We thank the two anonymous reviewers for their constructive comments. Below, we explain how the comments are addressed and make notes of the revisions in the revised manuscript. The reviewers' comments are in blue color. Our replies are in black, and our corresponding revisions in the manuscript are in red (line numbers are based on the tracked version of the revised manuscript).

Review of "Exploring Sources of Ice Crystals in Cirrus Clouds: Comparative Analysis of Two Ice Nucleation Schemes in CAM6" by Lyu et al. [Research Article, egusphere-2024-4144]

This study coupled a novel ice nucleation parameterization scheme based on Karcher (2022) into CAM6 and compared its representation of cirrus ice cloud microphysics against the default Liu and Penner (2005) scheme, with a particular focus on ice sources in cirrus cloud formation. The authors conducted a thorough assessment using both long-term simulations and case studies from the SPARTICUS and ORCAS campaigns. Their findings revealed several similarities between the two schemes, such as the climatological location of orographic gravity wave (OGW)-induced ice crystals and the same dominant source (OGW-induced) for orographic cirrus. Notable differences were also identified, primarily attributed to the distinct nucleation/competition mechanisms within the two schemes. Overall, the manuscript is well written, but its structure could be improved for better readability. For example, the excessive use of short paragraphs disrupts the flow, and combining some of them could enhance clarity. This work holds significant potential for advancing ice cloud simulations, particularly in refining parameter tuning and improving the representation of competition mechanisms. However, my major concern is the lack of sufficient physical explanations and robust evidence for the model biases and the differences found between the two schemes. If these issues can be addressed, I believe this paper will be well-suited for publication in ACP.

Thank you very much for your helpful and constructive comments. Following your comments, we have provided more physical explanations and robust evidence for the model biases and the differences found between the two schemes. We also improved our writing by combining some of the short paragraphs which are relevant.

Major comments:

1. A key concept in this study is the competition between homogeneous and heterogeneous freezing in ice cloud formation. The authors argued that the competition is stronger in the LP05 scheme than in K22 due to differences in their parameterization of homogeneous nucleation occurrence. However, this claim appears to be more of an assumption than a rigorously validated conclusion, as it is not directly substantiated from the parameterization formulas (not shown by the authors). The authors have used this assumption multiple times (e.g., Lines 246-248 and 268-270) to explain discrepancies in simulated ice cloud microphysics between the two schemes. I think a more appropriate way would be to first make this assumption explicitly and then examine it using supporting evidence from simulation results.

The authors found that fewer new ice crystals form in LP05 with the presence of pre-existing ice crystals (Line 247), which aligns with the assumption of stronger competition in LP05. However, a critical underlying assumption is that both schemes should have a similar or comparable number concentration of pre-existing ice crystals. If the LP05 experiments contain a higher concentration of pre-existing ice crystals than K22, it becomes difficult to determine whether the reduction in new ice formation is genuinely due to stronger competition in LP05 or a result of differing initial conditions. To address this issue, the authors should ensure that the number concentration of pre existing ice crystals is close across experiments or, at the very least, discuss the potential influence of variations in pre-existing ice concentrations on their results.

Additionally, the proposed indirect explanation for the increase in ice number concentration in K22 is not sufficiently substantiated. For example, the authors did not show evidence on how the changed circulation dynamics impact the sub-grid turbulence, making this explanation remain speculative rather than a well-supported conclusion.

Thank you very much for your comments.

First, we appreciate the reviewer's comment regarding that the competition among ice sources is stronger in the LP05 scheme than in the K22 scheme. While this assessment may appear to rely on assumptions, it is actually supported by the relevant figures, specifically Fig. 5b, 7b, 8b, and 10b. When the contribution (ΔN_i) of a specific ice source is negative, it indicates that incorporating this ice source leads to a reduction in total N_i, therefore suggesting a competitive interaction with other ice sources. In our simulations, the ΔN_i values for ice sources in the LP05 scheme are generally more negative than those in the K22 scheme. Thus, the assessment that competition among ice sources is stronger in the LP05 scheme is reasonable. To enhance clarity, we have provided further explanations to the related paragraphs to assist readers in understanding this point (line 513-518).

"Fig. 5b shows the differences in simulated N_i between the reference experiments (OGW) and sensitivity experiments (no_OGW, no_DET and no_TKE). Larger differences in simulated N_i between sensitivity experiments and the reference experiments indicate a more significant contribution from a respective ice crystal source (OGW-induced, detrained, or turbulence-induced). Specifically, increase or decrease of microphysical properties in the sensitivity experiments compared to the reference experiments reveals how each source contributes to enhancing or inhibiting the overall ice number concentrations."

In addition, we thank the reviewer for highlighting the need for more descriptions of the two nucleation schemes and the associated competition mechanisms. In response, we have expanded Section 2.2 by adding Section 2.2.2 to introduce the LP05 scheme and Section 2.2.3 to compare the two schemes for treating the competition between different ice sources.

We also appreciate the reviewer's suggestion to clarify how pre-existing ice crystals are treated in the two schemes, to ensure a fair comparison. The model simulates interactively the competition/interaction between new ice formation and pre-existing ice (which are the ice crystals that are formed in previous time steps in the model grid or that transport/settle from other model grids). The fact that the LP05 scheme simulates a lower ice number concentration suggests that it contains a lower (not higher) concentration of pre-existing ice crystals than K22. Thus, the reduction in new ice formation is truly due to the strong competition treated in LP05.

Lastly, we are grateful for the reviewer's recommendation to elaborate on how changes in circulation influence subgrid-scale turbulence. In response, we have shown in Figure S3 subgrid-scale vertical velocity changes between the two schemes and refined the related explanations in the relevant sections of the manuscript.

The corresponding sentences have been revised as follows (in lines 411-420 and 817-820):

"Similarly, subgrid-scale vertical velocity increases in the K22_OGW-Climo experiment compared to the LP05_OGW-Climo experiment, particularly in the upper troposphere at mid- and high latitudes (Fig. S3). While these changes may enhance ice nucleation locally, their overall impact on N_i remains limited, as vertical velocity changes are generally small (less than ±0.002 m s^{-1}) in most regions. Therefore, they are unlikely to explain the globally significant increase in N_i simulated in the K22 scheme (Fig. 2)."

"An increase in cloud frequency may induce changes in global temperature, potentially affecting subgrid-scale vertical velocity, thereby impacting ice nucleation. However, these factors are not the key factors that cause the significant increase in N_i."

2. Since one purpose of this paper is to evaluate the K22 scheme, incorporating climatological (6 year) observational data is important for assessing the performance of both schemes. If obtaining global vertical profiles is challenging, bulk or regional observational data would still be valuable in determining whether K22 improves ice cloud simulations compared to LP05 from a climatological perspective.

Thank you very much for your comments. We agree that it is highly valuable to compare simulation results with observed cirrus clouds from a climatological perspective. However, it is challenging to get suitable observational data. We see this as an important direction for future work and may pursue it in a separate study. We will conduct further evaluations of the K22 scheme based on model climatology in our future studies by comparing modeled cirrus clouds with regional observational datasets (e.g., Krämer et al., 2016; 2020) and global satellite data as in Lyu et al. (2023).

The corresponding sentences have been added as follows (in lines 884-886):

"Further evaluations of the K22 scheme based on model climatology will be conducted in the future by comparing modelled cirrus with regional observational datasets (Krämer et al., 2016; Krämer et al., 2020) and global satellite data (Lyu et al., 2023)."

3. To deepen the insights of this study, the authors could discuss the potential impact of incorporating K22 into CAM6 on high cloud feedback. For example, if the proposed indirect mechanism for the higher ice number concentrations in K22 is true, large-scale circulation changes induced by global warming could modify sub-grid turbulence, subsequently affecting ice nucleation, cloud frequency, and longwave radiative effects.

Thank you very much for your comments. Investigating the potential impact of different nucleation schemes on high cloud feedback is indeed an important direction. In the revised manuscript, we have included discussions comparing cloud properties between the K22 and LP05 schemes, as shown in Fig. R2-1. Note that Fig. R2-1 has been included in the Supplementary Material. We have also added some discussions on the impacts of different nucleation schemes on cloud properties, which can modify global temperature, large-scale circulation, and sub-grid turbulence, subsequently affect ice nucleation, cloud frequency, and cloud radiative effects, and have important implications for high cloud feedbacks.

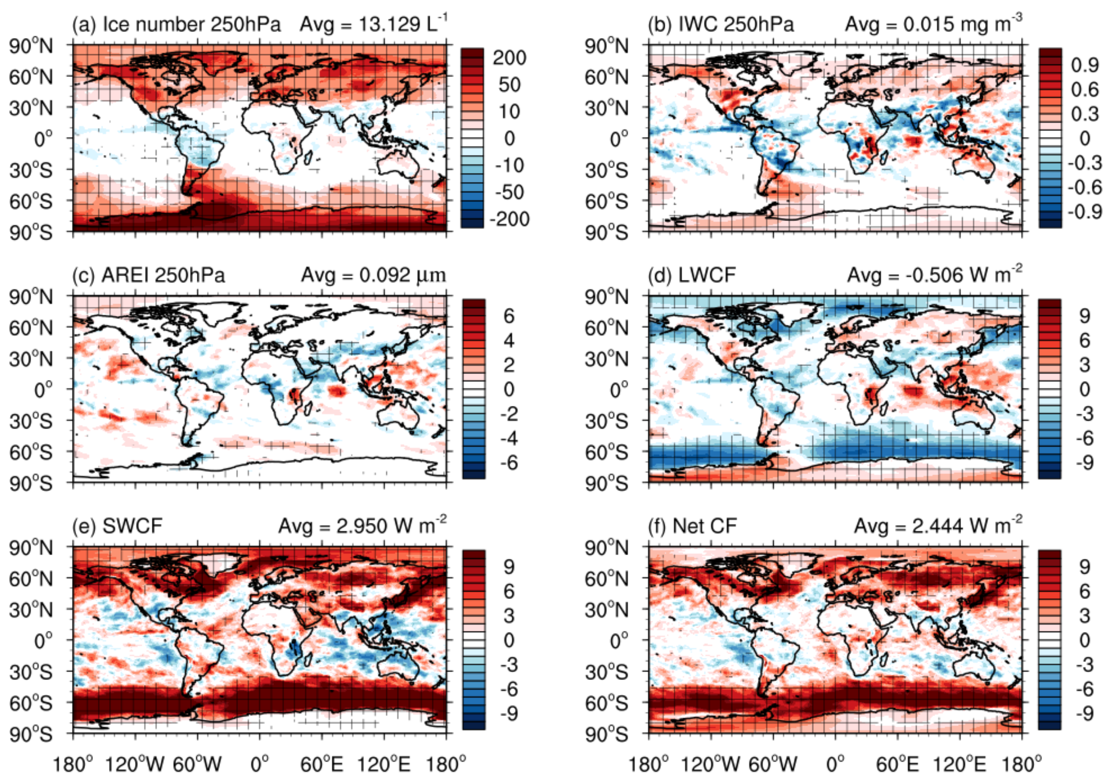

Figure R2-1. Annual mean differences between the K22_OGW-Climo and LP05_OGW-Climo experiments from 6-year climatological simulations (K22-LP05). Shown are grid-averaged ice number concentration (N_i) at 250 hPa, grid-averaged IWC at 250 hPa, grid-averaged ice effective radius (AREI) at 250 hPa, longwave cloud forcing (LWCF), shortwave cloud forcing (SWCF), and net cloud forcing (net CF). Meshed grid areas indicate values that are statistically significant at the 5% level.

When the nucleation scheme is switched from LP05 to K22, an increase in grid-averaged ice number concentration (N_i) is observed in the mid- and high- latitudes (Fig. R2-1a). Ice water content (IWC) also increases, particularly over high mountains (Fig. R2-1b), which may be attributed to enhanced depositional growth resulting from a greater number of smaller ice crystals in the K22 scheme.

The simulated ice effective radius (AREI) exhibits contrasting behavior over land and ocean in mid- and high latitudes (Fig. R2-1c). Over land, particularly mountainous areas, AREI tends to decrease, while over the ocean it increases. This suggests that compared to the LP05 scheme, the K22 scheme produces cirrus clouds with smaller ice crystals over elevated terrain and simulates larger crystals over oceanic regions.

In terms of longwave cloud forcing (LWCF), an increase is noted over high mountain areas in mid- and high latitudes (Fig. R2-1d). This is because the increase of N_i over mountains in the K22 scheme. Interestingly, negative LWCF can be found over oceans at mid- and high latitudes. This phenomenon is primarily associated with the dominance of optically thin cirrus clouds formed via in-situ nucleation in these regions, as previously reported (Sassen & Cho, 1992; Sassen et al., 2008; Wang et al., 1996; Winker & Wielicki, 2010). The K22 scheme tends to enhance the spatial extent and occurrence frequency of such clouds. Over oceans, where vertical velocities are weaker than over land, these optically thin clouds become even thinner. This allows more longwave radiation to space, resulting in negative LWCF over oceans, consistent with the previous findings (Muri et al., 2014; Spang et al., 2024).

Shortwave cloud forcing (SWCF) increases in mid- and high latitudes (Fig. R2-1e), which can be attributed to increases in N_i, total cloud fraction and the contrast in shortwave albedo between the surface and clouds. The shortwave surface albedo of the ocean can reach 50-80 % under low solar angles (when the sun is near the horizon), while snow-covered land can exhibit albedos of 80-90 %. In contrast, cirrus clouds typically have a shortwave albedo of about 10-40 %. In addition, due to the low solar angles in high latitudes, cirrus clouds with a higher concentration of small ice crystals in K22 may enhance forward scattering rather than reflection, allowing more shortwave radiation to reach the surface. As a result, in high-latitude regions, the K22 scheme simulates less shortwave radiation reflected, leading to an increase in SWCF.

These paragraphs have been included in the revised manuscript (line 488-505).

"When the ice nucleation scheme is switched from LP05 to K22, grid-averaged N_i increases in the mid- and high latitudes (Fig. S13a). Ice water content (IWC) also increases (Fig. S13b) especially over high mountains. Ice effective radius (AREI) over land tends to be smaller and that over ocean tends to be larger, compared to the LP05 scheme (Fig. S13c). In mid- and high latitudes, longwave cloud forcing (LWCF) is increased over high mountains, as can be seen in Fig. S13d. These changes can be explained by changes in the N_i (Fig. S13h), as the K22 scheme generally simulates more ice crystals over high mountains. Interestingly, negative LWCF over oceans can be found in mid- and high latitudes. This phenomenon is primarily associated with the dominance of optically thin cirrus clouds formed via in-situ nucleation in these regions, as previously reported (Sassen & Cho, 1992; Sassen et al., 2008; Wang et al., 1996; Winker & Wielicki, 2010). The K22 scheme tends to enhance the spatial extent and occurrence frequency of such clouds. Over oceans, where vertical velocities are weaker than over land, these optically thin clouds become even thinner. This allows more longwave radiation to space, resulting in negative LWCF over oceans, consistent with the previous findings (Muri et al., 2014; Spang et al., 2024). Shortwave cloud forcing (SWCF) increases in mid- and high latitudes (Fig. S13e), as the shortwave albedo of extensive cirrus clouds (10-40%) is lower than that of the underlying surface (ranging from 50-80% for oceans at low solar angles and 80-90% for snow-covered land). Changes in SWCF, LWCF and net cloud forcing (net CF) caused by the switch of ice nucleation scheme from LP05 to K22 are -0.51 W m^{-2}, 2.95 W m^{-2}, and 2.44 W m^{-2}, respectively. The change in the cloud radiative forcing may influence global temperature, which can modify large-scale circulation and sub-grid turbulence, subsequently affect ice nucleation, cloud frequency, and cloud radiative forcing, and have important implications for high cloud feedbacks (Murray & Liu, 2022)."

4. One structural issue in the manuscript is the overuse of short paragraphs, which disrupts the flow of the text. I recommend revisiting the paragraph structure and merging shorter paragraphs with logically related content to enhance readability and coherence. I will provide some specific suggestions in the minor comments, though they are not exhaustive.

Thank you very much for your thoughtful comments. In response, we have reorganized the paragraph structure and combined short paragraphs to improve the clarity and flow of the text.

Minor comments:

L7: I'd suggest reorganizing the abstract into two paragraphs or three at most.

Thank you very much for your valuable comments. In response, we have reorganized the abstract into two paragraphs for improved clarity and readability.

L88: Please give a brief reason why both field campaigns are used for validation. Any differences between these two or just for increasing the sample size?

Thank you very much for your comment. Observational data from field campaigns on cirrus clouds are generally considered to be more reliable compared to remote sensing methods such as satellite observations. We focus on the SPARTICUS and ORCAS campaigns in this study because they provide critical data on OGW-induced ice crystals. The SPARTICUS campaign involves flights over the mountainous regions from winter to summer, while the ORCAS campaign focuses on both ocean and continental regions during the summer. We added in the revised manuscript (line 243-246):

"We focus on the SPARTICUS and ORCAS campaigns in this study because they provide critical data on OGW-induced ice crystals. The SPARTICUS campaign involves flights over the mountainous regions from winter to summer, while the ORCAS campaign focuses on both ocean and continental regions during the summer."

L98: No definition for "DET" upon its first appearance.

Thank you very much for your comment. We have added necessary definitions as follows (line 249-250):

"To isolate the effects of each source, we designed three sensitivity tests: no_DET (no detrainment), no_TKE (no CLUBB-TKE) and no_OGW (no OGWs),…"

L127: "thermaldynamic" to "thermodynamic"

Done. Thank you very much for your comment.

L150: Suggest moving this paragraph up.

Thank you very much for your comments. We have merged the paragraphs as suggested.

(line 208-214):

"Overall, the K22 scheme provides a more continuous and interactive treatment of multiple ice nucleation pathways, with a stronger emphasis on the dynamic interplay between supersaturation, aerosol concentrations, and pre-existing ice crystals. On the other hand, the LP05 scheme employs a stepwise approach that directly compares the potential for nucleation with the concentration of pre-existing ice crystals, imposing a threshold when nucleation occurs. Uncertainties exist regarding the relationship between the reduction of supersaturation and the suppression of nucleation caused by pre-existing ice crystals. This relationship and its impact on the number of nucleated ice crystals requires further investigations."

L152: "compared" to "compared to"

Corrected. Thank you.

L211: Since OGW-induced cloud nucleation is a very important source for ice cloud formation, I'd suggest comparing the climatology simulation results between land and oceans. The results over the land might be more contrasting between the two schemes.

Thank you very much for your insightful comments. The comparison of climatology simulation results between land and oceans is very important and is shown in Fig. 4e and

4f. We have included relevant discussions in the revised manuscript as suggested (line 372-383):

"Fig. 4 shows the global longitude-latitude distribution of annual mean N_i at 250 hPa... Consistent with the results shown in Fig. 2, the K22_OGW-Climo experiment tends to produce higher ice number concentrations in all three types of simulated cirrus compared to the LP05_OGW-Climo experiment (Fig. 4a and 4b)…OGW-induced ice crystals in the K22 scheme are more abundant and broadly distributed over mountainous regions compared to the LP05 scheme (Fig. 4e and 4f). "

L215: Why more cirrus due to OGWs in high latitudes, particularly near the Poles (Figures 2e and 2f)?

Thank you very much for your comment. There are two reasons for this. First, there are many mountains and high plateaus in high latitudes, especially in Northern hemisphere and South Poles. These high lands are significant sources of orographic cirrus clouds. Second, other ice sources, such as convective detrainment and turbulence-induced ice crystals, are generally much weaker in high latitudes compared to low latitudes.

The relevant paragraph has been modified as follows (line 321-324):

"In both schemes, ice crystals detrained from convection are primarily concentrated in the tropical regions and mid-latitudes, and in situ nucleated ice crystals induced by turbulence are prevalent near the tropical tropopause layers (TTL) and in mid-latitudes. In contrast, due to the presence of mountains and high plateaus, orographic cirrus due to OGWs are concentrated over mid- and high latitudes."

L216: Please clarify the physical mechanisms for turbulence-induced ice nucleation.

Thank you very much for your comment. Turbulence-induced ice crystals are those ice crystals generated by vertical velocities from CLUBB-TKE. These vertical velocities result from small-scale turbulences with small Richarson numbers, which CLUBB is capable of capturing.

L232: "results" to "resulting", "resemble" to "resembles"

Done. Thank you.

L279: Any physical explanations for changes in sub-grid turbulence?

Thank you very much for your comment. The application of different ice nucleation schemes affects the formation of cirrus clouds in the simulation, which in turn influences temperature, leading to alternations in sub-scale turbulence.

L303: "Together with … (Fig. S7)" to "Together with simulated IWC and Dnum (Fig. S7)"

Thank you very much for your comments. We have modified the relevant sentence as suggested (line 509-510):

"Together with simulated IWC and D_{num} (Fig. S14), both schemes produce results that generally agree with observational data. "

L316: What does "Temperature in X-axis" represent? Pressure-level mean temperature?

Thank you very much for your comment. We use temperature as the x-axis because ice nucleation is dependent on temperature. Also, temperatures correspond to specific pressure levels in the troposphere.

L330: "ΔNi" to "ΔNi due to OGWs"

Thank you very much for your comments. We have modified the relevant sentence as suggested (line 540-541):

"Particularly in regions with temperatures below 215 K, where both schemes simulate their highest N_i peaks, ΔN_i due to OGWs peaks positively at the corresponding temperatures."

L336-337: Be specific. It looks dependent on the source types.

Thank you very much for your comment. We have modified the relevant sentences as follows (line 543-551):

"Detrained and turbulence-induced ΔN_i values show different signs, fluctuating between positive and negative at different temperatures, indicating that the effects of the other two sources are uncertain and vary between the two schemes. In the LP05 scheme, detrained and turbulence-induced ΔN_i values are generally negative, suggesting that ice crystals from both detrainment and turbulence tend to inhibit N_i. In contrast, the K22 scheme exhibits varied signs of detrained and turbulence-induced ΔN_i values, with stronger fluctuations between positive and negative, indicating that these sources can either enhance or inhibit N_i. Notably, the positive ΔN_i values in detrained and turbulence-induced ice crystals are smaller in the LP05 scheme, suggesting stronger competition (inhibition effects) between ice sources in the LP05 scheme."

L351: As in K22 the detrained ice crystals do not have a significant competition, I'd expect that Dnum is slightly lower in K22_no_DET-SP (red lines in Fig. S9) than in

K22_OGW-SP. However, why is it slightly higher in K22_no_DET-SP when T is less than 227 K?

Thank you very much for your comment. As shown in Figure 5, the detrained ice in the K22 scheme has a very small effect (competition) on the overall N_i, thus the difference of Dnum between K22_no_DET-SP and K22_OGW-SP is small, and within the uncertain range (25th percentile to the 75th percentile) of the model simulations.

We have removed the related sentences to avoid confusion.

L388: Suggest moving this paragraph up

Thank you very much for your comment. We have merged the relevant paragraphs and re-written as follows (line 619-634):

"As shown in Fig. 7, multiple observed N_i peaks correspond to different contributors to ΔN_i, revealing that cirrus clouds exhibit multilayer structures with distinct ice sources. Simulated N_i displays pronounced peaks above 225 K and near 210 K. At lower altitudes, where high N_i values are observed at temperatures above 225 K, both schemes simulate positive ΔN_i values, indicating that ice crystals due to OGWs and detrainment are the dominant contributors to simulated N_i in both schemes. In the LP05 scheme, turbulence-induced ΔN_i values are generally negative, implying that ice crystals from turbulence tend to suppress the overall N_i. In contrast, in the K22 scheme, turbulence-induced ΔN_i values fluctuate from negative to positive, suggesting inhibition between 215-230 K and enhancement of N_i at temperatures ⩾ 235 K. At the 210 K level, the overwhelmingly positive ΔN_i values due to turbulence in both schemes suggest that turbulence-induced ice crystals are the primary contributors to N_i (Fig. 7b). However, in the LP05 scheme, ΔN_i values due to OGWs are negative, suggesting that OGW-induced ice crystals tend to inhibit ice crystal formation. In contrast, their impacts are minimal (~0) in the K22 scheme. In addition, both schemes simulate generally negative ΔN_i values due to detrainment, implying that detrained ice crystals tend to suppress the following ice formation."

L391: Why is its magnitude so large between 220 and 230 K?

Thank you very much for your comment. The contribution (ΔN_i) of ice crystals generated by turbulence can reach up to -10 L^{-1}. While this may appear relatively large in the plot, it is not considered a large value.

L402: It seems like no_TKE experiment shows the highest peak. Please double check.

Thank you very much for your comment. We focused on the peaks in the OGW experiments (which include no-TKE experiments). We have modified the sentence to avoid any confusion as follows (line 654-656):

"Near 215 K, the OGW experiments in both schemes simulate high N_i peaks that closely match the observed high peak near 218 K."

L413: Please rephrase this sentence.

Thank you very much for your comments. We have rephrased the sentence to address the issue more clearly as follows (line 674-675):

"In the lower part of cirrus clouds (T > 225K), negative ΔN_i values of all three ice crystal sources in the LP05 scheme suggest universal competition among these sources."

L456: "OGW-induce" to "OGW-induced"

Done. Thank you.

L456: Are these dates selected when the simulations of both schemes align with the observations?

Thank you very much for your comment. The median N_i values from OGW experiments in both schemes fall within the observed N_i range. In addition, the primary contributor of ice crystals on these selected dates is the OGWs.

L481: "considering" to "with a focus on"

Done. Thank you.

L490-495: Are there any physical reasons, or formula-related proofs? If not, the first reason is more like an assumption.

Thank you very much for your comments. The competition between ice sources in both the LP05 and K22 schemes is based on certain assumptions in the schemes. We modified the sentences as follows (line 806-813):

"The direct reason lies in their different assumptions of treating the competition between pre-existing ice and nucleated ice crystals. The K22 scheme emphasizes the dynamic interplay between supersaturation, aerosol concentrations and pre-existing ice, allowing homogeneous nucleation, heterogeneous nucleation and the growth of pre-existing ice crystals to occur simultaneously. In contrast, the LP05 scheme is based on an empirical framework that favors a specific nucleation pathway. In the LP05 scheme, heterogeneous nucleation is favored at low supersaturation and high INP concentrations, while homogeneous nucleation dominates at high supersaturations. Pre-existing ice crystals consume supersaturation before new ice nucleation can occur. This may result in a stronger competition in the LP05 scheme, suppressing homogeneous nucleation. "

L496-500: Have you examined the changes in large-scale circulations and their association with sub-grid turbulence variations? If not, you would have to soften your tone when proposing the indirect reason.

Thank you very much for your valuable comments. We have softened our tone when we talk about the indirect reason. The relevant paragraph has been modified as follows (line 814-820):

"The indirect reason is related to the increase in ice number concentrations within the K22 scheme, which appears to lead to higher cloud frequency. This can be due to the presence of smaller ice crystals in the K22 scheme, which have lower fall speeds, allowing them to travel over broader regions before completely sublimated. An increase in cloud frequency may subtly induce changes in global temperature, potentially affecting turbulence and subgrid-scale vertical velocity, thereby impacting ice nucleation. However, these factors are not the key factors that cause the significant increase in N_i."

L524: Please move it to the last paragraph.

Thank you very much. We have merged the relevant paragraphs.

L532: Be specific for these critical INPs.

Thank you very much for your comments. We have modified the relevant sentence as follows (line 879-880):

"We note that other critical INPs (such as black carbon, metallic particles, biological materials) besides mineral dust are not currently represented in current ice nucleation schemes (Lin et al., 2025). "

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