

A Point-by-point Response to Review Comments

Dear Dr. Feingold,

We are submitting the revised manuscript (#acp-2018-499) for your consideration of publication in *Atmospheric Chemistry and Physics*. We have carefully studied the reviewers' comments and revised the manuscript accordingly. Please find the point-by-point response (marked as blue) to the review comments. We have provided a copy of track-change manuscript as well as a clean copy of the revised manuscript.

Please note that we submitted the response to reviewer #1 and #2 before the comment from reviewer #3 was posted. In this submission, we made revisions according to all reviewers' comments and made changes to the line numbers in the response to reviewer #1 and #2 accordingly.

Thank you for your consideration of this submission. We hope you find our response adequately address the review comments and the revision acceptable. We would greatly appreciate it if you could get back to us with your decision at your earliest convenience.

Sincerely,

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General response to all reviewers

We would like to thank you for the constructive comments and suggestions. We appreciate your time. As you will see, the manuscript has been revised follow each reviewer's suggestions. In the response, black are reviewers' comments and blue are our responses.

The major changes are:

1. The cloud and rain water mixing ratios are now collocated, and the method is described in Appendix A in the revised manuscript. We combine remote sensing and adiabatic assumption to jointly estimate cloud and rain liquid water content (CLWC and RLWC) within the cloud layer. We also estimate the uncertainties in enhancement factor based on our retrieval uncertainties and the results are shown in the updated Figure 4.
2. Following the suggestion of Reviewer 1, E_{auto} and E_{accr} in the revised manuscript are calculated at different layers of cloud to reveal the physical processes. We use averaged q_c in top five range gates to calculate E_{auto} and averaged q_c and q_r in five range gates around maximum reflectivity to calculate E_{accr} . Despite substantial changes in the data used in calculations, the trend of the new results is similar to previous one except that the values slightly increase. Thus, most of our conclusions still hold.
3. Instead of roughly assuming 10 m s^{-1} horizontal wind, we now use the mean wind speed within a cloud layer from ARM merged sounding data. The terminology is changed from '2-hour...5-hour time intervals' to '60-km and 180-km model grids' as we mimic the specific model grid sizes instead of specific time intervals.
4. Suggested by Reviewer 2, we did extensive literature reviews and rephrased sentences in both introduction and discussion sessions. Previous studies are properly cited and acknowledged.
5. Suggested by Reviewer 3, detailed discussion and comparison with former studies have been added to the revised manuscript as well as proposing future works that can be extended from our current study.

Specific responses to Review 1

The goal of this study is to extend the results of studies such as Lebsock et al. (2013) and Boutle et al. (2014) on quantifying the effects of sub-grid scale inhomogeneity on microphysical process rates applied in GCMs from observations. The central tenet is that inhomogeneity varies with length scale and meteorological regime, thus the currently standard use of “universal” constants to characterize inhomogeneity cannot adequately describe subgrid-scale variability across a range of horizontal grid sizes or environmental conditions. The authors use a temporally extensive remote sensing dataset primarily sampling shallow convection over Graciosa Island in the Azores to develop “scale-aware” enhancement factors for the autoconversion and accretion processes (E_{auto} and E_{accr} , respectively) for several commonly used bulk microphysical parameterizations. These enhancement factors are estimated from compositing of variances and covariances of instantaneous retrievals of cloud and rain liquid water path (CLWP and RLWP, respectively) and cloud drop number concentration N_c over varying time windows, which the authors argue are roughly equivalent to a GCM horizontal grid length if a constant wind speed is assumed.

Thank you for the comments.

As stated in general response, we now use collocated q_c and q_r in the calculations and we use wind speed from merged sounding over certain periods to mimic model grid size.

I agree with the authors’ basic premise that the use of constant values for E_{auto} and E_{accr} in GCM microphysics schemes is unrealistic and likely introduces precipitation biases similar (perhaps in magnitude if not sign) to assuming that grid-mean quantities (e.g. of N_c and cloud and rain liquid water mixing ratios q_c and q_r) are applicable to calculation of process rates in models with coarse grids (say horizontal grid length L greater than a kilometer or so). Furthermore, their assertion that enhancement factors should vary as a function of L as well as meteorological regime is well-stated, although they are not able to access independent information on aerosol-cloud interactions, which I suspect may be of comparable importance to the stability and LWP criteria analyzed.

Thank you for the comments.

In the revised manuscript, we keep the part of assessing enhancement factors for different grid sizes and add the uncertainties in enhancement factor calculations came from our retrieval uncertainties (Figure 4).

We agree that, within the same meteorological regime and similar LWP, aerosol-cloud-precipitation interactions will affect sub-grid cloud and precipitation variabilities. However, it is a challenge to quantitatively estimate this effect using our existing dataset, especially with large uncertainties in aerosol measurements during drizzling conditions. This is an interesting topic and worth to explore in the further.

For completeness and clarification, we add following to lines 488-490 in the revised manuscript: “The effect of aerosol-cloud-precipitation-interactions on cloud and precipitation sub-grid variabilities may be of comparable importance to meteorological regimes and precipitation status and deserves a further study.”

Despite agreeing with the importance and timeliness of the premise of the manuscript, I have several major issues with the relevance of the observations to diagnosis of microphysical process inhomogeneity. Most importantly, the retrievals of cloud and rain/drizzle properties are not collocated; drizzle properties are only retrieved below cloud base. Cloud and drizzle properties are convolved within cloud such that what is classified as CLWP in fact includes contributions from in-cloud drizzle as well. Microphysical process rate equations assume coincident cloud and rain water mixing ratios (accretion) and coincident cloud water and drop number concentration (autoconversion), so unless it could be shown from some other dataset (LES? Aircraft observations? Maybe even a simplified 1D model?) that subcloud RLWP correlates highly with in-cloud RLWP and has similar magnitude, I have serious doubts about the physical relevance of the retrieved covariances. This may explain the apparently low ratios of cloud to rain water presented in the paper (see lines 33-34 and 291-293, Fig. 2e-f), although the authors give no "expected" value of this ratio for comparison.

Thanks for your comments and suggestions.

In the revised manuscript, collocated joint retrieval of cloud and drizzle LWC is employed to obtain q_c and q_r simultaneously. We updated the calculations accordingly, now using the variance and covariance of in-cloud mixing ratios.

In Figures 2e and 2f, we superimpose the ratio of layer-mean q_r to q_c and the ratios are both less than 15% in the two panels. This is also evident in Figure 1b that 10 times of q_r is still less than q_c . The differences in magnitude are consistent with previous study (e.g., CloudSat and aircraft measurement presented by Boutle et al. 2014, their Figure 1a).

We add the following sentences to lines 332-334 in the revised manuscript: "In both panels, the ratios are less than 15%, which means that q_r can be one order of magnitude smaller than q_c . The differences in magnitude are consistent with previous CloudSat and aircraft results (e.g., Boutle et al. 2014)."

The use of column-integrated liquid water paths introduces further uncertainty because the partitioning of the collision-coalescence process into autoconversion and accretion sub-processes is heterogeneous in the vertical. In the shallow clouds typical of the ENA site, autoconversion will be dominant near cloud top where cloud droplets have reached a maximum size due to condensation and larger drizzle drops are rare while accretion dominates lower in cloud, where the drizzle drops initially formed at cloud top sediment and continue to grow by collecting cloud droplets. Erasing this coherent vertical variability by the use of integrated water paths may bias the results presented: in stratiform clouds, liquid water is at a maximum near cloud top (i.e. CLWP is weighted toward cloud top), such that the E_{accr} values in particular are using over-inflated liquid water values.

Thanks for your comments and suggestions.

We agree that autoconversion and accretion sub-processes dominate at different levels of cloud and it is physically reasonable to calculate them separately using different parts of the q_c and q_r profiles.

Following your suggestion, we add the followings to methodology part in lines 220-229 in the revised manuscript: "The autoconversion and accretion parameterizations partitioned from collision-coalescence process dominate at different levels in a cloud layer. Autoconversion

dominates around cloud top where cloud droplets reach maximum by condensation and accretion is dominant at middle and lower parts of the cloud where drizzle drops sediment and continue to grow by collecting cloud droplets. Complying with the physical processes, we estimate autoconversion and accretion rates at different levels of a cloud layer in this study. The averaged q_c within the top five range gates (~215 m thick) are used to calculate E_{auto} . To calculate E_{accr} , we use averaged q_c and q_r within five range gates around the maximum radar reflectivity. If the maximum radar reflectivity appears at the cloud base, then five range gates above the cloud base are used.”

I’m also confused about how the authors transformed liquid water paths to mixing ratios. They state that “CLWC [cloud liquid water content] values are transformed to q_c ...by dividing by air density” (lines 191-192) and similar for q_r (lines 194-195) but never define how they calculate CLWC or drizzle LWC. Are they dividing water path by cloud/drizzle shaft depth for an average value? Or are they applying the methods of Xie and Zhang (2015) and Wu et al. (2015) to the retrievals?

Thank you for the comments.

We first retrieve CLWC and RLWC profiles, then divided by air density vertical profiles calculated from temperature and pressure in merged sounding.

For clarification, we add the following sentences in the revised manuscript: “Using air density (ρ_{air}) profiles calculated from temperature and pressure in merged sounding, mixing ratio (q) can be calculated from LWC using $q(z) = LWC(z)/\rho_{air}(z)$.” to lines 213-214 and 559-561 in methodology and Appendix A.

Is the retrieval of N_c vertically resolved? This part of the methodology is insufficiently described to understand what the authors did, and regardless, it doesn’t address the issue that drizzle properties can only be retrieved below cloud using their approach.

Thank you for the comments.

In our study, N_c is not vertically resolved but is assumed to be constant in a cloud layer.

For clarification, the following is added to lines 208-209 in methodology part in the revised manuscript: “Cloud droplet number concentration (N_c) is retrieved using the methods presented in Dong et al. (1998, 2014a and 2014b) and are assumed to be constant in a cloud layer”.

The drizzle properties in the revised manuscript are not from below cloud only, instead, q_r is now vertically resolved.

Finally, the authors made no attempt to quantify the uncertainty of the reported enhancement factors, such that I cannot make a determination as to whether their E_{auto} and E_{accr} are statistically distinct from the constant values introduced by Morrison and Gettelman (2008). This is particularly relevant to Figure 4.

Thanks for your comments.

To assess the uncertainty associated with the retrieved q_c and q_r , we vary q_c and q_r within their corresponding uncertainties, e.g., $(1 \pm 0.18)q_d$ and $(1 \pm 0.3)q_c$ and re-do the calculations. The

mean differences are used as the boundaries of E_{auto} and E_{accr} as shown in Figure 4 in the revised manuscript.

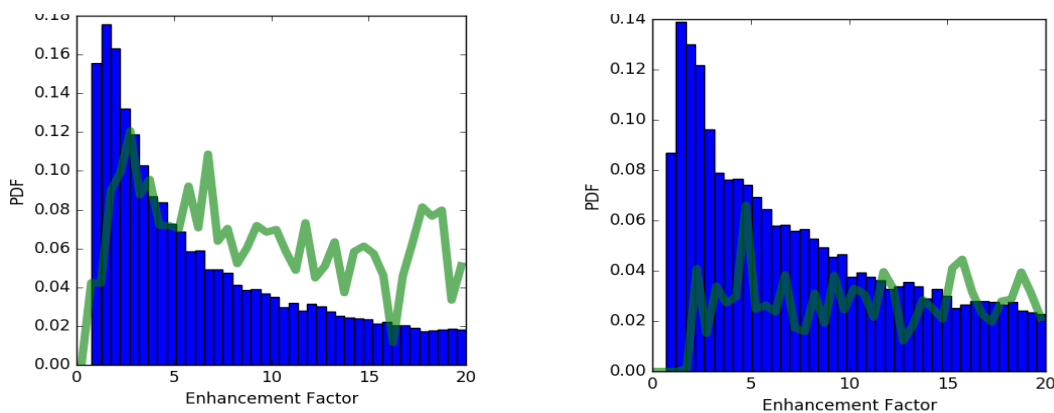
We add the following sentences to lines 215-219 to address the uncertainties of E_{auto} and E_{accr} : “The estimated uncertainties for the retrieved q_c and q_r are 30% and 18%, respectively (see Appendix A). We used the estimated uncertainties of q_r and q_c as inputs of Eqs. (4) and (7) to assess the uncertainties of E_{auto} and E_{accr} . For instance, $(1 \pm 0.3)q_c$ are used in Eq. (4) and the mean differences are then used as the uncertainty of E_{auto} . Same method is used to estimate the uncertainty for E_{accr} .”

Also, in the discussion of Figure 4, we add the following sentences to lines 396-340 in the revised manuscript “The shaded areas represent the uncertainties of E_{auto} and E_{accr} associated with the uncertainties of the retrieved q_c and q_r . When model grid increases, the uncertainty slightly decreases. The prescribed E_{auto} is close to the upper boundary of uncertainties except for the 30-km grid, while the prescribed E_{accr} is significantly lower than the lower boundary.”

I would also have liked to see the authors show the quantitative impact of treating q_c and N_c individually with respect to calculating E_{auto} , as their derivation of Equation 4 assumes that the covariability of q_c and N_c can be ignored. While the magnitude of E_{auto} is comparable for q_c or N_c individually, I don’t have a good sense for what including variability of both variables implies for the predicted E_{auto} values. It’s certainly a problem that CLWP and N_c are correlated in the ARM dataset employed, but that doesn’t change the fact that variability of N_c is likely substantial, especially for the longer time periods analyzed or in more cumuliform precipitation.

Thank you for the comments.

Due to N_c and LWP are highly correlated in our retrieval algorithm, we are currently unable to assess the covariance of q_c and N_c in autoconversion parameterization. In other words, the N_c is derived from LWP and other cloud variables (τ_c and cloud thickness). We can use the following two figures to show why these results are artificially high: the E_{auto} calculated from the covariance of N_c and q_c for 60-km (left panel) and 180-km grid (right panel) sizes superimposed by average precipitation frequency in each bin can reach 40-50. Therefore, we only assess the individual effect of N_c as shown in Figures 2c and 2d, which are similar to the effect of q_c as shown in Figures 2a and 2b. For simplicity and clarity, only E_{auto} calculated from q_c are included in the discussions afterward.



For clarification, we add the following sentences to lines 321-325 in the revised manuscript “Because the E_{accr} values calculated from q_c and N_c are close to each other, we will focus on analyzing the results from q_c only for simplicity and clarity. The effect of q_c and N_c covariance, as stated in Section 4.1, is not presented in this study due to the intrinsic correlation in the retrieval (Dong et al., 2014a and 2014b and Appendix A of this study).”

In light of these concerns, I must recommend that this manuscript be **rejected** in its current form. A revised version of the manuscript only addressing autoconversion would be more feasible and would also be very useful to the parameterization development community, although as mentioned above, I would ask that the authors address the question of whether ignoring covariability of q_c and N_c is a reasonable assumption.

Thank you for the comments.

In fact, we found very high covariance between the two variables, which is a result of our retrieval method in which N_c is derived from LWP and other cloud variables. As stated in the response to last comment, the results using N_c and q_c covariance could result in large variations of E_{auto} that are artificially high. To address this issue, independent retrieval methods for N_c and q_c are needed, that is what we plan to explore in the future.

Thanks for suggesting to use the jointly retrieved q_c and q_r , we think it is reasonable to keep accretion part in the manuscript.

I would be happy to review a revised and refocused manuscript. Until remote sensing datasets can unambiguously partition in-cloud condensed water into cloud and drizzle components, analysis of cloud-rain covariance from the present spatially disjoint cloud and rain retrievals cannot be used to inform accretion parameterizations.

Thank you for the comments.

Please see above responses that we tried to retrieve q_c and q_r profiles in the cloud and re-do the calculations.

A technique like that of Luke and Kollias (2013; doi:10.1175/JTECHD-11-00195.1) that uses skewness of the Doppler spectrum to differentiate between cloud and drizzle could be combined with a method similar to Frisch et al. (1998; doi:10.1029/98JD01827) to retrieve vertically-resolved profiles of cloud and rain water, albeit likely only in stratiform clouds. If such an approach could be developed, the analysis performed in this manuscript would be more tractable although it would likely need to be validated before application to the GCM cloud inhomogeneity problem given the amount of technical work necessary to provide confidence in the retrievals.

Thank you for the suggestions.

We used an alternative way as presented in Appendix A to retrieve CLWC and RLWC and then calculate q_c and q_r . The uncertainties of the retrieval are difficult to quantify without aircraft *in situ* data or other retrieval results. In the uncertainty analysis part, we used 18% as uncertainty for RLWC (rain LWC) from drizzle properties in Wu et al. (2015) and 30% for CLWC (cloud

LWC) from cloud properties in Dong et al. (2014a and 2014b). The actual uncertainties may vary depend on the accuracy of merged sounding data and WACR detectability near cloud base.

In Appendix A, we add the following sentences to address the retrieval uncertainties to lines 545-554: “It is difficult to quantitatively estimate the retrieval uncertainties without aircraft in situ measurements. For the proposed retrieval method, 18% should be used as uncertainty for RLWC from drizzle properties in Wu et al. (2015) and 30% for CLWC from cloud properties in Dong et al. (2014a and 2014b). The actual uncertainty depends on the accuracy of merged sounding data, the detectability of WACR near cloud base and the effect of entrainment on cloud adiabaticity during drizzling. In the recent aircraft field campaign, the Aerosol and Cloud Experiments in Eastern North Atlantic (ACE-ENA) was conducted during 2017-2018 with a total of 39 flights over the Azores, near the ARM ENA site on Graciosa Island. These aircraft in situ measurements will be used to validate the ground-based retrievals and quantitatively estimate their uncertainties in the future.”

References:

- Boutle, I. A., Abel, S. J., Hill, P. G., and Morcrette, C. J.: Spatial variability of liquid cloud and rain: Observations and microphysical effects. *Quart. J. Roy. Meteor. Soc.*, 140, 583–594, doi:10.1002/qj.2140, 2014.
- Dong X., Ackerman, T. P., and Clothiaux, E. E.: Parameterizations of Microphysical and Radiative Properties of Boundary Layer Stratus from Ground-based measurements, *J. Geophys. Res.*, 102, 31,681-31,393, 1998.
- Dong, X., Xi, B., Kennedy, A., Minnis, P. and Wood, R.: A 19-month Marine Aerosol-Cloud_Radiation Properties derived from DOE ARM AMF deployment at the Azores: Part I: Cloud Fraction and Single-layered MBL cloud Properties, *J. Clim.*, 27, doi:10.1175/JCLI-D-13-00553.1, 2014a.
- Dong, X., Xi, B., and Wu, P.: Investigation of Diurnal Variation of MBL Cloud Microphysical Properties at the Azores, *J. Clim.*, 27, 8827-8835, 2014b.
- Wu, P., Dong, X. and Xi, B.: Marine boundary layer drizzle properties and their impact on cloud property retrieval, *Atmos. Meas. Tech.*, 8, 3555–3562. doi: 10.5194/amt-8-3555-2015, 2015.

Specific responses to Review 2

This paper discusses how variability of cloud and rain at the GCM sub-grid scale affect the parametrizations of autoconversion and accretion that are typically used. This has become a popular topic in recent years with many papers and modelling centres using this as a method of improving warm rain simulation. The current paper has some novel aspects, for example the use of data from the Azores to evaluate parametrizations, but I feel would require some significant modifications before it is acceptable for publication.

We made the point-to-point response and thank for your suggestions that help us a lot improve the manuscript. We appreciate the references that you provided and add them in the revision.

Major comments:

1. I don't feel this paper fully or correctly acknowledges the previous work that has been done in this field, which leads to many statements which are either misleading, incorrect, in contradiction to previous studies without explanation, or presented as new when actually they have been published before. Specific examples of this are:

Thanks for your comments and suggestions on literature review. We have revised the sentences and properly acknowledged previous studies.

a) L31, 284, 390 and elsewhere - repeatedly the authors refer to "GCMs", implying that they are stating a common feature of many models, whereas in actual fact they are referring specifically to the MG08 microphysics scheme which is only used in a very small number of GCMs. This terminology needs to be more precise, to highlight the fact that not all GCMs make the same assumptions as MG08.

Thank you for the comment.

The terminology has changed in the revision, we mainly used MG08 scheme in the calculation and discussion. We also give the values for 60-km and 150-km grid sizes for other parameterizations listed in Table 1. Same approaches can be repeated for other parameterization schemes used in GCMs.

To avoid confusion, we add the following sentences at the end of the introduction: "Most of the calculations and analyses in this study is based on Morrison and Gettleman (2008, MG08 hereafter) scheme. The enhancement factors in several other schemes are also discussed and compared with the observational results and the approach in this study can be repeated for other microphysics schemes in GCMs." in lines 126-130 in the revised manuscript.

b) L99 - this statement is incorrect - whilst some models do use prescribed values regardless of meteorological conditions, the whole point of Boutle et al (2014), which is cited as introduction to this statement, is to provide a parametrization depending on meteorological conditions which can be used in GCMs. This parametrization is improved upon by Hill et al (2015), who add in a regime dependence to the parametrization, and implemented in a model by Walters et al (2017). The authors need to acknowledge this work in the context of their own.

Thanks for the correction.

This part has been rephrased to "Boutle et al. (2014) used aircraft in situ measurements and remote sensing techniques to develop a parameterization for cloud and rain, in which not only

consider the sub-grid variabilities under different grid scales, but also consider the variation of cloud and rain fractions. The parameterization was found to reduce precipitation estimation bias significantly. Hill et al. (2015) modified this parameterization and developed a regime and cloud type dependent sub-grid parameterization, which was implemented to the Met Office Unified Model by Walters et al. (2017) and found that the radiation bias is reduced using the modified parameterization.” In lines 99-106 in the revised manuscript.

c) L293-294 - this statement is just repeating the previous conclusions of Boutle et al (2014) and Lebsack et al (2013).

Thank you for the comment.

The two studies are cited and acknowledged in the context of our results.

d) L335 - Hill et al (2015) also show regime dependence and should be cited here.

Thanks for the comment.

The sentence is rephrased to “Therefore, as suggested by Hill et al. (2015), the selection of E_{auto} and E_{accr} values in GCMs should be regime-dependent.” in lines 382-383 in the revised manuscript.

e) L336-337 - I don’t understand this statement - why is it difficult to vary enhancement factors in GCMs? Walters et al (2017) using the parametrizations of Boutle et al (2014) does exactly that - there is nothing difficult here and no reason why other GCMs could not do similar.

Thanks for the comment.

We deleted this sentence and rephrased this part to “To properly parameterize sub-grid variabilities, the approaches by Hill et al. (2015) and Walters et al. (2017) can be adopted. To use MG08 and other parameterizations in GCMs as listed in Table 1, proper adjustments can be made according to the model grid size, boundary layer conditions, and precipitating status.” in lines 384-387 in the revised manuscript.

f) L364-368 - I don’t fully understand what is being claimed here, and it certainly is not supported by any evidence presented in the paper. But what I think the authors are saying is that in more cumulus-type (less stratiform) clouds, E_{auto} should be smaller. This appears contradictory to the results of Boutle et al (2014) (their Fig 10) and Hill et al (2015) which show that E_{auto} is higher in convective type cloud regimes. It also appears in contradiction to the authors own statement on L429-430 (a statement that appears with no justification or background), that unstable boundary layers give rise to larger E_{auto} values. Please clarify this.

Thanks for the comment.

For this statement, we are trying to say for the ‘cloud type under this study’ e.g., MBL stratocumulus in this study, the E_{auto} values should be smaller over land than that over ocean. To avoid confusion, we deleted this statement.

The statement in L429-430 of original manuscript “The E_{auto} values in both stable and mid-stable boundary layer conditions are smaller than the prescribed value of 3.2 used in GCMs, while those values in unstable boundary layers conditions are significantly larger than 3.2 regardless of whether or not the cloud is precipitating.” is the conclusion we draw from the values in Table 2

where the boundary layer is classified into three categories using lower tropospheric stability (LTS). For clarification, we added '(Table 2)' at the end of this statement. This statement is now in lines 479-482 in the revised manuscript.

g) L433 - as is done in Hill et al (2015) and Walters et al (2017).

Thanks for this comment.

The sentence is rephrased to "Therefore, the selection of E_{auto} and E_{accr} values in GCMs should be regime-dependent, which also has been suggested by Hill et al. (2015) and Walters et al. (2017)" in lines 483-484 the revised manuscript.

h) Fig 4 - despite the constant criticism of MG08 for using a fixed value of $E_{auto}=3.2$, this figure shows that at larger grid sizes, this value is actually incredibly good – some credit should be given to MG08 for this!

Thank you for the comment.

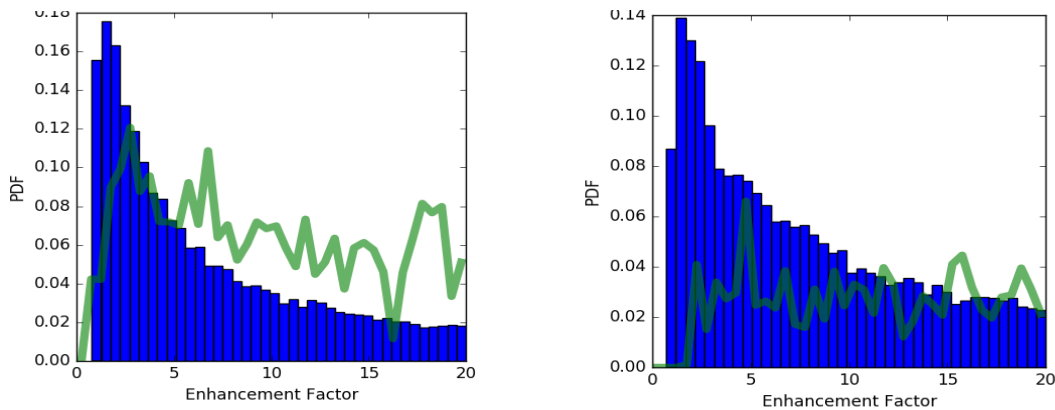
Yes, E_{auto} prescribed in MG08 is getting more and more close to those calculated from observations. In the revised Figure 4, the mean value from observation is exactly the same for 180 km model grid.

We rephrased the following "After that, the E_{auto} values remain relatively constant of ~ 3.18 when the model grid is 180 km, which is close to the prescribed value of 3.2 used in MG08. This result indicates that the prescribed value in MG08 represents well in large grid sizes in GCMs" in lines 391-394 in the revised manuscript.

2) L148, L151 - equations 4 and 5 are incorrect, the term in the denominator should be $\Gamma(\nu)$ not $\Gamma(a)$ as written (see Eq 7 of Boutle et al (2014) or Eq 6 of Pincus and Klein (2000)). I hope this is only a typo and not a problem with all of the data analysis! Also, I'm confused about whether or not you are investigating variability of N_c - the text seems to suggest you are, but this equation ignores any variability in N_c - please clarify the text and correct the equation if necessary.

Thanks for the corrections. These are typos and have been corrected. All the calculations and analysis in the original and revised manuscripts used the correct formulas.

We indeed include N_c in the calculation and the equation has been changed in the revision. We only assess the individual effect of N_c to E_{auto} , not for the covariance of q_c and N_c because q_c and N_c are highly correlated in the retrieval method and it is difficult to tell if the results are due to natural variability or due to mathematics in the retrieval. We can use the following two figures to show why these results are artificially high: the E_{auto} calculated from the covariance of N_c and q_c for 60 km (left panel) and 180 km grid (right panel) size superimposed by average precipitation frequency in each bin can reach 40-50. Therefore, we only assess the individual effect of N_c as shown in Figures 2c and 2d, which are similar to the effect of q_c as shown in Figures 2a and 2b. For simplicity and clarity, only E_{auto} calculated from q_c are included in the discussions afterward.



For clarification, we added the following to lines 321-325 in the revised manuscript “Because the E_{accr} values calculated from q_c and N_c are close to each other, we will focus on analyzing the results from q_c only for simplicity and clarity. The effect of q_c and N_c covariance, as stated in Section 4.1, is not presented in this study due to the intrinsic correlation in the retrieval (Dong et al., 2014a and 2014b and Appendix A of this study).”.

3) L207, 340 - simply using a constant wind speed is quite crude - most previous studies with ground based equipment (eg. Boutle et al 2014) have either used actual wind speeds or model derived reanalysis wind speeds to construct spatial scales from time averages. At the very least this simplification needs to be noted and possible errors due to this discussed.

Thank you for the comment and suggestion.

We agree that use actual wind speeds or model derived wind speeds can reduce the sampling uncertainty. In the revised manuscript, we use the averaged wind speed within cloud layer to mimic different model grid sizes.

The following paragraph is added to lines 238-245 in the methodology part: “To evaluate the dependence of autoconversion and accretion rates on sub-grid variabilities for different model spatial resolutions, an averaged wind speed within cloud layer was extracted from merged sounding and used in sampling observations over certain periods to mimic different grid sizes. For example, two hours of observations corresponds to a 72-km grid box if mean in-cloud wind speed is 10 m s^{-1} horizontal wind and if the wind speed is 5 m s^{-1} , four hours of observations is needed to mimic the same grid. We used six grid sizes (30-, 60-, 90-, 120-, 150-, and 180-km) and mainly show the results from 60-km and 180-km grids in Section 4.”

4) L220 onwards, L281, elsewhere - the analysis appears to be presented in terms of LWP and RWP, i.e. column integrals of quantities. This is very different to the LWC and RWC, i.e. grid-box mean quantities which are used in parametrizations. Most previous studies have used LWC and RWC to calculate the variability, and so the results are directly applicable to parametrizations. It’s not clear to me that results presented in LWP and RWP are so directly applicable. The authors need to investigate how applicable their results using column-integral quantities are to previous studies and parametrizations - it appears from the text that you do have direct observations of LWC and RWC, so it should not be too difficult to make this comparison, or re-do the analysis using the LWC and RWC data.

Thanks for the comment.

We agree that the use of CLWP and RLWP ignores the heterogeneity of collision-coalescence process in the cloud layer. In the revised manuscript, q_c and q_r are jointly retrieved and applied to the calculation.

We add the following sentences to methodology part lines 220-229 in the revised manuscript: “The autoconversion and accretion parameterizations partitioned from collision-coalescence process dominate at different levels in a cloud layer. Autoconversion dominates around cloud top where cloud droplets reach maximum by condensation and accretion is dominant at middle and lower parts of the cloud where drizzle drops sediment and continue to grow by collecting cloud droplets. Complying with the physical processes, we estimate autoconversion and accretion rates at different levels of a cloud layer in this study. The averaged q_c within the top five range gates (~215 m thick) are used to calculate E_{auto} . To calculate E_{accr} , we use averaged q_c and q_r within five range gates around the maximum radar reflectivity. If the maximum radar reflectivity appears at the cloud base, then five range gates above the cloud base are used.”

General comments:

Title - should probably be "Evaluation of ..."

Thanks. Title has been changed.

L50 - should say "a significant amount of drizzle is evaporated"

Thanks. This has been changed.

L56 - I'm not entirely sure I agree with this statement - change in albedo (i.e. the first indirect effect) is the most significant indirect effect. There is also an extensive literature on buffering of the 2nd indirect effect and mechanisms through which aerosol could even enhance convective precipitation. At the very least this statement needs to be more accurate in the context it is being used - increases in aerosol are mainly thought to suppress precipitation in MBL clouds.

Thanks for the comment and sorry for the confusion.

This sentence means that the aerosol indirect effect associated with MBL cloud constitutes the major part in global aerosol indirect effect.

To avoid confusion, this sentence is deleted in the revised manuscript.

L62 - MG08 is an odd reference here, given it discusses a microphysics parametrization, something which is required in models of all scales

Thank you for the comment. This reference is deleted in the revised manuscript.

L63 - the "process" of autoconversion and accretion only exist because modellers have partitioned the liquid water into "cloud" and "rain" categories - please rephrase this sentence, they are not real processes, all that happens in the real atmosphere is collision-coalescence of water droplets.

Thanks for the comment.

This sentence is rephrased to “For Example, warm rain parameterizations in most GCMs treat the condensed water as either cloud or rain in the process of collision-coalescence, which is partitioned into autoconversion and accretion sub-processes in model parameterizations”

L64, 72, 73, 122, 129 - the references to MG08 and LG13 are odd here, given they do not propose autoconversion or accretion parametrizations of their own, they use the scheme of KK00 which is already referenced.

Thank you for the comment. The odd references have been deleted.

L77 - using a prime to denote grid-mean quantities is somewhat non-standard – an overbar is the more typical symbol for a mean quantity.

Thank you for the suggestion. The symbols have been changed in the equations and text.

L79 - I'm not sure I follow why positive skewness is important - can you elaborate? It is only really the non-linear form of the equations that mean rates depend strongly on the sub-grid variability.

Thanks for the comment.

The skewness determines the degree of error by using mean value to represent entire domain. If LWP is normally distributed then mean value is equal to mode value, meaning that mean value can represent the value that most frequently occurs in the field. Whereas in skewed distributions, e.g., Gamma distribution where mean value is greater than mode, then the mean value only represents a relatively small portion of the samples. And using mean to represent entire field results in larger errors than that in normal distribution.

For clarification, we rephrased this sentence to “MBL cloud liquid water path (CLWP) distributions are often positive skewed (Wood and Hartmann, 2006; Dong et al. 2014a and 2014b), that is, the mean value is greater than mode value. Thus, the mean value only represents a relatively small portion of samples. Also, due to the nonlinear nature of the relationships, the two processes depend significantly on the sub-grid variability and co-variability of cloud and precipitation microphysical properties” in lines 77-81 in the revised manuscript

L100 - Boutle et al (2014) use a combination of aircraft, ground-based and satellite measurements.

Thanks for the comment. The citation to this reference has been changed to “Boutle et al. (2014) used aircraft in situ measurements and remote sensing techniques to develop a parameterization for cloud and rain, in which not only consider the sub-grid variabilities under different grid scales, but also consider the variation of cloud and rain fractions. The parameterization was found to reduce precipitation estimation bias significantly.” In lines 99-103 in the revised manuscript.

L312 - using flash flooding as an example when discussing drizzling marine stratocumulus is a bit of a leap, I suggest removing this statement unless you have any evidence that extreme rainfall rates are affected.

Thank you for the comment.

The flash flooding is not a suitable example in the context of marine stratocumulus. We have rephrased this sentence to: “providing limited information in estimating rain water evaporation and air-sea energy exchange” in lines 360-361 in the revised manuscript.

References:

- Boutle, I. A., Abel, S. J., Hill, P. G. and Morcrette, C. J. (2014). Spatial variability of liquid cloud and rain: observations and microphysical effects. *Q. J. R. Meteorol. Soc.*, 140, 583-594, doi:10.1002/qj.2140
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- Walters, D., Baran, A., Boutle, I., Brooks, M., Earnshaw, P., Edwards, J., Furtado, K., Hill, P., Lock, A., Manners, J., Morcrette, C., Mulcahy, J., Sanchez, C., Smith, C., Stratton, R., Tennant, W., Tomassini, L., van Weverberg, K., Vosper, S., Willett, M., Browse, J., Bushell, A., Dalvi, M., Essery, R., Gedney, N., Hardiman, S., Johnson, B., Johnson, C., Jones, A., Mann, G., Milton, S., Rumbold, H., Sellar, A., Ujiie, M., Whittall, M., Williams, K. and Zerroukat, M. (2017). The Met Office Unified Model Global Atmosphere 7.0/7.1 and JULES Global Land 7.0 configurations. *Geosci. Model Dev.*, doi:10.5194/gmd-2017-291
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Thank you for providing the references, we appreciate your time.

References:

- Dong, X., Xi, B., Kennedy, A., Minnis, P. and Wood, R.: A 19-month Marine Aerosol-Cloud Radiation Properties derived from DOE ARM AMF deployment at the Azores: Part I: Cloud Fraction and Single-layered MBL cloud Properties, *J. Clim.*, 27, doi:10.1175/JCLI-D-13-00553.1, 2014a.
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- Walters, D., Baran, A., Boutle, I., Brooks, M., Earnshaw, P., Edwards, J., Furtado, K., Hill, P., Lock, A., Manners, J., Morcrette, C., Mulcahy, J., Sanchez, C., Smith, C., Stratton, R., Tennant, W., Tomassini, L., van Weverberg, K., Vosper, S., Willett, M., Browse, J., Bushell, A., Dalvi, M., Essery, R., Gedney, N., Hardiman, S., Johnson, B., Johnson, C., Jones, A., Mann, G., Milton, S., Rumbold, H., Sellar, A., Ujiie, M., Whittall, M., Williams, K. and Zerroukat, M. The Met Office Unified Model Global Atmosphere 7.0/7.1 and

JULES Global Land 7.0 configurations. *Geosci. Model Dev.*, doi:10.5194/gmd-2017-291, 2017.

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Specific responses to Review 3

This manuscript uses ground-based observations and retrievals from the DOE ARM Mobile Facility at Graciosa Island over the Azores to calculate and characterize shallow cloud autoconversion and accretion enhancement factors as a function of temporal and spatial size, which help establish the observational benchmarks with which to compare against autoconversion and accretion factors in GCM parameterizations. This is a worthy goal, as many GCMs precipitate both too frequently and too lightly relative to observations, with the preliminary inference that the sub-grid enhancement factor for autoconversion in many parameterizations is too strong, and the factor for accretion is too weak. This is because autoconversion primarily determines precipitation initiation, and accretion primarily controls drizzle/precipitation intensity. The approach taken in this study both interesting and instructive, as the homogeneity of cloud/liquid water path (LWP) properties tends to be higher for smaller grid sizes, suggesting that GCMs with finer resolutions many have an even weaker accretion enhancement factor than coarser models. This appears to be an important consideration for models with a range of grid resolutions. While autoconversion and accretion biases are systematically characterized in this study, the additional novelty of this work is that the biases are not fixed, but rather regime dependent, with both lower tropospheric stability and precipitation playing a significant role.

[Thanks for the comments.](#)

The layout and results of this study have the potential to inform existing and future parameterizations about how to tailor precipitation enhancement factors as a function of local thermodynamics, resolution, temporal length, and precipitation itself. While other regions will need to be studied as well to gather and calculate additional autoconversion and accretion enhancement factors in other regimes and/or large-scale dynamics, this study is a good start in providing potential guidance for the modeling and model analysis communities. While there is much potential in this manuscript, there are also a number of minor to moderate technical and science questions which need addressing prior to consideration for publication, and these are mentioned below.

[Thanks for the comments. Please see the point-to-point response below.](#)

Though the manuscript was not intended to be an exhaustive study of all the factors that that may modulate the autoconversion and accretion enhancement factors, it might be complementary to the study to also consider a few additional large-scale factors, such as local vertical velocity profiles, as has recently been done in work examining entrainment velocities over the MAGIC campaign over the Northeast Pacific, in which even during the boreal summer, approximately 20% of the profiles were observed to have rising motion near cloud top. Whether rising motion would enhance accretion rates/enhancement factors might complement the findings presented in this study.

[Thanks for the comments and suggestions.](#)

[Vertical velocity within cloud layer can be inferred from cloud radar Doppler velocity. However, the drizzle presents ~46% of the time at Azores site, thus the vertical velocity signal is contaminated by the presence of drizzle. Unfortunately, we do not have a reliable retrieval](#)

method to determine the reliable vertical velocity from Doppler velocity. Based on your suggestion, we have proposed this work in the summary and future work session in the revised manuscript in lines 488-494: ‘The effect of aerosol-cloud-precipitation-interactions on cloud and precipitation sub-grid variabilities may be of comparable importance to meteorological regimes and precipitation status and deserves a further study. Other than the large-scale dynamics, e.g., LTS in this study, upward/downward motion in sub-grid scale may also modify cloud and precipitation development and affect the calculations of enhancement factors. The investigation of the dependence of E_{auto} and E_{accr} on aerosol type and concentration as well as on vertical velocity would be a natural extension and complement of current study.’

Finally, at the end of this review is an enumeration of grammatical suggestions/typos; the list is non-exhaustive such that a thorough proofreading will be essential prior to publication.

Thanks for catching the errors/typos. They have been corrected and a thorough proofreading is performed.

Science/Technical Questions and Comments:

1) On lines 33-34 (and also lines 291- 293), the authors state that “the ratios of rain to cloud liquid water at $E_{accr}=1.07$ and $E_{accr}=2.0$ are 0.048 and 0.119, respectively, further proving that the prescribed value of $E_{accr}=1.07$ used in GCMs is too small to simulate precipitation intensity”, but it is somewhat unclear to me how this proves this, unless the authors include (for clarity) the respective GCM RLWP-to-CLWP ratios as well in this statement.

Thanks for the comment.

The ratio of rain to cloud water mixing ratio at $E_{accr}=1.07$ is 0.063 in the revised manuscript, and this ratio keeps increasing until ~ 0.142 at around $E_{accr}=2$. The ratio between rain to cloud water mixing ratio at $E_{accr}=1.07$ is substantially smaller than that at $E_{accr}=2$, indicating that the fraction of rain water in total water is too low at $E_{accr}=1.07$. A higher E_{accr} value is accompanied by a higher ratio, which indicates an increased precipitation intensity. Since we did not perform a sensitivity study using GCM simulation in this study, it is hard for us to include GCM RLWP-to-CLWP ratios.

For clarification, this sentence is rephrased to ‘The ratio of q_r to q_c increases from $E_{accr}=1.07$ (0.063) to $E_{accr}=2.0$ (0.142), indicating that the fraction of rain water in total water using the prescribed E_{accr} is too low. This ratio could be increased significantly using a large E_{accr} value, therefore increasing precipitation intensity in the models. This further proves that the prescribed value of $E_{accr}=1.07$ used in MG08 is too small to correctly simulate precipitation intensity in the models.’ in lines 340-343 in the revised manuscript.

How does this range of ratios compare to those from Lebsock et al. (2011)? Based on their Figure 6, it seems that the RLWP-to-CLWP ratio is generally higher than 0.119, though of course other factors are work as well (e.g. cloud top effective radius, included in their Figure 8). If I am interpreting these differences correctly, what do the authors attribute to the apparently higher ratios in that observational study? Reference: Lebsock, M. D., T. S. L’Ecuyer, and G. L. Stephens, 2011: Detecting the ratio of rain and cloud water in low-latitude shallow marine clouds. *J. App. Meteor. Climatology*, 50, 419-432, doi: 10.1175/2010JAMC2494.1.

Thanks for the comment.

The ratios in the original manuscript are lower than those presented by Lebsock et al. (2011), because we only included RLWP below cloud base. In the revised manuscript, vertical profiles of q_v and q_r are retrieved and the ratios shown in Figures 2e-2f now are the ratios of layer-mean q_r to q_v , which are generally smaller than 0.1 (more than one order of magnitude lower). This is consistent with the CloudSat and aircraft measurements presented by Boutle et al. 2014 (their Figure 1a). The averaged RLWP-to-CLWP ratio from the partitioned rain and cloud retrieval is 0.21 (not included in the manuscript), which agrees reasonably well with those in Lebsock et al. (2011).

2) Lines 77-78 (and elsewhere): The authors use primes (‘) to denote grid means, and are consistent about this, but wouldn’t an overbar typically denote grid mean values? Often, but not always, primes are designated for deviations from the mean. Overall, this is a fairly minor comment.

Thanks for the comment. The grid mean quantities are represented by overbars in the revised manuscript. Corresponding text and equations have been changed.

3) Lines 144-145, and more generally the implications for the findings of this study: Is the shape parameter, somewhat analogous to the LWP homogeneity from Wood and Hartmann 2006 (which was simply the squared quantify of the ratio of the mean LWP to its standard deviation)? In that study, precipitation was not explicitly examined, but instead the brokenness of cloud fields was found to increase (total CF decrease) with decreasing LWP homogeneity. The greater shallow convective cellular structure with decreasing LWP homogeneity, however, may have been more conducive for heavier precipitation. In this study, the relationship appears to be the link between reduced LWP homogeneity or other cloud field homogeneity and an increase in precipitation intensity. The latter is often too small in climate models, and too homogeneous of fields may be the culprit. Perhaps even though the authors have cited Barker et al. (1996); Pincus et al. (1999), and Wood and Hartmann (2006), an even stronger parallel/analogy should be made between the objectives and findings here and those from those studies, particularly in the discussion section later on as appropriate.

Thanks for the comment.

The shape parameter in this study is calculated in the same way as in Wood and Hartmann (2006).

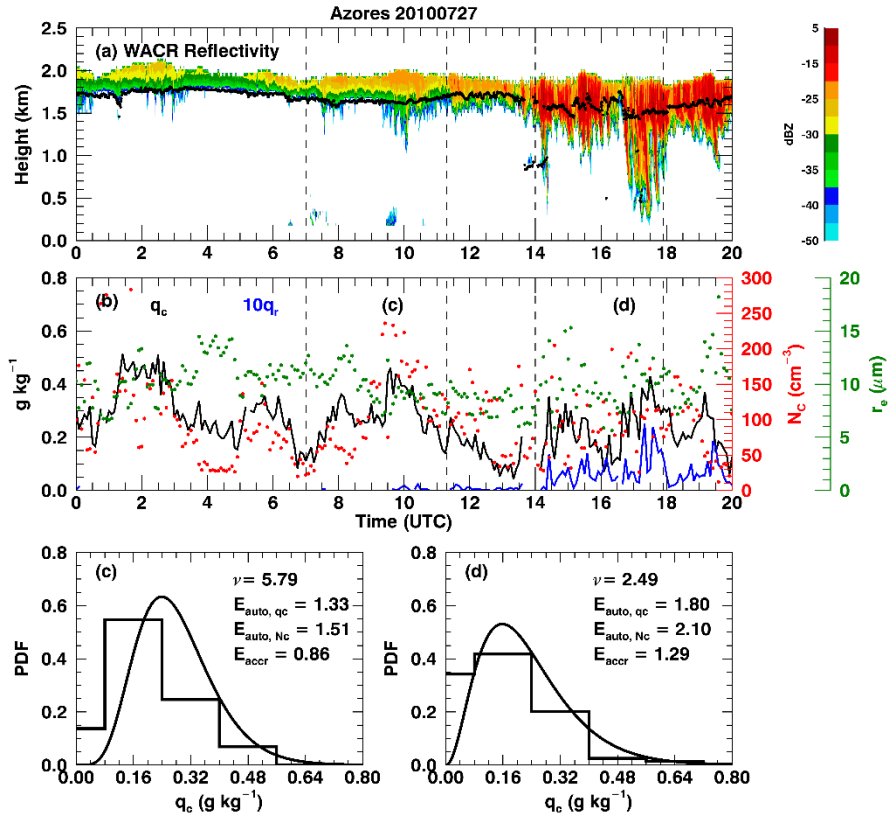
The following paragraph is added in the discussion in lines 279-285 in the revised manuscript: ‘Using the LWP retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) as an indicator of cloud inhomogeneous, Wood and Hartmann (2006) found that when clouds become more inhomogeneous, cloud fraction decreases, and open cells become dominant with stronger drizzling process (Comstock et al., 2007). The relationship between reduced homogeneity and stronger precipitation intensity is found in this study, which is similar to the findings in other studies (e.g., Wood and Hartmann, 2006, Comstock et., 2007, Barker et al., 1996; Pincus et al., 1999).’

3) Results in Figure 1: Traditionally, we think of the large number concentrations decreasing with precipitation, as heavier precipitation is dominated by fewer, larger drops. It perhaps seems a little surprising that a peak (red bin denoting N_c) emerges during the heavy drizzle phase of N_c values of 100 cm^{-3} (Figure 1d). However, there are fewer very high values of N_c (e.g. $>150 \text{ cm}^{-3}$) during the hours of moderate to heavy drizzle. From Fig. 1b as well, there does seem to be high values of N_c just before or after periods of heavier drizzle, but a suppression of N_c is observed somewhat during the stronger pulses of precipitation. Can the authors discuss perhaps why more of the larger number concentrations are not removed during the heavier drizzle events? On the other side of the spectrum, during most of the non-precipitating phase, there is a local maximum of N_c at 150 cm^{-3} . Have the authors considered looking at the corresponding time series of effective radius to include as perhaps another panel for Figure 1? This may complement the N_c observations quite nicely.

Thanks for the comments.

During the drizzling period (1d), the microwave radiometer retrieved cloud LWP, as well as retrieved r_e and N_c are dominated by cloud droplets, not drizzle. Therefore, the differences in LWP and N_c (as well as r_e) between non-drizzle and drizzling periods are not obvious in this study. From the retrieval method, r_e highly depend on LWP values. Whenever LWPs are close, the retrieved r_e are close. Dong et al. (2015) reported statistical results of r_e and N_c using six selected cases at the Azores and found that r_e is $8.2\text{-}9.5 \mu\text{m}$ in non-drizzling cloud and $11.0\text{-}18.9 \mu\text{m}$ in drizzling cloud, N_c is $119.1\text{-}145.9 \text{ cm}^{-3}$ in non-drizzling cloud and $25.1\text{-}100.3 \text{ cm}^{-3}$ in drizzling cloud. Thus, statistically, cloud particle size is larger and number concentration is lower in drizzling cloud compared with the non-drizzling counterpart. It is hard to draw conclusions from the values in one case.

Because this manuscript is not to focus on analyzing microphysical properties during precipitation and r_e was not used in the calculation and analysis, we do not include r_e in the figure and text.



4) Lines 196-197: Is this the traditional LTS definition of potential temperature at 700 hPa minus potential temperature at near the surface (or 1000 hPa)?

Yes, it is the traditional definition. To clarify, we added ' $LTS = \theta_{700 \text{ hPa}} - \theta_{1000 \text{ hPa}}$ ' to line 231 in Section 3.

5) Figure 2: Generally, the precipitation frequency ranges from about 0.1 to just above 0.4, which seems a little low (at least the highest end of precipitation incidence) compared to other observational studies (e.g. Kubar et al. 2009). What is the definition of precipitation frequency here – is it any precipitation observed in the column, or only that which reaches the surface? Reference: Kubar, T. L., D. L. Hartmann, and R. Wood, 2009: Understanding the importance of microphysics and macrophysics in marine low clouds, Part I: satellite observations. *J. Atmos. Sci.*, 66, 2953-2972, doi: 10.1175/2009JAS3071.1

Thanks for the comment.

The definition of precipitation frequency in Figure 2 is the average precipitation frequency of the samples in each bin and precipitation status is labelled using the criteria of maximum reflectivity below cloud base (greater than -37 dBZ as drizzling). The average precipitation frequency from Wu et al. (2015) is 47% using the same definition. Using a different definition (~ -50 dBZ at cloud base), Rémillard et al. (2012) got precipitation frequency of 70% at the same site.

Using the averaged LWP ($109\text{-}140 \text{ g m}^{-2}$) and r_e ($12.5\text{-}12.9 \text{ }\mu\text{m}$) from Dong et al. (2014), the precipitation frequency from Figure 11 of Kubar et al. (2009) are 0.1-0.7 and 0.2-0.75 depending

on the regions. The values in our study do not dependent on LWP or r_e values but agree within reasonable range of those in Kubar et al. (2009).

The following sentence is added to lines 302-304 in the revised manuscript for clarification: ‘Given the average LWP at Azores from Dong et al. (2014b, 109-140 g m⁻²), the precipitation frequency (black lines in Figures 2a and 2b) agrees well with those from Kubar et al. (2009, 0.1-0.7 from their Figure 11).’

6) Is the E_{auto} critical threshold of 4 of converting cloud to drizzle drops found by the authors from the results in Figure 2 considered a novel finding, or has this been reported elsewhere as well (or perhaps a slightly different threshold)?

Thanks for the comment.

In the revised manuscript in which the q_c and q_r are used in calculating E_{auto} and E_{accr} , precipitation rates have larger fluctuations than in the original manuscript. we are not able to conclude a critical value in E_{auto} to clearly separate precipitation rates especially for the 180-km grid (Figure 2b). The statement of critical E_{auto} was deleted from the manuscript. Lebsock et al. (2012) reported a unimodal distribution of E_{auto} with a range of 1-8. Boutle et al. (2014) binned E_{auto} according to cloud fraction and found that E_{auto} can be as high as 4. Other than those, no studies contrasted E_{auto} with precipitation frequency to our knowledge.

7) Lines 284-285 and Figure 4: The authors cite and use 1.07 as a representative value for E_{accr} (based on Morrison and Gettleman 2008); is this a fairly common value used in other GCM parameterizations as well? Presumably, based on this study, the range for E_{accr} in climate models is smaller than the observed/calculated 1-4 range for E_{accr} found in this study.

Thanks for the comment.

The $E_{accr} = 1.07$ in MG08 scheme has been widely used in most GCMs. However, other microphysical parameterizations are also used in GCMs like what we listed in Table 1. For clarification, we changed the terminology in the revised manuscript that specifically evaluate the performance of enhancement factors in MG08 scheme while giving suggested values for other parameterizations (Table 3).

Also, this study is not intended to comment on a specific scheme but to provide a method that can be applied to almost every microphysical scheme using ground-based observations and retrievals.

8) Lines 354-354 and implications of study: As alluded to in the Introductory remarks of this review above, an interesting finding of this study is that the enhancement factors are even more different/biased in finer-resolution GCMs versus observations than coarser-resolution models. Thus, even though a frequent goal is improving resolution in simulations, more care is needed to address the “too frequent/too light” precipitation problem. This study appears to be instructive in how to potentially overcome this barrier.

Thanks for the comments. We highlighted the possible explanation to the ‘too frequent yet too light’ problem in GCM precipitation estimations in the Abstract and summary part of the manuscript.

9) Also, as alluded to in the introduction, while the autoconversion/ accretion enhancement factor dependence on both scale and LTS regime is very intriguing, the authors may also want to expand (or propose for future work) the dependence on either near cloud-top vertical velocity (e.g. from reanalysis data such as ECMWF) and/or boundary layer vertical velocity. My assumption might be that the behavior may be similar to stability; for upward motion near cloud top, both autoconversion/ accretion factors may be higher (as they are for reduced LTS), but it would be interesting to know how comparable such an effect may be to LTS. In a somewhat similar vein, I do commend the authors for discussing that other variables (e.g. aerosol type and concentration) may be important as well for the two enhancement factors studied in this investigation in the very last paragraph. This at least sets up where the authors or others can proceed to continue to expand this line of research.

Thanks for the comments and suggestions.

The following is added to the last paragraph in lines 488-494 in the revised manuscript: ‘The effect of aerosol-cloud-precipitation-interactions on cloud and precipitation sub-grid variabilities may be of comparable importance to meteorological regimes and precipitation status and deserves a further study. Other than the large-scale dynamics, e.g., LTS in this study, upward/downward motion in sub-grid scale may also modify cloud and precipitation development and affect the calculations of enhancement factors. The investigation of the dependence of E_{auto} and E_{accr} on aerosol type and concentration as well as on vertical velocity would be a natural extension and complement of current study.’

10) Lines 398-399:

The authors list a number of studies from the mid-2000s which discuss existing parameterizations, but are the latest GCMs quite similar as well? Is there a good recent paper or series of papers which discuss recent parameterization updates, if they exist?

Thanks for the comment.

The autoconversion and accretion parameterizations listed in this study are typical and classical schemes that are used in cloud and precipitation microphysics parameterizations. Michibata and Takemura (2015) evaluated some of the widely used autoconversion parameterizations used in GCMs and four out of five schemes in Michibata and Takemura (2015) are listed in Table 1 in our study. To our best knowledge, a recently developed parameterization is the Lee and Baik (2017) scheme, in which a physically based autoconversion parameterization was derived by solving stochastic collection equation. The collection kernel is approximated using the terminal velocity of cloud droplets and the collision efficiency is obtained from a particle trajectory model. However, the equation is much more complicated than any of the parameterizations in Table 1, we do not include Lee and Baik (2017) scheme in our study.

For completeness, we added the two references to lines 441-449 to properly acknowledge the recent studies: ‘For a detailed overview and discussion of various existing parameterizations, please refer to Liu and Daum (2004), Liu et al. (2006a), Liu et al. (2004b), Wood (2005b) and Michibata and Takemura (2015). A physical based autoconversion parameterization was developed by Lee and Baik (2017) in which the scheme was derived by solving stochastic collection equation with an approximated collection kernel that is constructed using the terminal velocity of cloud droplets and the collision efficiency obtained from a particle trajectory model.

Due to the greatly increased complexity of their equation, we do not attempt to calculate E_{auto} here but should be examined in future studies due to the physics feasibility of the Lee and Baik (2017) scheme.’

Minor Notes and Grammatical Suggestions/Typos: (*Note – this is a thorough, albeit still incomplete list of typos. Please professionally edit this manuscript prior to resubmitting.)

1) Line 28: change “increase” to “increases”

Changed.

2) Line 50: change “drizzle are” to “drizzle is”

Changed.

3) Line 62: change “Example” to “example”

Changed.

4) Line 65: change “process that drizzle drops” to “process of drizzle drops”

This sentence is rephrased.

5) Line 212: change “19-month” to “19 months”

Changed.

6) Line 221: add an “a” before “more homogeneous”

Added.

7) Line 228: add an “a” prior to “similar”

Added.

8) Line 231: change “contribute” to “contributes” for proper subject (“combination”)-verb (“contributes”) agreement

Changed.

9) Line 240: add “the” before “cloud”

Added.

10) Line 246: change “5-hour” to “5-hours”; similarly, for line 251: change “2-hour” to “2-hours”

The terminology is changed to ‘180-km grid’ and ‘60-km grid’ in the revised manuscript.

11) Line 259: add “the” prior to “autoconversion”

Added.

12) Line 273: add “a” before “similar”

This sentence is rephrased in the revised manuscript.

13) Line 317: Consider changing “seem easier to produce drizzle” to “more easily produce drizzle”

Changed.

14) Line 372: change “are representing” to “represents”. Also, in general the sentence from Line 371 – 373 is slightly awkward and probably should be rewritten.

This sentence is written to ‘The q_c differences between models and observations are then calculated, which represent the q_c adjustment in models to get a realistic autoconversion rate in the simulations.’

15) Line 378: change “associate” to “associated”

Changed.

16) Line 385: add “a” before “variety”

Added.

17) Line 659: add “are for” before “2-hr”

Changed.

References:

- Boutle, I. A., Abel, S. J., Hill, P. G., and Morcrette, C. J.: Spatial variability of liquid cloud and rain: Observations and microphysical effects. *Quart. J. Roy. Meteor. Soc.*, 140, 583–594, doi:10.1002/qj.2140, 2014.
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Marked-up manuscript version (Below)

1 **Evaluation of autoconversion and accretion enhancement factors in GCM warm-rain**
2 **parameterizations using ground-based measurements at the Azores**

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9 Submitted to Atmospheric Chemistry and Physics (~~May~~ September 17-17, 2018)

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12 **Keywords:** MBL clouds, enhancement factors, autoconversion and accretion

13 ~~parameterizations~~ processes

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20 Sciences, University of Arizona, 1133 E. James E. Rogers Way, Tucson, AZ 85721-0011.

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22 Abstract

23 A great challenge in climate modelling is how to parametrize sub-grid cloud processes, such
24 as autoconversion and accretion in warm rain formation. In this study, we use ground-based
25 observations and retrievals over the Azores to investigate the so-called enhancement factors,
26 E_{auto} and E_{accr} , which are often used in climate models to account for the influences of sub-
27 grid variances of cloud and precipitation water on the autoconversion and accretion
28 processes. E_{auto} and E_{accr} are computed ~~at a variety of tempo-spatial scales corresponding~~
29 ~~to~~for different model resolutions. The calculated E_{auto} increases from 1.9679 (0.5 hr/306 km)
30 to 3.15 (3.5 hr/1206 km), and the calculated E_{accr} increases from 1.5325 (0.5 hr/306 km) to
31 1.766 (5 hr/180 km). Comparing the prescribed enhancement factors in Morrison and
32 Gettleman (2008, MG08) to the values from observations shows that GCMs-MG08 are
33 using a much-higher E_{auto} (3.2) ~~at small grids~~ -and lower E_{accr} (1.07). This helps to explain
34 why most of the GCMs produce too frequent precipitation events but with too light
35 precipitation intensity. The ratios of rain to cloud liquid-water mixing ratio at $E_{accr}=1.07$ and
36 $E_{accr}=2.0$ are 0.063 048 and 0.142419, respectively, further proving that the prescribed value
37 of $E_{accr}=1.07$ used in GCMs-MG08 is too small to simulate correct precipitation intensity.
38 Both E_{auto} and E_{accr} increase when the boundary layer becomes less stable, and the values are
39 larger in precipitating clouds ($CLWP>75 \text{ gm}^{-2}$) than those in nonprecipitating clouds

40 (CLWP<75 gm⁻²). Therefore, the selection of E_{auto} and E_{accr} values in GCMs should be
41 regime-dependent.

42

43 **1. Introduction**

44 Due to their vast areal coverage (Warren et al., 1986, 1988; Hahn and Warren, 2007) and
45 strong radiative cooling effect (Hartmann et al., 1992; Chen et al., 2000), small changes in the
46 coverage or thickness of marine boundary layer (MBL) clouds could change the radiative
47 energy budget significantly (Hartmann and Short, 1980; Randall et al., 1984) or even offset
48 the radiative effects produced by increasing greenhouse gases (Slingo, 1990). The lifetime of
49 MBL clouds remains an issue in climate models (Yoo and Li, 2012; Jiang et al., 2012; Yoo et
50 al., 2013; Stanfield et al., 2014) and represents one of the largest uncertainties in predicting
51 future climate (Wielicki et al., 1995; Houghton et al., 2001; Bony and Dufresne, 2005).

52 MBL clouds frequently produce precipitation, mostly in the form of drizzle (Austin et al.,
53 1995; Wood, 2005a; Leon et al., 2008; Wood, 2012). A significant amount of drizzle ~~are~~
54 evaporated before reaching the surface, for example, about ~76% over the Azores region in
55 Northeast Atlantic (Wu et al., 2015), which provides another water vapour source for MBL
56 clouds. Due to their pristine environment and their close vicinity to the surface, MBL clouds
57 are especially sensitive to aerosol perturbations and the associated aerosol indirect effect
58 constitute the central piece of global aerosol indirect effects in climate models (Quaas et al.,

59 2009; Kooperman et al., 2012). Most aerosol indirect effects are associated with precipitation
60 suppression (Albrecht, 1989; Ackerman et al., 2004; Lohmann and Feichter, 2005; Wood,
61 2007). Thus, accurate prediction of precipitation is essential in simulating the global energy
62 budget and in constraining aerosol indirect effects in climate projections.

63 Due to the coarse spatial resolutions of the general circulation model (GCM) grid, many
64 cloud processes cannot be adequately resolved and must be parameterized (~~Morrison and~~
65 ~~Gettleman, 2008~~). For Example, warm rain parameterizations in most GCMs treat the
66 condensed water as either cloud or rain ~~in from~~ the processes of collision-coalescence, which
67 is partitioned into autoconversion and accretion in model parameterizations (Kessler, 1969;
68 Tripoli and Cotton, 1980; Beheng, 1994; Khairoutdinov and Kogan, 2000; Liu and Daum,
69 2004; Morrison and Gettleman, 2008). Autoconversion ~~is represents~~ the process that drizzle
70 drops being formed through ~~the collision-coalescence of~~ cloud droplets and accretion ~~is~~
71 represents the process where rain drops grow by the coalescence of drizzle-sized drops with
72 cloud droplets. Autoconversion mainly accounts for precipitation initiation while accretion
73 primarily contributes to precipitation intensity. Autoconversion is often parameterized as
74 functions of cloud droplet number concentration (N_c) and cloud water mixing ratio (q_c), while
75 accretion depends on both cloud and rain water mixing ratios (q_c and q_r) (Kessler, 1969;
76 Tripoli and Cotton, 1980; Beheng, 1994; Khairoutdinov and Kogan, 2000; Liu and Daum,
77 2004; Wood, 2005b; ~~Morrison and Gettleman, 2008; Larson and Griffin, 2013~~). All the

78 previous studies proposed that these two processes as power law functions of cloud and
79 precipitation properties (See section 2 for details).

80 In conventional GCMs, the lack of information on the sub-grid variances of cloud and
81 precipitation leads to the unavoidable use of the grid-mean quantities ($\overline{N_c}$, $\overline{q_c}$, and
82 $\overline{q_r}$), where ~~prime-overbar~~ denotes grid mean, same below) in calculating autoconversion
83 and accretion rates. MBL cloud liquid water path (CLWP) distributions are often positive
84 skewed (Wood and Hartmann, 2006; Dong et al. 2014a and 2014b), that is, the mean value is
85 greater than mode value. Thus, the mean value only represents a relatively small portion of
86 samples. Also, due to the nonlinear nature of the relationships, the two processes depend
87 significantly on the sub-grid variability and co-variability of cloud and precipitation
88 microphysical properties. However, ~~due to the nonlinear nature of the relationships and~~
89 ~~positive skewness of MBL cloud liquid water path (CLWP) distributions from measurements~~
90 ~~(Wood and Hartmann, 2006), the two processes depend significantly on the sub-grid scale~~
91 ~~variability and co-variability of cloud and precipitation microphysical properties~~ (Weber and
92 Quass, 2012; Boutle et al., 2014). In some GCMs, sub-grid scale variability is often ignored
93 or hard coded using constants to represent the variabilities under all meteorological
94 conditions and across the entire globe (Pincus and Klein, 2000; Morrison and Gettleman,
95 2008; Lebsock et al. 2013). This could lead to systematic errors in precipitation rate
96 simulations (Wood et al., 2002; Larson et al., 2011; Lebsock et al. 2013; Boutle et al., 2014;

97 Song et al. 2018), where GCMs are found to produce too frequent but too light precipitation
98 compared to observations (Zhang et al., 2002; Jess, 2010; Stephens et al., 2010; Nam and
99 Quaas, 2012; Song et al. 2018). The bias is found to be smaller by using a probability density
100 function (PDF) of cloud water to represent the sub-grid scale variability in autoconversion
101 parameterization (Beheng, 1994; Zhang et al., 2002; Jess, 2010), or more complexly, by
102 integrating the autoconversion rate over a joint PDF of liquid water potential temperature,
103 vertical velocity, total water mixing ratio and rain water mixing ratio (Cheng and Xu, 2009).

104 Process rate enhancement factors (E) are introduced when considering sub-grid scale
105 variability in parameterizing grid-mean processes and they should be parameterized as
106 functions of the PDFs of cloud and precipitation properties within a grid box (Morrison and
107 Gettleman, 2008; Lebsock et al. 2013; Boutle et al., 2014). However, these values in some
108 GCMs parameterization schemes are prescribed as constants regardless of underlying surface
109 or meteorological conditions (Xie and Zhang, 2015). Boutle et al. (2014) used aircraft in situ
110 measurements and remote sensing techniques to develop a parameterization for cloud and
111 rain, in which not only consider the sub-grid variabilities under different grid scales, but also
112 consider the variation of cloud and rain fractions. The parameterization was found to reduce
113 precipitation estimation bias significantly. Hill et al. (2015) modified this parameterization
114 and developed a regime and cloud type dependent sub-grid parameterization, which was
115 implemented to the Met Office Unified Model by Walters et al. (2017) and found that the

116 radiation bias is reduced using the modified parameterization~~Previous studies used aircraft *in*~~
117 ~~*situ* measurements (Boutle et al., 2014) and satellite observations (Lebsock et al. 2013) to~~
118 ~~evaluate the dependence of E on sub-grid scale variability over oceans.~~ These studies found
119 ~~that sub-grid scale variability and covariance between cloud and precipitation properties~~
120 ~~significantly affect autoconversion and accretion parameterizations.~~ Using ground-based
121 observations and retrievals, Xie and Zhang (2015) proposed a scale-aware cloud
122 inhomogeneity parameterization that they applied to the Community Earth System Model
123 (CESM) and found that it can recognize spatial scales without manual tuning. The
124 inhomogeneity parameter is essential in calculating enhancement factors and affect the
125 conversion rate from cloud to rain liquid. Xie and Zhang (2015), however, did not evaluate
126 the validity of CESM simulations from their parameterization; the effect of N_c variability, or
127 the effect of covariance of cloud and rain on accretion process was not assessed. Most
128 recently, Zhang et al. (2018) derived the sub-grid CLWP and N_c from the MODIS cloud
129 product. They also studied the implication of the sub-grid cloud property variations for the
130 autoconversion rate simulation, in particular the enhancement factor, in GCMs. For the first
131 time, the enhancement factor due to the sub-grid variation of N_c is derived from satellite
132 observation, and results reveal several regions downwind of biomass burning aerosols (e.g.,
133 Gulf of Guinea, East Coast of South Africa), air pollution (i.e., Eastern China Sea), and active
134 volcanos (e.g., Kilauea Hawaii and Ambae Vanuatu), where the enhancement factor due to N_c

135 is comparable, or even larger than that due to CLWP. However, one limitation of Zhang et al.
136 (2018) is the use of passive remote sensing data only, which cannot distinguish cloud and rain
137 water.

138 Dong et al. (2014a and 2014b) and Wu et al. (2015) reported MBL cloud and drizzle
139 properties over the Azores and provided the possibility of calculating the enhancement
140 factors using ground-based observations and retrievals. A joint retrieval method to estimate q_c
141 and q_r profiles is proposed based on existing studies and is presented in Appendix A. Most of
142 the calculations and analyses in this study is based on Morrison and Gettleman (2008, MG08
143 hereafter) scheme. The enhancement factors in several other schemes are also discussed and
144 compared with the observational results and the approach in this study can be repeated for
145 other microphysics schemes in GCMs. This manuscript is organized as follows: section 2 will
146 include a summary of the mathematical formulas from previous studies that can be used to
147 calculate grid-mean process enhancement factors. Ground-based observations and retrievals
148 are introduced in Section 3. Section 4 presents results and discussion, followed by summary
149 and conclusions in Section 5. The retrieval method used in this study is in Appendix A.

150 **2. Mathematical Background**

151 Autoconversion and accretion rates in GCMs are usually parameterized as power law
152 equations (Tripoli and Cotton, 1980; Beheng, 1994; Khairoutdinov and Kogan, 2000; Liu and
153 Daum, 2004; ~~Morrison and Gettleman, 2008~~):

$$154 \left(\frac{\partial q_r}{\partial t} \right)_{auto} = A \bar{q}_c^{a1} \bar{N}_c^{a2} \bar{q}_e^{+a1} \bar{N}_e^{+a2},$$

155 (1)

$$156 \left(\frac{\partial q_r}{\partial t} \right)_{accr} = B (\bar{q}_c \bar{q}_r \bar{q}_e^+ \bar{q}_r^+)^b,$$

157 (2)

158 where A , $a1$, $a2$, B , and b are constants that change value depending on which scheme is

159 being used. Table 1 provides a list of ~~the some~~ schemes and their associated constants. ~~\bar{q}_e^+ , \bar{q}_r^+ ,~~

160 ~~and \bar{N}_e^+ , \bar{q}_c , \bar{q}_r , and \bar{N}_c~~ are grid-mean cloud water mixing ratio, rain water mixing ratio, and

161 droplet number concentration, respectively. Because it is widely used in model

162 parameterizations, the detailed results from Khairoutdinov and Kogan (2000)

163 ~~parameterization that been and used in Morrison and Gettleman (2008) MG08~~ scheme will be

164 shown in Section 4 while a summary will be given for other schemes.

165 Ideally, the covariance between physical quantities should be considered in the

166 calculation of both processes. However, ~~\bar{q}_c and \bar{N}_c , \bar{q}_e^+ and \bar{N}_e^+~~ in Eq. (1) are arguably not

167 independently retrieved in our retrieval method which will be introduced in the section

168 ~~below~~ Appendix A. We only assess the individual roles of q_c and N_c sub-grid variations in

169 determining autoconversion rate. q_c and q_r , on the other hand, are retrieved from two

170 independent algorithms as shown in Dong et al. (2014a and 2014b), ~~and~~ Wu et al. (2015) and

171 Appendix A, thus we will assess the effect of cloud and rain property covariance on accretion

172 rate calculations.

173 In the sub-grid scale, the PDFs of q_c and N_c are assumed to follow a gamma distribution
 174 based on observational studies of optical depth in MBL clouds (Barker et al., 1996; Pincus et
 175 al., 1999; Wood and Hartmann, 2006):

$$176 P(x) = \frac{\alpha^\nu}{\Gamma(\nu)} x^{\nu-1} e^{-\alpha x}, \quad (3)$$

177 where x represents q_c or N_c with grid-mean quantity \bar{q}_c or \bar{N}_c , represented by μ , $\alpha =$
 178 ν/μ is the scale parameter, σ^2 is the relative variance of x (= variance divided by μ^2), $\nu =$
 179 $1/\sigma^2$ is the shape parameter. ν is an indicator of cloud field homogeneity, with large values
 180 representing homogeneous and small values indicating inhomogeneous cloud fields.

181 By integrating autoconversion rate, Eq. (1), over the grid-mean rate, Eq. (3), with respect
 182 to sub-grid scale variation of q_c and N_c , the autoconversion rate can be expressed as:

$$183 \left(\frac{\partial q_r}{\partial t} \right)_{auto} = A \mu_{q_c}^{2.47a1} \mu_{N_c}^{-1.79a2} \frac{\Gamma(\nu+a)}{\Gamma(\nu2.47)\nu^a},$$

184 (4)

185 where $a = a1$ or $a2$. Comparing Eq. (4) to Eq. (1) gives the the autoconversion enhancement
 186 factors (E_{auto}) with respect to q_c and N_c :

$$187 E_{auto} = \frac{\Gamma(\nu+a)}{\Gamma(\nu2.47)\nu^a}.$$

188 (5)

189 In addition to fitting the distributions of q_c and N_c , we also tried two other methods to
 190 calculate E_{auto} . The first is to integrate Eq. (1) over the actual PDFs from observed or

191 retrieved parameters and the second is to fit a lognormal distribution for sub-grid variability
 192 like what has been done in other studies (e.g., Lebsock et al., 2013; Larson and Griffin,
 193 2013). It is found that all three methods get similar results. In this study, we use a gamma
 194 distribution that is consistent with ~~the widely used GCM parameterization (Morrison and~~
 195 ~~Gettleman, 2008MG08)~~. Also note that, in the calculation of E_{auto} from $\overline{N_c N_c'}$, the negative
 196 exponent (-1.79) may cause singularity problems in Eq. (5). When this situation occurs, we
 197 do direct calculations by integrating the N_c PDF rather than using Eq. (5).

198 To account for the covariance of microphysical quantities in a model grid, it is hard to
 199 apply bivariate gamma distribution due to its complex nature. In this study, the bivariate
 200 lognormal distribution of q_c and q_r is used (Lebsock et al., 2013; Boutle et al., 2014) and can
 201 be written as:

$$\begin{aligned}
 & P(\overline{q_c}, \overline{q_r}, \overline{q_c' q_r'}) = \frac{1}{2\pi \overline{q_c} \overline{q_r} \overline{q_c' q_r'} \sigma_{q_c} \sigma_{q_r} \sqrt{1-\rho^2}} \exp \left\{ -\frac{1}{2} \frac{1}{1-\rho^2} \left[\left(\frac{\ln \overline{q_c} \overline{q_c'} - \mu_{q_c}}{\sigma_{q_c}} \right)^2 - \right. \right. \\
 & \left. \left. 2\rho \left(\frac{\ln \overline{q_c} \overline{q_c'} - \mu_{q_c}}{\sigma_{q_c}} \right) \left(\frac{\ln \overline{q_r} \overline{q_r'} - \mu_{q_r}}{\sigma_{q_r}} \right) + \left(\frac{\ln \overline{q_r} \overline{q_r'} - \mu_{q_r}}{\sigma_{q_r}} \right)^2 \right] \right\}, \\
 & (6)
 \end{aligned}$$

205 where σ is standard deviation and ρ is the correlation coefficient of q_c and q_r .

206 Similarly, by integrating the accretion rate in Eq. (2) from Eq. (6), we get the accretion
 207 enhancement factor (E_{accr}) of:

$$E_{accr} = \left(1 + \frac{1}{v_{qc}}\right)^{\frac{1.15^2 - 1.15}{2}} \left(1 + \frac{1}{v_{qr}}\right)^{\frac{1.15^2 - 1.15}{2}} \exp(\rho 1.15^2 \sqrt{\ln\left(1 + \frac{1}{v_{qc}}\right) \ln\left(1 + \frac{1}{v_{qr}}\right)}). \quad (7)$$

209 3. Ground-based observations and retrievals

210 The datasets used in this study were collected at the Department of Energy (DOE)
 211 Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF), which was deployed
 212 on the northern coast of Graciosa Island (39.09°N, 28.03°W) from June 2009 to December
 213 2010 (for more details, please refer to Rémillard et al. 2012; Dong et al. 2014a and Wood et
 214 al. 2015). The detailed operational status of the remote sensing instruments on AMF was
 215 summarized in Figure 1 of Rémillard et al. (2012) and discussed in Wood et al. (2015). The
 216 ARM Eastern North Atlantic (ENA) site was established on the same island in 2013 and
 217 provides long-term continuous observations.

218 The cloud-top heights (Z_{top}) were determined from W-band ARM cloud radar (WACR)
 219 reflectivity and only single-layered low-level clouds with $Z_{top} \leq 3$ km are selected. Cloud-
 220 base heights (Z_{base}) were detected by a laser ceilometer (CEIL) and the cloud thickness was
 221 simply the difference between cloud top and base heights. The cloud liquid water path
 222 (CLWP) was retrieved from microwave radiometer (MWR) brightness temperatures
 223 measured at 23.8 and 31.4 GHz using a statistical retrieval method with an uncertainty of 20
 224 g m^{-2} for $\text{CLWP} < 200 \text{ g m}^{-2}$, and 10% for $\text{CLWP} > 200 \text{ g m}^{-2}$ (Liljegren et al., 2001; Dong et
 225 al., 2000). Drizzling status is identified through a combination of WACR reflectivity and

226 Z_{base} . As in Wu et al. (2015), we label the status of a specific time as “drizzling” if the
227 WACR reflectivity below the cloud base exceeds -37 dBZ.

228 The ARM merged sounding data has 1-min temporal and 20-m vertical resolution below 3
229 km (Trojan, 2012). In this study, the merged sounding profiles are averaged to 5-min
230 resolution. Pressure and temperature profiles are used to calculate air density (ρ_{air}) profiles
231 and to infer adiabatic cloud water content.

232 Cloud droplet number concentration (N_c) is retrieved using the methods presented in
233 Dong et al. (1998, 2014a and 2014b) and are assumed to be constant in a cloud layer.
234 Cloud microphysical properties (CLWC and N_c) are retrieved using the methods presented in Dong
235 et al. (2014a and 2014b). Vertical profiles of cloud and rain water content (CLWC and
236 RLWC) are retrieved by combining WACR reflectivity, CEIL attenuated backscatter and by
237 assuming adiabatic growth of cloud parcels. The detailed description is presented in
238 Appendix A with result from an example case. The CLWC and DLWC values are
239 transformed to q_c and q_r when calculating autoconversion and accretion rates by dividing by
240 air density (e.g., $q_c(z) = \text{CLWC}(z)/\rho_{\text{air}}(z)$). ~~Drizzle property, or rain LWP, (RLWP),~~
241 ~~below Z_{base} is retrieved using the method proposed in O'Connor et al. (2005) and used by Wu~~
242 ~~et al. (2015). Similarly, drizzle LWC (DLWC) is transformed to q_r when calculating the~~
243 ~~accretion rate.~~

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244 The estimated uncertainties for q_c and q_r retrievals are 30% and 18%, respectively (see
245 Appendix A). We used the range of q_r and q_c variations as inputs Eqs. (4) and (7) to assess
246 the uncertainties in E_{auto} and E_{accr} . For example, use $(1 \pm 0.3)q_c$ in Eq. (4) and the mean
247 difference in E_{auto} is then used as uncertainty. Same method is used to estimate the
248 uncertainties for E_{accr} .

249 The estimated uncertainties for the retrieved q_c and q_r are 30% and 18%, respectively (see
250 Appendix A). We used the estimated uncertainties of q_r and q_c as inputs of Eqs. (4) and (7) to
251 assess the uncertainties of E_{auto} and E_{accr} . For instance, $(1 \pm 0.3)q_c$ are used in Eq. (4) and
252 the mean differences are then used as the uncertainty of E_{auto} . Same method is used to
253 estimate the uncertainty for E_{accr} .

254 The autoconversion and accretion parameterizations partitioned from collision-
255 coalescence process dominate at different levels in a cloud layer. Autoconversion dominates
256 around cloud top where cloud droplets reach maximum by condensation and accretion is
257 dominant at middle and lower parts of the cloud where drizzle drops sediment and continue
258 to grow by collecting cloud droplets. Complying with the physical processes, we estimate
259 autoconversion and accretion rates at different levels of a cloud layer in this study. The
260 averaged q_c within the top five range gates (~215 m thick) are used to calculate E_{auto} . To
261 calculate E_{accr} , we use averaged q_c and q_r within five range gates around the maximum radar

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262 reflectivity. If the maximum radar reflectivity appears at the cloud base, then five range gates
263 above the cloud base are used.

264 The ARM merged sounding data (~~Troyan, 2012~~) are also used to calculate lower
265 tropospheric stability (~~LTS~~ $LTS = \theta_{700 \text{ hPa}} - \theta_{1000 \text{ hPa}}$), which is used to infer the boundary
266 layer stability. In this study, unstable and stable boundary layers are defined as LTS less than
267 13.5 K and greater than 18 K, respectively, and environment with an LTS between 13.5 K
268 and 18 K is defined as mid-stable (Wang et al. 2012; Bai et al. 2018). Enhancement factors in
269 different boundary layers are summarized in Section 4.2 and may be used as references for
270 model simulations. Further, two regimes are classified: CLWP greater than 75 g m^{-2} as
271 precipitating and CLWP less than 75 g m^{-2} as nonprecipitating (Rémillard et al., 2012).

272 To evaluate the dependence of autoconversion and accretion rates on sub-grid
273 variabilities for different model spatial resolutions, an averaged wind speed within cloud
274 layer was extracted from merged sounding and used in sampling observations over certain
275 periods to mimic different grid sizes. For example, two hours of observations corresponds to
276 a 72-km grid box if mean in-cloud wind speed is 10 m s^{-1} horizontal wind and if the wind
277 speed is 5 m s^{-1} , four hours of observations is needed to mimic the same grid. We used six
278 grid sizes (30-, 60-, 90-, 120-, 150-, and 180-km) and mainly show the results from 60-km
279 and 180-km grids in Section 4~~To evaluate the dependence of autoconversion and accretion~~
280 ~~rates on sub-grid scale variabilities for different model spatial resolutions, we use a variety of~~

281 ~~time intervals to mimic different grid sizes. For example, a 2-hour interval corresponds to a~~
282 ~~72-km grid box if assuming 10 m s^{-1} horizontal wind and a 5-hour interval corresponds to a~~
283 ~~180-km grid box. We used 10 time intervals (0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5 hour)~~
284 ~~and mainly show the results from 2-hour and 5-hour intervals in Section 4.~~

285 4. Results and discussions

286 In this section, we first show the data and methods using a selected case, followed by
287 statistical analysis based on 19-months of data and multiple time-intervals.

288 4.1 Case study

289 The selected case occurred at the Azores on July 27, 2010 (Figure 1a). This case was
290 characterized by a long time of non-drizzling or light drizzling cloud development (00:00-
291 14:00 UTC) before intense drizzling occurs (14:00-20:00 UTC). Wu et al. (2017) studied this
292 case in detail to demonstrate the effect of wind shear on drizzle initiation. Here, we choose
293 two periods ~~that corresponding to a 180-km grid and~~ with similar mean $CLWP_{gc}$ near cloud
294 ~~top: $81.028\text{ g kg}^{-1}\text{m}^{-2}$ for 7:00–12:00 UTC (period c) and $850.26\text{ g kg}^{-1}\text{m}^{-2}$ for 13:00–~~
295 ~~18:00 UTC (period d)~~ but with different distributions (Figures 1c and 1d). The PDFs of
296 $CLWP_{gc}$ are then fitted using gamma distributions to get shape parameters (ν) as shown in
297 Figures 1c and 1d. Smaller ν is usually associated with a more inhomogeneous cloud field,
298 which allows more rapid drizzle production and more efficient liquid transformation from
299 cloud to rain (Xie and Zhang, 2015) in regions that satisfy precipitation criteria, which is

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300 usually controlled using threshold q_r , droplet size or relative humidity (Kessler, 1969; Liu
 301 and Daum, 2004). The period d has a wider $CLWP_{gc}$ distribution than the period c, resulting
 302 in a smaller ν and thus larger E_{auto} . Using the fitted ν , the E_{auto} from $CLWP_{gc}$ is calculated
 303 from Eq. (5) and the period d is larger (1.804 vs. 1.33). The E_{auto} values for the periods d and
 304 c can also be calculated from N_c using the same procedure as $CLWP_{gc}$ with a similar result
 305 (2.1 vs. 1.51). The E_{accr} values for the periods d and c can be calculated from the covariance
 306 of $CLWP_{gc}$ and $RLWP_{gc}$ and Eq. (7). Not surprisingly, the period d has larger E_{accr} than
 307 the period c. The combination of larger E_{auto} and E_{accr} in the period d contributes to the rapid
 308 drizzle production and high rain rate as seen from WACR reflectivity and $RLWP_{gc}$.
 309 It is important to clarify the meaning of enhancement factors in precipitation
 310 parameterization. If we assume two scenarios for $CLWPs_{gc}$ with a model grid having the
 311 same mean values but different distributions: (1) The distribution is extremely homogeneous,
 312 there will be no sub-grid variability because the cloud has the same chance to precipitate and
 313 the enhancement factors would be unity (this is true for arbitrary grid-mean $CLWP_{gc}$ amount
 314 as well). (2) The cloud field gets more and more inhomogeneous with a broad range of
 315 $CLWPs_{gc}$ within the model grid box, which results in a greater enhancement factor and
 316 increases the possibility of precipitation. That is, a large enhancement factor can make the
 317 part of the cloud with higher $CLWPs_{gc}$ within the grid box become more efficient in
 318 generating precipitation, rather than the entire model grid.

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319 Using LWP from the Moderate Resolution Imaging Spectroradiometer (MODIS), Wood
320 and Hartmann (2006) found that cloud fraction decreases when the LWP field becomes more
321 inhomogeneous and open cells are generally more inhomogeneous than closed cells. Open
322 cells have been shown to be associated with stronger drizzling process (Comstock et al.,
323 2007). The relationship between reduced homogeneity and stronger precipitation intensity is
324 found in this study, which is similar as those in Wood and Hartmann (2006), Comstock et.
325 (2007), among other studies (e.g., Barker et al., 1996; Pincus et al., 1999).

326 It is clear that $CLWP_{q_c}$ and N_c in Figure 1b are correlated with each other. In addition to
327 their natural relationships, $CLWP_{q_c}$ and N_c in our retrieval method are also correlated (Dong
328 et al. 2014a and 2014b). Thus, the effect of $q_c CLWP$ and N_c covariance on E_{auto} is not
329 included in this study. In Figures 1c and 1d, the results are calculated using a time interval of
330 5-hour model grid of 180-km for the selected case on 27 July 2010. In Section 4.2, we will use
331 these approaches to calculate their statistical results for multiple time intervals grid sizes
332 using the 19-month ARM ground-based observations and retrievals.

333 4.2 Statistical result

334 For a specific time interval grid size, e.g. 260-hour, we estimate the shape parameter (ν)
335 and calculate E_{auto} through Eqns. (5) and (7). The PDFs of E_{auto} for both 60-km 2-hour and
336 180-km 5-hour intervals grids are shown in Figures 2a-2d. The distributions of E_{auto} values
337 calculated from $q_c CLWPs$ with 2-hour 60-km and 5-hour 180-km intervals grids (Figures 2a

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338 and 2b) are ~~similar~~ different to each other ~~with nearly the same mean values~~ (2.795 vs.
339 3.316). The calculated E_{auto} values range from 1 to 10, and most are less than 4 ~~with bi-model~~
340 ~~distributions~~. The average value for the ~~60-km grid 2-hour interval~~ (2.795) is smaller than that
341 for the ~~5-hour 180-km grid window~~ (3.216), indicating a possible dependence of E_{auto} on
342 model grid size. Because drizzle-sized drops are ~~initiated~~ from the autoconversion ~~process~~,
343 we investigate the relationship of E_{auto} and precipitation frequency, which we define as the
344 average percentage of drizzling occurrence based on radar reflectivity below cloud base.
345 Given the average LWP at Azores from Dong et al. (2014b, 109-140 g m⁻²), the precipitation
346 frequency (black lines in Figures 2a and 2b) agrees well with those from Kubar et al. (2009,
347 0.1-0.7 from their Figure 11). The precipitation frequency (~~black lines in Figures 2a and 2b~~)
348 within each PDF bin shows an increasing trend for E_{auto} from 0 to ~~4~~ 6, then ~~stays oscillates~~
349 around a relatively constant when $E_{auto} > 6$, indicating that in precipitation initiation process,
350 E_{auto} keeps increasing to a certain value (~~4~~ 6) until the precipitation frequency reaches a near-
351 steady state. Larger E_{auto} values do not necessarily result in higher precipitation frequency but
352 instead may produce more drizzle-sized drops from autoconversion process when the cloud is
353 precipitating. ~~Therefore, the E_{auto} value of 4 is a critical threshold for converting cloud~~
354 ~~droplets into drizzle drops within MBL clouds.~~

355 The PDFs of E_{auto} calculated from N_c also share similar patterns of positive skewness and
356 peaks at ~1.5-2.0 for the ~~60-km and 180-km grids 2-hour and 5-hour intervals~~ (Figures 2c

357 and 2d). Although the average values are close to their CLWP counterparts (2.5469 vs. 2.795
358 for ~~2-hr60-km~~ and 3.45 vs. 3.216 for ~~180-km5-hr~~), the difference between 60-km and 180-km
359 grids2-hour and 5-hour intervals becomes large. The precipitation frequencies within each bin
360 do not show similar slightly decreasing trend like what is shown in Figures 2a and 2b. This
361 suggests complicated effects of droplet number concentration on precipitation initiation and
362 warrants more explorations of aerosol-cloud-precipitation interactions. This is very intriguing
363 result, which suggests the existence of significant sub-grid variation of N_c and this variation
364 can significantly influence the warm rain process. As mentioned in Section 2, we also fit
365 q_c CLWP and N_c using lognormal distributions. The distributions of E_{auto} are close to Figure 2
366 (not shown here) with average values of 3.2833 and 3.8467, respectively, for 60-km and 180-
367 km grids2-hour and 5-hour intervals. Because the E_{accr} values calculated from q_c and N_c are
368 close to each other, we will focus on analyzing the results from q_c only for simplicity and
369 clarity. The effect of q_c and N_c covariance, as stated in Section 4.1, is not presented in this
370 study due to the intrinsic correlation in the retrieval (Dong et al., 2014a and 2014b and
371 Appendix A of this study).

372 The covariance of q_c CLWP and q_c RLWP (equivalently, q_e and q_r) is included in
373 calculating E_{accr} and the results are shown in Figures 2e and 2f. The calculated E_{accr} values
374 range from 1 to 4 with mean values of 1.6248 and 1.7660 for 60-km and 180-km grids2-hour
375 and 5-hour intervals, respectively. These two mean values are much greater than the

376 prescribed value used in ~~GCMs-MG08~~ (1.07 ~~for example from Morrison and Gettleman,~~
377 ~~2008~~). Since accretion ~~is parameterizes~~ the process ~~where in which~~ rain drops collect cloud
378 droplets, we superimpose the ratio of ~~q_r RLWP~~ to ~~q_c CLWP~~ within each bin (black lines in
379 Figures 2e and 2f) to represent the portion of rain water in the ~~atmospheric column~~ cloud layer.
380 ~~In both panels, the ratios are less than 15%, which means that q_r can be more than one order~~
381 ~~of magnitude smaller than q_c . The differences in magnitude are consistent with previous~~
382 ~~CloudSat and aircraft results (e.g., Boutle et al. 2014).~~ This ratio increases from $E_{accr}=0$ to ~ 2 ,
383 and then decreases, suggesting a possible optimal state for collision-coalescence process to
384 achieve maximum efficiency for converting cloud water into rain water at $E_{accr}=2$. In other
385 words, the conversion efficiency cannot be infinitely increased with E_{accr} under fixed
386 available cloud water. ~~The ratios of q_r to q_c increases from $E_{accr}=1.07$ (0.063) to $E_{accr}=2.0$~~
387 ~~(0.142), indicating that the fraction of rain water in total water is too low in the total water~~
388 ~~from the prescribed E_{accr} and using a larger E_{accr} value can increase this ratio, in other word,~~
389 ~~increase precipitation intensity. This further proves that the prescribed value of $E_{accr}=1.07$~~
390 ~~used in MG08 is too small to simulate correct precipitation intensity in the models.~~The ratios
391 ~~of RLWP to CLWP at $E_{accr}=1.07$ and $E_{accr}=2.0$ are 0.048 and 0.119, further proving that the~~
392 ~~prescribed value of $E_{accr}=1.07$ used in GCMs is too small to simulate correct precipitation~~
393 ~~intensity in the models.~~ Therefore, ~~similar as in Lebsack et al. (2013) and Boutle et al. (2014),~~
394 we suggest increasing E_{accr} from 1.07 to 1.5-2.0 in GCMs.

395 To illustrate the impact of using prescribed enhancement factors, autoconversion and
396 accretion rates are calculated using the prescribed values ~~in GCMs~~ (e.g., 3.2 for E_{auto} and 1.07
397 for E_{accr} , ~~Morrison and Gettleman, 20MG08~~; Xie and Zhang, 2015) and the newly calculated
398 ones in Figure 2 that use observations and retrievals. ~~The q_c and q_r are calculated by dividing~~
399 ~~cloud or rain water content by air density from the merged sounding.~~ Figure 3 shows the joint
400 density of autoconversion (Figures 3a and 3b) and accretion rates (Figures 3c and 3d) from
401 observations (x-axis) and model parameterizations (y-axis) for ~~60-km and 180-km grids~~
402 ~~hour and 5-hour intervals~~. Despite the spread, the peaks of the joint density of autoconversion
403 rate appear slightly above the one-to-one line, suggesting that cloud droplets in the model are
404 more easily to be converted into drizzle/rain drops than observations. On the other hand, the
405 peaks of accretion rate appear slightly below the one-to-one line which indicates that
406 simulated precipitation intensities are lower than observed ones. The magnitudes of the two
407 rates are consistent with Khairoutdinov and Kogan (2000), Liu and Daum (2004), and Wood
408 (2005b).

409 Compared to the observations, the precipitation in GCMs occurs at higher frequencies
410 with lower intensities, which might explain why the total precipitation amounts are close to
411 surface measurements over an entire grid-box. This ‘promising’ result, however, fails to
412 simulate precipitation on the right time scale and cannot capture the correct rain water

413 amount, thus providing limited information in estimating rain water evaporation and air-sea
414 energy exchange-severe weather warnings such as flash flooding.

415 Clouds in an unstable boundary layer have a better chance of getting moisture supply
416 from the surface by upward motion than clouds in a stable boundary layer. Precipitation
417 frequencies are thus different in the two boundary layer regimes. For example, clouds in a
418 relatively unstable boundary layer more easily ~~seem easier to~~ produce drizzle than those in a
419 stable boundary layer (Wu et al., 2017). Provided the same boundary layer condition, CLWP
420 is an important factor in determining the precipitation status of clouds. At the Azores,
421 drizzling clouds are more likely to have CLWP greater than 75 g m^{-2} than their nondrizzling
422 counterparts (Rémillard et al., 2012). To further investigate what conditions and parameters
423 can significantly influence the enhancement factors, we classify low-level clouds according
424 to their boundary layer conditions and CLWPs.

425 The averaged E_{auto} and E_{accr} values for each category are listed in Table 2. Both E_{auto} and
426 E_{accr} increase when the boundary layer becomes less stable, and these values become larger in
427 precipitating clouds ($CLWP > 75 \text{ gm}^{-2}$) than those in nonprecipitating clouds ($CLWP < 75 \text{ gm}^{-2}$).
428 In real applications, autoconversion process only occurs when q_c or cloud droplet size reaches
429 a certain threshold (e.g., Kessler, 1969 and Liu and Daum, 2004). Thus, it will not affect
430 model simulations if a valid E_{auto} is assigned to Eq. (1) in a nonprecipitating cloud. The E_{auto}
431 values in both stable and mid-stable boundary layer conditions are smaller than the prescribed

432 value of 3.2 ~~in GCMs~~, while the values in unstable boundary layers are significantly larger
433 than 3.2 regardless of if they are precipitating or not. All E_{accr} values are greater than the
434 constant of 1.07, ~~the constant used in GCMs~~. The E_{auto} values in Table 2 range from 2.324 to
435 6.9417 and the E_{accr} values vary from 1.42 to 1.867, depending on different boundary layer
436 conditions and CLWPs. Therefore, as suggested by Hill et al. (2015), the selection of E_{auto}
437 and E_{accr} values in GCMs should be regime-dependent.

438 ~~Although the difference of E_{auto} and E_{accr} between the model and the observations exist, it~~
439 ~~is difficult to vary enhancement factors for each grid box at each time step in GCM~~
440 ~~simulations. To properly parameterize sub-grid variabilities, the approaches by Hill et al.~~
441 ~~(2015) and Walters et al. (2017) can be adopted. To use MG08 and other parameterizations in~~
442 ~~GCMs as listed in Table 1, proper adjustments can be made according to the model grid size,~~
443 ~~boundary layer conditions, and precipitating status. Proper adjustments, however, can be made~~
444 ~~according to the model grid size, boundary layer conditions, and precipitating status. As~~
445 ~~stated in the methodology, we used a variety of time intervals, by assuming a 10 m s^{-1}~~
446 ~~horizontal wind model grid sizes, those intervals would correspond to different spatial scales~~
447 ~~implying different model resolutions.~~ Figure 4 demonstrates the dependence of both
448 enhancement factors on different ~~time intervals and~~ model grid sizes. The E_{auto} values (red
449 line) increase from 1.9779 at a grid box of 3048×3048 km to 3.145 at a grid box of
450 1208×1208 km, which are 4384% and 32% percent lower than the prescribed value ~~used in~~

451 ~~GCMs~~ (3.2, upper dashed line). After that, the E_{auto} values remain relatively constant of ~3.18
452 when the model grid is 180 km, which is close to the prescribed value of 3.2 used in MG08.
453 This result indicates that the prescribed value in MG08 represents well in large grid sizes in
454 GCMs. After that, the E_{auto} values remain relatively constant, at around 3.15, which is close to
455 the prescribed value used in GCMs. The E_{accr} values (blue line) increase from 1.5325 at a
456 grid box of ~~1830~~×~~3048~~ km to 1.7653 at a grid box of ~~1808~~×~~1808~~ km, those are ~~1743~~% and
457 ~~4364~~%, respectively, larger than the prescribed value used in GCMs (1.07, lower dashed
458 line). ~~These results suggest that the current GCMs should increase their prescribed E_{accr} value~~
459 ~~by 43% in their simulations of precipitation within a grid box of $1^{\circ} \times 1^{\circ}$.~~ The shaded areas
460 represent the uncertainties of E_{auto} and E_{accr} associated with the uncertainties of the retrieved
461 q_c and q_r . When model grid increases, the uncertainty slightly decreases. The prescribed E_{auto}
462 is close to the upper boundary of uncertainties except for the 30-km grid, while the prescribed
463 E_{accr} is significantly lower than the lower boundary.

464 It is noted that E_{auto} and E_{accr} depart from ~~GCM-their~~ prescribed values at opposite
465 directions as model grid size increases. For models with finer resolutions (e.g., ~~18-30-km or~~
466 ~~54 km~~), both E_{auto} and E_{accr} are significantly different from the prescribed values in GCMs,
467 which can partially explain the issue of ‘too frequent’ and ‘too light’ precipitation. Under
468 both conditions, the accuracy of precipitation estimation is degraded. For models with coarser
469 resolutions (e.g., ~~144 km or 180-km~~), average E_{auto} is close to exactly 3.2 while E_{accr} is much

470 larger than 1.07 when compared to finer resolution simulations. In such situations, the
471 simulated precipitation will be dominated by the ‘too light’ problem, in addition to regime-
472 dependent (Table 2) and as in Xie and Zhang (2015), E_{auto} and E_{accr} should be also scale-
473 dependent.

474 Also note that the location we choose to collect ground-based observations and retrievals
475 is on the remote ocean where the MBL clouds mainly form in a relatively stable boundary
476 layer and are characterized by high precipitation frequency. Even in such environments,
477 however, the GCMs overestimate the precipitation frequency (Ahlgren and Forbes, 2014).

478 ~~In an environment where boundary layer structures are more complicated and precipitation~~
479 ~~events occur less often, the continental US for example, using the fixed E_{auto} value would~~
480 ~~cause much larger errors than those that occur over the Azores. Therefore, for simulations~~
481 ~~over continents we suggest using E_{auto} values that are even smaller than what is suggested in~~
482 ~~Figure 4.~~

483 To further investigate how enhancement factors affect precipitation simulations, we use
484 E_{auto} as a fixed value of 3.2 in Eq. (4), and then calculate the ~~CLWPs~~ q_c needed for models to
485 reach the same autoconversion rate as observations. The q_c differences between models and
486 observations are then calculated, which represent the q_c adjustment in models to get a realistic
487 autoconversion rate in the simulations.~~The CLWP differences between models and~~
488 ~~observations are representing the amount of liquid water needed by models to adjust for~~

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489 ~~getting a realistic autoconversion rate in the simulations.~~ Similar to Figure 1, the PDFs of
490 q_c CLWP differences (model – observation) are plotted in Figures 5a and 5b for 60-km and
491 180-km grids~~2-hour and 5-hour intervals.~~ Figure 5c shows the average percentages of model
492 q_c CLWP adjustments for ~~all time intervals~~model grid sizes, ~~which corresponds to different~~
493 ~~model grid sizes.~~ The mode and average values for ~~both time intervals are~~30-km grid is
494 negative, suggesting that models need to simulate lower q_c CLWPs in general to get
495 reasonable autoconversion rates. Lower q_c CLWPs are usually associated with smaller E_{auto}
496 values that induce lower simulated precipitation frequency. On average, the percentage of
497 q_c CLWP adjustments decrease with increasing model grid size. For example, the adjustments
498 for finer resolutions (e.g., ~~18–54~~30-60 km) can be ~~more than ~~~20% of the q_c cloud water,
499 whereas adjustments in coarse resolution models (e.g., ~~144-120~~ – 180 km) are relatively small
500 because the prescribed E_{auto} (=3.2) is close to the values from observations (Figure 4) and
501 when model grid is 180-km, no adjustment is needed. The adjustment method presented in
502 Figure 5 however, changes cloud water substantially and may cause a variety of subsequent
503 issues, such as altering cloud radiative effects and disrupting the hydrological cycle. The
504 assessment we do in Figure 5 only provides a reference to the equivalent effect on cloud
505 water by using the prescribed E_{auto} value ~~in GCMs~~ as compared to those from observations.

506 All above discussions are based on the prescribed E_{auto} and E_{accr} values (3.2 and 1.07) in
507 MG08 GCMs and WRF from Morrison and Gettelman (2008). Whereas there are quite a few

508 parameterizations that have been published so far. In this study, we list E_{auto} and E_{accr} for
509 three other widely used parameterization schemes in Table 3, which are given only for 60-km
510 and 180-km grids~~2-hour and 5-hour intervals~~. The values of the exponent in each scheme
511 directly affect the values of the enhancement factors. For example, the Beheng (1994)
512 scheme has highest degree of nonlinearity and hence has the largest enhancement factors. The
513 values for Liu and Daum (2004) scheme ~~is~~are very similar to the Khairoutdinov and Kogan
514 (2000) scheme because both schemes have a physically realistic dependence on cloud water
515 content and number concentration (Wood, 2005b). For a detailed overview and discussion of
516 various existing parameterizations, please refer to Liu and Daum (2004), Liu et al. (2006a),
517 Liu et al. (2004b)~~,~~and Wood (2005b) and Michibata and Takemura (2015). A physical based
518 autoconversion parameterization was developed by Lee and Baik (2017) in which the scheme
519 was derived by solving stochastic collection equation with an approximated collection kernel
520 that is constructed using the terminal velocity of cloud droplets and the collision efficiency
521 obtained from a particle trajectory model. Due to the greatly increased complexity of their
522 equation, we do not attempt to calculate E_{auto} here but should be examined in future studies
523 due to the physics feasibility of the Lee and Baik (2017) scheme.

524 **5. Summary**

525 To better understand the influence of sub-grid cloud variations on the warm-rain process
526 simulations in GCMs, we investigated the warm-rain parameterizations of autoconversion

527 (E_{auto}) and accretion (E_{accr}) enhancement factors in MG08. These two factors represent the
528 effects of sub-grid cloud and precipitation variabilities when parameterizing autoconversion
529 and accretion rates as functions of grid-mean quantities. ~~In current GCMs, E_{auto} and E_{accr} are~~
530 prescribed as 3.2 and 1.07, respectively, in the widely used ~~Morrison and Gettleman~~
531 ~~(2008)~~MG08 scheme. To assess the dependence of the two parameters on sub-grid scale
532 variabilities, we used ground-based observations and retrievals collected at DOE ARM
533 Azores site to reconstruct the two enhancement factors in ~~a variety of time intervals and~~
534 different model grid sizes.

535 The calculated E_{auto} values from observations and retrievals increase from 1.796 at a grid
536 box of ~~3048~~3048 km to 3.15 at a grid box of ~~408120~~408120 km. These values are ~~4438~~4438%
537 and ~~32~~32% lower than the prescribed value of 3.2 ~~in Morrison and Gettleman (2008) scheme~~.
538 The prescribed value in MG08 represents well in large grid sizes in GCMs. On the other
539 hand, the E_{accr} values increase from 1.2553 at a grid box of ~~1830~~1830 km to 1.7653 at a
540 grid box of ~~1808~~1808 km, which are ~~1743~~1743% and ~~4364~~4364% higher than the prescribed value
541 (1.07). The ~~much~~ higher E_{auto} and lower E_{accr} prescribed in GCMs help to explain ~~why most~~
542 ~~produce~~the issue of too frequent precipitation events with ~~a too light~~a too light precipitation intensity
543 ~~that is too light~~. The ratios of rain to cloud liquid water increase with increasing E_{accr} from 0
544 to 2, and then decrease after that, suggesting a possible optimal state for the collision-
545 coalescence process to achieve maximum efficiency for converting cloud water into rain

546 water at $E_{accr}=2$. The ratios of RLWP to CLWP at $E_{accr}=1.07$ and $E_{accr}=2.0$ are 0.0~~6348~~ and
547 0.1~~4249~~, further proving that the prescribed value of $E_{accr}=1.07$ ~~used in GCMs~~ is too small to
548 simulate correct precipitation intensity in models.

549 To further investigate what conditions and parameters can significantly influence the
550 enhancement factors, we classified low-level clouds according to their boundary layer
551 conditions and CLWPs. Both E_{auto} and E_{accr} increase when the boundary layer conditions
552 become less stable, and the values are larger in precipitating clouds ($CLWP > 75 \text{ gm}^{-2}$) than
553 those in nonprecipitating clouds ($CLWP < 75 \text{ gm}^{-2}$). The E_{auto} values in both stable and mid-
554 stable boundary layer conditions are smaller than the prescribed value of 3.2 ~~used in GCMs~~,
555 while those values in unstable boundary layers conditions are significantly larger than 3.2
556 regardless of whether or not the cloud is precipitating ([Table 2](#)). All E_{accr} values are greater
557 than the prescribed value of 1.07 ~~used in GCMs~~. Therefore, the selection of E_{auto} and E_{accr}
558 values in GCMs should be regime-dependent, which also has been suggested by Hill et al.
559 (2015) and Walters et al. (2017). ~~Therefore, the selection of E_{auto} and E_{accr} values in GCMs~~
560 ~~should be regime dependent.~~

561 This study, however, did not include the effect of uncertainties in GCM simulated cloud
562 and precipitation properties on sub-grid scale variations. For example, we did not consider
563 the behavior of the two enhancement factors under different aerosol regimes, a condition
564 which may affect precipitation formation process. The effect of aerosol-cloud-precipitation-

565 interactions on cloud and precipitation sub-grid variabilities may be of comparable
566 importance to meteorological regimes and precipitation status and deserves a further study.
567 Other than the large-scale dynamics, e.g., LTS in this study, upward/downward motion in
568 cloud-scale may also modify cloud and precipitation development and affect the calculations
569 of enhancement factors. The investigation of the dependence of E_{auto} and E_{accr} on aerosol type
570 and concentration as well as on vertical velocity would be a natural extension and
571 complement of current study. In addition, other factors may also affect precipitation
572 frequency and intensity even under the same aerosol regimes and even if the clouds have
573 similar cloud water contents. Wind shear, for example as presented in Wu et al. (2017), is an
574 external variable that can affect precipitation formation. Further studies are needed to
575 evaluate the role of the covariance of q_c and N_c in sub-grid scales on E_{auto} determinations,
576 which is beyond the scope of this study and requires independent retrieval techniques.

577

578 Appendix A: Joint cloud and drizzle LWC profile estimation

579 If a time step is identified as non-drizzling cloud, the cloud liquid water content (CLWC)
580 profile is retrieved using Frisch et al. (1995) and Dong et al. (2014a and 2014b). The
581 retrieved CLWC is proportional to radar reflectivity.

582 If a time step is identified as drizzling (maximum reflectivity below cloud base exceeds -
583 37 dBZ), CLWC profile is first inferred from temperature and pressure in merged sounding

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584 by assuming adiabatic growth. Marine stratocumulus is close to adiabatic (Albrecht et a.
585 1990) and was used in cloud property retrievals in literature (e.g., Rémillard et al. 2013). In
586 this study, we use the information from drizzle properties near cloud base to further constrain
587 the adiabatic CLWC ($CLWC_{adiabatic}$).

588 Adopting the method of O'Connor et al. (2005), Wu et al. (2015) retrieved drizzle
589 properties below cloud base (CB) for the same period as in this study. In Wu et al. (2015),
590 drizzle particle size (median diameter, D_0), shape parameter (μ), and normalized drizzle
591 droplet number concentration (N_W) are retrieved for the assumed drizzle particle size
592 distribution (PSD):

$$593 \quad n_d(D) = N_W f(\mu) \left(\frac{D}{D_0}\right)^\mu \exp\left[-\frac{(3.67+\mu)D}{D_0}\right] \quad (A1)$$

594 To infer drizzle properties above cloud base, we adopt the assumption in Fielding et al.
595 (2015) that N_W increases from below CB to within the cloud. This assumption is consistent
596 with the *in situ* measurement in Wood (2005a). Similar as Fielding et al. (2015), we use
597 constant N_W within cloud if the N_W decrease with height below CB. The μ within cloud is
598 treated as constant and is taken as the average value from the four range gates below CB.
599 Another assumption in the retrieval is that the evaporation of drizzle particles is negligible
600 from one range gate above CB to one range gate below CB thus we assume drizzle particle
601 size is the same at the range gate below and above CB.

602 With the above information, we can calculate the reflectivity contributed by drizzle (Z_d)
 603 at the first range gate above CB and cloud reflectivity (Z_c) is then $Z_c = Z - Z_d$, where Z is
 604 WACR measured reflectivity. Using cloud droplet number concentration (N_c) from Dong et
 605 al. (2014a and 2014b), CLWC at the first range gate above CB can be calculated through

$$606 \quad Z_c = 2^6 \int_0^\infty n_c(r) r^6 dr = \frac{36}{\pi^2 \rho_w^2} \frac{CLWC^2}{N_c} \exp(9\sigma_x^2) \quad (A2)$$

607 where $n_c(r)$ is lognormal distribution of cloud PSD with logarithmic width σ_x which is set to
 608 a constant value of 0.38 (Miles et al. 2000), ρ_w is liquid water density.

609 We then compare the adiabatic CLWC and the one calculated from Z_c ($CLWC_{reflectivity}$)
 610 at the first range gate above CB. A scale parameter (s) is defined as $s = \frac{CLWC_{reflectivity}}{CLWC_{adiabatic}}$ and
 611 the entire profile of $CLWC_{adiabatic}$ is multiplied by s to correct the bias from cloud sub-
 612 adiabaticity. Reflectivity profile from cloud is then calculated from Eq. (A2) and the
 613 remaining reflectivity from WACR observation is regarded as drizzle contribution. Drizzle
 614 particle size can then be calculated given that N_W and μ are known and drizzle liquid water
 615 content (DLWC) can be estimated.

616 There are two constrains used in the retrieval. One is that the summation of cloud and
 617 drizzle liquid water path (CLWP and DLWP) must be equal to the LWP from microwave
 618 radiometer observation. Another is that drizzle particle size (D_0) near cloud top has to be
 619 equal or greater than $50 \mu m$ and if D_0 is less than $50 \mu m$, we decrease N_W for the entire
 620 drizzle profile within cloud and repeat the calculation until $50 \mu m$ criteria is satisfied.

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621 It is difficult to quantitatively estimate the retrieval uncertainties without aircraft in situ
622 measurements. For the proposed retrieval method, 18% should be used as uncertainty for
623 DLWC from drizzle properties in Wu et al. (2015) and 30% for CLWC from cloud properties
624 in Dong et al. (2014a and 2014b). The actual uncertainty depends on the accuracy of merged
625 sounding data, the detectability of WACR near cloud base and the effect of entrainment on
626 cloud adiabaticity during drizzling. In the recent aircraft field campaign, the Aerosol and
627 Cloud Experiments in Eastern North Atlantic (ACE-ENA) was conducted during 2017-2018
628 with a total of 39 flights over the Azores, near the ARM ENA site on Graciosa Island. These
629 aircraft in situ measurements will be used to validate the ground-based retrievals and
630 quantitatively estimate their uncertainties in the future.

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631 Figure A1 shows an example of the retrieval results. The merged sounding, ceilometer,
632 microwave radiometer, WACR and ceilometer are used in the retrieval. Whenever one or
633 more instruments are not reliable, that time step is skipped, and this results in the gaps in the
634 CLWC and DLWC as shown in Figures A1(b) and A1(c). Using air density (ρ_{air}) profiles
635 calculated from temperature and pressure in merged sounding, mixing ratio (q) can be
636 calculated from LWC using $q(z) = LWC(z)/\rho_{air}(z)$.

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648

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886 **Table 1. The parameters of autoconversion and accretion formulations for four**
887 **parameterizations.**
888

	A	$a1$	$a2$	B	b
Khairoutdinov and Kogan (2000)	1350	2.47	-1.79	67	1.15
Liu and Daum (2004)	$1.3 \times 10\beta_6^6$, where $\beta_6^6 = [(r_v + 3)/r_v]^2$, r_v is mean volume radius. modification was made by Wood (2005b)	3	-1	N/A	N/A
Tripoli and Cotton (1980)	3268	7/3	-1/3	1	1
Beheng (1994)	3×10^{34} for $N_c < 200 \text{ cm}^{-3}$ 9.9 for $N_c > 200 \text{ cm}^{-3}$	4.7	-3.3	1	1

889

890 **Table 2. Autoconversion (left) and accretion (right) enhancement factors in different**
 891 **boundary layer conditions (LTS > 18 K for stable, LTS < 13.5 K for unstable and LTS**
 892 **within 13.5 and 18 K for mid-stable) and in different LWP regimes (LWP ≤ 75 g m⁻² for**
 893 **non-precipitating and LWP > 75 g m⁻² for precipitating).**
 894

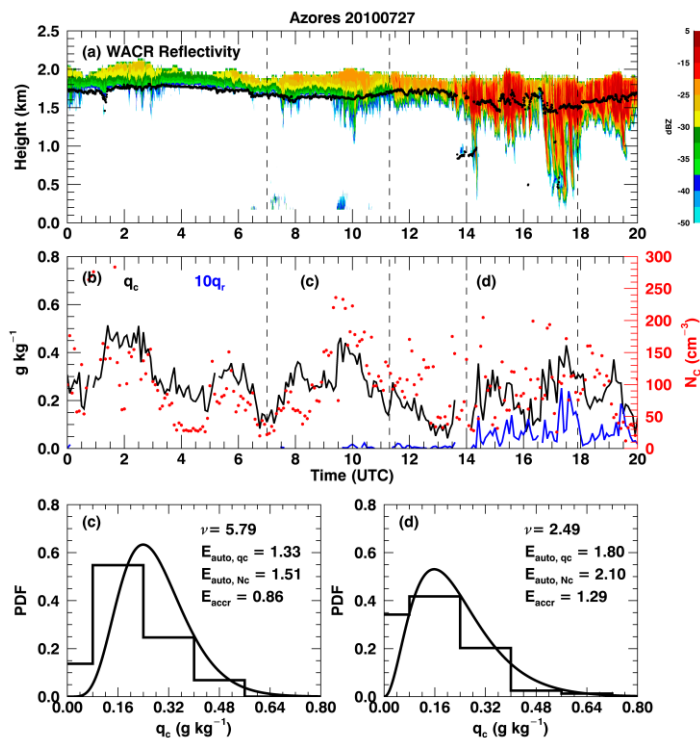
LTS (K)	LWP ≤ 75 g m ⁻²	LWP > 75 g m ⁻²
> 18	2.324 / 1.420	2.7558 / 1.4952
(13.5, 18)	2.6156 / 1.473	3.07298 / 1.6863
< 13.5	4.6245 / 1.7251	6.9447 / 1.8670

895

896 **Table 3. Autoconversion and accretion enhancement factors (E_{auto} and E_{accr}) for the**
 897 **parameterizations in Table 1 except the Khairoutdinov and Kogan (2000) scheme. The**
 898 **values ~~2-hr and 5-hr interval~~ are are -averaged s for 60-km and 18-km model grids.**
 899

	E_{auto}		E_{accr}	
	2-hour <u>60-km</u>	5-hour <u>180-km</u>	2-hour <u>60-km</u>	5-hour <u>180-km</u>
Liu and Daum (2004)	3.76 <u>3.82</u>	4.23 <u>4</u>	N/A	N/A
Tripoli and Cotton (1980)	2.46 <u>55</u>	2.69 <u>71</u>	1.25 <u>47</u>	1.31 <u>56</u>
Beheng (1994)	6.94 <u>73</u>	5.88 <u>00</u>	1.25 <u>47</u>	1.31 <u>56</u>

900

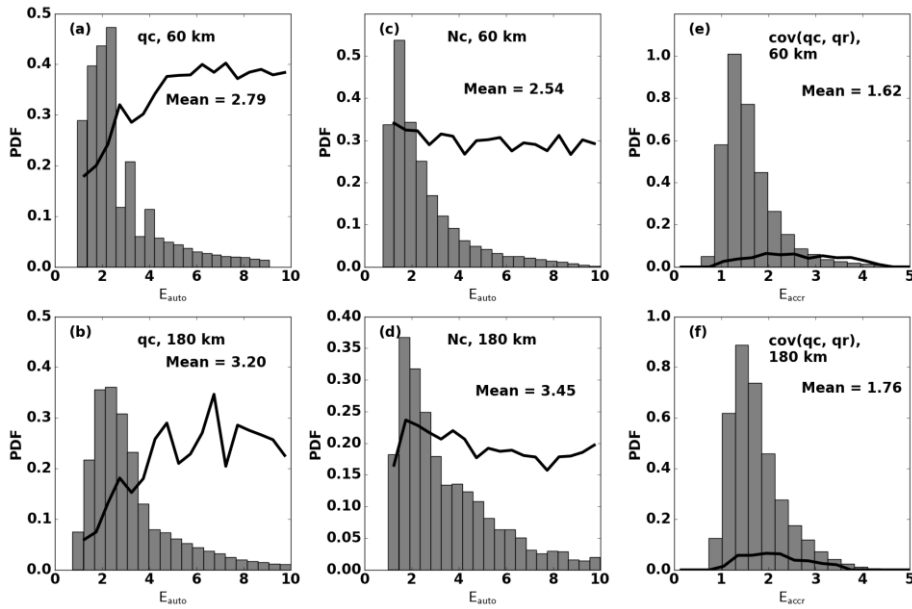


901

902 Figure 1. Observations and retrievals over Azores on 27 July 2010. (a) W-band ARM
 903 cloud radar (WACR) reflectivity (contour) superimposed with cloud-base height (black
 904 dots). (b) Black line represents average cloud water mixing ratio (q_c) in the top five
 905 range gates, Cloud and blue line represents rain ($\times 10$) liquid water path/water mixing
 906 ratio in five range gates around maximum reflectivity (CLWP in black and 10RLWP in
 907 blue), red dots are the retrieved cloud droplet number concentration (N_c). Dashed lines
 908 represent two time-periods that have 60 km model grids with similar mean- q_c CLWP but
 909 different distributions as shown by black step lines in (c) and (d). Black curved lines in
 910 (c) and (d) are fitted gamma distributions with the corresponding shape parameter (ν)
 911 shown on the upper right. Red step lines show N_c distributions are not shown. The
 912 calculated autoconversion ($E_{\text{auto}, \text{CLWP-}q_c}$ from q_c CLWP and E_{auto, N_c} from N_c) and
 913 accretion (E_{accr}) enhancement factors are also shown.

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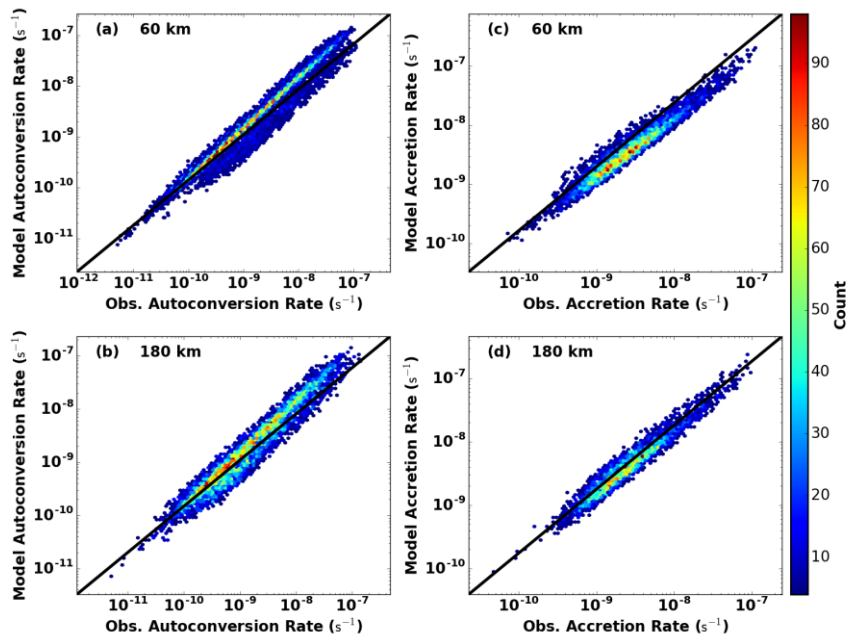
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918 **Figure 2. Probability density functions (PDFs) of autoconversion (a - d) and accretion (e**
919 **- f) enhancement factors calculated from q_c -CLWP (a-b), N_c (c-d), and the covariance of**
920 **q_c -CLWP and q_r -rain-LWP (RLWP) (e-f). First two rows show the results from 60-km²-**
921 **hr and 5-hr-180-km model gridsintervals, respectively, with their average values. Black**
922 **lines represent precipitation frequency in each bin in (a)-(d) and the ratio of layer-mean**
923 **q_r -RLWP to q_c -CLWP in (e)-(f).**

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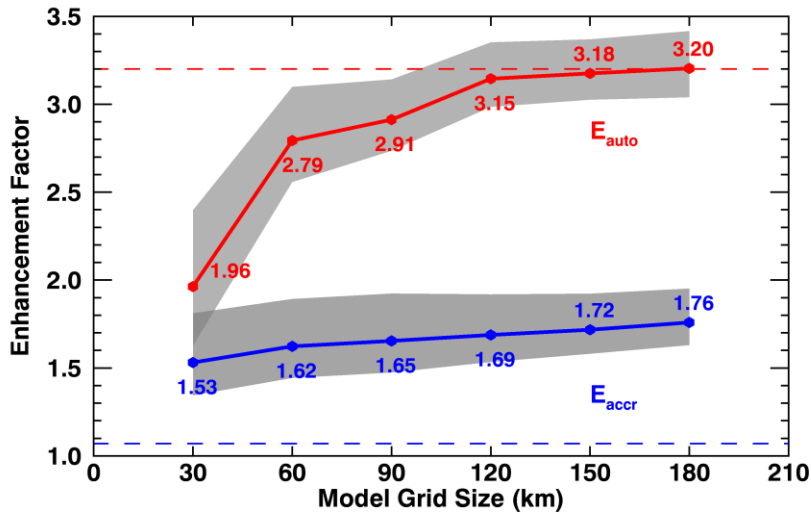


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926 **Figure 3. Comparison of autoconversion (a-b) and accretion (c-d) rates derived from**
 927 **observations (x-axis) and from model (y-axis). Results are for 2-hr 60-km (a and c) and**
 928 **5-hr 180-km model grids intervals. Colored dots represent joint number densities.**

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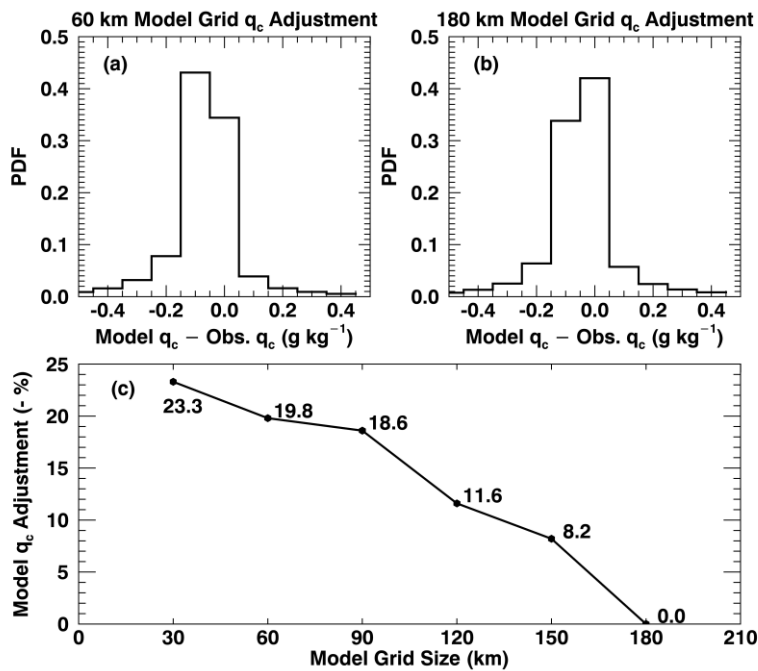


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932 Figure 4. Autoconversion (~~solid-dotred~~ line) and accretion (~~dashed-dotblue~~ line)
933 enhancement factors as a function of ~~time interval (of surface observations)~~ model grid
934 size. ~~The shaded areas are calculated by varying q_c and q_r within their retrieval~~
935 ~~uncertainties. The model grid box sizes on the top X-axis are calculated using a~~
936 ~~horizontal wind of 10 m s^{-1} .~~ The two dashed lines show the constant values of
937 autoconversion (3.2) and accretion (1.07) enhancement factors used in GCMsMG08.

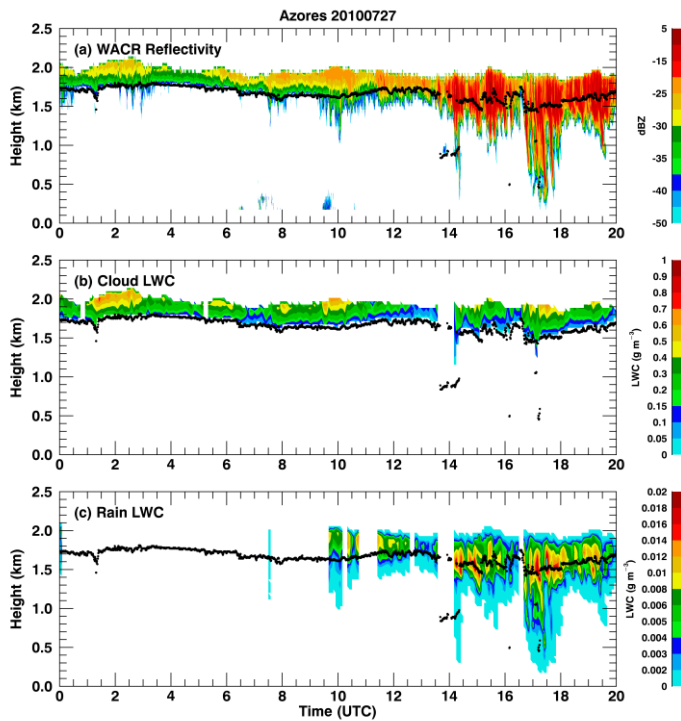
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940 Figure 5. q_c CLWPs needed for models to adjust to reach the same autoconversion rate
 941 as observations for (a) 2-hour-60-km and (b) 5-hour-180-km model gridsintervals.
 942 Positive biases represent increased q_c CLWPs are required in models and negative biases
 943 mean decreased q_c CLWPs. The average percentages of adjustments for different model
 944 grid sizes are shown in panel (c) and note that the percentages in the vertical axis are
 945 negative.

946



947

948 **Figure A1. Joint estimation of cloud and drizzle liquid water content (CLWC and**
 949 **RLWC) for the same case as in Figure 1. (a) WACR reflectivity, (b) CLWC, and (c)**
 950 **LWC. The black dots represent cloud base height. Blank gaps are due to the data from**
 951 **one or more observations are not available or reliable. For example, the gap before 14**
 952 **UTC are due to multiple cloud base are detected whereas we only focus on single layer**
 953 **cloud.**

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