P2.52 DRIZZLE RATES AND GIANT SEA-SALT NUCLEI IN SMALL CUMULUS

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1. INTRODUCTION

The generation of large sea-salt particles from whitecaps generated by wind over the ocean is well documented (Woodcock, 1953). It is, however, not clear to what degree these large hygroscopic particles act as condensation nuclei that initiate precipitation in small cumulus clouds (Cu). Blyth et al (2003) suggested that in SCMS (Small Cumulus Microphysics Study) cumuli giant and ultra-giant (UGN; sea-salt particles > than 2-um dry radius) affected the appearance of initial precipitation, while Goeke et al (2007) concluded that sea salt had no effect for the same cumuli. Investigations of small trade-wind cumuli during RICO (Rain in Cumulus over the Ocean) likewise found a negligible effect of sea-salt particles on initial precipitation (Colon-Robles et al, 2006; Hudson and Mishra, 2007; Knight et al, 2008). An observational study (Gerber et al, 2008) following the microphysical evolution with height of RICO cumuli found a significant number of large drizzle drops associated with UGN concentrations below cloud base. A simple coalescence parcel model constrained by near cloud-base microphysics was in approximate agreement with the observed “drizzle tail” in the droplet size spectrum near mean cloud top. However, a conclusion could not be reached in this study as to the role of this drizzle in precipitation initiation at cloud base.

The present study expands the results given in Gerber et al (2008) by performing a modeling sensitivity analysis where droplet spectra and sub-cloud sea-salt spectra are varied about measured spectra obtained from RICO flight RF12. Drizzle rates are estimated at 1100 m and ~250 m below cloud top. The goal is to compare these new results to all other RICO flights, and to parameterize the drizzle rate as a function of wind speed over the ocean and incloud droplet concentration.

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2. RICO DROP SPECTRA

Average incloud droplet and subcloud particle spectra for RICO flight RF12 are shown in Fig. 1 for 5 levels above Cu cloud base for the former and about 100 below the base for the latter. The incloud spectrum at each level is an average of 7 spectra measured near the center of 7 Cu. This sub-set of spectra was obtained from NCAR C-130 penetrations through cumuli with actively growing cores and about 250-m below cloud top where the first radar echoes of precipitation have been observed in small Cu (Knight and Miller, 1998). Those choices were assumed to mimic Lagrangian evolution of these Cu.

Figure 1 shows the surprising result that the droplet spectra measured by the FSSP are approximately constant with height. This suggests that for these Cu detrainment, entrainment and activation of new CCN, and coalescence losses roughly balance each other as the Cu grow. The figure also shows that the larger drizzle drops increase in size and concentration with height.

The subcloud spectra are assumed to consist of salt-solution droplets at equilibrium with the ambient RH at that flight level below cloud base. The Giant Nuclei Impactor data consisting of dry particles was compared to Woodcock’s sea-salt particle distribution vs Beaufort Wind Force (wind speed) with the measured wind speed near the ocean’s surface and gave good agreement. Adjustment of this data for the ambient RH produced the good comparison seen for the subcloud spectra in Fig. 1.

3. MODEL SENSITIVITY STUDY

3.1 Sea-salt and Droplet Spectra

Taking advantage of the approximately constant small droplet spectra with height, and of the approximate agreement of the parcel model’s prediction of the drop spectrum at Cu top, a

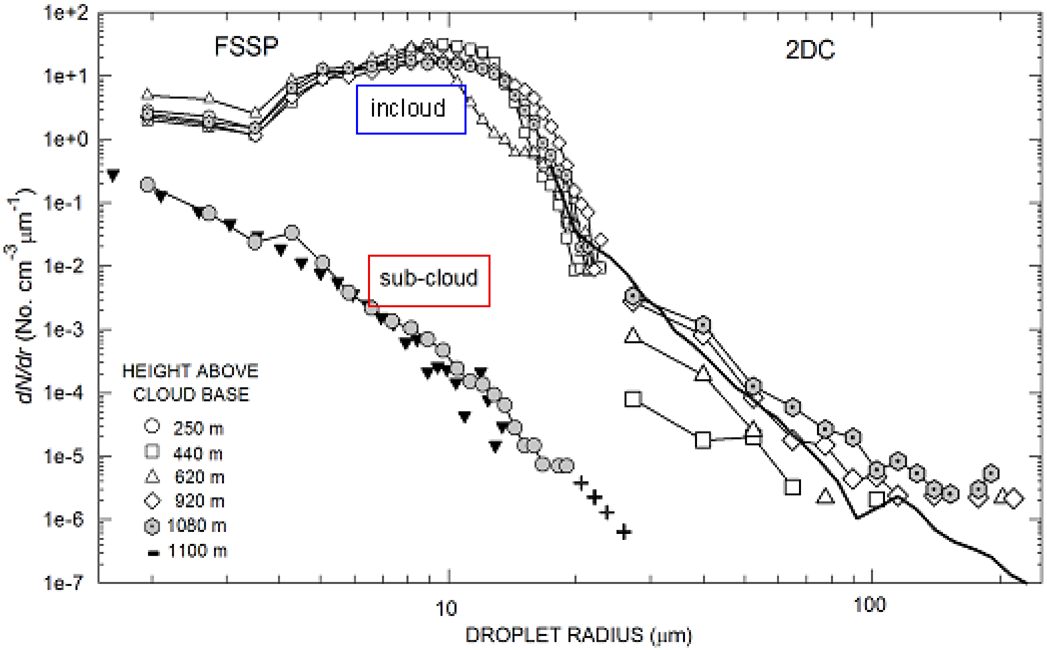

Figure 1 - Incloud droplet and drizzle size spectra measured in trade-wind Cu during RICO flight RF12 using the FSSP and 2DC probes as a function of height above cloud base. Each spectrum is the average of 5 spectra measured for each height. The subcloud spectra are from FSSP measurements and from the NCAR (RAF) Giant Nuclei Impactor. A parcel model estimate of the spectrum at Cu top is shown by the solid curve. (From Gerber et al, 2008 with changes)

sensitivity study using the same parcel model is undertaken by varying the incloud small droplet spectrum, and by varying the wind speed over the ocean which affects the subcloud sea-salt spectrum. The measured incloud spectrum (~100 drops/cm^3) near cloud base is chosen as the baseline spectrum

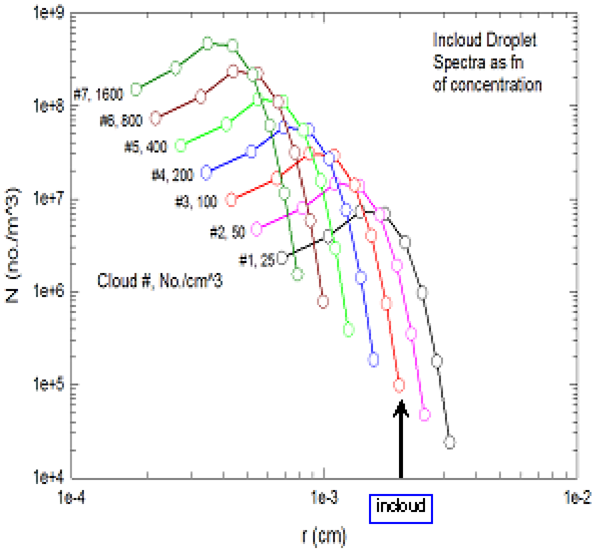

Figure 2 - Droplet spectra chosen for the parcel-model sensitivity test. The red incloud spectrum is the baseline spectrum that corresponds to the incloud spectrum near cloud base shown in Fig. 1.

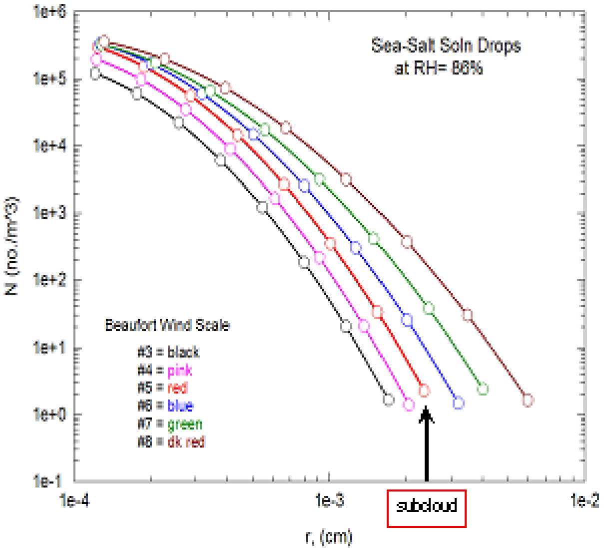

Figure 3 - Droplet radius spectra of sea-salt solution drops at equilibrium at 86% RH as a function of Beaufort Wind Scale over the ocean.

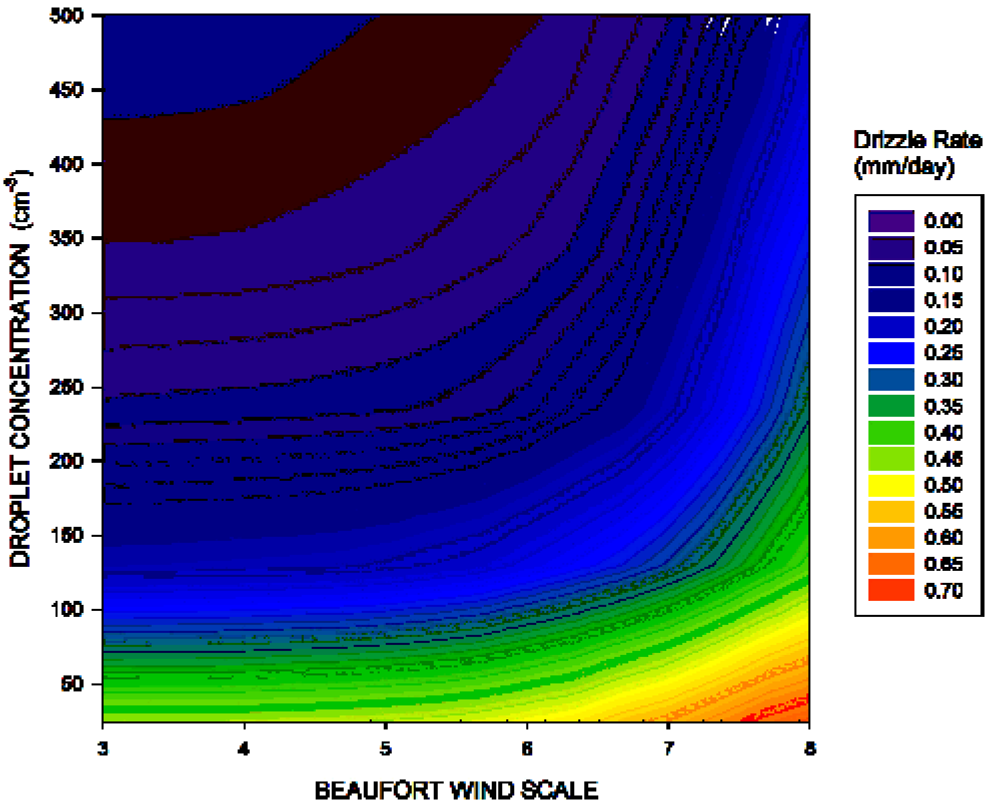

Figure 4 - Drizzle rate in mm/day at 1100 m above cloud base and ~250 m below mean Cu top as a function of cloud droplet concentration and Beaufort Wind Scale (3 to 8 or 5 m/s - 18 m/s wind speed)

about which other initial incloud spectra with other droplet concentrations are varied from 25/cm^3 to 1600/cm^3; see Fig. 2. The geometrical shape of the chosen spectra and their liquid water content (LWC) remain the same.

Figure 3 shows the chosen sea-salt solution droplet spectra as a function of Beaufort Wind Scale. The spectra are based on Woodcock's sea-salt particle measurements vs wind speed near the ocean surface. The red curve in Fig. 3 is the baseline spectrum obtained from the subcloud salt-solution spectrum shown in Fig. 1.

3.2 Parcel Model

The parcel model and its assumptions are described in detail in Gerber et al (2008). A brief summary is given here: The earlier use of this model used only the baseline spectra shown in Figs. 2 and 3, and one Beaufort wind speed consistent with the wind speed measurement for flight RF12. Here the parcel model is applied to 42 spectra each of which are combinations of the spectra shown in Figs. 2 and 3 where each spectrum in Fig. 2 is combined with each spectrum in Fig.3. The vertical domain of the model extends to 1100-m above cloud base and is divided into ten 100-m thick layers.

Condensational and coalescence growth are applied to the 1st layer. To achieve a degree of stochastic behavior the growth calculation is repeated 64 times for the 1st layer using a random distribution in space of the drops in the spectrum each time resulting in a total of 4096 new drop sizes. The coalescence scheme uses the classical approach with collision efficiencies as compiled from sources listed by Cooper (1997 et al). The measured mean vertical velocity transfers the drops to the next higher level where the growth calculation is repeated, but with a reduction in the number of new drop sizes. The reduction is accomplished by first sorting the drops according to drop size, and then combining adjacent drop sizes while conserving LWC, nuclei content, and drop concentration. This procedure results in a drop

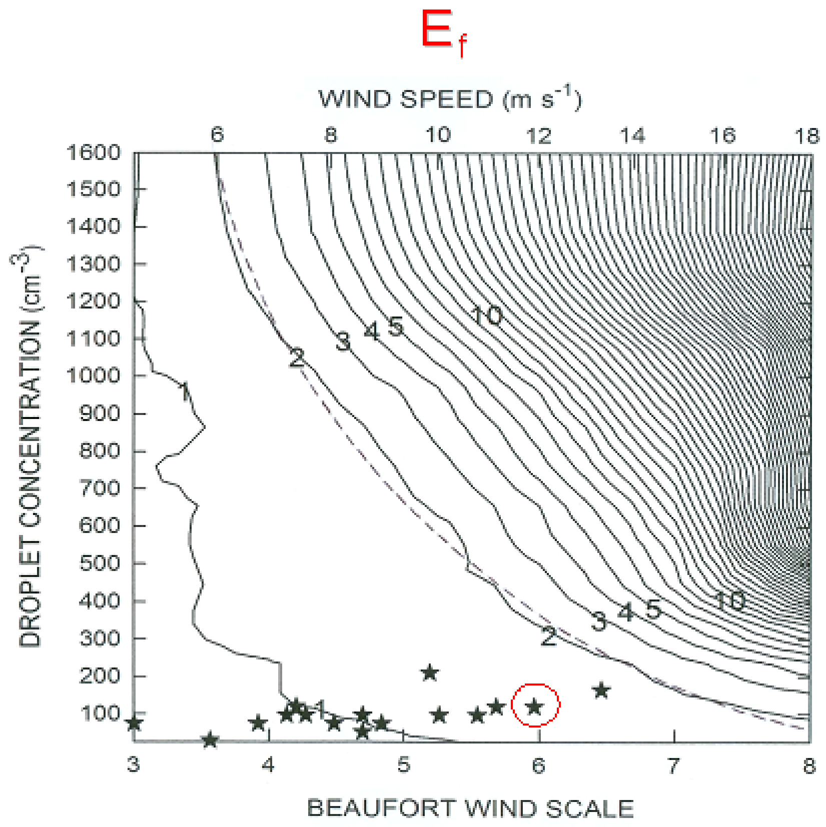

Figure 5 -The numerical (1 - 10) drizzle rate enhancement factor E_f as a function of cloud droplet concentration and wind speed over the ocean as predicted by the parcel model. The stars indicate the measured mean droplet concentration and wind speeds for each of the RICO C-130 flights; the red circled star is for flight RF12. The dashed curve is a segment of a circle fit to a E_f curves and used for parameterization.

spectrum again with 16 sizes which are used for the next higher level. While this procedure makes these calculations practical, it is expected that the largest drops generated by this quasi-stochastic procedure may be smaller than the largest drops using a true stochastic approach.

3.3 Results

The drizzle rate (mm/day) 1100-m above cloud base for the trade-wind Cu predicted by the parcel model as a function of Beaufort Wind Scale over the ocean and droplet concentration is shown in Fig. 4. As expected at low droplet concentration the drizzle rate is significant. The effect of the sea-salt UGN on the drizzle rate is only apparent at Beaufort Wind Scales larger than about 5, with a strong enhancement at the largest values of the Wind Scale.

The parcel model was run for the spectra combining sea-salt solution and cloud drops spectra as shown in Fig. 4, and was run again with only the cloud droplet spectra. This permitted the definition of a “drizzle rate enhancement factor” for the 1100-m cloud level given by the ratio

$$E_f = \frac{\text{cloud-drop and salt-solution-drop drizzle rate}}{\text{cloud-drop drizzle rate}}$$

which is given by the curves in Fig. 5.

As shown, the value of E_f is nil at low wind speed but rapidly increases for increasing wind speed as well as for increasing droplet concentration. The stars represent mean measured values of droplet concentration and wind speed for each of the RICO flights through the trade-wind Cu, and suggest that the sea-salt UGN generated on

PARAMETERIZATION

$$E_f = 932.2718 - 376.9414R + 51.1108R^2 - 2.3193R^3$$

$$R = \{(B - 10.55)^2 + ([N \times .003175] - 6.873)^2\}^{1/2}$$

B = Beaufort Wind Scale
N = No. of Drops/cm^3

APPLICABILITY

Range of E_f: $\sim 1.5 < E_f < \sim 10$
Range of B: $3.5 < B < 8$
Range of N: $100/cc < N < 1600/cc$

Figure 6 - Parameterization of the E_f curves in Fig. 5 with a 3d order polynomial dependent on the Beaufort Wind Scale and cloud droplet concentration. The estimated range of applicability of the parameterization is shown.

RICO flights had a minimal effect on enhancing the drizzle rate 100-m above cloud base. This result resembles the findings of Colon-Robles et al (2006), Hudson and Mishra (2007), and Knight et al (2008) who concluded that UGN did not affect precipitation in the RICO Cu.

The E_f curves in Fig. 5 resemble approximately segments of circles which permit parameterization of E_f as a function of droplet concentration and Beaufort Wind Scale as shown in Fig. 6.

4. CONCLUSIONS

We have demonstrated the sensitivity of the drizzle rate 1100-m above cloud base to the near surface wind speed over the ocean and to the incloud droplet concentration by applying a simple parcel model to sub-cloud sea-salt solution spectra and to cloud-droplet spectra constrained by measured spectra in growing RICO trade-wind Cu. The wind speed is converted to the concentration of ultra-giant sea-salt nuclei (UGN) using Woodcock's (1953) measurements so that the modeling results reflect the sensitivity of the drizzle rate to the concentration and size of UGN.

We found that the drizzle rate increases sharply with higher wind speeds, but the increase is minimal for wind speeds less than ~ 8 m/s. At a given wind speed the rate also increases for increasing droplet concentration suggesting that accretion of small cloud by larger drops formed on the salt nuclei cause this increase.

A drizzle rate enhancement factor E_f based on the model results in Fig. 5 is defined by rationing the drizzle rate produced at the 1100-m cloud level by the sea-salt-nuclei and cloud-droplet combination with drizzle produced only by the cloud droplets. This factor predicts that UGN do not enhance drizzle to a significant degree during the RICO flights given their measured wind speeds and droplet concentrations; although, for several of the flights with the highest wind speed some drizzle enhancement is suggested. The lack of a significant UGN effect in the RICO trade-wind Cu is consistent with work published earlier. Here we show that the UGN effect is not a yes or no process, but a continuous effect that goes from a negligible influence to a very large influence. The results suggest that the influence is small for clean maritime regions unless high wind speeds exist, but may be significant when UGN are in the presence of a larger number small droplets in a polluted air mass such as UGN blowing onshore or polluted air blowing off continents.

The modeling was done with a simple parcel model and rather coarsely resolved droplet size spectra leading to the question: Are these modeling results reliable? To test the resolution issue some additional model runs were made. First the use of 64 repeat calculations of the spectra for each level was tested by increasing the repeats to 256 and also to 1024; minimal changes were found in model's drizzle-rate output. Second, the resolution of each model spectra was changed from 16 sizes to 32 sizes and also to 64 sizes. The drizzle-rates increased by about 20% for the 64-size resolution suggesting that the quasi-stochastic coalescence approach used here has some dependence on the size resolution of the model spectra. The largest-sized and lowest-concentration drops found for the 64-size resolution only slightly exceeded the largest drops found for the 16-size resolution modeling runs.

Is is tempting to assume that a yet to be chosen threshold E_f value at 1100-m above cloud base indicates the initiation of precipitation at cloud base. That may be a possibility for these small trade-wind Cu; however, other factors, such as the size and depth of Cu, must also be considered.

5. ACKNOWLEDGMENT

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