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Atmospheric Chemistry and Physics Discussions

Interactive comment on "A-Train estimates of the sensitivity of warm rain likelihood and efficiency to cloud size, environmental moisture, and aerosols" *by* Kevin M. Smalley and Anita D. Rapp

Anonymous Referee #1

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Overview

The authors examine warm rain efficiency (WRE) in marine liquid clouds using rain water path estimates from the CloudSat Cloud Profiling Radar and cloud water path from MODIS. They show that WRE increases as cloud extent increases after controlling for cloud top height and low level relative humidity. AOD shows little correlation with WRE when conditioned by cloud top height indicating potentially limited aerosol impacts on WRE once warm rain has begun. WRE increases as expected with SST due to clouds that are deeper with more condensed water but this study also shows that WRE also increases with cloud extent for a given SST and cloud extents grow with SST. Thus, increased WRE as SST increases could also partly result from larger clouds that are more protected from dry air entrainment.

I can somewhat buy into the primary argument of this study that larger clouds are more protected from deleterious dry air entrainment and thus are more apt to form rain. However, there are a number of additional considerations that have to be discussed before such a conclusion can be reached, highlighted in the major comments below. In addition, some plots and methods used need improvement, again highlighted in more detail below.

Major Comments

1. The title indicates that "warm rain likelihood" is examined in addition to warm rain efficiency but nearly the entire study focuses on warm rain efficiency and does not consider clouds that are not already raining. Thus, I recommend changing the title of the paper.

2. The clouds being analyzed in this study are repeatedly referred to as shallow cumulus clouds but the cloud length scales examined are 1.7 to 18 km, so this is combining quite robust cumulus clouds at the short end of the spectrum with wider presumably stratocumulus clouds at the longer end of the spectrum. This makes the "shallow cumulus" terminology misleading for me. Applying a simple 18.55 K lower tropospheric stability separator will not filter out all stratocumulus clouds. In addition, many shallow cumulus are smaller than the CloudSat CPR footprint of 1.8 x 1.4 km, so the clouds at this end of the spectrum will suffer from non-uniform beam filling that can bias retrievals (e.g., Battaglia et al. 2020).

3. The assumption that clouds are shallow cumulus feeds into the assumption that lateral entrainment is the key process controlling WRE, which is stated repeatedly throughout the study. Lateral entrainment is important for km-scale cumulus clouds but cloud top entrainment is important for 10s of kilometers scale stratocumulus clouds. In addition, is there anything to suggest that once a relatively shallow liquid cloud is

wider than multiple kilometers that its core is not protected from lateral entrainment? There are too many assumptions being made regarding the importance of entrainment without supporting evidence.

Another potentially major contributor to warm rain efficiency that also correlates with cloud size is cloud lifetime, which should be discussed but isn't. Larger clouds typically live longer, which could increase the probability of rain formation. Other factors that could impact WRE that are not mentioned but should be include turbulent enhancement of droplet collision-coalescence, updraft speed controls on the supersaturation and number of droplets condensed, and potential time lags between peaks in rain water path and cloud water path due to raindrops consuming cloud droplets.

4. Lines 67-68: It is made to seem like there are very few studies examining relationships between cloud water and precipitation in shallow cumulus as a function of cloud size, moisture, or aerosol conditions, but this isn't true, and I encourage a more through literature review. For example, consider the many studies that have been published using Dominica Experiment (DOMEX) field campaign data. A number of field campaigns and modeling studies have focused on entrainment and precipitation formation in cumulus clouds over land and ocean, and even more have examined stratocumulus clouds. 5. The methodology could use some improvements and clarifications. a. Line 80: The CloudSat CPR cannot always observe non-raining cloud drops because its sensitivity is limited, which has been proven with comparisons to ground sensors (Lamer et al. 2020). In addition, it has ground clutter issues below 1-km altitude. These are important caveats that should be mentioned that could bias sampling. b. What are the uncertainties of the rain water path and cloud water path estimates? On line 92, it indicates that any rain water paths greater than 0 are considered but there should be a minimum value used that is equal to the retrieval uncertainty. For example, for cloud water path, this is typically ~20 g m-2. c. Lines 122-123: Average relative humidity below 3 km is a very strange metric for environmental moisture when most of these shallow clouds are interacting with a variable altitude inversion layer. This met-

ric would mix boundary layer air with typically much drier free tropospheric air, which would be weighted by the inversion altitude (which increases as one moves from stratocumulus to trade cumulus regions). The relevant moisture metric for lateral or cloud top entrainment would be the relative humidity in the lower free troposphere.

6. The single line in Figure 2 begs for the spread to be shown and statistical significance tests to be performed. The same applies to Figures 3-5. How large is the spread? Are the median lines shown statistical significant? In addition, some numbers and symbols are missing in the legends of Figure 3-5. Lastly, edge lines in Figure 4b are not blue as described in the caption.

7. Lines 117-119: More important caveats to list than the type of aerosol not being considered are AOD not necessarily scaling with CCN number due to its dependence on size, AOD being offset from the actual clouds, AOD being column integrated such that aerosols may not be making it into the cloud, and AOD being positively correlated with relative humidity due to aerosol swelling.

8. The studies cited on lines 176-177 as supporting the conclusion that more protection from entrainment is what is causing the larger clouds to rain more are not necessarily relevant in that they are analyzing kilometer-scale cumulus congestus and deep convective clouds, not 10 km wide shallow clouds.

Minor Comments

1. Lines 47-50: Romps (2014) examined precipitation efficiency with respect to relative humidity but relative humidity typically remains approximately constant over oceans as a function of temperature and it is absolute humidity that increases with SST and temperature, so Lau and Wu (2003) is not consistent with Romps (2014) because one is analyzing relative humidity, which impacts evaporation rate, while the other is examining absolute humidity, which impacts condensed mass.

2. Lines 50-53: Why are larger droplets necessarily expected near cloud base? Drizzle

typically forms first near the top of the cloud in an updraft where the condensed mass and turbulence is greatest. Is it the falling of this drizzle and collection of cloud droplets during falling that produces the largest droplets near cloud base?

3. Line 58: Please clarify whether cloud water and raindrop concentration refer to number concentration or mass concentration.

4. Line 66: missing a verb after "aerosol loading".

5. Line 103: Symbol is missing in parentheses.

6. Line 107: Insert "Rayleigh" before "reflectivity".

7. Lines 135-138: More important than relative humidity impacted evaporation to increasing rain water path is absolute humidity, which controls how much condensation occurs.

8. Lines 146-147: Is "east" supposed to be "west"? And why is "north" used with respect to the ITCZ?

9. Line 160: Be more specific than "environmental moisture". This implies absolute humidity but in fact what is analyzed is relative humidity.

10. Lines 165-168: The different vertical gradients of reflectivity near cloud edges as compared to near cloud centers does not conclusively show that larger droplets are present near cloud base at cloud center than on the edge because we don't know the absolute reflectivity magnitudes.

References

Battaglia, A., Kollias, P., Dhillon, R., Lamer, K., Khairoutdinov, M., and Watters, D., 2020: Mind the gap – Part 2: Improving quantitative estimates of cloud and rain water path in oceanic warm rain using spaceborne radars, Atmos. Meas. Tech., 13, 4865–4883, https://doi.org/10.5194/amt-13-4865-2020.

Lamer, K., Kollias, P., Battaglia, A., and Preval, S., 2020: Mind the gap – Part 1: Accurately locating warm marine boundary layer clouds and precipitation using spaceborne radars, Atmos. Meas. Tech., 13, 2363–2379, https://doi.org/10.5194/amt-13-2363-2020.

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Discussion paper