Author's response

Manuscript title: Observation-based analysis of horizontally oriented ice crystals using dual-angle polarization lidar and cloud Doppler radar in Beijing
Manuscript ID: egusphere-2026-3314

Dear Editor and Referees,

We sincerely thank the editor and the three anonymous referees for their careful evaluation of our manuscript and for their constructive comments and suggestions. We have revised the manuscript accordingly. Below, we provide our point-by-point responses to all comments. The referees' comments are reproduced first, followed by our responses and the corresponding changes made in the revised manuscript. Page and line numbers refer to the revised manuscript.

On behalf of all authors,
Zhaolong Wu

Response to Referee #1's comments

This is a very solid and scientifically valuable piece of work. The authors conducted a systematic, year-long observational analysis of horizontally oriented ice crystals (HOICs) using a unique ground-based combination of dual-angle polarization lidars and a cloud radar in Beijing. For the first time, the study provides long-term statistical constraints on the occurrence frequency, macrophysical characteristics, environmental conditions, and relationships of HOICs with supercooled liquid water clouds (SWCs) and turbulence, filling a critical gap in this field. The data are of high quality, the analysis methodology is rigorous, and the results are of significant reference value for improving ice-cloud microphysics parameterization schemes in climate models. The paper is well structured and the arguments are well supported, but some details still need improvement. Therefore, a minor revision is recommended before acceptance.

Reply: We sincerely thank Referee #1 for reviewing our paper and providing constructive comments for improvement. Responses to these comments are provided below. In this author's comment, we reply (in blue font) to Referee #1's comments (in black font). The relevant part in the revised version is in green font.

1. Is Figure 5(a) based on statistics over all temperatures? The fraction of water clouds in 2022 is only 5.2% – could this be double-checked?

Reply: Thank you for the comment. Figure 5(a) is based on statistics over all temperatures. We have double-checked the calculation and confirmed that warm liquid-water clouds account for 5.2% of all identified cloud range bins in 2022. It should be emphasized that this percentage represents a **range-bin-based fraction (5 min × 15 m)** rather than the fraction of time during which liquid-water clouds occurred.

Stratiform liquid-water clouds generally have a smaller vertical extent than ice clouds, and optically thick liquid-water clouds may also be underrepresented because strong lidar attenuation limits the penetration of the laser beam. In contrast, vertically extended ice clouds contribute a much larger number of cloud range bins for a given observation period. Therefore, the relatively small fraction of warm liquid-water cloud range bins does not imply that liquid-water clouds occurred during only 5.2% of the cloudy periods.

For comparison, in our previous paper (Wu et al., 2026), the fraction of water clouds is 5.3 % using rigorous cloud mask.

2. For Figure 6 (rigorous cloud mask) and Figure 7 (relaxed cloud mask), the numbers of statistical cases are 735 and 693 respectively, with a difference of more than 5%. Could the corresponding reasons be provided?

Reply: Thank you for the comment. Although the relaxed cloud mask identifies more HOIC range bins than the rigorous cloud mask, many of these additional bins fill temporal or vertical gaps between HOIC fragments that are treated as separate events under the rigorous mask. According to our event-grouping criteria (Δt < 60 min, Δh < 2 km), these newly connected HOIC fragments are therefore merged into the same event. Consequently, the relaxed cloud mask yields fewer but more complete individual HOIC events (693) than the rigorous cloud mask (735). We have added the corresponding explanation to the revised manuscript (Line 469–472):

"Although the relaxed cloud mask identifies more HOIC range bins, many of the additional bins bridge temporal or vertical gaps between HOIC fragments that are treated as separate events under the rigorous mask. Under the event-grouping criteria (Δt < 60 min and Δh < 2 km), these fragments are therefore merged into fewer but more complete HOIC events, reducing the number of identified events from 735 to 693."

3. The paper cites previous studies multiple times, but as an independent paper for publication, it should appropriately explain those previous studies. For example, in the sentence "Moreover, HOICs produce much stronger backscatter in the zenith-pointing lidar than in the off-zenith-pointing lidar, making cloud-layer detection more easily triggered in the zenith observations (Zhao et al., 2014; Wu et al., 2025)," the physical mechanism should be articulated within this paper.

Reply: Thank you for this important comment. We agree that the physical mechanism should be explained explicitly rather than only referred to through citations. We have therefore revised the relevant part of Sect. 2.2 to clarify the angle-dependent specular reflection of HOICs and its influence on cloud-layer detection. The relevant passage in Sect. 2.2 has been revised as follows:

"Moreover, HOICs can produce mirror-like specular reflection. For the zenith-pointing lidar, the incident laser beam is nearly perpendicular to the main facets of the HOICs, so a strong specular reflection component is returned to the receiver. At 15° off zenith, the incident laser beam is no longer close to normal incidence, and most of the specular reflection component is reflected away from the receiver, resulting in much weaker backscatter (Wu et al., 2025). Because the cloud-layer detection algorithm identifies cloud bins when the backscatter-related quantity exceeds a predefined threshold, HOIC-containing cloud bins are more readily detected in the zenith observations (Zhao et al., 2014)."

4. The paper states: "both confirming a statistically significant difference in their overall EDR distributions ($p \ll 0.001$). Interestingly, the calculated Cliff's Delta yields a small overall effect size ($d = -0.060$)." The formulas for p and d should be provided.

Reply: Thank you for this constructive suggestion. We fully agree that providing explicit mathematical formulas for both the statistical hypothesis test (p-value calculation via the Mann–Whitney U test and Kolmogorov–Smirnov test) and the effect size metric (Cliff's Delta, *d*) enhances the clarity and reproducibility of our methodology. We have now added the mathematical definitions and formulas for *p* and *d* in Sect. 2.5:

"Let $X = \{x_i\}_{i=1}^{m}$ and $Y = \{y_j\}_{j=1}^{n}$ denote the cloud-property samples for HOICs and ROICs, respectively. The Mann–Whitney U statistic corresponding to the HOIC sample was calculated from the pooled ranks as:

$$U_{\text{obs}} = R_X - \frac{m(m+1)}{2} \tag{1}$$

where R_X is the sum of the pooled average ranks assigned to the m HOIC observations. A one-sided alternative, assuming that the HOIC values are stochastically smaller than the ROIC values, was used, and its *p*-value was defined as

$$p_{\text{MW}} = \Pr_{H_0}(U \le U_{\text{obs}}) \tag{2}$$

where U_{obs} is the observed Mann–Whitney statistic, U denotes the corresponding random statistic under the null hypothesis H_0, and $\Pr_{H_0}$ denotes probability under the null hypothesis H_0 that the HOIC and ROIC samples originate from the same underlying distribution. Given the large sample sizes, the Mann–Whitney *p*-value was evaluated using the asymptotic implementation in SciPy (scipy.stats.mannwhitneyu; Virtanen et al., 2020), with correction for ties and the default continuity correction.

For the two-sided two-sample Kolmogorov–Smirnov test, the observed statistic was defined as:

$$D_{\text{obs}} = \sup_z |F_m(z) - G_n(z)| \tag{3}$$

with the corresponding *p*-value

$$p_{\text{KS}} = \Pr_{H_0}\left(D_{m,n} \ge D_{\text{obs}}\right) \tag{4}$$

where F_m and G_n are the empirical cumulative distribution functions of the HOIC and ROIC samples, respectively; $\sup_z$ denotes the supremum over all possible z; $D_{m,n}$ denotes the random two-sample Kolmogorov–Smirnov statistic for sample sizes m and n under H_0; and H_0 denotes that the two underlying distributions are identical. The *p*-value was evaluated via the asymptotic Kolmogorov–Smirnov test in SciPy (scipy.stats.ks_2samp; Virtanen et al., 2020).”

We further added:

“Cliff's Delta was calculated directly from the Mann–Whitney statistic returned for the HOIC sample:

$$d = \frac{2U_{\text{obs}}}{mn} - 1 \tag{5}$$

where *m* and *n* are the HOIC and ROIC sample sizes, respectively. "

We also corrected several instances in which hyphens were incorrectly used instead of en dashes.

We have also corrected the reference for the two-sample Kolmogorov–Smirnov test. The previously cited goodness-of-fit paper by Massey (1951) has been replaced with the paper specifically addressing the maximum deviation between two empirical cumulative distribution functions: Massey, F. J., Jr. (1951), “The distribution of the maximum deviation between two sample cumulative step functions.”

Reference:

Wu, Z., Li, C., He, Y., Baars, H., and Seifert, P.: Horizontally Oriented Ice Crystals Observed with the Combination of Zenith and 15-degree off-Zenith pointing Polarization Lidar over Beijing

(116.3°E40.0°N), China, EPJ Web Conf., 362, 02021, https://doi.org/10.1051/epjconf/202636202021, 2026.

Massey, F. J., Jr.: The distribution of the maximum deviation between two sample cumulative step functions, Ann. Math. Statist., 22, 125–128, https://doi.org/10.1214/aoms/1177729703, 1951.

Response to Referee #2's comments

Comment on "Observation-based analysis of horizontally oriented ice crystals using dual-angle polarization lidar and cloud Doppler radar in Beijing" by Wu et al.

This study presents comprehensive case studies and statistical analyses of horizontally oriented ice crystals (HOICs) using a full year (2022) of synergistic observations in Beijing, China, combining a zenith-pointing micropulse lidar, a collocated 15° off-zenith polarization lidar, and a Ka-band cloud Doppler radar. Applying a novel height-resolved classification method based on dual-angle polarization lidars, HOICs are identified with high spatiotemporal resolution. Many novel findings have been found in this study, making it highly worthy for prompt publication. For example, HOICs are found to be common, accounting for 15.0 % of all ice-containing cloud data points annually and peaking at 24.6 % in summer, with maximum occurrence at temperatures from −20 °C to −10 °C. Also, HOICs preferentially occur in stable environments with turbulent eddy dissipation rates below 10^{-2} m^2 s^{-3} and exhibit lower fall velocities than ROICs. The manuscript is generally well written, logically organized, and addresses an important source of uncertainty in cloud remote sensing and radiative-transfer parameterizations. Minor comments have been provided as follows.

Reply: We sincerely thank Referee #2 for reviewing our paper and providing constructive comments for improvement. Responses to these comments are provided below. In this author's comment, we reply (in blue font) to Referee #2's comments (in black font). The relevant part in the revised version is in green font.

General comment

- The retrieval of particle diameter and Reynolds number follows the method introduced in the authors' previous study. However, these calculations are presented only for HOICs and not for randomly oriented ice crystals (ROICs). Is it possible to calculate those for ROICs?

Reply: Thank you for your comment. In principle, the same aerodynamic framework could be applied to ROICs if their particle habit and orientation were known. However, ROICs may include plates, columns, aggregates, and irregular particles with different mass, projected-area, and drag relationships. The need to assume particle habit and orientation makes the retrieval highly model-dependent. Therefore, the radar Doppler velocity alone cannot uniquely determine their diameter and Reynolds number. We have clarified this limitation in the revised manuscript (Section 4.6, Line 761–763):

"The retrieval was not applied to ROICs because their particle habits and orientations are not independently constrained, preventing unique estimates of Reynolds number and diameter from Doppler velocity alone."

- The retrieved median equivalent diameter of HOICs is 1187 μm, which is larger than the sizes commonly reported for pristine plates and dendrites in previous in-situ studies. The authors acknowledge that cloud-radar measurements are strongly weighted toward larger particles and may not detect smaller HOICs in optically thin cirrus. To avoid possible overinterpretation of Table 1 and Figure 14, please state explicitly in the main text or figure/table captions that the retrieved diameters and Reynolds numbers represent radar-reflectivity-weighted estimates for the radar-detectable HOIC population, rather than an unbiased size distribution of all HOICs.

Reply: Thank you for your comment. We have added "radar-reflectivity-weighted diameter and Reynolds-number estimates for the radar-detectable HOIC population" at the Fig. 14 and Table 1 captions as you suggested.

- The HOIC classification and the resulting cloud-phase fractions depend on a fixed combination of thresholds, including a zenith-to-off-zenith attenuated-backscatter ratio of 2 and a depolarization-ratio threshold of 0.6. How will the conclusion of cloud phase fraction change with varying the thresholds? Is the distribution sensitive to the fixed thresholds?

Reply: Thank you for your important comment. To evaluate the robustness of the retrieved cloud-phase fractions, we repeated the annual classification using three combinations of the zenith-to-off-zenith attenuated-backscatter ratio and depolarization-ratio thresholds.
First, the zenith-to-off-zenith attenuated-backscatter ratio of 2 and a depolarization-ratio threshold of 0.6 were used as the baseline, which is the current thresholds used in the manuscript. The results are shown in Fig. S1.

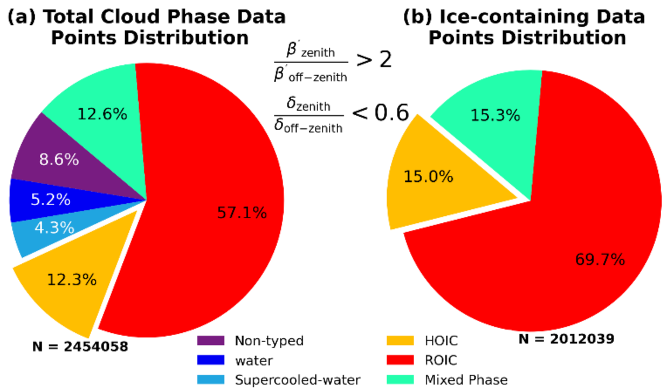

Figure S1. Statistical characteristics of cloud phase distributions in Beijing for 2022: (a) Cloud phase distribution pie charts of all cloud data points annually (b) Cloud phase distribution pie charts of ice containing cloud data points annually. Zenith-to-off-zenith attenuated-backscatter ratio of 2 and a depolarization-ratio threshold of 0.6 are used. Cloud-phase statistics in this figure are based on the relaxed cloud mask. Abbreviations: Water (warm water cloud), SWC (supercooled liquid water cloud), HOIC (horizontally oriented ice crystal), ROIC (randomly oriented ice crystal), MPC (mixed-phase cloud).

The fraction of HOICs among total cloud phase data points and among ice-containing cloud data points is 12.3% and 15.0%, respectively.

We jointly perturbed the two thresholds to construct stricter and more relaxed HOIC criteria. The first extra sensitive experiment was conducted. The zenith-to-off-zenith attenuated-backscatter ratio of 2.2 and a depolarization-ratio threshold of 0.5 were used. This represents a stricter criterion for HOICs, which requires the two lidars have stronger contrast of attenuated backscatter and depolarization ratio. The results are shown in Fig. S2.

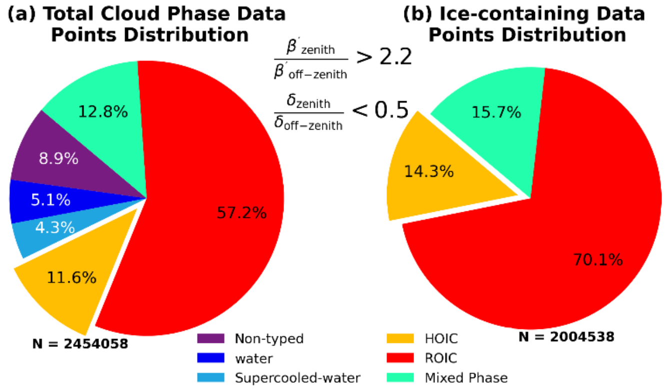

Figure S2. As in Fig. S1, but using Zenith-to-off-zenith attenuated-backscatter ratio of 2.2 and a depolarization-ratio threshold of 0.5.

The fraction of HOICs among total cloud phase data points and among ice-containing cloud data points is 11.6% and 14.3%, respectively.

Then the second extra sensitive experiment were conducted. The zenith-to-off-zenith attenuated-backscatter ratio of 1.8 and a depolarization-ratio threshold of 0.7 were used. This represents a more relaxed criterion for HOICs. The corresponding results are shown in Fig. S3.

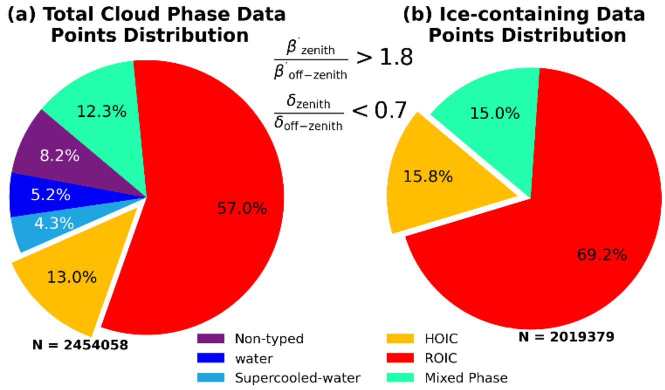

Figure S3. As in Fig. S1, but using Zenith-to-off-zenith attenuated-backscatter ratio of 1.8 and a depolarization-ratio threshold of 0.7.

The fraction of HOICs among total cloud phase data points and among ice-containing cloud data points is 13.0% and 15.8%, respectively.

The three experiments are summarized in Table S1. Under the baseline, stricter, and relaxed criteria, HOICs accounted for 12.3%, 11.6%, and 13.0% of all classified cloud data points, respectively, and for 15.0%, 14.3%, and 15.8% of all ice-containing cloud data points. Relative to the baseline, the maximum change is 0.7 percentage points for all cloud data and 0.8 percentage points for ice-containing cloud data. These results indicate that the inferred cloud-phase fractions show only limited sensitivity to the tested threshold combinations, and the main conclusion remains robust. In general, cloud phase fraction is not sensitive to the fixed thresholds. As the fixed thresholds change, the fraction of HOICs fluctuates slightly. As shown in Fig. 3 of the manuscript. The two baseline thresholds (0.6 and 2) are selected to isolate cases in which the zenith-pointing depolarization ratio is significantly lower than the off-zenith value and the zenith-pointing scatter is significantly higher than the off-zenith one. The majority of conventional cloud data (with a ratio near 1) is excluded from being misidentified.

Table S1. Summary fraction of HOICs using different fixed thresholds for two lidars

Fixed thresholds for two lidars	The fraction of HOICs among total cloud phase data points	The fraction of HOICs among ice-containing cloud data points
$\frac{\beta'_{\mathrm{zenith}}}{\beta'_{\mathrm{off-zenith}}} > 2, \frac{\delta_{\mathrm{zenith}}}{\delta_{\mathrm{off-zenith}}} < 0.6$	12.3%	15.0%
$\frac{\beta'_{\mathrm{zenith}}}{\beta'_{\mathrm{off-zenith}}} > 2.2, \frac{\delta_{\mathrm{zenith}}}{\delta_{\mathrm{off-zenith}}} < 0.5$	11.6%	14.3%
$\frac{\beta'_{\mathrm{zenith}}}{\beta'_{\mathrm{off-zenith}}} > 1.8, \frac{\delta_{\mathrm{zenith}}}{\delta_{\mathrm{off-zenith}}} < 0.7$	13.0%	15.8%

After careful examination, we also corrected the total number of the datapoints used in the manuscript of Fig. 5, which does not change the conclusion.

Minor comments:

Line 71, Actually, the authors did not provide detailed descriptions of previous studies, while they provide descriptions regarding the limitations of observations to HOICs. Thus, I would like to suggest the authors remove “these” in the sentence to say “Most of previous studies did not”

Reply: Thank you! We have removed “these” as you suggested.

Line 78-80, I would suggest the authors do not need to emphasize their previous study. Instead, they can simply say “Wu et al. (2025) introduced a range-bin-resolved method for …”.

Reply: Thank you! Done!

Line 144-145, To introduce the method proposed by other studies which the authors select to compare with, I would suggest changing the description as “Griesche et al. (2020) retrieved turbulent dissipation rates from cloud radar observations, which has been validated using tethered-balloon in situ measurements”.

Reply: Thank you! Done!

Line 148, Similar as earlier comment, the authors can simply say “in the Appendix of Wu et al. (2025)”.

Reply: Done!

Line 171, please keep the citation format the same and correct, such as Wu et al. (2025).

Reply: Done!

Line 173, please indicate the time zone for this study, local time or UTC?

Reply: We have added “local time”.

Line 182, “It is highly convincing that HOICs exist above our lidar station” is not necessary to

mention, which is a repeat to other information, and I would like to suggest removing it.
Reply: Done!

Line 205, The authors may add "unless an inversion layer exists within clouds".
Reply: Thank you! Done!

Line 259, No need to explain the median "diamonds" and interquartile range "horizontal lines", since they have been explained in the figure caption.
Reply: Thank you for the comment. We have removed "diamonds" and "horizontal lines" in the revised text.

Line 305, "introduced in" should be better as "introduced by"
Reply: Thank you! Done!

Line 314-315, I would suggest removing "finally".
Reply: Done!

Line 319-320, Note that temperature threshold -40 degree C is used earlier, different from the value -38 degree C used here. I would suggest the authors keep using the same value in this study.
Reply: Thank you for pointing out this inconsistency. We agree and have adopted −38 °C consistently as the temperature boundary between the mixed-phase and pure-ice-cloud regimes. The −40 °C value used earlier in the discussion of Fig. 3 as the mixed-phase/pure-ice temperature threshold was a rounded approximation and has now been revised to −38 °C.

Line 502, "generally stronger than that at night"
Reply: Thank you! Done!

Line 520-521, I would suggest combining this sentence into the last paragraph.
Reply: Done!

Line 687-689, "Consistent with our estimates" and "which is in good agreement with the findings in our study" are redundant to each other, please only keep one of them.
Reply: Thank you for the comment. We have removed "which is in good agreement with the findings in our study".

Line 756, I would suggest changing ":" to ","
Reply: Done!

Line 813-814, Do the authors mean "it would be desirable if such data sets are available at different sites over several years and to further examine the sensitivity of the inferred HOIC properties to cloud classification strategy, ice-crystal habit assumptions, and environmental variability"?
Reply: Thank you for pointing out this! We have rephrased the sentence as following (Line 844-

Line 846):

"In the future, it would be desirable if such datasets were available at different sites over several years to further examine the sensitivity of the inferred HOIC properties to cloud classification strategy, ice-crystal habit assumptions, and environmental variability."

Response to Referee #3's comments

This manuscript presents a valuable and comprehensive investigation of horizontally oriented ice crystals (HOICs) using a near-year-long dataset covering 354 observation days with dual-angle polarization lidars and a cloud Doppler radar. Given the scarcity of long-term, range-resolved observations of HOIC occurrence at high spatial and temporal resolutions, the dataset presented in this study is particularly valuable. The authors combine statistical analyses with representative case studies, providing useful insights into the macrophysical and microphysical characteristics of HOICs.

The methodology is generally appropriate, the observational dataset is substantial, and the manuscript is well structured and clearly written. The topic falls within the scope of Atmospheric Chemistry and Physics. I recommend publication after the authors address the following minor comments and technical corrections.

Reply: We sincerely thank Referee #3 for reviewing our paper and providing constructive comments for improvement. Responses to these comments are provided below. In this author's comment, we reply (in blue font) to Referee #3's comments (in black font). The relevant part in the revised version is in green font.

Specific Comments:

1. Please moderate definitive expressions such as "fully demonstrates." For example, Section 3.2, line 234 states, "This case fully demonstrates that⋯". Because evidence from a single case can illustrate or support an interpretation but cannot fully demonstrate a general mechanism, I suggest replacing "fully demonstrates" with "illustrates," "suggests," or "provides evidence that."

Reply: Thank you for your comment! We agree that the original wording was overly definitive for evidence derived from a single case. We have replaced "fully demonstrates" with a more cautious expression "illustrates" as you suggested. The revised sentence (Sect. 3.2, Line 259–260) reads:

"This case illustrates that the presence of SWCs is a favorable condition for the occurrence of HOICs."

2. The caption of Figure 11 states, "To ensure a causal relationship⋯". This wording is too strong. Requiring the selected SWCs to occur earlier in time and above the ice-crystal observations makes the analysis physically consistent with the sedimentation process, but it does not establish a causal relationship. I suggest revising this sentence to: "To make the analysis physically consistent with ice-crystal sedimentation, the selected SWCs must temporally precede and be located above the observed ice crystals." Related causal statements in the main text should also be moderated where appropriate.

Reply: Thank you for the suggestion. We have revised the sentence in the caption of Fig. 11 to:

"To make the analysis physically consistent with ice-crystal sedimentation, the selected SWCs must temporally precede and be located spatially above the observed ice crystals."

In the main text, we have also reviewed the related discussion and moderated causal wording to emphasize the observed spatial and temporal association between SWCs and HOICs rather than a demonstrated causal relationship.

"This phenomenon is underpinned by a distinct cloud microphysical mechanism" is changed as (Line 629 in revised version):

"This phenomenon is physically consistent with a potential cloud microphysical mechanism."

"we propose that the formation of HOICs is closely linked to microphysical processes dominated by supercooled liquid water layers" is changed as (Line 630 in revised version):

"we propose that the formation of HOICs may be closely linked to microphysical processes involving supercooled liquid water layers"

3. The manuscript identifies an EDR of approximately (10^{-2} m^2 s^{-3}) as a dynamical threshold for maintaining the horizontal orientation of ice crystals. Because this value is derived from observations at a single site during one year and may depend on the retrieval and classification methods, "threshold" could imply a universal and sharply defined physical limit. Please consider describing it as an "approximate empirical threshold," "characteristic transition value," or "observed transition range," and clarify that its broader applicability requires further evaluation.

Reply: Thank you for pointing this out. This EDR value of approximately 10^{-2} m^2 s^{-3} is based on our observation in the Beijing dataset in 2022, which may not be a universal physical threshold. We agree with your suggestions; we should be careful about the wording. We have changed the "dynamical threshold" to "approximate empirical dynamical threshold" in the main text (Line 678–Line 679):

"An EDR of approximately 10^{-2} m^2 s^{-3} can be considered one of the approximate empirical dynamical thresholds for maintaining large-scale horizontal alignment of ice crystals."

4. Figures 1, 8, and 9 use local time. Please specify the corresponding time zone and UTC offset in the figure captions and, where appropriate, for example, "China Standard Time (UTC+8)" if this is the time standard used throughout the study.

Reply: Thank you for the comment. Throughout this study, we use local time (China Standard Time, UTC+8). We have added "China Standard Time (UTC+8)" to the corresponding description in the last sentence of Sect. 2.1 to describe the time zone used:

"The time used in the paper is local time (China Standard Time, UTC+8)."

We have also revised the captions of Figs. 1, 8, and 9 to specify "Local time (UTC+8)."