P1.36 DRIZZLE FORMATION IN MARINE STRATOCUMULUS CLOUD - EXPERIMENTAL AND MODELING STUDIES

Piotr Rasinski * and Hanna Pawlowska
Institute of Geophysics, Warsaw University, Poland
Wojciech W. Grabowski
NCAR, Boulder, CO, USA

1. INTRODUCTION

This paper describes a study of microphysical processes in drizzling marine stratocumulus using aircraft observations and a simple cloud model. The overall goal is to further the understanding of precipitation formation processes that influence the indirect effects of atmospheric aerosols on climate. Drizzle formation in stratocumulus (Scu) depends both on macrophysical cloud properties (e.g., the cloud depth) and on cloud microphysics (i.e., cloud droplet number concentration, CDNC). This is because drizzle is typically observed in Scu when the maximum mean volume diameter of cloud droplets reaches approximately 20 μm (e.g., Pawlowska and Brenguier, 2000). This critical size can be obtained either when Scu is sufficiently deep for a given CDNC, or when CDNC is sufficiently low for a given cloud depth. In cloud observations, these macro- and microphysical factors are convoluted because observed clouds have different depths and different CDNCs.

Data presented in this paper are in-situ airborne measurements from the Second Aerosol Characterization Experiment (ACE2) and the Second Dynamics and Chemistry of Marine Stratocumulus Experiment (DYCOMS-II). This large data set provides good opportunity to study drizzle and cloud processes in cloud-topped marine boundary layer. As anticipated, the observed amount of drizzle is positively correlated with the stratocumulus depth and negatively correlated with CDNC. To investigate the non-linearity of drizzle formation and to separate the impact of the CDNC from the cloud depth effect, a simple two-dimensional cloud model with prescribed flow pattern and detailed microphysics was developed and used in a series of idealized simulations. This study continues research on drizzle formation based on ACE2 observations documented in Pawlowska and Brenguier (2003).

2. AIRBORNE DATA SET AND PROCESSING

Airborne measurements were collected by Meteo-France M-IV (Merlin) aircraft during ACE2 and by NCAR C-130 (Hercules) aircraft during DYCOMS-II. ACE2 was held from 15 June to 23 July 1997 in the sub-tropical eastern Atlantic, in the vicinity of the Canary Islands. CLOUDYCOLUMN part of this experiment addressed changes of cloud properties resulting from changes

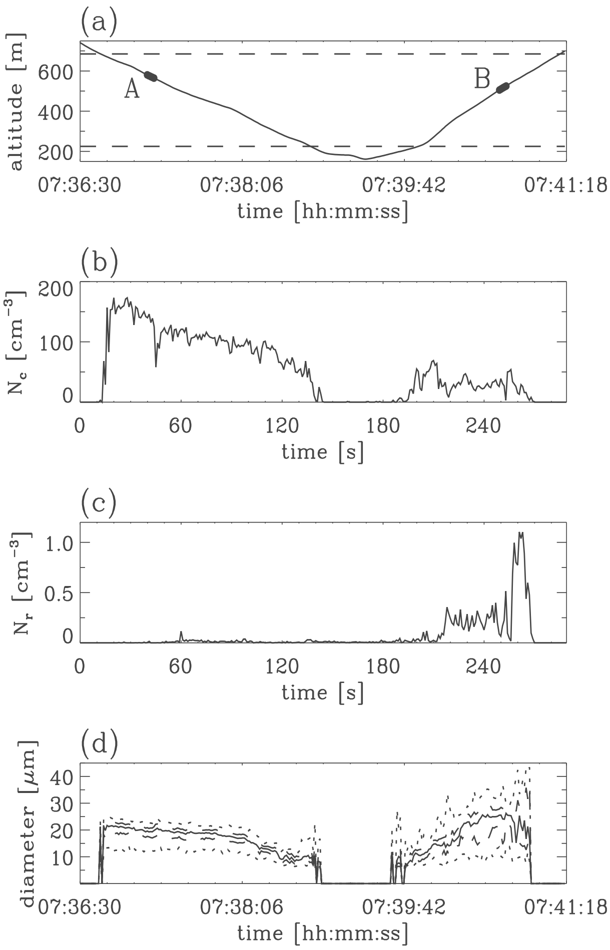


Fig. 1: Example of 1 Hz data from DYCOMS-II on the 20 July 2001. The four panels show: (a) aircraft track; (b) concentration of cloud droplets measured by the Fast-FSSP (N_c); (c) concentration of drizzle drops measured by OAP-260X (N_r); (d) schematic representation of cloud droplet spectrum using percentiles. See text for details.

*Corresponding author address: Piotr Rasinski, Institute of Geophysics, Warsaw University, ul. Pasteura 7, 02-093 Warszawa, Poland; e-mail: rasinski@igf.fuw.edu.pl

in the properties of aerosols and their loading in the boundary layer (Brenguier et al., 2000). DYCOMS-II took place in July 2001 in the eastern subtropical Pacific, a few hundred nautical miles to the west and south-west of San Diego, California. One of the goals of DYCOMS-II was to better understand the processes that control formation and evolution of drizzle (Stevens et al., 2003). Both data sets are particularly suited for the characterization of physical parameters that are representative for scales resolved by general circulation models (GCMs) because the aircrafts tracks comprise either 60 km long squares (for ACE2) or circles of diameter of 60 km (for DYCOMS-II). The cloud droplet spectra were measured with the Fast Forward Scattering Spectrometer Probe (Fast-FSSP, Brenguier et al., 1998). The drizzle drop spectra were sampled with two versions of the One-dimensional Array Probe (OAP; OAP-200Y during ACE2 and OAP-260X during DYCOMS-II). Fast-FSSP samples cloud droplets; it covers diameter range of 5 - 44 μm with 256 classes. The OAPs cover the range of 15 - 645 μm with 10 μm bin width and thus sample drizzle drops. First three classes of the OAPs measurements were omitted due to low accuracy (Korolev et al., 1998).

Evaluation of macro- and microphysical parameters are based on the procedures described by Pawlowska and Brenguier (2003). As discussed above, the cloud depth and CDNC are the two crucial parameters. The data have been processed with 1 Hz frequency resolution that corresponds to about 100 m spatial averages.

3. MICROPHYSICAL CLOUD STRUCTURE

Figure 1 illustrates microphysical characteristics observed during the flight hc0106 on July 20 in DYCOMS-II. A small fraction of the flight is shown, only about 5 min in duration (from 07:36:30 to 07:41:18 UTC), with the aircraft descending and later ascending through the cloud layer. Fig. 1a shows the aircraft height within the cloud layer, with dashed lines marking the cloud base (estimated at 220 m) and cloud top (at about 685 m). The first part of the track - around point A - shows light drizzle, whereas the second one, around B, shows heavy drizzle. CDNC is 103 cm^{-3} near A, and 32 cm^{-3} near B. Drizzle concentration near B reaches 1.2 cm^{-3} (Fig. 1c). Fig. 1d shows a time series of droplet spectrum represented by 5-th and 95-th percentiles (dotted line), 25-th and 75-th percentiles (dashed line) and 50-th percentile (solid line). Presence of drizzle is accompanied by lower concentration of cloud droplets, bigger droplet sizes, and wider spectrum. Difference in CDNC between cloud segments near A and B is striking. As the difference in the aerosol characteristics is an unlikely explanation of the difference in CDNC, the central issue is whether the small CDNC in the second part of the track is the *cause* or the *effect* of drizzle formation. An answer to this question will be suggested in the section 5.

The classical theory of drizzle and rain formation in warm (ice-free) clouds involves three stages. First, cloud condensation nuclei (CCN) are activated near the cloud base and small cloud droplets form. Second, droplets grow by vapor diffusion during further ascent of the air parcel. Since the droplet growth rate is inversely proportional to the droplet size, the small droplets grow faster than the big ones and the droplet spectrum becomes narrower with altitude. However, measurements in convective clouds have revealed that cloud droplet spectra are often broader than predicted by such a simple model (Chaumat and Brenguier, 2001). This is probably due to a combination of various effects, such as cloud turbulence (e.g., Jonas, 1996), giant CCN (e.g., Feingold 1999) and entrainment-mixing processes (e.g., Burnet and Brenguier 2006). The third stage involves collision between cloud particles and their coalescence, referred to as collision-coalescence. Droplets with diameter smaller than 12 μm have a negligible probability of collision-coalescence. Above this size, the probability increases sharply.

The drizzle rate (R) is a common variable used to characterize drizzle intensity. R in stratocumulus is usually expressed in mm per day and is defined as (e.g., Pruppacher and Klett 1997):

$$R = 6\pi\rho_w \sum_{i=1}^{nb} D_i^3\, n_i v_i \quad , \tag{1}$$

where ρ_w is the water density; nb is the number of bins applied to represent the size distribution; n_i is the number of droplets with size D_i per unit volume of air; and D_i and v_i are droplet diameter and terminal velocity of droplet in i-th bin, respectively.

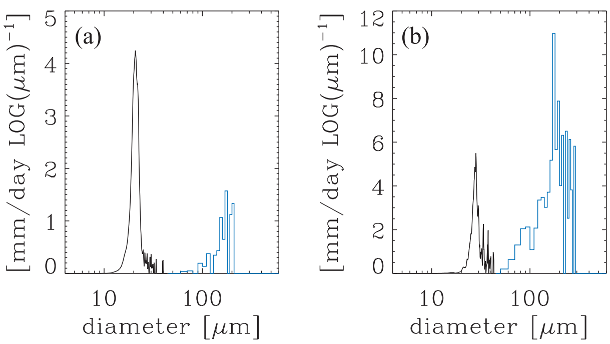


Fig. 2: Cloud droplets (black line) and drizzle drops (blue line) precipitation rate R near (a) A and (b) B in Fig. 1

Figure 2a shows precipitation rate R for cloud droplets and drizzle drops for light drizzle near A, where the mean drizzle rate peaks at 0.2 mm/day. The right panel (Fig. 2b) shows precipitation near B with heavy drizzle (the mean drizzle rate is around 2.3 mm/day). Note that the vertical scale is different in both panels.

4. MODEL DESCRIPTION AND VALIDATION

A simple cloud model developed for this study applies a two-dimensional (x-z) prescribed time-invariant flow pattern, mimicking a single large eddy within the stratocumulus-topped boundary layer. The shape and magnitude of prescribed velocity field (the vertical velocity is illustrated on Fig. 3) is based on airborne measurements.

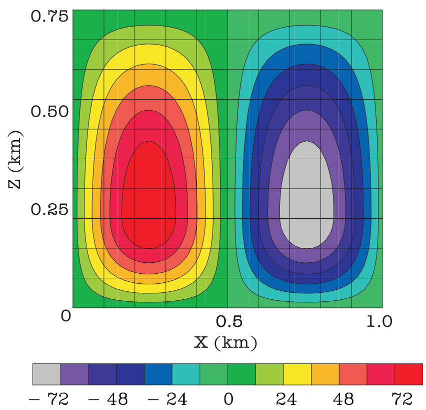


Fig. 3: Vertical velocity (in cm/s) in the kinematic framework.

The model solves equations describing advective transport of the water vapor, temperature, and condensed water, as well as gravitational sedimentation of cloud droplets and drizzle drops. In the steady-state, the model is thought to mimic drizzling stratocumulus. The model domain is 1000 m wide and its depth varies depending on the assumed cloud depth, with the model bottom and top boundaries corresponding to the sea surface and the cloud top, respectively. The horizontal/vertical grid length is 20/15 m. The time step is 2 s in the advection, sedimentation, and coalescence schemes, sub-stepped for condensational growth (time step of 0.25 s).

Microphysical processes are represented explicitly using detailed (bin) microphysics. The use of cloud droplet spectra divided into bins allows including all major microphysical processes, such as droplet nucleation, growth by condensation, and collision-coalescence. Collision-coalescence process is treated as a stochastic process with a numerical solution obtained by a mass conserved flux method (Bott, 1998). The grid in diameter space is linear for cloud droplets (to minimize the numerical dispersion during condensational growth) and exponential for larger drops (up to diameter of 884 μm). This range is covered with 70 bins. The steady-state is typically reached after 2-3 hours of the simulation time.

Ensemble of 6 simulations were performed for each CDNC and cloud depth to account for thermodynamical variability of the cloud and numerical sensitivity of the model. Each ensemble member uses slightly different initial conditions, modified pattern and magnitude of the vertical velocity, and different formulation of the collision kernel in cloud microphysics. The magnitude of vertical velocity was increased (decreased) by 20 % with reduction (addition) of the CCN concentration to maintain the same CDNC for all ensemble members simulations. Long (1974) polynomial approximation for the hydrodynamical kernel is used for all ensemble members except one, where the kernel based on Hall (1980) collision efficiencies is applied.

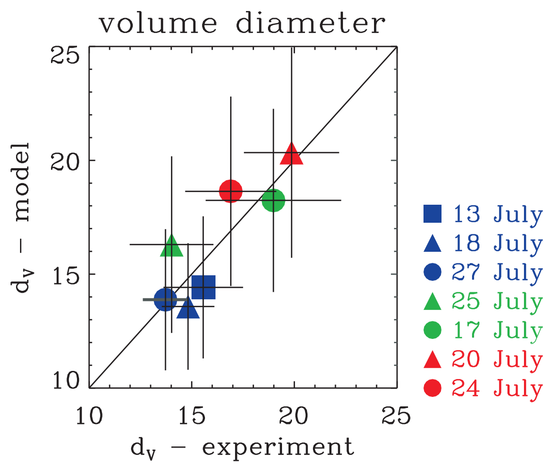


Fig. 4: Comparison between average observed and simulated mean volume diameter of cloud droplets based on DYCOMS-II data.

As a first step, the model was validated against observational data from DYCOMS-II. Mixing ratios and concentrations of cloud droplets and drizzle drops were compared to the experimental data. Fig. 4 illustrates the comparison between the mean volume diameter of cloud droplets calculated by the model (averages over the entire computational domain) and obtained from airborne measurements (averages over the entire flight).

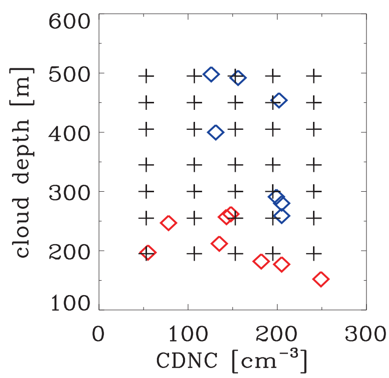


Fig. 5: Set of model simulations, marked by black crosses and airborne measurements as diamonds: red for ACE2 and blue for DYCOMS-II.

Colors demonstrate classification of the fights into three major categories: blue - flights without or with very little drizzle, green - flights with at most light drizzle, and red - flights with heavy drizzle. Black lines represent one standard deviation of the observational data and one standard deviation of the ensemble of model simulations. The figure shows that the simple model captures the observed cloud microphysical variability.

5. EXAMPLE OF MODEL RESULTS

To separate the dependence of drizzle formation on CDNC and on the cloud depth, a series of model simulations were performed with CDNC and cloud depth varied separately as illustrated in Fig. 5.

For illustration, the steady-state fields of the droplet and drizzle number concentrations and mixing ratios are shown in the four panels of Fig. 6 for one of the simulations.

The figure shows the following features of the simulated cloud: nucleation of cloud droplets in the updraft near the cloud base; depletion of cloud droplet number concentration due to the development of drizzle; high drizzle mixing ratio and low drizzle concentration in the updraft near the cloud base; high drizzle concentrations and small mixing ratios in the descending branch of the circulation. This is the case of heavy drizzle due to relatively deep cloud and low CDNC.

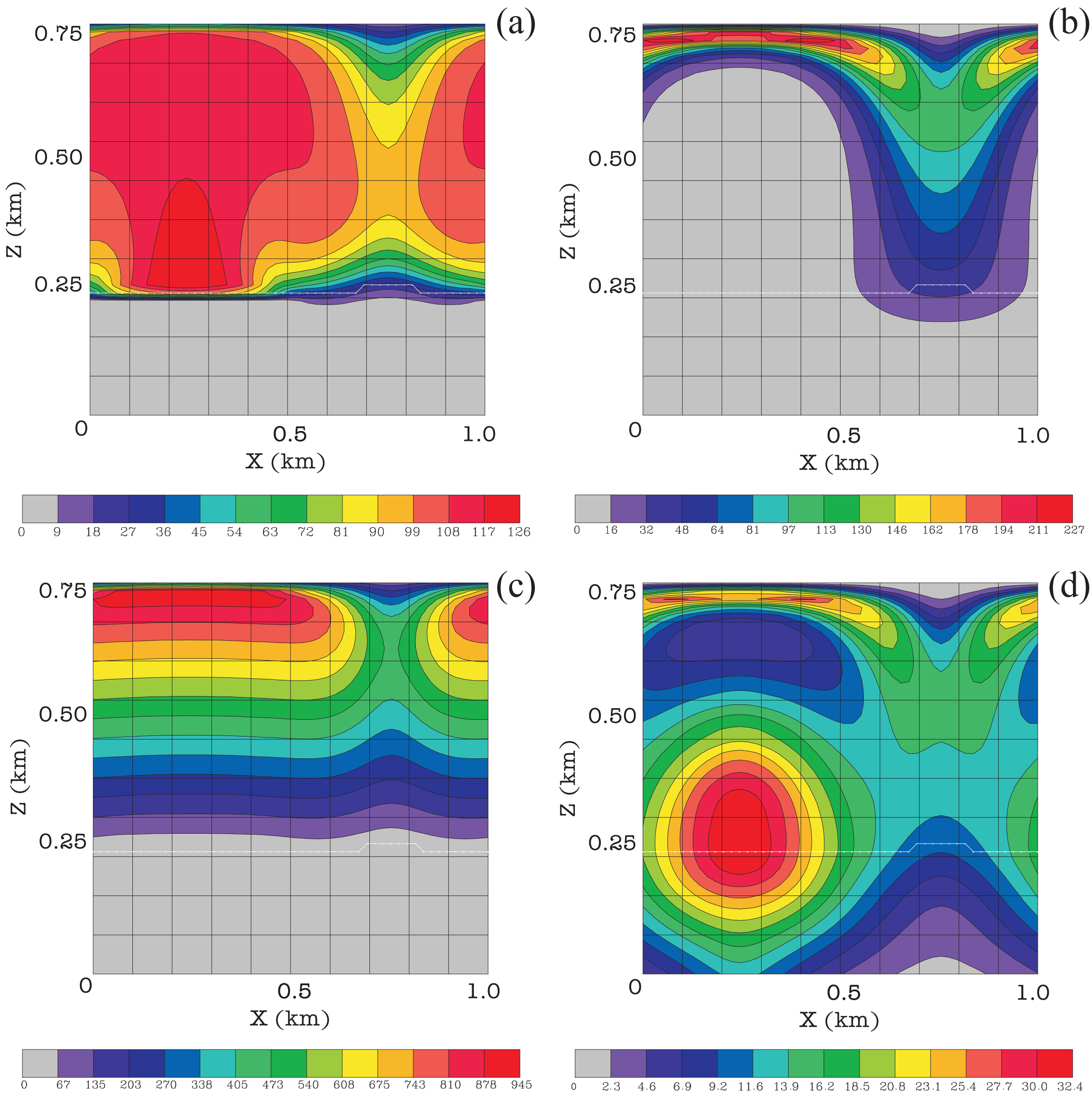


Fig. 6: Model results in steady-state: (a) cloud droplet number concentration in cm^{-3}; (b) drizzle concentration in $liter^{-1}$; (c) cloud water mixing ratio in mg/kg; (d) drizzle mixing ratio in mg/kg

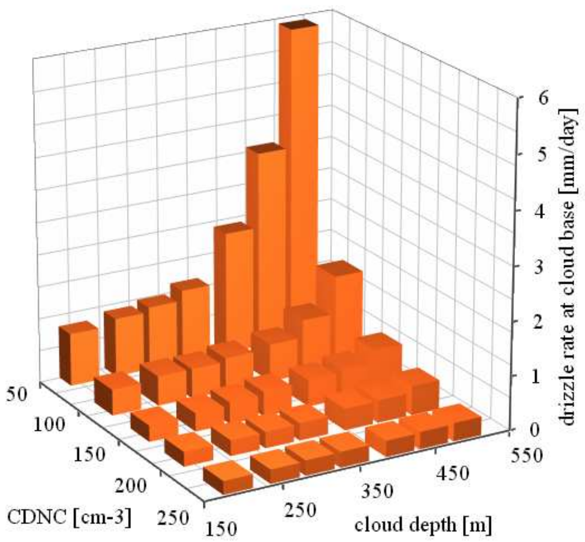


Fig. 7: Drizzle rate at the cloud base as a function of the cloud depth and CDNC. Each bar represents the average of all six ensemble members.

Figure 7 compiles results from all the simulations to document the dependence of the drizzle rate on the CDNC and the cloud depth. The mean cloud-base drizzle rate reaches 6 mm/dayin a deep (500 m) stratocumulus with a low CDNC (50 cm^{-3}). For shallow clouds with large CDNC, the cloud-base drizzle rate is below 0.1 mm/day. The figure shows a highly non-linear relationship between CDNC, cloud depth, and the drizzle rate.

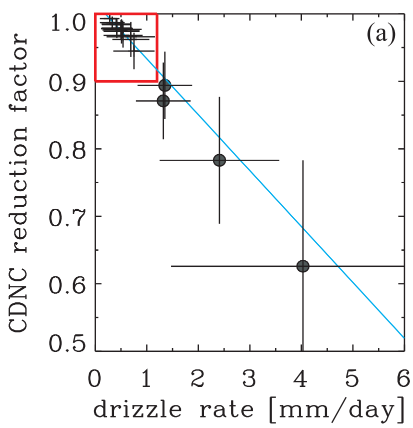
To understand the role of the reduction of CDNC due to the presence of drizzle, additional set of simulations was performed without growth by collision-coalescence. The difference between CDNC in this additional set and CNDC in the corresponding simulations with collision-coalescence (i.e., those discussed above) represents the impact of drizzle scavenging cloud droplets. This is quantified by defining the CDNC reduction factor, the ratio between the mean CDNC in simulations with and without collision-coalescence. The CDNC reduction factor is plotted as a function of the drizzle rate in Fig. 8. It appears that the CDNC reduction factor decreases linearly with drizzle rate. For the drizzle rate of 6 mm/day (cf. Fig.1), the model-predicted CDNC reduction factor is around 0.5. This is actually higher when compared to the changes in CDNC between segments near A and B in Fig.1, which is around 0.3. It is thus quite likely that the change in CDNC shown in Fig.1 is due to scavenging of cloud droplets by drizzle.

6. CONCLUSIONS AND PERSPECTIVES

Drizzle was common during ACE2 and DYCOMS-II. Drizzle formation is local and non-linear, it typically occurs at low CDNC and in a relatively deep stratocumulus. To understand the dependence of drizzle formation on both macro- and microphysical cloud characteristics, a simple cloud model with detailed (bin) microphysics was developed. Despite simplicity of the model, simulation results compared favorably with the few observed cases. Systematic investigation of the dependence of the drizzle rate on cloud depth and CDNC suggests that relatively simple scaling relationships can be developed using the model data. Moreover, it appears feasible to represent the reduction of CDNC in drizzling Scu due to drizzle scavenging. These relationships will be useful in the development of improved representations of Scu in large-scale models of weather and climate.

7. ACKNOWLEDGMENTS

This work is sponsored by the European Union under grant EVK2-CT2002-80010-CESSAR and by the Polish State Committee for Scientific Research (KBN) under grant SPUB-M. WWG was partially supported by NOAA grant NA05OAR4310107.



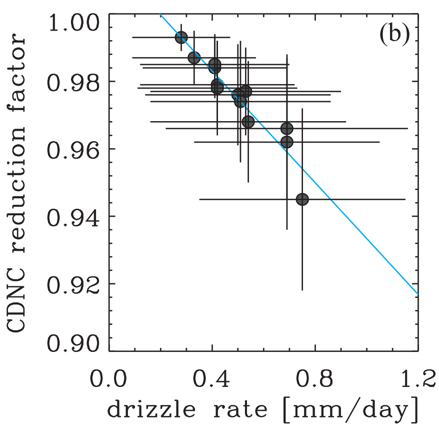


Fig. 8: CDNC reduction factor vs drizzle rate in cloud in a set of simulations. Fig. 8b is an extended part of Fig. 8a enclosed in red box.

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