Modeling condensation in nonhydrostatic cloud-scale models

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Grabowski, W. W., and D. Jarecka, 2015: Modeling condensation in shallow nonprecipitating convection. *J. Atmos. Sci*., **72**, 4661-4679.

Grabowski W. W., and H. Morrison, 2016: Modeling condensation in deep convection. *J. Atmos. Sci*. (in review).

BULK MODEL OF CONDENSATION:

$$\frac{D\theta}{Dt} = \frac{L_v\theta}{c_pT}C_d$$

$$\frac{Dq_v}{Dt} = -C_d$$

$$\frac{Dq_c}{Dt} = \quad C_d$$

θ - potential temperature
q_v - *water vapor* mixing ratio
q_c - *cloud water* mixing ratio
L_v - latent heat of condensation/evaporation
C_d - condensation rate
Note: θ/T function of pressure only ($\approx \theta_e/T_e$, i.e., environmental hydrostatic pressure)

C_d is defined such that cloud is always at saturation:

$$q_c = 0 \quad \text{if} \quad q_v < q_{vs}$$

$$q_c > 0 \quad \text{only if} \quad q_v = q_{vs}$$

where $q_{vs}(p,T) = 0.622\dfrac{e_s(T)}{p - e_s(T)}$ is the water vapor mixing ratio at saturation

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Simple and easy: just 3 variables, straightforward numerics (e.g., no limit on time step…)

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COMPREHENSIVE MODEL OF CONDENSATION:

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$$C_d \sim N \, \frac{dm}{dt}$$

N - droplet concentration, $\frac{dm}{dt}$ - droplet mass growth rate

$$\frac{dr}{dt} = A \, \frac{S}{r} \; , \quad A = A(p,T) \; , \quad S - \text{supersaturation}$$

$$S = \frac{q_v}{q_{vs}} - 1$$

$$C_d \sim N \; r \; S$$

$$\boxed{C_d \sim N \; r \; S}$$

DOUBLE-MOMENT SCHEME:

$$\frac{D\theta}{Dt} = \frac{L_v \theta}{c_p T} C_d$$

$$\frac{Dq_v}{Dt} = -C_d$$

$$\frac{Dq_c}{Dt} = C_d$$

$$\frac{DN_c}{Dt} = S_{act}$$

4 variables…

BIN SCHEME:

$$\frac{D\theta}{Dt} = \frac{L_v \theta}{c_p T} \sum_{i=1}^{N} C_d^{(i)}$$

$$\frac{Dq_v}{Dt} = -\sum_{i=1}^{N} C_d^{(i)}$$

$$\frac{Dq_c^{(i)}}{Dt} = C_d^{(i)} + S_{act}^{(i)}$$

$i = 1, N$ – number of bins

dozen(s) variables…

$$\boxed{C_d \sim N \; r \; S}$$

More complicated:

- Prediction of S (cumbersome!)
- Bin: dozens of variables
- More involved time integration, often time sub-stepping wrt dynamics needed

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$i = 1, N$ – number of bins

dozen(s) variables…

All single-moment bulk microphysical schemes and most double-moment bulk schemes use bulk condensation…

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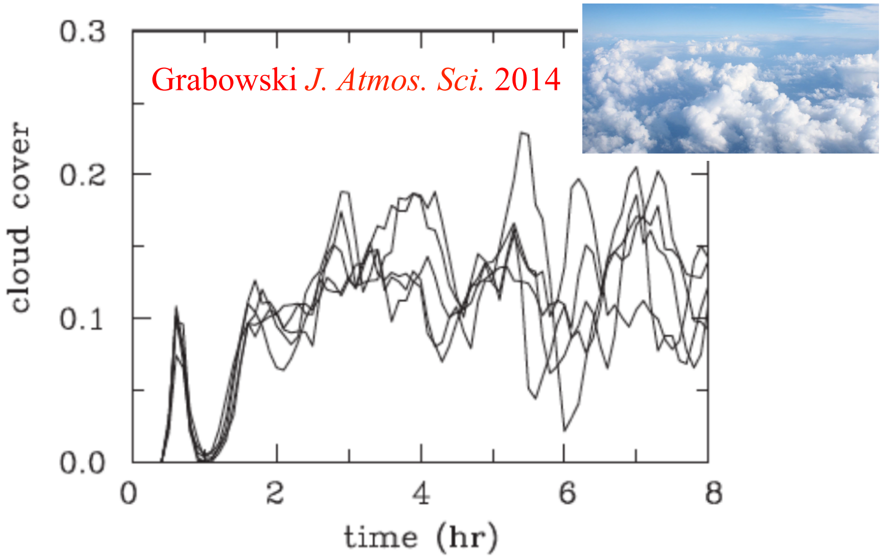
Does it matter for the simulated cloud dynamics?

Methodology:

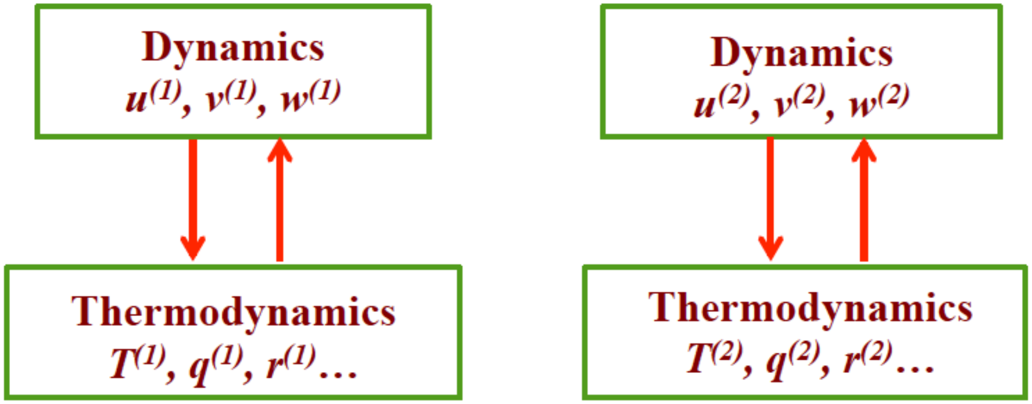
Because of the nonlinear fluid dynamics, separating physical impacts from the effects of different flow realizations (“the butterfly effect”; Ed Lorenz) is nontrivial.



Grabowski *J. Atmos. Sci.* 2014

Evolution of cloud cover in 5 simulations of shallow cumulus cloud field. The only difference is in random small temperature and moisture perturbations at t=0.

Traditional approach: parallel simulations with different microphysical schemes or scheme parameters



Dynamics
$u^{(1)}, v^{(1)}, w^{(1)}$

Thermodynamics
$T^{(1)}, q^{(1)}, r^{(1)} \ldots$

scheme or parameter (1)

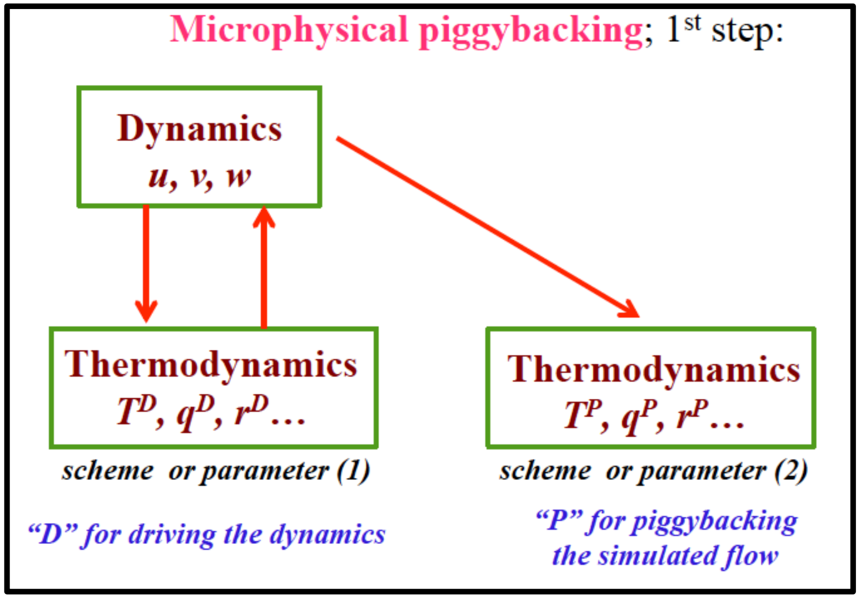
Dynamics
$u^{(2)}, v^{(2)}, w^{(2)}$

Thermodynamics
$T^{(2)}, q^{(2)}, r^{(2)} \ldots$

scheme or parameter (2)

The separation is traditionally done by performing parallel simulations where each simulation applies modified model physics.

Novel modeling methodology*: the piggybacking*



Microphysical piggybacking; 1st step:

Dynamics
u, v, w

Thermodynamics
$T^D, q^D, r^D\ldots$

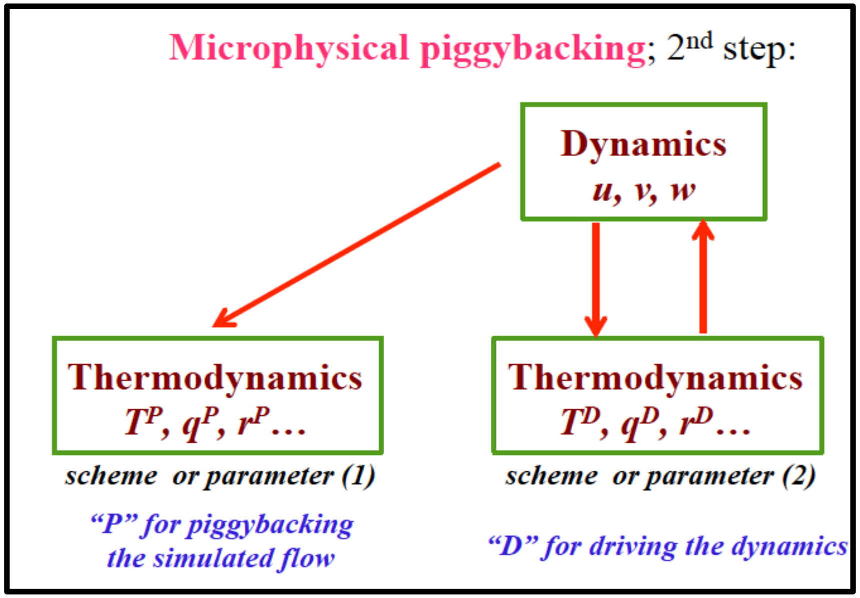
scheme or parameter (1)

"D" for driving the dynamics

Thermodynamics
$T^P, q^P, r^P\ldots$

scheme or parameter (2)

"P" for piggybacking the simulated flow



Microphysical piggybacking; 2nd step:

Dynamics
u, v, w

Thermodynamics
$T^P, q^P, r^P\ldots$

scheme or parameter (1)

"P" for piggybacking the simulated flow

Thermodynamics
$T^D, q^D, r^D\ldots$

scheme or parameter (2)

"D" for driving the dynamics

Grabowski, W. W., 2014: Extracting microphysical impacts in large-eddy simulations of shallow convection. *J. Atmos. Sci*. **71**, 4493-4499.

Grabowski, W. W., 2015: Untangling microphysical impacts on deep convection applying a novel modeling methodology. *J. Atmos. Sci*., **72**, 2446-2464.

Grabowski, W. W., and D. Jarecka, 2015: Modeling condensation in shallow nonprecipitating convection. *J. Atmos. Sci*., **72**, 4661-4679.

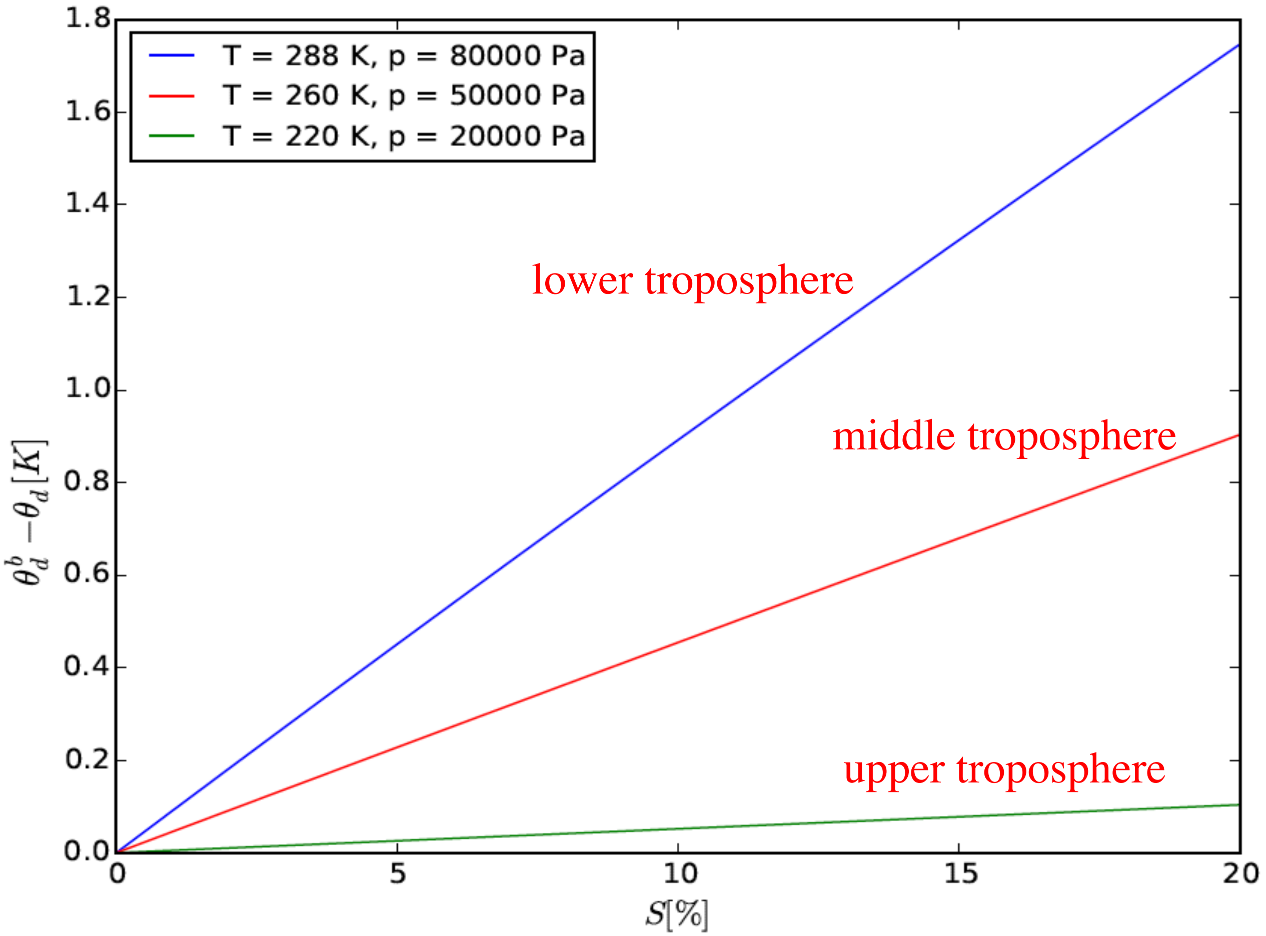
Grabowski, W. W., and H. Morrison, 2016: Untangling microphysical impacts on deep convection applying a novel modeling methodology. Part II: Double-moment microphysics. *J. Atmos. Sci*., **73**, 3749--3770.

Grabowski W. W., and H. Morrison, 2016: Modeling condensation in deep convection. *J. Atmos. Sci*. (submitted).

Theoretical considerations: impact of a finite supersaturation on cloud buoyancy

Grabowski and Jarecka *JAS* 2015

$$\theta_d^b \approx \theta_d + \Delta q \, \frac{L}{c_p} \left(\frac{p_o}{p} \right)^{R_d/c_p} (1 + \epsilon q_v - q_c)$$

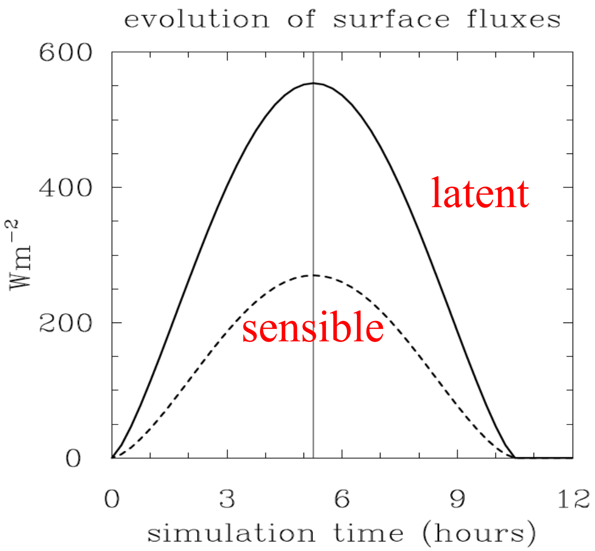


Impact of finite supersaturations on cloud buoyancy in deep convection

Q. J. R. Meteorol. Soc. (2006), **132**, pp. 317–344 doi: 10.1256/qj.04.147

Daytime convective development over land: A model intercomparison based on LBA observations

By W. W. GRABOWSKI[1]*, P. BECHTOLD[2], A. CHENG[3], R. FORBES[4], C. HALLIWELL[4],
M. KHAIROUTDINOV[5], S. LANG[6], T. NASUNO[7], J. PETCH[8], W.-K. TAO[6], R. WONG[8],
X. WU[9] and K.-M. XU[3]



Cloud-resolving simulations of LBA shallow to deep convection transition applying piggybacking methodology:

- 50 x 50 x 24 km^3 domain;

- 400 m horizontal gridlength;

- stretched grid in the vertical: 81 levels, ~50 m near the surface, ~300 m in the middle troposphere, ~600 m near the upper boundary;

- 4 s time step;

- run for 12 hrs, 3D fields saved every 6 min, time-averaged surface rain saved every 3 min.

Simulations with double-moment bulk microphysics of Morrison and Grabowski (*JAS* 2007, 2008a,b):

SPRE: predicting supersaturation
SADJ: applying saturation adjustment

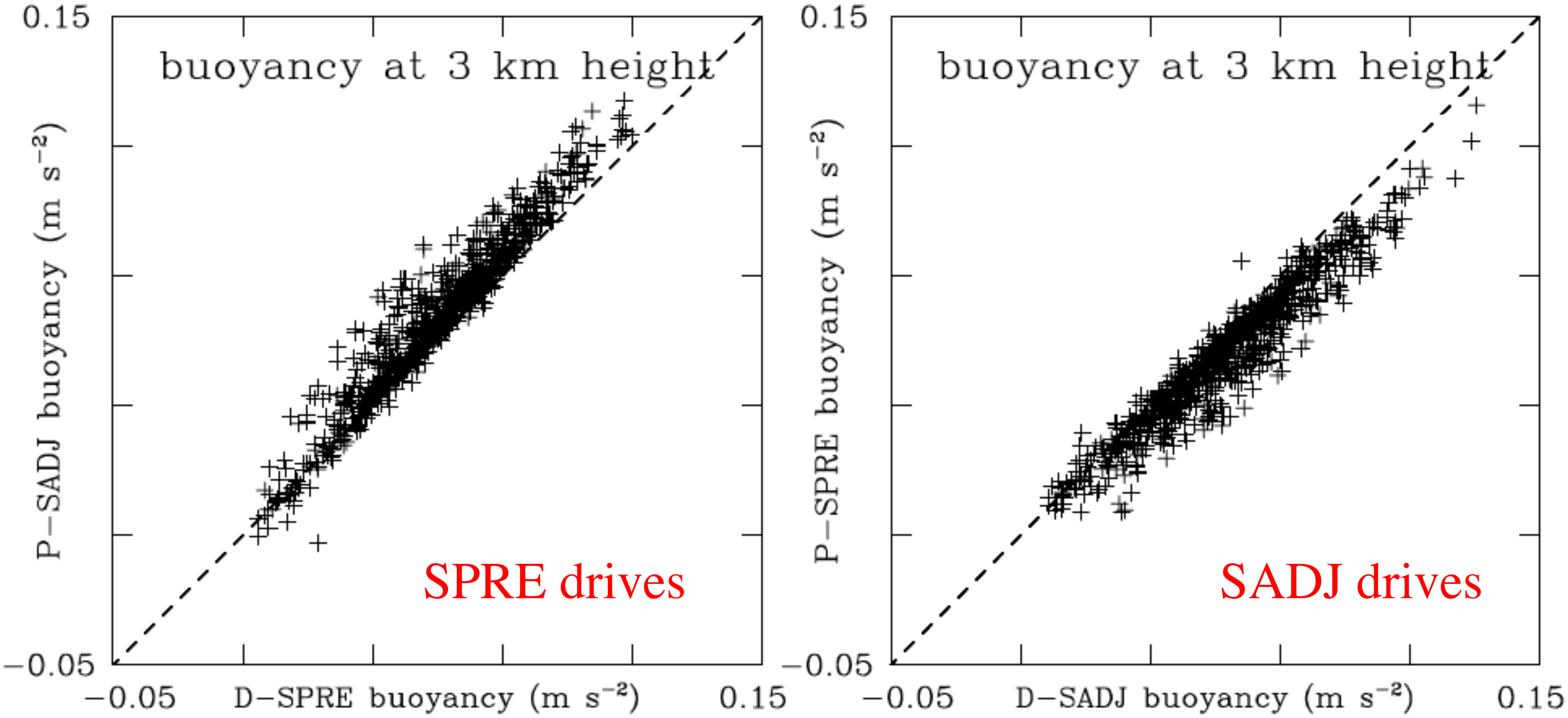
Vertical-velocity-based CCN activation parameterization
(100, 200, 300, 400 cm^{-3} droplet activated at 1, 5, 10 and 20 m s^{-1})

the same ice initiation in SPRE and SADJ

Piggybacking: D-SPRE/P-SADJ: SPRE drives, SADJ piggybacks
D-SADJ/P-SPRE: SADJ drives, SPRE piggybacks

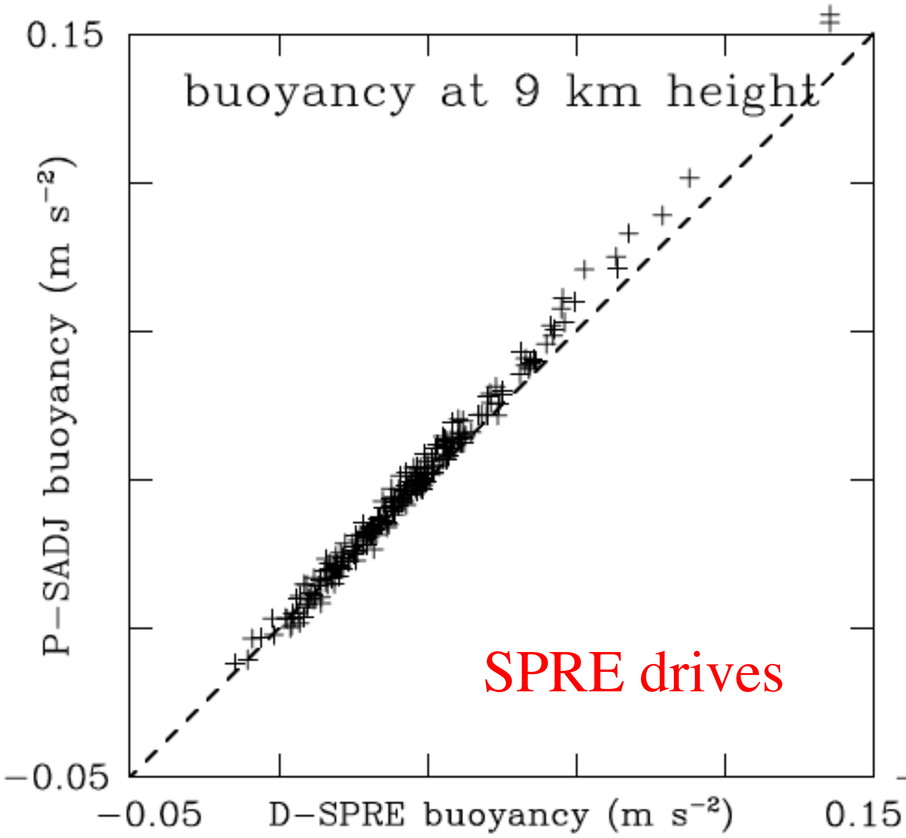
Five-member ensemble for each

Driver versus piggybacker buoyancy at 3 km (9^{o}C)

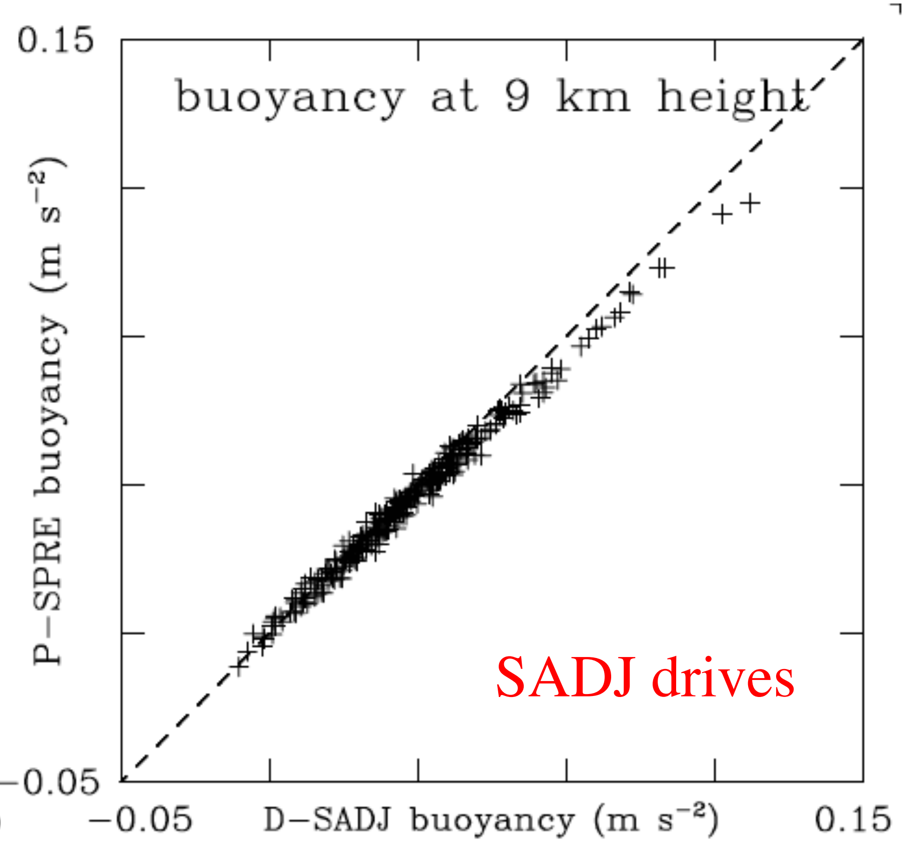


for gridpoints with w >1 m/s and $q_c+q_r+q_{id}+q_{ir} > 0.1$ g/kg

Driver versus piggybacker buoyancy at 9 km (-27^{o}C)

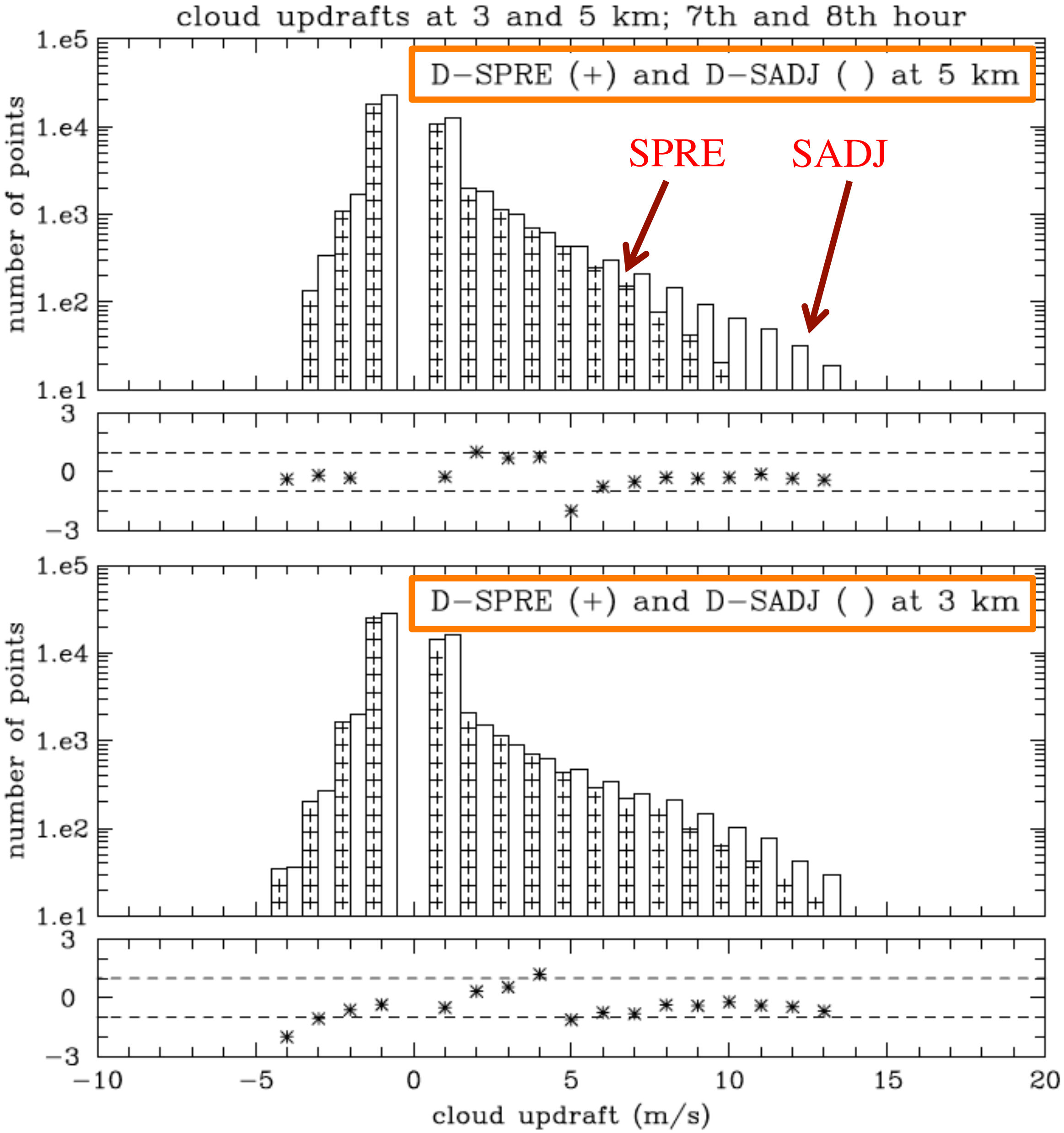


SPRE drives



SADJ drives

for gridpoints with w >1 m/s and $q_c+q_r+q_{id}+q_{ir} > 0.1$ g/kg



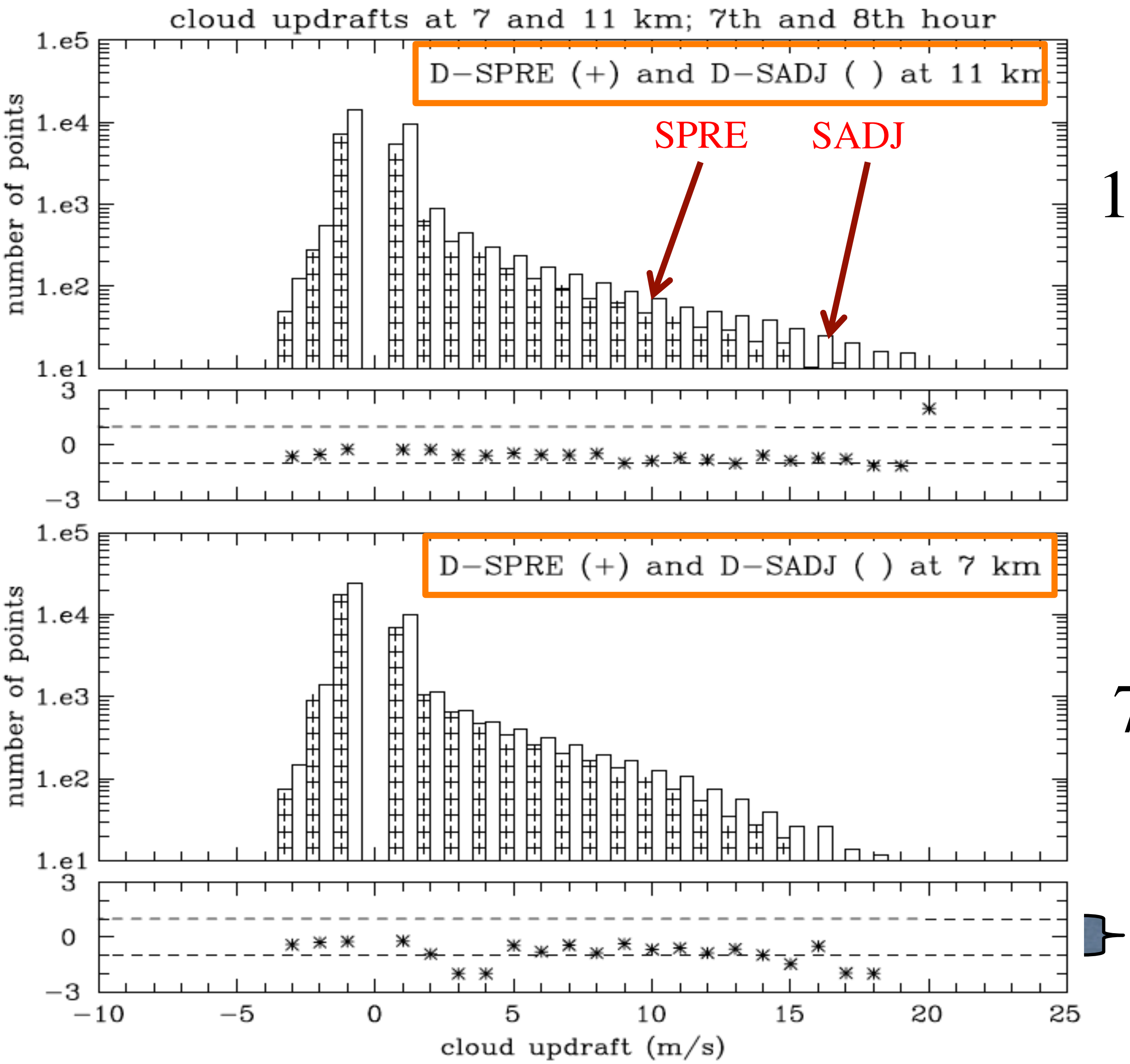
SPRE

SADJ

5 km

3 km

Difference is statistically significant (at 95% confidence level) if the star is inside this range



11 km

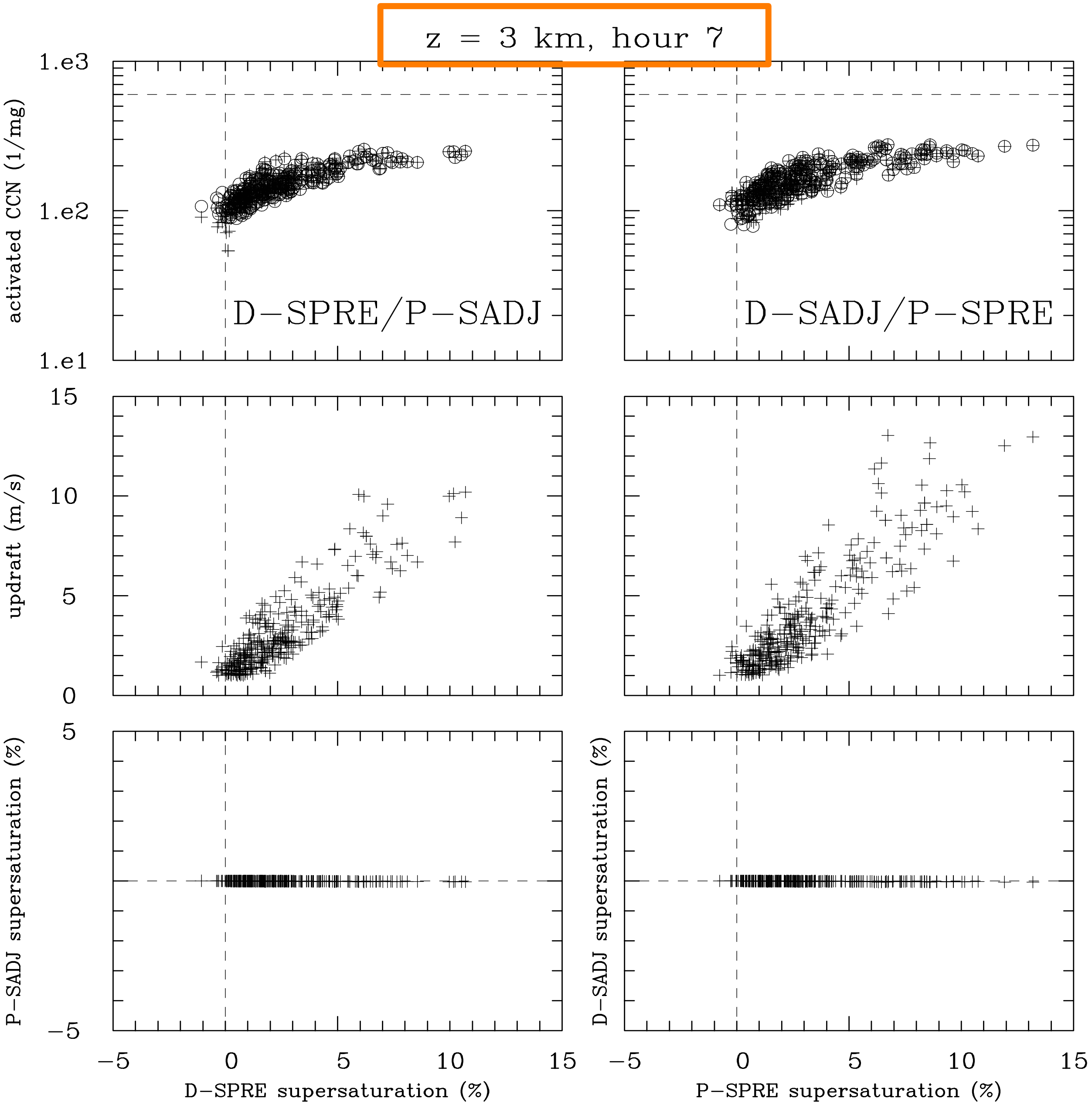
7 km

Difference is statistically significant (at 95% confidence level) if the star is inside this range

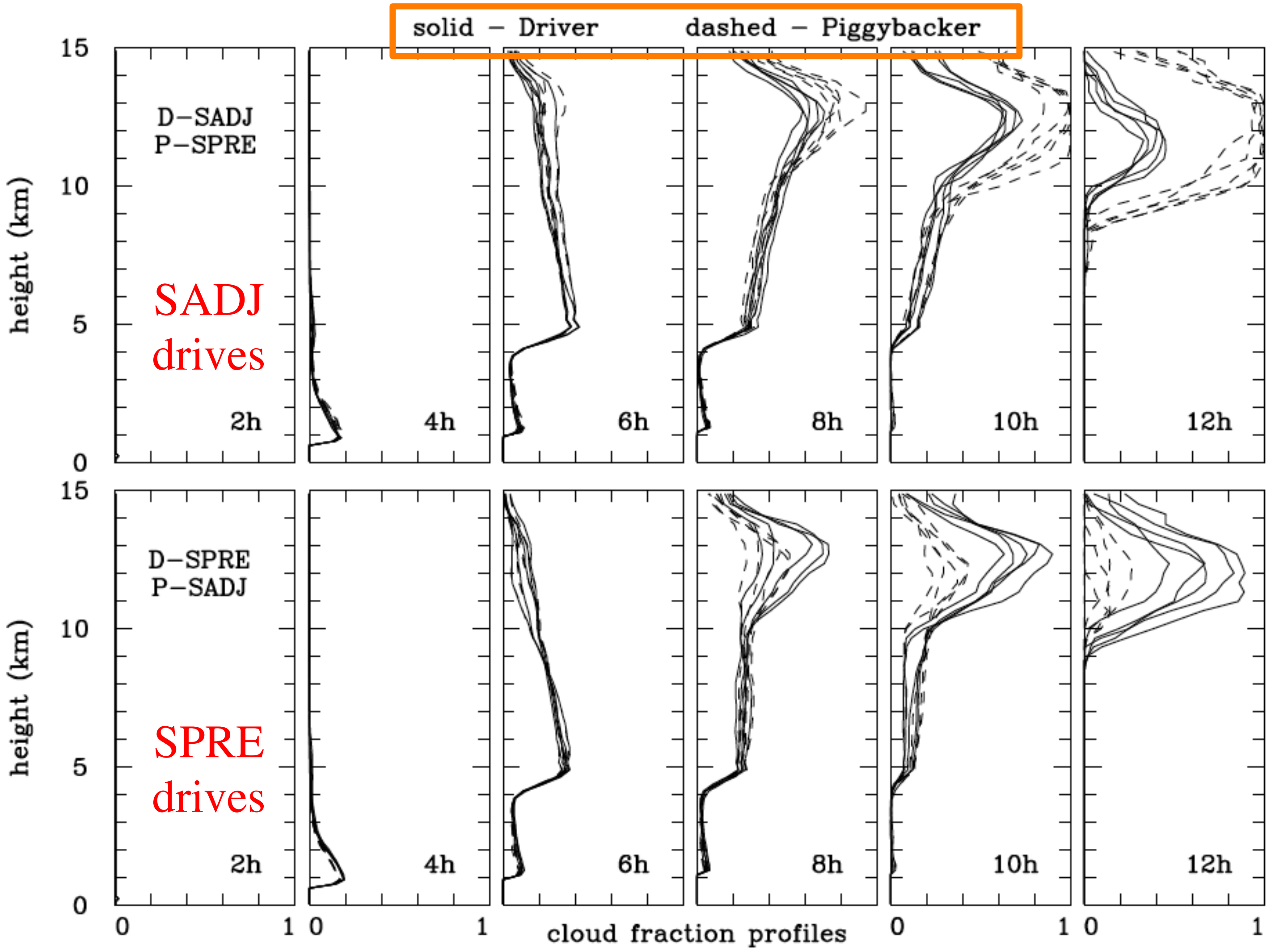
More CCN activated in stronger updrafts as expected…

Saturations increase with the updraft magnitude; stronger updrafts when SADJ drives…

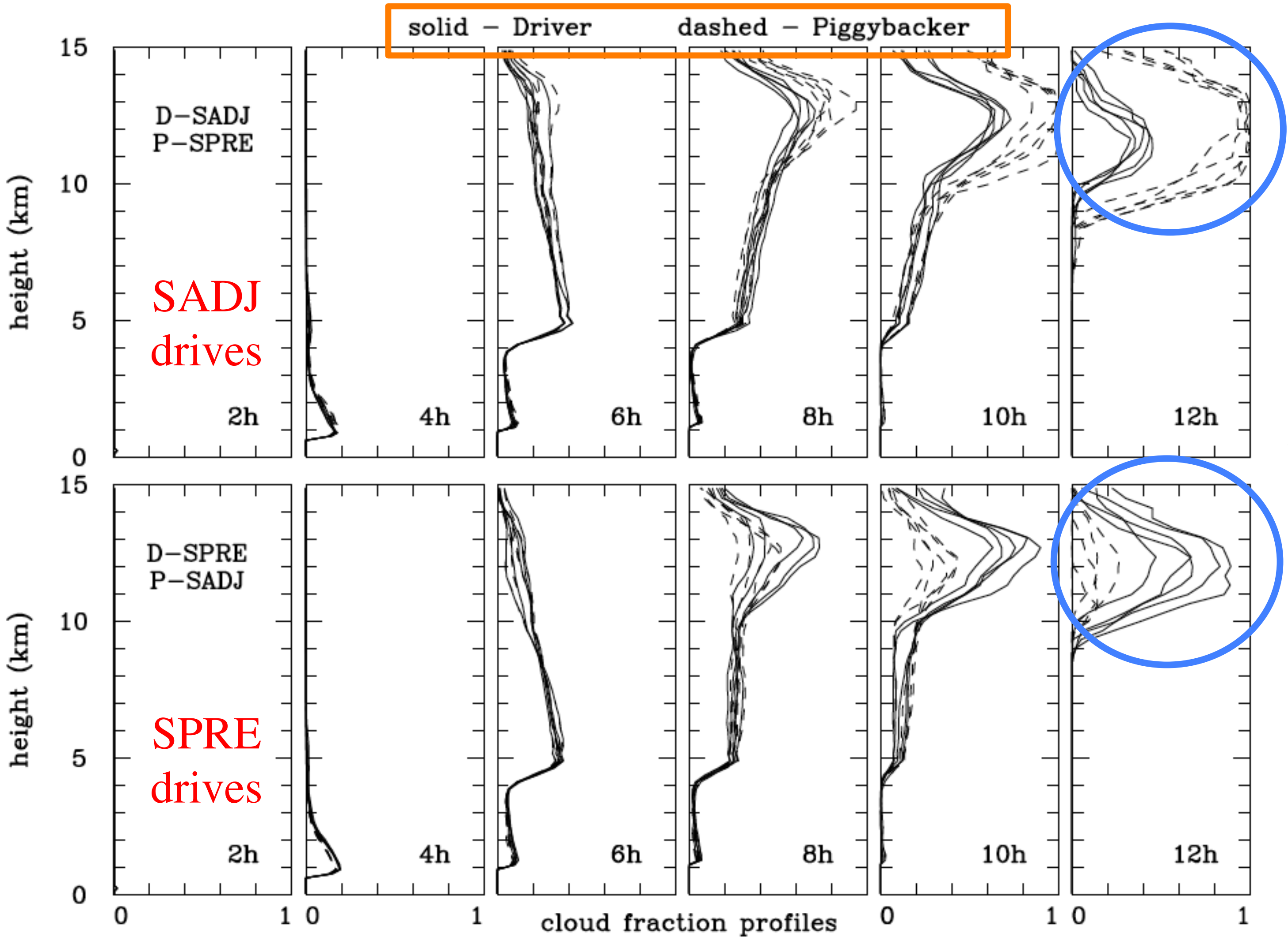
Saturation adjustment work correctly in SADJ; SPRE supersaturations are large…


z = 3 km, hour 7

evolution of cloud fraction profiles in 5-member ensembles D-SADJ/P-SPRE and D-SPRE/P-SADJ



evolution of cloud fraction profiles in 5-member ensembles D-SADJ/P-SPRE and D-SPRE/P-SADJ

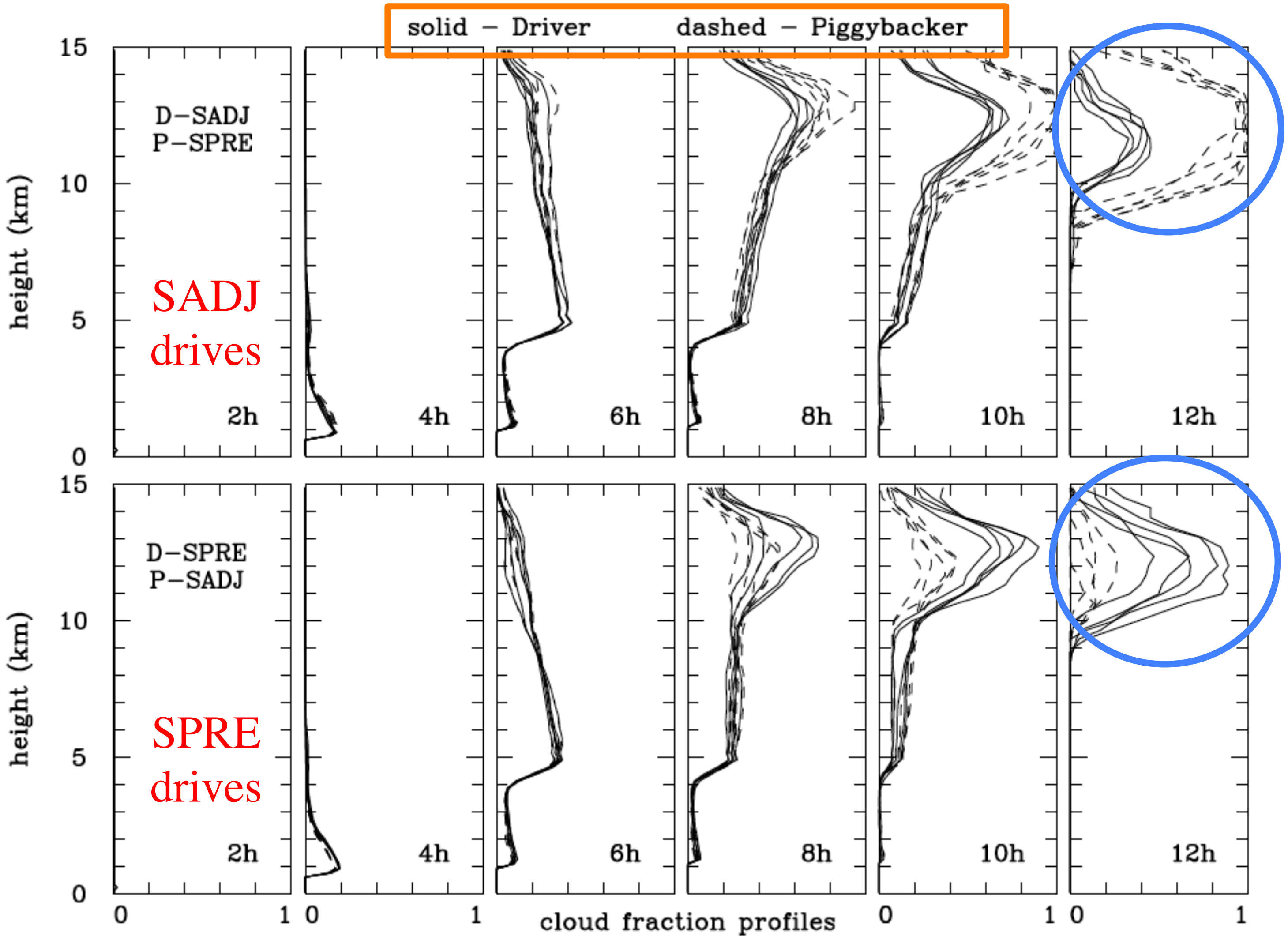


SADJ drives

SPRE drives

SPRE has much larger fractions of anvil clouds after convection ceases regardless which drives…

evolution of cloud fraction profiles in 5-member ensembles
D-SADJ/P-SPRE and D-SPRE/P-SADJ



SADJ drives

SPRE drives

larger fractions of anvil clouds are present when SADJ drives…

Conclusions:

Supersaturations in simulated deep convective updrafts are large, several percent. These are similar to pristine versus polluted CCN simulations in Grabowski and Morrison (*JAS* 2016).

These high supersaturations noticeably reduce cloud buoyancy and affect convective updraft statistics. Surface rainfall is about 3% larger when saturation adjustment is used.

There is a significant *microphysical* impact on convective anvils in the specific case considered and applying the specific supersaturation-dependent ice initiation scheme.