We appreciate the reviewer’s helpful comments and suggestions that helped us improve this manuscript. Reviewer comments are in black. Our responses are red, and the updated text shown in this document is blue.

This paper is a useful analysis of the production of warm rain in cumulus clouds based primarily on cloud and rain water measurements from the CloudSat and MODIS satellite datasets. The main new result is that the efficiency of production of warm rain appears to increase with the horizontal size of the cloud, even when controlling for variations in cloud depth and sea surface temperature. The results imply that dilution of cloud updrafts due to entrainment is less effective in larger clouds than smaller clouds which are presumably better protected by the larger scale of the clouds. This is a plausible hypothesis supported by some prior modeling. The paper shows consistent results between an examination of the ratio of precipitation water to cloud water andthe vertical gradient in CloudSat reflectivity. I have some comments about the resolution of the measurements used, the quantification of “warm rain efficiency”, and the conclusions the authors draw about the aerosol sensitivity of warm rain efficiency. The paper should be suitable for publication in ACP subject to some revisions.

Major Comments

1. Some aspects of the scales of the clouds in this investigation are left unanswered, but are potentially critical because of the resolution of the measurements employed. The CloudSat rain water data used here has a footprint of 1.4 x 1.8 km. The cloudwater path data from MODIS has a nominal resolution of~1 km at nadir. According To the methods, the cloud water path is based on a 9-pixel average, which suggests that the horizontal scale of the cloud water measurements are on the scale of 10 km. Nevertheless, clouds are shown varying from about 1.7 km to greater than 18 km. So,one question is: are the cloud water values really representative of the true values for clouds smaller than 10 km? Can we then be certain that the strong dependence of the ratio of precipitation water to cloud water on cloud scale shown in figure 2 for clouds smaller than 10 km is not influenced by the resolution of the cloud water quantity?

    a. **To address the reviewer's concerns, we used a 3x3 grid (nine pixel) average surrounding each CloudSat pixel and only averaged cloud water path values that are > 0 g m^{-2}. We did this, because one CloudSat Pixel could overlap multiple MODIS pixels within that 3x3 grid, meaning that an average of multiple pixels is the best way to match MODIS cloud water path to each CloudSat pixel. However, we tested our results to check if matching the nearest pixel or nearest nine pixels would impact our results. We found that our results are consistent no matter what method is used to match MODIS cloud water path. To address this, the following text has been modified in the methods to clarify how we match cloud water path to each CloudSat pixel and mention that matching both a nine-pixel average and nearest-neighbor cloud water path does not change our overall results (Page 5, Lines 136-143)** ***"Due to horizontal resolution differences between CloudSat and MODIS, one CloudSat pixel may overlap multiple MODIS pixels within a surrounding 3x3 km grid. As a result, W_C is then calculated for each CloudSat pixel by averaging the nearest nine non-zero MOD-06-1KM (Platnick et al. 2003) pixels within a 3x3 grid surrounding each CloudSat pixel, which have been previously matched to the CloudSat track in the MOD-06-1KM product (Cronk and Platnick, 2018). There could be concerns that the averaging W_C within the nearest nine MODIS pixels may not properly represent the W_C at the appropriate scales relative to the horizontal footprint of each CloudSat pixel, however we tested our results using W_C within the nearest MODIS pixel and found that our overall results do not change."*****.**

2. The authors state that "prior studies [of biases in MODIS cloud water] have found them to be small in comparison to other satellite retrievals". I suspect that this result may be resolution dependent and that in fact uncertainties for cloud smaller than several km in scale may be quite significant. For example, Cho et al. (2015) find that the MODIS cloud property retrievals from which the cloud water path is derived can have substantial errors in cumulus cloud fields because of partially cloudy pixels and horizontal homogeneity of cloud properties within the satellite footprint. Can the authors provide some greater support for the notion that the cloud water values are representative of the true value at the scales on the small end of the spectrum shown in this analysis?

   a. **Thank-you for pointing out Cho et al. (2015) and that failure rates are higher in regions of broken cumulus. This should have been highlighted and caveated in the manuscript. Therefore we modified the following text (Pages 4-5, Lines 121-131) to account for this:** ***“Cho et al. (2015) found that MODIS effective radius and optical depth retrieval failure rates are higher in regions of broken trade cumulus than regions of predominantly stratocumulus, and they primarily attributed this to the presence of partially filled and inhomogeneous cloudy pixels. They also found that a large fraction of unexplained MODIS retrieval failures are related to the presence of precipitation after comparing MODIS failure rates to non-precipitating and precipitating pixels classified by CloudSat. This is attributed to a higher frequency of failures due to effective radius being too large. Considering the retrieval of effective radius and optical depth are required to derive W_c and higher failure rates within broken trade cumulus, we suspect unavoidable sampling bias exists in W_c matched to the smallest cloud objects and/or those containing large droplets and heavy rain. However on a global scale, prior studies have found the uncertainties in MODIS W_c are small in comparison to other satellite retrievals (Seethala and Horvath, 2010; Lebsock and Su, 2014), with the global mean of MODIS W_c being within 5 g m^{-2} of W_c determined using the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) (Seethala and Horvath, 2010).”*****.**

3. Fine resolution satellite imagery indicates that warm cumulus clouds substantially smaller than 1.7 km are common and in fact may be more prevalent than clouds larger than 1.7 km (e.g. Mieslinger et al. 2019). Presumably some of these clouds may be precipitated. Obviously, comparable data to the CloudSat data are not available at smaller scales from satellites. Nevertheless, do the authors expect that there may be a substantial population of precipitating cumulus clouds that are not captured in their analysis? Furthermore, one might expect that warm cumulus clouds might be limited inscale. Assuming crudely that cumulus clouds typically have an aspect ratio of around 1, one might presume that cumulus clouds broader than 5-10 km might also be tall enough to contain ice or mixed phase microphysical processes occurring. What characteristics ensure that the clouds included here are both warm liquid phase and truly cumulus clouds, or is the analysis expecting to include some stratocumulus clouds as well?

a. **The reviewer is correct in assuming that there is likely a large population of raining shallow cumulus smaller than CloudSat can detect leading to non-uniform beam filling. To address this (Pages 9-10, Lines 288-294) see the following text:** ***"At the small end of the shallow cumulus horizontal size spectrum, CloudSat is limited to observing cloud objects no smaller than 1.4 x 1.8 km. Given prior ground observational studies, it is likely that there is a significant population of shallow cumulus cloud objects not identified by our study (e.g. Kollias et al., 2003; Mieslinger et al., 2019) due to non-uniform beam filling effects. Battaglia et al. (2020) noted that this results in an underestimation of path integrated attenuation, potentially introducing error into the retrieval of W_p. Unfortunately, this limitation is unavoidable given CloudSat's horizontal resolution.".***

b. **To address the potential issue of mixed phase clouds, we now explain in the following text (Page 4, lines 104-107) how we ensure that our analysis only includes warm cloud objects** ***"To ensure that none of the cloud objects examined here contain ice, we only include cloud objects with tops entirely below the freezing level as defined in 2C-PRECIP-COLUMN Haynes et al. 2009)."***

4. The authors use the ratio of precipitation water to cloud water as their measure of“warm rain efficiency”. Although, as the authors note, this quantity is just a proxy for the true efficiency. I think the authors are correct to make this point clear. I also think that perhaps it would be helpful for the authors to clarify what defines a proper quantitative measure of the warm rain efficiency. Presumably, it is not so easily observed, which is why they have chosen a proxy, which is fine. Given the brevity of this paper, however,I think a short elaboration on this point would be helpful. Furthermore, if the ratio used in this paper is merely a proxy for the true efficiency, is it really appropriate to be using “warm rain efficiency” throughout the manuscript to refer to this quantity? I suggest that the authors perhaps consider a different name so that readers are not confused about what is the true measure of the efficiency and what is the approximation of it. Alternatively, if there is a quantitative comparison of the ratio to the true efficiency, perhaps from a theoretical study, then it might be appropriate to refer to the proxy value as a measure of the efficiency with some quoted uncertainty value.
    a. **We agree that we should have defined warm rain efficiency in a proper context, therefore we added the following text (Pages 2-3, Lines 51-59) to the paper:** ***“Prior studies have defined precipitation efficiency in two ways: 1) as the large-scale precipitation efficiency and 2) as the cloud microphysical precipitation efficiency. Generally, observational studies have based their definition of precipitation efficiency on the large-scale definition, which has simply been defined as the ratio of surface rain rate to the sum of both vapor mass flux in/out of a cloud and surface evaporation (e.g. Chong and Hauser, 1989; Tao et al., 2004; Sui et al., 2007), whereas the cloud microphysical definition, or the ratio of surface rain rate to the sum of vapor condensation and deposition rates, has been primarily used in cloud modeling studies (e.g. LI et al., 2002; Sui et al., 2005; Gao et al., 2018). Although both the large-scale and cloud microphysical definitions of precipitation efficiency are useful (Sui et al., 2005; Sui et al., 2007), variations in the ratio of cloud water to rain water (WRR) in response to changes in evaporation can theoretically be used as a proxy for warm rain efficiency based on the cloud microphysical definition.”*** **Additionally, we changed any reference to WRE, in the context of this paper, to the ratio of cloud water to rain water (WRR) as well as** ***“warm rain efficiency”*** **in the title to** ***“the ratio of cloud water to rain water”.***

5. The corroboration of the inferences based on the ratio of precipitating water to cloudwater with the inferences from the vertical gradient in reflectivity (VGZ) is a valuable contribution of this paper and certainly strengthens the case that the authors are making. In lines 174 to 180 the authors argue that the dependence of VGZ on cloud-top height supports the notion that updrafts in larger clouds are protected from entrainment. Why would this dependence on cloud-top height not simply result from collision/coalescence happening through a deeper cloud layer independent of any difference in entrainment? Presumably the taller clouds are provide a broader distance from cloud base to cloud top through which raining drops can fall and collect cloud drops. Likewise, perhaps a stronger updraft that yields a taller cloud is better at promoting the coalescence of cloud drops through turbulent collisions. Could these similarly explain the differences between clouds of differing heights?

a. **Yes, these factors could also explain differences in VGZ as a function of extent as well as differences in the ratio of cloud water to rain water for cloud objects with different heights. To address this we added the following text in a section called *"Limitations of analysis and observations"* to our paper (Page 9, Lines 268-287)**
   "This study has emphasized the potential for the decreasing impact of entrainment on cloud cores, resulting in higher WRR, as cloud size increases; however, it is important to point out other factors related to cloud size that may also impact WRR. Figure 3 shows WRR is higher when cloud objects are taller, which may be simply because we are sampling more mature clouds that have had more time for the collision-coalescence process to result in rain formation. Deeper shallow cumulus not only live longer which would give cloud droplets more time to grow to raindrop size (e.g. Burnet and Brenguier, 2010), but they are more likely to have more intense updrafts which could result in more water vapor being transported to higher altitudes within a cloud. Stronger updrafts are then more likely to be able to suspend cloud droplets higher in the cloud for longer periods of time which allows them to grow larger before they begin to fall and collision-coalescence is initiated. Once cloud droplets do begin to fall, they are not only potentially larger but able to collect more droplets over a larger distance than droplets falling through a shallower cloud. This could potentially result in higher WRR, however there is likely a lag between the peaks in cloud water path and rain water path as cloud drops grow to raindrop size in a developing cloud. Earlier modeling studies have also noted that turbulent flow potentially enhances the likelihood of warm rain formation (e.g. Brenguier and Chaumat, 2001; Seifert et al., 2010; Wyszogrodzki et al., 2013; Franklin, 2014; Seifert and Onishi, 2016; Chen et al., 2018). Seifert et al. (2010) found that turbulence effects are largest near cloud tops in shallow cumulus, which they note is an important region for initial rain formation. While these additional processes may impact WRR, the satellite observations used in this study are instantaneous snapshots in time. We attempted to remove some of these life cycle impacts by binning cloud objects by top height. Within a given cloud top height bin, WRR (Figure 3) and the magnitude of VGZ$_{CP}$ (Figure 4c) still increase as a function of extent. While we acknowledge that this cannot fully remove these impacts, these results support the idea that processes other than those related to cloud lifetime, like lateral entrainment, may also influence

the WRR of shallow cumulus of different horizontal sizes".

6. Finally, the authors explore the dependence of their proxy for warm rain efficiency on the aerosol optical thickness in the vicinity of the cloud. They conclude that there is little dependence of the efficiency on aerosols, which is an interesting result. I suggest, though, that the authors remove the word "surprisingly" from the abstract where this result is reported. As noted by the authors, by excluding non-precipitating clouds from their analysis they are likely missing the expected dominant effect, which is the suppression of rain formation. Is there not a CloudSat study looking at the dependence of the occurrence of rain in CloudSat retrievals upon AOD? I think that a citation to such a study would be appropriate in the discussion of the results presented in this paper. If not, I think the authors should point out that this might be the more fruitful path to quantifying aerosol effects.
    a. **We have removed "surprisingly" from the abstract**
    b. **To address the second part of your comment regarding the dependence of the occurrence of rain in CloudSat retrievals upon AOD, we added a figure (Figure 5d) which shows the rain likelihood determined using CloudSat cloud objects at a given AOD. For reference, it is described in the following text on Pages 8-9, Lines 261-264:** ***"Figure 5d shows the likelihood of rain occurrence at a given AOD determined by the ratio of raining cloud objects to the total number of cloud objects. As expected, Figure 5d shows that the likelihood of rain decreases as AOD increases, with rain likelihood of about 50% in the cleanest environments decreasing to about 40% for an AOD approaching 0.75. These results imply that once the condensation-coalescence is initiated, aerosol loading has a smaller impact on the conversion of cloud water to rain than other cloud or environmental characteristics."*****.**

References:

Cho, H.-M., Zhang, Z., Meyer, K., Lebsock, M., Platnick, S., Ackerman, A. S., Di Girolamo, L., C.-Labonnote, L., Cornet, C., Riedi, J., and Holz, R. E.: Frequency and causes of failed MODIS cloud property retrievals for liquid phase clouds over global oceans, Journal of Geophysical Research: Atmospheres, 120, 4132–4154, https://doi.org/https://doi.org/10.1002/2015JD023161, https://agupubs.onlinelibrary. 390 wiley.com/doi/abs/10.1002/2015JD023161, 2015.