Response to the Comments of Referees

Journal: Atmospheric Chemistry and Physics
Manuscript Number: egusphere-2024-3662
Title: Aerosol-cloud interactions in liquid-phase clouds under different meteorological and aerosol backgrounds
Author(s): Jianqi Zhao, Xiaoyan Ma, and Johannes Quaas

We thank the reviewers and editor for providing helpful comments to improve the manuscript. We have revised the manuscript according to the comments and suggestions of the referees.
The referee's comments are reproduced (black) along with our replies (blue). All the authors have read the revised manuscript and agreed with the submission in its revised form.

Anonymous Referee #1

This manuscript shows real-world simulations of a cloud-aerosol interaction case and compares it to observations. The simulations are sophisticated, e.g., they use bin microphysics. The simulations are potentially informative, but I had difficulty understanding the manuscript. E.g., several times, the authors claim that one of their figures shows some phenomenon, but when I look at the figure, I don't see that phenomenon. Some instances are listed below. Maybe the figures need to be redesigned, for instance, split up and simplified. In addition, while there are lots of words describing what is (purportedly) plotted in the figures, a key issue of how the aerosol affects rainfall is not convincingly explained.

Thank you very much for your comments. We have made substantial revisions to the manuscript, including re-running the model with more appropriate configurations, revising the figures to improve readability, providing correspondence and statistical analysis for the text, and providing more reasonable explanations for some of the content. Details of the revisions can be found in the following responses.

Abstract: Please state what type of cloud you'll be exploring. Stratocumulus? Cumulus? Shallow clouds? Deep clouds?

The reviewer raises a good question, and we clarified the scope now early on. We study liquid-phase clouds of different kinds, and analyze the effect of aerosols on the liquid-phase cloud in different environments. We thus do not make a more detailed classification of liquid-phase clouds.

Abstract: The abstract leads the reader to believe that the manuscript will discuss liquid-only clouds: "We conduct a comparative analysis of aerosol-cloud responses in liquid-phase clouds". But only a few sentences later it talks about mixed-phase clouds "the transition of liquid-phase clouds into mixed-phase or ice-phase clouds." Can the wording be clarified?

The reviewer has a good point. Previously we were to discuss some anomalies in the aerosol-cloud relationship due to the transformation of liquid-phase clouds into other phases under the influence of aerosols. In the revised manuscript, we have excluded these cases and analyzed only the liquid-phase cloud. The manuscript is revised to clarify this.

Line 48: “in non-precipitating clouds, CLWP first increases and then decreases with the increase in Nd.” This is somewhat similar to the result found by Chen et al. (2024)’s paper entitled “Magnitude and timescale of liquid water path adjustments to cloud droplet number concentration perturbations for nocturnal non-precipitating marine stratocumulus”.

This reference helped us improve the introduction, and we have now cited it.

Line 90: “resolutions of 12 km and 2.4 km”. A 2.4-km grid spacing won’t be able to fully resolve turbulent updrafts (see Fig. 4), and hence won’t activate aerosol accurately. Are subgrid updrafts parameterized in the model? If so, how? Can you make some comments on the accuracy of the simulated vertical velocity?

This was indeed an omission in the previous manuscript and is clarified in the revision. Yes, we used the Grell-3 scheme to treat subgrid convection, and we added this note to Table 1 and provided the namelist file of WRF-Chem-SBM as Table S3 in the supplement.

Due to the difficult nature of the observations, we were unable to acquire usable vertical velocity data. The heights at pressure levels are generally influenced by the static equilibrium and thermal structure of the atmosphere, and this affects the distribution of vertical velocities. To address this, we added the simulated heights at each pressure level to Fig. S1 as an indirect evaluation of the vertical velocities. In addition, the accuracy of the vertical velocity simulation is a key factor in the accuracy of the simulation of atmospheric saturation and aerosol activation, and the evaluation of dewpoint depression and N_d can also, to some extent, corroborate the model's simulation of vertical velocities.

Line 113: “Sen experiment (counterfactual scenario)” I’ve never before heard the expression “Sen experiment”. Is “Sen” an abbreviation for “sensitivity”? If so, please say so.

The reviewer is right that this is not a universally-known abbreviation. Since there is only one sensitivity experiment in this study, the abbreviation “Sensitivity” is used directly to represent the experiment for ease of mention. We added the note 'Sen (abbreviation for “Sensitivity”) experiment' at this place.

Fig 5: How does the precipitation profile differ between the NT and T runs? Could you include the precipitation profile in Fig. 5? It looks like the T time period has a greater reduction in CLWP. Is this what one would expect given the theory described in Ackerman et al. (2004)’s paper entitled “The impact of humidity above stratiform clouds on indirect aerosol climate forcing”? (However, in the T case, the RWP decreases when the continental aerosols are omitted, which may differ from what Ackerman found.)

This is a useful suggestion, and we have incorporated the precipitation profile as Fig. 6d in the revised manuscript.

Continental aerosols lead to a greater increase in CLWP during T than NT. Our results do not contradict the findings of Ackerman et al. (2004). Ackerman et al (2004). pointed out that "only when the overlying air is humid or droplet concentrations are very low does sufficient precipitation reach the surface to allow cloud water to increase with droplet concentrations. Otherwise … cloud water is reduced as droplet concentrations increase." In relatively dry conditions with a higher number of cloud droplets, such as below 800 m during the NT period, an increase in cloud droplets leads to a decrease in CLWC and RWC (as shown in Figs. 6 and 7). However, during the relatively humid T period, or at altitudes where high RH (800–1000 m) and extremely low cloud droplet concentrations (above 1000 m) during the NT period, an increase in cloud droplets results in an increase in CLWC and RWC. These findings are consistent with those of Ackerman et al. (2004). We have revised the last paragraph of Section 3.2 to explain that an excessive number of small cloud droplets suppresses precipitation while also showing that in some areas lacking CCN, continental aerosols can enhance precipitation by providing CCN. Additionally, we clarified that during relatively humid T periods, some areas experience deep cloud development under the influence of continental aerosols, leading to precipitation. This does not conflict with the theory proposed by Ackerman et al. (2004) because they target different subjects. Additionally, some studies, such as Haghighatnasab et al. (2022), have also addressed this point.

Reference

Haghighatnasab, M., Kretzschmar, J., Block, K., and Quaas, J.: Impact of Holuhraun volcano aerosols on clouds in cloud-system-resolving simulations, Atmos. Chem. Phys., 22, 8457–8472, https://doi.org/10.5194/acp-22-8457-2022, 2022.

Line 274: "Continental aerosols have a significant impact on precipitation in ECO (Fig. 7). In the absence of continental aerosols, during the more unstable NT with stronger vertical motion, the rainwater path (RWP) in ECO (4.7 g·m^{-2}) is much higher than during T (2.2 g·m^{-2}). However, in the environment with high aerosol concentrations that includes continental aerosols, Nd increases, and cloud droplet sizes decrease to below the precipitation threshold, leading to precipitation being significantly suppressed in areas with high rainwater content (RWC) in the Sen experiment." These sentences are hard to understand. Are continental aerosols included, or is this the Sen experiment? Which RWP is greater than which other RWP? In these sentences, why not include mention of the titles of the panels in Fig. 7 (Sen_RWC_NT, Sen_RWC_T, etc.)? In general, I don't understand why Sen_RWC_T has *less* rain than Control_RWC_T (see Figs. 7 and 8). It seems counterintuitive, from the perspective of the Albrecht lifetime hypothesis.

We thank the reviewer for highlighting this unclear formulation. We have rewritten this paragraph to improve its readability.

Regarding the comment about whether the fact that Sen_RWC_T is lower than Control_RWC_T under the Albrecht lifetime hypothesis goes against intuition, we believe it does not. Albrechtsuggests that for shallow marine clouds, an increase in aerosol leads to an increase in N_d, which results in a reduction in droplet size, thereby suppressing drizzle and increasing the low-level cloud lifetime. In this study, the main precipitation area during NT and the precipitation area in the southeast during T align with this theory. What appears to contradict Albrecht's theory is the increase in RWC in the northwest precipitation area during T, but we argue that there is no conflict. The increase in RWC in that area is due to clouds developing more deeply with continental aerosols, which enhances condensation and collision processes to form stronger precipitation. This does not satisfy the premise of "low-level" and "shallow marine clouds" (this study focuses on winter liquid-phase clouds, most of which are shallow clouds, but not all. Under the influence of continental aerosols, clouds become deeper and cloud top heights can exceed 4,000 meters in some areas), so there is no contradiction. Additionally, related modeling studies on liquid-phase clouds, such as Haghighatnasab et al. (2022), also point out that "Inside the [polluted airmass], there is a decrease in light rain and an increase in heavy rain … Cloud droplets must grow larger, leading to deeper clouds in order to reach the size that they can start to precipitate. This leads to a shift in the LWP distribution to the higher values inside the plume." This is similar to the situation in this study.

Reference

Haghighatnasab, M., Kretzschmar, J., Block, K., and Quaas, J.: Impact of Holuhraun volcano aerosols on clouds in cloud-system-resolving simulations, Atmos. Chem. Phys., 22, 8457–8472, https://doi.org/10.5194/acp-22-8457-2022, 2022.

Line 298: "As shown in Fig. 8, RH exhibits a relatively clear negative correlation with LTS over the four areas during NT and the following 12 hours. In contrast, LTS is relatively high, and there is no significant correlation between RH and LTS during T, suggesting that changes in RH during this period are mainly driven by horizontal variations 300 in temperature and water vapor content." I don't see the "clear negative correlation with LTS".

We revised this paragraph to discuss the relationship between supersaturation and RH and LTS based on statistical analysis.

Line 318: "Overall, while continental aerosols lead to a decrease in CLWP in some conditions, they generally have a positive impact on CLWP." Do you mean *the presence of* continental aerosols?

We have rewritten this paragraph to discuss aerosol-cloud interactions in different environments based on a more accurate description and statistical analysis.

Line 321: "The additional continental aerosols also accelerate a transition to ice-phase and mixed-phase clouds by elevating cloud top heights, for example, during the first 12 hours in areas A and B." Where is ice plotted? By the way, in Fig. 8, I don't even see a line for CWP. The legend for CWP is blank.

Previously the CWP was indicated by blue shading. In the revised manuscript, we filtered out the grids containing ice phases to avoid their interference with the analysis of liquid-phase cloud aerosol-cloud interactions, and the CWP is no longer needed and is removed.

Line 324: "1) for low LTS conditions,such as in areas A, B, and C from 12:00 on the 2nd to 00:00 on the 3rd, continental aerosols cause a relatively brief and explosive increase in CLWP. 2) For high LTS conditions, such as during T in the four areas, continental aerosols lead to relatively prolonged high values of CLWP (around 10 hours) in ECO." I don't see this in Fig. 8. Rather, I see peaks in CLWP both between 12:00 on the 2nd to 00:00 on the 3rd, and also during period T.

We have rewritten this paragraph, supporting the discussion with more accurate statistics.

Line 330: "In terms of precipitation, during the relatively dry NT, continental aerosols cause reductions in both the number concentration of raindrops (Nr) and RWP." The RWP line is barely distinguishable from zero. It is hard to see.

We changed the RWP in Figure 8 to RWP multiplied by three to make the lines more visible.