9.2 HOW ENTRAINMENT AND MIXING SCENARIOS AFFECT DROPLET SPECTRA IN CUMULUS CLOUDS

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1. INTRODUCTION

The EMPM (Explicit Mixing Parcel Model) predicts the evolving in-cloud variability due to entrainment and finite-rate turbulent mixing using a 1D representation of a rising cloudy parcel. The 1D formulation allows the model to resolve fine-scale variability down to the smallest turbulent scales (about 1 mm). The EMPM calculates the growth of thousands of individual cloud droplets based on each droplet's local environment.

We used the EMPM to investigate the impact on droplet spectra evolution in cumulus clouds of the following aspects of entrainment and mixing:

Parcel trajectory: isobaric versus ascending

Entrained CCN concentration: zero versus cloud base concentration

We were motivated by aircraft measurements in cumulus clouds of cloud droplet number concentration (N) and mean volume radius (r_v), averaged over 10-m intervals, normalized by their adiabatic values, and plotted on a diagram with coordinates N/N_a and r_v^3/r_{va}^3. The product of the coordinates is the LWC normalized by its adiabatic value. Such a diagram (from Burnet and Brenguier 2006) for cloud traverses about 1500 m above cloud base for a case during SCMS (Small Cumulus Microphysics Study) is shown in Fig. 1. The challenge is to explain the observed distributions.

Burnet and Brenguier proposed that isobaric mixing, combined with buoyancy sorting, can explain the the observed distributions of N and r_v in cumulus clouds. However, we propose that additional processes (ascent of entrained air and entrainment of CCN) are likely to be important.

Entrainment followed by *isobaric* mixing reduces the droplet number concentration by dilution ("weeding") and the LWC and mean volume radius by droplet evaporation. As long as no droplets completely evaporate, the entrained air fraction determines N, and mixtures of entrained and adiabatic (undiluted cloud-base) air define the so-called "homogeneous" mixing line on the N-r_v^3 diagram. For entrainment into cumulus clouds, the mixing line depends primarily on the relative humidity (RH) of the entrained air (at a given level). Burnet and Brenguier used a simple mixing model to demonstrate that isobaric entrainment and mixing events can produce (N, r_v^3) pairs anywhere on the diagram between the "homogeneous" mixing line and $N = 0$.

If a cloudy parcel *ascends* during entrainment and mixing, the RH of the entrained air will increase, thereby shifting the mixing line upwards and increasing the LWC ("feeding"). If N remains constant, r_v will also increase. Due to ascent and adiabatic cooling, newly entrained air may become supersaturated and some of the entrained CCN may be activated, thereby increasing N ("seeding") but decreasing r_v (for constant LWC).

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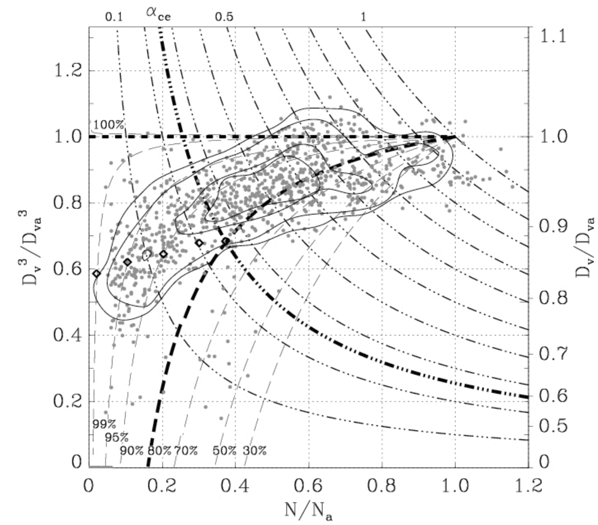

Figure 1: N-V diagram from SCMS for 10 August 1995. Plotted are 909 cloud samples, each of 10-m length. From Burnet and Brenguier (2006).

To explore the range of potential N-r_v^3 distributions that might be encountered in cumulus clouds and to relate them to cloud processes, we applied the EMPM to a variety of realistic entrainment and mixing scenarios. The consequences of parcel trajectory (isobaric versus ascending), and entrained CCN concentration (zero versus cloud base concentration) on N-r_v^3 distributions in entraining, non-precipitating cumulus clouds as predicted by the EMPM are presented in Section 2. Conclusions follow in Section 3.

2. ENTRAINMENT AND MIXING IN THE EMPM

2.1 *Isobaric mixing*

Figure 2 shows the stages involved in mixing after an entrainment event. The first stage (panel 2) involves breakdown of the entrained blob into smaller segments, with little droplet evaporation. This reduces N locally, but does not decrease r_v.

During the second stage (panels 3 and 4), droplets evaporate until local saturation is achieved. This reduces the local r_v, but does not change the local N unless some droplets totally evaporate. In this case, no droplets totally

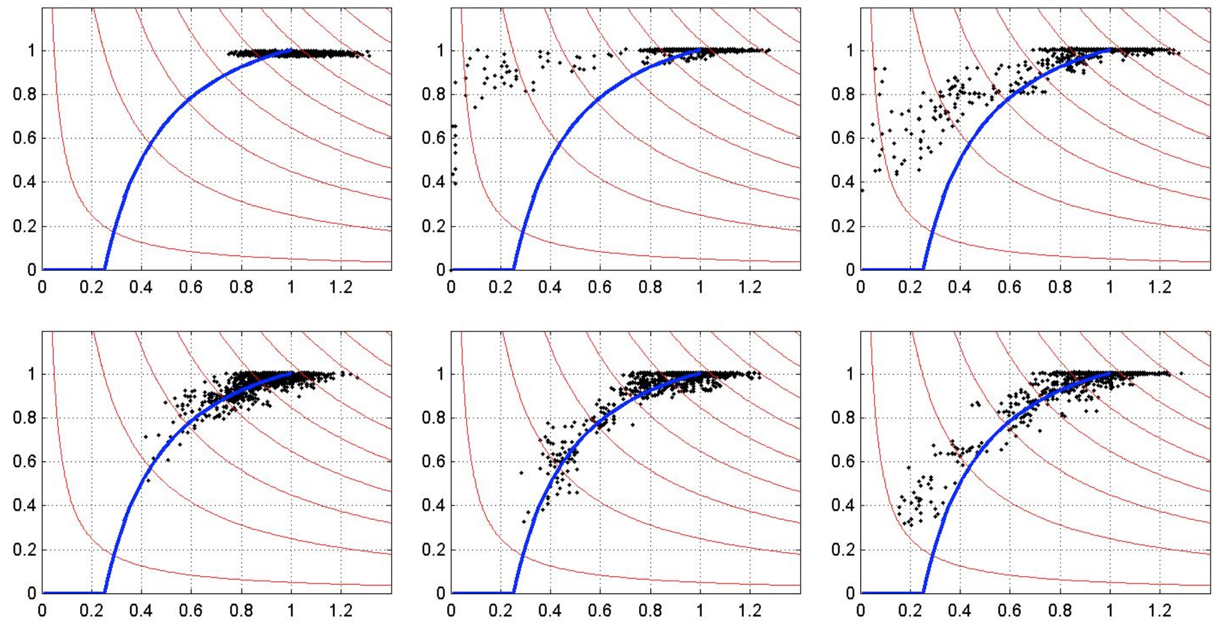

Figure 2: N-V diagram for isobaric mixing in the EMPM after an entrainment event. Each point is a 1-m average. Plotted in each panel are points from 11 "traverses" of the 80-m EMPM domain during an 8.25-s interval. Time increases clockwise from the upper left panel.

evaporate. The blue line indicates all possible values of (N,r_v) in *saturated* mixtures in which no droplets have totally evaporated. Therefore, the N-r_v distribution moves downwards towards the blue line during the second stage.

During the third stage (panels 5 and 6), the resulting saturated parcels mix. Because the blue line is also a mixing line for saturated parcels, the N-r_v distribution converges towards its domain average during this stage.

Figure 3 presents the distributions of the domain averages of two EMPM simulations of isobaric mixing in a 20-m domain with 7 sequential entrainment events. In this case, the domain averages are completey determined by the entrained air properties (entrainment fraction and RH), and indicate nothing about the mixing process. Note that *entrained CCN have no impact when the mixing is isobaric.*

2.2 *Ascent with and without entrained CCN*

The two plots in Fig. 4 show the dramatic impact of entrained CCN in an *ascending* parcel (80-m domain) with sequential entrainment events. Without entrained CCN (left panel), r_v^3 grows to 150 percent of adiabatic at the highest level (1500 m above cloud base), while N decreases to 25 percent of adiabatic ("weed and feed"). When CCN are entrained at cloud base concentrations (right panel), r_v^3 decreases to about 40 percent of adiabatic, while N only slightly decreases, to about 90 percent of adiabatic ("weed, seed, and feed").

Figure 5 shows the time series of all 10-m averages for an EMPM simulation in a 200-m domain without entrained CCN. Compared to the domain-averaged results, the 10-m averages are much more variable (and realistic) because the entrained air fraction in each 10-m segment is determined by the EMPM's stochastic mixing process, rather than being specified. As a result, the 10-m averages from the 200-m domain results can be directly compared to aircraft measurements, such as those shown in Fig. 1.

Figure 6 shows the time series of all 10-m averages for an EMPM simulation in an 80-m domain with entrained CCN at one half of cloud base concentrations, while Fig. 7 shows the same for an EMPM simulation with entrained CCN at cloud base concentrations.

3. CONCLUSIONS

These (and other) comparisons between EMPM results and observations indicate that without entrained CCN, r_v is too large and N is too small, and suggest that distributions of N and r_v similar to those observed can be produced in an ascending parcel by entraining air with intermediate CCN concentrations.

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REFERENCES

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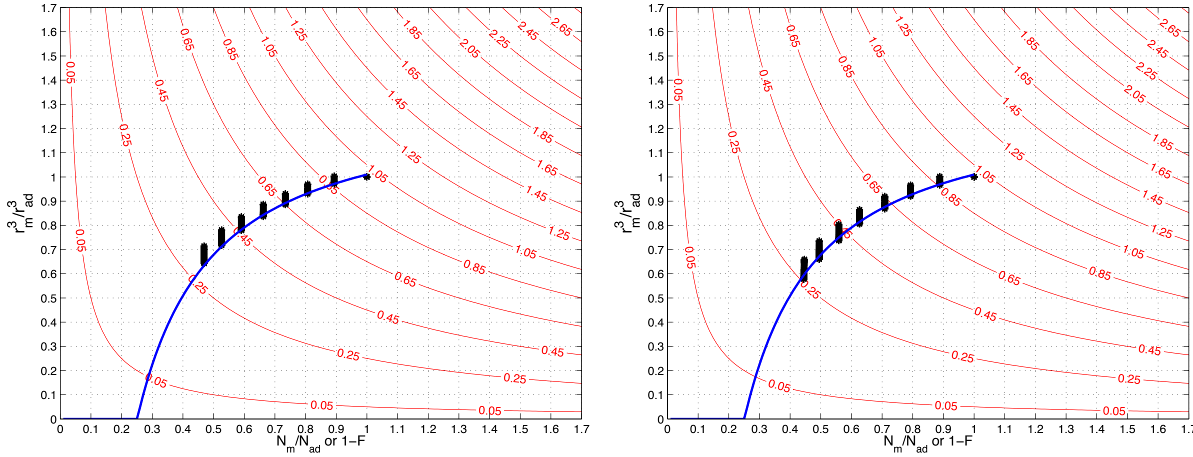

Figure 3: Domain averages for isobaric mixing in the EMPM (20-m domain) after 7 sequential entrainment events. Left: No entrained CCN. Right: with entrained CCN.

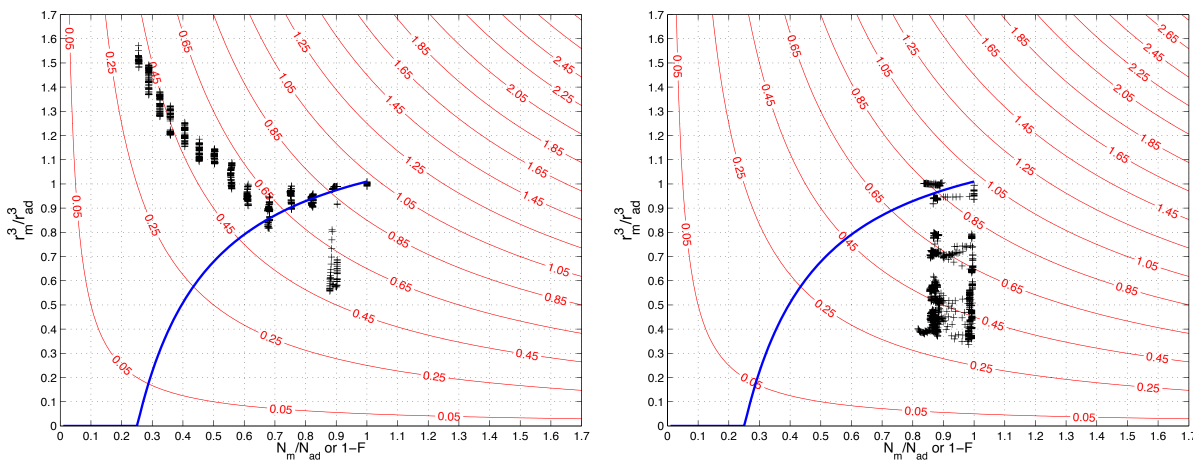

Figure 4: Like Fig. 3 except for ascent in an 80-m EMPM domain.

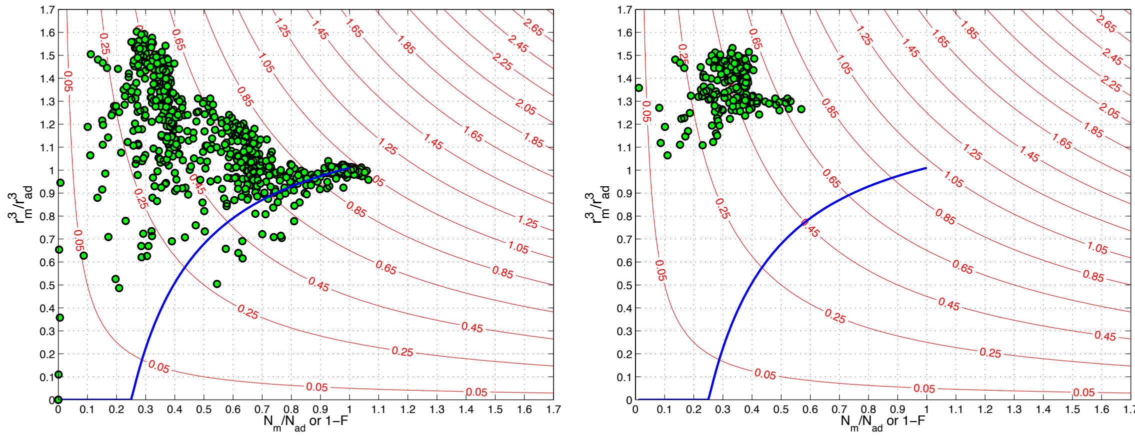

Figure 5: 10-m averages for an EMPM simulation in a 200-m ascending domain without entrained CCN. Left: All values. Right: Values for a short time interval, similar to what would be sampled by an aircraft traverse.

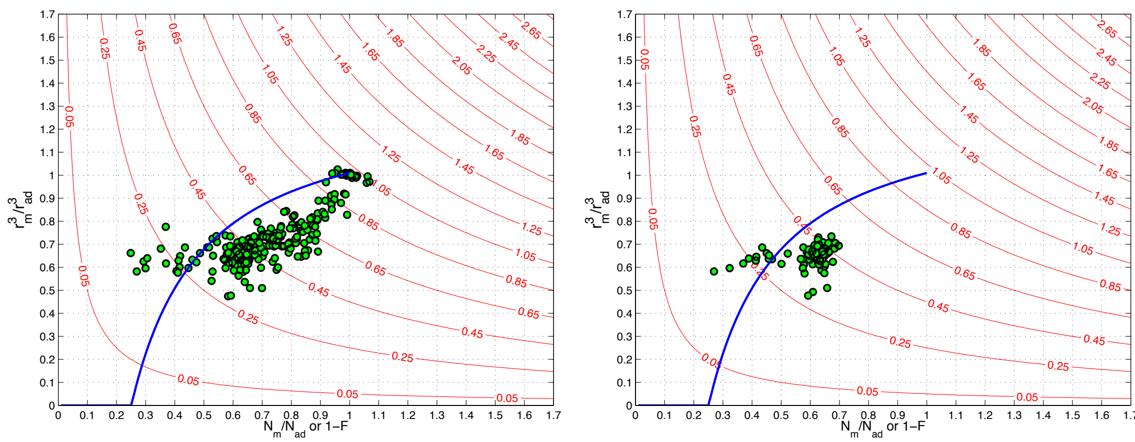

Figure 6: Like Fig. 5 but for entrained CCN at one half of cloud base concentrations.

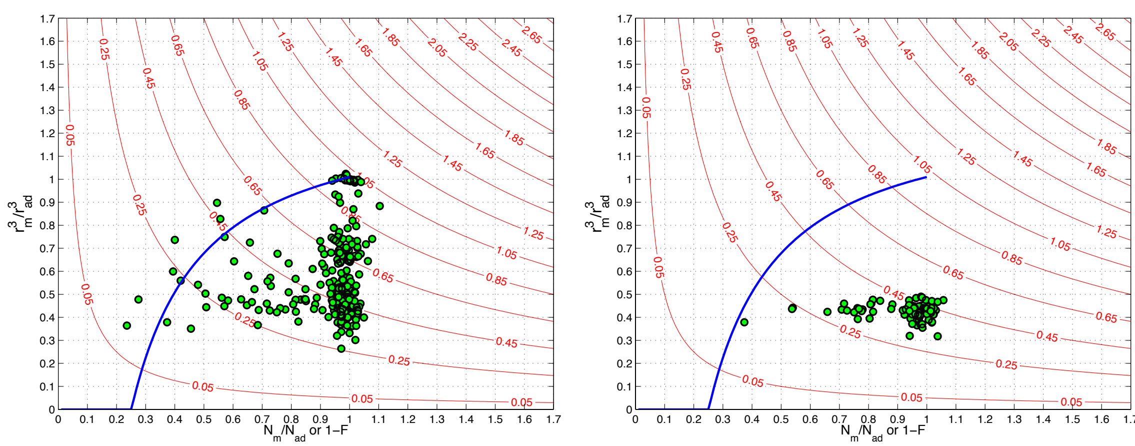

Figure 7: Like Fig. 5 but for entrained CCN at cloud base concentrations.