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).

Recommendation: Return to Authors for Major Revisions

Overview:

The study by Lyu et al. (2024), titled "Exploring Sources of Ice Crystals in Cirrus Clouds: Comparative Analysis of Two Ice Nucleation Schemes in CAM6," is interesting and valuable for the field of cloud physics and development of Earth system model. However, this manuscript needs significant improvements before being published. Below are my comments, questions and suggestions.

Thank you very much for your helpful and constructive comments.

Major comments/questions:

1. The grammar and wording of this manuscript is poor. I added some revision suggestions in the minor comment/questions part, but strongly recommend the authors carefully go through the whole manuscript to improve the writing. Also, the logic in several sections is difficult to follow, which also needs to improve.

Thank you very much for your comments. We have carefully reviewed the manuscript to improve both the writing and the logic flow. First, we refined the language by adding more detailed explanations and clarified previously ambiguous points. Second, we improved the structural coherence of the manuscript by reorganizing paragraphs and sections to ensure a more logical presentation of the content.

2. Generally, the INP activation differences between K22 and LP05 could be explained by activation efficiency difference and aerosol difference. It is great that both factors are analyzed in Section 4.1. However, it seems the biases analysis in Sections 4.2 and 4.3 only focuses on INP activation efficiency, while totally neglects aerosol concentration. This really needs improvement by adding aerosol concentration evaluation and comparison.

Thank you very much for your comments. We did not include aerosol concentration evaluation in Section 4.2 and Section 4.3 because there were no aerosol measurements during the flights. Both the SPARTICUS and ORCAS campaigns primarily focused on cirrus clouds, and no corresponding aerosol observational data were available to support the model validation. However, we agree with the reviewer that comparing the aerosol concentrations between the two schemes adds important value. Therefore, we have included the comparisons of simulated coarse mode dust number concentrations during the SPARTICUS and ORCAS campaigns (Figures R1-1, R1-2, R1-3, and R1-4). These figures have been included in the supplementary materials, and the corresponding text has been incorporated into Section 4.2 and 4.3 to reflect these additions.

The relevant paragraph has been modified as follows (line 593-596):

"The simulated coarse mode dust number concentrations are shown in Fig. S17, which shows higher values in the K22 scheme than those in the LP05 scheme. However, the dust concentrations are very low (< 1 L^{-1}) in both schemes, which supports the dominance of homogeneous ice nucleation for cirrus cloud formation during the SPARTICUS campaign."

(line 610-612):

"The simulated coarse mode dust number concentrations are presented in Fig. S19, which shows higher values with the K22 scheme compared to the LP05 scheme."

(line 644-645):

"Figure S20 shows the simulated coarse mode dust number concentrations, with the K22 scheme generally simulating higher dust concentrations compared to the LP05 scheme."

(line 692-694):

"Simulated coarse mode dust number concentrations from both schemes are compared in Fig. S21, showing that the K22 scheme simulates much higher dust concentrations than the LP05 scheme."

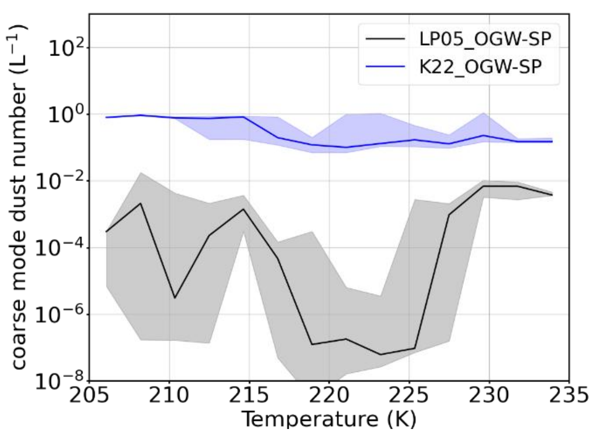

Figure R1-1. Comparison of coarse mode dust number concentrations between LP05_OGW-SP and K22_OGW-SP during the SPARTICUS campaign.

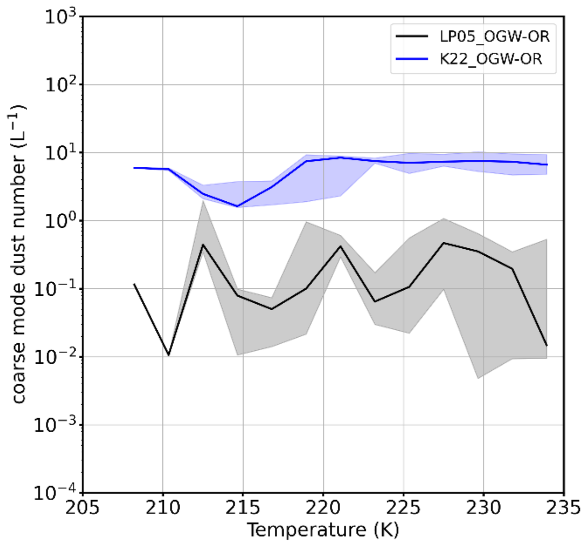

Figure R1-2. Comparison of coarse mode dust number concentrations between LP05_OGW-OR and K22_OGW-OR during the ORCAS campaign in Region 1.

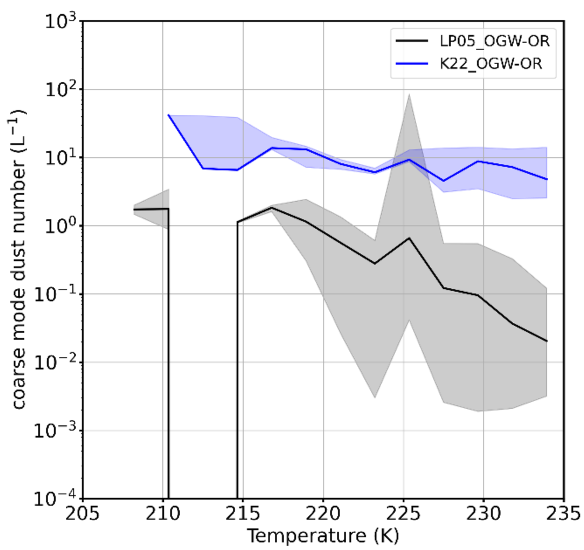

Figure R1-3. Comparison of coarse mode dust number concentrations between LP05_OGW-OR and K22_OGW-OR during the ORCAS campaign in Region 2.

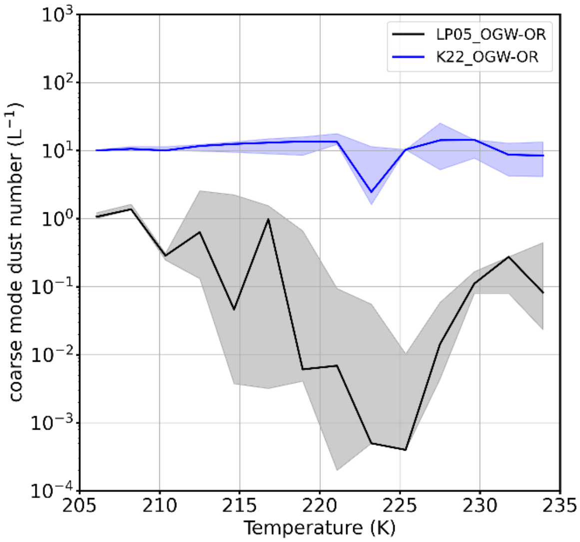

Figure R1-4. Comparison of coarse mode dust number concentrations between LP05_OGW-OR and K22_OGW-OR during the ORCAS campaign in Region 3.

3. All conclusions in this study are based on one precondition that Ni is mainly dominated by INP activation, while other source/sink terms like secondary ice production, ice sedimentation and sublimation are totally neglected. In my view, this leads to incomplete discussion. More effort is needed to verify that the INP activation dominates Ni.

Thank you very much for your comments. In this study, we do not have the precondition that N_i is mainly dominated by ice nucleation, and acknowledge that other processes such as secondary ice production, ice sedimentation and sublimation can also impact N_i and contribute to the discrepancies between model results and observations. We have added some discussions.

For the SPARTICUS campaign, the relevant paragraph has been modified as follows (line 602-604):

"Additionally, discrepancies between the simulations and observations may stem from limitations in model representations of other microphysical processes, such as ice depositional growth, cloud ice to snow autoconversion and accretion, and ice sedimentation."

For the ORCAS campaign where multi-layer cirrus clouds frequently occurred, ice sedimentation and sublimation can be important for determining N_i in these clouds. The model may also miss other sources of ice crystals in these clouds when compared with observations. The relevant paragraph has been modified as follows (line 679-680 and line 685-687):

"The fact that no ΔN_i values from a single source are overall positive in both schemes may suggest that the dominant ice source is missing from the model."

"In addition, other important N_i source and sink processes, such as secondary ice production, ice sublimation and sedimentation should be examined."

In the Summary and Conclusions section, we added (line 871-873):

"Furthermore, our comparison between simulated cirrus clouds with observations highlights the need for refining the model representation of key processes governing cirrus cloud evolution. They include detrainment, ice crystal growth mechanisms (ice deposition, and accretion), secondary ice production, sublimation, and ice crystal sedimentation."

4. The competition between homogeneous and heterogeneous freezing seems to be sensitive to three important physical mechanisms: ice detrainment, OGW and TKE, and their impacts are discussed. However, the homogeneous and heterogeneous freezing rates in experiments are not shown, and the corresponding conclusions are based on speculation. Please show the freezing rates to support your conclusions.

Thank you very much for your comments. The MG2 scheme computes ice number (N_i(t) which represents ice number at time t) using both ice number (N_i(t-1)) and number tendency (ΔN_i(t-1)) at time t-1 with time step (30 minutes). This allows us to distinguish between pre-existing (N_i(t-1)) and newly generated ice crystals (ΔN_i(t)) at a specific time t and model grid. However, the model calculates the number of homogeneously and heterogeneously nucleated ice crystals at each time step and model grid and then derives the corresponding freezing rates.

Fig. R1-5 and Fig. R1-6 show the annual mean ice number tendency due to heterogeneous nucleation (ΔN_{i_het}) from 6-year climatology simulations, shown as zonally distributed (Fig. R1-5) and at 250 hPa (Fig. R1-6). Both schemes simulate ΔN_{i_het} are concentrated at mid- and high-latitudes in the upper troposphere (Fig. R1-5a, b), indicating that heterogeneous nucleation is most active in these regions. High ΔN_{i_het} values extend over land and ocean regions (Fig. R1-6a, b). Compared to the LP05 scheme, the K22 scheme simulates higher ΔN_{i_het} values in mid and high latitude regions. This enhancement aligns with the higher coarse mode dust number in the K22_OGW-climo experiment (see Fig. S4 in the supplementary material). Both schemes show similar ΔN_{i_het} distributions from convective detrainment between no_DET and OGW experiments (Fig. R1-5c, d and Fig. R1-6c, d), indicating that heterogeneous nucleation is not directly influenced by convective detrainment. In contrast, the no_OGWs experiments (Fig. R1-5e, f and Fig. R1-6e, f) show pronounced reduction in ΔN_{i_het} in the mid- and high latitudes compared to OGW experiments, revealing the significant role of OGWs in enhancing heterogeneous nucleation. This effect is especially evident in the K22 scheme, which shows substantial ΔN_{i_het} reductions over continental regions, especially over mountainous areas such as the Himalayas, Andes, Alps and Rockies, indicating a strong sensitivity of heterogeneous ice nucleation to OGWs. The LP05 scheme exhibits more limited changes in ΔN_{i_het}, suggesting a weaker enhancement from OGWs. These different results between the two schemes are due to their distinct parameterizations of heterogeneous nucleation. For turbulence-induced ΔN_{i_het} (Fig. R1-5 g, h and Fig. R1-6g, h), both the K22_noTKE and LP05_noTKE experiments simulate reduced ΔN_{i_het} compared to their respective OGW-Climo experiments. This result indicates that turbulence reinforces INP activation.

Fig. R1-7 and Fig. R1-8 present the zonal mean and 250 hPa ice number tendency due to homogeneous nucleation (ΔN_{i_hom}). In both schemes, homogeneous nucleation primarily occurs over high mountains in mid- and high latitudes, as well as in the tropical tropopause layers (TTL). Overall, the K22 scheme produces larger ΔN_{i_hom} compared to the LP05 scheme. The LP05_no_DET experiment exhibits enhanced ΔN_{i_hom} in the tropopause (Fig. R1-7c and R1-8c), compared to the LP05_OGW-Climo experiment, indicating that convective detrainment suppresses homogeneous nucleation in the LP05 scheme. In contrast, the K22_no_DET experiment exhibits limited changes compared to the K22_OGW-Climo experiment, indicating that detrainment has a limited effect on homogeneous nucleation in the K22 scheme (Fig. R1-7d and R1-8d,). Both schemes simulate significantly reduced ΔN_{i_hom} over high mountains compared to the OGW experiments (Fig. R1-7e, f and R1-8e, f), emphasizing the role of OGWs in promoting homogeneous nucleation. Similarly, the no_TKE experiments (Fig. R1-7g, h and R1-8g, h) produce reduced ΔN_{i_hom} in the TTL for both schemes, revealing that turbulence enhances homogeneous nucleation in this region.

The above discussions have been included in the manuscript (line 437-463).

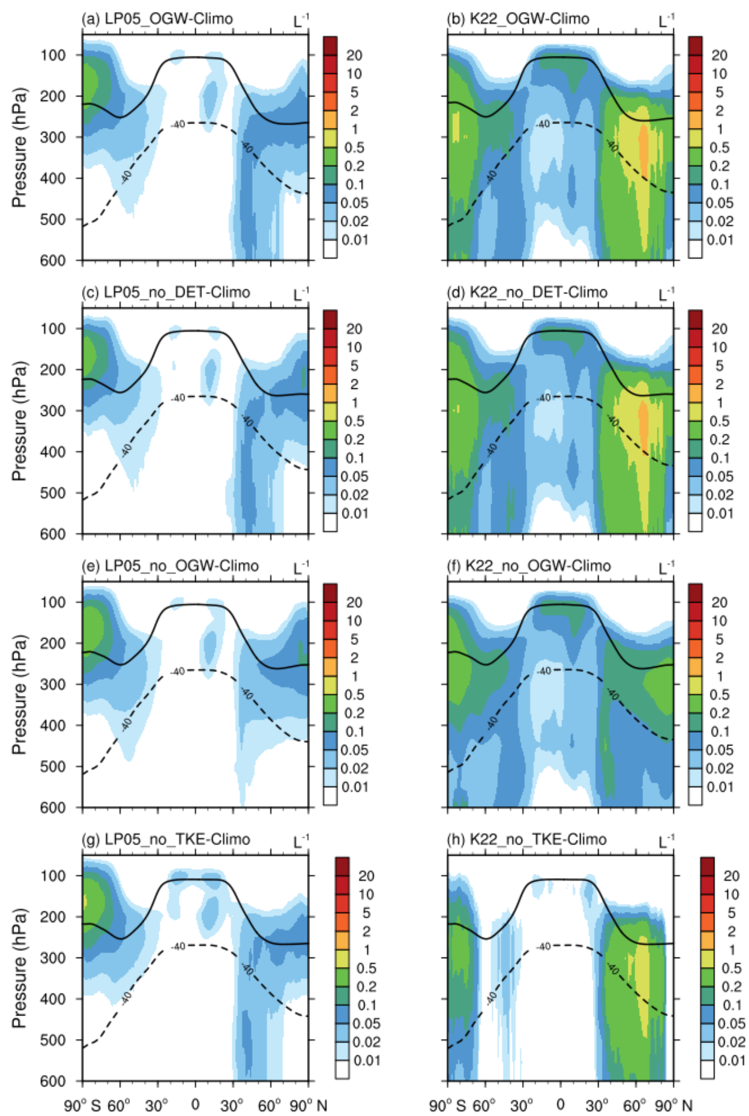

Figure R1-5. Annual zonal ice number tendency due to heterogeneous nucleation ΔN_{i_het} from 6-year Climatology simulations in the upper troposphere (above 600 hPa). Dashed lines indicate the annual mean -40 ℃ isothermal line, and solid lines represent the tropopause in the corresponding simulations.

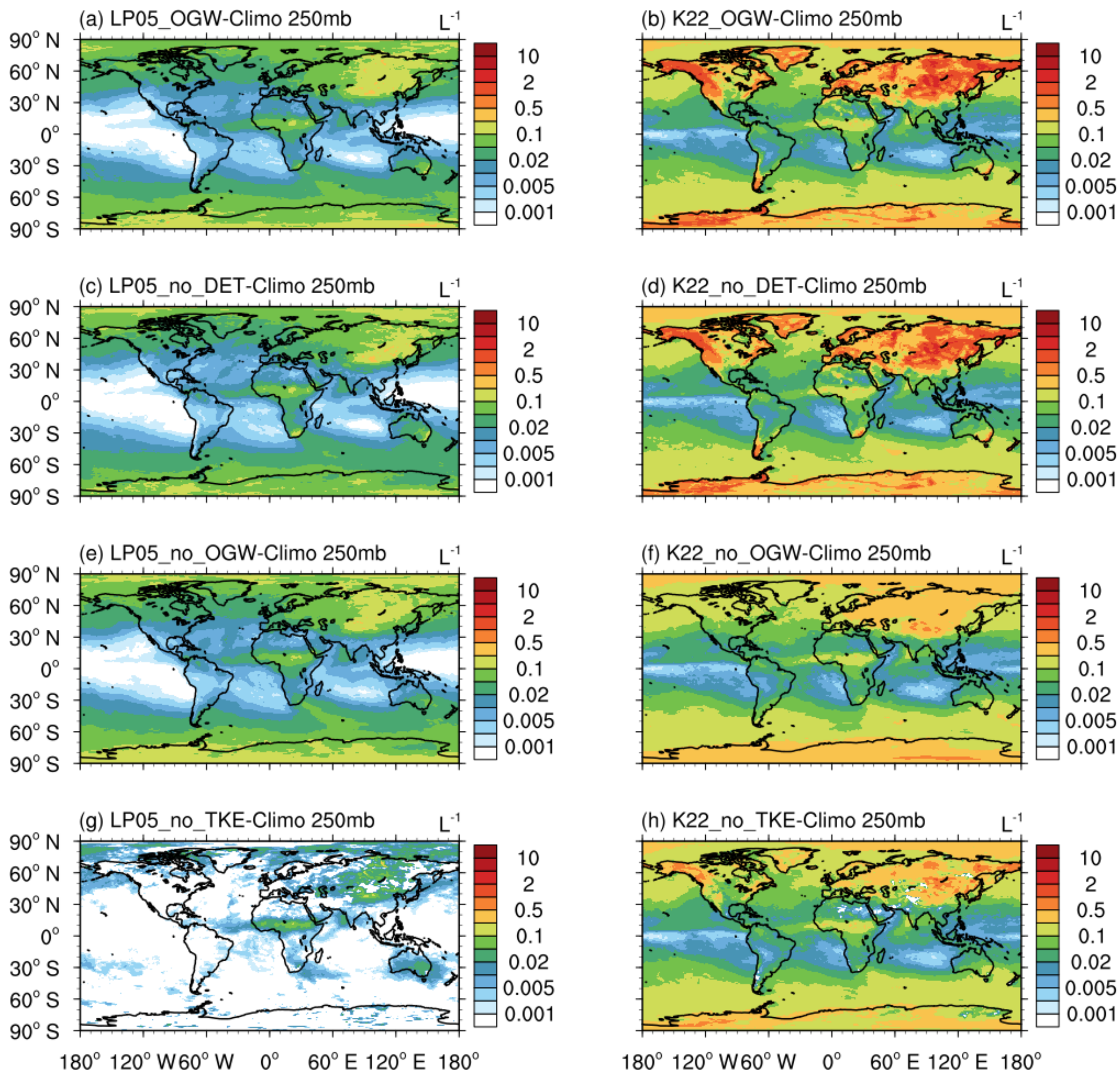

Figure R1-6. Annual ice number tendency due to heterogeneous nucleation ΔN_{i_het} from 6-year climatology simulations at 250 hPa.

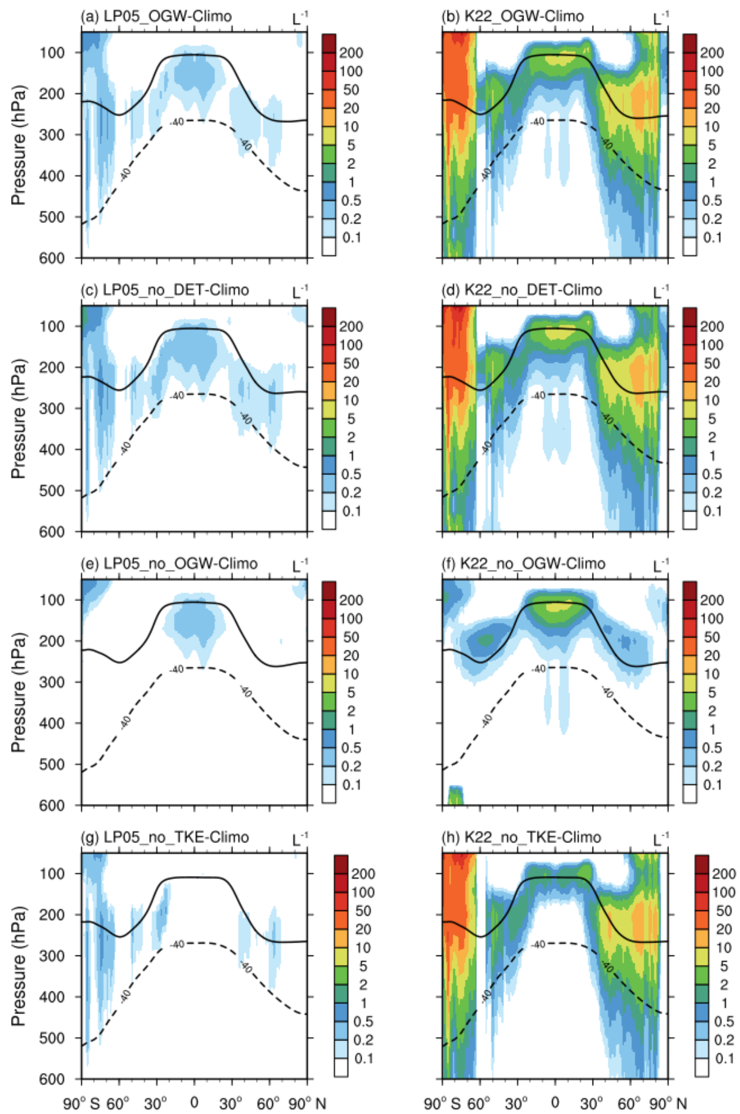

Figure R1-7. Annual zonal ice number tendency due to homogeneous nucleation ΔN_{i_hom} from 6-year Climatology simulations in the upper troposphere (above 600 hPa). Dashed lines indicate the annual mean -40 °C isothermal line, and solid lines represent the tropopause in the corresponding simulations.

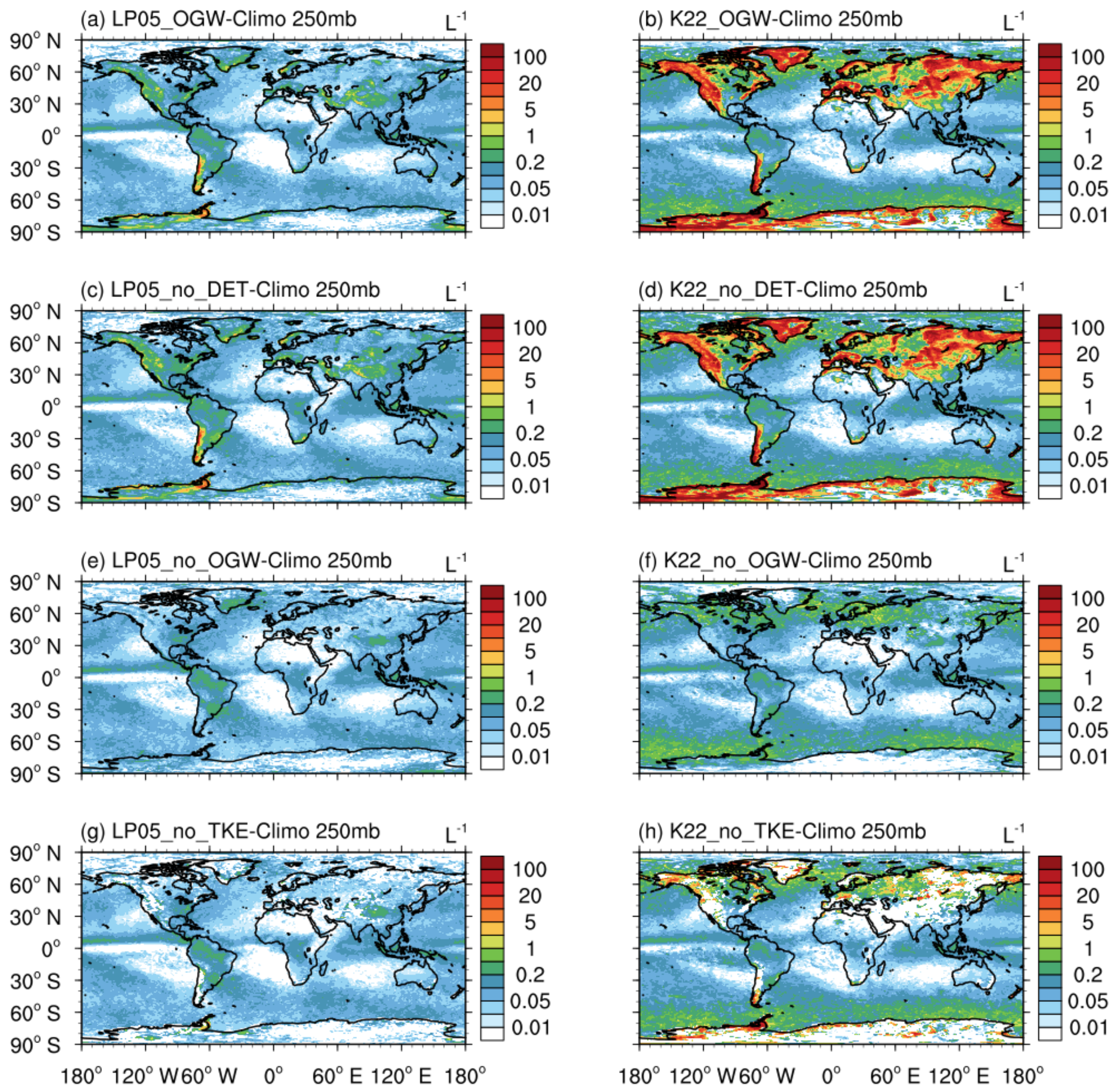

Figure R1-8. Annual ice number tendency due to homogeneous nucleation ΔN_{i_hom} from 6-year climatology simulations at 250 hPa.

Minor comments/questions:

1. Line 11: Consider revising "detrained" to "detrainment."

Thank you very much for your comments. We have modified the word as suggested.

The relevant paragraph has been modified as follows (line 10-11):

"To investigate ice formation in cirrus clouds, sensitivity tests are conducted to analyze three ice sources from orographic gravity waves (OGWs), convection detrainment, and turbulence."

2. Lines 15-16: This sentence could be clarified. Do you mean that ice crystals from detrainment and formed by turbulence are primarily concentrated in low- and mid-latitudes?

Thank you very much for your comment. We have modified the relevant sentence as suggested.

The relevant paragraph has been modified as follows (line 15-17):

"Both schemes simulate that convection detrained and turbulence-induced ice crystals are concentrated in low- to mid-latitudes, whereas OGW-induced ice crystals are concentrated in mid- to high latitudes."

3. Lines 19-21: Further clarification is needed. Since Lines 15-16 indicate that the importance of ice sources varies by latitude, could you explain why orographic gravity waves (OGWs) are identified as the dominant ice source?

Thank you very much for your valuable comment. We have included additional explanations regarding orographic cirrus clouds (i.e., cirrus over high terrains). In these clouds, ice crystals are primarily generated by OGWs.

To better address the issue, the relevant paragraph has been modified as follows (line 20-21):

"In orographic cirrus over high terrains at mid- to high latitudes, both schemes identify OGW-induced ice crystals as the dominant ice source."

4. Lines 26-27: Please provide references to support the statement: "These ice clouds can reflect solar radiation back to space, cooling the planet."

Thank you very much for your comment. We have included a reference to support the statement. This is also supported by the reference by Liou (1986).

The sentence has been modified as follows (line 27-28):

"These ice clouds can reflect solar radiation back to space, cooling the planet (Chen et al., 2024; Forster et al., 2023). ""

5. Lines 36-41: Citations are needed to substantiate the claim that homogeneous freezing typically results in cirrus clouds with Ni > 100 L^{-1}, whereas heterogeneous freezing generally produces cirrus with Ni < 10 L^{-1}.

Thank you very much for your comment. These results are based on Heymsfield et al. (2017) and Froyd et al. (2022). We have added these citations as follows (in line 42-43):

"This process generally produces low ice number concentrations (< 100 L^{-1}) (Heymsfield et al., 2017; Froyd et al., 2022)."

6. Line 48: Does “vertical velocity” refer specifically to subgrid vertical velocity? If so, is grid-scale vertical velocity considered in the ice-nucleating particle (INP) scheme?

Thank you very much for your comment. Yes, this refers to subgrid-scale vertical velocity. In current GCMs, the horizontal grid spacing is about 1 degree (~100 km), which allows grid-scale vertical velocity can be represented in the temperature and supersaturation. Because subgrid-scale motions dominate the vertical uplift necessary for ice nucleation, subgrid-scale vertical velocity is explicitly incorporated into the ice nucleation parameterization.

The relevant paragraph has been rearranged and modified as follows (line 50-51):

“For example, most GCMs treat turbulence as the sole subgrid-scale vertical velocity mechanism driving ice nucleation.”

7. Line 53: As mentioned in Lines 32-33, cirrus clouds can form through detrainment or in-situ nucleation. Could you clarify which mechanism is responsible for orographic cirrus formation?

Thank you very much for your comment. We have modified the sentence as follows (line 38):

“Ice crystals in in-situ cirrus clouds, such as orographic cirrus over high terrains, are primarily nucleated by aerosols.”

8. Lines 57-60: A more detailed explanation of the complexity of INP parameterization would be helpful. Two major sources of uncertainty are (1) aerosol properties and (2) supersaturation levels. This study focuses on refining supersaturation calculations by incorporating OGW effects and evaluating the sensitivity of different INP activation efficiencies (LP05 and K22 schemes). If this understanding is correct, consider refining this section to better reflect this logic.

Thank you very much for your valuable comment. We have modified the corresponding sentences to highlight the two sources of uncertainty from your comment as follows (line 62-70):

“Aerosols such as dust, soot, metallic particles, and biological particles, can act as INPs, inducing heterogeneous nucleation and potentially suppressing homogeneous nucleation (Fan et al., 2016; Froyd et al., 2022; Heymsfield et al., 2017; Kärcher & Ström, 2003; Knopf & Alpert, 2023). The activation efficiency of INPs is determined by their chemical components, which is highly dependent on their sources (Beall et al., 2022; Chen et al., 2024; Tobo et al., 2019). Limited knowledge of the number concentration, chemical composition, and activation efficiency of INPs in the upper troposphere complicates the model prediction of cirrus clouds microphysical properties (Knopf & Alpert, 2023). Moreover, currently conventional GCMs cannot resolve the subgrid-scale vertical velocity, which drives the water vapor supersaturation for ice nucleation, posing additional uncertainty for model simulations."

9. Lines 80-84: Could you confirm whether subgrid-scale vertical velocities from OGW and turbulence are explicitly incorporated into the INP scheme? Additionally, is the turbulence-driven vertical velocity derived from TKE? If so, please clarify this point in the text.

Thank you very much for your valuable comments. Yes, subgrid-scale vertical velocities from OGW and turbulence are explicitly incorporated into the ice nucleation schemes.

Yes, the turbulence-driven vertical velocity is derived from TKE. We have included additional explanations to clarify this point as follows (line 91-95):

"Since CLUBB effectively represents turbulence with a small Richardson number but struggles to produce perturbations caused by gravity waves (Golaz et al., 2002a, 2002b; Huang et al., 2020), subgrid-scale vertical velocities from orographic gravity waves (OGWs) and turbulence are incorporated into the ice nucleation schemes (Lyu et al., 2023). The turbulence-driven vertical velocity is derived from TKE calculated by CLUBB."

10. Line 85: Should "cloud-borne state" be revised to "ice-borne state"? Are you referring to aerosols incorporated into ice crystals?

Thank you very much for your comment. In CAM6, cloud-borne state is used to represent both ice-borne and liquid-borne aerosols in warm and cold clouds. There is no separation of ice-borne state and liquid-borne state. So, we keep using "cloud-borne" state.

11. Lines 91-95: The LP05 scheme should be described as explicitly as the K22 scheme. Could you provide additional details on how subgrid-scale vertical velocity is used to compute supersaturation? How are aerosol properties (e.g., number concentration, size distribution, and chemical composition) incorporated into INP activation calculations? Additionally, are there differences in how the LP05 scheme treats homogeneous versus heterogeneous freezing, and how does it account for competition between these two processes?

Thank you very much for your comments. We have added further explanations (Section 2.2.2) as you suggested (line 176-194):

"The LP05 ice nucleation scheme incorporates two primary mechanisms: homogeneous and heterogeneous nucleation (Liu & Penner, 2005). It is based on fitted simulation results from a cloud parcel model with varying vertical velocities. The maximum supersaturation is determined in the parcel model from the balance between the production due to adiabatic cooling by updrafts and loss due to vapor deposition on ice crystals. The number of nucleated ice crystals is derived based on ice supersaturation, temperature, aerosol number concentration and composition, and vertical velocity. Subgrid vertical velocity can be derived from TKE calculated by CLUBB, from OGWs, or from the combined contribution of both components.

Homogeneous nucleation in the LP05 scheme, similar to the K22 scheme, adopts the parameterization by Koop et al. (2000). Sulfate aerosols in the Aitken mode with diameters greater than 0.1 μm is applied to fit to ice number concentrations (Gettelman et al., 2010). On the other hand, heterogeneous nucleation considers the coarse mode dust as potential source of INPs. The number of ice crystals formed due to heterogeneous nucleation n in the LP05 scheme is calculated using $n = n_{dust} \cdot \Phi(T, w, S_i)$, where n_{dust} is the coarse mode dust number concentration from MAM4, and Φ is active aerosol fraction, empirically derived as a function of temperature (T), vertical velocity (w), and ice supersaturation (S_i).

The LP05 scheme considers the competition between homogeneous and heterogeneous nucleation. It determines the critical dust INP concentration, above which homogeneous nucleation is completely switched off. Below that, homogeneous nucleation occurs partially and is gradually transitioned to the pure homogeneous nucleation at lower INP concentrations. The LP05 scheme is modified to consider the effect of pre-existing ice crystals (Shi et al., 2015), which is parameterized by reducing the vertical velocity for ice nucleation as a result of water vapor deposition on pre-existing ice."

12. Subsections 2.1 and 2.2: The organization of these sections could be improved for readability. Consider the following structure: (1) A brief introduction to CAM6 (e.g., currently covered in Lines 74-83). (2) A detailed explanation of the LP05 and K22 schemes (e.g., Lines 91-95, but needs to be expanded, and content from Subsection 2.2). (3) A description of the experimental setup (e.g., Lines 88-90 and 96-100), with additional details on the objectives and configurations.

Thank you very much for your good suggestions. We have reorganized the paragraphs as you suggested (see Section 2.1, 2.2, 2.3).

13. Line 117: Does Equation (1) apply to homogeneous or heterogeneous freezing? Lines 109-114 discuss homogeneous freezing but do not include equations, whereas Lines 122-123 reference heterogeneous freezing. Clarifying this distinction would be helpful.

Thank you very much for your valuable comments. Equation 1 only applies to heterogeneous nucleation on INPs. We have clarified this.

14. Line 118: To which aerosol species does the INP number concentration here correspond? How does K22 handle aerosol mixing state parameterization?

Thank you very much for your comments. This study considers only coarse mode dust as INPs. We don't consider the difference in the INP activation efficiency depending on the dust mixing state.

15. Subsection 2.2: The mathematical formulation of K22 is unclear. Could you clarify how the loss term in Equation (3), Wq,het, and Wq,pre are computed? Also, does w (the first term on the right-hand side of Equation (5)) represent subgrid vertical velocity derived from TKE and/or OGW?

Thank you very much for your comments. w_q including contributions from heterogeneous nucleation and pre-existing ice is calculated as follows (line 164-167):

"Quenching velocities w_q are defined as:

$$w_q = \frac{\int_0^{s} \frac{4\pi}{v n_{sat}} \frac{dn}{ds} \left(\int_{\tau(s')}^{t(s)} r^2 \frac{dr}{dt} dt \right) ds'}{a(s+1)}, \quad (4)$$

where the loss term includes contributions from heterogeneous nucleation and pre-existing ice."

Yes, w in the first term on the right-hand side of Equation (5) represents subgrid vertical velocity derived from TKE and/or OGWs.

16. Line 151: Please specify which scheme is being referenced by "the scheme."

It refers to the LP05 scheme.

17. Lines 150-154: The distinction between the LP05 and K22 schemes is not entirely clear. To enhance clarity, (1) Provide a more explicit description of LP05, similar to the level of detail used for K22. (2) Compare the two schemes in terms of their treatment of vertical velocity, supersaturation parameterization, INP activation efficiency, and aerosol representation.

Thank you very much for your valuable comments. To facilitate better understanding, we have added section 2.2.2 to provide a more explicit description of LP05 equations and section 2.2.3 to compare the two schemes. Overall, both the two schemes use the input of subgrid-scale vertical velocity and aerosols from the host model (e.g., CAM6) and solve the equation of ice supersaturation (Equation 3). However, the INP activation efficiency, and the competition between ice nucleation mechanisms (homogeneous versus heterogeneous) and preexisting ice are treated differently as discussed in section 2.2.3.

18. Lines 150-160: Understanding the differences between LP05 and K22 would be challenging until both schemes, particularly their mathematical formulations, are clearly described.

Thank you very much for your comment. We have introduced a new section 2.2.3 to address the issue in greater detail.

19. Line 167: Does “size” refer to ice crystal diameter? If so, consider specifying.

Thank you very much for your comments. Yes, in this context, the size refers to the diameter of the detected particles. The relevant paragraph has been modified as follows (line 265-267):

“Ice crystals with diameters ranging from 10 to 3000 μm were measured using two-dimensional stereo-imaging probes (2D-S).”

20. Lines 203-205: What is the key distinction between regions 2 and 3? Please clarify.

Thank you very much for your comment. Region 2 is located downwind of the Andes Mountains and Antarctic high plateaus, thus experiencing the additional influence from OGWs on observed cirrus. However, Region 3 is not affected in this way.

21. Line 212: The description of Panel 3-h in Figure 2 is not mentioned in Tables 1 and 2. Should this be added, or did I overlook something?

Thank you very much for your comment. The model results shown in Figure 2h in Figure 2 are based on K22_OGW-Climo and K22_no_TKE-Climo experiments in Table 1. This is noted in Figure 2 caption.

22. Lines 241-248: This paragraph is somewhat unclear. Consider rewording for clarity.

Thank you very much for your comment. We have revised the paragraph as suggested. The relevant paragraph has been modified as follows (line 351-361):

“The K22 scheme simulates higher activated number concentrations of aqueous aerosols for homogeneous nucleation compared to the LP05 scheme. This difference can be attributed to both direct and indirect influences. The direct effect stems from how each scheme represents the competition between nucleated and pre-existing ice crystals. As described in Section 2.2.3, the number of nucleated ice crystals in the LP05 scheme tends to be more suppressed by the competition between pre-existing ice crystals and newly formed ice crystals, compared to the K22 scheme. Consequently, the presence of pre-existing ice crystals leads to fewer ice crystals that are formed, producing overall lower ice number concentrations in the LP05 experiments. The indirect effects are associated with differences in temperatures and vertical velocity fields between the two schemes. ”

23. Lines 268-269: The conclusion here is difficult to verify based on Section 2.2. Improving Section 2.2 would help clarify why competition between homogeneous

nucleation and pre-existing ice is less pronounced in K22 compared to LP05. Does this primarily depend on supersaturation?

Thank you very much for your comment. Yes, this depends on how the two schemes treat the effect of pre-existing ice on supersaturation. We have included a corresponding section (2.2.3) in the main text to enhance understanding.

24. Lines 275-277: Could you provide supporting evidence for the statement that temperature changes smaller than 0.25°C have a negligible impact on ice number concentration? Do you have references to support this claim? Additionally, is the 0.25°C variation based on monthly-mean data? How does it compare to instantaneous temperature fluctuations?

Thank you very much for your comments. This 0.25°C variation is based on monthly-mean data. The instantaneous temperature fluctuations can be larger. However, the temperature changes are mostly positive in the K22_OGW-Climo experiment compared to the LP05_OGW-Climo experiment. Based on previous studies (Kay & Wood, 2008; Liu & Shi, 2018), 1°C warming could reduce N_i by 5-20%. This temperature increase should suppress the ice nucleation and cannot explain the increased ice number concentration in the K22 scheme. We have revised the sentence to clarify the meaning as follows (line 408-410):

"However, these temperature changes are generally small (typically smaller than ± 0.25 ℃) and mostly positive, suggesting a suppression of ice nucleation. Therefore, the impact of temperature difference on global N_i is expected to be negative and unlikely to account for a globally significant increase in N_i observed in the K22 scheme (Fig. 2)."

25. Figures S2 and S3: Do LP05 and K22 yield identical latitude distributions for the -40°C layer and tropopause? Why is only one tropopause and -40°C layer shown in these figures? Also, does "corresponding simulation" in the figure captions refer to a specific case?

Thank you very much for your comment. The -40°C layer and the tropopause could be slightly different between the two schemes because of the temperature differences. We have clarified the descriptions of -40°C layer and the tropopause in the figure captions:

"Dashed lines represent the annual mean -40℃ isothermal line, and solid lines are the tropopause in the LP05_OGW-Climo experiment."

26. Lines 282-284: A vertical velocity change of 0.002 m/s seems quite small to significantly influence ice nucleation rates. Could you provide quantitative evidence to support this?

Thank you very much for your comment. Based on previous studies (Hoyle et al., 2005; Kärcher & Lohmann, 2002; Kay & Wood, 2008), an increase of vertical velocity by 0.1 m/s, N_i may increase by a factor of 2-4 depending on temperatures.

27. Lines 289-293: To support the discussion, consider including plots of surface wind speed differences, dust emissions, and deposition rates.

Thank you very much for your comment. Surface wind, dust emission and dust deposition rates are indeed important factors for the distribution of dust number concentrations. Figure R1-9 illustrates the differences in surface wind speed between the K22 and LP05 schemes, showing that the K22 scheme tends to increase surface wind speed over Greenland, Europe, Africa and South America. Figure R1-10 displays the differences in coarse mode dust surface emissions, indicating emissions are enhanced in some regions while suppressed in others. Figures R1-11 and R1-12 present the differences in coarse mode dust wet and dry deposition rates, respectively. The major differences seem that the dry deposition rate of coarse mode dust in the K22 scheme is reduced over dust source regions (e.g., northern Africa, central Asia), which likely leads to the increase in dust number concentrations in the upper troposphere (Figure S4).

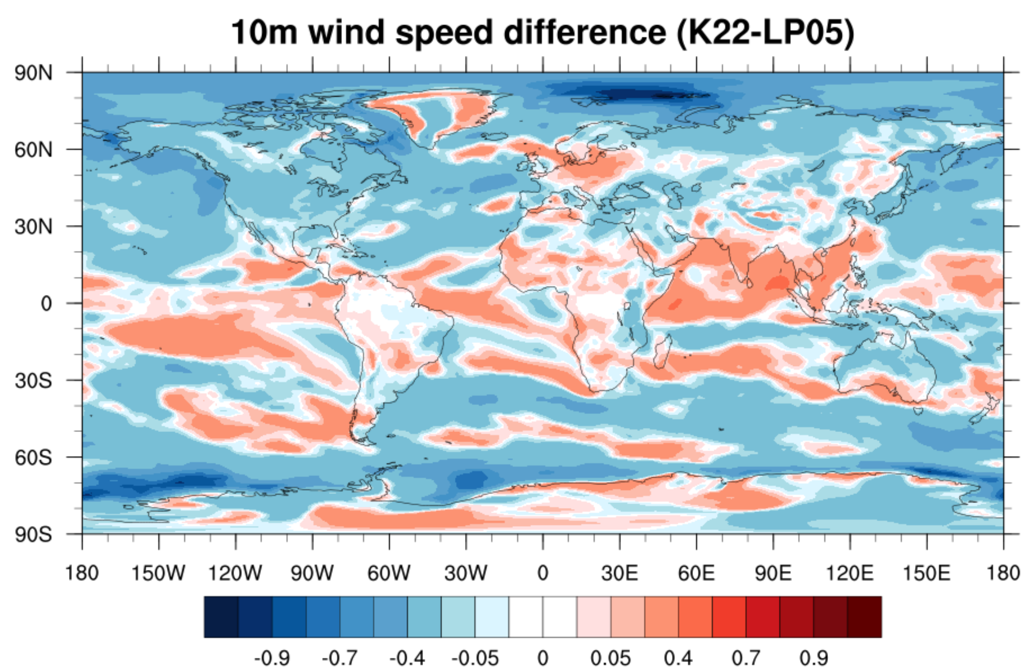

Figure R1-9. Differences of annual mean 10 m wind speed (m s^{-1}) between K22_OGW-Climo and LP05_OGW-Climo experiments.

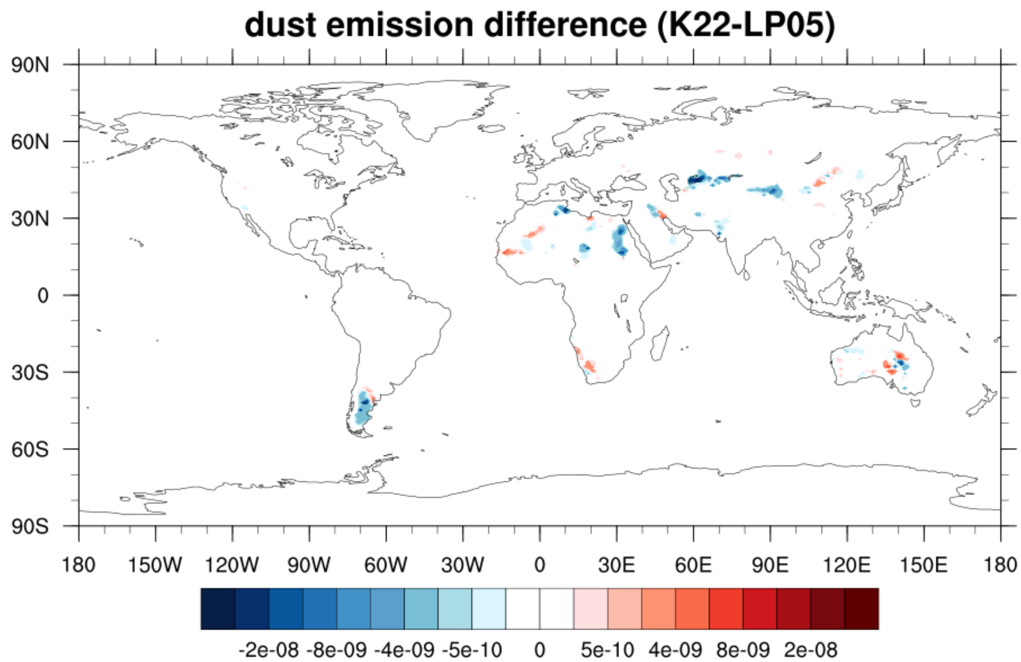

Figure R1-10. Differences of coarse mode dust surface emission (kg m^{-2} s^{-1}) between K22_OGW-Climo and LP05_OGW-Climo experiments.

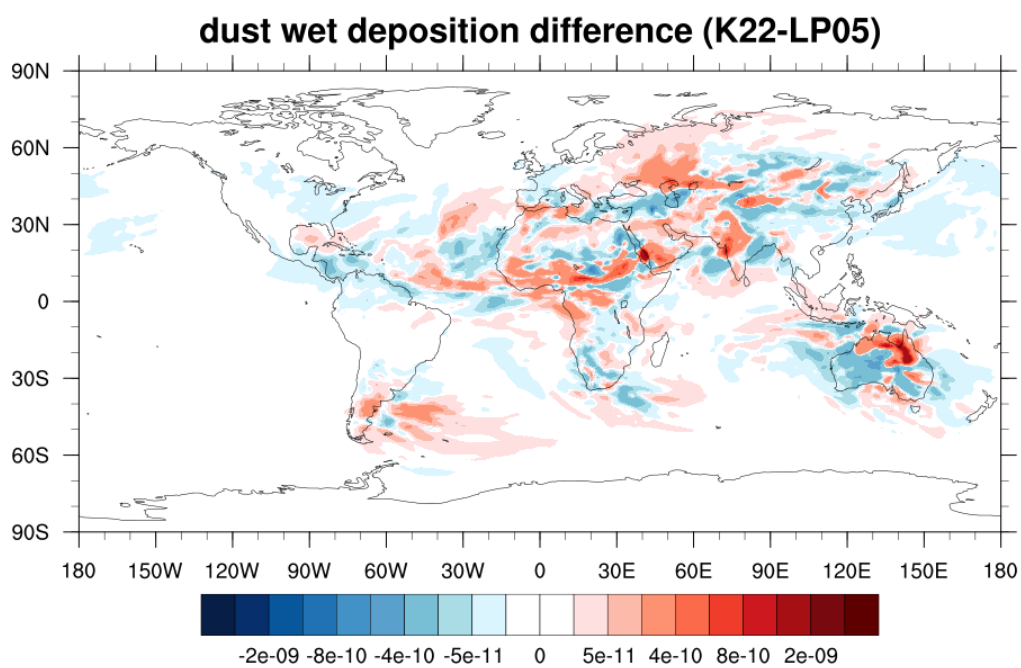

Figure R1-11. Differences of coarse mode dust wet deposition rate (kg m^{-2} s^{-1}) between K22_OGW-Climo and LP05_OGW-Climo experiments.

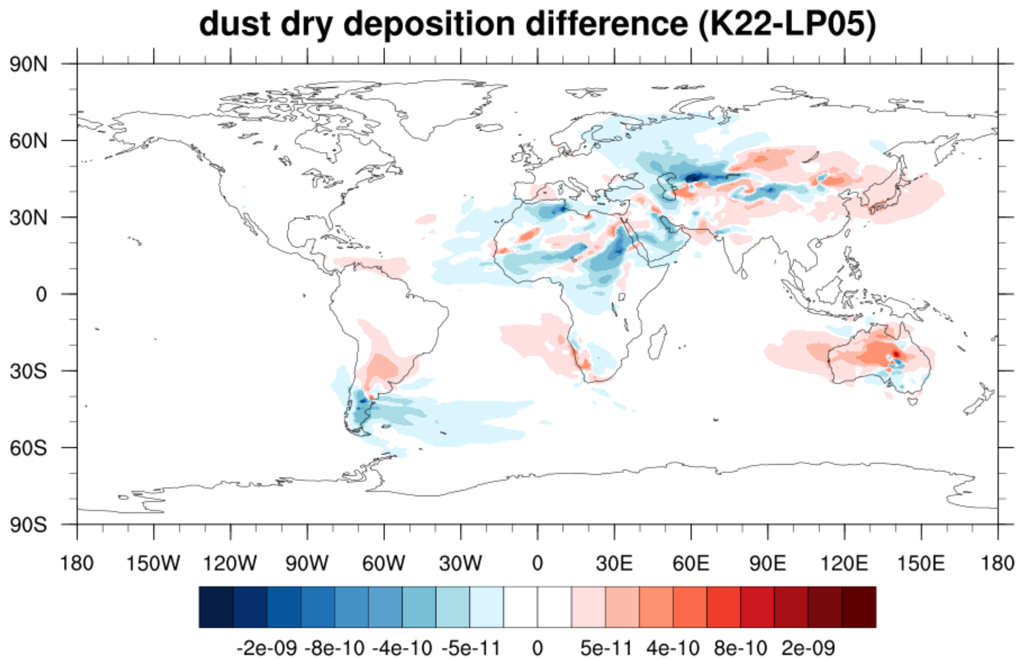

Figure R1-12. Differences of coarse mode dust dry deposition (kg m^{-2} s^{-1}) between K22_OGW-Climo and LP05_OGW-Climo experiments.

28. Lines 297-299: Please provide plots of heterogeneous and homogeneous nucleation rates to substantiate the discussion.

Thank you very much for your comments. Following your comment, we plot the heterogeneous and homogenous nucleation tendencies (Figure R1-13 and R1-14), similar to the plots in our response to your major comment/question No.4 above. The results show that, in the K22_OGW_Shan-Climo experiment, homogeneous nucleation is enhanced while heterogeneous nucleation is suppressed (Figure R1-13 and R1-14). The related figures have been included in the supplementary materials.

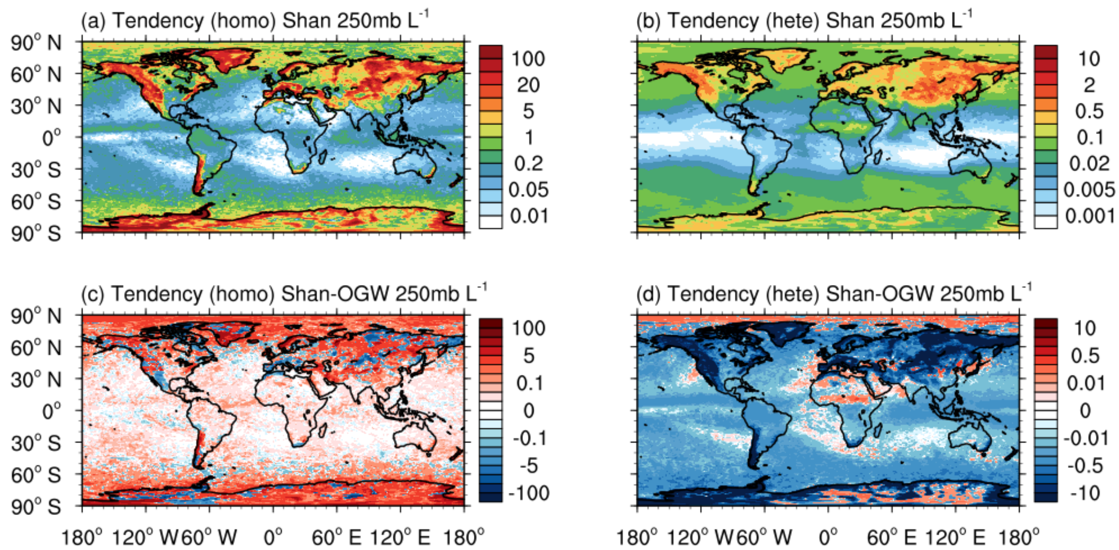

Figure R1-13. Annual ice number tendencies due to homogeneous ΔN_{i_hom} and heterogeneous nucleation ΔN_{i_het} from 6-year climatology K22_OGW_Shan-Climo experiment at 250 hPa. The second row shows the tendency differences between K22_OGW_Shan-Climo and K22_OGW-Climo experiments.

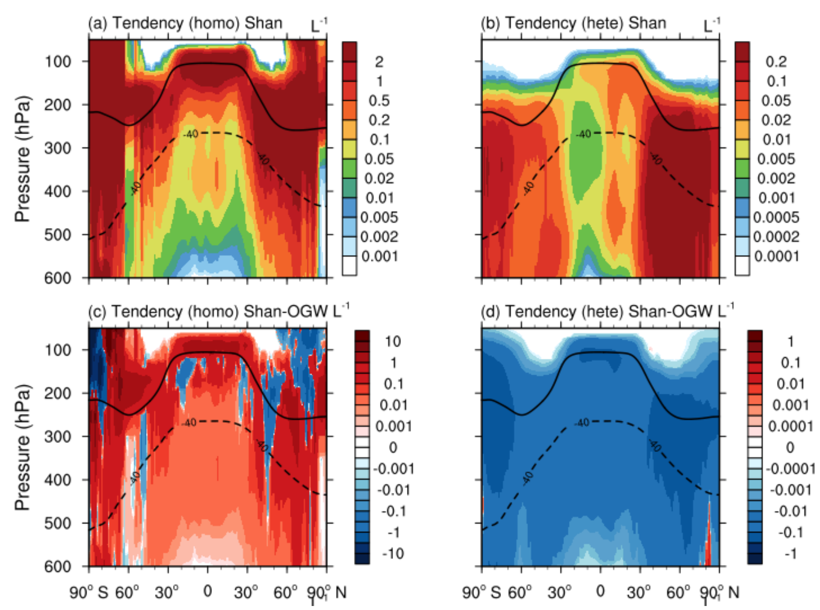

Figure R1-14. Annual zonal mean ice number tendencies due to homogeneous ΔN_{i_hom} and heterogeneous nucleation ΔN_{i_het} from 6-year climatology K22_OGW_Shan-Climo experiment. The second row shows the tendency differences between K22_OGW_Shan-Climo and K22_OGW-Climo experiments.

The relevant paragraphs have been modified as follows (line 464-470):

"Further insight into the role of aerosol processes in ice nucleation is provided by the K22_OGW_Shan-Climo experiment, which incorporates an improved treatment of aerosol wet removal by convections based on Shan et al. (2021). In this configuration, dust aerosol concentrations are reduced due to more efficient convective scavenging (Fig. S9), particularly in convectively active low latitude regions. The resulting lower dust number concentrations lead to a reduced heterogeneous nucleation rate, thereby enhancing the homogeneous nucleation rate due to reduced competition from heterogeneous nucleation on dust (Fig. S10 and 11). In this case, improvements in aerosol wet removal may help optimize upper tropospheric aerosol concentrations and can leads to a general increase in N_i (Fig. S12). "

29. Lines 278-300: The logical flow in these paragraphs could be improved. The discussion aims to explain the causes of Ni differences between LP05 and K22, but the explanation is somewhat difficult to follow. In particular, the role of activated INP fraction (Φ) in Lines 296-287 is unclear. Since Φ is influenced by vertical velocity, temperature, and water vapor, could you clarify why it is considered an independent factor driving Ni? Consider: (1) Listing all key factors influencing Ni concentration. (2) Comparing these factors between LP05 and K22.

Thank you very much for your comments. The relevant paragraphs have been modified to list all key factors influencing N_i concentrations and then compare these factors between the two ice nucleation schemes as follows (line 401-436):

"To analyze the factors driving differences in N_i between the LP05 and K22 schemes, several key variables should be considered. These factors include temperature, which affects ice nucleation thresholds and saturation vapor pressure; subgrid-scale vertical velocity, which determines the supersaturation necessary for ice formation; and dust aerosol number concentration, along with the fraction of activated INPs (Φ), which together determine the number of heterogeneously nucleated ice crystals.

In high latitudes, temperature increases in the upper troposphere are found in the K22_OGW-Climo experiment compared to the LP05_OGW-Climo experiment (Fig. S2), likely due to localized warming associated with increased cirrus cloud occurrence (Fig. S1). However, these temperature changes are generally small (typically smaller than ± 0.25 ℃) and mostly positive, suggesting a suppression of ice nucleation. Therefore, the impact of temperature difference on global N_i is expected to be negative and unlikely to account for a globally significant increase in N_i observed in the K22 scheme (Fig. 2).

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).

The most substantial differences in N_i between the two schemes arise from microphysical processes, particularly those governing heterogeneous ice nucleation. Both the K22 and LP05 schemes account for the activation of coarse mode dust particles, but the K22 scheme simulates higher dust aerosol number concentrations, especially in the upper troposphere (Fig. S4). This enhancement is likely driven by changes in large scale circulation patterns and surface wind fields resulting from differences in the applied ice nucleation schemes, which influence both dust emission and atmospheric transport pathway. As a result, the K22 scheme shows an increase in ice number concentration nucleated from dust particles heterogeneously, as shown in Fig. 3c and 3d. The activated INP fraction Φ also plays a crucial role in controlling heterogeneous nucleation. While Φ depends on local thermodynamic conditions, such as temperature, vertical velocity, and supersaturation in the LP05 scheme, the K22 scheme simplifies this dependence, with Φ relying on supersaturation only. Differences in the treatment of Φ, combined with elevated dust concentrations in the K22 scheme may influence heterogeneous nucleation on coarse mode dust. However, since the number of coarse mode dust is limited (~10-30 L^{-1}) in the upper troposphere (Fig. S4), even if all the dust particles are nucleated heterogeneously to form ice crystals, their contribution to increased N_i will not reach the levels (~100 L^{-1}) observed in the K22 scheme. Therefore, these two factors are unlikely to explain the globally significant increase in N_i seen in the K22 scheme compared to the LP05 scheme (Fig. 2a and Fig. 2b). This also implies that competition between preexisting ice and new ice nucleation is a more dominant factor influencing the simulated N_i. ”

30. Line 326: Does OGW always increase Ni? Consider revising for clarity.

Thank you very much for your comment. OGWs influence the vertical velocity, which determines ice supersaturation. In the SPARTICUS orographic cirrus, *N*i is dominantly formed from homogeneous nucleation, OGWs can increase vertical velocity and potentially increase *N*i. However, in cirrus cases where *N*i can be influenced by many other processes, OGWs do not always lead to an increase in *N*i.

The relevant paragraph has been modified as follows (line 537-540):

“Fig. 5b shows that in both LP05 and K22 schemes, the changes in N_i (ΔN_i) due to OGWs are always positive and larger than those from the other two sources in these cirrus clouds. This indicates that OGWs play a significant role in enhancing the formation of ice crystals in cirrus clouds identified as orographic cirrus during the observed five-days period. ”

31. Lines 332-339: Additional evidence is needed to support this statement. Could you provide plots showing the changes in homogeneous and heterogeneous freezing rates to illustrate their respective contributions? Also, please consider refining the wording, as the term “contribution” can imply either a positive or negative effect. I assume “contribution and inhibition” refer to invigoration and suppression, respectively. Could you confirm?

Thank you very much for your valuable comments. We use the ΔN_i (similar to ice number tendency) to evaluate the contribution, and we do not show the changes from homogeneous and heterogeneous freezing rates, because we are also interested in the effect of convective detrainment and separate effects of OGWs and turbulence on N_i (through ice nucleation). We have improved the wording and used "enhancement" instead of "contribution" when the effects are positive.

The relevant paragraph has been modified as follows (line 537-551):

"Fig. 5b shows that in both LP05 and K22 schemes, the changes in N_i (ΔN_i) due to OGWs are always positive and larger than those from the other two sources in these cirrus clouds. This indicates that OGWs play a significant role in enhancing the formation of ice crystals in cirrus clouds identified as orographic cirrus during the observed five-days period. 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. This suggests that OGW-induced ice crystals enhance the overall N_i in these cirrus clouds. 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 detrained and turbulence-induced ΔN_i values, with stronger fluctuations between positive and negative with temperature, 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. "

32. Lines 340-341: Could you clarify the definition of Dnum?

Thank you very much for your comments. Dnum is defined as the number weighted diameter. Assuming the ice size distribution follow gamma distribution with coefficients N_0 and λ, ($D_{num} = \frac{\int_0^\infty N_0 D e^{-\lambda D} dD}{\int_0^\infty N_0 e^{-\lambda D} dD}$).

To better address the issue, the relevant paragraph has been modified as follows (line 558-559):

"Regarding the simulated number weighted diameter of ice crystals D_{num} in the LP05 and K22 experiments (Fig. S15 and S16),…. "

33. Line 354: Dnum should be defined upon first mention for clarity.

Thank you very much for your comments. The D_{num} is first defined in Section 3.1 at line 257. The relevant sentence is as follows (line 283-286) :

"Additionally, the microphysical properties (such as ice number N_i, ice water content IWC and number-weighted diameters D_{num}) of ice crystals with diameters larger than 20 μm from CAM6 results are derived using the size cut method described by Eidhammer et al. (2014), consistent with the measurements obtained by the 2D-Stereo Particle Probe (2D-S) but excluding the first size bin. "

34. Lines 356-357: "This characteristic helps explain why the K22 scheme results in increased cloud frequency compared to the LP05 scheme." Could you provide a more detailed explanation? Specifically, why do cirrus clouds with a higher number of smaller ice crystals lead to increased cloud frequency?

Thank you very much for your comment. We have clarified the issue as follows (line 815-817):

"This can be due to the presence of smaller ice crystals in the K22 scheme, which have smaller fall speeds, allowing them to travel over broader regions before completely sublimated. "

35. Lines 376-377: Please specify the number of simulation and observational samples used in the analysis. It would also be helpful to include the corresponding sample sizes for SPARTICUS and the experiments.

Thank you very much for your comments. We have included additional information about sample sizes in the article. There are 53987 (6236) data samples in the SPARTICUS observational and simulation datasets (in five days identified as orographic cirrus events). The datasets during the ORCAS campaign include 341410 samples. The relevant paragraphs have been modified as follows (line 268-270):

"A total of 6236 data points are available in both observational and simulated datasets during the five days identified as orographic cirrus events (Muhlbauer et al., 2014)."

(line 606-608):
"In Region 1,... The dataset used in the analysis includes 83559 data points."

(line 640-642):
"Region 2, ... The dataset used in the analysis includes 146139 data points."

(line 689-691):
"In Region 3, ... There are 111712 data points used in the analysis."

36. Lines 386-387: "However, in the LP05 scheme, ice crystals due to OGWs and detrainment tend to inhibit the formation of simulated Ni, whereas their effects are minimal in the K22 scheme." To support this statement, I recommend including plots of homogeneous and heterogeneous freezing rates. Similar evidence is needed for the statements in Lines 387-391. Additionally, aerosol number concentrations (for both sulfate and dust) should be provided to help explain the differences in Ni.

Thank you very much for your comments. Fig. 7b shows the ΔN_i (i.e., ice number tendencies) due to ice nucleation from OGWs and turbulence and due to detrainment. We would like to show the competition between different ice sources, i.e., ice nucleation by OGWs and turbulence and by convective detrainment. We believe that this is a clearer explanation than showing the ice nucleation rates from homogeneous and heterogeneous freezing.

The relevant paragraph has been modified as follows (line 629-634):

"At the 210 K level, the overwhelmingly positive ΔN_i values due to turbulence in both schemes suggests that turbulence-induce ice crystals are the primary contributors (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 (OGW-induced ΔN_i) are minimal (~0) in the K22 scheme, indicating no evident inhibitory effect. In addition, both schemes simulate generally negative ΔN_i values due to detrainment, implying that detrained ice crystals tend to suppress further ice formation. "

(line 543-551):

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

(line 652-664):

"In Fig. 8a, similar to Region 1, multiple high N_i peaks again correspond to different primary ΔN_i contributors, suggesting a multilayer structure of cirrus clouds in Region 2. Near 215 K, the OGW experiments in both schemes simulate high N_i peaks that closely match the observed high peak near 218 K. The corresponding positive OGW-induced ΔN_i values in both schemes (Fig. 8b) suggest that a large portion of these ice crystals are generated by OGWs originating from mountains and high plateaus. The contributions from other sources (detrained ΔN_i and turbulence-induced ΔN_i) differ between the schemes. In the LP05 scheme, generally positive detrained ΔN_i and fluctuating turbulence-induced ΔN_i near 215K suggest an enhancing role from detrained ice crystals and a mix of enhancing and inhibiting effects from turbulence-induced ice crystals. In contrast, the K22 scheme exhibits negative ΔN_i values for both sources, indicating overall inhibition effects. These findings imply that the N_i peaks around 215 K are strongly related to the mountainous terrain upwind of Region 2. "

(line 674-688):

"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. In contrast, in the K22 scheme, only detrained ΔN_i values are negative, implying inhibition effects, while positive ΔN_i values from OGWs and turbulence suggest these ice crystals enhance N_i. . The fact that no single ΔN_i value is positive in both schemes may suggest that the dominant ice source is missing from the model. Previous studies have highlighted the importance of additional ice nucleation mechanisms, such as frontal gravity waves, in cirrus formation over oceans, and identified crucial INPs including dust, metallic particles, soot and biological materials (Fan et al., 2016; Froyd et al., 2022; Heymsfield et al., 2017; Kärcher & Ström, 2003; Knopf & Alpert, 2023). However, in CAM6, only orographic gravity waves are included in ice nucleation scheme, and only coarse mode dust is considered as INPs. In addition, other important N_i source and sink processes, such as secondary ice production, ice sublimation and sedimentation should be examined. Future studies are therefore necessary to incorporate these potential dynamic and microphysical sources to improve simulations of cirrus clouds over oceanic regions. "

37. Line 403: The phrase "predominantly generated from OGWs" may not be entirely appropriate, as turbulence-induced increases in Ni in the K22 scheme are also significant. Please consider rewording this statement to more accurately reflect the relative contributions of different mechanisms.

Thank you very much for your comments. We have modified the relevant sentence as follows (line 656-658):

"The corresponding positive OGW-induced ΔN_i values in both schemes (Fig. 8b) suggest that a large portion of these ice crystals are generated by OGWs originating from mountains and high plateaus. "

38. Lines 411-412: The phrase "wider spread of ice crystals" is somewhat unclear. Are you referring to ice redistribution due to advection? Please clarify.

Thank you very much for your comments. We have modified the relevant sentences as follows (line 670-673):

"In the K22 scheme, however, the high N_i (>100 L^{-1}) extends over a larger area, facilitating interaction and competition between OGW-induced ice sources with other ice sources even far from the mountainous regions."

39. Line 430: Could you clarify why this does not qualify as a clean oceanic environment?

Thank you very much for your comment. This is primarily an oceanic environment, and in our analysis, we do not classify it as a “clean” or “polluted” environment because we do not have relevant aerosol or other tracer gas observational data to validate.

40. Lines 430-431: “At the cloud top, ice crystals due to turbulence make the most significant contributions to the simulated Ni peaks when T < 210 K in both schemes (Fig. 9b).” This sentence is unclear. How was Ni at the cloud top identified?

Thank you very much for your comments. We have modified the relevant sentence as follows (line 709-711):

“At low temperature levels (T < 209 K), both schemes exhibit positive turbulence-induced ΔN_i values, suggesting that ice crystals due to turbulence make the most contributions to the N_i at these cold temperatures (Fig. 9b). ”

41. Lines 431-435: A general comment: The analysis of the “main ice source” may be affected by uncertainties in three drivers: ice crystal detrainment from deep convection, TKE, and OGWs. If this is the case, it would be beneficial to discuss the uncertainties in these drivers in the study, perhaps in the discussion section.

Thank you very much for your comments. We completely agree that the “main ice source” may be affected by the uncertainties in the three drivers: ice crystal detrainment from deep convection, TKE, and OGWs. We have added some sentences in discussions section 5 (line 880-884):

“Further studies should also consider incorporating additional dynamic processes, such as frontal and convective gravity waves (Yook et al., 2025). In addition to gravity waves, uncertainties in the representation of other drivers of ice sources, such as turbulence and convective detrainment, should be reduced. Recent incorporations of convective cloud microphysics in deep convection (Lin et al., 2021; Song & Zhang, 2011) should help to reduce the uncertainty in detrained ice properties. ”

42. Lines 436-449: The discussion in this section could be better structured. First, the uncertainties in the INP activation rate arise from two primary factors: (1) supersaturation and (2) aerosol concentrations. The detrainment, OGW, and TKE influence supersaturation, which may only partially explain the biases in Ni. Second, other source and sink terms beyond INP activation, such as secondary ice production, ice sublimation, and sedimentation, may also play a significant role. Could you clarify how these processes contribute?

Thank you very much for your comments. We agree with the reviewer regarding the processes influencing ice number N_i in cirrus clouds, first, ice formation depending on supersaturation and aerosols, and then ice evolution depending on secondary ice production, ice sublimation and sedimentation. We have modified the relevant paragraphs to better structure the discussion as follows (line 712-727):

"In the lower levels of cirrus (T > 227 K), most of the simulated N_i peaks occur (Fig. 9a). At these temperatures, turbulence-induced ΔN_i values are mostly positive and generally exceed OGW-induced and detrained ΔN_i values in both schemes, suggesting a strong enhancement of N_i from turbulence. However, OGW-induced and detrained ΔN_i values differ between the two schemes. In the K22 scheme, positive OGW-induced and detrained ΔN_i values suggest significant enhancements to N_i from OGWs and detrainment. In contrast, the LP05 scheme shows large variability, with OGW-induced and detrained ΔN_i values fluctuating between positive and negative, indicating more complex and varied effects from these ice sources in the simulations.

Numerous studies have demonstrated that turbulence from CLUBB-TKE can hardly predict perturbations from gravity waves (Golaz et al., 2002a, 2002b; Huang et al., 2020). To accurately simulate cirrus clouds over oceans in Region 3, it is necessary to incorporate representations of other key dynamic drivers for ice nucleation, such as frontal and convective gravity waves. It is also important to incorporate key INPs (e.g., marine organic aerosols) besides mineral dust into ice nucleation schemes. Other source and sink terms beyond ice nucleation, such as secondary ice production, ice sublimation, and sedimentation, may also play a significant role in influencing the N_i evolution over oceans. "

43. Line 451: "Both K22 and LP05 schemes can effectively simulate the dominant ice sources." Could you confirm whether the dominant ice source in this study is INP activation? As far as I understand, secondary ice production may surpass INP activation in driving Ni.

Thank you very much for your comment. We agree that secondary ice production is a very important ice source. We have modified the sentence to avoid any misunderstandings as follows (line 740-741):

"Both K22 and LP05 schemes can effectively simulate the ice nucleation as a dominant ice source in orographic cirrus clouds, though they exhibit different effects from other ice sources on simulated N_i. "

44. Lines 458-462: While OGWs are known to induce high supersaturation conducive to ice formation, the large increase in Ni may result from both INP activation and secondary ice production (e.g., ice multiplication during solution droplet freezing). Is there any evidence indicating that INP activation is the dominant process in this case?

Thank you very much for your comment. It is known that secondary ice production (SIP) can lead to an increase in ice number by several orders of magnitudes over N_i from primary ice nucleation. Our simulations without considering SIP in the model can reproduce the N_i in orographic cirrus observed in SPARTICUS reasonably well. Thus, we don't expect that the SIP is the main factor for the observed N_i here. Furthermore, ice shattering during solution droplet freezing requires drizzle size drops (>100 μm) at much larger temperatures (Luke et al., 2021), which don't exist in these cold cirrus clouds.

45. Lines 469-470: "OGW-induced ice crystals are the dominant contributors in these 16 days of cirrus clouds (Fig. 10b)." Based on Figure 10b, it appears that OGWs primarily dominate Ni in the K22 scheme but not in LP05. Additionally, in the K22 scheme, detrainment appears to contribute comparably to OGWs. Would you consider revising this statement to better reflect these findings?

Thank you very much for your comment. We found an error in our plotting script for Figure 10b. After correcting it, detrainment plays a much smaller role compared to OGWs in the K22 scheme. OGWs still dominate N_i in LP05 compared to other contributors (detrainment and turbulence), although the magnitude from OGWs is smaller in LP05 than in K22.

46. Lines 473-474: More evidence is needed to support the assertion that the assumed detrainment ice size is inappropriate. Ice crystals above the -40°C layer are typically smaller than 50 µm, correct? If so, please provide references or observational data to substantiate this claim. Additionally, since both the K22 and LP05 schemes employ the same ice size assumption, why does LP05 underestimate Ni? It seems that Lines 340-344 attempt to explain this, but the connection between ice nucleation competition and Dnum changes is unclear. Could you provide a clearer explanation, particularly regarding the underlying physical mechanisms?

Thank you very much for your comments. We agree that there are uncertainties on assumed detrained ice size. Unfortunately, we find limited references in literature that directly address detrained ice sizes. It is true that both the K22 and LP05 schemes use the same assumed ice size of 50 µm for detrained ice. Because detrainment plays a minor role in the orographic cirrus identified in SPARTICUS (see corrected Figure 10b), we have deleted these sentences to avoid confusion.

47. Lines 497-498: Further evidence is needed to support the claim that smaller ice crystals have longer lifetimes. While smaller ice crystals indeed fall more slowly, their larger collective surface area may enhance sublimation in subsaturated conditions. Could you compare these competing mechanisms?

Thank you very much for your comment. A small ice crystal falls more slowly than a large one and typically has smaller surface area for sublimation. These two factors allow small ice crystals to remain in the atmosphere for longer periods. However, if ice water content of ice crystals is the same, the collective surface area of fewer large ice crystals would be smaller than that of small ones. The total sublimation rate of the large ones would be therefore lower than that of small ones. However, the role of sedimentation appears to be more important, because if ice crystals fall slowly they tend to stay within clouds and thus less subject to the sublimation in subsaturated conditions.

We have modified the sentence in the revision (line 815-817):

"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. "

48. Lines 498-500: The changes in cloud frequency and circulation dynamics do not appear to be particularly striking. Since the vertical velocity used in the INP scheme corresponds to subgrid-scale processes, while the ascending motion of large-scale circulation is represented by grid-scale vertical velocity, how do you reconcile this difference in scale?

Thank you very much for your comments. The magnitude of large-scale circulation is typically on the order of 0.001 m/s, while subgrid-scale vertical velocities generally range from 0.01 to 0.1 m/s. In this paper, we emphasize that the indirect influence of N_i between different nucleation schemes are not driven by changes in subgrid-scale vertical velocity. We modified the sentence to make it clearer (line 817-820):

"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. "

49. Lines 501-503: As mentioned here, there are clear differences in dust concentrations between the K22 and LP05 schemes. Could you also discuss the dust differences in the nudging runs? In Sections 4.2-4.3, the differences in Ni between K22 and LP05 are attributed primarily to detrainment, OGWs, and TKE. However, the impact of dust concentration differences on Ni is not discussed. Could you clarify why dust differences were not considered in these sections?

Thank you very much for your comment. As shown in Fig. R1-1 above, the nudged experiments during the SPARTICUS campaign indicate that coarse mode dust number concentration in the K22 scheme tends to be higher than that in the LP05 scheme. However, dust number concentrations appear to be very low (< 1 L^{-1}) and thus heterogeneous nucleation on dust tends to be less important for N_i compared to other factors.

50. Lines 507-508: See my earlier comment on Line 45. It does not appear that OGWs dominate Ni in both the LP05 and K22 schemes. Additionally, conclusions drawn from short simulations covering only a few days may not be sufficiently robust. Could you comment on the limitations of these short-term results?

Thank you very much for your comment. We have modified the relevant sentences as follows (line 827-829):

"Both the LP05 and K22 schemes identify OGWs as the dominant ice crystal source in orographic cirrus clouds observed during SPARTICUS, but the LP05 scheme exhibits greater competition from detrainment and turbulence sources than the K22 scheme. "

51. Lines 521-523: While it is clear that low-level moisture is generally higher over the ocean than over land, I am particularly interested in how significant this difference is in the upper troposphere and lower stratosphere. Could you provide a moisture profile plot to illustrate this difference?

Thank you very much for your comments. We have included specific humidity (Q) profiles over land and oceans from the OGW experiments in the two schemes during the ORCAS and SPARTICUS campaigns. The Q vertical profiles are similar in both schemes (Fig. R1-16 and R1-17). During the ORCAS campaign, the Q profiles over land and ocean are comparable, with slightly higher Q over land near 600hPa, indicating that high-level moisture over land is not necessarily lower than over ocean.

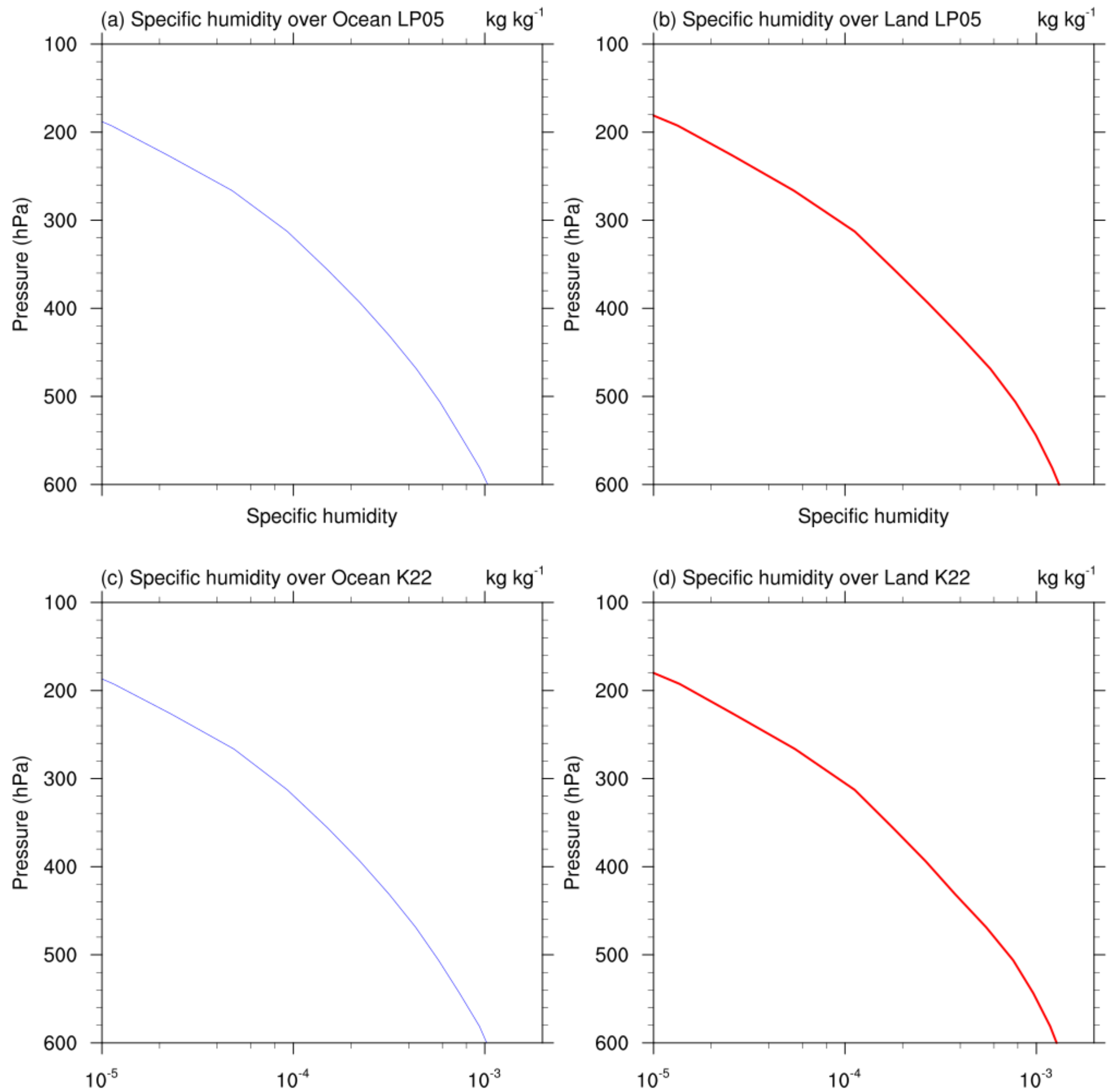

Fig. R1-16. Average specific humidity (Q) profiles over land and ocean in LP05_OGW-OR and K22_OGW-OR experiments along the flight tracks during the ORCAS campaign.

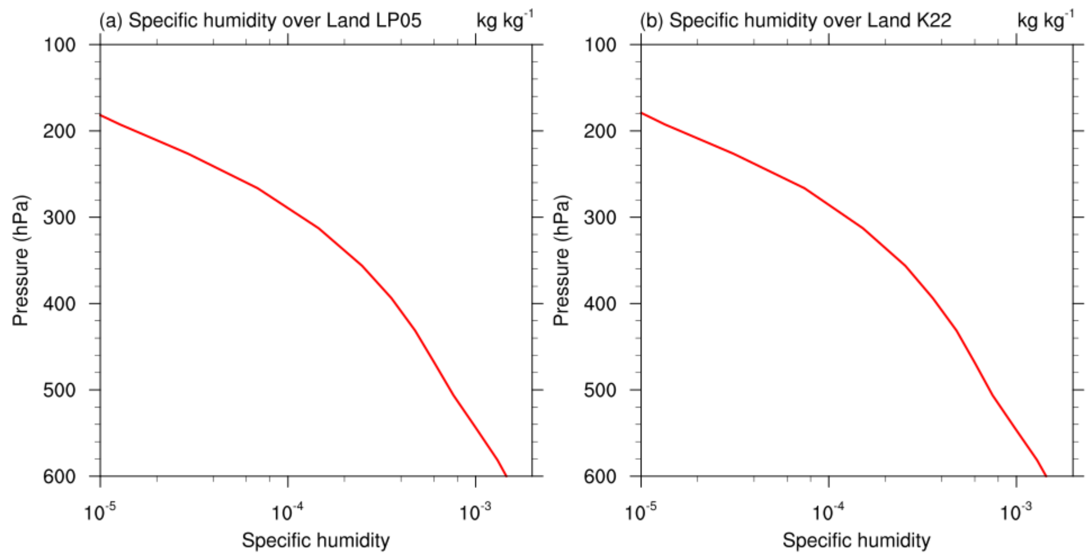

Fig. R1-17. Average specific humidity (Q) profiles over Land in LP05_OGW-SP and K22_OGW-SP experiments along the flight tracks during the SPARTICUS campaign.

Reference:

Beall, C. M., Hill, T. C. J., DeMott, P. J., Köneman, T., Pikridas, M., Drewnick, F., Harder, H., Pöhlker, C., Lelieveld, J., Weber, B., Iakovides, M., Prokeš, R., Sciare, J., Andreae, M. O., Stokes, M. D., & Prather, K. A. (2022). Ice-nucleating particles near two major dust source regions. *Atmos. Chem.Phys.*, *22*(18), 12607-12627. https://doi.org/10.5194/acp-22-12607-2022

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