud interactions over the entire study region. Median values, while useful in some contexts, do not always represent the overall distribution of values effectively, especially in large-scale simulations where mean values are more representative of regional-scale processes. Therefore, we did not conduct median value analyses in this study.

We hope these changes provide the necessary clarifications and that the new section addressing the statistical methods and thresholds enhances the transparency of our approach.

**Table S3.** Mean values of cloud-related variables with and without threshold filtering applied to cloud grids, based on the meridional mean vertical cross-sections shown in Fig. 5. The filtering criterion is that the sum of the ice water mixing ratio and liquid water mixing ratio exceeds  $10^{-6}$  kg kg<sup>-1</sup>. The abbreviations used are as follows: ICNC (ice crystal number concentration; L<sup>-1</sup>), ICER (ice crystal effective radius;  $\mu$ m), IWC (ice water content; mg m<sup>-3</sup>), CDNC (cloud droplet number concentration; 10<sup>3</sup> L<sup>-1</sup>), CDER (cloud droplet effective radius;  $\mu$ m), and LWC (liquid water content; mg m<sup>-3</sup>). The “NoFilter” row corresponds to results without threshold filtering, while the “Filter” row corresponds to results with threshold filtering applied.

Scenarios	Averaging method	ICNC	ICER	IWC	CDNC	CDER	LWC
NoINPs	NoFilter	6.80E-01	3.00E+01	3.10E+00	1.60E+00	1.60E+01	3.30E+00
	Filter	1.10E+00	3.50E+01	4.40E+00	2.20E+00	1.70E+01	4.50E+00
MixINPs	NoFilter	4.60E-03	1.30E-01	1.10E-01	-7.70E-02	1.40E-02	-7.60E-02
	Filter	2.90E-03	2.00E-01	1.50E-01	-1.00E-01	2.10E-02	-1.00E-01
IceINPs	NoFilter	6.30E+00	-1.30E+00	1.20E+00	-2.60E-01	3.90E-01	-2.40E-01
	Filter	9.40E+00	-2.00E+00	1.70E+00	-3.50E-01	4.00E-01	-3.40E-01
MixIceINPs	NoFilter	6.30E+00	-1.30E+00	1.30E+00	-2.70E-01	3.90E-01	-2.70E-01
	Filter	9.50E+00	-2.00E+00	1.80E+00	-3.70E-01	4.00E-01	-3.80E-01
(MixINPs – NoINPs) / NoINPs	NoFilter	0.68%	0.43%	3.55%	-4.81%	0.09%	-2.30%
	Filter	0.26%	0.57%	3.41%	-4.55%	0.12%	-2.22%
(IceINPs – NoINPs) / NoINPs	NoFilter	926.47%	-4.33%	38.71%	-16.25%	2.44%	-7.27%
	Filter	854.55%	-5.71%	38.64%	-15.91%	2.35%	-7.56%
(MixIceINPs – NoINPs) / NoINPs	NoFilter	926.47%	-4.33%	41.94%	-16.88%	2.44%	-8.18%
	Filter	863.64%	-5.71%	40.91%	-16.82%	2.35%	-8.44%

**Table S4.** Mean values of cloud-related variables with and without threshold filtering applied to cloud grids, based on the horizontal distributions shown in Fig. 6. The filtering criterion is that the sum of the ice water mixing ratio and liquid water mixing ratio exceeds  $10^{-6}$  kg kg<sup>-1</sup>. The abbreviations used are as follows: ICND (ice crystal number density; vertically integrated ice crystal number concentration;  $10^6$  m<sup>-2</sup>), ICER (ice crystal effective radius; vertically averaged;  $\mu$ m), IWP (ice water path; vertically integrated ice water content; g m<sup>-2</sup>), CDND (cloud droplet number density; vertically integrated cloud droplet number concentration;  $10^9$  m<sup>-2</sup>), CDER (cloud droplet effective radius; vertically averaged;  $\mu$ m), and LWP (liquid water path; vertically integrated liquid water content; g m<sup>-2</sup>). The “NoFilter” row corresponds to results without threshold filtering, while the “Filter” row corresponds to results with threshold filtering applied.

Scenarios	Averaging method	ICND	ICER	IWP	CDND	CDER	LWP
NoINPs	NoFilter	1.50E+01	3.20E+01	5.50E+01	2.20E+01	1.60E+01	4.40E+01
	Filter	1.40E+01	3.40E+01	5.60E+01	2.20E+01	1.60E+01	4.40E+01
MixINPs	NoFilter	7.00E-02	1.30E-01	1.80E+00	-1.40E+00	2.50E-02	-1.30E+00
	Filter	6.60E-02	3.70E-01	1.80E+00	-1.40E+00	3.10E-02	-1.30E+00
IceINPs	NoFilter	1.30E+02	4.30E-01	2.30E+01	-4.20E+00	4.70E-01	-3.70E+00
	Filter	1.30E+02	4.00E-01	2.30E+01	-4.20E+00	5.00E-01	-3.80E+00
MixIceINPs	NoFilter	1.30E+02	4.80E-01	2.30E+01	-4.50E+00	4.70E-01	-4.10E+00
	Filter	1.30E+02	4.50E-01	2.40E+01	-4.50E+00	5.10E-01	-4.10E+00
(MixINPs – NoINPs) / NoINPs	NoFilter	0.47%	0.41%	3.27%	-6.36%	0.16%	-2.95%
	Filter	0.47%	1.09%	3.21%	-6.36%	0.19%	-2.95%
(IceINPs – NoINPs) / NoINPs	NoFilter	866.67%	1.34%	41.82%	-19.09%	2.94%	-8.41%
	Filter	928.57%	1.18%	41.07%	-19.09%	3.13%	-8.64%
(MixIceINPs – NoINPs) / NoINPs	NoFilter	866.67%	1.50%	41.82%	-20.45%	2.94%	-9.32%
	Filter	928.57%	1.32%	42.86%	-20.45%	3.19%	-9.32%

Limitation to only dust INP: Meanwhile it is widely accepted that ice formation at temperatures above  $-15^{\circ}\text{C}$  is mostly determined by biological particles (Cornwell et al., 2023). This was not discussed at all by the authors. There should be some information about this important INP type provided in the introduction and in the conclusions section. Another important INP type, especially at Cirrus level is smoke (Ansmann et al., 2025), which might also deserve some discussion in the introduction and conclusions.

**Response:** We thank the reviewer for this insightful and constructive comment. We agree that biological particles at relatively warm temperatures above  $-15^{\circ}\text{C}$  and smoke particles in cirrus regimes represent important INP types that deserve discussion. Our original manuscript focused exclusively on dust INPs in order to isolate their microphysical and radiative impacts. However, we acknowledge that this focus should be better contextualized within the broader INP framework.

We have revised both the *Introduction* and the *Conclusions* sections to explicitly (1) acknowledge the role of biological particles in ice nucleation at warmer temperatures in mixed-phase clouds, and the potential contribution of smoke particles in cirrus clouds, and (2) discuss the importance of these particles in ice nucleation processes during the spring in East Asia. We further clarify that our study design intentionally isolates dust to reduce complexity and enable mechanistic interpretation.

The revision to the *Introduction* section in the revised manuscript (Lines 62–78) is shown below:

*“Other aerosol types may also contribute to heterogeneous ice formation under certain conditions. For example, biological particles such as bacteria, fungal spores, and pollen fragments can dominate ice nucleation at relatively warm temperatures above about  $-15^{\circ}\text{C}$  (Cornwell et al., 2023). Biomass-burning smoke may also act as INPs under cirrus conditions, although their ice-nucleating efficiency depends strongly on particle composition and atmospheric processing (Mertes et al., 2007; Phillips et al., 2013; Vergara-Temprado et al., 2018; Nichman et al., 2019).”*

The revision to the *Conclusions* section in the revised manuscript (Lines 987–995) is shown below:

*“It should be noted that this study focuses exclusively on mineral dust as the source of INPs. The simulations were conducted for spring over East Asia, a period characterized by frequent dust outbreaks originating from the Taklimakan and Gobi deserts. Under these conditions, mineral dust is expected to dominate the regional INP population and therefore represents the primary driver of heterogeneous ice nucleation in the simulated environment. Nevertheless, other aerosol types such as biological particles, biomass-burning smoke may also contribute to ice nucleation under different environmental conditions or during other seasons. Their potential roles should therefore be investigated in future studies.”*

Lack of referencing to observational studies of INP/ICNC relationships under ambient conditions: There are meanwhile plenty of observational studies discussing relationships between INP concentration and cloud properties. It would be nice if the authors would add some to their study (introduction). Here some examples (e.g., Zhang et al., 2018; Ansmann et al., 2019; He et al., 2025, Villanueva et al., 2025). There are also nice detailed spectral-bin simulations of the impact of perturbations in INP on mixed-phase cloud properties (Lee et al., 2024).

**Response:** We thank the reviewer for this insightful and constructive comment. In response, we have revised the Introduction to incorporate references to several relevant observational studies that discuss the relationship between INP concentrations and cloud properties. Specifically, we added references to studies highlighting the association between dust loading and ice particle production in mixed-phase clouds (Zhang et al., 2018), lidar-derived INP concentrations in Saharan dust layers explaining ice crystal number concentrations (Ansmann et al., 2019), and long-term observations demonstrating the influence of INP variations on mixed-phase cloud microphysics and precipitation formation (He et al., 2025). We also included satellite analyses suggesting the role of dust-driven droplet freezing in determining cloud-top phase (Villanueva et al., 2025). Additionally, we discussed high-resolution spectral-bin simulations (Lee et al., 2024) that provide process-level insight into how perturbations in INP concentrations can influence mixed-phase cloud microphysics.

We have included observational studies and spectral-bin simulations in the *Introduction* section, as suggested by the reviewer (Lines 88–110). The revised text is shown below:

*“Observational studies have provided important constraints on the relationship between INPs and cloud microphysics. For example, collocated A-Train satellite observations reveal that enhanced ice particle production in mid-level stratiform mixed-phase clouds is associated with elevated dust loading, indicating that dust-induced ice formation can substantially modify cloud phase and ice crystal number concentrations (Zhang et al., 2018). Aerosol–cloud closure studies further demonstrate that lidar-derived INP concentrations in Saharan dust layers can explain observed ice crystal number concentrations within an order of magnitude, highlighting the importance of heterogeneous nucleation on mineral dust in altocumulus and cirrus (Ansmann et al., 2019). More recently, long-term observations from two sites with contrasting aerosol conditions, characterized by desert dust and continental aerosols versus marine aerosol, also indicate that variations in INP concentrations can significantly influence mixed-phase cloud microphysics and precipitation formation (He et al., 2025). At larger spatial scales, satellite analyses further suggest that dust-driven droplet freezing plays a key role in determining cloud-top phase across the Northern Hemisphere (Villanueva et al., 2025).”*

*“Process-level insight into these interactions has also been obtained from high-resolution spectral-bin simulations. For example, Lee et al. (2024) demonstrated that higher INP concentrations lead to smaller ice particles and more irregular crystal*

*shapes, highlighting the influence of INP levels on ice particle morphology, number, and cloud microphysics. However, these studies typically focus on idealized cloud systems and therefore do not directly quantify the large-scale impacts of INPs on cloud evolution and radiation.”*

Impact for future studies: I suggest to the authors to extend their conclusions a bit by means of an outlook. Their study has the potential to evaluate how projected changes in landuse and surface type will probably effect the regional climate in China and surrounding parts of Asia. It would be an easy task to just modify the dust immersion scheme in order to investigate how clouds and radiation would change with changing emissions (and a certainly warmer climate). Such a future study would be a really nice follow-up to the presented one.

**Response:** We thank the reviewer for this insightful and constructive suggestion. We agree that including a forward-looking perspective on factors influencing dust emissions and their subsequent influence on regional climate would be a valuable addition to the conclusions. In response, we have expanded the Conclusions section to include a brief outlook on how future studies could investigate the effects of climate change and land use changes (such as afforestation) on key factors such as vegetation cover, soil moisture and wind speed, which in turn affect dust emissions. These changes in dust emissions could further impact cloud properties and radiative effects through dust-cloud interactions, providing an important direction for extending the current study.

The revision has been made in accordance with the reviewer’s suggestion in the revised manuscript (Lines 1000–1005). The revised text is shown below:

*“Looking ahead, future studies could investigate how climate change and land use changes (such as afforestation) might alter vegetation cover, soil moisture, and wind speed, which in turn affect dust emissions. These changes in dust emissions would likely influence cloud properties and radiative effects through dust-cloud interactions, offering an important area for further research in the context of regional climate impacts in East Asia and surrounding regions.”*

We hope these revisions effectively address the reviewer’s suggestion by providing a forward-looking perspective on the potential implications of future changes in dust emissions due to climate change and carbon-neutral policies.

All figures: I kindly request that the authors aim on increasing the size of fonts and legends in all of their figures to the maximum. The figures are very hard to read. I was hardly able to read any number in the printed version of the manuscript. Especially Figs. 5 and 6.

**Response:** We thank the reviewer for pointing out this issue. Following the reviewer’s suggestion, we have increased the font sizes of all labels, tick marks, legends, and

annotations in every figure to improve readability. Particular attention was given to Fig. 5 and 6, where the labels and legends have been significantly enlarged to ensure that all values and annotations are clearly readable in the printed version of the manuscript.

## Reference

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