TURBULENT ENTRAINMENT IN A SHEARLESS MIXING LAYER AT THE EDGE OF A CLOUD

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Abstract Three-dimensional direct numerical simulations which combine the Eulerian description of temperature, vapor content and velocity with a Lagrangian ensemble of cloud water droplets are used to study the turbulent entrainment and subsequent mixing of clear air with a cloudy air filament. The study is conducted in a shearless mixing layer setup which is adjusted to realistic conditions at a cumulus cloud boundary. The magnitude of turbulent velocity fluctuations in- and outside the cloud can be varied independently. We find that the evolution of the cloud water droplet ensemble depends slightly only on the contrast of turbulent velocity fluctuations in- and outside the cloud filament. The buoyancy feedback on the flow via the evaporating droplets causes a transient amplification of all fluctuations before the turbulence eventually decays. We study the evolution of the probability density functions of droplet size as well as of supersaturation, temperature and vorticity at the droplet positions.

Keywords: *turbulent entrainment, shearless mixing layer, cloud-clear air interface, two-phase turbulence*

INTRODUCTION

The turbulent entrainment and the subsequent mixing of clear environmental and cloudy air is a process that determines the lifetime and microphysical properties of the cloud. This mixing process is present on all scales reaching from a few hundreds of meters (or even more) down to the centimeter scale and thus causing a wide spectrum of eddy turnover times. Compared to the droplet evaporation time scale (which is a reaction time scale in our problem) these times can be large or small thus causing the Damköhler number Da to be large or small, respectively. In other words, turbulent entrainment in clouds combines inhomogeneous large-scale mixing ($Da \gg 1$) with homogeneous small-scale mixing ($Da \ll 1$) simultaneously. Our direct numerical simulations (DNS) aim at slowly working towards the inhomogeneous mixing regime which are in line with a successive increase of the domain size of the cloud sub volume in order to capture larger eddies while still resolving the microphysical processes around the Kolmogorov scale in detail. The eventual goal of our ongoing DNS studies is to provide a more detailed picture on the local fluctuations of supersaturation and the small-scale intermittency both of which enter subgrid-scale parameterizations in large-eddy simulations of a whole cloud. Here, we focus to one subproblem, the lateral cloud boundary of a cumulus cloud.

NUMERICAL MODEL

Our numerical experiment combines the Boussinesq equations for velocity and temperature together with an advection-diffusion equation for vapor content and a Lagrangian ensemble of individual cloud water droplets. Condensation rate, liquid water content and local supersaturation determine the growth of the individual cloud water droplets. Typical cloud droplet concentrations of the order of $10^2 cm^{-3}$ result in about 10 to 100 million individual droplets in our domain. They are treated as inertial point particles with Stokes drag and gravitational settling. We monitor their position, their velocity and the droplet radius. The simulation domain consists of an equally spaced mesh grid with up to 1024 $\times$ 512 $\times$ 512 grid points. The slab $L_x \times L_y \times L_z$ has a size of $1m \times 0.5m \times 0.5m$ with periodic boundary conditions in all three directions. The smallest grid size matches the Kolmogorov scale which is typically about $\eta_k = 1mm$ for the atmosphere. In the initial case, the left half of the rectangular box consists of liquid water (seeded droplets), supersaturated water vapor and dry air, the right half contains only dry air and unsaturated water vapor. Therefore the left half represents the cloud slab, the right half the clear air area. In terms of the equations and numerical methods, our work builds on former DNS of cloudy–clear air mixing, as reported in [2, 3, 4]. The initial conditions in the initial shearless mixing layer are matched with recent high-resolution field measurements of trade-wind cumuli in the CARRIBA campaign over Barbados [1, 5]. Two cases are considered. Either the turbulent velocity fluctuations are equal in- and outside the cloud or they are much smaller outside, the actual shearless mixing layer setup.

RESULTS

The turbulence is allowed to decay, except for a transient feedback of the buoyancy field to the velocity field. In our model, buoyancy is a function of temperature, water vapor and liquid water contents. The mixing process passes through three different stages in all runs. In the first stage, the difference of turbulence levels in- and outside the cloud filament is relevant for the evolution of the droplet size distribution. In the case of a shearless mixing layer, large-scale intermittency is present and turbulent velocity bursts from the cloud slab enter the clear air region. Since water vapor mixing ratio $q_v(\boldsymbol{x},t)$ and temperature fluctuations $T(\boldsymbol{x},t)$ are advected by the fluid the lateral mixing is then somewhat weaker causing a slight delay of droplet evaporation. Equal turbulence levels in- and outside the clouds cause a faster evaporation. However, after $t > 0.7\,T_L$, with $T_L = 14s$ as the large eddy turnover time, a second stage begins at which intense lateral entrainment perpendicular to the cloud boundary is present in both cases. The process leads to final evaporation of all droplets and stronger downdrafts located outside the cloud. They cause a transient growth of turbulent kinetic energy and energy dissipation. It is well-known from measurements [1] that subsiding shells can form around cumulus clouds. The probability density functions of radius and supersaturation develop pronounced exponential tails to the left side in all cases. Figure 1 shows a slice plot of temperature and vapor mixing content fields together with cloud water droplets which are colored with respect to their radius. In the middle of both panels a strong burst of cloudy air with cloud droplets is visible. Droplets which are subject to rapid evaporation will cool the surrounding area slightly. This is visible in the bottom panel of the figure where clustered particles during their evaporation stage are located in a low temperature patch. Note that the y-axis is directed outside the paper plane. At the final stage, i.e., after about $t = 2.8\,T_L$ the Eulerian fields are more or less homogenized and droplets are equally distributed over the whole domain. At this stage the two cases with equal or different turbulent velocity fluctuations are no longer distinguishable. Our next immediate step is to study the connection between supersaturation and vorticity in order to investigate the role of small-scale intermittency on the droplet dynamics.

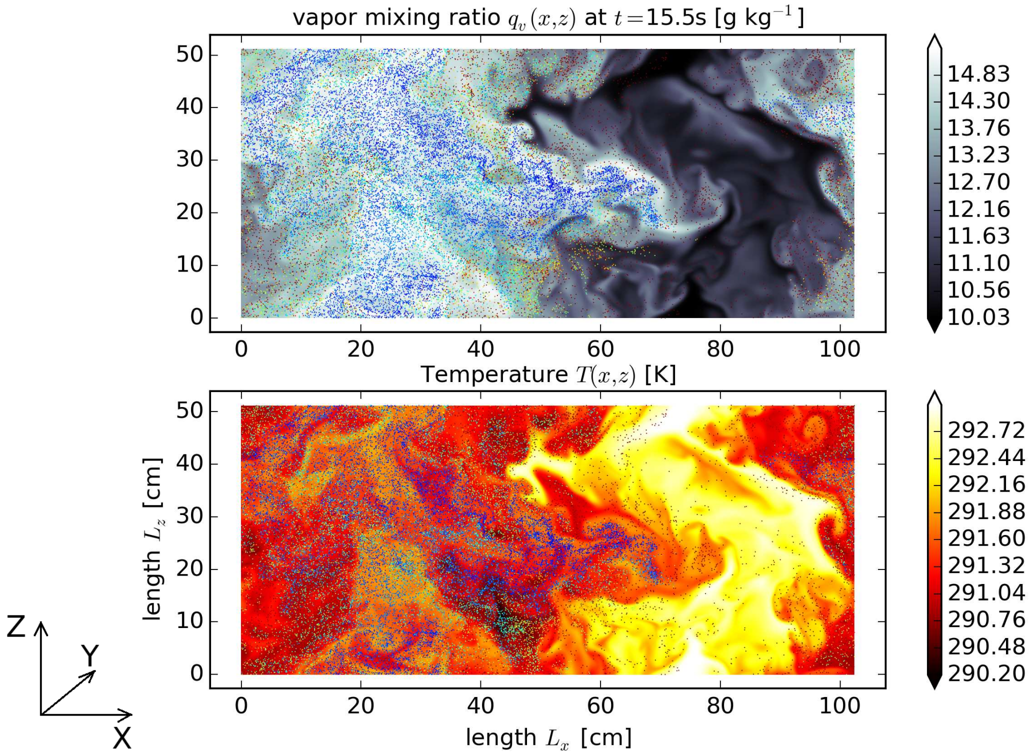

Figure 1. Contour plots of a snapshot of vapor content $q_v(\boldsymbol{x}, t)$ (top panel) and temperature $T(\boldsymbol{x}, t)$ (bottom panel) shown together with the droplets in the plane. The color bars denote the corresponding values of the Eulerian fields. The particle colors represent the droplet radius reaching from blue for $16\mu m$ to red for $12\mu m$. More than 15 million mono-disperse droplets have been seeded initially in the left half of the simulation domain. Different turbulence levels in- and outside the cloud have been chosen initially.

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