Droplet activation and mixing in large-eddy simulation of a shallow cumulus field

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INTRODUCTION

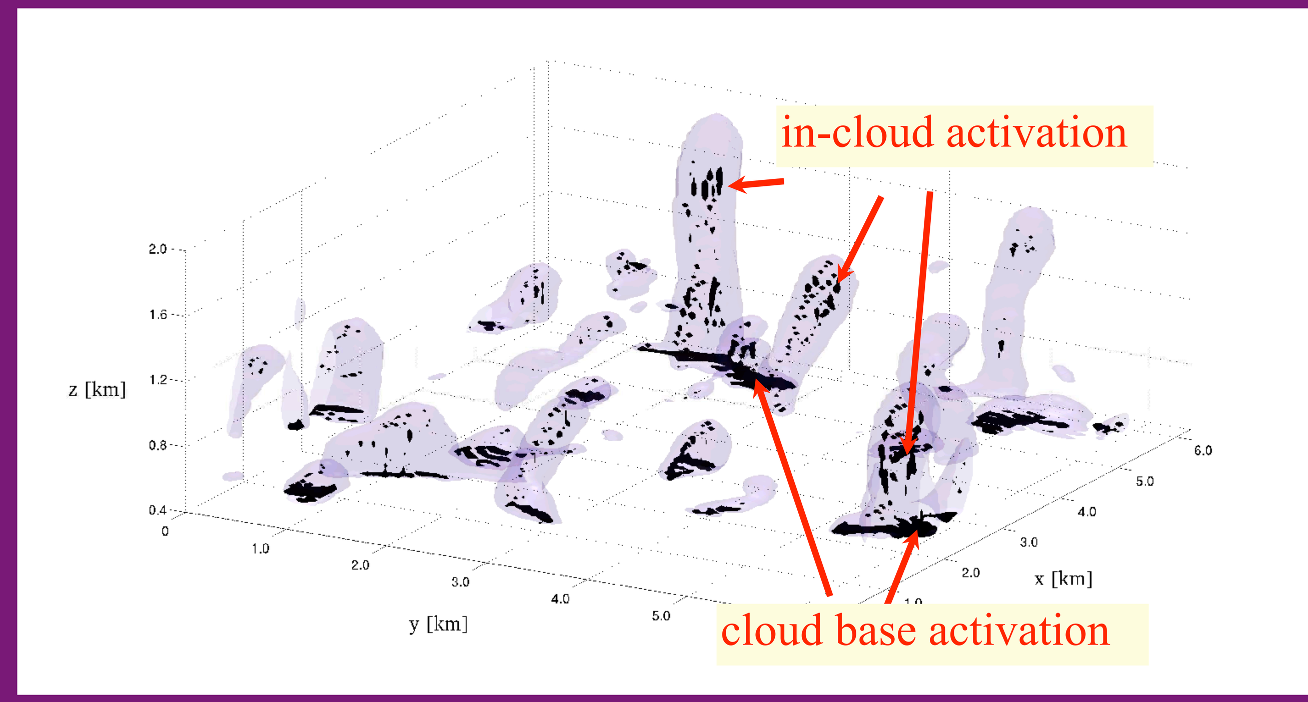
Tropical and subtropical boundary layer clouds such as subtropical stratocumulus and trade-wind cumulus reflect back to space a significant fraction of the incoming solar radiation. The albedo of a field of shallow convective clouds depends critically on macrophysical (e.g., cloud cover) and microphysical (e.g., droplet spectra) cloud properties. Cloud microphysical properties are strongly affected by characteristics of the cloud condensation nuclei (CCN) and by processes impacting droplet spectra within clouds, such as entrainment/mixing and in-cloud activation.

Here we report results of numerical simulations of a field of shallow cumuli and illustrate the critical role in-cloud activation plays in shaping cloud microphysical properties. The model applies the double-moment bulk warm-rain microphysics scheme of Morrison and Grabowski (2007, 2008). The scheme includes prediction of the supersaturation and thus allows secondary in-cloud activation above the cloud base. This is in contrast to traditional bulk schemes that apply saturation adjustment and consequently exclude in-cloud activation.

TOOLS AND SETTINGS

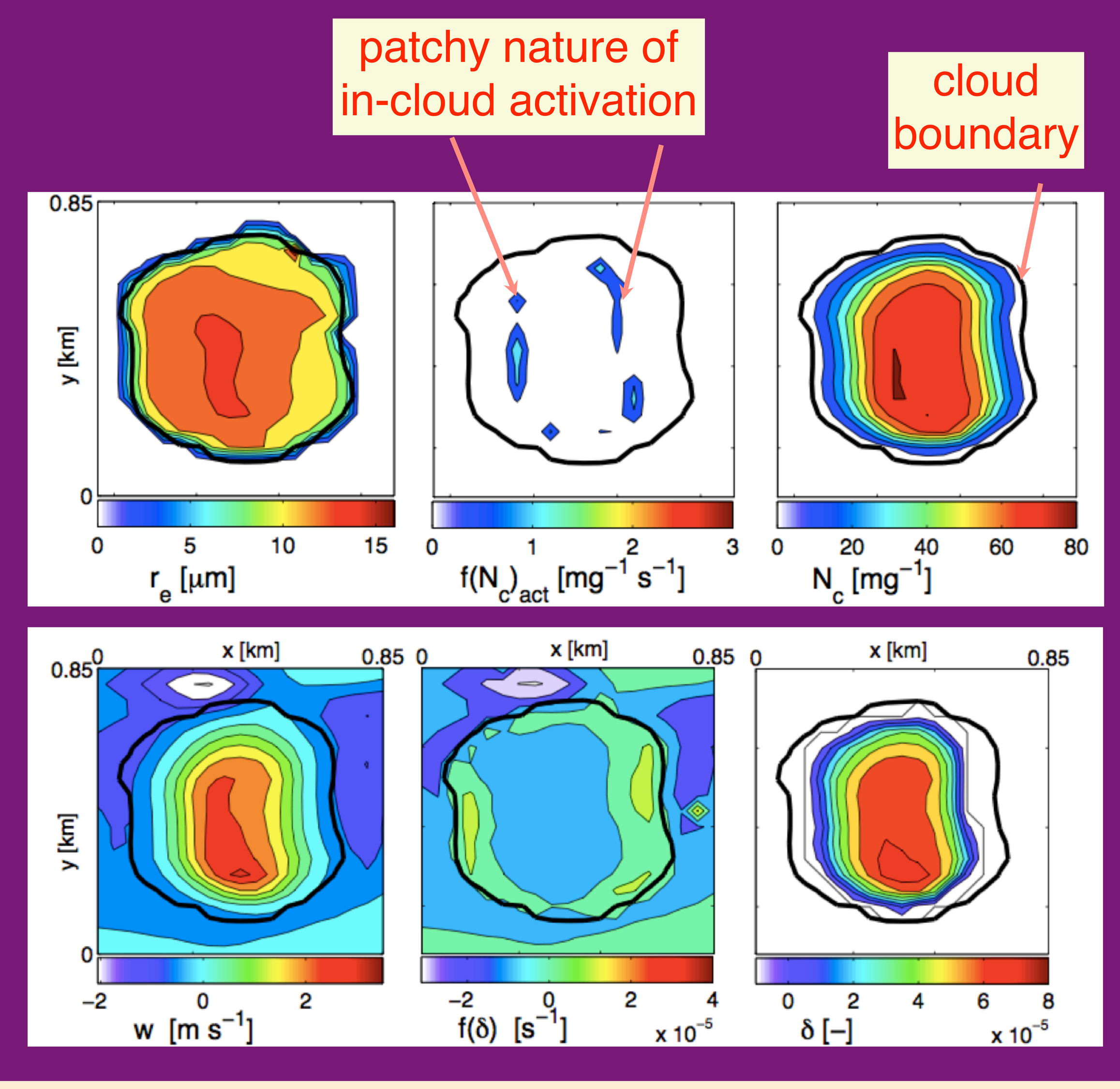
- Numerical model **EULAG**, 3-dimensional LES
- **Two-moment bulk scheme** (Morrison and Grabowski 2007, 2008)
- Predicted variable: cloud and rain water mixing ratios and concentration (q_c, N_c, q_r, N_r)
- Prediction of in-cloud supersaturation. Concentration of activated CCN depends of the local supersaturation and predicted concentration of previously activated CCN.
- various mixing scenarios for subgrid-scale mixing: homogeneous (h) or extremely inhomogeneous (ex)
- assumed background aerosol concentration: pristine (100 mg^{-1}) or polluted (1000 mg^{-1})
- Simulated case: **BOMEX**: setup from Siebesma et al. (2003) domain: 6.4 km × 6.4 km × 3 km; 50 m × 50 m × 20 m Δt =1s, analyzed time: 3-6 h of simulations
- Sensitivity tests: in-cloud activation turned off (activation suppressed above 700m)

Snapshot of the cloud water field (violet isosurface) and the activation tendency (black isosurface) for the pristine homogeneous case.



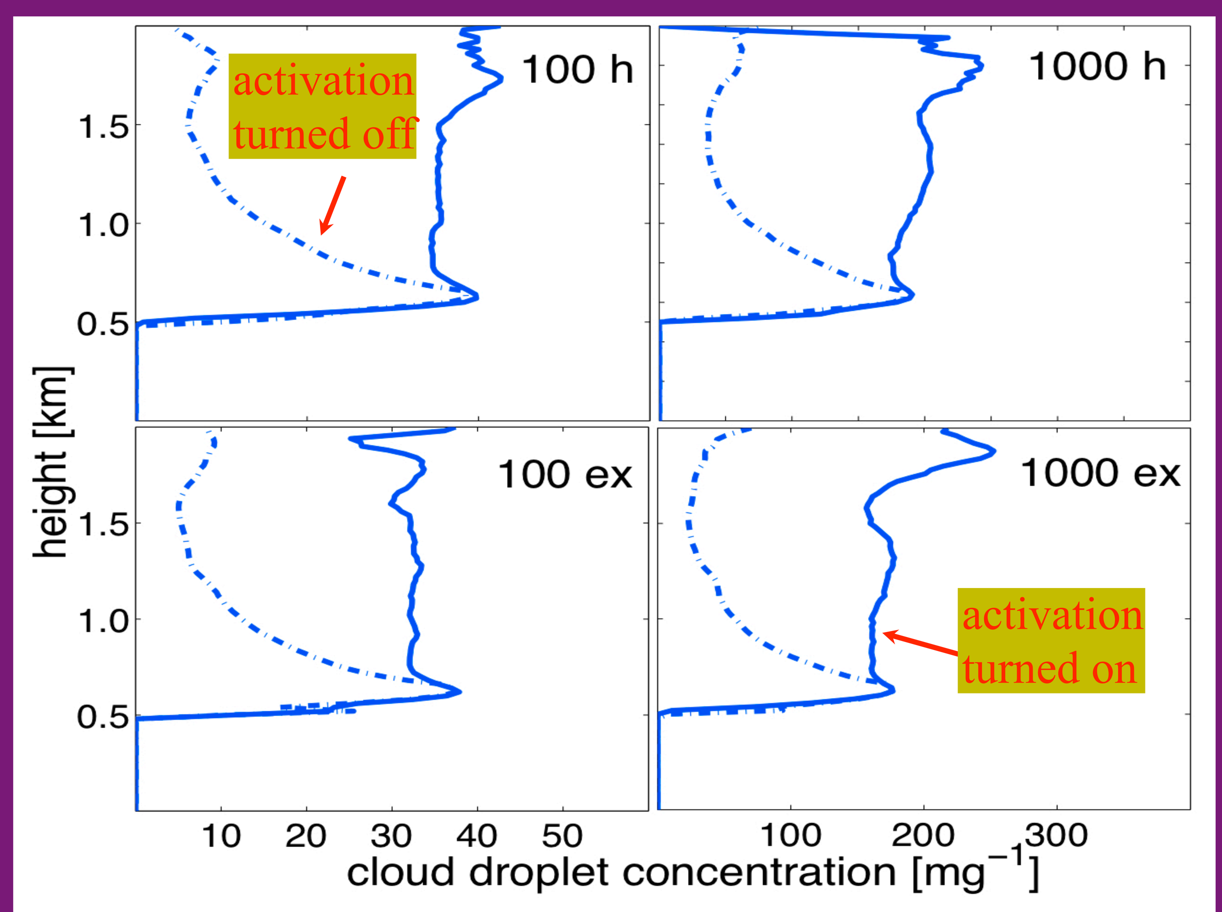
The in-cloud activation occurs in specific places, typically well inside a cloud near edges of the maximum updraft, the largest droplet concentration, and the largest supersaturation.

This pattern seems to mimic entrainment-related activation seen in previous high-resolution simulations of shallow convective clouds (Brenguier and Grabowski 1993).



Horizontal cross-section, with x and y distance in km, through a selected cloud at a height of 900 m. The cloud boundary is marked by the thick black solid contour of q_c = 0.01 g kg^{-1}. Colored fields are (upper panel): the **effective radius** r_c [µm]; **cloud droplet activation tendency** $f(N_c)_{act}$ [mg^{-1} s^{-1}]; **cloud droplet concentration** N_c [mg^{-1}]; (lower panel): the **vertical velocity** w [m s^{-1}]; **supersaturation tendency** f(δ) [s^{-1}]; **supersaturation** δ [-]

THE IMPACT OF IN-CLOUD ACTIVATION



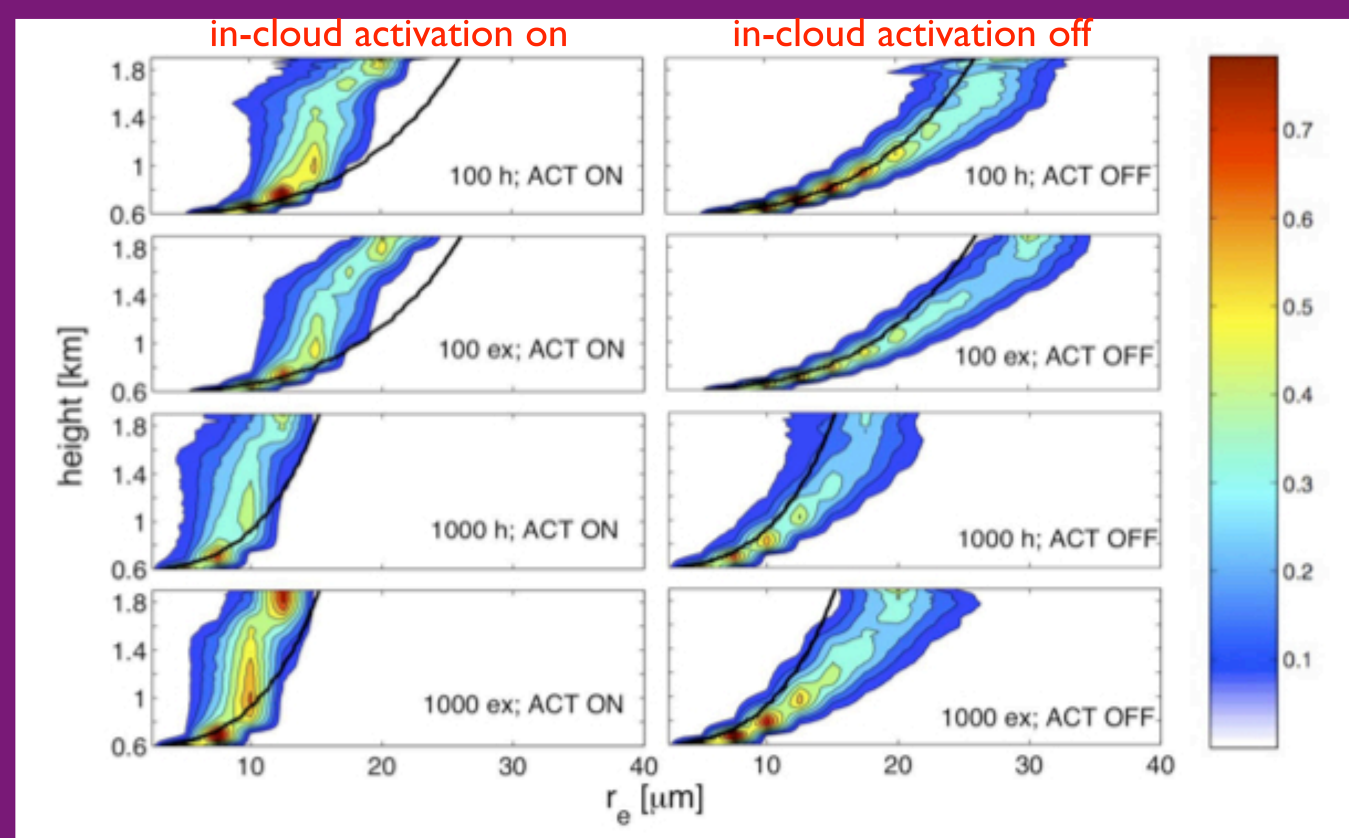
The mean cloud droplet concentrations reach similar values near the cloud base in simulations with and without in-cloud activation, namely around 40 and 200 mg^{-1} in pristine and polluted cases.

The mean concentrations are approximately constant with height in simulations that allow in-cloud activation, but they decrease strongly when in-cloud activation is suppressed.

Significant in-cloud activation is needed to maintain the approximately constant-with-height mean cloud droplet concentration. 40 % of cloud droplets originate from CCN activated above the cloud base.

The simulated approximately constant-with-height mean cloud droplet concentration is broadly consistent with many cloud observations, including observations of Montana cumuli reported in Blyth and Latham (1985; 1991) and RICO trade-wind cumuli discussed in Gerber et al (2008) and in Arabas et al. (2009).

MICROPHYSICAL AND OPTICAL PROPERTIES OF SIMULATED CLOUDS



CFADs of the effective radius and profiles of the adiabatic effective radius (black lines) for constant droplet concentrations of 40 and 200 mg^{-1} for pristine and polluted cases, respectively.

Table 2: Optical thickness (τ), mean effective radius ($\bar{r}_e$), mean TOA albedo (A_{cloudy}) and cloud droplet lifetime (τ_d) for pristine (100) or polluted (1000) cases with homogeneous (h) or extremely inhomogeneous (ex) mixing scenario, with in-cloud activation turned on (ACT ON) or off (ACT OFF). See text for details.

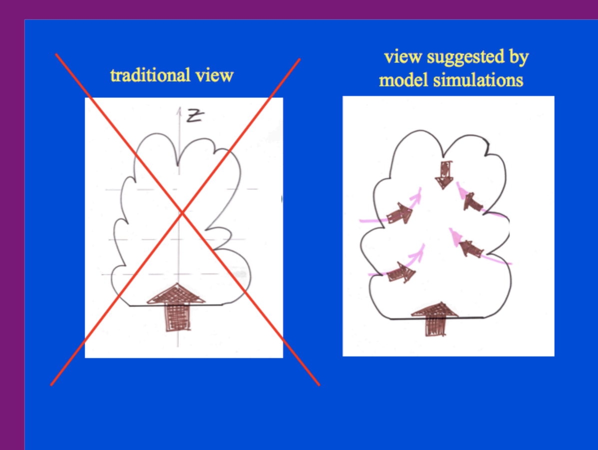
	τ	$\bar{r}_e$ [µm]	A_{cloudy}	τ_d [min]
100 h; ACT ON	6.28	18.37	0.270	4.00
100 ex; ACT ON	5.64	18.77	0.265	3.20
1000 h; ACT ON	9.68	11.37	0.347	3.48
1000 ex; ACT ON	8.52	11.71	0.338	2.91
100 h; ACT OFF	5.14	24.62	0.238	4.20
100 ex; ACT OFF	5.48	27.43	0.233	3.48
1000 h; ACT OFF	7.37	15.61	0.308	4.53
1000 ex; ACT OFF	6.93	17.71	0.289	3.71

The in-cloud activation significantly affects the vertical distribution of the effective radius and thus the mean albedo of the cloud field.

In-cloud activation reduces the mean effective radius below the adiabatic value.

Without in-cloud activation, cloud droplets show significant super-adiabatic growth.

Neglecting in-cloud activation has a significant impact on the cloud albedo. It changes from 0.27 to 0.24 for pristine homogeneous case.



CONCLUSIONS

Activation of cloud droplets above the cloud base is essential for realistic simulation of cloud microphysics.

In simulations reported here, about 40% of cloud droplets is activated above the cloud base.

Key features of observed shallow cumuli, such as the constant with height mean cloud droplet concentration is only simulated if in-cloud activation is allowed.

Activation seems to mimic entrainment-related activation observed in higher-resolution cloud simulation.

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