

We thank RC1 and RC2 for their thorough reading of our manuscript and for their valuable comments.

We provide detailed responses to all comments below; the responses are shown in blue, and all revisions in the manuscript are highlighted in red.

Summary

This paper uses observations and modelling to discuss the impact of aerosols on cloud properties at different heights within liquid, mixed-phase, and ice clouds. The main finding is that an increase in aerosol concentration shifts the cloud droplet spectra from bimodal to unimodal. I thought the authors did a good job of discussing and explaining their figures and the mechanisms behind these aerosol-cloud interactions. Most of my comments are about additional details needed in the Data and Methods section and the way that Figure 3 is presented.

We thank the reviewer for the positive assessment of our study and for the constructive comments. We also appreciate the reviewer's suggestions regarding the need for additional details in the Data and Methods section, as well as improvements to the presentation of Figure 3. A detailed, point-by-point description of the revisions is provided below.

Major Comments

- One of my main concerns with this paper is Fig. 3 and the claims drawn from it. Presented with scatter points, I struggled to find most of the authors' claims to be evident from the figure, especially in panels b, c, i, j, k, and l. I would suggest presenting these figures as bin-averaged line plots with error bars or shading to represent variability in the observations to make the claims in Sect. 3.2 more obvious from the figure. I really felt like I needed a line for each subset to be able to compare and see/understand the patterns. Panels o and p in this figure are also switched compared to all other rows.
 - Additionally, it was difficult for me to keep track of rows and columns in Figs. 2 and 3, and it would be helpful to label these on the figures.

We sincerely thank the reviewer for the constructive suggestions regarding the presentation of Figure 3 and the clarity of Figures 2 and 3. We agree that the original scatter-point representation made it difficult to clearly identify the trends discussed in Section 3.2.

Following the reviewer's suggestion, we have revised Figure 3 to improve the readability and interpretability of the results. Specifically, the scatter plots have been replaced with bin-averaged vertical profiles based on the normalized cloud height (H). For each aerosol condition and cloud phase, the observations were grouped into vertical bins, and the mean value within each bin is now presented as a line. In addition, shaded regions representing ± 1 standard deviation have been added to illustrate the variability of the observations. These modifications make the vertical variations in number concentration, effective diameter, spectral dispersion, and water content

more clearly visible and facilitate comparisons between high- and low-aerosol conditions.

We have also carefully re-examined the panel arrangement and found that panels (o) and (p) were inadvertently swapped in the original figure. This issue has now been corrected in the revised manuscript.

Finally, to further improve the readability of Figures 2 and 3, we have revised the figure legends. The updated figures and corresponding captions are provided below.

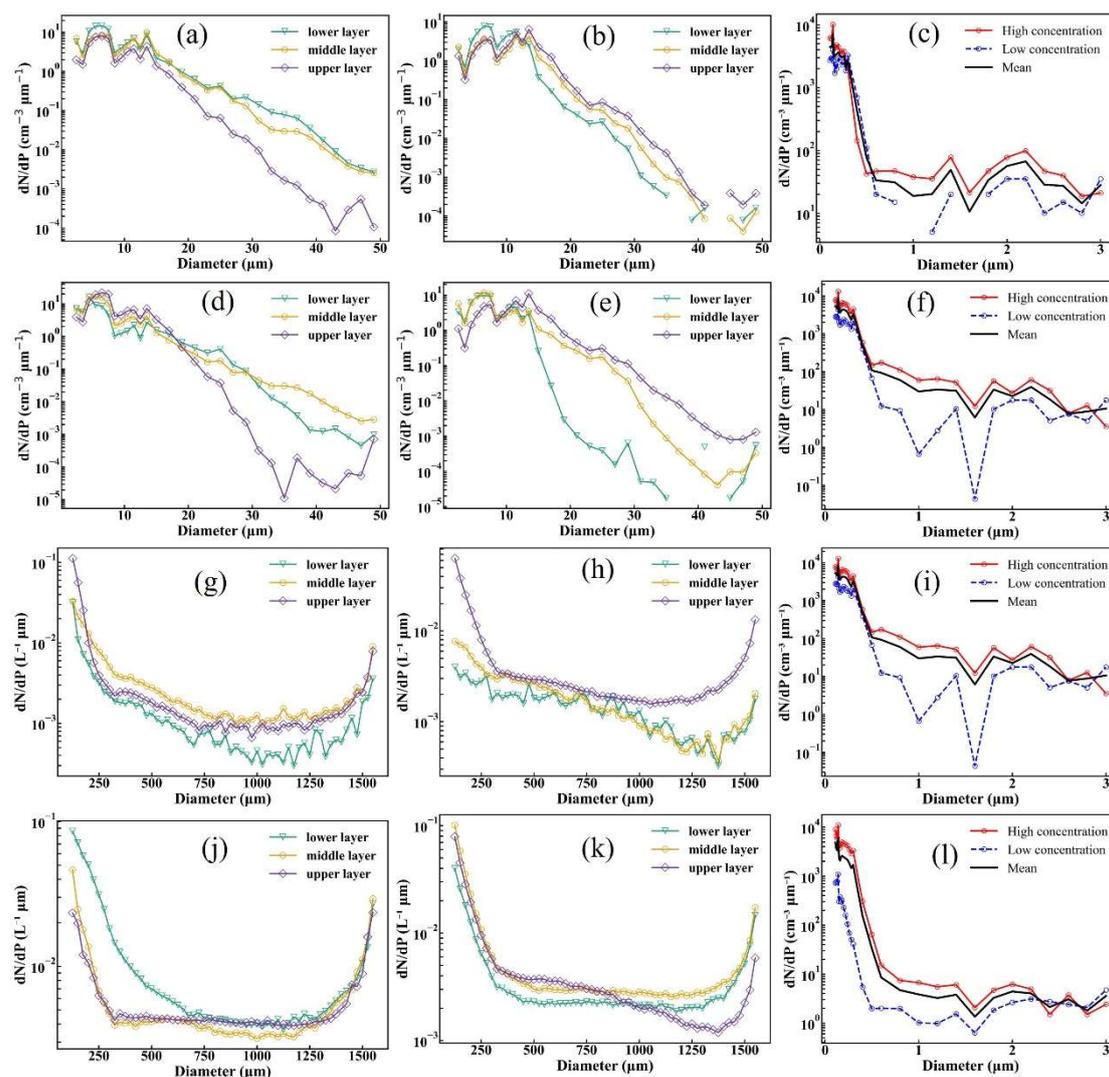


Figure 3. Size distributions of cloud particles in different regions of the observed clouds and aerosol size distributions below the clouds under varying aerosol concentrations. Panels (a–b) show the droplet size distributions in warm clouds, and (d–e) show those in mixed-phase clouds. Panels (g–h) present the ice crystal size distributions in mixed-phase clouds, while (j–k) correspond to ice clouds. Panel (c), (f), (i), and (l) show the aerosol size distributions below the clouds under high- and low-aerosol concentration conditions, together with the mean spectrum. In panels (a–b), (d–e), (g–h), and (j–k), the green, yellow, and purple curves represent the cloud base, middle, and top, respectively. In panels (c), (f), (i), and (l), the red and

blue curves denote high- and low-aerosol concentrations, respectively, and the black curve represents the mean aerosol spectrum.

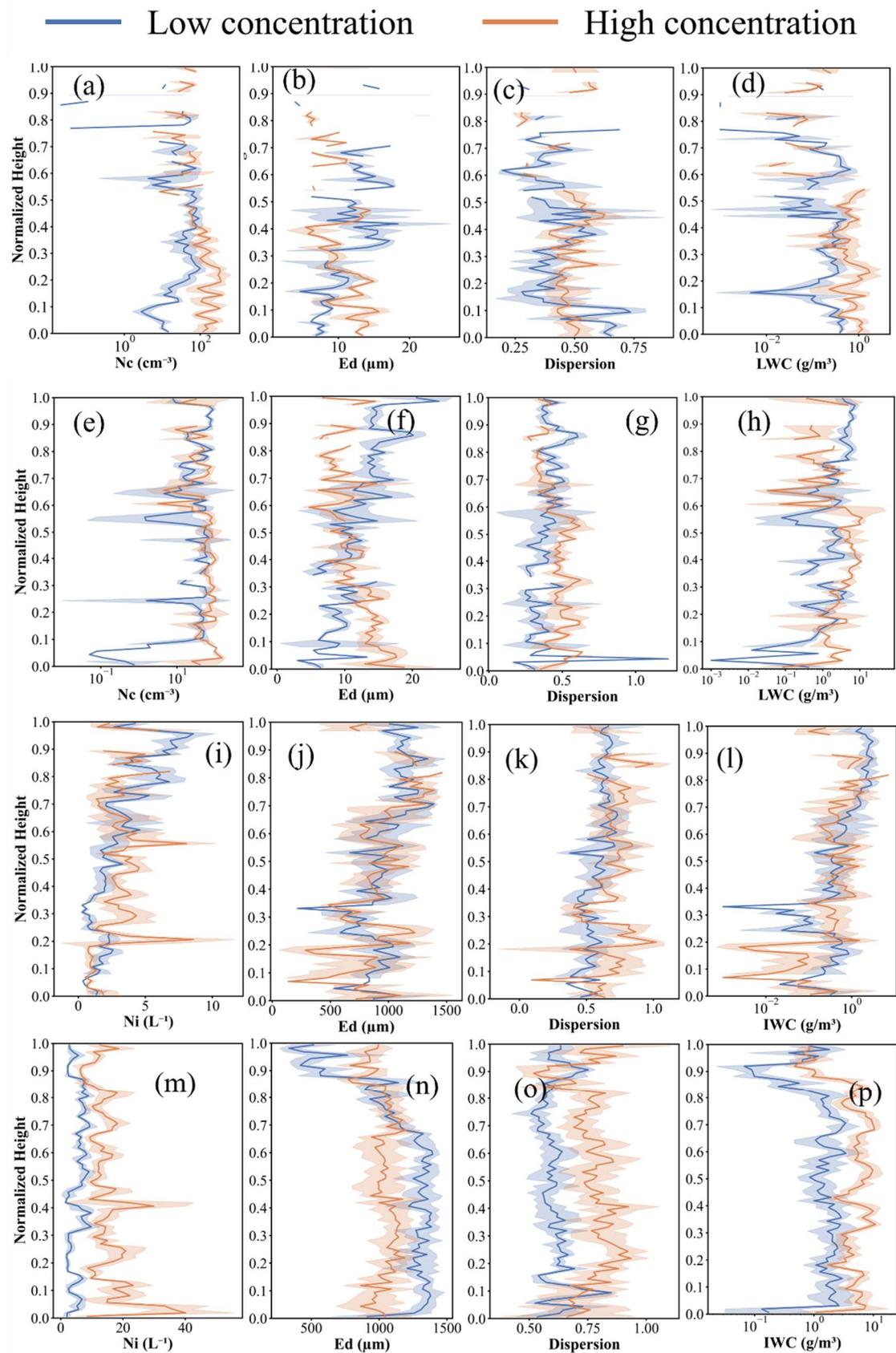


Figure.4 Vertical distributions of different cloud particle characteristics. (a–d) water cloud droplets, (e–h) mixed-phase clouds droplets, (i–l) ice crystals in mixed clouds, (m–p) ice crystals in ice clouds. For each cloud type, the panels from left to right represent number concentration, effective diameter, dispersion, and water content, respectively.

- The data and methods section would benefit from more detail about the following:
 - Aircraft observation platform and instruments:
 - What size droplets are measured by the CDP?
 - What meteorological variables are used from the AIMMS-20?
 - Does the AE-33 need to be mentioned if no data from it is used in the rest of the study (as far as I understood)?

We thank the reviewer for the valuable suggestion to provide more detailed descriptions of the aircraft instruments used in this study. We fully agree that including additional information improves the clarity and reproducibility of the methodology. Accordingly, we have revised the Aircraft Observation Platform and Instruments section to provide a more comprehensive description. First, we have clarified the measurement size range of the Cloud Droplet Probe (CDP). The CDP measures cloud droplet size distributions over an approximate diameter range of 2–50 μm , using multiple size bins to derive droplet number concentration, size distribution, and liquid water content. For clarity, the key parameters of all instruments are now summarized in a dedicated table. Second, the AIMMS-20 provides measurements of air temperature, pressure, relative humidity, wind speed, wind direction, and vertical velocity. Air temperature is used to distinguish cloud types, while both air temperature and relative humidity are applied for quality control to identify and exclude anomalous data. Third, we have reconsidered the inclusion of the AE-33 aethalometer. As the AE-33 data are not directly used in the analyses presented in this study, we have removed the description of this instrument from the revised manuscript to avoid potential confusion and to maintain focus on the instruments relevant to the results.

The aircraft platforms employed in this study include the modified King Air 350 (K350) and Y-12 aircraft, both of which are operated by the Hebei Weather Modification Office (HBWMO). Each platform was outfitted with an identical suite of observational instruments, comprising a Cloud Droplet Probe (CDP, The CDP measured particle sizes in the range of 2–50 μm .), a Cloud Imaging Probe (CIP), a Passive Cavity Aerosol Spectrometer Probe (PCASP-100). The 20 Hz Atmospheric Integrated Meteorological Measurement System (AIMMS-20) primarily provided basic meteorological parameters, including wind speed, wind direction, temperature, humidity, and air pressure., and a Global Positioning System (GPS).

Table.1 Summary of airborne probes used in this study.

Instrument	Measurement range (μm)	Number of channels	Variables used in this study
PCASP	0.1–3.0	30	Aerosol size distribution, aerosol

CDP	2–50	30	number concentration Droplet size distribution, droplet number concentration (N_c), effective diameter (E_d), spectral dispersion, liquid water content (LWC)
CIP	25–1600	64	Ice particle size distribution, ice crystal number concentration (N_{ice}), effective diameter, ice water content (IWC)

- Data processing:
 - Can you be more specific or provide a map of where these flights took place? What aerosol types are expected in this region (rural vs. urban)?
 - All equations need to be numbered.

We thank the reviewer for the helpful suggestions regarding the description of the observation region and the presentation of the equations. First, we agree that providing more information about the geographical locations of the aircraft observations would improve the clarity of the study. In the revised manuscript, we have added a map showing the flight tracks. In addition, we have included a brief description of the aerosol environment in the study region. Second, following the reviewer's suggestion, we have revised the manuscript so that all equations are now numbered sequentially.

The aircraft observations were conducted over the North China Plain, with most sampling flights located over Hebei Province, particularly in the region surrounding Shijiazhuang (Figure 1). This area is characterized by a complex aerosol environment influenced by both urban emissions and regional anthropogenic sources. Major contributors include industrial emissions, traffic-related pollution, and secondary aerosols such as sulfate, nitrate, and organic aerosols. In addition, rural and agricultural activities contribute to regional aerosol loading, and the region is occasionally affected by dust transport from northern China. Therefore, the observed aerosol population represents a mixture of urban pollution aerosols and regional background aerosols.

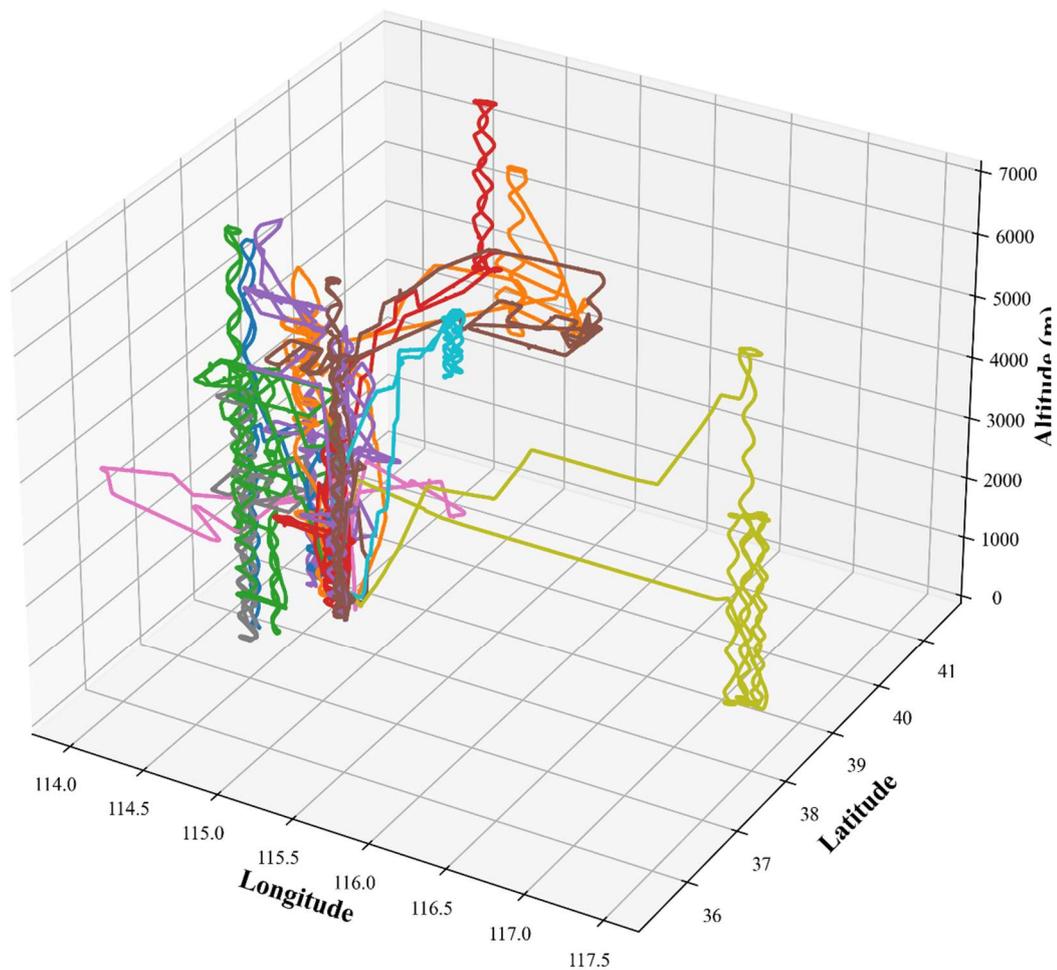


Figure.1. Map of the aircraft flight tracks and observation region over the North China Plain.

- Cloud phase determination:
 - What does “normal” mean in Line 150? Does this refer to a lognormal distribution or continuous as opposed to piecewise?
 - I see details about how the small and large size ranges are defined in Lines 166-167, but I think it should be defined before the fitting in Fig. 1 (Lines 151-156). Additionally, how many observations does the fit in Fig. 1 represent? How many days/flights are accounted for there? Are they for all cloud phases?

We thank the reviewer for the careful reading of the manuscript and the helpful suggestions.

First, the term “normal” used in Line 150 was a textual error and should refer to a lognormal distribution. We have corrected this description in the revised manuscript to avoid confusion.

Second, following the reviewer's suggestion, we have moved the definition of the small- and large-size aerosol ranges to the section describing the fitting method used in Figure 1. The size classification is now introduced before the fitting procedure is described, which improves the logical flow of the methodology.

Third, we have clarified the data source used for the aerosol spectrum fitting shown in Figure 1. The aerosol size distribution displayed in Figure 1 represents observations from a single aircraft flight, which is shown as an illustrative example of the piecewise fitting method. For the parcel model simulations, however, the aerosol parameters were not obtained from a direct average of aerosol spectra across flights. Instead, the aerosol spectrum for each individual flight was first fitted using the piecewise lognormal–Junge formulation, and the resulting fitting parameters were then averaged across all available flights and across all cloud phases to obtain representative aerosol parameters for the simulations.

Notably, in the model, the traditionally assumed lognormal aerosol distribution was replaced with a piecewise spectrum fitted to in situ observations at the cloud base. The aerosol size distribution was divided into small-particle and large-particle ranges, separated by a cutoff diameter of $0.35\ \mu\text{m}$, which provided the best agreement with the observed spectra. In the small range, the distribution follows a lognormal function, which can be expressed as follows:

- Several details in the results would also benefit from more detail and motivation:
 - I am not clear about how the high and low aerosol concentration groups (Line 174-175) or the different cloud layers are determined (Line 185).

We thank the reviewer for pointing out that the criteria used to classify aerosol concentrations and cloud layers were not sufficiently clear in the original manuscript. First, the classification of high and low aerosol concentration groups was based on the observed aerosol number concentrations below the cloud base. Observations with aerosol concentrations below $1000\ \text{cm}^{-3}$ were assigned to the low-concentration group, whereas those greater than or equal to $1000\ \text{cm}^{-3}$ were classified as the high-concentration group. This threshold was chosen to distinguish relatively clean conditions from more polluted environments in the study region.

Second, the cloud layers were defined using the normalized cloud height (H), which ranges from 0 at the cloud base to 1 at the cloud top. Based on this normalized height, the cloud was divided into three layers: lower layer ($H < 0.3$), middle layer ($0.3 \leq H < 0.7$), and upper layer ($H \geq 0.7$). This normalization allows observations from different flights and clouds with varying thicknesses to be compared within a consistent vertical framework.

Environmental conditions at different altitudes influence physical and chemical processes, thereby affecting the formation, growth, and dissipation of cloud particles. In this study, clouds were divided into lower (0–0.3), middle (0.3–0.7), and upper (0.7–1) layers based on normalized height, and the particle distributions were analyzed

within each layer. the clouds were stratified into lower, middle, and upper layers, and the particle distributions were analyzed within each layer.

- I am unclear about the purpose of splitting data in column 3 of Fig. 2 into separate distributions for both high and low aerosol concentration. It seems this makes the “low concentration” line noisier, presumably because there is less data. It may help to combine those or better motivate the split.
 - Fig. 2: It is not clear from the text or caption why there are two rows for ice clouds. Column 3 is not described in the caption. The colors for cloud top, middle, and base also need to be fixed in the caption to yellow, green, and purple. Additionally, would it be possible to show values of spectral width as calculated in the methods? This might be more intuitive than a visual determination of spectral width (Line 184).

We thank the reviewer for this helpful comment. The purpose of separating the data in Column 3 of Figure 2 into high- and low-aerosol concentration groups was to examine whether aerosol loading influences the shape of the particle size distributions or primarily affects their number concentrations. Our intention was to demonstrate that the overall distribution shape remains largely consistent under different aerosol conditions, while the main difference lies in the magnitude of the number concentration. To improve the clarity of the figure, we have revised it by adding the average distribution derived from all observations.

First, we clarify that the two rows showing ice crystals in Figure 2 do not represent two different types of ice clouds. Instead, one row corresponds to ice crystals in mixed-phase clouds, while the other represents ice crystals in pure ice clouds. To avoid confusion, we have revised the figure caption and the corresponding text to clearly state this distinction.

Second, we have improved the figure caption by explicitly describing Column 3, which presents the aerosol size distributions below the clouds under different aerosol conditions.

Third, we have corrected the color descriptions in the caption to ensure consistency with the figure, where yellow, green, and purple represent the cloud top, middle, and base, respectively.

Finally, we agree that a quantitative representation of the spectral width improves the clarity of the analysis. We have therefore added the calculated spectral width values (as defined in the Methods section).

Figure 3. Size distributions of cloud particles in different regions of the observed clouds and aerosol size distributions below the clouds under varying aerosol concentrations. Figure 2. Size distributions of cloud particles in different regions of the observed clouds and aerosol size distributions below the clouds under varying aerosol concentrations. Panels (a–b) show cloud droplet spectra in warm clouds under high and low aerosol loading, respectively; (d–e) show cloud droplet spectra in mixed-phase clouds; and (g–h) show ice crystal spectra in mixed-phase clouds. Panels (j–k) present ice crystal

spectra in ice clouds. In each panel, yellow, green, and purple curves represent the cloud top, middle, and base, respectively. Panels (c), (f), (i), and (l) show the corresponding aerosol size distributions below the clouds under high- and low-aerosol conditions, along with the mean distribution (black line).

Minor comments

- Line 13-15: Can you make it explicit that you are describing droplet size at which number concentration peaks? As it reads right now, I was expecting to see peak number concentration values.

We thank the reviewer for pointing out this ambiguity in the description. The intention of this sentence was to describe the droplet sizes at which the number concentration peaks occur, rather than the peak values of the number concentration itself. Following the reviewer's suggestion, we have revised the sentence to make this point explicit.

In liquid and mixed-phase clouds, droplet number concentration peaks occur at droplet diameters of 5–7 μm and 14–15 μm , whereas ice and mixed-phase clouds exhibit ice crystal peaks occur at particle sizes of about 125 and 1550 μm .

- Lines 16-17: Similarly, can “concentrations within the intermediate range” be specified to mean intermediate droplet sizes? Unless this is referring to something else.

We thank the reviewer for pointing out this ambiguity in the description. In the original manuscript, the phrase “concentrations within the intermediate range” indeed referred to particle number concentrations corresponding to intermediate droplet sizes.

Following the reviewer's suggestion, we have revised the sentence to explicitly indicate that this expression refers to intermediate droplet size ranges, thereby improving the clarity of the description and avoiding potential misunderstanding.

Regarding ice crystals, high aerosol loading enhance number concentrations at both small and large sizes, whereas number concentrations at intermediate particle sizes are lower than those under low aerosol loadings.

- Line 23-24: It looks like this sentence got cut off here.

This error has been corrected in the revised manuscript to ensure that the sentence is now clearly and fully expressed.

- Line 28-31: You might consider rephrasing to say that when aerosols act as CCN and IN, this results in modulation of cloud properties. Current phrasing makes it sound like these are two separate processes.

We thank the reviewer for this helpful suggestion. Following the reviewer's suggestion, we have revised the sentence to clarify that when aerosols act as CCN and IN, they modulate cloud microphysical properties, including droplet and ice crystal formation. This revision improves the clarity and accuracy of the description.

Aerosols can act as cloud condensation nuclei (CCN) and ice nuclei (IN), thereby influencing cloud microphysical properties by affecting the formation of cloud droplets and ice crystals as well as cloud particle number concentrations, size distributions, and liquid and solid water contents (Chen et al., 2019; Sun and Ariya, 2006).

- Line 49-50: Can you give a brief example of these significant findings?

We thank the reviewer for this helpful suggestion. In the original manuscript, the phrase "numerous significant findings" was not accompanied by specific examples, which may have reduced the clarity of the statement. Following the reviewer's suggestion, we have revised the sentence by adding brief examples of the findings obtained from previous aircraft observations, such as insights into cloud microphysical properties, aerosol–cloud interactions, and the vertical structure of clouds.

For example, in South China's Guangxi region, Liu et al. (2025) analyzed nine aircraft flights conducted in 2020 to investigate the diurnal variation of stratocumulus clouds and the impact of aerosols on cloud microphysical properties. They found that aerosol number concentration and cloud droplet effective radius exhibited the typical Twomey effect and highlighted the important influence of boundary-layer height on the microphysical structure. Based on 35 aircraft flights conducted over the North China Plain during 2019–2021, Ke et al. (2025) further investigated the influence of boundary-layer–cloud coupling processes on cloud microphysical variables.

- Line 54: It looks like there is an error with this reference.

This reference has now been corrected in the revised manuscript, and we have also rechecked the reference list to ensure the accuracy and consistency of all citations.

- Line 69: Need to define E3SM.

We thank the reviewer for pointing out this oversight. In the revised manuscript, the abbreviation E3SM has now been defined as the Energy Exascale Earth System Model

Christensen et al. (2023) compared observed CCN concentrations and airborne/ground measurements with E3SMv1(Energy Exascale Earth System Model) simulations to assess aerosol impacts on cloud properties and radiative forcing in low-level clouds.

- Line 105 and 108: I would not refer to the number concentration within

individual size channels as a “distribution.” Additionally, do you have a reference for this N_i equation or can you describe it in a bit more detail? This is not a conversion I have seen before.

We thank the reviewer for this helpful comment. We agree that referring to the number concentration within individual size channels as a “distribution” was not accurate. In the revised manuscript, this wording has been corrected to “number concentration density” to more precisely describe the physical quantity in each size channel.

In addition, we have clarified the definition of the N_i equation in the Methods section. The equation describes the number concentration density per size interval, which is calculated using the particle counts in each channel, the sampled air volume, and the width of the corresponding size bin. To improve clarity, we have provided a more detailed description of the variables used in the equation and included an appropriate reference to support the calculation method.

The number concentration per size interval for each size channel of the CDP, CIP, and PCASP instruments was calculated as follows:

$$N_i = \frac{n_i}{1000V_i\Delta r_i}$$

where N_i represents the number concentration density of the i -th channel for each instrument ($\text{cm}^{-3}\cdot\mu\text{m}^{-1}$), n_i is the number of particles in the i -th channel, V_i is the sampled volume for the i -th channel (L), and Δr_i is the bin width of the i -th channel (μm).

- Line 117: “Channel” is repeated twice.

We thank the reviewer for pointing out this typographical error. The repeated word “channel” has been corrected in the revised manuscript.

- Sections 2.3 and 2.4 have the same title.

We thank the reviewer for identifying this issue. The duplicate section title was caused by an editing oversight. The title of **Section 2.4** has been corrected in the revised manuscript.

- Line 167: Critical diameter usually refers to the size needed for CCN activation. Is that the same way it’s being used here?

We thank the reviewer for pointing out this potential source of confusion. In the original manuscript, the term “critical diameter” was intended to represent the cutoff size used to separate small and large aerosol particles in the analysis. However, we agree that this term is commonly used to refer to the critical activation diameter for CCN, which may lead to misunderstanding.

To avoid confusion, we have revised the wording in the manuscript by replacing “critical diameter” with “cutoff diameter”, clearly indicating that this value represents the threshold used to divide small and large aerosol size ranges, rather than the critical activation diameter for CCN.

- Line 171: Can you specify what environmental conditions you’re referring to here?

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We thank the reviewer for pointing out that the environmental conditions referred to in Line 171 were not clearly specified in the original manuscript. In the revised manuscript, we have clarified the environmental background of the observation region, including the general aerosol and meteorological conditions over the North China Plain and Hebei Province, where the aircraft observations were conducted. This additional description provides context for the environmental conditions influencing the observed cloud microphysical properties. The relevant information has been added to the Methods section (Section 2.2) of the revised manuscript.

This area is characterized by a complex aerosol environment influenced by both urban emissions and regional anthropogenic sources. Major contributors include industrial emissions, traffic-related pollution, and secondary aerosols such as sulfate, nitrate, and organic aerosols. In addition, rural and agricultural activities contribute to regional aerosol loading, and the region is occasionally affected by dust transport from northern China. Therefore, the observed aerosol population represents a mixture of urban pollution aerosols and regional background aerosols.

- Line 179: Are these aerosols actually measured “in” cloud, or should this maybe be “below?”

We thank the reviewer for pointing out this ambiguity. In this study, the aerosol measurements used for classification were taken below the cloud base, rather than within the cloud.

The original wording was intended to describe the aerosol conditions associated with the observed clouds, but the expression “in cloud” was misleading. In the revised manuscript, we have corrected this wording to “below the cloud”.

- Line 247: Can you elaborate a bit on what you mean by saying the CCN concentration is “insufficient?”

We thank the reviewer for pointing out that the phrase “insufficient CCN concentration” was not sufficiently clear in the original manuscript.

In this context, “insufficient CCN concentration” refers to conditions in which the available cloud condensation nuclei are relatively low compared with the amount of water vapor and supersaturation in the cloud environment. Under such conditions, fewer aerosol particles are activated into cloud droplets, which leads to lower droplet

number concentrations and larger mean droplet sizes due to reduced competition for water vapor.

- Line 272: Before describing the finding from Fig. 6 can you explain what is plotted and what you're trying to assess with it?

We thank the reviewer for this helpful suggestion. We agree that the original manuscript did not clearly introduce the purpose and content of the figure before discussing the results.

In the revised manuscript, the figure has been updated and is now presented as Figure 7. We have added a brief description before presenting the results to clarify what variables are shown and the objective of the analysis.

Figure 7 shows the responses of key cloud microphysical parameters simulated by the parcel model to increasing aerosol concentration. The figure is intended to assess how variations in aerosol loading influence droplet number concentration, effective diameter, and spectral dispersion during cloud development.

- Line 272-275: I do not understand the claim that effective diameter and spectral dispersion both increase as aerosol concentration increases but then they decrease. From this figure I see a levelling-off, but it is not obvious to me that either quantity is decreasing.

We thank the reviewer for this helpful comment. We agree that the original description may have overstated the decreasing tendency of effective diameter and spectral dispersion at high aerosol concentrations.

In most cases shown in the figure, both effective diameter and spectral dispersion initially increase with increasing aerosol concentration and then tend to level off. Only in some specific cases, such as when the large-particle concentration is set to 100, a slight decrease can be observed. Therefore, the overall behavior is better described as an initial increase followed by a stabilization, rather than decrease.

- Fig. 7: Might it make more sense to present and label the middle row as supersaturation? Also, VMR is undefined.

We thank the reviewer for this helpful suggestion. We agree that presenting the middle row as supersaturation provides a clearer and more physically meaningful interpretation of the results.

In addition, we acknowledge that the abbreviation VMR was not defined in the original manuscript. This has now been corrected, and VMR is explicitly defined as the water vapor mixing ratio in both the figure caption and the main text.

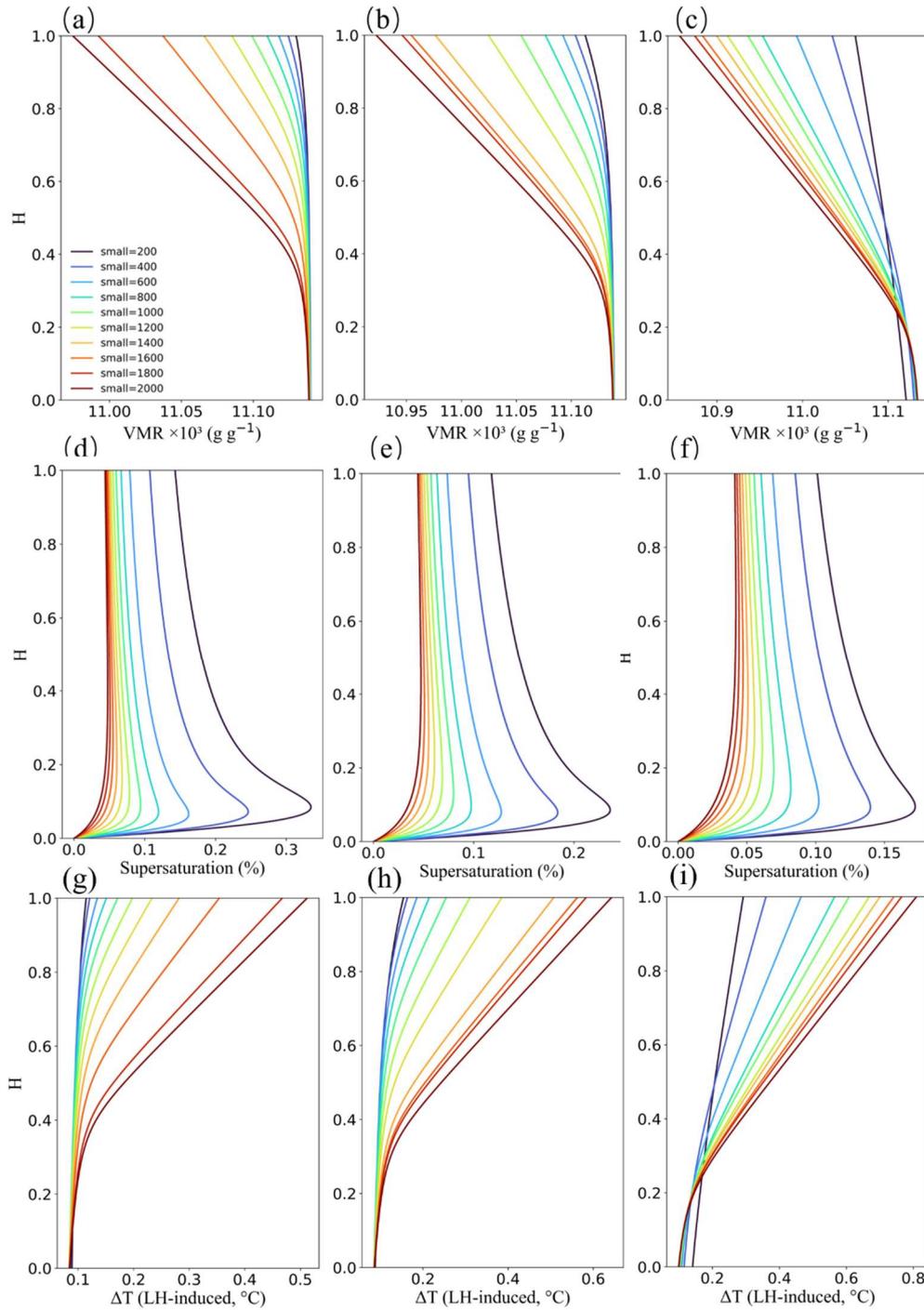


Figure.8 Vertical profiles of cloud water vapor mixing ratio (VMR) (a-c), supersaturation (e-f), and condensation-induced environmental warming (g-i) under different aerosol concentrations. Colored curves represent different aerosol concentrations, and the vertical coordinate H denotes the normalized cloud height.