Evolution of droplet size distributions during the transition of an ultraclean stratocumulus cloud system to open cell structure: an LES investigation using Lagrangian microphysics

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Key Points:
• The first Lagrangian microphysics simulation of the stratocumulus transition from closed to open cell structure is documented
• During the transition, the rain rate increases sharply as the coalescence timescale decreases relative to the large eddy turnover
• Drop size distributions in open cell stratocumulus are broader in downdrafts than updrafts from coalescence, evaporation and drop mixing

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Abstract

A state-of-the-art Lagrangian microphysics scheme is used in a large-eddy simulation to investigate the stratocumulus transition from closed to open cell structure. Processes controlling precipitation development, which is a key to the transition, are analyzed by leveraging unique benefits of Lagrangian microphysics, particularly the ability to track computational drops in the flow. Sufficient time is needed for coalescence growth of cloud drops to drizzle within the updraft-downdraft cycle of large eddies. This favors broad drop size distributions (DSDs) and drizzle growth in downdrafts, where drops are typically much older than in updrafts. During the closed cell stage, mean cloud drop radius is too small, and the DSDs are too narrow, so that the timescale for coalescence is much longer than the large eddy turnover time and drizzle growth is limited. The closed-to-open cell transition occurs when these timescales become comparable and the precipitation flux increases sharply.

Plain Language Summary

Low-level stratocumulus clouds critically impact Earth’s energy budget by reflecting incoming solar radiation. Accurate representation of these shallow clouds in climate models requires information on fine-scale cloud properties and processes (e.g., cloud and drizzle drop sizes and their growth) due to significant variability driven by turbulent flow. Sufficient drizzle formation in these clouds changes their flow structure, shifting clouds from a uniform layer to a layer with an open cell structure. Using a state-of-the-art particle-based cloud model, this study showed that cloud droplet sizes and their coalescence growth change during this process in a way that sharply enhances precipitation. Once the clouds change to an open structure, cloud and drizzle drop sizes and growth differ in upward and downward moving branches of large turbulent eddies, with more drizzle formation and variation in drop sizes in downward flow regions. Information on the drop size variability and growth presented here could lead to better representation of clouds in climate models and measurements using ground and satellite-based instruments.

1 Introduction

Shallow boundary layer clouds remain a large source of uncertainty in global climate models. Complex, multi-scale interactions between large-scale dynamics, turbulence, microphysics, and radiation are a critical challenge in parameterizing these clouds (Wood, 2012). Aerosol-cloud-precipitation interactions strongly affect micro- and macro-scale cloud properties and processes, which have been shown, for example, to drive a transition of stratocumulus from closed to open or open to closed cellular structure (Wood, 2012; Stevens et al., 2005; Savic-Jovcic & Stevens, 2008; Wood et al., 2008; H. Wang & Feingold, 2009; Goren & Rosenfeld, 2012). Closed and open cellular regions differ not just dynamically but also in cloud properties and radiative forcing. Thus, accurate representation of these transitions are important for the overall radiative forcing in Earth system models.

Previous modeling studies of closed-to-open cell transitions mainly used bulk microphysics schemes with highly idealized representations of aerosol processing (e.g., Savic-Jovcic & Stevens, 2008; H. Wang & Feingold, 2009; Kazil et al., 2011; Feingold et al., 2015, and others). Bulk microphysics schemes have limitations due to assumptions regarding the shape of droplet size distributions (DSDs) and simplified process rates formulations (Khain et al., 2015; Morrison et al., 2020). Simulations using DSD-resolving microphysics schemes (e.g., Magaritz et al., 2009; Andrejczuk et al., 2010; Witte et al., 2019; Hoffmann & Feingold, 2019, and others) used domains too small to capture the mesoscale dynamics of closed-to-open cell transitions. As a result, understanding of the processes driving DSD evolution during these transitions is limited. This is an impor-
tant knowledge gap because DSD properties critically impact precipitation development (Pruppacher & Klett, 1997), radiative forcing (Martin et al., 1994; Liu & Daum, 2000), and dynamical feedbacks (e.g., S. Wang et al., 2003; Ackerman et al., 2004; Bretherton et al., 2007; Mellado, 2017). To address this gap, we performed the first (to our knowledge) large-eddy-simulation (LES) of a closed-to-open cell transition using Lagrangian cloud microphysics (the super-droplet method SDM, Shima et al., 2009) with explicit aerosol activation, scavenging, and processing. SDM tracks Lagrangian trajectories of “super-droplets” (computational particles) which represent a multitude of real drops having identical properties in the flow. This approach has several advantages over traditional Eulerian bin schemes, including eliminating numerical diffusion of cloud variables, explicit representation of aerosol processes by tracking cloud-borne aerosol in super-droplets, and ability to represent stochastic aspects of drop collision-coalescence (Jaruga & Pawlowska, 2018; Morrison et al., 2018; Grabowski et al., 2019; Chandrakar et al., 2022).

Using this novel modeling framework, we address several outstanding questions related to stratocumulus evolution: 1) How do DSDs vary spatially and temporally during the closed-to-open cell transition? 2) What are the processes associated with this variability? 3) How do these processes contribute to the increased precipitation flux driving the cellular transition? Supersaturation variability is hypothesized to cause DSD broadening in a clean environment (e.g., Chandrakar et al., 2016; Glienke et al., 2017). In addition to the influence of changing aerosol size and concentration through cloud processing and scavenging, the impact of supersaturation variability on DSD width may vary during the transition (Chandrakar et al., 2017). We address these questions using model data and qualitatively compare simulated DSD outputs with observations of drizzling stratocumulus during the CSET (Cloud System Evolution in the Trades) field campaign (Albrecht et al., 2019). While the main goal of this work is to improve understanding of microphysical processes during the transition, it is also relevant to bulk cloud parameterizations.

2 Overview of The Simulation Setup

We simulate the closed-to-open cell transition with a standard case of drizzling marine stratocumulus (the second research flight (RF02) of the Dynamics and Chemistry of Marine Stratocumulus (DYCOMS-II) (Ackerman et al., 2009) using Lagrangian microphysics (SDM) in a LES framework (Cloud Model 1, CM1, Bryan & Fritsch, 2002). Lagrangian microphysics is uniquely suited for the closed-to-open cell stratocumulus problem because of its detailed treatment of aerosol processing and ability to track computational drops in the flow. The CM1-SDM setup and its advantages compared to Eulerian bin schemes are discussed in detail in the Supplemental Information (SI). We follow the default case specifications except initial winds and large-scale shear are set to zero and the initial aerosol concentration is reduced by a factor of five to accelerate the transition. The computational domain is 50 × 25 km² horizontally and 1.5 km vertically, and the horizontal and vertical grid spacings are 100 m and 5 m, respectively.

3 Results and Discussion

3.1 Transition of the cloud field from closed to open cellular structure

Figure 1a-b shows differences in the modeled cloud field during the closed (earlier) and open cell (later) phases. Well-documented (e.g., Wood, 2012) features of stratocumulus convection are evident: more extensive cloud cover with smaller and weaker updrafts and little precipitation during the closed cell phase versus less cloud cover but stronger, more concentrated updrafts and substantial precipitation during the open cell phase. Figure 2 displays the evolution of different cloud quantities during the cellular transition. After an initial spin-up period, mean in-cloud cloud water mixing ratio \( q_{cm} \) increases slowly to a peak at \( \sim 4 \) hr (Fig. 2a); hereafter “in-cloud” refers to grid cells with \( q_c \geq \)
10^{-5} \text{ kg kg}^{-1} \text{ and } 40 \mu \text{m} \text{ drop radius } R \text{ separates cloud and rain. During this period, mean in-cloud rainwater mass (}\qr\text{m}\text{) and number mixing ratios also increase, but at a marginal rate. The liquid and cloud water paths (LWP and CWP) also peak between 3–4 hr (Fig. 2b). After an initial decrease, cloud droplet number concentration (}\nu\text{) is nearly constant between 2–3.5 hr (Fig. 2c), indicating a balance between loss from coalescence and evaporation and generation by droplet activation, and thereafter it decreases.}

A key aspect of microphysical evolution is the DSD width, quantified here by the radius standard deviation \sigma_R \text{ in a grid cell. The mean } \sigma_R \text{ (averaged over all in-cloud grids) closely follows the time evolution of supersaturation standard deviation } \sigma_s, \text{ consistent with DSD broadening from mixing of drops experiencing different supersaturations and growth histories. Both } \sigma_R \text{ and } \sigma_s \text{ peak around } 2 \text{ hr coinciding with the peak entrainment velocity, decrease between } 2 \text{ and } 3.5 \text{ hr, and increase steadily thereafter. These trends closely follow those of the phase relaxation timescale } \tau_r \equiv (4\pi\nu_s R)^{-1} \text{ (Fig. 2f), the response timescale of the droplet population to a change in the supersaturation field. Here, } \alpha \text{ is a thermodynamic factor (Politovich & Cooper, 1988).}

Precipitation-generated asymmetry in the vertical cooling profile is a critical driver of the cellular transition (Feingold et al., 2010). What processes in turn control precipitation rate? Drops must spend sufficient time inside cloud to grow to drizzle size by collision-coalescence. This implies that the characteristic timescale for coalescence \tau_{\text{col}} \equiv (\qr m + \qr \text{m})/\alpha must be similar to or less than the eddy turnover timescale (Feingold et al., 1996) \tau_{\text{tw}} \equiv H/\sigma_w \text{ for significant precipitation generation. Here, } H \text{ is the average cloud layer depth, } \sigma_w^2 \text{ is the in-cloud resolved } w \text{ variance, and } \alpha \text{ is the integral mass transfer rate towards larger sizes from the coalescence of drop pairs in a grid cell. Figure 2f shows how these timescales change during the transition. The coalescence timescale increases from about 1500 to 1800 sec between 2 and 3 hr owing to the decrease of } \sigma_R \text{ (narrower DSDs). However, after this time it decreases quickly – meaning faster coalescence – as both mean radius and } \sigma_R \text{ increase. In contrast, the eddy turnover time is relatively steady with only a small increase from about 700 to 900 sec between 3 and 7 hr. } \tau_{\text{col}} \text{ approaches } \tau_{\text{tw}} \text{ between } \sim 4.5 \text{ and } 5.5 \text{ hr, and the surface precipitation rate } P \text{ correspondingly increases rapidly (Fig. 2c). At } 5.7 \text{ hr, } \tau_{\text{col}} \text{ crosses over and becomes smaller than } \tau_{\text{tw}}, \text{ and } P \text{ continues to increase until } \sim 6.5 \text{ hr.}

Scavenging of aerosols is an underlying driver of microphysical changes during the transition. Figure 3f,i shows evolution of the aerosol size distribution (concentration distributions and normalized PDFs, including interstitial and cloud-borne aerosol). Aerosol number loss occurs over time due to scavenging and drop coalescence, driving a reduction of } \nu\text{ and increase in mean drop radius after 3.5 hr (Fig. 3c–d). Smaller aerosols in the simulation have lower probability of activation and subsequent removal through drop coalescence. Thus, their loss is slower over time. While there is a decrease in the concentration of all aerosol sizes less than } \sim 600 \text{ nm, the largest relative decrease is for sizes between 20 and } 200 \text{ nm (Fig. 3f). Over time, the normalized PDFs exhibit a shift in the relative concentrations from 20-200 nm to sizes greater than } 300 \text{ nm (Fig. 3i). Coalescence produces large drops, many of which evaporate and regenerate giant cloud condensation nuclei (CCN). These large CCN can easily grow to form relatively large drops (Jensen & Nugent, 2017), contributing to DSD broadening in updrafts near cloud base. However, such an impact is small overall and other processes (e.g., supersaturation variability) dominate DSD broadening in the ultraclean condition in this simulation. For higher background CCN concentrations, the impact of large CCN could be more significant initially, but supersaturation being more important once the cloud system becomes clear.

### 3.2 Evolution of DSDs during the closed-to-open cell transition

We next show DSD evolution at different altitudes during the stratocumulus transition to open cellular convection (Fig. 3). The DSDs in this figure are normalized (giv-
Figure 1. (a)-(b) Iso-surfaces of cloud ($qc$) and rain water ($qr$) mixing ratio during the closed- and open-cell phases. (c)-(d) Sample super-droplet trajectories for time periods ($\Delta t_l$) of 30 min (c) and 15 min (d) during the open-cell phase. Trajectories in (c) were selected based on a minimum length of 1000 m and in (d) by a minimum length of 800 m and end radius $R > 10 \mu m$, respectively.
Figure 2. Timeseries of mean (a) cloud water \( (q_{cm}) \) and rainwater \( (q_{rm}) \) mixing ratios; (b) cloud droplet number \( (n_d) \) and raindrop number \( (n_r) \) mixing ratios; (c) domain-mean cloud water path \( (CWP) \), liquid water path \( (LWP; \text{cloud plus rain}) \) paths, and surface precipitation rate \( (P) \); (d) mean \( (R) \) and standard deviation \( (\sigma_R) \) of droplet radius; (e) mean \( (S_m) \) and standard deviation \( (\sigma_s) \) of supersaturation for grids with vertical velocity \( w \geq 0 \text{ m s}^{-1} \); and (f) mean in-cloud eddy turnover \( (\tau_{tw}) \), collision-coalescence \( (\tau_{col}) \), and phase relaxation timescales \( (\tau_c) \). The vertical dashed line indicates the closed-to-open cell transition time (defined here by cloud cover < 60%). Quantities in (a), (b), (d), (e), and (f) are calculated for in-cloud points. Note \( \sigma_s \) is calculated from the resolved supersaturation field.
Figure 3. (a)-(c) DSDs averaged over grid cells with $q_c + q_r \geq 10^{-5}$ kg kg$^{-1}$ at different altitude ($Z$) ranges and at different times during closed-to-open cell transition. (d)-(e) DSDs averaged over in-cloud grid cells at different $w$ and $Z$ ranges during the open cellular phase. (g)-(h) Average merged DSDs measured in open cell stratocumulus during CSET flight RF14 (see SI for details). (f),(i) Total aerosol (interstitial plus cloud-borne) dry solute radius ($R_a$) distributions averaged over 200 $\leq Z \leq$ 700 m initially and during the closed and open cell phases. (f) shows the aerosol distribution in terms of concentration, and (i) the normalized PDF.
Figure 4. Variation of (a)-(d) relative dispersion ($\sigma_{R}/R$), (e)-(h) coalescence rate ($A_c$), and (i) drop lifetime ($\Delta t_{\ell}$) with vertical velocity $w$. $\sigma_{R}/R$ and $A_c$ include data from all cloudy grid cells. (j)-(l) In-cloud average vertical profiles of $\sigma_{R}/R$ and $A_c$ in downdrafts ($w < 0$ m s$^{-1}$) and strong updrafts ($w \geq 0.5$ m s$^{-1}$). All results in this figure are from the open cell phase. Note, individual particle data is sampled for 30 min during the open cell phase, and thus the lifetime of some drops could be longer than that. The coalescence rate is the integral mass transfer rate from smaller to larger drops from the coalescence of drop pairs in a grid cell. The colorbars show normalized counts for each $w$ bin. Mean $A_c$ values in (e)-(h) calculated using a threshold of $10^{-6}$ g kg$^{-1}$ s$^{-1}$ are denoted by squares while pluses show mean values without the threshold.
To investigate the spatial variability of DSDs and their dependence on cloud dynamics during the open cell phase further, we classified DSDs based on vertical velocity $w$ (Figure 3d-e). DSDs are narrower for both the left and right tails in relatively strong updrafts ($w > 0.5 \text{ m s}^{-1}$, which we will refer to as “strong” updrafts) compared to downdrafts ($w < 0 \text{ m s}^{-1}$). In strong updrafts, there is a narrowing of the DSDs with altitude above cloud base from condensation due to large mean supersaturation and limited mixing of drops with different growth histories (Fig. 3e). In contrast, evaporation in downdrafts causes broadening to small drop sizes at lower and middle cloud levels (Fig. 3d). The interface between strong updraft and downdraft regions also has fairly broad DSDs due to mixing of drops with different growth histories (see Figure S5). Mixing also contributes to DSD broadening within both updraft and downdraft regions, although it is compensated by DSD narrowing from condensation in updrafts.
A key difference between updraft and downdraft DSDs is the wide shoulder of drizzle drops extending to the right of the main cloud mode in the downdraft DSDs, which is mostly absent in strong updrafts (Fig. 3d-e). Correspondingly, the mean concentration of drizzle drops with radius $> 40 \, \mu m$ is 4.5 times larger in downdrafts than strong updrafts (0.09 versus 0.02 cm$^{-3}$). The mean concentration of drizzle drops in downdrafts also increases with decreasing altitude within the cloud. This is caused by additional coalescence growth in downdrafts consistent with our trajectory analysis. Figure 4e-h, k-l, which shows frequency distributions of coalescence rate (integral mass transfer rate from small to large drops associated with all collision pairs) as a function of vertical velocity and mean coalescence rate profiles in updrafts and downdrafts, confirms strong coalescence growth in downdrafts ($w < 0$) at all cloud levels. Near cloud base, mean coalescence rates within the cloud are about an order of magnitude greater in downdrafts compared to updrafts (Fig. 4e, k, l). Without applying any threshold, mean coalescence rates are lower in downdrafts than strong updrafts above 550 m. However, large coalescence rates ($\geq 10^{-2} \, g \, kg^{-1} \, s^{-1}$) occur predominantly in downdrafts at all altitudes within the cloud. This behavior is consistent with substantial inhomogeneity and skewness of the coalescence rate distribution in downdrafts. Transport of smaller drops from updraft and significant evaporation from entrainment, suppressing drop coalescence in some downdraft grid cells, could be partly responsible for this strong inhomogeneity.

Why are downdraft regions favored for large coalescence growth rates? An analysis of cloud/drizzle drop lifetimes sheds light on this question (Fig. 4i). The drop lifetime is defined as the period over which $R > 1 \, \mu m$ during the previous 30 min sampling. There is large variability in drop lifetime at all vertical velocities, while the mean lifetime is generally $> 15$ min in downdrafts, similar to (or greater than) the eddy turnover time, but $< 5$ min in strong updrafts. These results are consistent with (Kogan, 2006), who analyzed in-cloud residence time of air parcels in LES of stratocumulus rather than drop trajectories. Our results therefore give the following conceptual picture of microphysical evolution in open cell stratocumulus convection: generation of new cloud droplets by activation near cloud base, their ascent and condensational growth in updrafts, transport to downdrafts, and accelerated coalescence growth in downdrafts as the drops continue to age. In other words, large drops are favored in downdrafts because it takes time for coalescence growth to occur over the course of one large eddy turnover. Before the transition to open cells, the coalescence timescale is much longer than one eddy turnover time, and hence there is not enough time for significant coalescence growth in an updraft-downdraft cycle. In this case, the mean DSDs resemble the relatively narrow DSDs in updrafts in the open cell regime, particularly at the cloud DSD mode and to its right. Once the coalescence timescale becomes similar to the eddy turnover timescale, coalescence growth is enhanced and there is a rapid shift from non-precipitating (or barely-precipitating) to precipitating regimes.

Differences in modeled DSDs between updrafts and downdrafts are generally consistent with observations of drizzling stratocumulus (open cellular) during CSET (Fig. 3g-h). The mode radius of the observed mean DSDs increases, and the left tail decreases with altitude as expected. Both the right and left tails near the primary mode are broader in downdrafts than in updrafts. There is a broad shoulder extending from the DSD mode toward drizzle drop sizes in downdrafts but a sharp drop in concentration to the right of the mode in strong updrafts. Correspondingly, the mean $\sigma_R$ is about a factor of two larger in downdrafts than in updrafts from both the model and observations, although the modeled $\sigma_R$ values are larger by $\sim 1-3 \, \mu m$. Similarly, the observed mean drizzle drop concentration (radius $> 40 \, \mu m$) is a factor of 1.7 higher in downdrafts than in strong updrafts, qualitatively similar to the updraft/downdraft differences in the simulation though somewhat smaller in magnitude. These findings are also consistent with measurements for another case with a lower droplet concentration (see Figure S4).
Investigating the relationship between DSD width and cloud dynamics (vertical velocity) is relevant to bulk microphysics schemes, many of which make assumptions about the DSD width typically quantified by the relative dispersion, $\sigma_R/R$. Figure 4a-d,j shows the variation of $\sigma_R/R$ with vertical velocity and altitude. For a given altitude range, mean $\sigma_R/R$ is fairly constant with vertical velocity for downdrafts but with a sharp decrease at vertical velocities between roughly $-0.5$ and $0.5$ m s$^{-1}$. It then decreases slightly with increasing vertical velocity for $w > 0.5$ m s$^{-1}$. This trend of $\sigma_R/R$ is consistent with the DSDs in Fig. 3 indicating much broader DSDs in downdrafts than updrafts, toward both small and large drop sizes. Note that trends in $\sigma_R$ are similar to $\sigma_R/R$. This spatial structure of DSD width is neglected in bulk microphysics schemes, likely impacting modeled cloud-radiative interactions since cloud droplet effective radius depends on $\sigma_R/R$ (Martin et al., 1994). Furthermore, with a few exceptions (e.g., Seifert & Beheng, 2001; Liu & Daum, 2004), most autoconversion formulations in bulk schemes (representing the conversion of cloud droplets to drizzle/rain via coalescence) do not include a dependence on DSD width. Such schemes may therefore struggle to represent correctly the preferential growth of drizzle drops in downdrafts related to the coalescence timescale and large eddy turnover. This in turn could impact simulation of other features tied to precipitation using bulk schemes, including aerosol scavenging and the closed-to-open cell dynamical transition itself.

4 Conclusions

We investigated DSD evolution and variability in an ultraclean environment during a stratocumulus closed-to-open cell transition using LES coupled with a particle-based Lagrangian cloud microphysics scheme. This scheme is uniquely suited for the problem since it gives the Lagrangian growth and transport history of individual computational particles, explicitly tracks cloud-borne aerosol, and has other numerical advantages outlined in the introduction. As suggested in past studies (see Wood, 2012, and references therein), the development of precipitation is a key driver of the closed-to-open cell transition. We showed that a decrease in the collision-coalescence timescale relative to the large eddy-turnover timescale triggers a sharp increase in surface precipitation. The collision-coalescence timescale depends on other microphysical process timescales relative to the dynamics that control the DSD shape, for example, aerosol scavenging and phase relaxation timescales. Supersaturation variability and mixing of droplets with different growth histories also contribute to the transition through their influence on DSD width. Sufficient drop residence time within a large eddy updraft-downdraft cycle is needed for growth to drizzle size via coalescence, favoring coalescence growth of older drops in downdrafts. In contrast, DSDs in updrafts are narrower and comprise mainly younger drops. Prior to the open cell transition, the timescale for coalescence growth is long relative to the eddy turnover time, DSDs are narrow and precipitation is hampered. These results highlight how spatial and temporal variability of DSDs is a key feature of the closed-to-open cell transition. This variability cannot be represented in current bulk microphysics schemes that assume constant cloud DSD dispersion or relate it to droplet number concentration (e.g., Thompson et al., 2008; Morrison et al., 2009), which potentially explains why the bifractal structure of rain produced by these schemes in LES is minimally intermittent and overly smooth compared to observations (Witte et al., 2022). Relationships between DSD dispersion, collision-coalescence rate, and vertical velocity identified in this study could help improve bulk schemes as well as remote sensing retrievals.

Open Research

CM1 code with detail documentation is available at https://www2.mmm.ucar.edu/people/bryan/cm1/. SDM code provided by Shin-ichiro Shima is available at https://doi.org/10.5281/zenodo.3483650. The CSET field data used in this study is avail-
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