Saturation adjustment in a cloud-topped convective boundary layer

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Abstract

In contrast to classical Rayleigh-Bénard convection, convection in the atmospheric boundary layer is characterized by the presence of water in different phases. The release and absorption of latent heat due to evaporation and condensation affect the energy budget of the system and significantly influence its dynamics – most evidently in the formation of clouds. Most cases assume an infinitely fast saturation adjustment to equilibrium between the liquid and the vapor phases of water. This, however, implies that the adjustment processes act on by far shorter time scales than the turbulent dissipation, which is debatable for realistic atmospheric conditions. Here, we investigate the effect of "slow" saturation adjustment on cloud dynamics in a cloud-topped convective boundary layer.

A slow saturation adjustment can cause localized patches of supersaturation. The relative importance of supersaturation fluctuations can be quantified in terms of a Damköhler number $Da = \tau_{fl}/\tau_{ph}$ defined as the ratio of the flow's mixing time scale τ_{fl} over the phase relaxation time scale of supersaturation τ_{ph}. While the assumption of phase equilibrium corresponds to $Da \to \infty$, estimates of realistic atmospheric conditions rather suggest an effective $Da_\eta = \mathcal{O}(10^{-2} - 10^{-1})$ with respect to the smallest flow scales, i.e., the Kolmogorov time scale. This indicates that supersaturation fluctuations begin to play a more prominent role.

We perform 3D direct numerical simulations of a (stratocumulus) cloud-topped convective boundary layer at $Re = 5000$ and analyze the influence of "slow" supersaturation relaxation for $10^{-2} \leq Da_\eta \leq 10^{1}$ compared to the case with phase equilibrium assumption $Da_\eta = \infty$. The supersaturation in our simulations is limited to the cloud layer and therein mostly correlating with ascending flow. The largest values of supersaturation up to 4% are found at the cloud base, while within and at the top of the cloud layer, supersaturation is mostly limited to a few tenths of percent. In contrast to these local extreme values, we find that, spatially, cloud bulk and top are (super)saturated to a greater extent than the cloud base. Most crucially, we find that the clouds liquid water content is decreasing for $Da_\eta > 1$, while it is stable for $Da_\eta \approx 1$ and even increasing for $Da_\eta < 1$. This implies that clouds tend to dry out and desiccate under phase equilibrium assumption, while they might be rather accumulating in realistic conditions.

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