P1.16 LES microphysical study of interactions between cloud dynamics and drizzle

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1. INTRODUCTION[1]

Although basic processes affecting warm cloud microstructure and rain initiation are well known, the interactions between microphysical processes, cloud dynamics, and turbulence, as well as their effects on drizzle, are still poorly understood.

Of particular interest is the interaction between boundary layer turbulence and drizzle. The large-scale turbulent eddies in addition to their effect on cloud local parameters, may also alter the time air parcels spent in the cloud and, thus, affect the duration of the coagulation process. This interaction was studied using the CIMMS LES stratocumulus cloud model with explicit microphysics and the Trajectory Ensemble Model (TEM) driven by the LES velocity fields.

2. MODEL

The CIMMS LES explicit (size-resolving) microphysical model is described in detail in Kogan (1991) and Khairoutdinov and Kogan (1999). The current experiment was initialized with data observed during Atlantic Stratocumulus Transition Experiment (ASTEX) (Albrecht et al. 1995) flight A209 on 12-13 June 1992 (see Khairoutdinov and Kogan (1999) for a detailed case description). The initial CCN concentration was 85 cm^{-3}, a value typical for a clean marine air mass. The integration domain extends 3.0 km in the two horizontal directions and 1.25 in the vertical direction, with 40×40×51 grid points uniformly spaced 75 m in the horizontal and 25 m in the vertical. Time steps for dynamics and microphysics are 4 seconds and 0.2 seconds, respectively. Under the specified conditions, horizontally averaged drizzle rates varied during the 5 hour simulation in the 0.2-0.6 mm/day range. The simulated cloud layer was about 300-400 m thick with cloud base and top varying between 300-400 m and 710-770 m, respectively (Fig. 1).

Two additional high resolution (HR) experiments were conducted using the bulk microphysics version of the CIMMS LES model, which describes microphysical processes based on a five-moment scheme and predicts concentrations of CCN, cloud and drizzle drops, as well as cloud and drizzle mixing ratios (Khairoutdinov and Kogan, 2000). These high resolution experiments were conducted in the same integration domain, but with 100×100×126 grid points uniformly spaced 10 m in the vertical and 30 m in the horizontal.

The first HR experiment was conducted using the same thermodynamical and background aerosol conditions, as the baseline low resolution experiment described above. This experiment (HRDR – high resolution drizzle) resulted in the same drizzling stratocumulus cloud. For evaluation of the effect of drizzle, the second HR experiment was conducted using the same thermodynamical profiles, but with CCN concentration of 250 cm^{-3} measured during ASTEX flight A209 in a continental air mass outbreak (profile P1). This experiment (HRND-high resolution no-drizzle) produced a non-drizzling cloud in a well-mixed boundary layer. The thermodynamical profiles for drizzling and non-drizzling cases are contrasted in Fig. 1. They show familiar features of well mixed and decoupled boundary layers (Stevens et al. 1998). Skewness in the well-mixed case is negative throughout most of the BL, indicating predominance of narrow strong downdrafts typical for a radiatively-cooled cloud. In the drizzling case the evaporation of drizzle below cloud and ensuing decoupling dramatically affects the velocity skewness, which in this case is positive throughout most of the BL indicating predominance of weak downdrafts and narrow strong updrafts.

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3. RESULTS

In drizzling Sc cloud the air parcels' in-cloud residence time (τ_r) is 2 to 5 times larger than the characteristic cloud eddy turnover time, τ_c. The latter is defined as L/σ_w (L cloud depth, σ_w - is the standard deviation of the vertical velocity averaged over the cloud layer depth) and, for conditions of our case, is about 9-10 min. About 95% of all air parcels reside in cloud for more than one full cycle ($=2\tau_c$), about 70% will cycle in the cloud more than two times, and about 50% more than three times (Fig. 2). These results clearly indicate that repeated air cycling is an essential feature of drizzling stratocumulus cloud dynamics.

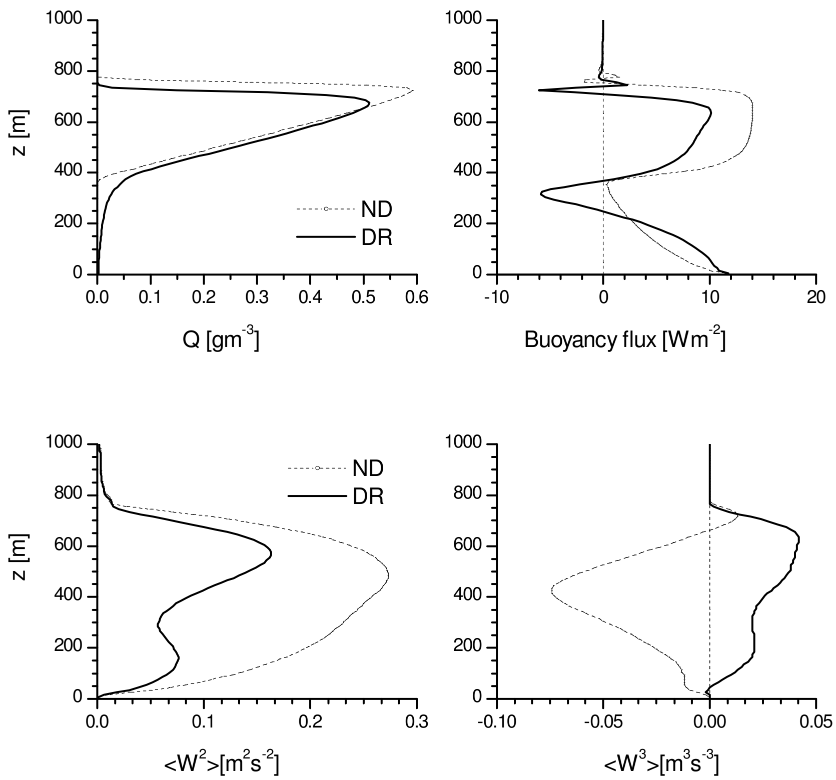

Figure 1. Profiles of liquid water content (Q), buoyancy flux, vertical velocity variance and skewness at three hours into simulation in high resolution experiments for drizzling (DR) and non-drizzling (ND) conditions.

The simulated drizzling stratocumulus cloud represented a decoupled boundary layer where flow is dominated by eddies confined to the cloud layer. In a non-drizzling well-mixed boundary layer, where prevailing eddies have characteristic size of the boundary layer depth, the in-cloud residence time is significantly smaller (Fig 2, case HR-ND).

The sensitivity of these results to model grid resolution can be evaluated by contrasting the τ_r statistics for bulk high resolution and low resolution runs (Fig. 2). The distributions of τ_r in HR-DR and LR-DR experiments both exhibit a similar long tail indicative of substantial repeated air parcel cycling in drizzling stratocumulus. The statistical parameters differ by about 5-15%, however, even this small difference should not be attributed only to change in flow characteristics, as the cloud in the HR-DR run has also somewhat different geometrical parameters, namely, it is slightly thinner and had a higher maximum cloud water, Q_c.

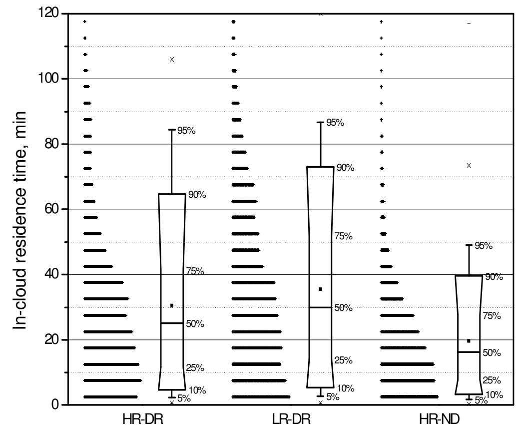

Fig. 2. Box-charts of in-cloud residence time statistics for drizzling high (HR-DR) and low (LR-DR) resolution experiments, as well as for high resolution non-drizzling experiment (HR-ND).

The difference between high and low resolution experiments has to be contrasted with the difference caused by the effect of drizzle on decoupling and, consequently, on the boundary layer flow circulation. Fig. 2 shows that in the non-drizzling well-mixed case, the mean value of τ_r is on the order of boundary layer turnover time (~20 min); other statistical parameters of τ_r show a significant reduction in the number of long time trajectories (Kogan, 2006). For instance, in the drizzling case about 25% of air parcels reside in the cloud for more than 40 min, however, this number is only 10% in the non-drizzling case.

Figures 3 and 4 show trajectories that end up in particular air volumes in the cloud simulated under drizzling and non-drizzling conditions. In the decoupled drizzling case there are more trajectories confined to the cloud layer, while the well-mixed non-drizzling case is dominated by trajectories circulating over the entire boundary layer. The difference is apparent when comparing air volumes in less crowded panels (e.g., #2 in Fig. 3 with #1 in Fig. 4).

Figures 3 and 4 also show that air parcels in a particular volume have quite different histories and significant variability in their in-cloud residence time. The bottom panel in Fig 4, for example, shows an air volume where all parcels came directly from the surface layer in updrafts of different intensities. These parcels have small (3-12 min) in-cloud residence time τ_r. On the other hand, air parcels in air volume #2 in Fig 3 have repeatedly cycled in the cloud and have τ_r exceeding 60-80 min. The other panels show examples of various degree of mixture of air parcels with τ_r's varying in a wide range.

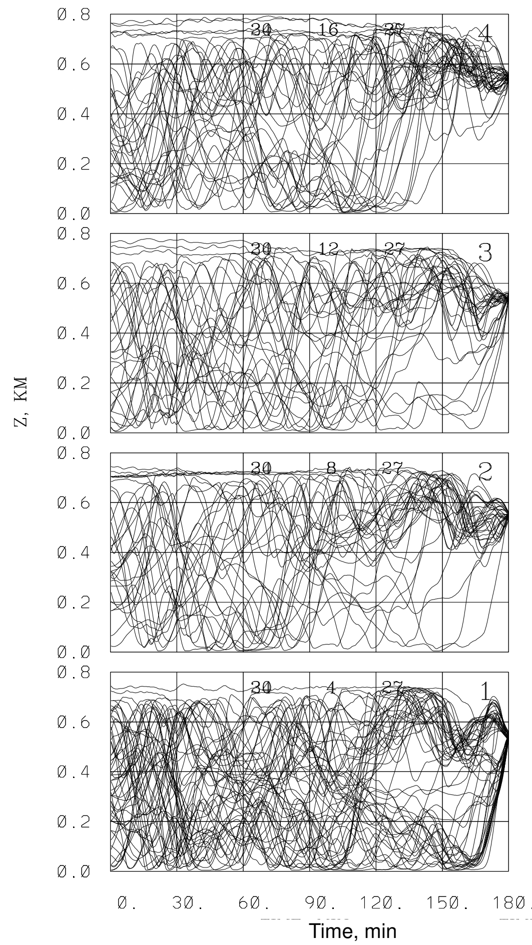

Fig. 3. Air parcels height-time trajectories in selected air volumes in drizzling stratocumulus cloud simulation (HD-DR).

4. CONCLUSIONS.

Based on large eddy simulations of stratocumulus clouds we analyzed a trajectory ensemble data set of tens of thousands air parcels tracked for four hours. The analysis focused on in-cloud timescale statistics, as well as on the spatial variability of timescales.

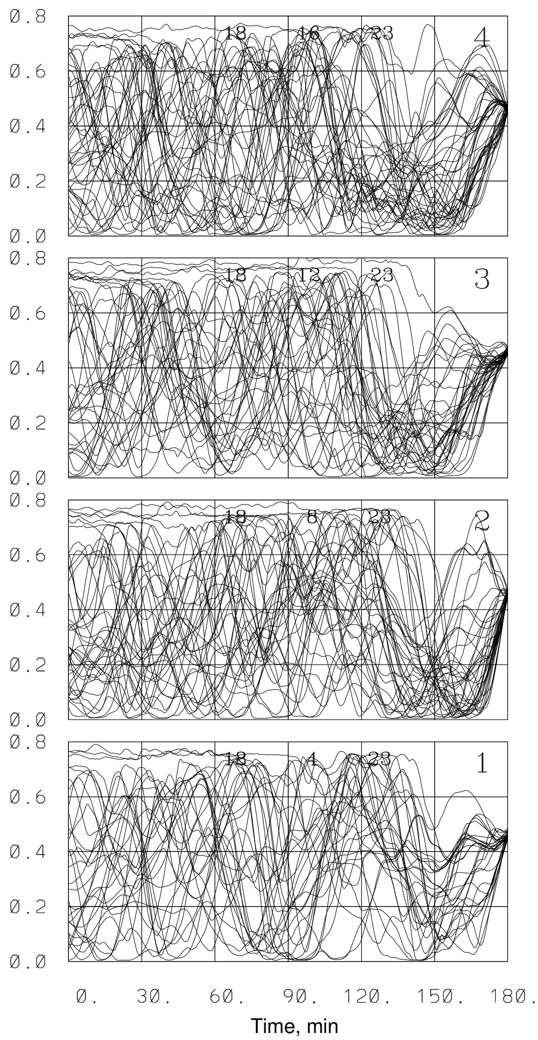

Fig. 4. Air parcels height-time trajectories in selected air volumes in non-drizzling stratocumulus cloud simulation (HD-ND).

The results show that residence times of air parcels in drizzling Sc are significantly larger than the cloud eddy turnover time, t_c, defined as L/w^* (L cloud depth, w*- convective scaling velocity). The latter for conditions of our simulations is about 9-10 min. About 95% of all air parcels reside in cloud for more than one full cycle (=2τ_c), about 70% will cycle in the cloud more than two times, and about 50% more than three times. These results clearly indicate that repeated air cycling is an essential feature of drizzling stratocumulus cloud dynamics.

An interesting result of the study is the considerable spatial inhomogeneity of air parcels in-cloud timescales, which will obviously lead to inhomogeneity in cloud microphysical parameters. The effects of residence time spatial inhomogeneity on cloud microstructure are obvious and quite significant. The older parcels contain larger droplets and previously processed CCNs. Non-adiabatic mixing between old and new parcels will provide new embryos for coagulation and accelerate drizzle formation. In the framework of parcel mixing, the drop spectral broadening may be the result of mixing of parcels with different histories, i.e., representing drop size distributions at different stages of their evolution.

Our results also suggest the following interesting mechanism for transition from non-drizzling to drizzling stratocumulus cloud. Mild evaporation of drops below cloud base in the initially non-drizzling cloud will lead early on to weak destabilization of the subcloud layer which, in turn, will result in the increase in the number of air parcels confined to the cloud layer. These parcels with long timescale trajectories will favor enhanced drizzle growth, which, in turn, will lead to stronger evaporation below cloud base followed by a stronger increase in stability of the subcloud layer and decoupling, all resulting in more air parcel cycling in cloud and more drizzle. The described positive feedback mechanism may eventually lead to stratocumulus cloud breakup described in Stevens et al (1998).

Acknowledgement. This research was supported by ONR Grants N00014-05-1-0550 and N00014-03-1-0304, and by the Office of Science (BER), U.S. Department of Energy, Grant No. DE-FG02-05ER64062.

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