Response to Reviewer 2

This paper introduces a framework that categorizes convective cloud features from UAE into 5 different microphysical zones using satellite data. The effectiveness of this framework is then evaluated using aircraft observations from UAE 2019 Airborne Campaign. Overall, this paper is easy to follow. However, while the framework is somewhat interesting, there are several flaws in the methodology that requires some re-work.

We appreciate the valuable comments from the reviewer.
Our responses are in blue below each comment from the reviewer.

Major comments:

1. If I am understanding correctly, this paper targets the microphysics of continental convective clouds. However, it is surprising that for deriving the in situ measured cloud droplet size distribution and cloud effective radius (Reff), this paper is only using the FCDP. The author claims that this choice is based on the fact that the LWC derived from FCDP has higher correlation with the Nevzorov probe measured LWC. However, if you are studying the different microphysical processes (diffusional growth vs. collision coalescence), are having both liquid and ice phased clouds in your sampling, it is almost common practice to combine the FCDP/FFSSP with 2DS (or even HVPS), (see Rosenfeld and Lensky 1998, Painemal and Zuidema 2011, Kang et al. 2021). By using FCDP only, the in situ Reff will be biased towards the smaller droplets.

Rosenfeld, D., and I. M. Lensky, 1998: Satellite-Based Insights into Precipitation Formation Processes in Continental and Maritime Convective Clouds. Bull. Amer. Meteor. Soc., 79, 2457–2476, https://doi.org/10.1175/1520-0477(1998)079<2457:SBIIPF>2.0.CO;2.

Painemal, D., and P. Zuidema (2011), Assessment of MODIS cloud effective radius and optical thickness retrievals over the Southeast Pacific with VOCALS-REx in situ measurements, J. Geophys. Res., 116, D24206, doi:10.1029/2011JD016155.

Kang, L., Marchand, R. T., & Smith, W. L. (2021). Evaluation of MODIS and Himawari-8 low clouds retrievals over the Southern Ocean with in situ measurements from the SOCRATES campaign. Earth and Space Science, 8, e2020EA001397. https://doi.org/10.1029/2020EA001397

We appreciate the reviewer's suggestion and the reference. We agree with the reviewer and will recalculate the effective radius (ER) in this study using the combined cloud particle size distribution from FCDP, 2DS, and HVPS. Following Fu et al. (2022), we use 40 µm as a fixed break point to combine the FCDP and 2DS particle size distribution. The break point between 2DS and HVPS is 1000 µm. Only size distributions with total number concentrations greater than 10 cm^{-3} are included in calculating ERs (Fu et al., 2022). According to our tests, the new ERs based on combined size distribution (FCDP, 2DS, and HVPS) tend to be slightly larger (around or below 5%) than the ERs based on FCDP for most cloud penetrations (CPs). Because the large particle size (>40 µm) concentration from 2DS is much lower compared to the particle size concentration from FCDP, and the concentration from HVPS is extremely low (close or equal to 0) for most CPs (e.g., Figures 6 and 13 in the manuscript). Meanwhile, the difference between the new ERs and FCDP ERs becomes larger for those CPs at a cold temperature (e.g., around -12°C), which might be related to the appearance and increase of ice particles. In the revised manuscript, we will recalculate the ER, add a paragraph to describe the calculation of ER in Section 2 Dataset and Methodology, and modify the text accordingly throughout the manuscript.

Fu, D., Di Girolamo, L., Rauber, R. M., McFarquhar, G. M., Nesbitt, S. W., Loveridge, J., ... & Scarino, A. J. (2022). An evaluation of the liquid cloud droplet effective radius derived from MODIS, airborne remote sensing, and in situ measurements from CAMP 2 Ex. Atmospheric Chemistry and Physics, 22(12), 8259-8285.

2. The authors use the in-situ probe measured Reff to characterize the cloud microphysics, but then use the satellite measured Reff to build the framework to identify the different microphysical zones of convective clouds. This works under the assumption that the satellite measurements are representative of the in-situ measurements. However, the authors need to keep in mind that passive satellite retrieved Reff is a cloud top effective radius (which is not vertically resolved in any way), and the in situ Reff could be sampled from anywhere within a cloud (depending on where the cloud pass/penetration took place). These are conceptually different, and the authors need to be careful when using the different Reffs to characterize cloud microphysical processes.

We thank the reviewer for the valuable feedback. We acknowledge that these two measurements represent slightly different physical quantities, with the in-situ measurements capturing the microphysical properties at specific levels within the cloud, while the satellite retrievals provide a broader, less vertically resolved perspective. In our study, we used the satellite-derived ER to build the framework for identifying the microphysical zones of convective clouds, assuming that the satellite measurements can provide a consistent, albeit generalized, representation of the cloud's microphysical state. However, we agree that this assumption requires careful consideration, especially when compared with in situ data that offers a more detailed view of the cloud's vertical structure.

To address this, we will revise the manuscript to more explicitly discuss the limitations and assumptions of using satellite-derived information to characterize cloud microphysics. We will highlight the differences between the cloud-top measurements from satellites and the within-cloud measurements from in situ probes, emphasizing the implications for identifying microphysical zones. Additionally, we will include a more detailed discussion of the potential discrepancies and how they might affect the interpretation of the cloud microphysical processes.

3. I don't think the authors elaborated on how the collocation between the aircraft measurements and the satellite observations were done.

We appreciate the opportunity to elaborate on this aspect of our methodology.

The collocation between the aircraft measurements and satellite observations was carefully conducted to ensure the accuracy and relevance of our comparative analysis. The process will be described in more detail in Section 3 of the manuscript. We will detail the steps taken to match the aircraft cloud penetration data with the corresponding satellite data. To summarize:

- Temporal Collocation: We applied a temporal threshold of 5 minutes between the aircraft cloud penetrations and the satellite observations to ensure that the measurements were as close in time as possible. This was necessary because of the 15-minute temporal resolution of the products from the SEVIRI sensor onboard the MSG satellite.

- Spatial Collocation: For spatial collocation, we applied a spatial threshold of 3 km, which allowed us to match the cloud features observed by the aircraft with the satellite data. The aircraft data provides a high-resolution, detailed view of specific cloud penetrations, and this proximity ensures that the satellite data used for comparison represents the same cloud features.
- Verification of Collocation: The collocated data points were further verified by comparing the retrieved ERs from both the satellite and aircraft data. As shown in Figure 7 of the manuscript, the satellite-derived ER values were compared with those measured by the aircraft, and we found that the aircraft-measured ER values generally corresponded well with the satellite data, particularly when considering the differences in measurement techniques and resolutions.

4. The thresholds used in the framework is somewhat confusing. What is the rational of choosing the 50th percentile Reff or the 25th percentile Reff in the different zones? The mixed-phase zone also seems to overlap quite a bit with the collision-coalescence zone and the supercooled water zone. Is it really necessary to have 5 different microphysical zones?

We used the 50th percentile of ER for zones 1 and 3, but used the 75th percentile of ER for zones 2, 4, and 5 to focus more on the relatively large cloud particles. For zones 2 and 4, although there are still many small droplets, some particles may start to grow quickly due to coalescence (droplet growth in zone 2) or ice particle formation (ice growth in zone 4), which will result in a long tail in the particle size distribution. The figure below shows an example from one cloud penetration at temperature -5.2°C from SF03. The 75th percentile is more sensitive to relatively larger droplets compared to the 50th percentile and indicates that collisions are producing larger droplets. Therefore, we use the 75th percentile of ER for those zones when we need to detect a tail in the particle size distribution.

The mixed-phase zone is colder (-10°C > T > -38°C) and has larger particles (75th ER > 20μm) compared to the coalescence zone, which is warmer than -10°C and has relatively smaller particles (75th ER < 20μm). The difference between the mixed-phase zone and the supercooled water zone is the particle growth rate. The growth rate of the mixed-phase zone is larger than the growth rate of the supercooled water zone as shown in Figure 8. Overall, the 5 zones have different physical features, and their definitions are motivated by the requirements of the cloud seeding operator to conduct hygroscopic and glaciogenic seeding as labeled in Figure 8. Therefore, we defined 5 different microphysical zones.

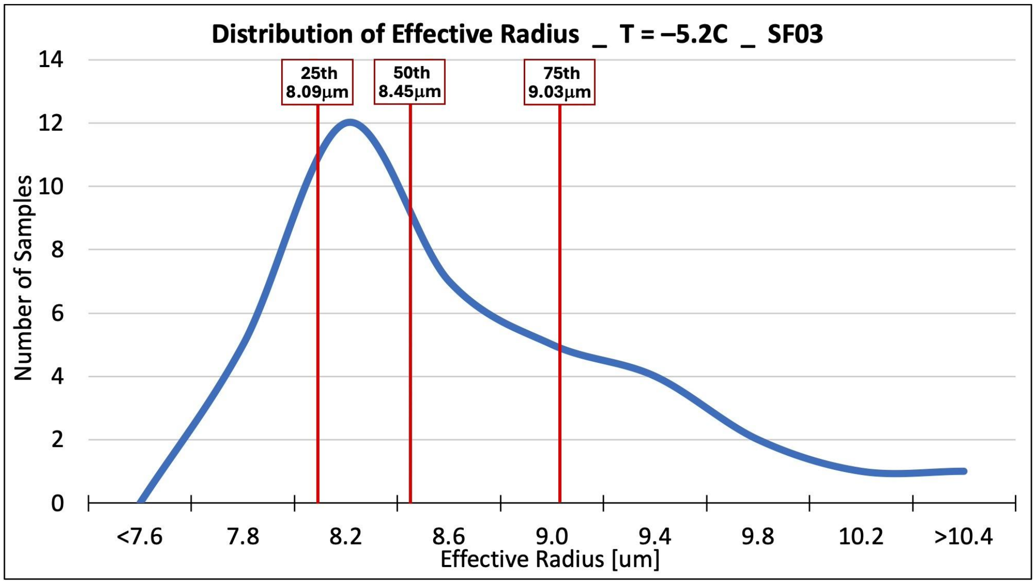

Figure: The distribution of cloud particle effective radius for one cloud penetration at temperature -5.2°C from flight SF03. The three red vertical bars from left to right indicate the 25th, 50th, and 75th percentiles of the effective radius.

Minor comments:

Line 28: precipitation-producing clouds -> precipitating clouds

We will revise it as suggested.

Line 208: Any possible reason why the LWC from FFSSP has a much lower correlation with the LWC from Nevzorov?

Based on our comparison of the data obtained in this UAE airborne campaign, the LWC from FFSSP has a lower correlation with the LWC from Nevzorov compared to the LWC from the FCDP. Possible reasons for the difference in correlation could be related to sampling bias and/or instrument response, as well as the collection efficiency of droplets in the Nevzorov probe. In this study, we focus on the comparison of the FCDP and FFSSP, both forward scattering spectrometers, with a different instrument that uses other physical properties of droplet sizing, in this case the hotwire mechanism in the Nevzorov LWC. The finding that the FCDP correlates better with the Nevzorov gives us confidence that the FCDP provides higher accuracy compared to the FFSSP.

Line 210: It is surprising that you are using FCDP alone to derive effective radius for convective clouds…

As we responded to the major comment 1, we will recalculate all the effective radii in this manuscript using the combined particle size distribution from FCDP, 2DS, and HVPS. Please see our response to major comment 1 for more details.

Line 220: How is this “mean effective radius” defined? Is the range indicating the range of “mean effective radius for each CP”?

In each cloud penetration, there are one to several observed values (one observed value per second). The mean effective radius here is defined as the average effective radius of all observed values in each cloud penetration. We will add one sentence to clarify in the revised manuscript.

Line 371: If I am understanding this correctly, this 15 µm threshold was derived from AVHRR measurements, is this applicable to the in situ measured Reff?

The 15 µm precipitation threshold in convective clouds from Lensky and Drori (2007) and Lensky and Shiff (2007) was derived from satellite measurements. Meanwhile, Freud and Rosenfeld (2012) defined 14 µm as the precipitation threshold for warm rain in convective clouds based on aircraft-retrieved data. We will revise those sentences to include these citations in the revised manuscript.

Line 377: (d) total water content from Nevzorov.

We will revise it as suggested.

Line 450: why are there ice cloud effective radius retrievals at T~ 10°C from in situ probes?

The effective radii from aircraft observation (black dots) in Figure 7 are all the effective radius values obtained from the in-situ probes during flight SF03, and they could be from water or ice clouds. The total, water, and ice cloud labels in panels a-c are specifically for the satellite data. We will modify the caption of Figure 7 to clarify.

Line 464: why choosing to use FCDP to derive cloud effective radius when you are targeted at convective clouds?

As we responded to the major comment 1, we will recalculate all the effective radii in this manuscript using the combined particle size distribution from FCDP, 2DS, and HVPS. Please see our response to major comment 1 for more details.

Line 468 to 470: I cannot agree with the statement that “the ERs from aircraft and satellite datasets have a fair agreement”, your Figure 7 is suggesting otherwise…which really questions the validity of using ERs from satellite data to build the different cloud zones.

The aircraft ERs in Figure 7 are calculated from FCDP particle size distribution, which measures the size of particles in the 2-50 µm diameter range and is sensitive to water droplets. Therefore, they tend to be close to the water cloud ERs from satellites but smaller than the ice cloud ERs due to the lack of sensitivity of the FCDP to ice particles. As we mentioned in our response to major comment 1, we will recalculate all the ERs in this manuscript using the combined particle size distribution from FCDP, 2DS, and HVPS. Based on some tests, the difference between the new ERs and the ice cloud ERs from the satellite is a bit smaller, although there are still some differences between the ERs from aircraft and satellite. Some previous studies (e.g., Rosenfeld and Lensky, 1998) found similar differences between the ERs measured by aircraft in-situ probes and satellites. In the figure below, the aircraft FSSP ERs (empty circles) tend to be smaller than the satellite ERs, which is similar to our result in Figure 7.

Rosenfeld, D., & Lensky, I. M. (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bulletin of the American Meteorological Society, 79(11), 2457-2476.

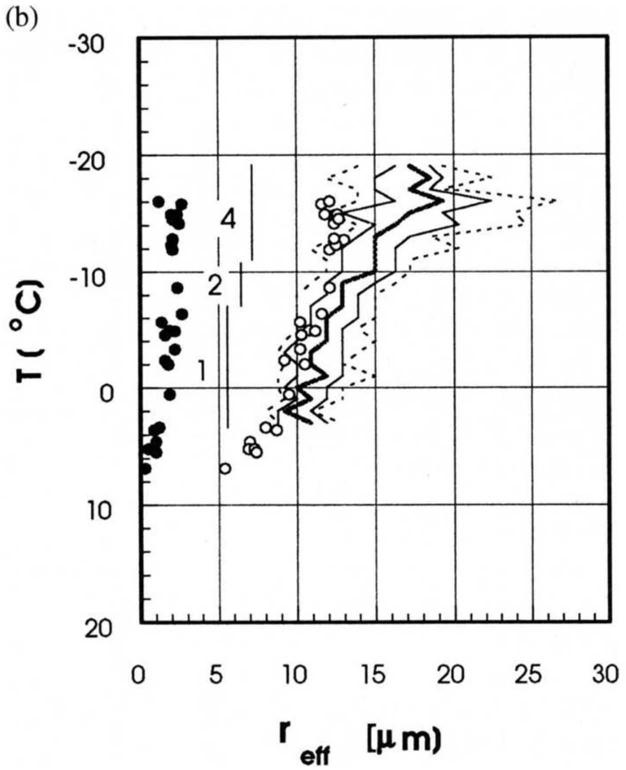

Figure 11b from Rosenfeld and Lensky, 1998. The 10th, 25th, 50th, 75th, and 90th percentiles of the effective radius. The median is indicated by the thick line. The vertical bars denote the different microphysical zones as numbered in the text. The aircraft FSSP effective radius measurements are denoted as empty circles, and the CLWC (g m^-3) are in plotted black circles.

Line 497: Why in some of the zones the ER thresholds are using the 75th percentile, and in others the 50th percentile is used?

The criteria used in the 5 zone framework is somewhat ambiguous. If I am understanding this correctly, the authors are trying to formulate the 5 zone framework using thresholds of ER, dER/dt, BT, wouldn't this cause some overlap between different zones? I would suggest sticking with the same percentile (whether 25th, 50th, or 75th) and be consistent.

We use the 75th percentile for zones 2, 4, and 5 because we want to detect the relatively large particles in the tail of the particle size distribution that form by coalescence or ice formation. The figure in the response to major comment 4 shows an example from one cloud penetration at temperature -5.2°C from SF03. The 75th percentile is more sensitive to those large particles compared to the 50th percentile.

There might be some gaps between different zones. However, the detection of these zones in this study aims to provide guidance for detecting cloud seeding targets, determining if a cloud patch is a suitable seeding target or not. Although there might be some small gap between different zones, it will not impact the detection of those microphysical zones that are intended for the cloud seeding application.

Line 540: Figure 9 is suggesting that water cloud Reff is used in zone 1 and zone 2 and zone 3, total cloud Reff is used in zone 4, ice cloud Reff is used in zone 5. This was not mentioned in the main text.

We mentioned using different cloud phases to detect different zones in the definition and identification of each zone at lines 488-515 and in the description of Figure 9 at lines 530-535.