Response to Reviewer 1

This study proposes a methodology to infer precipitation-forming processes based on satellite retrievals of the vertical profiles of convective clouds' particle effective radius and phase. The satellite is the METEOSAT Second Generation (MSG) over the Indian Ocean. The target clouds are over the UAE. The objective is to determine the clouds' seedability based on conceptual models. The general idea and objectives are of great interest, but major methodological issues require a major revision before the paper can get accepted.

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

Major comments:

The satellite retrieved cloud drop effective radius product (RE) has three types: water, ice, and total cloud. However, these retrievals, as presented here, raise many questions:

How can ice retrievals of RE exist for clouds with temperature > 0C (e.g., Fig. 7b)?

Why are the total and water cloud RE values different at T>0C, where ice cannot exist?

How can water retrievals of RE exist for clouds with temperature < -40C (e.g., Fig. 10d), where water cannot exist?

Why are the total and ice clouds RE different at T <-40C, where water cannot exist?

We thank the reviewer for their thorough review and for raising these methodological points. We appreciate the detailed comments and would like to address these points as follows:

First, we acknowledge the confusion regarding the presence of ice retrievals in conditions where temperatures > 0°C. To avoid confusion, we will remove all data points related to ice retrievals at temperatures above 0°C. This adjustment will ensure that our analysis remains within the physically realistic bounds. We also understand the concern regarding the differences between total and water cloud RE values at temperatures greater than 0°C, where ice should not exist. The ATBD (2016) explains that the retrieval algorithm may mistakenly attribute large CRE values to water clouds due to differential absorption characteristics in the 1.6 µm channel. As quoted from the ATBD: "The ice-water absorption differential in the 1.6 µm channel (daytime only, see section 3.1 of ATBD) means that a scene that contains ice clouds but is interpreted as water clouds would appear to have very large CRE values. These are identified as being larger than the physical limits set on the water CREs, and in this case, a switch to the ice phase is made. The reverse process can occur in the case that ice is assumed and in reality, water clouds are present". To mitigate this issue, we will include a filtering step to eliminate such anomalies in our revised analysis and explain this limitation in the manuscript.

Additionally, the differences observed between total and ice cloud RE at temperatures below -40°C suggest retrieval errors. As these cases are rare (only 1-3 samples of "Noise"), we will remove these outliers from our analysis to ensure that only physically consistent data is presented. We will also revise Figures 10c and 10g to reflect these corrections, ensuring that data plotted for ice clouds are limited to temperatures below 0°C and that any inconsistencies between total and phase-specific RE are addressed.

We believe these revisions will enhance the clarity and accuracy of our study, and we appreciate your constructive feedback.

The methodology depends critically on the definitions of the microphysical zones, as defined in Figure 8. The cloud phase is used for the zones' definitions, but it is not explicitly given by the OCA EUMETSAT cloud data, as all three types (water, total, and ice) have the effective radius (RE) at all temperatures.

Zone 1, diffusional droplet growth is defined by water phase cloud at T>0C and RE < 10 um. However, clouds can have diffusional growth at temperatures well below 0C, and at RE >10 um, until significant coalescence starts increasing RE beyond the drop growth rate by condensation only. This happens at RE>12 um, or even higher. A case in point is clouds with cold bases, as typical to the UAE. The lower parts of these clouds must be in the diffusional growth zone, as they are composed of very small water droplets.

We agree with the reviewer's comment about diffusional growth at ER > 10 μm and at temperatures < 0°C. We selected the ER and temperature thresholds for the diffusional zone based on the cloud penetration ER in the UAE during the summer (2019 August). Figure 3 of the manuscript shows that the mean effective radius is always < 10 μm at temperatures > 0C. Our choice of diffusional droplet growth at T > 0°C and RE < 10 μm is to identify extreme cases of diffusional growth and to also eliminate cases when coalescence may be marginally active. This is to identify the best targets for cloud seeding using hygroscopic particles, which is most effective in cases when coalescence is not active.

Zone 2, droplet coalescence growth zone. The description in Figure 8 has details that are not described in the text (lines 494-500) and are not understandable. What is T21? Why is the 75th percentile taken and not the 50th percentile? Anyway, the 25th percentile should be the relevant number because this pertains to the smaller ER in the growing convective elements. In Figure 8 there is the condition of 20>ER>15 um. There seems to be an uncovered gap between Zones 1 and 2.

The reviewer accurately points out that we did not describe all the details in Figure 8 and we intend to correct that in the revised manuscript. T_{Z1} is the coldest temperature of zone 1, which means the warmest temperature of zone 2 should be lower than the coldest temperature in zone 1 but higher than -10°C. This is done to create a separation between zone 1 and zone 2, so that clouds with active coalescence are not targeted for hygroscopic seeding. We will add the relevant description text in the revised manuscript.

We use the 75th percentile because we want to identify the relatively large droplets developed by collision and coalescence. Although there are still many small droplets, some droplets may start to grow quickly due to coalescence, which will result in a long tail in the droplet 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 those large droplets compared to the 50th percentile.

Based on the ER threshold, there is a gap between zones 1 (50th ER < 10μm) and 2 (15μm < 75th ER < 20μm), but the ER is only one of the metrics to identify these zones. In addition, the selection of those thresholds for different 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.

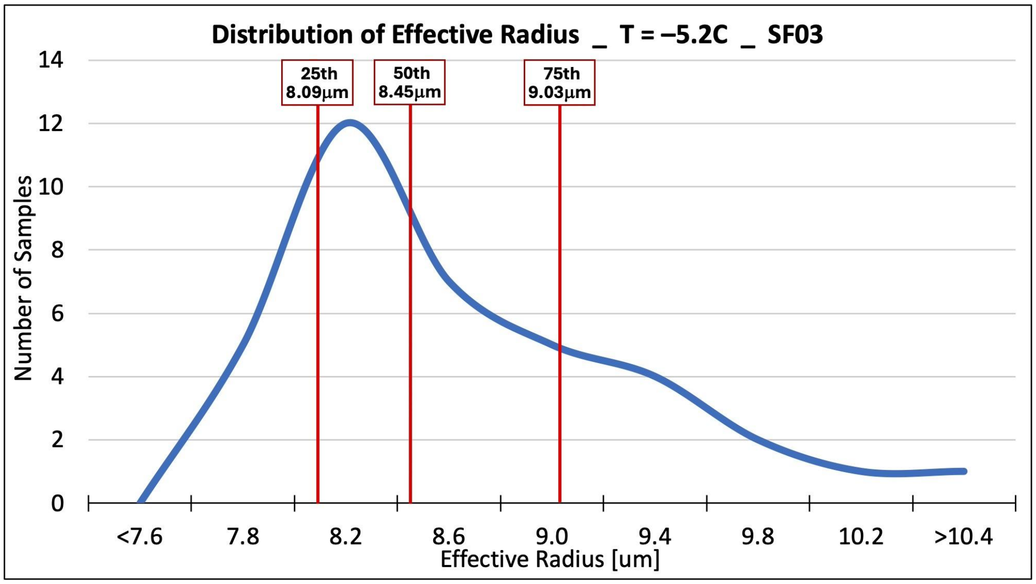

Figure: The distribution of cloud particle effective radius for one cloud penetration at temperature -5.2°C from flight SF03. The three red vertical bars from left to right indicate the 25th, 50th, and 75th percentiles of the effective radius.

Zone 3, Supercooled water zone. Why should the supercooled water zone be independent of the diffusional growth or coalescence zones? Both can occur at temperatures < 0 and contain supercooled water. It just does not make sense in both logical and physical ways. There is a potential overlap in the conditions for the zones because the same scene can have conditions that fulfill both Zone 2 and 3. This should not happen. The extension of mixed-phase to temperatures colder than -35 C in all presented cases with identification of that zone is unreasonable physically. Such cold glaciation temperatures were documented by aircraft only in storms with severe updrafts that caused large hail. Furthermore, VIIRS views of similar clouds in the same region generally resulted in a glaciation temperature of -20 C, due to the dusty conditions. This determination is based on the unique channel combination of VIIRS that allows us to detect unambiguously the glaciated clouds.

The algorithm development is motivated by the requirements of the cloud seeding operator to conduct hygroscopic and glaciogenic seeding. In glaciogenic seeding, the operators will target supercooled water, even when this supercooled region overlaps with the presence of high coalescence activity.

In addition, our algorithm separates zone 3 and zone 2 using droplet growth rates (dER/dT). Since supercooled drops are more likely to develop in the absence of coalescence, the growth rate in the supercooled zone is defined as being smaller than that in the coalescence zone as shown in Figure 8.

In the revised manuscript we will analyze the glaciation temperature in VIIRS channels as suggested by the reviewer. This analysis will give us a more accurate representation of glaciation temperature in zones 3, 4, and 5, given that the aircraft data did not sample clouds cold enough to reach this level.

Zone 4, Mixed phase zone. The mixed phase is defined only for clouds colder than -10C, but it can occur at higher temperatures. According to the text, the total cloud ER is used here, but this is not mentioned in Figure 8. Again, since different kinds of ER are used for zones 2 and 3, there can be much overlap in conditions not recognized here, causing definition ambiguity.

We agree that the mixed phase could occur at a temperature higher than -10°C. However, based on the aircraft observation in this UAE campaign in August of 2019, the warmest temperature when ice particles appear is at least -10°C. Therefore, we use -10°C as the threshold.

We will add the "total cloud" product in the box of zone 4 in Figure 8.

Yes, zones 2 and 3 may have some overlap if only based on ER thresholds. However, as we mentioned above, we used different droplet growth rate thresholds to differentiate between zone 2 and zone 3.

Zone 5, Glaciated cloud. Its definition relies on the ice ER. But ice ER seems to be unreliable in many ways. It exists for warm clouds with T>0C. In Figure 10g it has the same large ice ER>25 um at all temperatures. Its ER in some cases (e.g., Fig 10c) is extremely small, much smaller than is almost ever detectable at -45 C by MODIS.

We understand the concern that the cloud phase, critical for defining the microphysical zones, is represented by all three types (water, total, and ice) with an effective radius (RE) at all temperatures. This could lead to confusion, particularly in the Zone 5 (Glaciated cloud) definition. As explained by the OCA ATBD (please see the figure below that shows the distribution of effective radius for the ice phase clouds), most of the population contributes to the 23 µm peak, while a peak is observed at 5.0 µm for the water phase. However, some noise in the data is explained in the algorithm documentation, highlighting limitations related to broken or sub-pixel clouds, highly heterogeneous clouds, and mixed-phase clouds.

To address this, we will revise the definition of Zone 5 (Glaciated cloud) and filter out data for temperatures greater than 0°C, as discussed in our previous response, to ensure it aligns with the expected physical characteristics. Specifically, we will reassess the reliance on the ice ER and consider alternative criteria for defining this zone, particularly given the potential unreliability of the ice ER at specific temperatures.

Additionally, in the manuscript, we will provide a detailed explanation of the anomalies observed, such as the large ice ER values across all temperatures and the minimal ice ER values at very low temperatures. This explanation will draw on insights from the OCA product guide and relevant literature to contextualize these findings and ensure a clear understanding of the data presented.

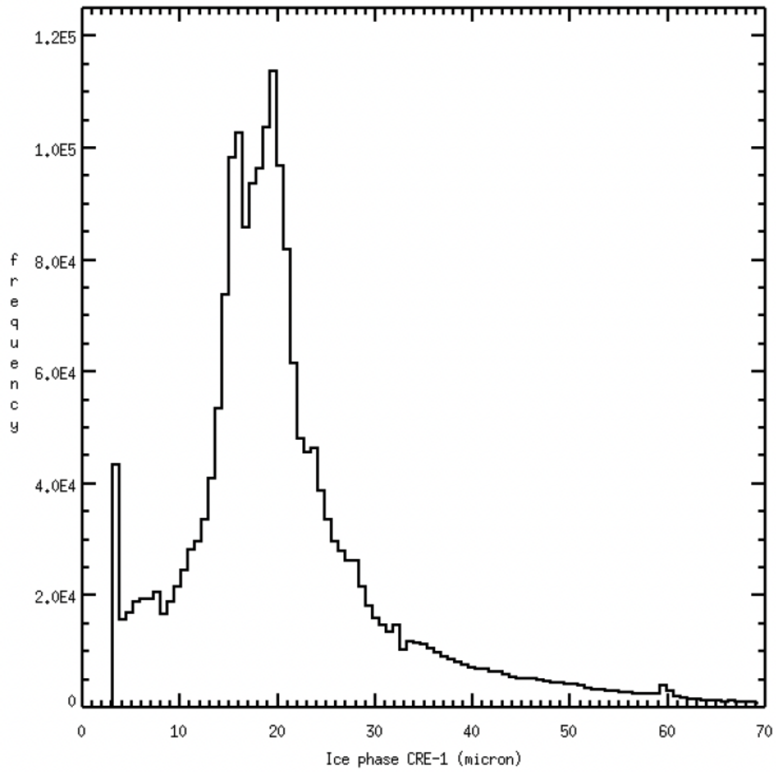

Figure: Histograms of CRE associated with ice phase clouds.
This figure is from the EUMETSAT Optimal Cloud Analysis: Product Guide (online):
https://user.eumetsat.int/s3/eup-strapi-media/Optimal_Cloud_Analysis_Product_Guide_366f360a7c.pdf

The criteria selection is based on and validated by comparing aircraft in situ cloud measurements. However, the aircraft did not penetrate clouds colder than -13C, so there is no aircraft validation to the zones below that temperature. But the authors claim, and rightly so, that seeding potential is best at clouds with supercooled water that extend deepest, which pertains mostly to the unvalidated temperature range.

Therefore, I recommend that the authors calibrate and validate the MSG retrievals against VIIRS and then redo all their calculations and revise their inferences as necessary.

We appreciate the reviewer's valuable suggestion. We will proceed with this analysis if the data coincides in time and space with aircraft data. If the data does not coincide, we can still perform an analysis of glaciation temperature to adjust thresholds in zones 3, 4, and 5.

Minor comments:

Line 87: Growth of precipitation particles cannot occur "through collision and coalescence of the ice multiplication process".

We will fix the error (changing "of" to "or"), and the new sentence in the revised manuscript is "Growth of precipitation particles can either occur through collision and coalescence or the ice multiplication process or a combination of the two."

Line 88: Raindrops cannot form by diffusional growth alone in convective clouds with any cloud base temperature.

We will modify this sentence as suggested: "Raindrops cannot form by diffusional growth alone in convective clouds."

Line 371: Please be aware and discuss the gap between the satellite-retrieved rain threshold of 15 um (e.g., Lensky and Shiff, 2007) and the aircraft-retrieved threshold of 12 um (Freud and Rosenfeld, 2012).

We will add a couple of sentences to discuss the gap between the satellite-retrieved rain threshold (e.g., Lensky and Shiff, 2007) and the aircraft-retrieved threshold (Freud and Rosenfeld, 2012) as suggested.