Separating dynamical and microphysical impacts of aerosols on deep convection applying piggybacking methodology

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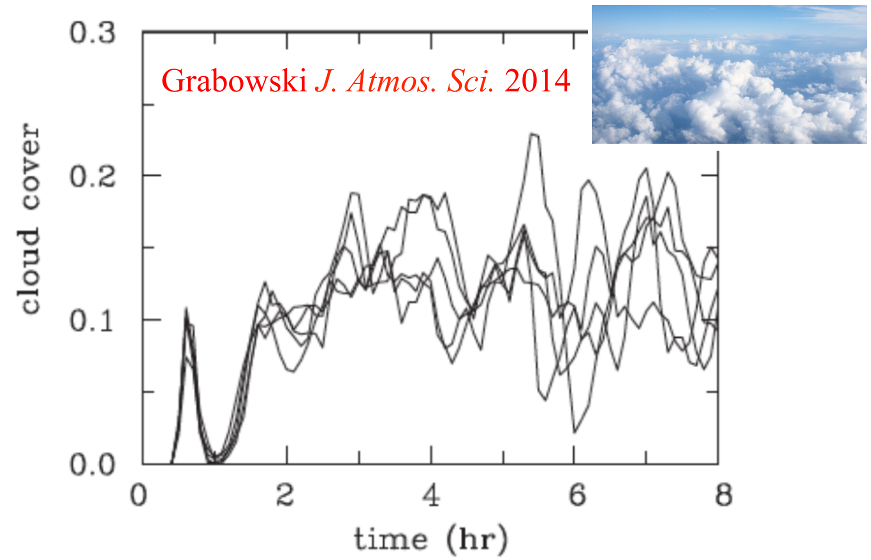
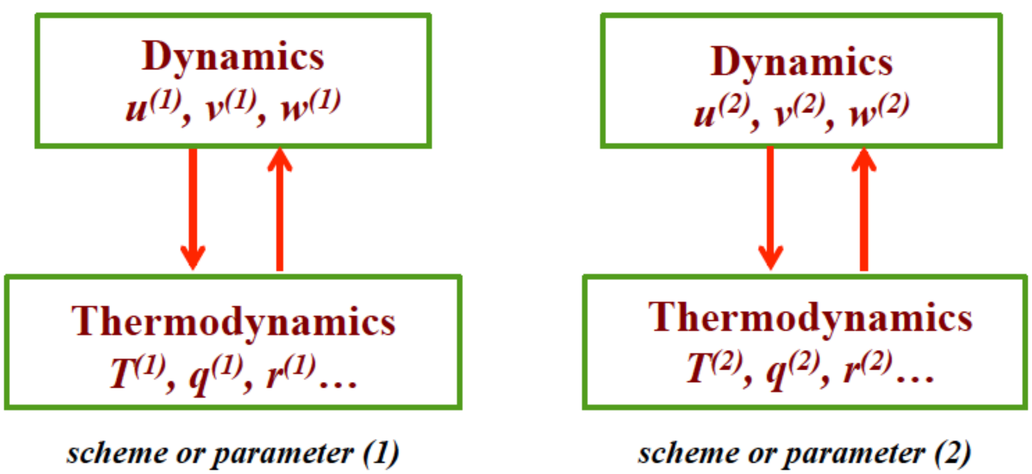
Methodology:

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



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.

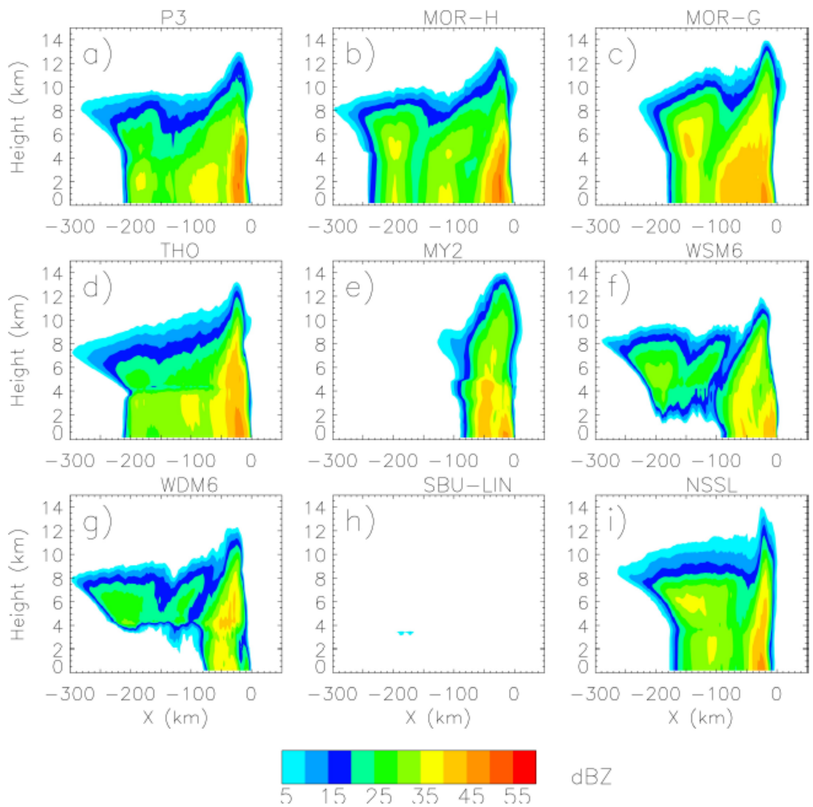
Traditional approach: parallel simulations with different microphysical schemes or scheme parameters



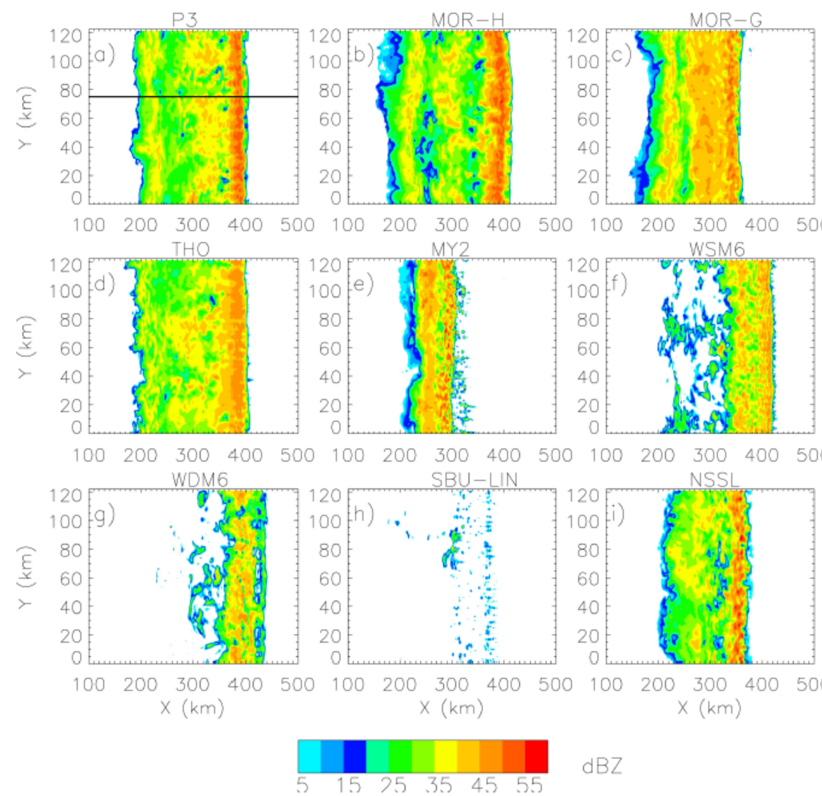
The separation is traditionally done by performing parallel simulations where each simulation applies modified model physics.

squall line simulations with different microphysics schemes:

y-averaged reflectivity



x-y reflectivity at ~1.1 km

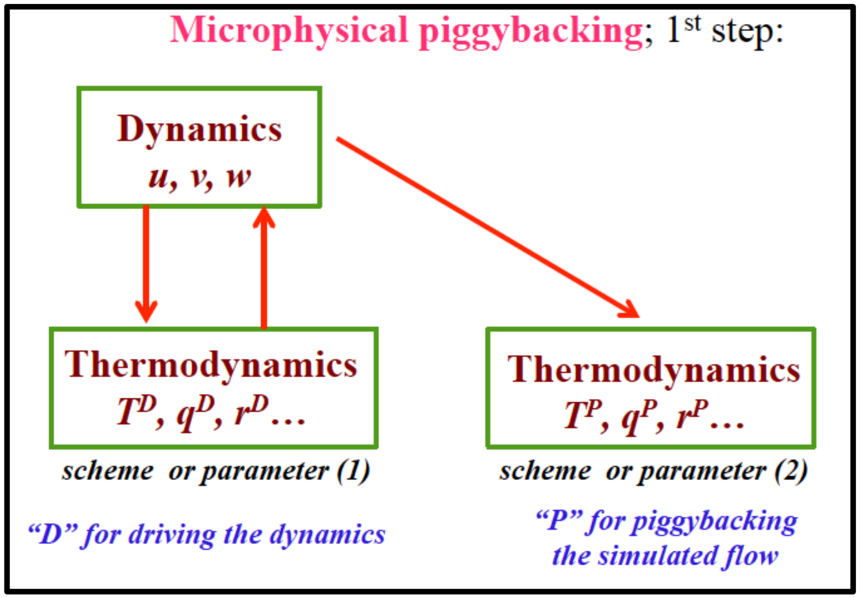


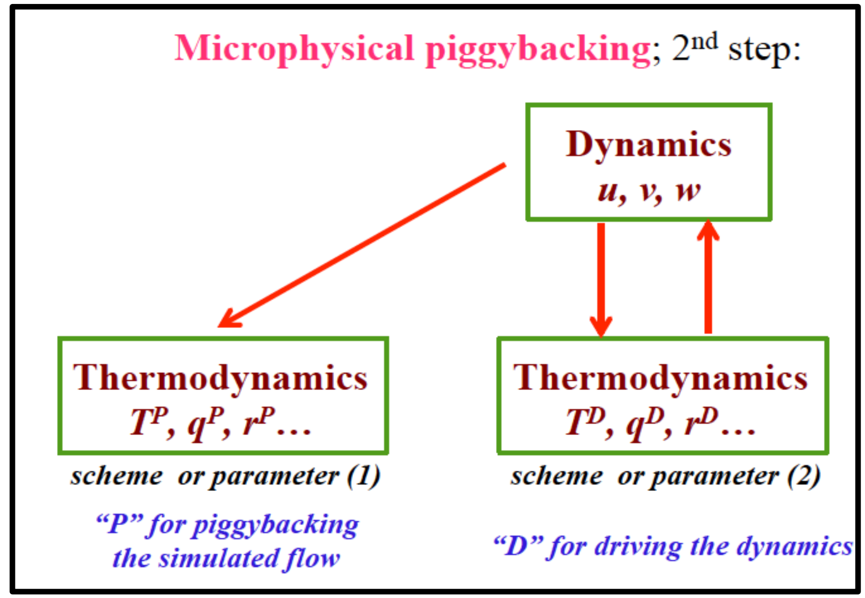
different flow realizations?

microphysics alone or microphysics impact on dynamics?

Morrison et al. *JAS* 2015

Novel modeling methodology: *the piggybacking*





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.

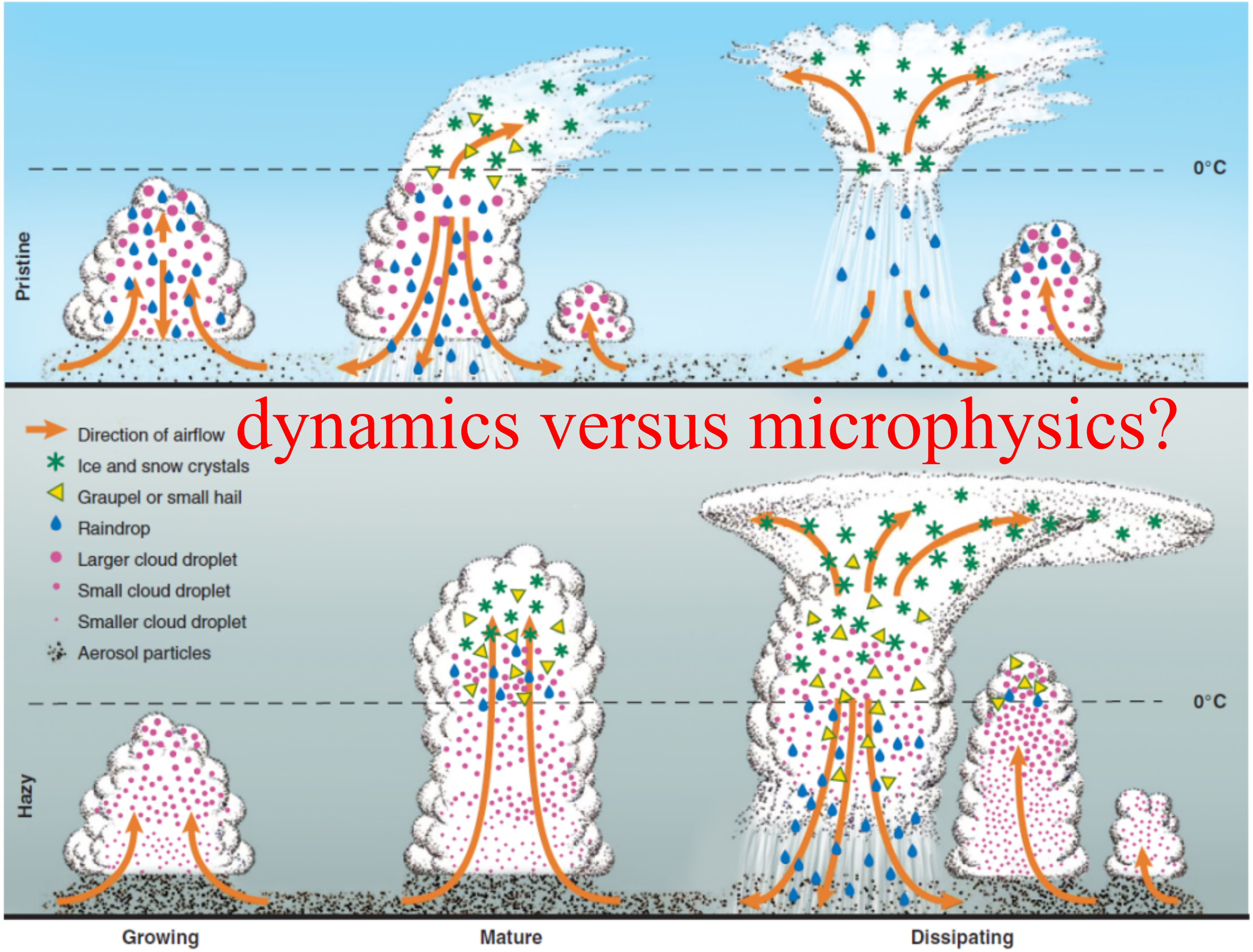
Grabowski, W. W., and D. Jarecka, 2015: Modeling condensation in shallow nonprecipitating convection. *J. Atmos. Sci*., **72**, 4661-4679.

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).

clean

polluted



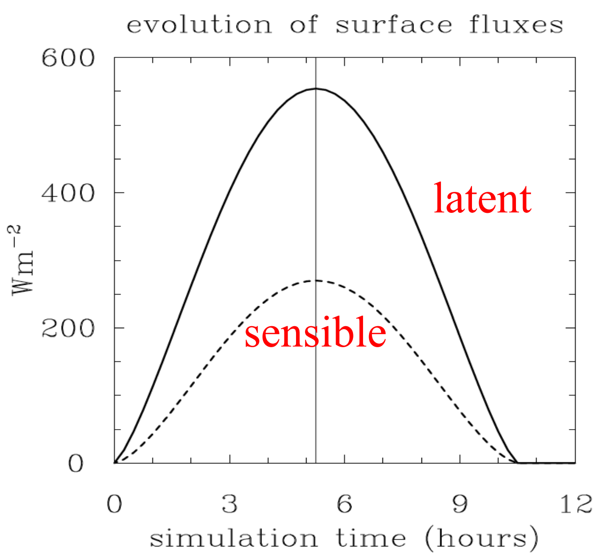
dynamics versus microphysics?

Rosenfeld et al. *Science*, 2008
"Flood or Drought: How Do Aerosols Affect Precipitation?"

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]



BabyEULAG cloud-resolving simulations of LBA shallow to deep convection transition applying piggybacking methodology with 2-moment bulk microphysics:

- 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):

N_c, q_c - cloud water
N_r, q_r - drizzle/rain water
N_i, q_{id}, q_{ir} - ice

Important differences from single-moment bulk schemes:

1. Supersaturation is allowed.
2. Ice concentration linked to droplet and drizzle/rain concentrations.

Lognormal single-mode CCN distribution:

$$f_d = \frac{dN_a}{dr_d} = \frac{N_t}{\sqrt{2\pi}\,\ln\sigma_d r_d}\exp\left[-\frac{\ln^2(r_d/r_{d0})}{2\ln^2\sigma_d}\right]$$

r_d is the dry aerosol radius

N_t is the total aerosol number — **PRI, pristine: 100 mg $^{-1}$**
POL, polluted: 1000 mg^{-1}

σ_d is the standard deviation — **2.0**

r_{d0} is the geometric mean radius of the dry particles — **0.05 µm**

as in Morrison and Grabowski (*JAS* 2007, 2008a)

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

PRI: pristine case, CCN of 100 per cc
POL: polluted case, CCN of 1,000 per cc

The same ice initiation for POL and PRI

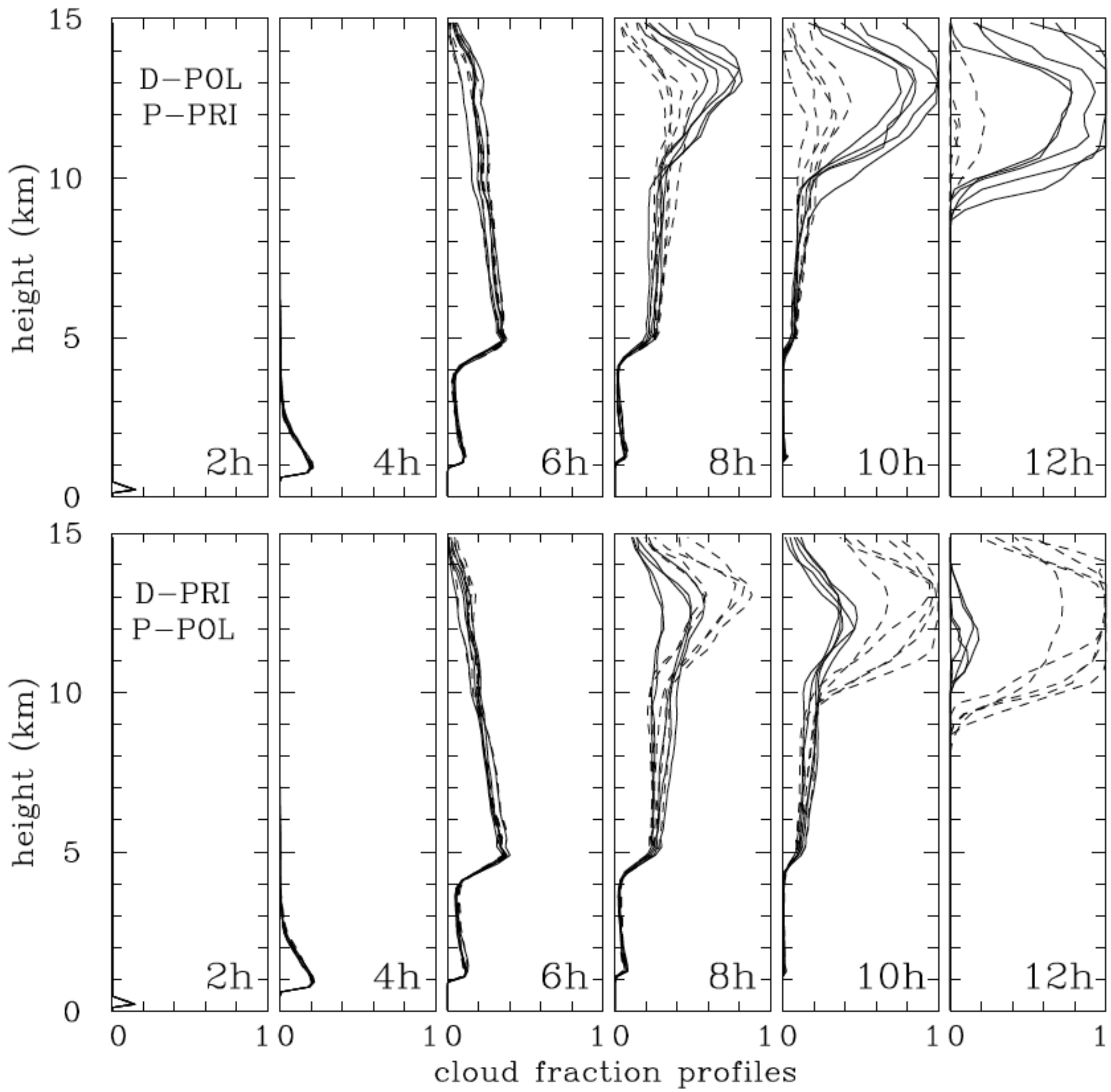
Piggybacking: D-PRI/P-POL: PRI drives, POL piggybacks
D-POL/P-PRI: POL drives, PRI piggybacks

Five-member ensemble for each

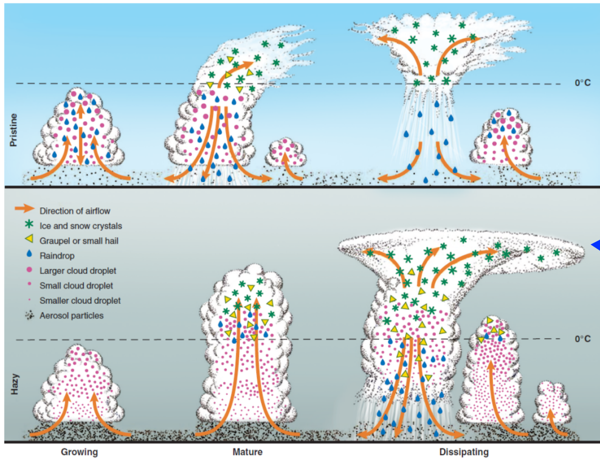
solid lines: driving set
dashed lines: piggybacking set

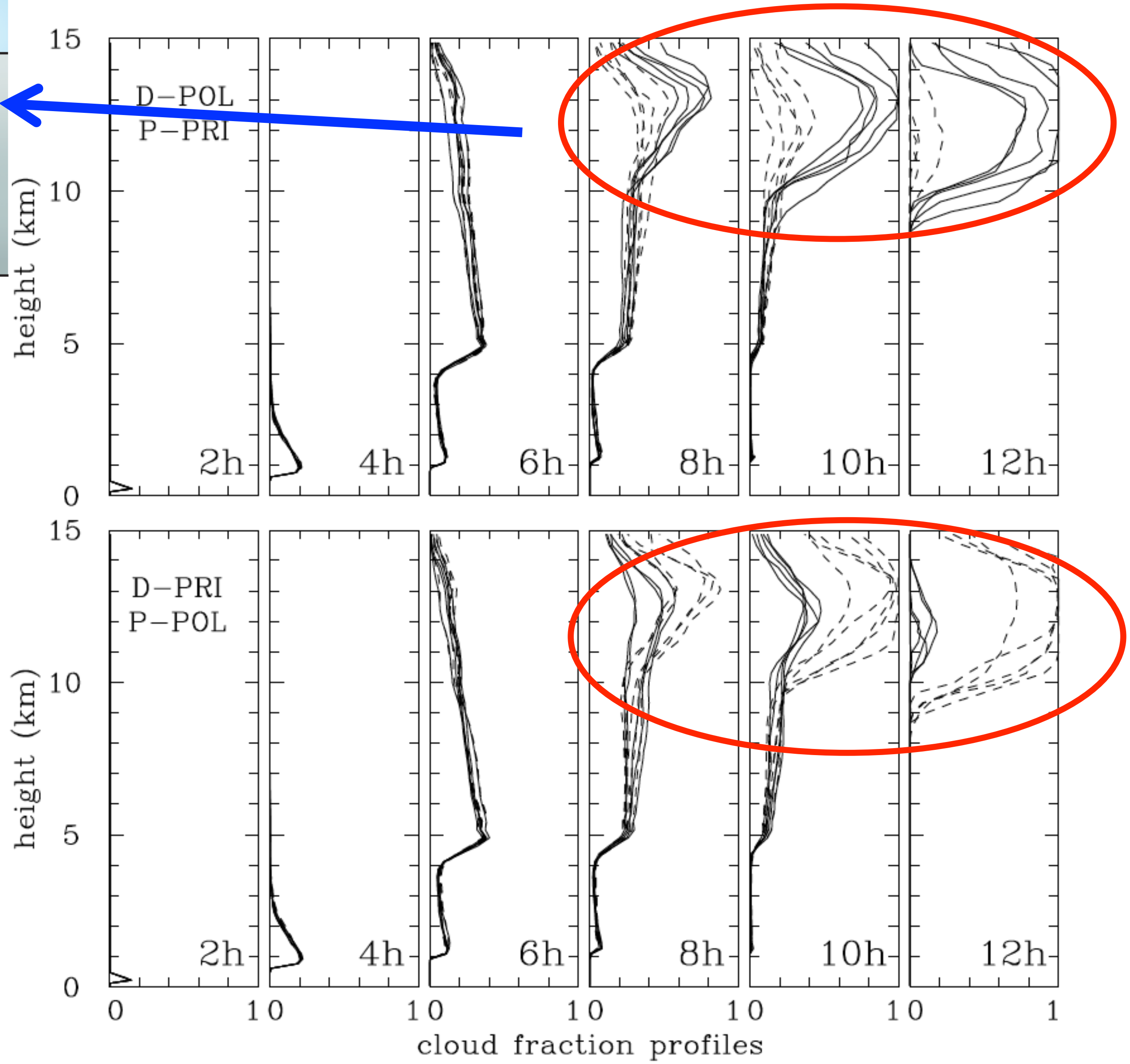
POL drives,
PRI piggybacks

PRI drives,
POL piggybacks



solid lines: driving set
dashed lines: piggybacking set





solid lines: driving set
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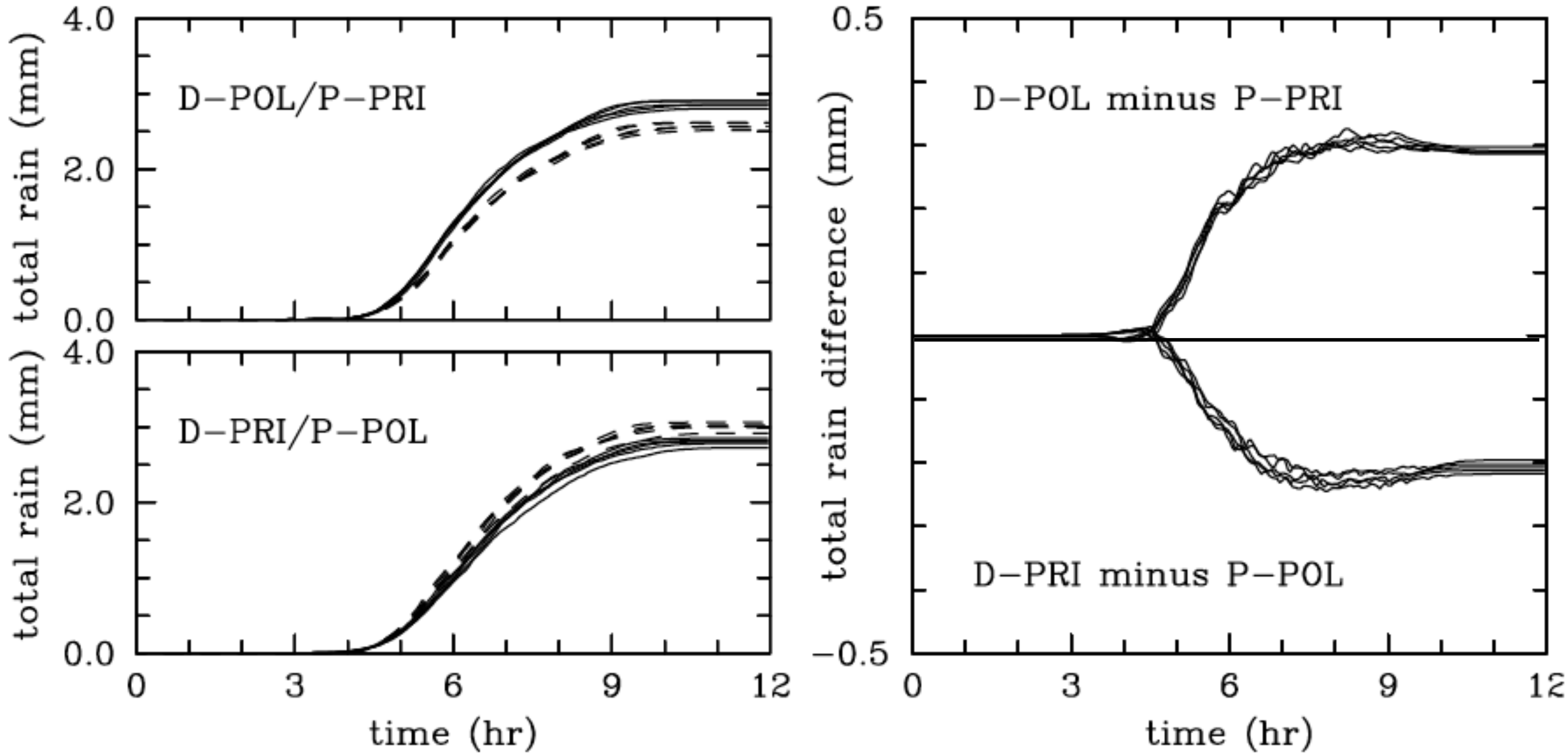
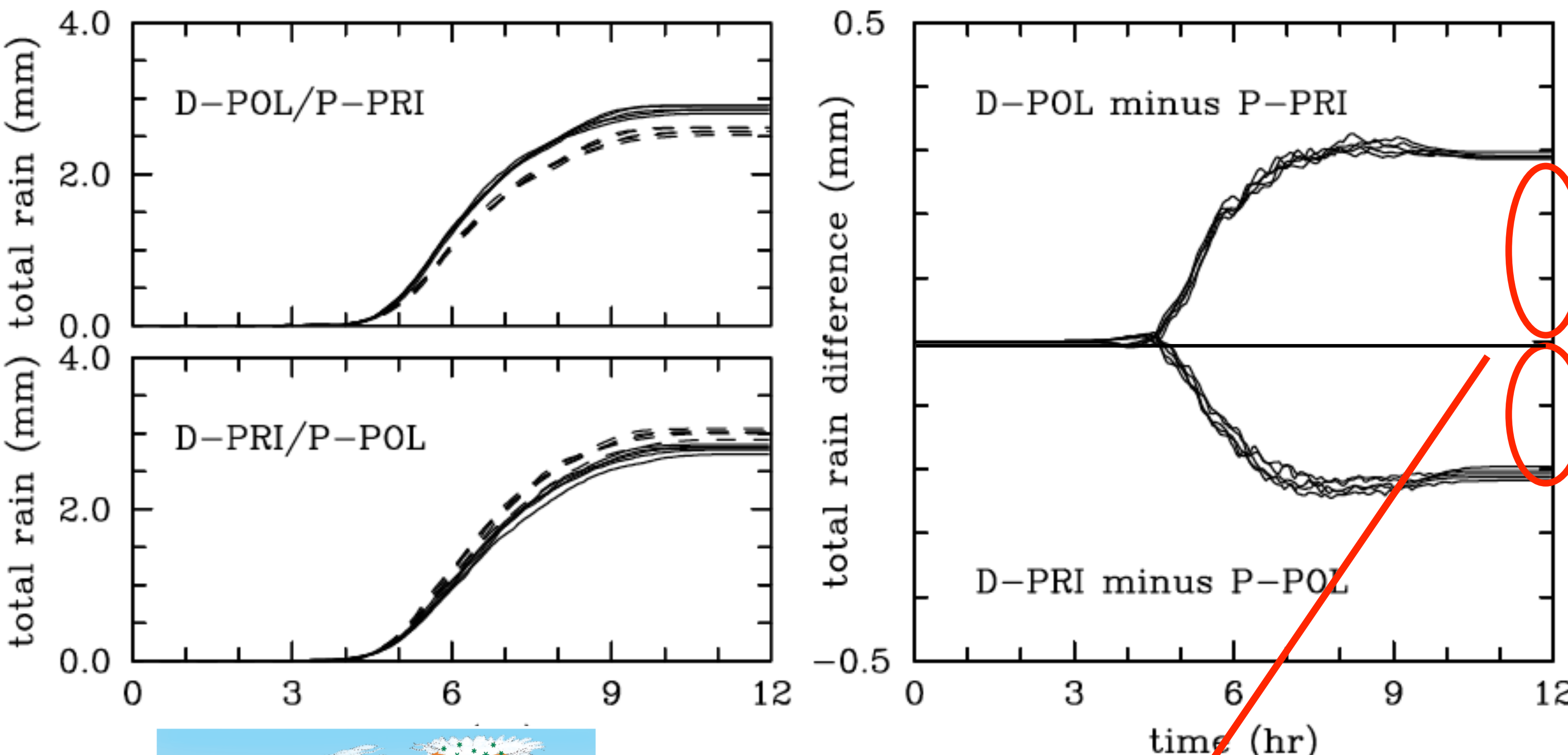
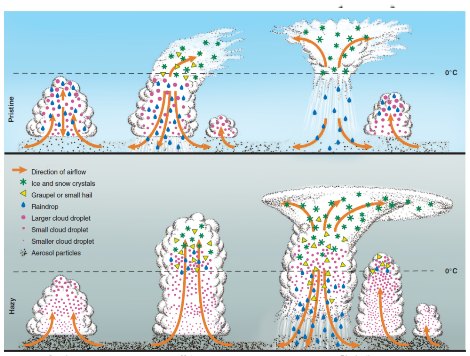


solid lines: driving set
dashed lines: piggybacking set

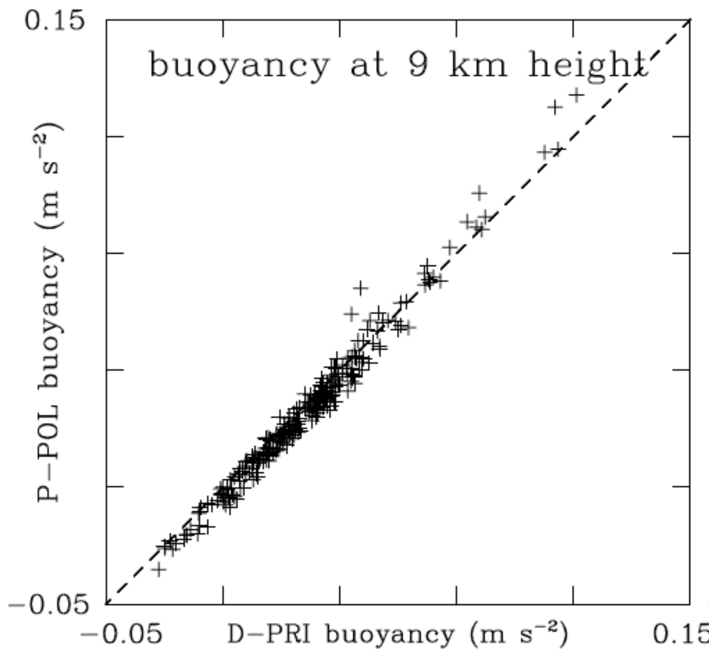




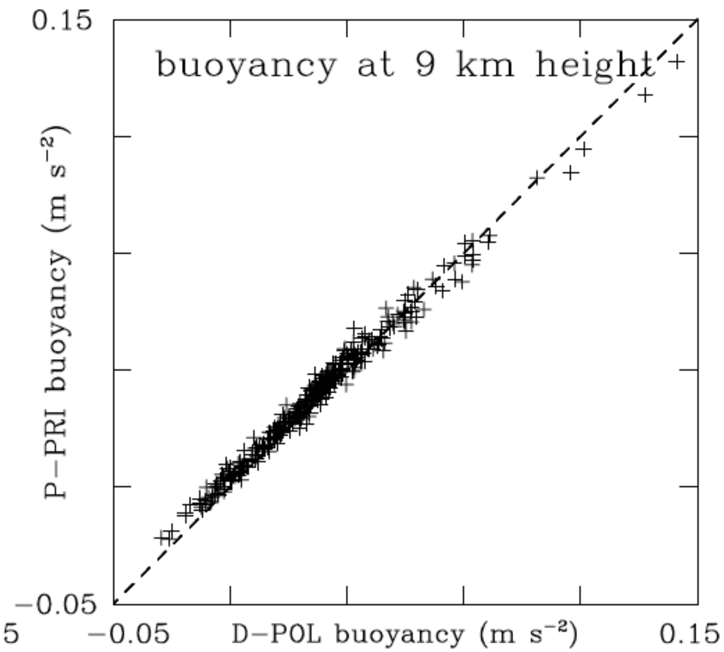
impact on the cloud dynamics?

Comparing buoyancy between driving and piggybacking sets (hour 6):

D-PRI/P-POL



D-POL/P-PRI



1 K $\approx$ 0.03 m s^{-2}

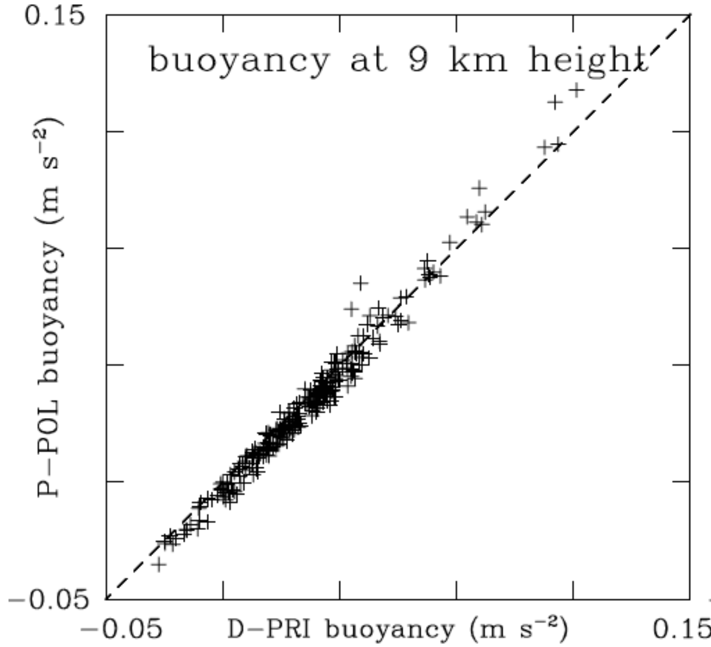
at 9 km (-27 degC)

(Rosenfeld et al. mechanism…)

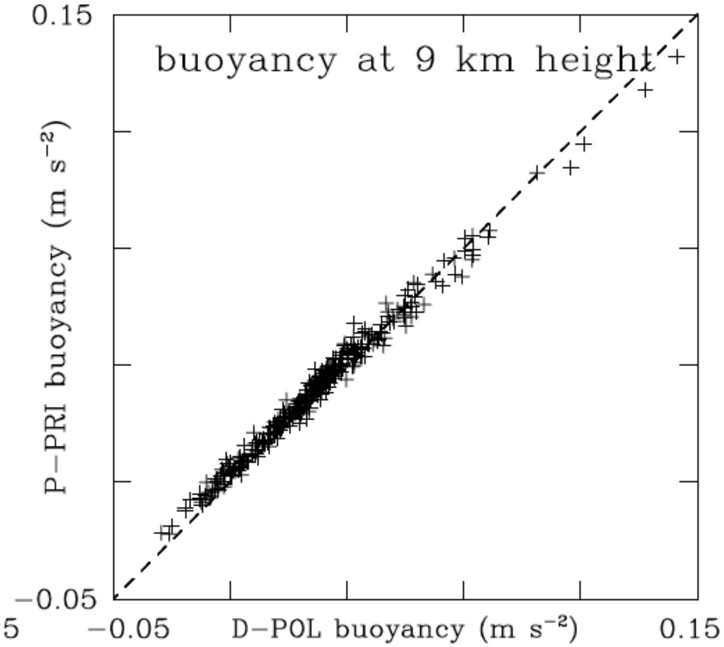
Comparing buoyancy between driving and piggybacking sets (hour 6):

$1\ K \approx 0.03\ m\ s^{-2}$

D-PRI/P-POL



D-POL/P-PRI

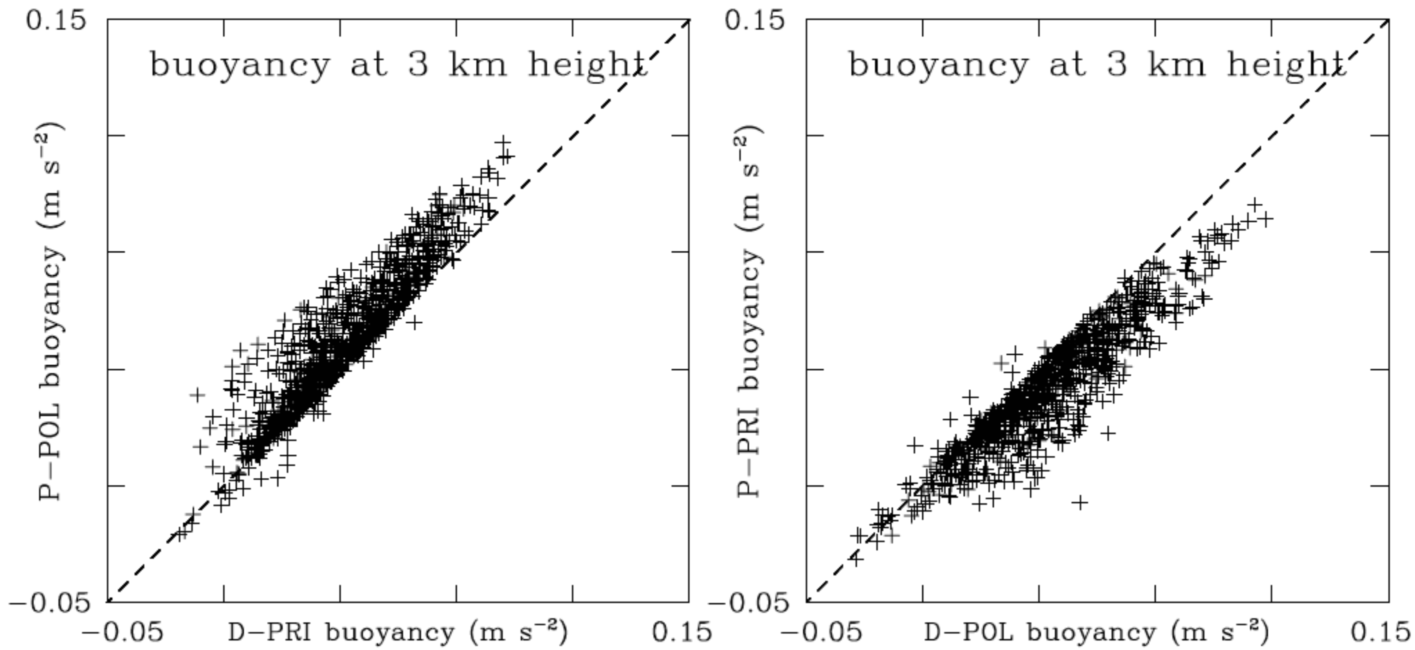


POL has slightly less buoyancy than PRI…

Comparing buoyancy between driving and piggybacking sets (hour 6):

1 K ≈ 0.03 m s^{-2}

D-PRI/P-POL   D-POL/P-PRI

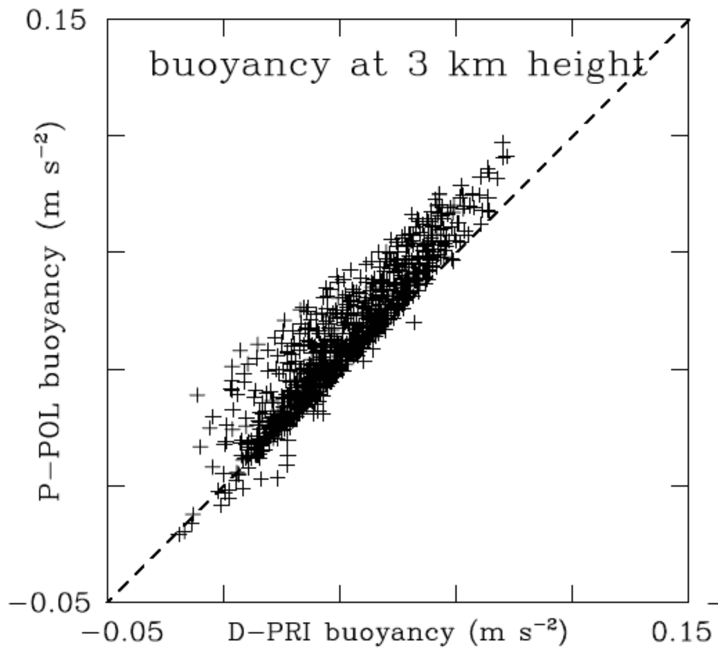


at 3 km (9 degC)

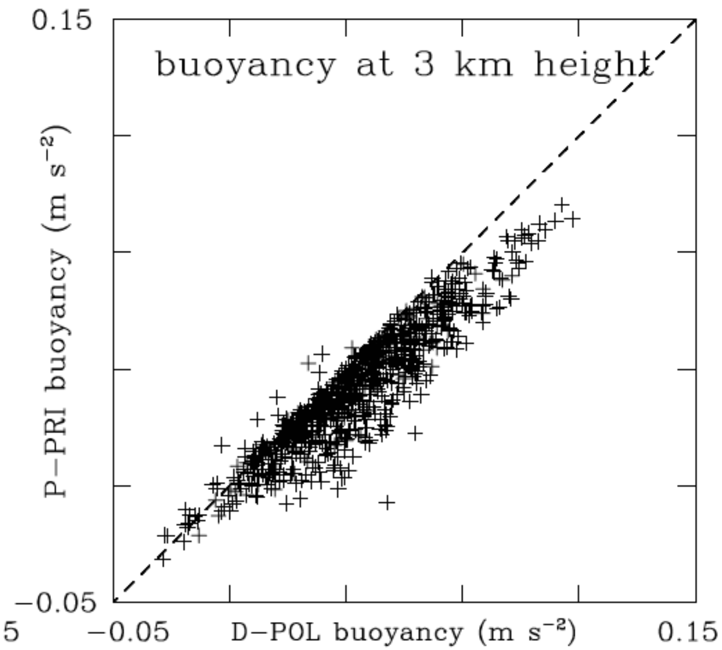
Comparing buoyancy between driving and piggybacking sets (hour 6):

$1\ K \approx 0.03\ m\ s^{-2}$

D-PRI/P-POL

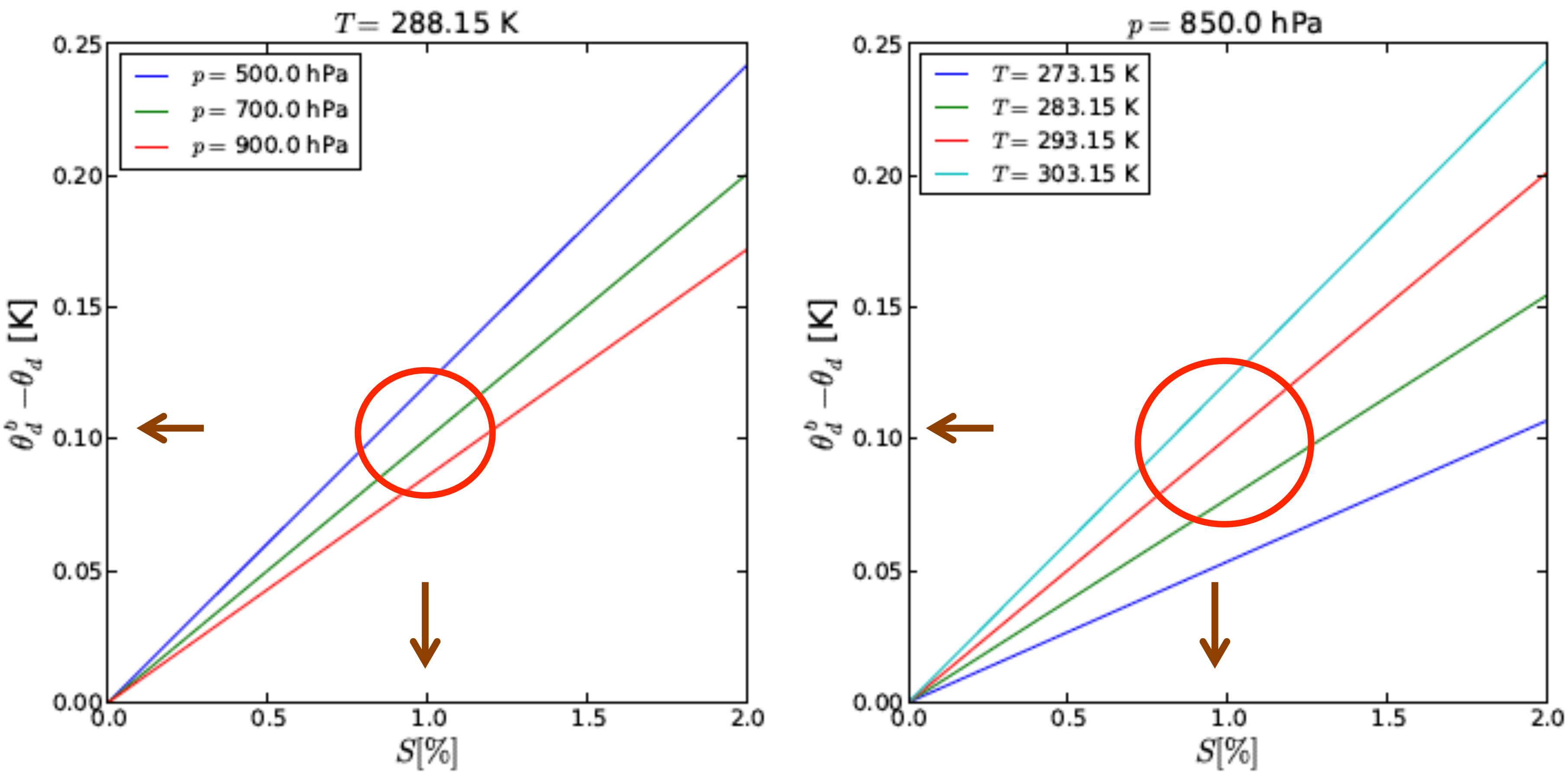


D-POL/P-PRI



POL can have significantly more buoyancy than PRI…

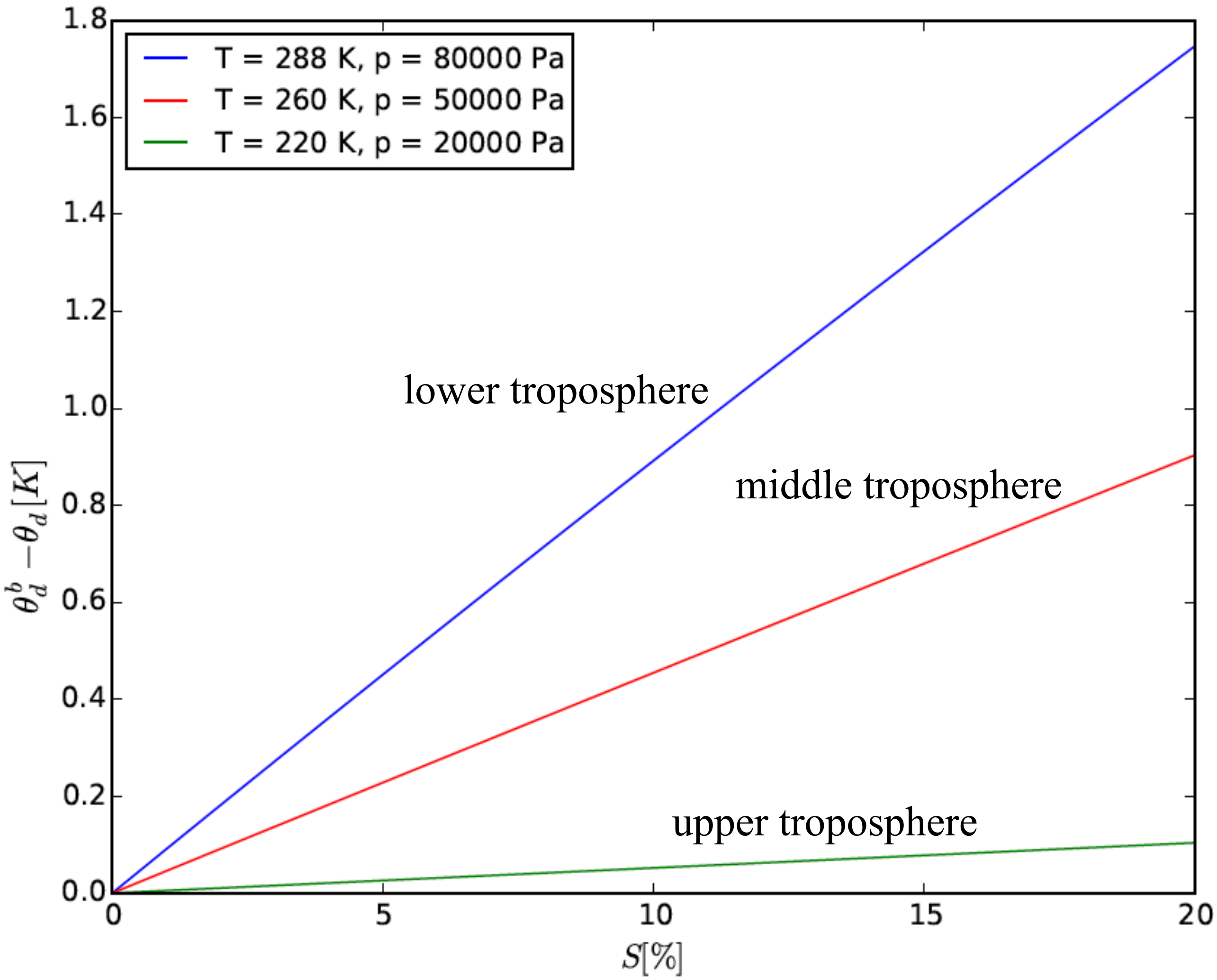
Comparing Θ_d with finite supersaturation with Θ_d at S=0, Θ_d^b



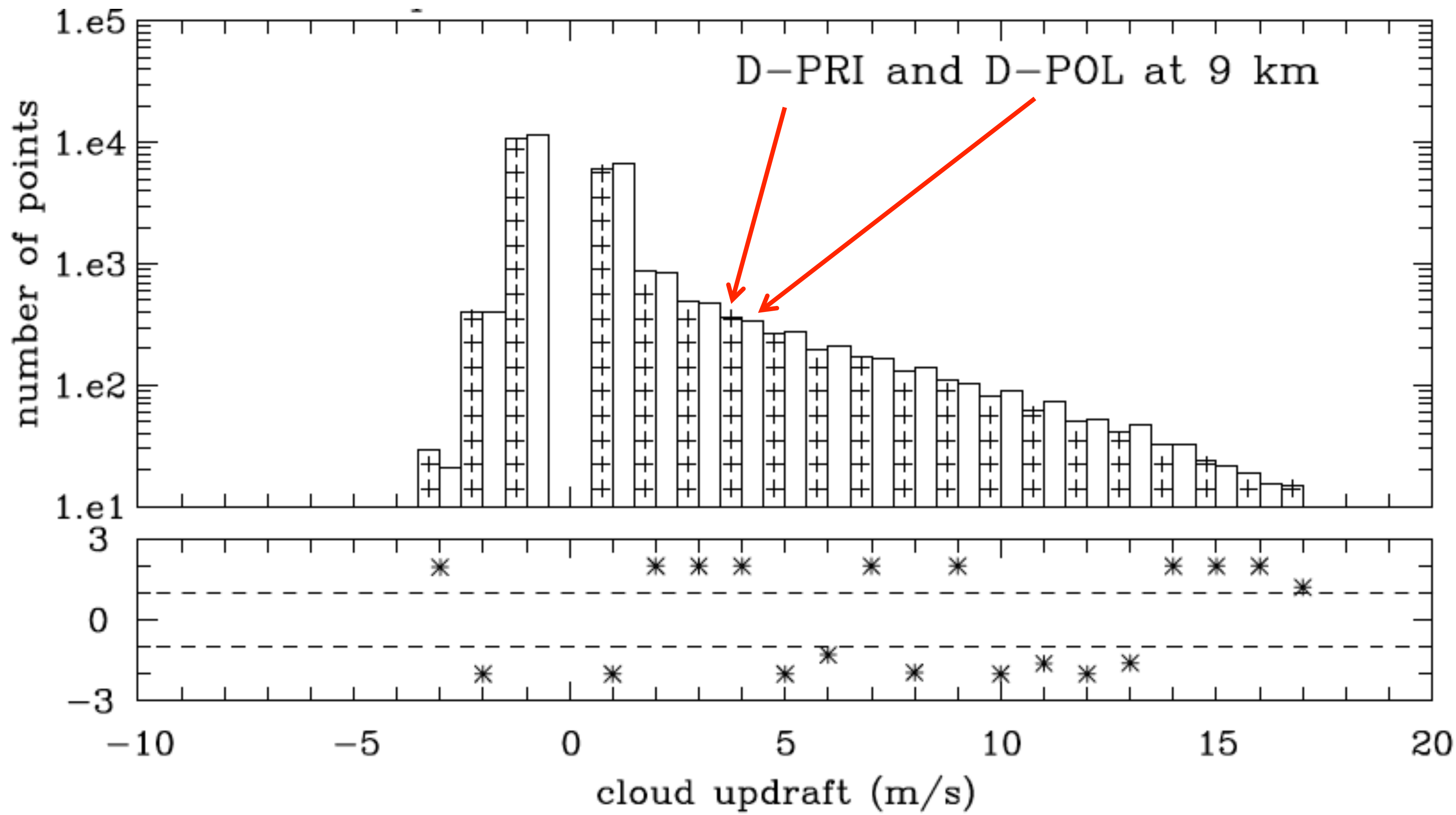
1% supersaturation ≈ 0.1 K density temperature reduction

Grabowski and Jarecka (*JAS*, 2015)

Comparing Θ_d with finite supersaturation with Θ_d at S=0, $\Theta_d{}^b$



Vertical velocity statistics for D-PRI and D-POL **at 9 km**,
measure of statistical significance of the D-PRI and D-POL difference



Vertical velocity statistics for D-PRI and D-POL **at 3 km**,
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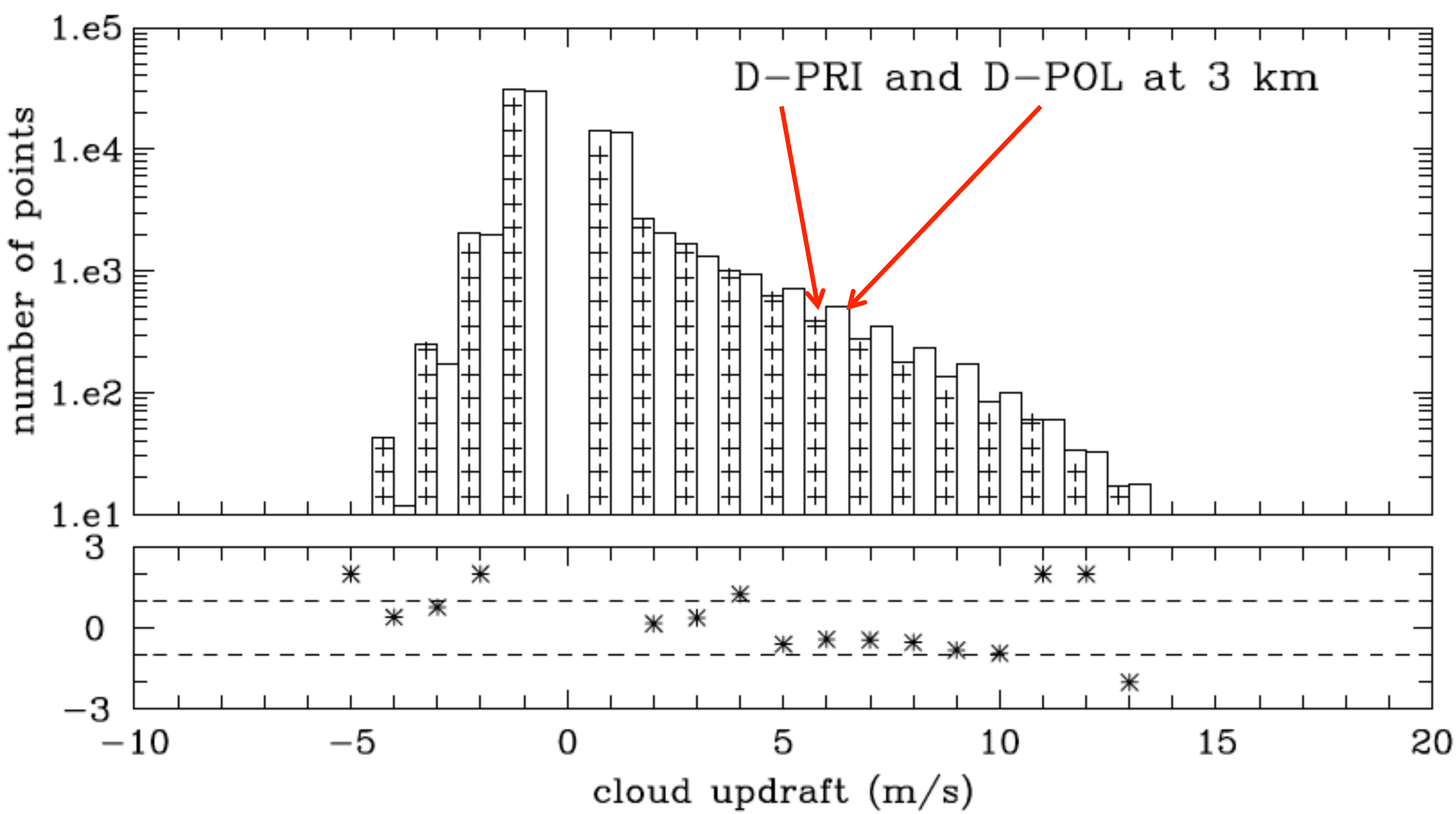
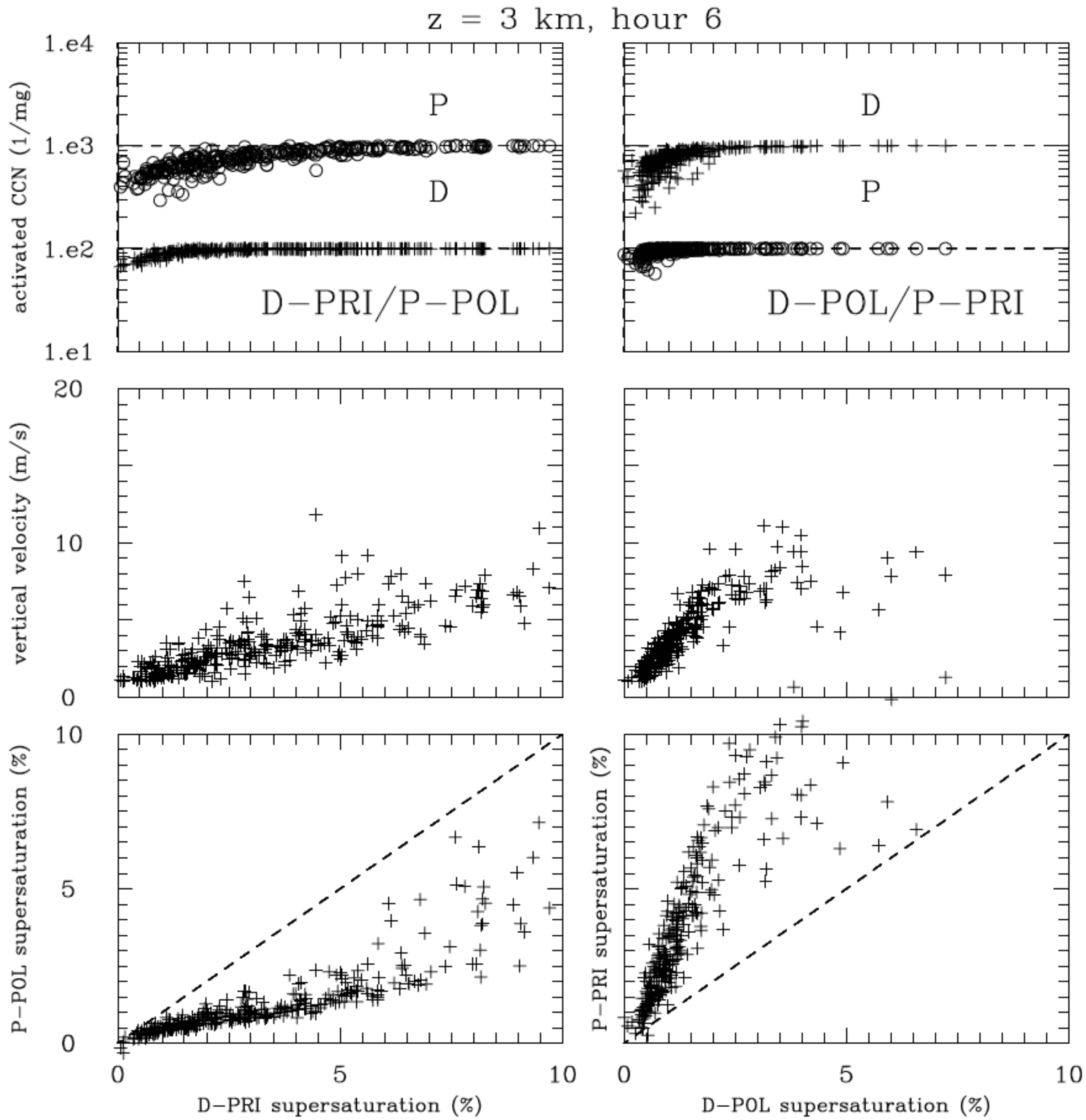


Hour 6, z = 3 km (9 degC), points with w > 1 m/s, Q > 1 g/kg

activated CCN

updraft velocity

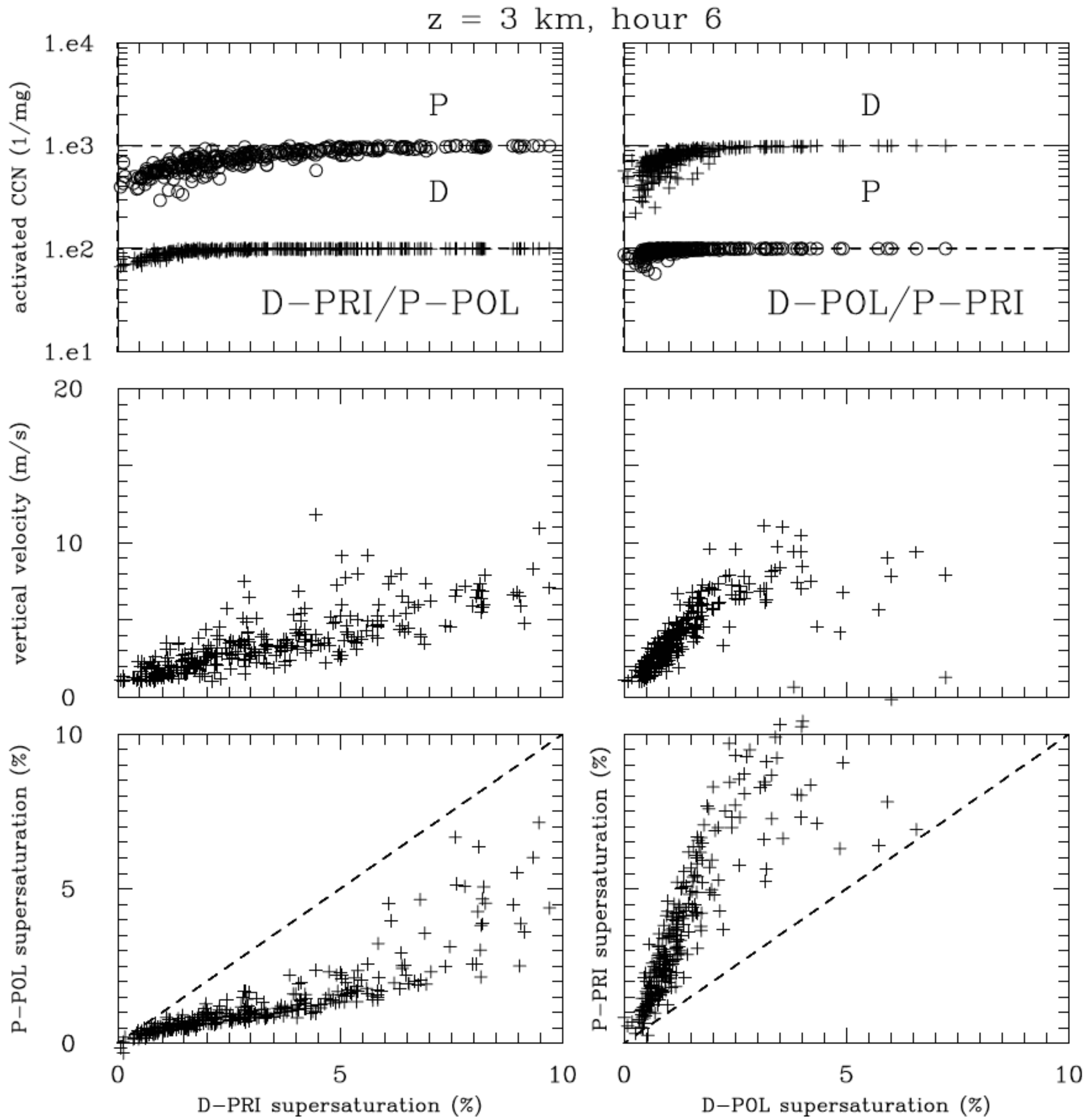
supersaturation



Hour 6, z = 3 km (9 degC), points with w > 1 m/s, Q > 1 g/kg

Almost all CCN is activated for the strongest updrafts…

PRI supersaturations are higher than POL…



Lognormal double-mode CCN distribution:

$$f_d = \frac{dN_a}{dr_d} = \frac{N_t}{\sqrt{2\pi}\,\ln\sigma_d r_d}\exp\left[-\frac{\ln^2(r_d/r_{d0})}{2\ln^2\sigma_d}\right]$$

r_d is the dry aerosol radius

N_t is the total aerosol number **PRI, pristine: 100 + 500 mg $^{-1}$**
POL, polluted: 1000 + 5000 mg^{-1}

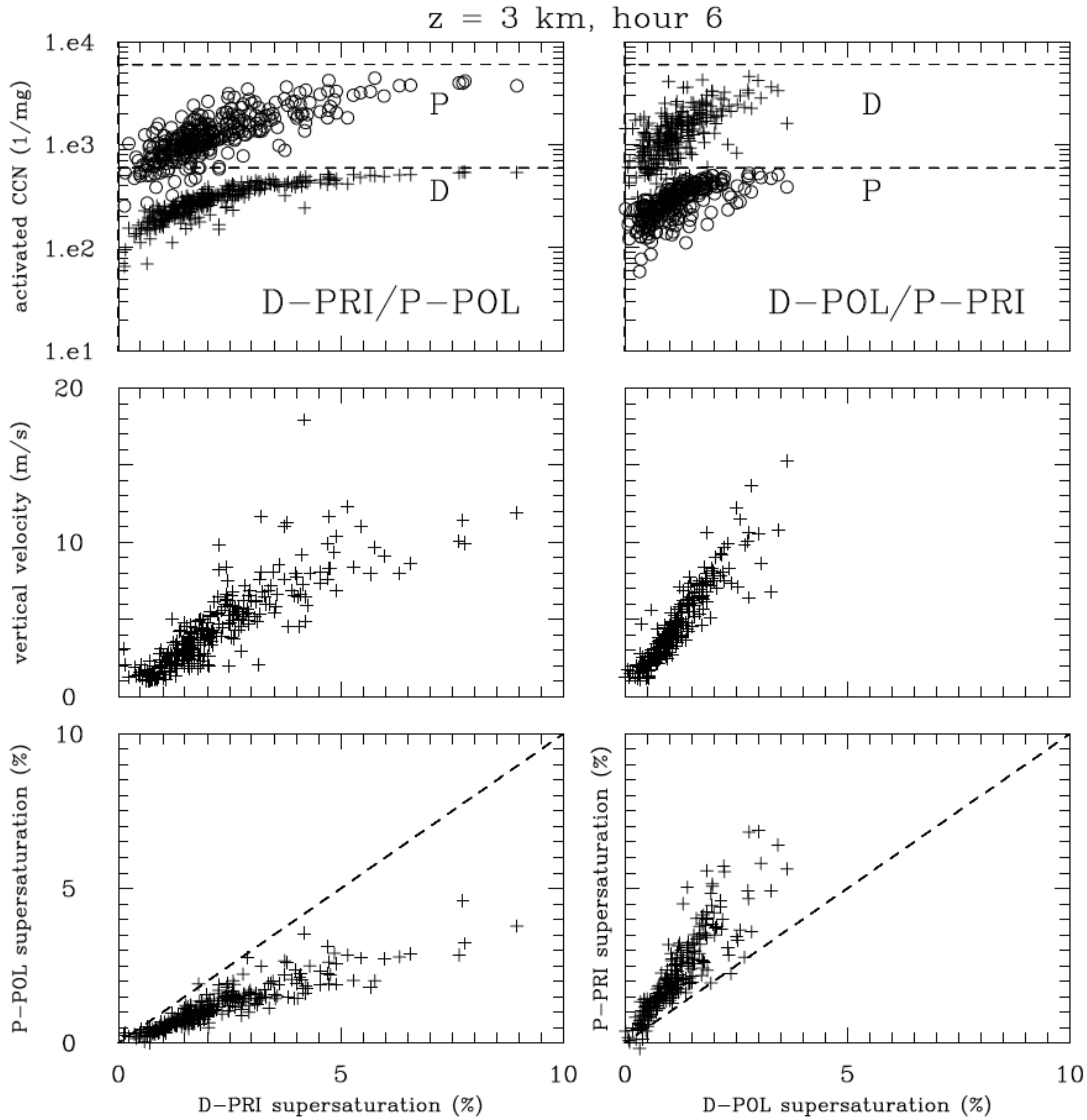
σ_d is the standard deviation **2.0**

r_{d0} is the geometric mean radius of the dry particles **0.05 + 0.01 μm**

as in Morrison and Grabowski (*JAS* 2007, 2008a)

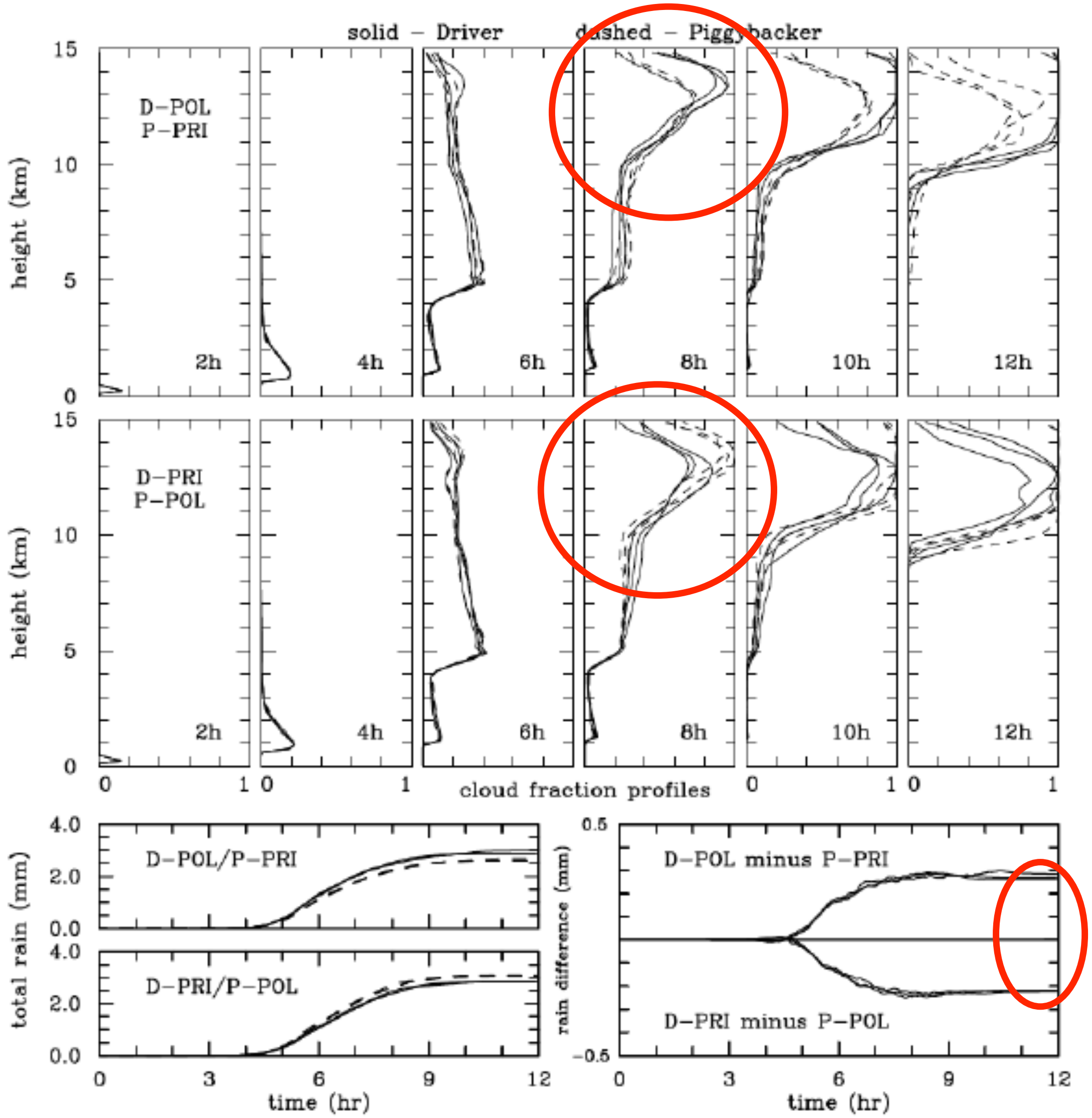
Hour 6, z = 3 km (9 degC), points with w > 1 m/s, Q > 1 g/kg

Not all CCN is activated even for the strongest updrafts…



Supersaturations are smaller now, but still up to several percent…

Smaller difference between POL and PRI for upper-tropospheric anvils…



POL minus PRI still significantly larger when POL is driving…

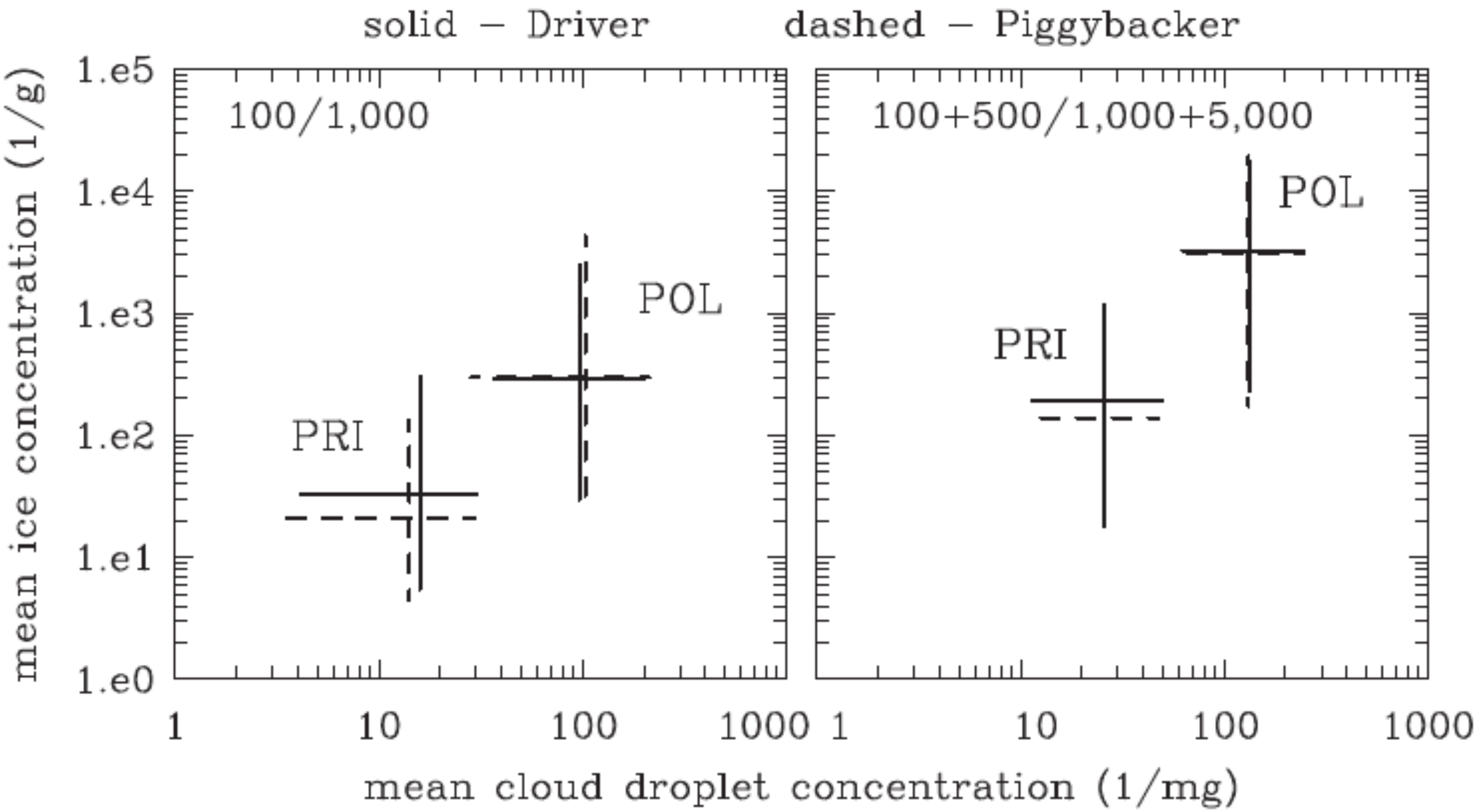


FIG. 14. Mean ice crystal concentration in the upper troposphere as a function of the mean cloud droplet concentration below the freezing level in deep convective columns for simulations with (left) a single CCN mode and (right) two CCN modes. Each cross represents the range from the 10th to 90th percentiles, and the intersection is the median value. Solid (dashed) lines are from sets of thermodynamic variables driving (piggybacking) the simulation. The vertical lines in the right panel overlay each other.

Conclusions:

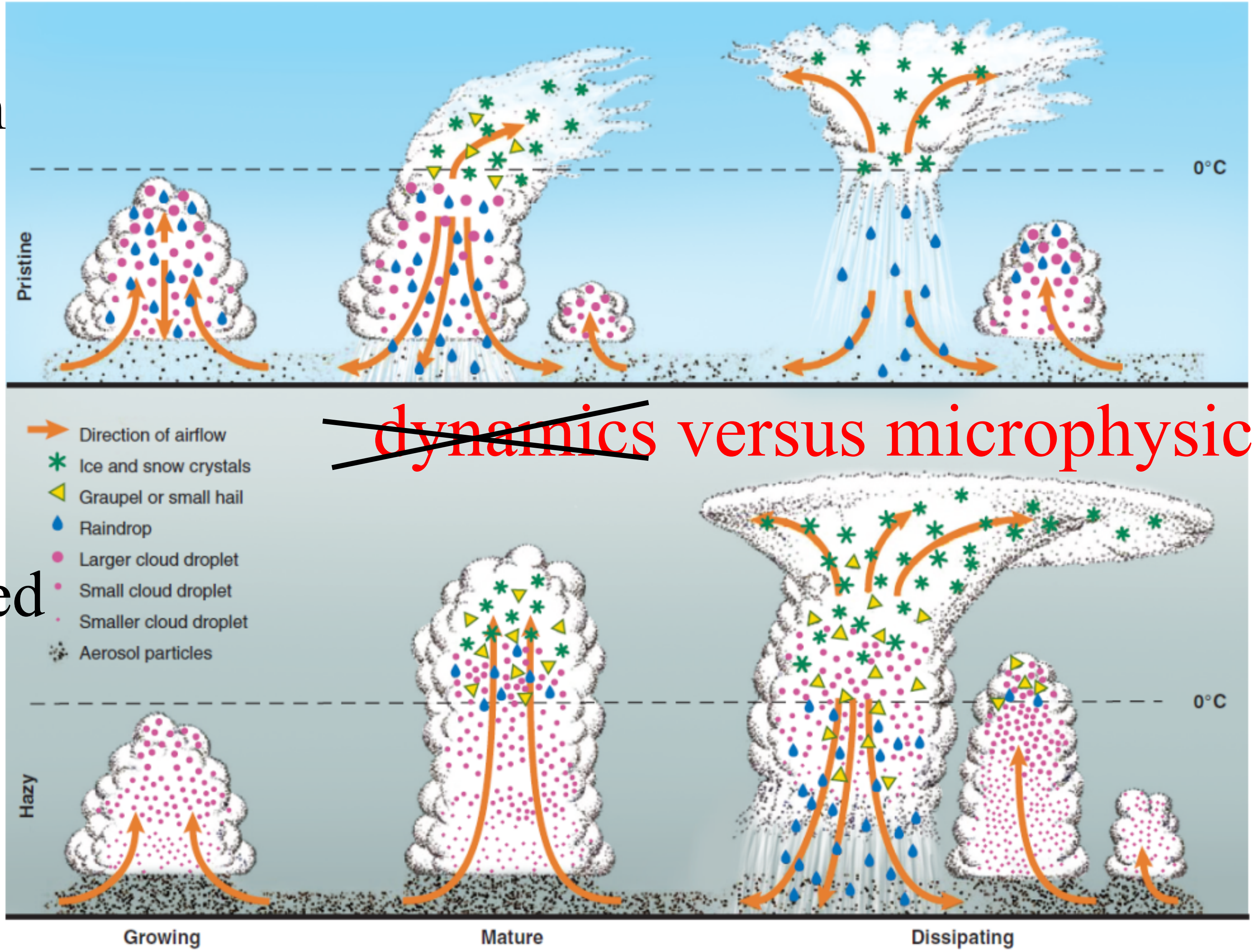
The piggybacking methodology clarifies the dynamic basis of convective invigoration in polluted environments.

Double-moment bulk scheme - POL versus PRI:

- **small modification of the cloud dynamics in the warm-rain zone due to differences in the supersaturation field, ~10% more rain in polluted cases;**
- **significant *microphysical* impact on convective anvils.**

Bulk schemes with saturation adjustment are likely inappropriate for deep convection.

clean



polluted

~~dynamics~~ versus microphysics?

Rosenfeld et al. *Science*, 2008

"Flood or Drought: How Do Aerosols Affect Precipitation?"