

Reply on RC1

Overview

I appreciate that the authors made revisions carefully and replied to my comments in detail.

However, I still have some questions about the revised manuscript.

General comments

Dear editor and reviewers,

Thank you for your thorough review of the manuscript. We have read the reviewer's comments carefully, and have responded and taken your comments into consideration and revised the manuscript accordingly. All the changes have been highlighted in the revised manuscript. Our detailed responses, including a point-by-point response to the reviews and a list of all relevant changes, are as follows:

1. The authors did not respond to my comments #35.

comments #35: L328-330: What is the basis for the authors to divide this case into 3 phases?

A: Thank you for your careful review of the manuscript.

The three-phase division was based on an event-centered compositing approach relative to the occurrence time of dust–precipitation at each station. Given that dust–precipitation events do not occur simultaneously across different stations in Region 2, a common absolute time reference cannot represent the evolution of the event across the region.

Specifically, time steps and grid points are selected as dust–precipitation stations only when they satisfy the criteria of $PM_{2.5}/PM_{10} < 0.6$ and surface precipitation exceeding 0.1 mm. For a given station, the time step when both dust and precipitation conditions were satisfied was defined as Phase 2. Phase

1 corresponds to the state 6 hours prior to that event time at the same station, when the dust–precipitation conditions were not satisfied. Phase 3 corresponds to the state 6 hours after the event time, also under non–dust–precipitation conditions. The regional means were therefore derived from an event-centered composite, so the samples in each phase represent the same relative time with respect to the dust–precipitation event at each station, rather than the same absolute time across the region.

In the first-round revision, the phased comparison (Phases 1–3) was removed, and the manuscript now focuses exclusively on the cloud hydrometeor variations during the dust–precipitation period. We apologize for not explicitly addressing this point in our previous response.

2. What is the reason for the suppressed heterogeneous ice nucleation process above 7 km in T_IN case compared to T_CTL case?

A: Thank you for pointing out this issue. The reduced heterogeneous ice nucleation above 7 km in the T_IN case does not indicate that the on-line aerosol-IN nucleation scheme suppresses ice formation. Instead, it reflects a correction of the overestimation present in the original T_CTL simulation.

In T_CTL, heterogeneous ice nucleation is primarily controlled by temperature. Previous studies have shown that ice nucleation efficiency peaks within a moderate temperature range (approximately -20 to 0 °C) (Haarig et al., 2019; He et al., 2021; He et al., 2023). In the real atmosphere, the number concentration of effective ice-nucleating particles often reaches a maximum in the mid-troposphere rather than at the highest altitudes (He et al., 2023). As a result, a temperature-only formulation tends to overestimate heterogeneous ice nucleation at higher altitudes.

In contrast, the T_IN experiment explicitly links heterogeneous ice nucleation to aerosol ice-nucleating particles. This introduces a constraint on

ice formation based on the available ice-nucleating particles, leading to reduced nucleation rates above 7 km where the number concentration of effective ice nuclei is relatively low. Therefore, the decreased heterogeneous ice nucleation in T_IN above 7 km represents a more physically realistic redistribution of ice formation.

The manuscript has been revised in line 365-368:

In the real atmosphere, the number concentration of effective ice-nucleating particles often reaches a maximum in the mid-troposphere rather than at the highest altitudes (He et al., 2023), suggesting that the continuous increase of IN at higher altitudes in T_CTL may inconsistent with typical observed .

3. And what is the reason for the weakened droplet activation and condensational growth in T_IN compared to T_CTL case?

A: Thank you for your question.

To understand the weakened droplet activation and condensational growth in T_IN compared to T_CTL, we examined the vertical profiles of temperature and water vapor averaged over the dust–precipitation stations during the period when the dust impact was most pronounced, from 18:00 UTC 11 April to 18:00 UTC 12 April.

The results show that, in both the near-source region (region 3) and the downstream region (region 2), the introduction of the on-line aerosol–IN nucleation scheme leads to temperature increases below 4 km, with changes of about 0.16 to 0.52 K (Fig. 1a), while the water vapor mixing ratio changes by -0.04 to 0.19 g kg⁻¹ during this period (Fig. 1b). These changes lead to a decrease in relative humidity within the warm-cloud layer.

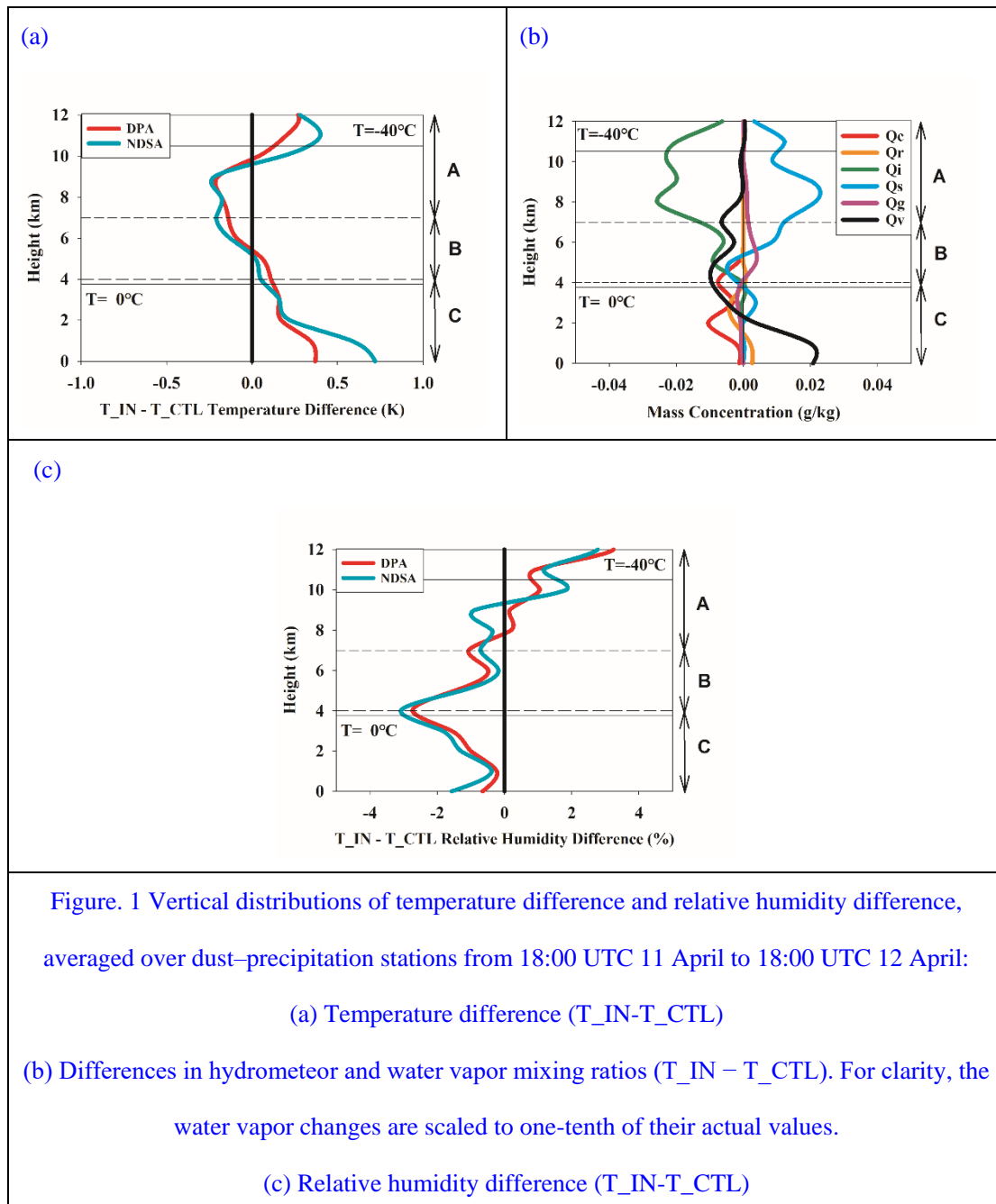
The relative humidity averaged over the dust–precipitation stations decreases by up to about 3% in Region 2 during this period. In Region 3, it locally reaches reductions of 6–7% around 4 km at 06:00 UTC 12 April (Fig. 1c). The reduced relative humidity suppresses droplet activation and condensational growth, thereby inhibiting the development of warm clouds in T_IN compared to T_CTL.

The manuscript has been revised in line 389-394:

To further examine the thermodynamic conditions responsible for the weakened production rate of cloud droplet activation from CCN in T_IN in Figure 4, the vertical profiles of temperature and water vapor were analyzed, averaged over the dust–precipitation stations in DPA and NDSA during the period when the dust impact was most pronounced (18:00 UTC 11 April to 18:00 UTC 12 April) (Figure 5).

In line 482-492:

Fig 5 show that, over dust–precipitation stations in both the NDSA and the DPA, the introduction of the on-line aerosol–IN nucleation scheme leads to temperature increases below 4 km, with changes of about 0.16 to 0.52 K, while the water vapor mixing ratio changes by -0.04 to 0.2 g kg⁻¹ during this 18:00 UTC 11 April to 18:00 UTC 12 April. These changes lead to a decrease in relative humidity within the warm-cloud layer. The relative humidity averaged over the dust–precipitation stations decreases by up to about 3 percentage points in the DPA during this period. In the NDSA, it locally reaches reductions of 6–7 percentage points around 4 km at 06:00 UTC 12 April. The reduced relative humidity suppresses droplet activation and condensational growth, thereby inhibiting the development of warm clouds in T_IN compared to T_CTL.



Specific comments:

- Line 33-35: "Below 4 km, dust suppresses the conversion of water vapor to cloud water and of cloud water to rain, reducing the liquid-phase hydrometeor content to 90-95% of T_{CTL} ." What is the reason for that?

A: Thank you for this question.

The suppressed conversion from water vapor to cloud water and from cloud water to rain below 4 km is mainly associated with a decrease in relative humidity within the warm-cloud layer in T_IN.

As shown in the Fig. 1, the introduction of the on-line aerosol-IN nucleation scheme leads to temperature increases below 4 km, with changes of about 0.16 to 0.52 K, while the water vapor mixing ratio changes by -0.04 to 0.19 g kg^{-1} . These changes result in a decrease in relative humidity within the warm-cloud layer. The relative humidity averaged over the dust-precipitation stations decreases by up to about 3% in the main analysis region. The reduced relative humidity suppresses droplet activation and condensational growth, which in turn weakens the conversion of water vapor to cloud water and the subsequent conversion of cloud water to rain.

2. Line 62-64 and Line 215-218: The authors mentioned that the ice nucleation scheme developed by Jiang et al. (2016) was based on “dust events observed in Xinjiang, Huangshan, and Nanjing in China”. Does that mean the dust events observed in Jiang et al. (2016) originated from Xinjiang, Northwest China and eventually reached to Huangshan and Nanjing? Please check Jiang et al. (2016) carefully. As I learned from Jiang et al. (2016), the IN measurements were conduct during May 14 to May 24, 2014 at Xinjiang, September 27 to October12, 2012 at Mt. Huangshan, and August 5 to August 30, 2013 at Nanjing.

A: Thank you for pointing out this issue.

The reviewer is correct. The IN measurements at Xinjiang, Mt. Huangshan, and Nanjing reported in Jiang et al. (2016) were conducted during different periods and at different locations, rather than representing a single dust transport event. These experiments used a consistent sampling and measurement approach. Atmospheric aerosol particles were collected using a high-voltage electrostatic aerosol collector (HVEAC) and their ice-nucleating ability was analyzed with a static vacuum vapor diffusion chamber based on

the FRIDGE (Frankfurt Ice Nuclei Deposition Freezing Experiment) design (Bundke et al., 2008; Klein et al., 2010; Su et al., 2014). The observations from different sites and periods, including those reported in Yang et al. (2013) and Jiang et al. (2015), were combined in Jiang et al. (2016) to characterize aerosol ice-nucleating properties and to develop the aerosol-IN parameterization.

The manuscript has been revised in line 66-69:

Jiang et al. (2016) combined IN measurements during dust conditions at multiple sites in China, including Xinjiang (Jiang et al., 2016), Mt. Huangshan (Jiang et al., 2015), and Nanjing (Yang et al., 2013), and found that IN concentrations were significantly higher than those under non-dust conditions.

Line 212-220:

The parameterization used here follows the formulation of Chen et al. (2019). In Jiang et al. (2016), the ice-nucleating ability of dust aerosols was derived from measurements conducted at several sites in China (Yang et al., 2013; Jiang et al., 2015; Jiang et al., 2016), using a static vacuum vapor diffusion chamber based on the FRIDGE (Frankfurt Ice Nuclei Deposition Freezing Experiment) design. Chen et al. (2019) further refined the parameterization to explicitly represent deposition and condensation freezing processes within a specified temperature range. The number concentration of ice nuclei produced by deposition and condensation freezing, N_{icenu} (m^{-3}), is calculated as follows:

3. **Line 215-218: I don't understand this sentence. What does "...using the static vacuum vapor diffusion chamber Frankfurt Ice nucleation Deposition freezing Experiment..." mean?**

A: Thank you for pointing out this issue. The manuscript has been revised in line 212-220:

The parameterization used here follows the formulation of Chen et al. (2019). In Jiang et al. (2016), the ice-nucleating ability of dust aerosols was derived from measurements conducted at several sites in China (Yang et al., 2013; Jiang et al., 2015; Jiang et al., 2016), using a static vacuum vapor diffusion chamber based on the FRIDGE (Frankfurt Ice Nuclei Deposition Freezing Experiment) design. Chen et al. (2019) further refined the parameterization to explicitly represent deposition and condensation freezing processes within a specified temperature range. The number concentration of ice nuclei produced by deposition and condensation freezing, N_{icenu} (m^{-3}), is calculated as follows:

4. **Line 218-219: “Then some parameters of it was refined and extended it to represent both deposition and immersion freezing by Chen et al. (2019).” The authors mentioned that the ice nucleation scheme developed by Jiang et al. (2016) was extended to represent “both deposition and immersion freezing” by Chen et al. (2019). Please double check if it is true.**

A: Thank you for pointing out this issue.

In Jiang et al. (2016), the parameterization was derived from IN measurements of dust aerosols at different sites, but the formulation did not explicitly distinguish between specific heterogeneous nucleation modes, nor did it define a fixed temperature range such as 248–258 K. Therefore, the original statement in the manuscript was not sufficiently precise.

In Chen et al. (2019), the parameterization was further refined to explicitly represent deposition and condensation freezing processes within a specified temperature range. Accordingly, the description of “both deposition and immersion freezing” in the original manuscript was inaccurate.

In the present study, we follow the formulation given in Chen et al. (2019). We have revised the manuscript to clarify the literature relationship and to avoid implying that these processes were directly formulated in Jiang et al. (2016).

The manuscript has been revised in line 212-220:

The parameterization used here follows the formulation of Chen et al. (2019). In Jiang et al. (2016), the ice-nucleating ability of dust aerosols was derived from measurements conducted at several sites in China (Yang et al., 2013; Jiang et al., 2015; Jiang et al., 2016), using a static vacuum vapor diffusion chamber based on the FRIDGE (Frankfurt Ice Nuclei Deposition Freezing Experiment) design. Chen et al. (2019) further refined the parameterization to explicitly represent deposition and condensation freezing processes within a specified temperature range. The number concentration of ice nuclei produced by deposition and condensation freezing, N_{icenu} (m^{-3}), is calculated as follows:

5. **Line 176-179: “In the original WDM6 scheme, when the temperature is below 0 °C, the production rate of cloud ice is attributed to two processes: heterogeneous nucleation (P_{igen}) and deposition- sublimation rate of cloud ice (P_{idep}). Both consume water vapor to form ice clouds.” Here I think the “production rate” refer to the nucleation process (e.g., heterogeneous nucleation), while deposition/ sublimation process indicates the growing of ice particles.**

A: Thank you for pointing out this issue.

In the revised manuscript, we have clarified the description. In the original WDM6 scheme, when the temperature is below 0 °C, the increase in cloud ice mass concentration arises from two processes: heterogeneous nucleation (P_{igen}) and deposition–sublimation of cloud ice (P_{idep} , when positive). Both processes consume water vapor, with P_{igen} representing the

formation of new ice crystals through heterogeneous nucleation and Pidep representing the deposition–sublimation growth of existing ice particles.

The manuscript has been revised in line 174-176:

In the original WDM6 scheme, when the temperature is below 0 °C, the increase in cloud ice mass concentration arises from two processes: heterogeneous nucleation (Pigen) and deposition–sublimation of cloud ice (Pidep, when positive).

6. Line 211-214: “The initial size of the ice crystals is comparable to that of the smallest droplets (Chen et al., 2019)”. I don’t understand why the size of newly formed ice crystal through deposition and condensation freezing (from vapor phase) is comparable to the smallest droplets. The supercooled droplets do not participate into the deposition and condensation freezing processes.

A: Thank you for pointing out this issue. The reviewer is correct.

The description was based on Chen et al. (2019), where newly formed ice crystals through deposition and condensation freezing were assigned to the first size bin of ice crystals (1–3 μm) in a bin microphysics framework. However, in the WDM6 scheme used in this study, the size distribution of newly formed ice crystals is not explicitly represented, and the microphysical processes are described in terms of bulk mass tendencies. Therefore, the growth of individual ice particles cannot be represented in the same way as in a size-resolved bin scheme. We have removed the sentence: “ The initial size of the ice crystals is comparable to that of the smallest droplets (Chen et al., 2019) ”.

In the present study, based on ice nucleating particle observations in East Asia (Um et al., 2018; Chen et al., 2021; Yang et al., 2021), the parameters

r_{df} and r_{if} represent the characteristic sizes of ice crystals for deposition/condensation freezing(Pinud) and immersion freezing(Pinui).

The manuscript has been revised in line 241-244:

Considering ice crystals generally grow from smaller particles and the radius of initial ice crystal size are often smaller than observed values, and with reference to the bin sizes of aerosol particles in CUACE (Um et al., 2018; Chen et al., 2021; Yang et al., 2021), this study assumes the characteristic radius of ice crystals of r_{df} and r_{if} to be:

7. Line 361-364 and 276-279: I don't understand both sentences.

A: Thank you for pointing out this issue. Both sentences have been revised as follows:

The manuscript has been revised in line 277-281:

Considering that many radar observations and model studies have indicated that dust mainly participates in heterogeneous ice nucleation as ice nuclei within the mid-tropospheric layer (-20 - 0 °C) (Haarig et al., 2019; He et al., 2021; He et al., 2023), which corresponds to altitudes between 4 and 7 km in the present case, Fig. 1c shows the simulated dust concentration within this layer.

The manuscript has been revised in line 375-381:

As immersion freezing is the dominant heterogeneous nucleation mechanism (DeMott et al., 2015; Hiranuma et al., 2015), this study compares the number concentration of ice-nucleating particles activated by immersion freezing with those activated by deposition and condensation freezing. The DP-event-averaged results indicate that the activated IN number concentration

from immersion freezing exceeds that from deposition and condensation freezing by approximately 4–5 orders of magnitude.

8. Line 481-483: “across 116°E, 33°–50°N and 33°N, 103°–116°E”. I don’t understand what these latitude and longitude information stands for? It might be more clearly if the authors can plot the selected regions on the map.

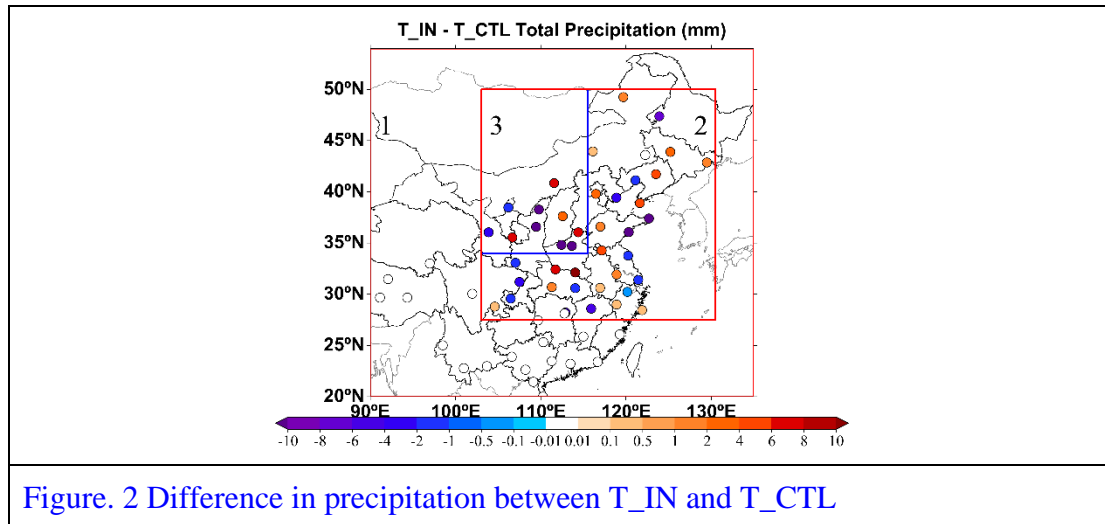


Figure. 2 Difference in precipitation between T_IN and T_CTL

A: Thank you for pointing out this issue.

The two coordinate descriptions refer to the vertical and horizontal cross sections used to divide the study area. The line along 116°E (33°–50°N) represents the north–south cross section, and the line along 33°N (103°–116°E) represents the west–east cross section. These two lines divide the study region into the near-source region (Region 3), where precipitation is suppressed, and the downstream region (Figure. 2).

Following the reviewer’s suggestion, the corresponding cross-section lines and selected regions have now been clearly marked in the map figure.

9. Figures 3d: Why does ice crystal exist from surface to 4 km (with temperature above 0 °C) as shown in Figure 3d?

A: Thank you for pointing out this issue.

The study domain covers 103 °–130.5 °E and 27.5 °–50 °N, which includes both lower-latitude warm regions and higher-latitude cold regions. The temperature shown in the figure represents a regional mean averaged over the dust–precipitation stations and dust–precipitation periods. However, at the northern stations within the domain, surface temperatures are lower and the 0 °C level can occur below 4 km. As a result, ice crystal can still exist in the 0–4 km layer at those colder northern locations.

10. Figure 4: The authors argued that the heterogeneous ice nucleation is promoted between 4–7 km in T_IN, and Figure 4a shows increased value of Pigen. But why was the value of Pidep decreased in T_IN compared to that in T_CTL? And the decreasing trend of Pidep is much more significant than the increasing trend of Pigen (black line vs. red line in Figure 4a).

A: Thank you for this insightful comment. In the WDM6 scheme, Pidep represents the net vapor deposition–sublimation tendency of cloud ice and is strongly controlled by the relative humidity, as well as the ice particle number concentration and particle size.

In the 4–7 km layer, introducing dust in T_IN substantially enhances heterogeneous ice nucleation (Pigen), producing a much larger number of newly formed ice crystals. As a result, the cloud ice number concentration increases, while the cloud ice mass concentration decreases, indicating that the additional ice particles are predominantly small. The effective diameters of cloud ice also decrease to 77%–97% of those in T_CTL, with occasional reductions exceeding 50%. The smaller ice crystals reduce the efficiency of depositional growth, leading to a decrease in Pidep in T_IN relative to T_CTL. In addition, the relative humidity in this layer is slightly reduced in T_IN (Fig.

1c), which further weakens vapor deposition onto ice particles. These combined effects lead to a decrease in P_{dep} in T_{IN} relative to T_{CTL} .

In Table 2, P_{dep} was defined as “Production rate for deposition- sublimation rate of cloud ice”, so it might be the net effect of deposition and sublimation. Can the authors check the depositional growth rate and sublimation rate separately to see if the former parameter is larger with more ice crystal being produced in T_{IN} test?

In WDM6, P_{dep} is diagnosed as a net tendency including both vapor deposition and sublimation, and the model output does not provide separate diagnostic terms for depositional growth and sublimation. In our case, P_{dep} in the 4–7 km layer remains positive, indicating that deposition dominates over sublimation in this region.

11. The x-axis name of Figure 4a is the same as that of Figure 4c.

A: Thank you for pointing out this issue. The x-axis label in Figure 4a has been corrected in the updated manuscript.

12. Authors’ response to comment #9: I don’t understand the authors’ explanation. It seems that the authors tried to explain the negative correlation between dust events and precipitation at the interannual scale from aspect of the role of dust acting as cloud condensation nuclei (CCN). If it is correct, dust can also act as CCN at event or monthly scale. But why it shows a positive correlation at monthly scale?

A: Thank you for pointing out this issue.

The previously cited reference mainly presented correlation results and did not provide a comprehensive physical explanation for the seasonal differences in dust–precipitation relationships. Therefore, we have simplified the corresponding discussion in the Introduction.

In the revised manuscript, the original reference has been replaced, and the revised text now focuses on the complexity of dust–precipitation interactions:

Based on chemistry (WRF-Chem) model and multiple observational and reanalysis data, Wang et al. (2024) found that dust aerosols can suppress light precipitation by increasing atmospheric stability and inhibiting the conversion of cloud droplets into raindrops.

13. Authors' response to comment #10: The authors mentioned that “Cloud effective diameters also tends to increase, which further weakens warm-rain processes.” What is the reason for the weakened warm-rain process induced by the increased cloud effective diameters? Furthermore, the authors attributed the suppressed precipitation in spring to dust’s direct radiative effect (absorbing solar radiation and heating the cloud layer). The radiative effect of dust can also exist in the summer, but why was the precipitation increased with more dust aerosols with an opposite effect compared to spring?

A: Thank you for pointing out this issue. The previously cited reference mainly presented correlation results and did not provide a comprehensive physical explanation for the seasonal differences in dust–precipitation relationships. Therefore, we have simplified the corresponding discussion in the Introduction.

In the revised manuscript, the original reference has been replaced, and the revised text now focuses on the complexity of dust–precipitation interactions:

Based on chemistry (WRF-Chem) model and multiple observational and reanalysis data, Wang et al. (2024) found that dust aerosols can suppress light precipitation by increasing atmospheric stability and inhibiting the conversion of cloud droplets into raindrops.

14. Authors' response to comment #21: The authors cited several literatures to explain why the density of cloud ice was set to 500 kg/m³. But I still don't understand what is the physical reason to use value of 500 kg/m³ instead of the density of pure ice (900 kg/m³).

A: Thank you for pointing out this issue.

Observational studies have shown that cloud ice particles in real clouds are typically irregular, porous aggregates rather than compact pure ice crystals, resulting in bulk effective densities that are substantially lower than the density of pure ice ($\sim 900 \text{ kg m}^{-3}$). For example, aircraft in situ observations indicate that the effective density of small ice particles under mid-latitude conditions is on the order of $\sim 700 \text{ kg m}^{-3}$ (Cotton et al., 2013). Based on such observational evidence and extensive applications and evaluations in numerical models, an effective cloud-ice density of 500 kg m^{-3} is used in this study to represent the average physical properties of cloud ice particles.

15. Authors' response to comment #35: Does "rain accretion (Paacw)" stand for the growing process of rain drops by collecting cloud droplet? This process does not absorb or release latent heat, why is it a "warming-related microphysical process"? Table 2 show the definition of Paacw as "Production rate for accretion of cloud water by averaged snow/graupel". I don't understand this sentence. And I still don't understand why the ice nucleation occurs at 2~4 km with temperature above 0 °C (as shown in Figure 2c).

A: Thank you for pointing out this issue.

In the WDM6 microphysics scheme, Paacw represents the accretion of cloud water by ice-phase hydrometeors, mainly snow and graupel, that is, the process in which snow or graupel particles collect cloud droplets. The thermodynamic effect of this process depends on the ambient temperature. Under subfreezing conditions ($T < 0 \text{ }^\circ\text{C}$), the collected droplets are typically supercooled and freeze onto the surface of snow or graupel particles. In this

case, cloud water is converted into snow or graupel, and latent heat of fusion is released, contributing to local warming.

Under above-freezing conditions ($T > 0\text{ }^{\circ}\text{C}$), the accreted droplets do not freeze. Instead, the process effectively represents the conversion of cloud water into rainwater, and no latent heat is released. Therefore, this process is categorized as a warming-related microphysical process only when it occurs in subfreezing conditions.

Regarding the occurrence of ice nucleation at 2–4 km in Fig. 2c, the temperature shown in the figure represents a regional average over the study domain (103°E – 130.5°E , 27.5°N – 50°N). Because the domain spans a large latitudinal range, stations located in the northern part of the region experience substantially lower temperatures, and the $0\text{ }^{\circ}\text{C}$ level there is often below 4 km. As a result, ice nucleation still exist within the domain at those altitudes.

16. Authors' response to comments #38 and #39: I don't understand why the existence of dust "suppress the production rate for cloud droplet activation from CCN in warm clouds". What is the physical mechanism for it?

A: The suppressed production rate for cloud droplet activation from CCN in T_IN is mainly related to the reduction of relative humidity in the warm-cloud layer.

As shown in the Fig. 1, the introduction of the on-line aerosol-IN nucleation scheme leads to temperature increases below 4 km, with changes of about 0.16 to 0.52 K, while the water vapor mixing ratio changes by -0.04 to 0.19 g kg^{-1} . These changes result in a decrease in relative humidity within the warm-cloud layer. The relative humidity averaged over the dust-precipitation stations decreases by up to about 3% in the main analysis region. The reduced relative humidity suppress the production rate for cloud droplet activation from CCN in warm clouds.

17. Authors' response to comment #42: Please state the method for calculating the horizontal hydrometeor fluxes in Figure 6.

A: Thank you for pointing out this issue.

The horizontal hydrometeor fluxes shown in Fig. 6 are calculated using a grid-based mass transport formulation. For each model layer, the flux is computed as

$$F = \rho_{air} q_x V \Delta z \Delta s$$

where F is the hydrometeor flux (kg s^{-1}), ρ_{air} is the air density (kg m^{-3}), q_x is the mass mixing ratio of the hydrometeor species (kg kg^{-1}), V_n is the wind component normal to the cross section (m s^{-1}), Δz is the layer thickness (m), and Δs is the horizontal grid spacing along the cross section (m).

The manuscript has been revised in line 329-334:

The horizontal hydrometeor fluxes shown in Section 3.3 are calculated using a grid-based mass transport formulation. For each model layer, the flux is computed as

$$F = \rho_{air} q_x V \Delta z \Delta s \quad (9)$$

where F is the hydrometeor flux (kg s^{-1}), ρ_{air} is the air density (kg m^{-3}), q_x is the mass mixing ratio of the hydrometeor species (kg kg^{-1}), V_n is the wind component normal to the cross section (m s^{-1}), Δz is the layer thickness (m), and Δs is the horizontal grid spacing along the cross section (m).

18. Authors' response to comment #44: "As a result, the peak values shown in T_IN can reach 103-104 L-1, while the peak values shown in T_IN can reach 100-101 L-1." I don't understand this sentence.

A: Thank you for pointing out this error. This sentence has been corrected:

As a result, the peak values in T_IN can reach 10^3 – 10^4 L⁻¹, while the peak values in T_CTL are about 10^0 – 10^1 L⁻¹.

19. Authors' response to comment #46: The authors did not explain why the heterogeneous ice nucleation is suppressed above 7 km in T_IN compared to T_CTL case.

A: Thank you for pointing out this issue.

The reduced heterogeneous ice nucleation above 7 km in the T_IN case does not indicate that the improved parameterization suppresses ice formation. Instead, it reflects a correction of the overestimation present in the original T_CTL simulation.

In T_CTL, heterogeneous ice nucleation is primarily controlled by temperature. As temperature decreases with height, the scheme tends to produce increasing numbers of activated ice nuclei. This leads to an overestimation of IN concentrations at higher altitudes, where the availability of effective ice-nucleating particles is actually limited. Previous studies have shown that ice nucleation efficiency peaks within a moderate temperature range (approximately -20 to 0 °C) (Haarig et al., 2019; He et al., 2021; He et al., 2023), and that the number concentration of effective ice-nucleating particles often reaches a maximum in the mid-troposphere rather than at the highest altitudes (He et al., 2023).

In contrast, the T_IN explicitly links heterogeneous ice nucleation to the concentration of aerosol ice-nucleating particles. This introduces an aerosol constraint on ice formation. Above 7 km, the number concentration of

effective ice nuclei is relatively low, and therefore the nucleation rate is reduced compared with T_CTL.

20. Authors' response to comment #48: What is the reason for weakened cloud droplet activation process in T_IN case compared to T_CTL case? And I don't understand that the accretion of cloud rain is suppressed but "the conversion of rainwater into ice-phase hydrometeors (Psaci, Pgaci, and Piaci) is enhanced". What is the source of rainwater for conversion into ice-phase hydrometeors since the rain accretion process was suppressed?

A: The weakened cloud droplet activation in T_IN is mainly related to the reduction of relative humidity in the warm-cloud layer. The introduction of the on-line aerosol-IN nucleation scheme leads to temperature increases below 4 km, which reduce relative humidity, thereby suppressing droplet activation from CCN.

Regarding the apparent inconsistency between the suppressed rain accretion and the enhanced conversion of rainwater into ice-phase hydrometeors, we note that the relevant terms are Psacr, Pgacr, and Piacr, which represent the accretion of rain by cloud ice, snow, and graupel, respectively. These processes depend on the fall speeds and the number or mass concentrations of the ice-phase hydrometeors.

In T_IN, the increased cloud ice number concentration enhances the accretion of rain by cloud ice, while the increased snow mass also contributes to stronger rain accretion by snow. However, much of this accretion occurs near the 0 °C level, where the accreted ice-phase hydrometeors rapidly melt back into rainwater. Therefore, although the conversion of rainwater into ice-phase hydrometeors is locally enhanced, it does not require an additional rainwater source, because the accreted particles quickly return to the rain category through melting.

Related References

- Chen, J., Wu, Z., Chen, J., Reicher, N., Fang, X., Rudich, Y., and Hu, M.: Size-resolved atmospheric ice-nucleating particles during East Asian dust events, *Atmospheric Chemistry and Physics*, 21, 3491–3506, <https://doi.org/10.5194/acp-21-3491-2021>, 2021.
- Chen, Q., Yin, Y., Jiang, H., Chu, Z., Xue, L., Shi, R., Zhang, X., and Chen, J.: The Roles of Mineral Dust as Cloud Condensation Nuclei and Ice Nuclei During the Evolution of a Hail Storm, *Journal of Geophysical Research Atmospheres*, 124, <https://doi.org/10.1029/2019JD031403>, 2019.
- Cotton, R., Field, P. R., Ulanowski, J., Kaye, P. H., Hirst, E., Greenaway, R., Crawford, I. A., Crosier, J., and Dorsey, J.: The effective density of small ice particles obtained from in situ aircraft observations of mid-latitude cirrus, *Quarterly Journal of the Royal Meteorological Society*, 139, <https://doi.org/10.1002/qj.2058>, 2013.
- DeMott, P. J., Prenni, A. J., McMeeking, G. R., Sullivan, R. C., Petters, M. D., Tobo, Y., Niemand, M., Möhler, O., Snider, J. R., Wang, Z., and Kreidenweis, S. M.: Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles, *Atmospheric Chemistry and Physics*, 15, 393–409, <https://doi.org/10.5194/acp-15-393-2015>, 2015.
- Haarig, M., Ansmann, A., Walser, A., Baars, H., Urbanneck, C., Weinzierl, B., Schöberl, M., Dollner, M., Mamouri, R., and Althausen, D.: Estimation of dust related ice nucleating particles in the atmosphere: Comparison of profiling and in-situ measurements, *E3S Web Conf.*, 99, 04002, <https://doi.org/10.1051/e3sconf/20199904002>, 2019.
- He, C., Yin, Y., Huang, Y., Kuang, X., Cui, Y., Chen, K., Jiang, H., Kiselev, A., Möhler, O., and Schrod, J.: The Vertical Distribution of Ice-Nucleating Particles over the North China Plain: A Case of Cold Front Passage, *Remote Sensing*, 15, 4989, <https://doi.org/10.3390/rs15204989>, 2023.

He, Y., Zhang, Y., Liu, F., Yin, Z., Yi, Y., Zhan, Y., and Yi, F.: Retrievals of dust-related particle mass and ice-nucleating particle concentration profiles with ground-based polarization lidar and sun photometer over a megacity in central China, *Atmospheric Measurement Techniques*, 14, 5939–5954, <https://doi.org/10.5194/amt-14-5939-2021>, 2021.

Hiranuma, N., Augustin-Bauditz, S., Bingemer, H., Budke, C., Curtius, J., Danielczok, A., Diehl, K., Dreischmeier, K., Ebert, M., Frank, F., Hoffmann, N., Kandler, K., Kiselev, A., Koop, T., Leisner, T., Möhler, O., Nillius, B., Peckhaus, A., Rose, D., Weinbruch, S., Wex, H., Boose, Y., DeMott, P. J., Hader, J. D., Hill, T. C. J., Kanji, Z. A., Kulkarni, G., Levin, E. J. T., McCluskey, C. S., Murakami, M., Murray, B. J., Niedermeier, D., Petters, M. D., O’Sullivan, D., Saito, A., Schill, G. P., Tajiri, T., Tolbert, M. A., Welti, A., Whale, T. F., Wright, T. P., and Yamashita, K.: A comprehensive laboratory study on the immersion freezing behavior of illite NX particles: a comparison of 17 ice nucleation measurement techniques, *Atmospheric Chemistry and Physics*, 15, 2489–2518, <https://doi.org/10.5194/acp-15-2489-2015>, 2015.

Jiang, H., Yin, Y., Su, H., Shan, Y., and Gao, R.: The characteristics of atmospheric ice nuclei measured at the top of Huangshan (the Yellow Mountains) in Southeast China using a newly built static vacuum water vapor diffusion chamber, *Atmospheric Research*, 153, 200–208, <https://doi.org/10.1016/j.atmosres.2014.08.015>, 2015.

Jiang, H., Yin, Y., Wang, X., Gao, R., Yuan, L., Chen, K., and Shan, Y.: The measurement and parameterization of ice nucleating particles in different backgrounds of China, *Atmospheric Research*, 181, 72–80, <https://doi.org/10.1016/j.atmosres.2016.06.013>, 2016.

Um, J., McFarquhar, G. M., Stith, J. L., Jung, C. H., Lee, S. S., Lee, J. Y., Shin, Y., Lee, Y. G., Yang, Y. I., Yum, S. S., Kim, B.-G., Cha, J. W., and Ko, A.-R.:

Microphysical characteristics of frozen droplet aggregates from deep convective clouds, *Atmospheric Chemistry and Physics*, 18, 16915–16930, <https://doi.org/10.5194/acp-18-16915-2018>, 2018.

Wang, J., Wang, T., Yasheng, D., Wang, X., Lei, Y., Li, X., Wang, Z., and Shi, B.: Modulations of dust aerosols on precipitation: Evidence from a typical heavy sandstorm event, *Atmospheric Research*, 304, 107411, <https://doi.org/10.1016/j.atmosres.2024.107411>, 2024.

Yang, J., Hu, X., Lei, H., Duan, Y., Lv, F., and Zhao, L.: Airborne Observations of Microphysical Characteristics of Stratiform Cloud Over Eastern Side of Taihang Mountains, *Chinese Journal of Atmospheric Sciences*, 45(1), 88–106, 2021.

Yang, L., Yin, Y., Yang, S., Jiang, H., Xiao, H., Chen, Q., Su, H., and Chen, C.: Measurement and Analysis of Atmospheric Ice Nuclei in Nanjing, *CJAS*, 37, 579–594, <https://doi.org/10.3878/j.issn.1006-9895.2012.11242>, 2013.

Reply on RC2

Overview

The authors have revised the manuscript thoroughly in response to the reviewers' comments. In particular, they have added a microphysical analysis, corrected the references, and clarified the differences among the IN schemes.

Nevertheless, a key concern remains regarding the lack of direct observational evaluation. The authors explain the difficulty of performing observational verification for this specific case, thus they attempt to assess the model results using available observational evidence from previous field and laboratory studies. This limitation should be stated more clearly in the Abstract, Summary, and Results sections.

Dear editor and reviewers,

Thank you for your thorough review of the manuscript. We have read the reviewer's comments carefully, and have responded and taken your comments into consideration and revised the manuscript accordingly. All the changes have been

highlighted in the revised manuscript. Our detailed responses, including a point-by-point response to the reviews and a list of all relevant changes, are as follows:

1. Related to previous general comment #1.

The authors have made efforts to validate the model behavior using previous observational studies. Please explicitly include sentences describing the magnitude of cloud ice number concentration reported in in-situ observational studies (e.g., Lawson et al., 2001; Wang et al., 2023), which were mentioned in the response letter, and compare these values with the magnitudes simulated in the revised manuscript.

A: Thank you for your careful review of the manuscript and for this helpful suggestion. Following your recommendation, we have explicitly included observational constraints on cloud ice number concentrations in the revised manuscript and compared them with the simulated values.

The manuscript has been revised in line 447-454:

In the aircraft observations reported, small ice particles ($>50 \mu\text{m}$) reached concentrations of up to 300 L^{-1} , whereas large ice crystals ($>600 \mu\text{m}$) were only about 3 L^{-1} (Wang et al., 2023). Despite their much lower number concentrations, the larger particles contributed more to the ice mass because of their substantially greater sizes. In the present simulation, the cloud ice number concentrations in T_IN reach on the order of 10^1 L^{-1} in the main mixed-phase layer, which is substantially higher than in T_CTL and closer to the observed magnitudes, although still lower than some aircraft measurements.

2. Related to previous general comment #3.

What criteria were used to divide the atmosphere into three layers (A, B, and C)? The merit of analyzing three distinct layers is unclear, given that the microphysical budget analysis has already been presented as a function of altitude. In addition, please clarify whether the new Figure 4 is time-averaged, domain-averaged, or both.

A: Thank you for pointing out this issue.

The three layers (A, B, and C) were defined based on the vertical temperature structure and the dominant microphysical regimes in this case. In mixed-phase clouds, heterogeneous ice nucleation by dust is most active within the temperature range of approximately -20 to 0 ° C, which typically corresponds to the mid-tropospheric layer (Haarig et al., 2019; He et al., 2021; He et al., 2023). In the real atmosphere, the number concentration of effective ice-nucleating particles often reaches a maximum in the mid-troposphere rather than at the highest altitudes (He et al., 2023).

Accordingly, layer B (4–7 km) represents the main mixed-phase region where heterogeneous ice nucleation is most active. Layer C (below 4 km) corresponds to the warm-cloud and melting layer, where liquid-phase processes dominate. Layer A (above 7 km) represents the colder upper-level ice-cloud region. This classification helps distinguish the different dominant microphysical regimes and provides a clearer physical interpretation of the dust impacts, complementing the altitude-resolved budget analysis.

Regarding the averaging method, Figures 3 and 4 show vertical profiles of hydrometeor mass and microphysical process rates that are both time-averaged over the dust–precipitation period (00 UTC 11 April–00 UTC 15 April 2018) and spatially averaged over dust–precipitation stations. We have revised the text and figure captions to explicitly clarify this averaging procedure.

The manuscript has been revised in line 384-389:

Figure 3 shows the DP-event-averaged vertical distributions of hydrometeors in T_CTL and T_IN , averaged over the dust–precipitation period (00 UTC 11 April–00 UTC 15 April 2018) and over dust–precipitation stations, as well as their difference ($T_IN - T_CTL$), by using budget analysis. Figure 4 shows the differences in the production rates of different hydrometeors ($T_IN - T_CTL$).

In Figure:

Figure 3. Distributions of hydrometeors, averaged over the dust–precipitation period (00 UTC 11 April–00 UTC 15 April 2018) and over dust–precipitation stations:

Figure 4. Vertical distributions of production rate difference for hydrometeors, averaged over the dust–precipitation period (00 UTC 11 April–00 UTC 15 April 2018) and over dust–precipitation stations:

3. Technical and formatting issues.

Nicenud is written in italics in some parts of the manuscript but in normal font elsewhere. A similar inconsistency appears for “ ρ ” (air density). Please ensure consistent formatting of mathematical notation and the names of microphysical budget terms throughout the manuscript. In addition, units such as (kg m^{-3}) should be written in normal (roman) font

A: Thank you for pointing out these formatting issues. We have carefully checked the entire manuscript and revised the notation to ensure consistency throughout. All microphysical variables (e.g., Nicenud) and physical parameters (e.g., air density ρ) are now presented in a consistent format, and all units (e.g., kg m^{-3}) are written in normal (roman) font. These corrections have been applied uniformly across the text, equations, tables, and figure captions.

Related References

Haarig, M., Ansmann, A., Walser, A., Baars, H., Urbanneck, C., Weinzierl, B., Schöberl, M., Dollner, M., Mamouri, R., and Althausen, D.: Estimation of dust related ice nucleating particles in the atmosphere: Comparison of profiling and in-situ measurements, E3S Web Conf., 99, 04002, <https://doi.org/10.1051/e3sconf/20199904002>, 2019.

He, C., Yin, Y., Huang, Y., Kuang, X., Cui, Y., Chen, K., Jiang, H., Kiselev, A., Möhler, O., and Schrod, J.: The Vertical Distribution of Ice-Nucleating Particles

over the North China Plain: A Case of Cold Front Passage, *Remote Sensing*, 15, 4989, <https://doi.org/10.3390/rs15204989>, 2023.

He, Y., Zhang, Y., Liu, F., Yin, Z., Yi, Y., Zhan, Y., and Yi, F.: Retrievals of dust-related particle mass and ice-nucleating particle concentration profiles with ground-based polarization lidar and sun photometer over a megacity in central China, *Atmospheric Measurement Techniques*, 14, 5939–5954, <https://doi.org/10.5194/amt-14-5939-2021>, 2021.

Wang, Y., Kong, R., Cai, M., Zhou, Y., Song, C., Liu, S., Li, Q., Chen, H., and Zhao, C.: High small ice concentration in stratiform clouds over Eastern China based on aircraft observations: Habit properties and potential roles of secondary ice production, *Atmospheric Research*, 281, 106495, <https://doi.org/10.1016/j.atmosres.2022.106495>, 2023.