Drizzle rates and large sea-salt nuclei in small cumulus

H. Gerber[1] and G. Frick[2]

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[1] The role of large sea-salt condensation nuclei generated by wind blowing over the ocean surface is evaluated by applying a Lagrangian parcel model to a range of conditions based on observations made during NCAR research flight RF12 of the Rain in Cumulus over the Ocean (RICO) trade wind cumulus (Cu) study in the Caribbean near Antigua. The model utilizes droplet condensation growth, a simplified droplet sedimentation scheme, and quasi-stochastic coalescence to calculate drizzle rates 1100 m above Cu base. The calculations are repeated without the sea-salt solution droplets to permit calculation of a drizzle rate enhancement factor (Df) owing to the large nuclei. The model predicts a small effect of the large nuclei on the RF12 drizzle rate, as well as suggesting the same for other RICO flights in agreement with radar studies of the same Cu that also show at most a small effect on precipitation due to the large nuclei. These findings are contrary to those some other studies of the Cu. The present study agrees with several previous studies that large nuclei affect the drizzle rate for wind speeds greater than about 10 m s^{-1}, that the rate increases as wind speed increases, and that the rate increases as droplet concentration becomes larger at constant wind speed. Df values are fit with an analytical expression relating drizzle rate with wind speed and in-cloud droplet concentration.

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1. Introduction

[2] Classical theory predicts that warm precipitation in cumulus clouds (Cu) forms early and is abundant when Cu have a low concentration of droplets formed on a low concentration of cloud condensation nuclei (CCN), whereas the precipitation is suppressed when the CCN concentration is high because of the greater colloidal stability of clouds with small droplets. Further, if Cu contain sufficient concentrations of large CCN (identified in the following as large sea-salt nuclei, N_s, that may include giant nuclei GN with dry radii 1 μm < r_d < 10 μm as well as ultragiant nuclei UGN with dry nuclei r_d > 10 μm as defined by *Beard and Ochs* [1993]), coalescence between droplets and precipitation is enhanced. Much has been written about these microphysical topics; however, defining and quantifying their effects has remained difficult, especially for the role of N_s. Recent work shows different effects of N_s. *Blyth et al.* [2003] concluded from the Small Cumulus Microphysics Study (SCMS) of Cu formed over Florida that N_s were responsible for initiating precipitation. However, another study of the same Cu by *Göke et al.* [2007] suggested the larger number of CCN rather than N_s dominated the precipitation. And *Hudson and Yum* [2001] found that the number of smaller CCN related to the presence of drizzle drops rather than N_s. These differences were part of the motivation for holding another small-Cu field campaign (Rain in Cumulus over the Ocean (RICO) [*Rauber et al.*, 2007]) this time in the Caribbean trade wind regime. A scientific issue for RICO was again to determine the role of N_s in causing the onset and the amount of precipitation.

[3] RICO generated a new set of publications dealing with N_s using microphysical and radar observations, parcel modeling, and large-eddy simulation (LES) with results again being inconsistent. In-cloud observations showed the previously observed large droplet "drizzle tail" in droplet size distributions attributed in RICO to N_s [*Gerber et al.*, 2008; *Lowenstein et al.*, 2010]. Also, *Hudson et al.* [2011] found substantial correlation between subcloud N_s and drizzle concentrations higher in the Cu, all suggesting that N_s play a role in the precipitation process. However, earlier, *Colón-Robles et al.* [2006] and *Hudson and Mishra* [2007] found a negative correlation between the observed number of large drops and N_s near cloud base suggesting the opposite. The minor importance of N_s is also supported by radar estimates of precipitation in RICO Cu [*Knight et al.*, 2008; *Reiche and Lasher-Trapp*, 2010; *Nuijens et al.*, 2009; *Minor et al.*, 2011]; but as noted by *Nuijens et al.* [2009] the role of sea-salt nuclei is not sufficiently understood. Parcel models with detailed microphysics including N_s [*Gerber et al.*, 2008; *Reiche and Lasher-Trapp,* 2010; *Lowenstein et al.*, 2010] produce drizzle drops attributed to N_s, but not without applying needed simplifications and assumptions. The LES results from *Stevens and Seifert* [2008] showed that an important factor for Cu that rained more was a more humid boundary layer and taller clouds. Similar conclusions were reached by *Reiche and Lasher-Trapp* [2010], *Nuijens et al.*

[1]Gerber Scientific, Inc., Reston, Virginia, USA.
[2]Naval Research Laboratory, Washington, D. C., USA.

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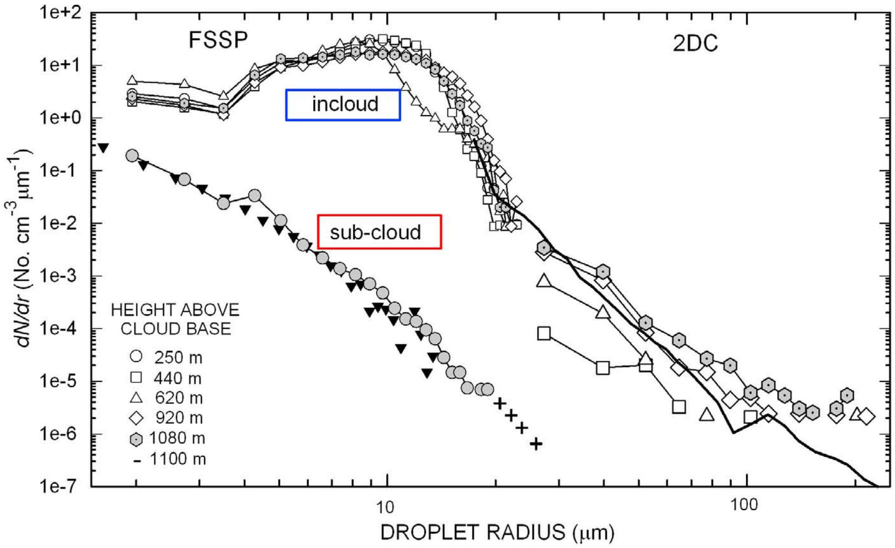

Figure 1. In-cloud droplet (FSSP) and drizzle (2DC) size spectra measured in trade wind cumulus (Cu) during RICO flight RF12. Each in-cloud spectrum is the average of five spectra measured in each cloud core by the FSSP at each height. The subcloud spectra are sea-salt solution droplets measured at an ambient relative humidity of 86% by the FSSP (gray circles) and the giant nuclei impactor (triangles; RAF, NCAR). (From *Gerber et al.* [2008] with changes.)

[2009], and *Arthur et al.* [2010] from their radar studies. This factor as well as other factors potentially affecting precipitation, such as subsidence strength and zonal wind speed [*Nuijens et al.*, 2009], and the complexity of some Cu that "pulsed" [*Rauber et al.*, 2007] or were formed by mesoscale forcing [*Minor et al.*, 2011], must complicate seeing and quantifying the role of sea-salt N_s.

[4] The present modeling study is another attempt to explain the role of N_s in generating drizzle in RICO trade wind Cu. Here advantage is taken of a unique set of observations made in the trade wind Cu during the 11 January 2005 RICO flight RF12 [*Gerber et al.*, 2008]. On this flight with small amounts of precipitation the NCAR C-130 research aircraft flew at five levels above the sea surface through more than 200 Cu of which 35 Cu were chosen by conditional sampling to mimic vertical Lagrangian growth of the Cu (see Figure 1). The Cu were chosen from growing Cu and from aircraft traverses through the core of the ascending "bubble" near cloud top of each Cu where the first radar echo and subsequent precipitation were often observed [*Knight and Miller*, 1998; *Blyth et al.*, 2003]. Surprising results were that the in-cloud droplet size spectra varied little in the vertical in these cores, and that the liquid water content (LWC) was approximately constant with height [see *Gerber et al.*, 2008, Table 3]. Curves fitted to the in-cloud droplet spectra and to the sea-salt nuclei spectra measured below cloud base formed inputs to a parcel model used to calculate the drizzle drop spectrum that resembled the drizzle spectrum at the highest level of the Cu (see Figure 1) [*Gerber et al.*, 2008]. The present study extends those modeling results by specifying additional in-cloud droplet and subcloud nuclei spectra for the same parcel model to estimate drizzle rate sensitivity. The total condensate for the in-cloud spectra in the Cu cores is assumed to remain the same as suggested by the RF12 measurements, and the subcloud nuclei spectra are based on sea-salt spectra measured by *Woodcock* [1953] for various wind speeds over the ocean.

[5] This study follows a similar sensitivity study for RF12 Cu using LES [*Cheng et al.*, 2009] where two pairs of different CCN and N_s concentrations are evaluated for their effect on producing precipitation. Cheng et al. found that both CCN and N_s concentrations affect the precipitation process, and that N_s can have a greater effect on the precipitation rate for greater concentrations of CCN. The latter was also a modeling result for stratocumulus clouds [*Feingold et al.*, 1999; *Lasher-Trapp et al.*, 2008] and for larger Cu [*van den Heever and Cotton*, 2007]; see also *Ochs and Semonin* [1979] and *Johnson* [1982].

[6] The following sections include a brief description of the parcel model including the choice of the baseline spectra for initializing the model. Results include modeled values of drizzle rates at Cu top and the parameterization of the drizzle rate as a function of in-cloud droplet concentration (N_c) and near sea-surface wind speed. The modeled drizzle rate is compared to the precipitation rate measured by radar, performance of the various means for estimating the importance of N_s is discussed, and conclusions are given.

2. Parcel Model

[7] The Lagrangian parcel model (see *Gerber et al.* [2008] for details) calculates the droplet spectrum greater than ~2 μm and less than 200 μm radius (r) and the drizzle rate as a function of height up to a level of 1100 m above Cu base which is 250 m below Cu top. The 1100 m layer is divided into eleven 100 m layers in which the growth of the droplets is calculated. Condensation growth is applied in only the lowest two layers, while quasi-stochastic coalescence growth is applied in all layers. Droplet sedimentation is applied in each layer by subtracting the droplet sedimentation velocity that depends on droplet size from the

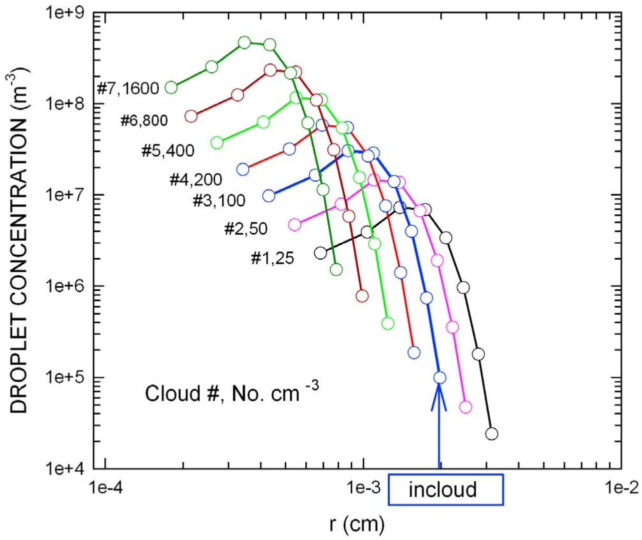

Figure 2. Cloud droplet size distributions used in combination with the spectra in Figure 3 to initialize the parcel model. The baseline distribution labeled in-cloud is based on measurements from RICO flight RF12 shown in Figure 1.

measured mean vertical velocity (1.53 m s^{-1}) in the RF12 Cu resulting in a longer residence time t′ for droplets within each layer. Here t′ is only applied to droplets <80 μm radius to avoid excessive values of t′; for larger droplets t′ is assumed to be 150 s. All drops grown in each layer are advected to the next higher layer. The coalescence calculations are done with the droplets dispersed randomly in each layer, and with an analytical approximation applied to a compilation of collection efficiencies from the parcel model described by *Cooper et al.* [1997].

[8] A set of size spectra of cloud droplets and sea-salt solution droplets is chosen as the input for the sensitivity study. The choice is constrained by using the in-cloud droplet spectra and the subcloud spectra of salt solution droplets measured on RICO flight RF12 and shown in Figure 1. The salt solution droplets are assumed to have formed on N_s that have deliquesced to equilibrium size at the relative humidity (RH) of 86% found at the subcloud level flown by the aircraft.

[9] As mentioned, the in-cloud droplet spectra (each spectrum averaged over 100 m in the Cu cores) at the five levels in Figure 1 show surprisingly small variation. The lack of variation in the spectra as well as the rationale and procedure for conditional sampling of the 35 Cu are described in detail by *Gerber et al.* [2008]. A baseline spectrum labeled cloud 3, 100 in Figure 2 is fitted to the in-cloud spectra in Figure 1. The units on the ordinate axis on Figure 2 as well as on Figure 3 differ from that of Figure 1 in that the differential number concentration in Figure 1 is multiplied by droplet radius intervals on the abscissa to yield the ordinate units in Figures 2 and 3 used in the parcel model. Six other spectra are constructed in Figure 2 on either side of cloud 3 by varying droplet concentration between 25 cm^{-3} and 1600 cm^{-3} while keeping the geometric shape of the spectra and LWC the same (the parcel model uses three droplet concentrations that are greater than the maximum mean droplet concentration of ∼200 cm^{-3} measured in RICO Cu [*Colón-Robles et al.* [2006]) All spectra are defined by 8 droplet sizes. Figure 1 also shows drizzle measurements (drizzle is here assumed to consist of drops >25 μm radius) made by the 2DC probe, and shows one run of the parcel model using the averaged in-cloud and subcloud spectra. The model underestimates the drizzle drop amount in comparison to the 2DC measurements for the largest drops.

[10] Figure 3 shows the baseline subcloud salt solution droplet spectrum obtained from a fit to the measured subcloud spectra in Figure 1 and is labeled with a Beaufort Wind Scale number (B_w) of 5. This value of B_w is found by matching the measured near sea-surface wind speed (U, 9.6 m s^{-1}) for RF12 to B_w curves given by *Woodcock* [1953] that relate his measured wind speeds to dry sea-salt nuclei spectra generated near the sea surface (see *Gerber et al.* [2008] for details). (B_w and U are related approximately by $B_w = 0.8827 + 0.4842\,U - 0.005\,U^2$, and $U = -0.4653 + 1.1240\,B_w + 0.1649\,B_w^2$.) Five other spectra of salt solution droplets are calculated from Woodcock's curves and are included in Figure 3, with B_w values ranging from 3 to 8. Each spectrum is again defined by eight values of r.

[11] Each spectrum in Figure 2 is combined with each spectrum in Figure 3 to yield a total of 42 spectra used to initialize the lowest model level for 42 model runs. The parcel model is also initialized using just the seven in-cloud spectra to test for the enhancement of drizzle by N_s.

[12] Small droplets with a small sedimentation velocity only stay in each 100 m layer for ∼65 s assuming that the mean updraft velocity applies. This does not provide enough time for the rare collision and collection of drops in the coalescence process to be called a true stochastic process. For this reason the parcel model is run 64 times in each layer resulting in a spectrum with a total of 1024 new droplet sizes (16 sizes in each spectrum × 64 runs). The calculation is done in a binless manner [*Gerber*, 1991] to avoid droplet

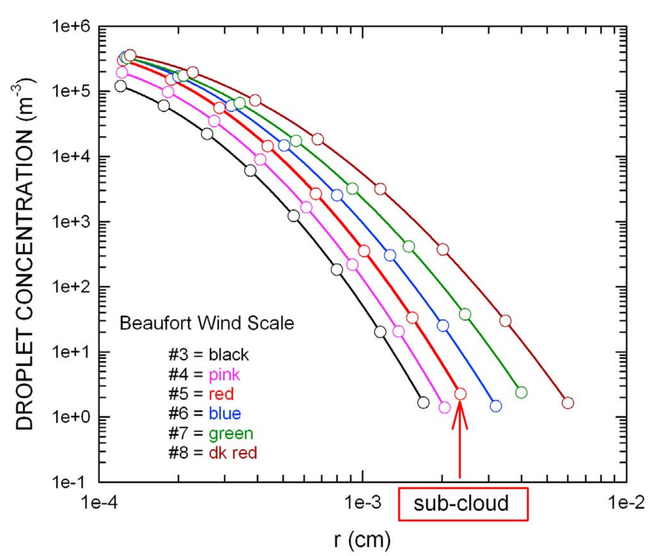

Figure 3. Sea-salt solution droplet size distributions used in combination with spectra in Figure 2 to initialize the parcel model. The distribution labeled subcloud is based on the measurements shown in Figure 1.

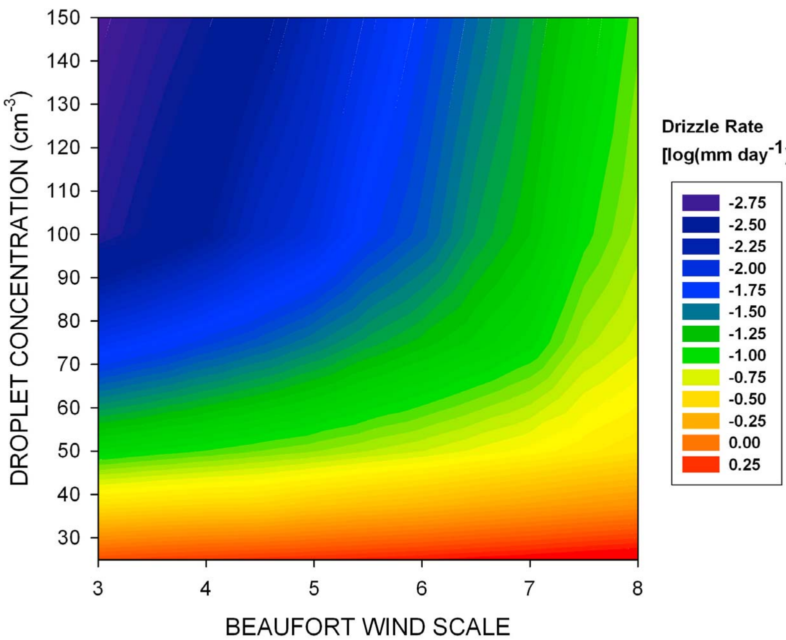

Figure 4. Drizzle rate in log (mm d^{-1}) 1100 m above Cu base predicted by the parcel model as a function of droplet concentration (N_c) and Beaufort Wind Scale (B_w).

size broadening, and the final spectrum at cloud top is changed back to the familiar differential form. The use of the multiple runs in this quasi-stochastic coalescence approach would quickly lead to a very large number of droplet sizes since all the new sizes in each layer are advected to the next higher layer. Here the 1024 new sizes in the lowest layer are reduced by first sorting the drops according to drop size, and then combining adjacent drop sizes while conserving LWC, nuclei content, and drop concentration until a spectrum with 16 sizes is again produced and used in the next higher layer.

[13] As mentioned, condensation growth caused by applying a small value of supersaturation (101.25% RH) is only used in the lowest two layers of the model, which has the effect of growing the sea-salt solution spectra to approximately match the FSSP in-cloud droplet spectra for larger droplets as Figure 1 illustrates. At all higher layers of the model RH = 100% is used, because the appearance of drizzle drops beyond the FSSP spectrum proves to be largely independent of further application of condensation growth given the slow growth rates of the larger drops. The important condensation growth occurs rapidly establishing the measured in-cloud spectra which extend somewhat beyond the classical coalescence threshold of 19 μm radius as Figure 1 shows. The condensation also grows the subcloud sea-salt solution droplet spectra rapidly because the droplets are assumed to be initially at equilibrium at the subsaturated value of -14% RH $\sim$100 m below cloud base. The appearance and growth in the model of drizzle drops is dominated by a process termed accretion where coalescence causes larger drops to collect smaller ones.

3. Results

[14] A visualization of the drizzle rate in mm d^{-1} calculated by the parcel model from the 42 initial spectra and for 1100 m above Cu base is shown by the contour plot in Figure 4 as a function of N_c and B_w. Trends in Figure 4 are as expected, with the largest drizzle rate occurring for the smallest values of N_c and the largest values of B_w. As more N_s are generated for increasing values of B_w the drizzle increases at an accelerating rate; and the reduction of drizzle with increasing N_c is less rapid when the B_w is large. Calculated drizzle rates are also shown over the entire N_c range by the smoothed curves in Figure 5 where the seven values

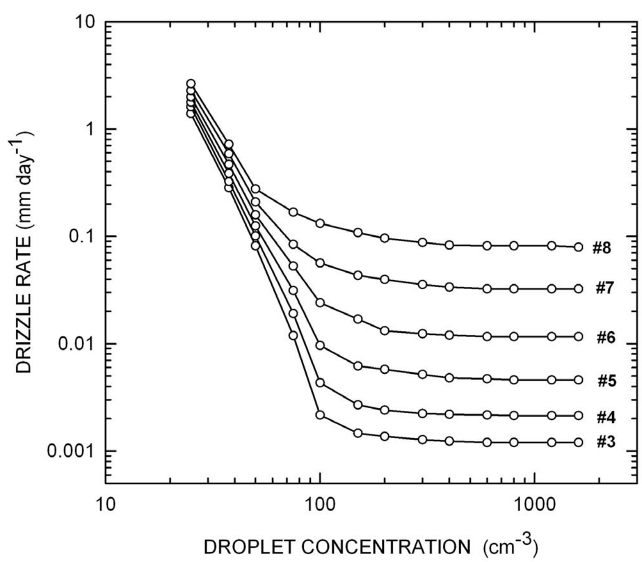

Figure 5. Calculated drizzle rates at 1100 m above Cu base as a function of in-cloud droplet concentration (N_c) and Beaufort Wind Scale (B_w).

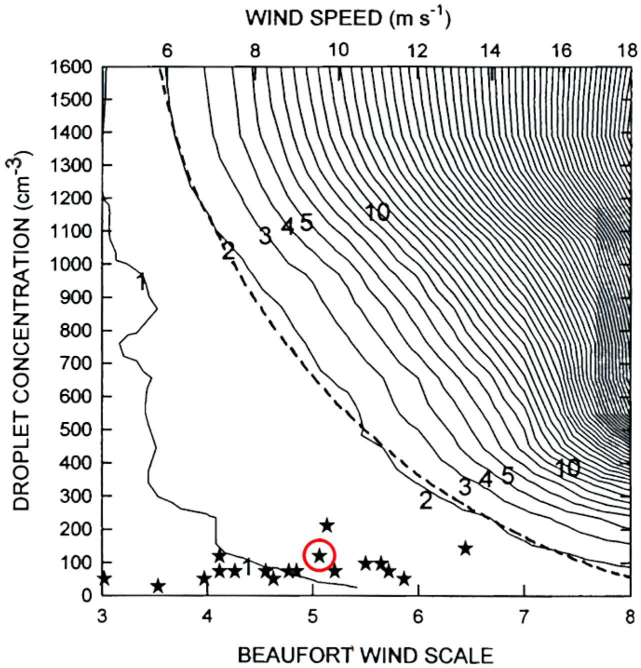

Figure 6. Drizzle enhancement factor (Df, numbers 1 to 10) as a function of Beaufort Wind Scale, wind speed, and in-cloud droplet concentration. Stars indicate the mean conditions for each RICO C-130 flight, and the red circle refers to flight RF12. The dashed line is an analytical fit to the Df curve (see equations (1) and (2)).

of N_c for the original in-cloud baseline spectra have been increased to 13 by interpolating between adjacent N_c values. The calculated drizzle values extend over 3.5 orders of magnitude and show rapid increases of the drizzle rate for N_c less than about 100 cm^{-3}.

[15] The drizzle rate values shown in Figure 5 can be compared to the precipitation rate measured by radar for flight RF12. L. Nuijens (personal communication, 2011) compiled precipitation rates for the "NE radar domain" near Antigua where the C-130 aircraft was located on most of the RICO flights. The radar precipitation rate for RF12 is ~10 times larger than the modeled drizzle rate given the measured mean N_c and U near the ocean's surface. The trade wind Cu on RF12 grew larger later in the day, and some precipitation below cloud base was observed possibly contributing to this difference. Large differences are also found between the modeled drizzle rate and the radar precipitation rate for the other RICO flights (linear correlation coefficient of ~0.62). These large differences may be due to the radar being sensitive to precipitation throughout as well as below the Cu and due to large precipitation drops observed by the radar but not included in the model.

[16] In order to estimate how much N_s in the parcel model affect drizzle for flight RF12 as well as for the chosen baseline in-cloud and subcloud spectra a relative drizzle rate enhancement factor (Df) is evaluated:

$$\mathrm{Df} = \frac{\text{drizzle rate of cloud and sea-salt solution droplets}}{\text{drizzle rate of cloud droplets}},$$

where the numerator is calculated by applying the model to each of the 42 combined spectra, and where the denominator is determined by again running the model with only a contribution from the cloud droplet spectra shown in Figure 2. Figure 6 shows Df as a function of wind speed and N_c, which again suggests that N_s do not affect the drizzle rates for small values of wind speed and low N_c. The mean measured values of N_c and U are also added to Figure 6 for the other RICO flights. This addition requires validation given that Figure 6 is based on the parcel model that is related only to RF12 measurements. However, the pattern of measurements and the Df values in Figure 6 are in keeping with the radar studies of RICO Cu precipitation [*Knight et al.*, 2008; *Reiche and Lasher-Trapp*, 2010; *Lowenstein et al.*, 2010] that also indicate a small effect of N_s on precipitation.

[17] Figure 6 also shows that Df increases with increasing N_c in agreement, at least qualitatively, with findings of *Feingold et al.* [1999] and *Lasher-Trapp et al.* [2008] for Sc, *van den Heever and Cotton* [2007] for large Cu, and *Cheng et al.* [2009] for a limited LES sensitivity study of RICO flight RF12 Cu. *Feingold et al.* [1999] conclude that drizzle production decreases with increasing CCN regardless of the relative impact of N_s that also increases with more CCN. Our results in Figure 5 show instead that drizzle rates at given wind speeds become nearly constant as N_c increases to large values, at least for the range of N_c dealt with here.

[18] The pattern of the Df curves in Figure 6 shows very high values of Df as both wind speed and N_c increase to large values. This reflects the importance of N_s and potentially also of other types of giant particles for efficiently collecting smaller cloud droplets if both small droplets and giant particles are plentiful. This pattern, although noisy for Df ~ 1 and for large Df, can be fit with an analytical expression, because the curves over a limited Df range resemble segments of circles as illustrated by the circle segment dashed line matched to Df = 2 in Figure 6. A third-order polynomial is fit to the Df curves in Figure 6:

$$\mathrm{Df} = 932.2718 - (376.941 \times \mathrm{R}) + \left(51.1108 \times \mathrm{R}^2\right) - \left(2.3193 \times \mathrm{R}^3\right), \quad (1)$$

where R is the radius of each fitted circle segment given by

$$\mathrm{R} = \left\{(\mathrm{B_w} - 10.55)^2 + ([\mathrm{N_c} \times 0.003175] - 6.873)^2\right\}^{1/2}. \quad (2)$$

The ranges of applicability of equation (1), taking into account the noisy Df data and the range of the model calculations, are estimated to be

$$1.5 < \mathrm{Df} < 10,$$
$$3.3 < \mathrm{B_w} < 8,$$
$$100\ \mathrm{cm}^{-3} < \mathrm{N_c} < 1600\ \mathrm{cm}^{-3}.$$

4. Discussion

[19] Assumptions in the present parcel model can generate uncertainties in the predicted drizzle rates. Furthermore, the model results reflect flight RF12 so that application of the results to other small Cu substantially different from the ones found during that flight leads to uncertainty. A source of

quantitative error in the model is the use of only 16 droplet size classes in the modeled spectra. When the number of classes for one model run is increased to 32, a larger drizzle rate is found. A further increase to 64 classes only increases the rate an additional small amount with a total increase of the rate from 16 classes of ∼20%. The model may underestimate the drizzle rate, because the droplet calculations are limited to droplet sizes less than 200 μm radius. More uncertainty results from the obvious lack of dynamics in the model, from the neglect of explicit entrainment, and from inertial effects that are not included in the formulation of the coalescence collection efficiency. Also, the chosen maximum value of the residence time (t′) of the larger drops due to their sedimentation in each model layer is a guess based on the possibility of toroidal motions near Cu cloud top lengthening droplet residence times [*Blyth*, 1993; *Damiani et al.*, 2006]. Further, the use of the mean vertical velocity in the model may be incorrect. The two other parcel models applied to flight RF12 [*Reiche and Lasher-Trapp*, 2010; *Lowenstein et al.*, 2010] both find a drizzle "tail," but differ in certain aspects with each other as well as with the present results. Both use a version of the parcel model of *Cooper et al.* [1997] which has no droplet sedimentation and uses adiabatic LWC in the parcel ascent. *Reiche and Lasher-Trapp* [2010] reduce LWC to 75% of adiabatic and use parameterized initial spectra. As in the present model, they are unable to produce enough drizzle in comparison with radar precipitation estimates, unless they increase the residence time of the droplets in the model by assuming that individual Cu have repeating "pulses" [*Rauber et al.*, 2007] that lengthens this time. Perhaps the lack of droplet sedimentation is a factor causing the insufficient drizzle. The *Lowenstein et al.* [2010] parcel model estimates the subcloud sea-salt solution droplets in a similar way as done here; and they use adiabatic LWC and the maximum measured vertical velocity in their model. They conclude that the modeled and observed drizzle, which show good agreement, are a result of condensation growth of the subcloud and in-cloud droplets over the ∼2000 m height above cloud base, and that coalescence only becomes important above this level. Their conclusion may be a result of using adiabatic LWC which is too large for the RF12 Cu given that measured values, even in the cores of the Cu, can be only about one third of adiabatic. Also their use of the maximum vertical velocity to advect their parcel may be too large. Both effects can enhance supersaturations unrealistically resulting in excessive condensation growth. The present model differs in showing that drizzle growth by coalescence caused by large droplets formed on N_s (accretion process) is already evident a few hundred meters above cloud base.

[20] The LES of RICO Cu by *Stevens and Seifert* [2008] suggests that factors other than N_s affect precipitation. The microphysical conclusions in both this LES and the one by *Cheng et al.* [2009] must depend on suitable subgrid parameterization of microphysics where understanding is still incomplete. We know that grid spacing of the LES is still substantially larger than the measured entrainment scales that were found to be on the order of meters in these Cu [*Gerber et al.*, 2008]. *Cheng et al.* [2009] use horizontal grid spacing of 100 m and vertical spacing of 40 m in their LES for RF12 Cu, which have an average width of only ∼600 m likely causing uncertainty about their conclusion that "susceptibility" of small cloud droplet evaporation in the Cu affects total area cloud coverage as also suggested by *Jiang et al.* [2009].

5. Conclusions

[21] This parcel model sensitivity study for trade wind Cu relating near sea surface wind speed, large sea-salt nuclei (N_s), and in-cloud droplet concentrations (N_c) to drizzle rates near Cu top finds typical trends in agreement with earlier work: drizzle and N_s increase with wind speed, and drizzle decreases with larger N_c. The agreement between the modeled drizzle rates and the precipitation rates measured by radar for the RICO flights is marginal preventing the former from being a reliable predictor of precipitation in the small Cu. A drizzle enhancement factor (Df), which is the modeled ratio of drizzle rate in the Cu with and without the contribution of N_s, predicts that the drizzle rate results for RICO flight RF12 are enhanced by a factor only slightly larger than 1.0 by the presence of N_s. The factor is mostly less than 1.5 for the other RICO flights suggesting that N_s plays a smaller role in generating drizzle near Cu cloud top than N_c and CCN. However, the inclusion of the other flights must be considered speculative without additional validation given that the calculation of the Df field is based only on the microphysics constraints from measurements made during RF12. Although the conclusion that N_s play a smaller role in RICO Cu is supported by the radar measurements of the same Cu. This resulting dependence of Df on N_c and near sea surface wind speed gives a pattern with approximately circular segments that are approximated with an analytical expression.

[22] The study has illustrated that assessing the role of N_s in drizzle and precipitation formation in small Cu using either parcel or LES models can lead to different results. The former can deal with the details of N_s and droplet growth but lacks the realism of growing Cu, while the latter benefits from the inclusion of cloud dynamics but faces difficulties including factors such as entrainment and microphysical evolution.

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G. Frick, Naval Research Laboratory, 4555 Overlook Ave. SW, Code 7228 Bldg. 2, Rm. 246, Washington, DC 20375, USA.

H. Gerber, Gerber Scientific, Inc., 1643 Bentana Way, Reston, VA 20190, USA. (hgerber6@comcast.net)