Response to Reviewer 2 Comments

General comments

This manuscript presents a study of aerosol (especially giant particles such as mineral dust) & cloud interactions over UAE regions by using aircraft measurements. Comparative analysis from penetrated sampling by two research flights gives important information on cloud microphysical characterizes and precipitation formation mechanisms over this region. Among many recent studies on aerosol-cloud interaction, this research provides a new insight into understanding the influence of aerosols on cloud and precipitation processes, as well as its application for hygroscopic cloud seeding. This paper is overall well-written, but some scientific discussions tend to draw conclusions quickly without a strong statement, especially the linkage between aerosol properties and cloud microphysical process in section 5. In general, minor revisions are needed before the acceptance of this manuscript. Below listed are the comments and suggestions.

We thank Reviewer 2 for the many insightful comments and suggestions. Below is our point-by-point response to the provided comments.

Specific comments

1) Comment 1: In section 1: This part is a review of the roles that aerosols play in the cloud microphysical process. However, it lacks some important introductions such as the aerosol effect on precipitation or its application on hygroscopic seeding, as the title includes "… aerosol-cloud interactions … precipitation formation …". Please give a literature review about research that has been conducted in association with aerosols (especially giant CCN) as an agent of cloud seeding (you can put this part in this section or section 5.3):

   - *Jung, E., Albrecht, B. A., Jonsson, H. H., Chen, Y.-C., Seinfeld, J. H., Sorooshian, A., Metcalf, A. R., Song, S., Fang, M., and Russell, L. M.: Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds, Atmospheric Chemistry and Physics, 15, 5645-5658, 2015.*
   - *Rosenfeld, D., Axisa, D., Woodley, W. L., and Lahav, R.: A quest for effective hygroscopic cloud seeding, Journal of Applied Meteorology and Climatology, 49, 1548-1562, 2010.*
   - *Ghate, V. P., Albrecht, B. A., Kollias, P., Jonsson, H. H., and Breed, D. W.: Cloud seeding as a technique for studying aerosolâ��cloud interactions in marine stratocumulus, Geophysical Research Letters, 34, 2007.*
   - *Wang, F., Li, Z., Jiang, Q., Wang, G., Jia, S., Duan, J., and Zhou, Y.: Evaluation of hygroscopic cloud seeding in liquid-water clouds: a feasibility study, Atmospheric Chemistry and Physics, 19, 14967-14977, 2019.*

- Response to Comment 1: We expanded the introduction of Section 5.3 to provide more context on aerosol-cloud interactions, particularly the role of giant CCN and their suggested concentrations for hygroscopic seeding.

- Changes to Manuscript:

  Line 321–348: "Ghate et al. (2007) studied the impact of introducing giant (salt) seeding aerosols (1–5 µm) into marine stratocumulus clouds using in situ aircraft observations off the central coast of

California. Seeding plumes were identified using a threshold of 250 cm^{-3} for the PCASP concentrations compared to a background concentration of ~80 cm^{-3}. They observed a 5-fold increase in the number of large drops (20–40 µm) relative to the background, which was attributed to the activation of the seeding GCCN – a small fraction of the total aerosols produced by the flares. Furthermore, Jung et al. (2015) tested even larger seeding particles (1–10 µm) again in marine stratocumulus clouds off the central coast of California and reported a 4-fold increase in the rainfall rate associated with seeding GCCN concentrations of 10^{-2}–10^{-4} cm^{-3}. More recently, Wang et al. (2019) reported on a cloud seeding case study over the eastern coast of Zhejiang, China and observed the hygroscopic growth of larger-mode seeding particles (>2 µm) up to a limit of ~18 µm drop sizes associated with the competition effect.

The characteristics of the background aerosol population, namely their size, concentration and chemical composition are considered key precursory properties to determine, and potentially improve, the effectiveness of seeding. Segal et al. (2004) report optimum seeding CCN concentrations of 700 cm^{-3} in Mediterranean and extreme continental background conditions. This concentration is unrealistic in seeding operations and does not account for the impact of large background CCN which is further investigated by their simulations comparing seeded parcels with/without large, natural CCN centered on a diameter of 0.6 µm with concentrations of 0.15 and 0.3 cm^{-3}. Their results show a decrease in seeding impact when the large, natural CCN concentrations increased from 0.15 to 0.3 cm^{-3}. This was attributed to the competition with the prescribed seeding particles centered on a 10 µm diameter with a concentration of 0.032 cm^{-3}. Moreover, the original calculations of Ivanova et al. (1977) suggest CCN diameters larger than 5 µm serve as efficient raindrop embryos, while Segal et al. (2007) establish a minimum concentration of 0.025 cm^{3} for such particles to cause a noticeable increase in warm rain production from a rising cloud parcel under typical conditions in Texas.

The UAE measurements show natural GCCN diameters (5–10 um) concentrations between 0.25–0.15 cm^{-3} which are an order of magnitude larger than the seeding concentration suggested by Segal et al. (2004, 2007). Also, the UAE sub-cloud aerosol sizes extend from 0.01–100 µm with total concentrations ranging from 500–800 cm^{-3}. Hence, all three conceptual models for hygroscopic seeding outlined by Rosenfeld et al. (2010) are applicable to clouds studied over the UAE, namely, accelerating collision-coalescence by the competition effect (~1 µm), broadening the cloud drop size distribution by the tail effect (1–10 µm), and introducing ultra-giant seeding particles (>10 µm) to serve as rain drop embryos. These effects need to be thoroughly tested in model simulations based on the observations presented here."

Line 364–365: "The modelling work with different seeding material is in progress and is summarized in Geresdi et al. (2021)."

2) <u>Comment 2</u>: In section 5 It looks interesting that almost all the droplets in the negative temperature zone are supercooled water. According to glaciogenic seeding theory, does it mean the rich potential of cloud seeding in the UAE region?

- <u>Response to Comment 2</u>: The primary objective of the UAE campaign was carried out to investigate a potential secondary ice process (SIP) that may be activated by large amounts of super-cooled liquid drops in the subzero levels of mixed-phase clouds (Lawson et al., 2017). Our results indicate that the collision-coalescence (C-C) process was not activated in these clouds which suggests a low potential for a natural SIP in upper levels. Modeling studies can help assess the effectiveness of perhaps larger hygroscopic seeding particle sizes (10–15 µm), relative to background aerosols, in initiating C-C a potential SIP.

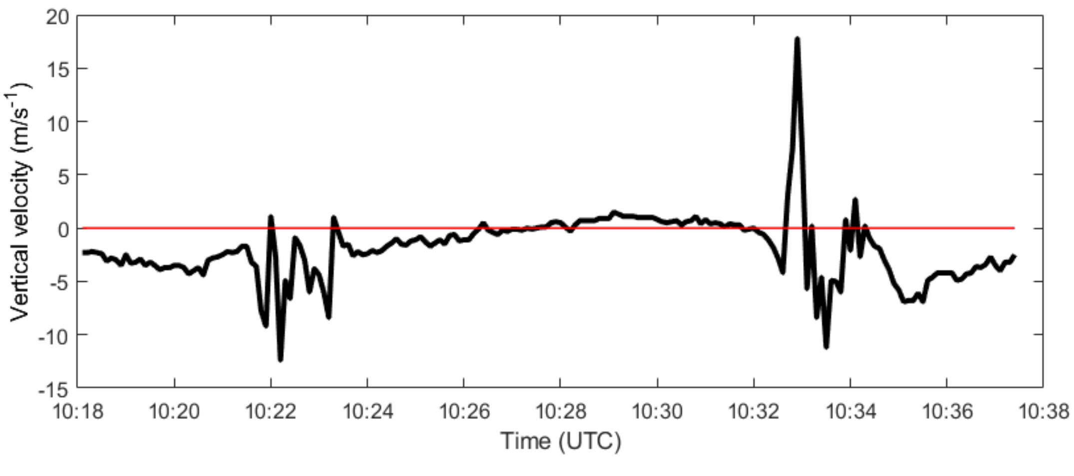
In terms of glaciogenic seeding potential, as noted by Kumar and Suzuki (2019), the large amounts of super-cooled liquid water observed in clouds over the northeastern UAE, especially during the winter season, may be transformed into ice by the ingestion of ice nuclei. Further modeling studies incorporating the in situ observations in this paper can help assess the potential of galciogenic seeding for UAE clouds, where current operations are limited to hygroscopic seeding at cloud base.

- Changes to Manuscript: Lines 384–388: “Furthermore, no indication of C-C is observed within any of the upper levels listed in Table 2 and displayed in Figures 9, 10 and 11. In the upper levels of SF1 (-12.6 and -12.4 °C), a dominant population of liquid drops (d<50 µm) is observed with very few ice particles showing a habit of sector plates (expected by nucleation at -12 °C). LWCs of ~1.4 g.m^{-3} with strong updrafts (~17.8 m.s^{-1}) and MVDs less than 20 µm are observed at these sub-freezing levels. Similar observations are also recorded in the upper levels of SF4 with no signs of ice multiplication.”

3) Comment 3: Line 255-258: Please show the relationship between vertical velocity and spatial position (or time series) during cloud penetration with a diagram to illustrate the huge difference of updraft (17.8 m s^{-1}) and downdraft (-12.4 m s^{-1}) measured in the upper portion of SF1.

- Response to Comment 3: The below figure shows the variation of the vertical velocity during the first two penetrations in the upper-level of SF1.

- Changes to Manuscript: The below figure is added as an inset in Figure 7a and referenced on Page 25.



4) Comment 4: Line 266-267: Why does drop size in the lower portion of SF1 seem smaller than that of SF4 from CIP image? As the fallout of ice irregulars or graupel are observed in both cloud penetrations.

- Response to Comment 4: Very few ice particles with a habit of sector plates are captured by the CPI at -12.4 °C in a decaying turret from SF1 (see Figure 9b and tail of Figure 11a). Alternatively, a relatively larger number of mm-sized irregulars and graupel are observed at -10.6 °C in a growing turret from

SF4 (see Figure 10b and tail of Figure 11b). This explains the larger contribution from fallout ice to the lower portions of SF4 compared to SF1.

5) Comment 5: Line 274-276: In contrast to 8.3 °C and -0.3 °C, 8.6 °C and 8.3 °C are almost at the same height during SF4 cloud penetration, please explain why spectrum broadening is obviously observed.

- Response to Comment 5: Despite the marginal altitude difference (~120 m) between the 8.6 °C and 8.3 °C levels, Figure 10 shows that their penetrations are borderline – just below cloud base and within the sub-cloud region, respectively. Broadening is therefore more pronounced at the 8.3 °C level, which transitions from out-of-cloud to in-cloud conditions.

6) Comment 6: Figure 9 and 10: How to determine the red oval in camera photo corresponds to the measurement by 2ds and cpi? Please add descriptions.

- Response to Comment 6: The cloud penetration locations (red ovals in Figures 9/10) were determined by visually inspecting video footage from the forward-facing cockpit camera within 1 minute of each cloud approach. A description is added to the caption on Figure 9 (Page 27).

Technical corrections

1) Line 93: "in favour of" -> "in favor of".

Line 93: corrected.

2) Line 161: "compliment" -> "complement".

Line 161: corrected.

3) Line 205-206: "…with high concentrations of around 1000 cm^{-3}…" -> "…with high concentrations of aerosols (around 1000cm^{-3}) …".

Line 205-206: revised to "…with high concentrations of aerosols (~ 1000cm^{-3}) …".

4) Line 254: "-12 C" -> "-12 °C".

Line 267: corrected.

5) Line 287: What is "PSD" short for? Please give the full name of the acronym when it first appears.

Line 300: "… particle size distribution (PSD) …" – the spell out of all acronyms at first use was checked.

6) Figure 1: Please mark the location of the airport.

Page 19: The location of the airport is marked as "Al Ain" on Figure 1 and stated in the figure caption.

7) Figure 2 and 3: Please improve the graph resolution.

The quality and resolution of Figures 2 and 3 have been improved.

8) Table1: The second annotation was not marked on the table.

Corrected.

9) Table 2: Please add standard deviation of the data.

Standard deviations added in Table 2.

10) Reference: Please unify the format of journal titles, such as “Atmospheric Chemistry & Physics” and “Atmospheric Chemistry and Physics, “Atmospheric environment” and “Atmospheric Environment” …

Journal titles are now unified in the reference list.

Authors’ References

- Geresdi, I., Chen, S., Wehbe, Y., Bruintjes, R., Lee, J., Tessendorf, S., Weeks, C., Sarkadi, N., Rasmussen, R. M., and Grabowski, W.: Sensitivity of the Efficiency of Hygroscopic Seeding on the Size Distribution and Chemical Composition of the Seeding Material, 101st American Meteorological Society Annual Meeting, 2021,
- Ghate, V. P., Albrecht, B. A., Kollias, P., Jonsson, H. H., and Breed, D. W.: Cloud seeding as a technique for studying aerosol-cloud interactions in marine stratocumulus, Geophysical research letters, 34, 2007.
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- Kumar, K. N., and Suzuki, K.: Assessment of seasonal cloud properties in the United Arab Emirates and adjoining regions from geostationary satellite data, Remote sensing of environment, 228, 90-104, 2019.
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- Rosenfeld, D., Axisa, D., Woodley, W. L., and Lahav, R.: A quest for effective hygroscopic cloud seeding, Journal of applied meteorology and climatology, 49, 1548-1562, 2010.
- Segal, Y., Khain, A., Pinsky, M., and Rosenfeld, D.: Effects of hygroscopic seeding on raindrop formation as seen from simulations using a 2000-bin spectral cloud parcel model, Atmospheric Research, 71, 3-34, 2004.
- Segal, Y., Pinsky, M., and Khain, A.: The role of competition effect in the raindrop formation, Atmospheric research, 83, 106-118, 2007.
- Wang, F., Li, Z., Jiang, Q., Wang, G., Jia, S., Duan, J., and Zhou, Y.: Evaluation of hygroscopic cloud seeding in liquid-water clouds: a feasibility study, Atmospheric Chemistry and Physics, 19, 14967-14977, 2019.