Invigoration of deep convection in polluted environments: myth or reality?

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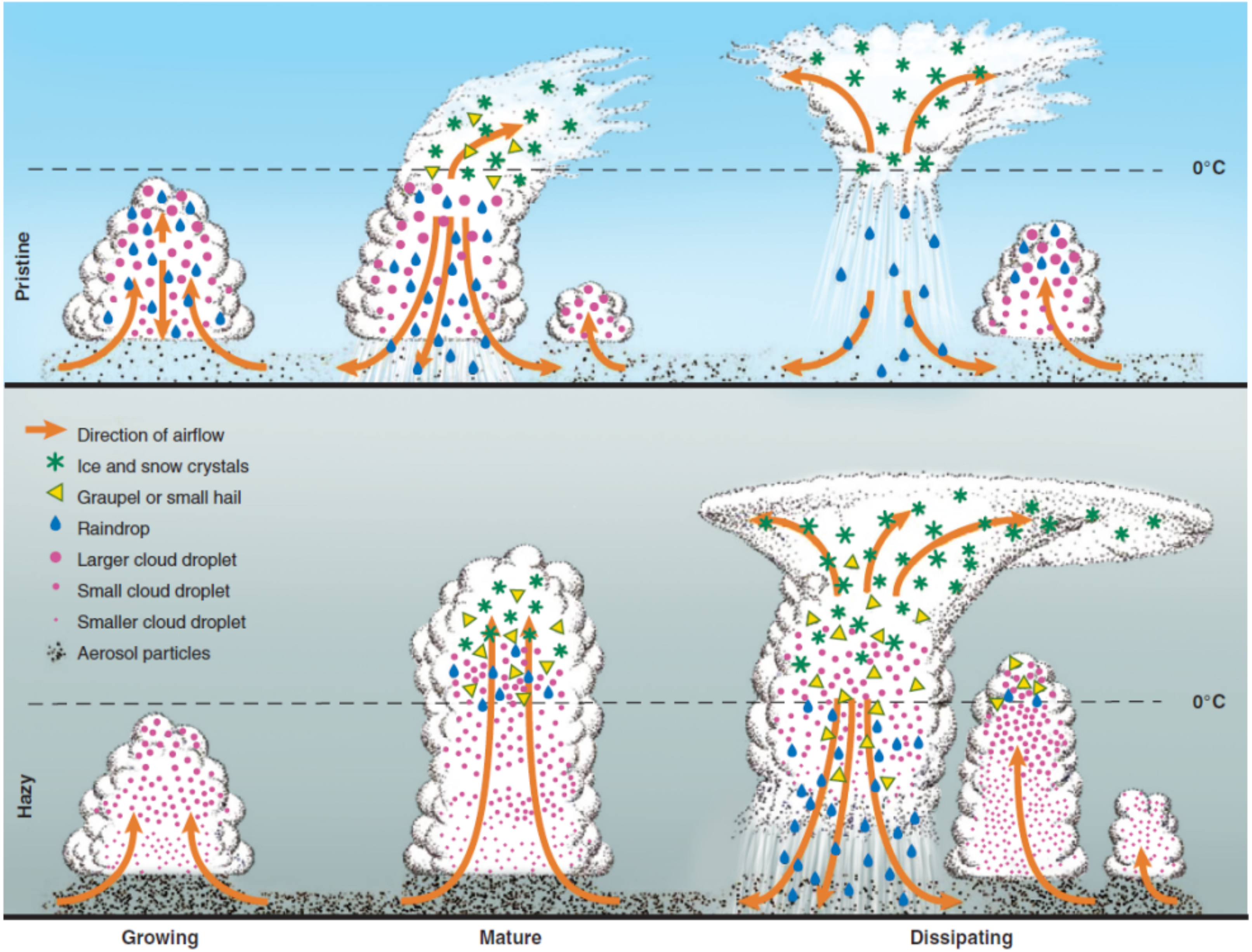
Results to be discussed are from two papers:

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., 2018: Can the impact of aerosols on deep convection be isolated from meteorological effects in atmospheric observations? *J. Atmos. Sci.* (in press).

clean

polluted



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

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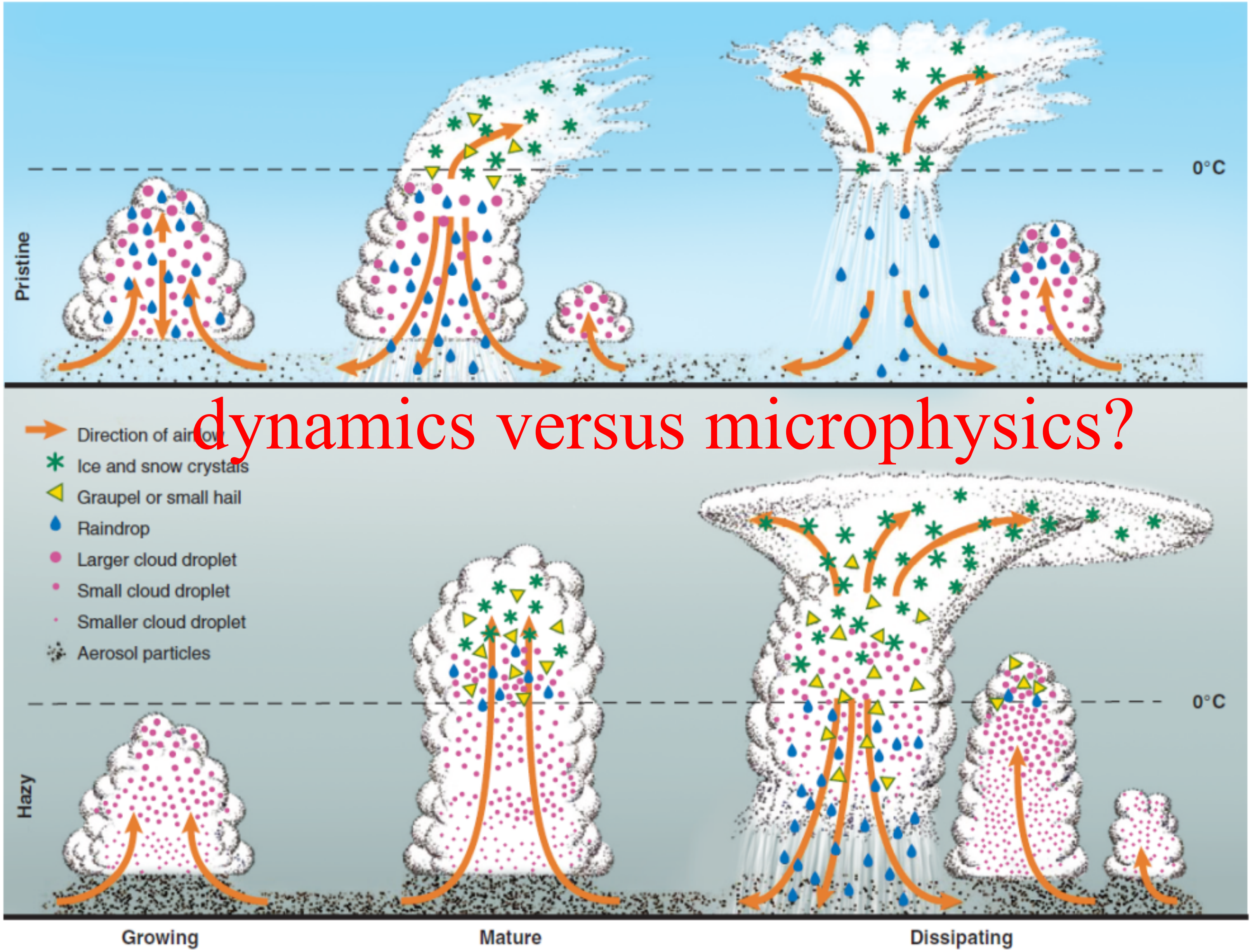


dynamics versus microphysics?

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

Cloud buoyancy: the potential density temperature

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c - q_p)$$

$\varepsilon \approx 0.6$

q_v – water vapor mixing ratio

q_c – cloud condensate mixing ratio
(small fall velocity; ~cm/s)

q_p – precipitation mixing ratio
(large fall velocity; ~m/s)

Condensation: the impact on latent heating exceeds vapor/condensate effects:

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c)$$

δq – change of vapor mixing ratio

$$\delta\Theta_d \sim \delta\Theta + \Theta\,\delta q$$

$$\delta\Theta \sim L_v/cp\,\delta q \sim 2 \cdot 10^3\,\delta q$$

$L_v \sim 2 \cdot 10^6\ J/kg$

$$\Theta\,\delta q \sim 3 \cdot 10^2\,\delta q$$

Liquid condensate freezing: the impact of latent heating approximately balances loading effect:

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c)$$

δq – change of cloud water mixing ratio

$$\delta\Theta_d \sim \delta\Theta + \Theta\,\delta q$$

$$\delta\Theta \sim L_f/cp\,\delta q \sim 3 \cdot 10^2\,\delta q \qquad L_f \sim 3 \cdot 10^5\,J/kg$$

$$\Theta\,\delta q \sim 3 \cdot 10^2\,\delta q$$

Condensate off-loading: q_c is converted into q_p, q_p falls out:

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c - q_p)$$

Rosenfeld et al. mechanism: freezing of liquid condensate carried through the 0 degC level:

$$\theta_d = \theta(1 + \varepsilon q_v - q_c)$$

latent heating increases buoyancy…

…but condensate loading reduces buoyancy

Rosenfeld et al. mechanism: freezing of liquid condensate carried through the 0 degC level:

$$\theta_d = \theta(1 + \varepsilon q_v - q_c)$$

latent heating increases buoyancy…

…but condensate loading reduces buoyancy

The two almost perfectly balance each other, thus off-loading is the key. Does it work?

Finite supersaturation impacts Θ, q_v, and q_c:

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c)$$

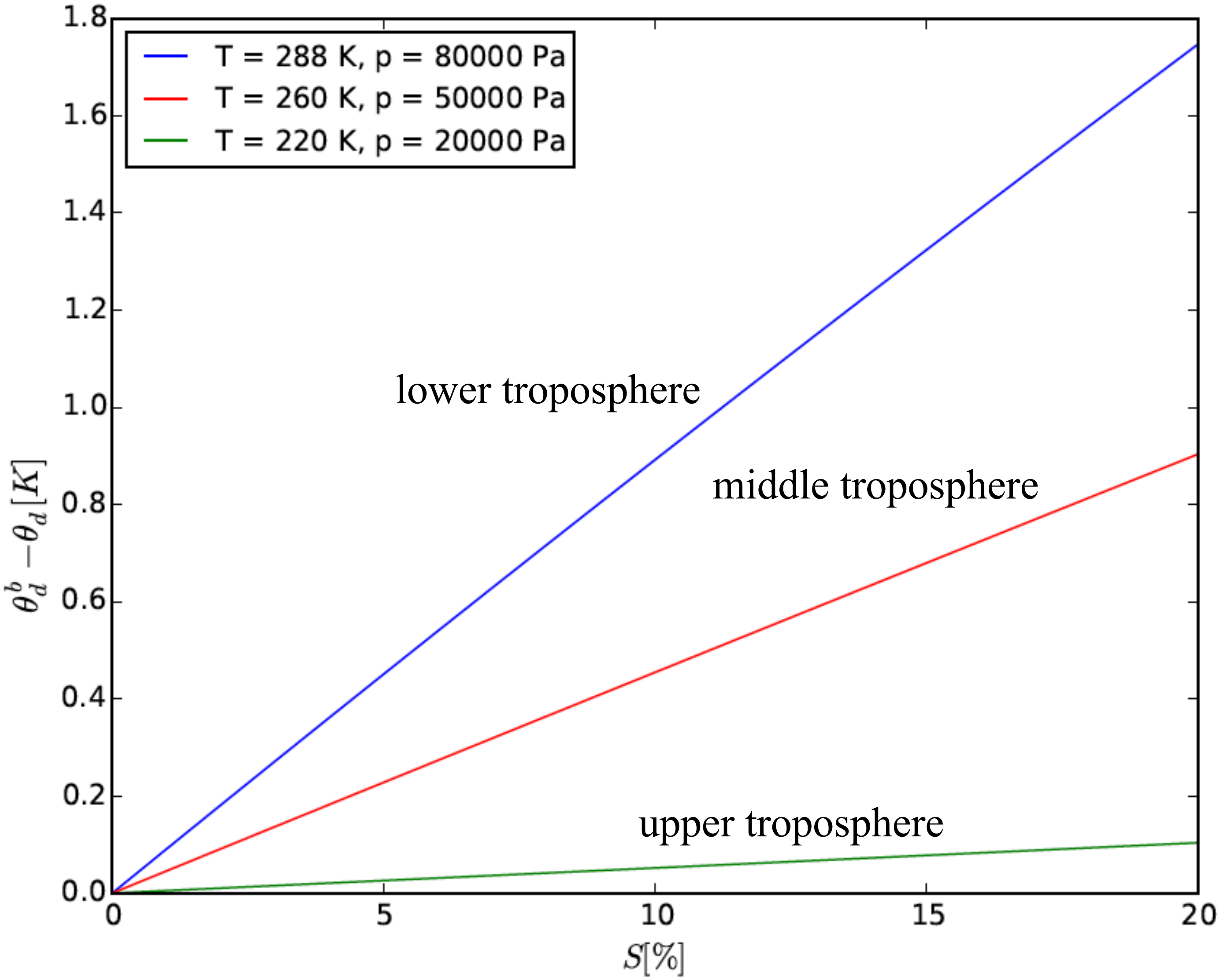
Comparing Θ_d with finite supersaturation and bulk Θ_d (i.e., S=0), $\Theta_d^{\,b}$:

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

the amount of water vapor that
needs to condense to bring the
air back to saturation

Grabowski and Jarecka *JAS* 2015

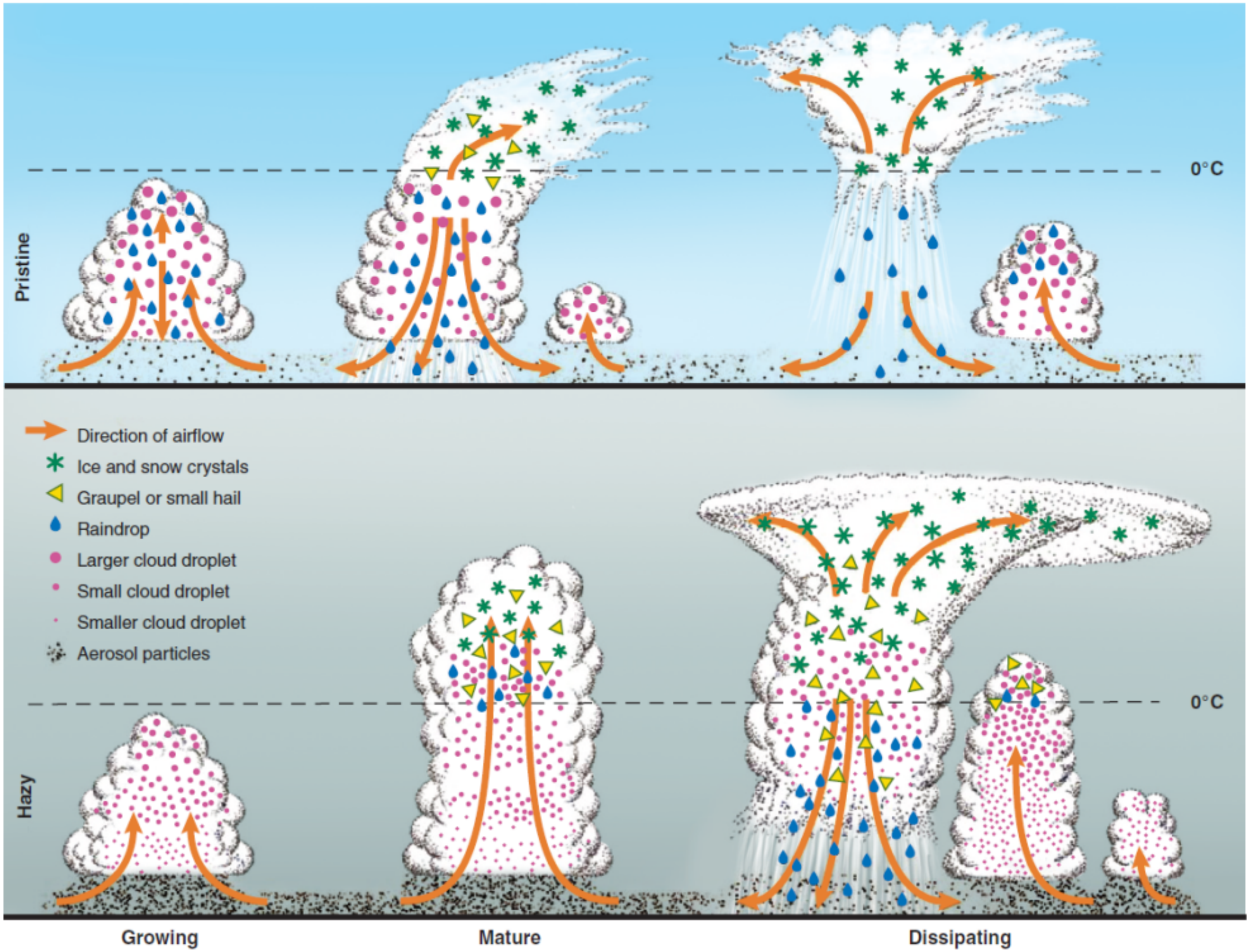
Comparing Θ_d with finite supersaturation and bulk Θ_d (i.e., S=0), $\Theta_d^{\,b}$:



10% supersaturation reduces buoyancy by several tenth of 1K…

clean

polluted



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

So it seems that documenting aerosol effects of deep convections should be relatively simple in observations…

However, there are two key problems:

- Correlations between aerosol and convection do not imply causality: aerosols and meteorology can co-vary.

- Atmospheric observations may not be accurate enough to exclude meteorological factors.

Observations: correlation does not imply causality!

Li et al. (*Nature Geo* 2011) show correlation between clouds and aerosols over ARM SGP site; they say in the abstract:

"…precipitation frequency and rain rate are altered by aerosols"

(Varble *JAS* 2018 shows that aerosols and meteorology co-vary at SGP!)

Storer et al. (*JGR* 2014) show correlation between aerosol and tropical convection over Atlantic; they say in the abstract:

"These observations suggest that convective invigoration occurs with increased aerosol loading, leading to deeper, stronger storms in polluted environments"

Observations show correlations, but it is difficult (impossible?) to deduce causality using observations...

Models are perfect tools to consider causality, but they have to be used carefully...

- single-cloud short simulations are inappropriate (spin-up problem);
- inability to separate physical impact from different flow realizations.

Example of a good application of a numerical model:

Atmos. Chem. Phys., 12, 709–725, 2012
www.atmos-chem-phys.net/12/709/2012/
doi:10.5194/acp-12-709-2012

Atmospheric Chemistry and Physics

Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model

A. Seifert[1], C. Köhler[1,2], and K. D. Beheng[3]

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[2]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre,Oberpfaffenhofen, Germany
[3]Karlsruher Institut für Technologie, Institut für Meteorologie und Klimaforschung, Karlsruhe, Germany

Correspondence to: A. Seifert (axel.seifert@dwd.de)

Received: 6 July 2011 – Published in Atmos. Chem. Phys. Discuss.: 18 July 2011
Revised: 5 December 2011 – Accepted: 8 January 2012 – Published: 16 January 2012

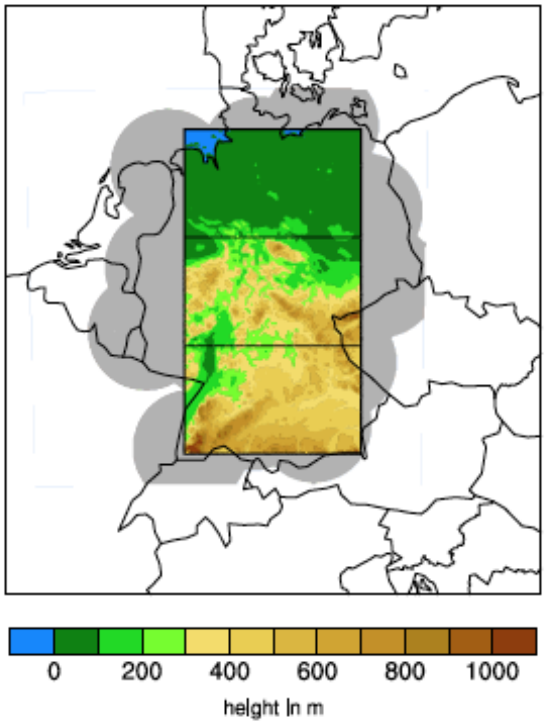


Fig. 1. COSMO-DE model domain, with insertions of coverage of the German radar composite (grey), and the three evaluation sub-domains with the model orography.

Table 3. Experiments performed for this study. The data can be accessed from DWD using the database IDs given here for individual experiments and years.

No.	ID in database 2008	ID in database 2009	ID in database 2010	microphysics scheme	CCN	IN
1	7544	7451	7895	two-moment	high	low
2	7545	7452	7899	two-moment	low	low
3	7547	7454	7954	two-moment	high	high
4	7907	7906	7955	two-moment	low	high
5	7546	7453	8013	two-moment	high	very low
6	8056	8055	8026	two-moment	low	very low
7	7483	7450	7897	one-moment	–	–

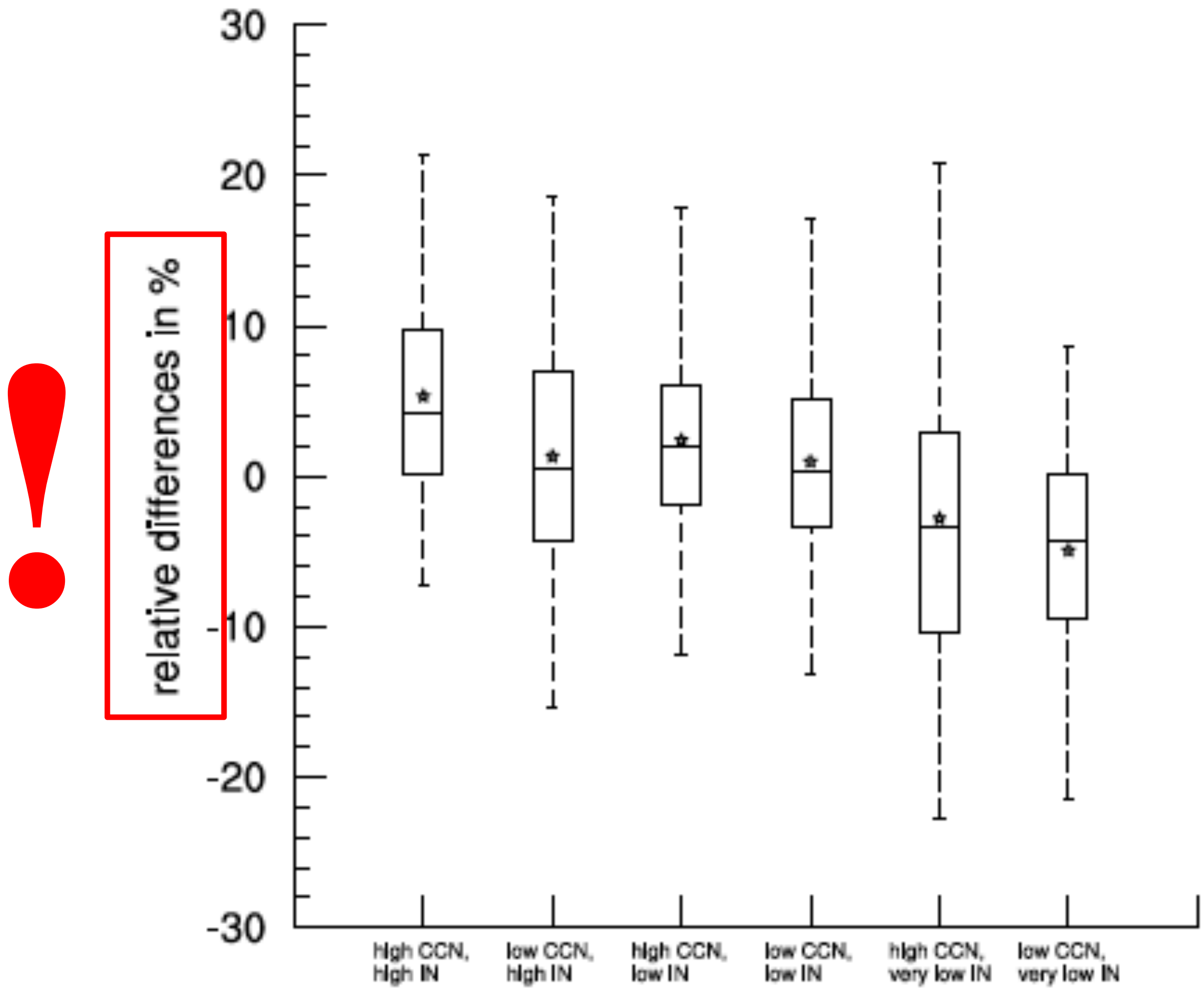
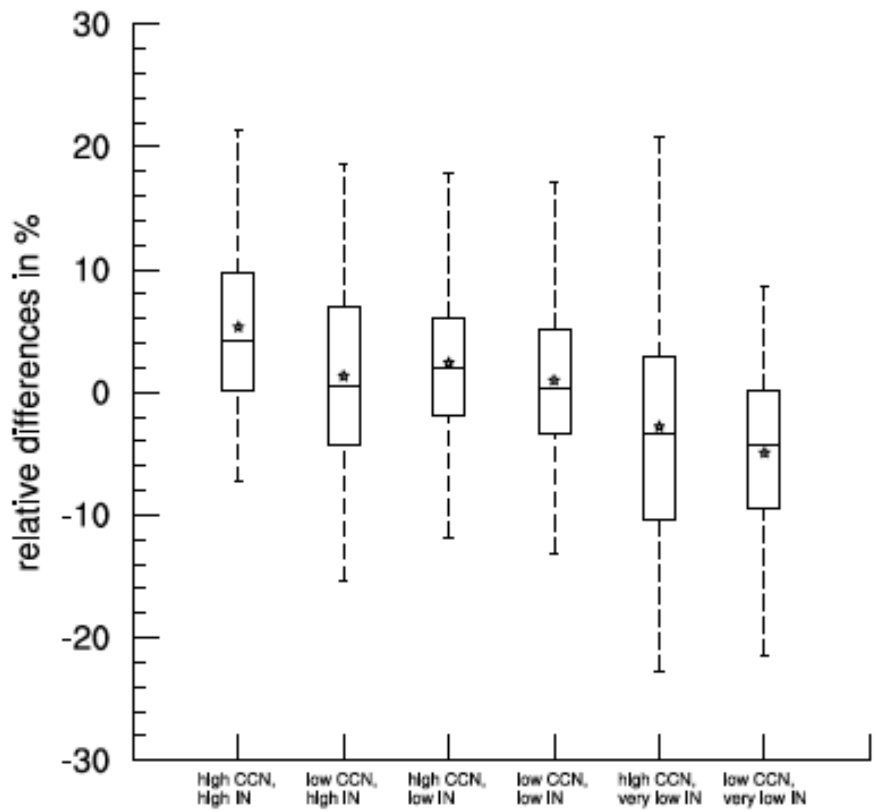


Fig. 9. Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008–2010. Shown are anomalies relative to the mean of Exps. 1–6. The precipitation data has been averaged over either one of the three subdomains. The bottom and top of the boxes are the lower and upper quartiles, the line near the middle of the boxes is the median, whiskers are the 5th and 95th percentiles and the stars represent the mean value.

"…CCN and IN assumptions have a strong effect on cloud properties, like condensate amounts of cloud water, snow and rain as well as on the glaciation of the clouds, but the effects on surface precipitation are—when averaged over space and time—small…"



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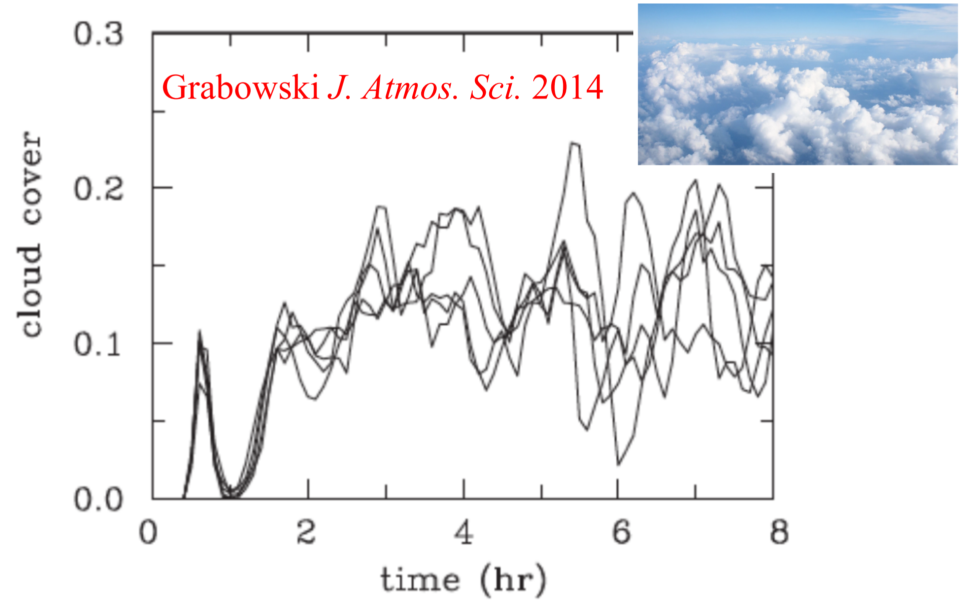
Observations show correlations, but it is difficult (impossible?) to deduce causality using observations...

Models are perfect tools to consider causality, but they have to be used carefully...

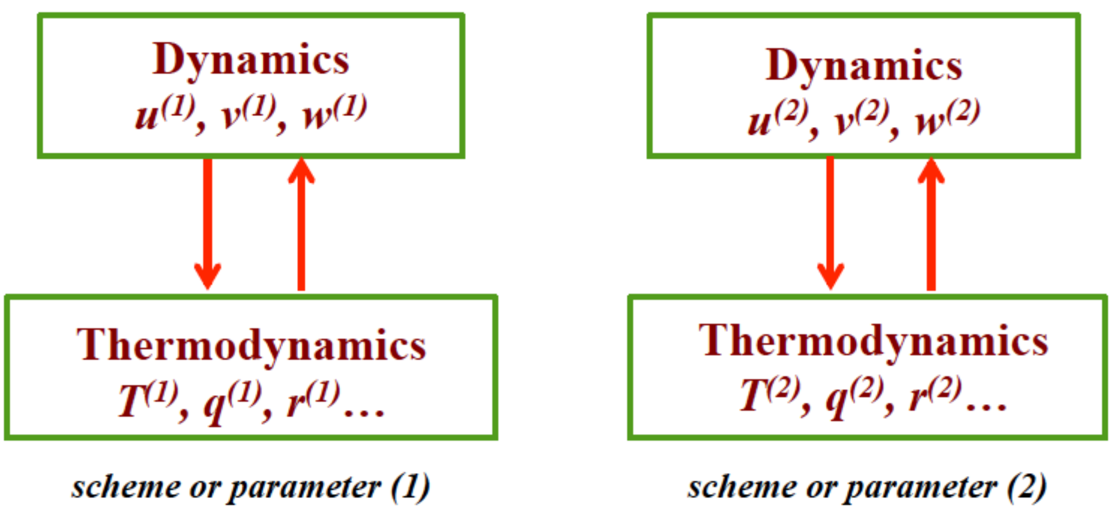
- single-cloud short simulations are inappropriate (spin-up problem);
- inability to separate physical impact from different flow realizations.

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

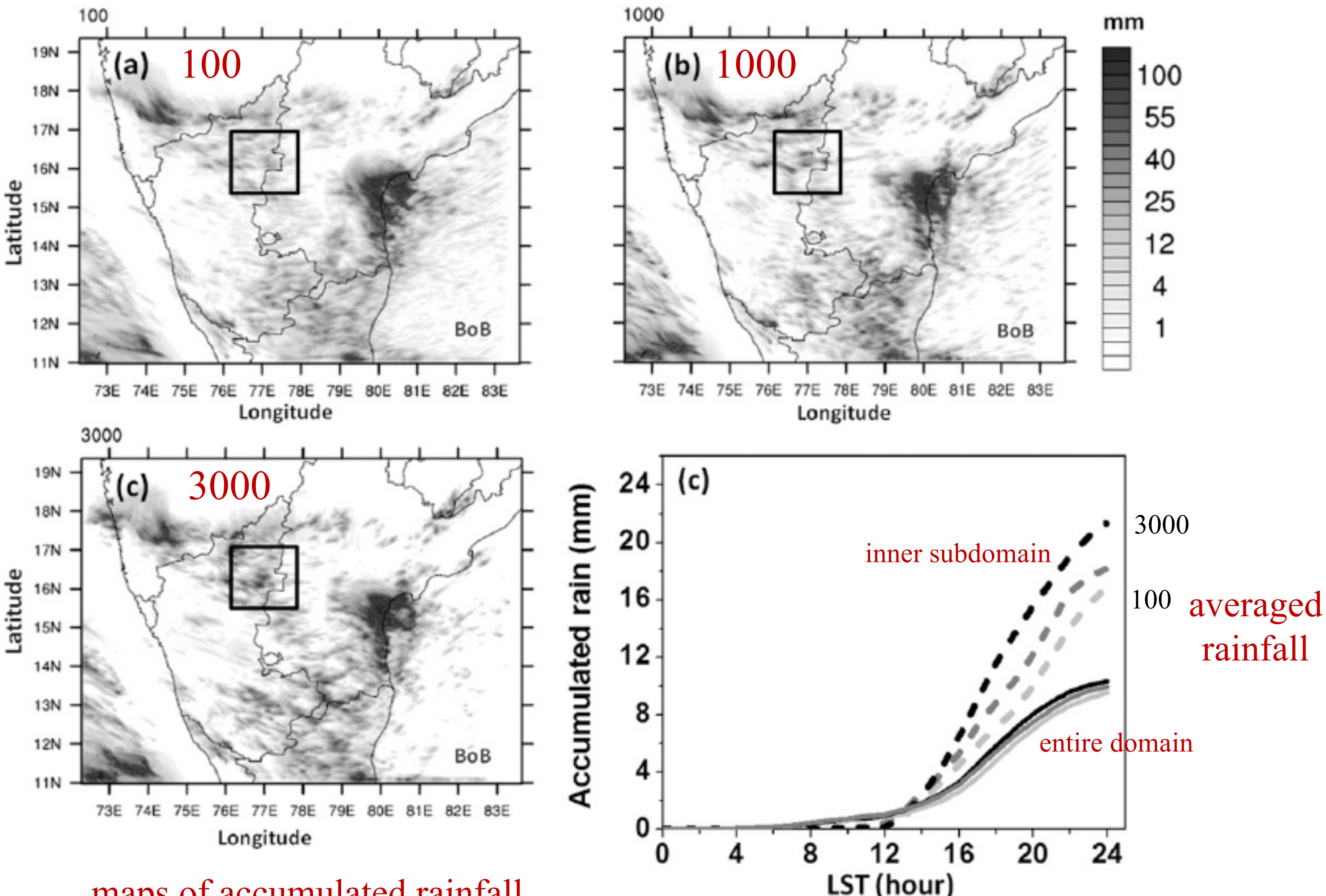


The separation is traditionally done by performing parallel simulations where each simulation applies modified model physics.

Separation of physical impacts from different flow realizations: three 24-hr simulations with CCN of 100, 1000, and 3000 per cc

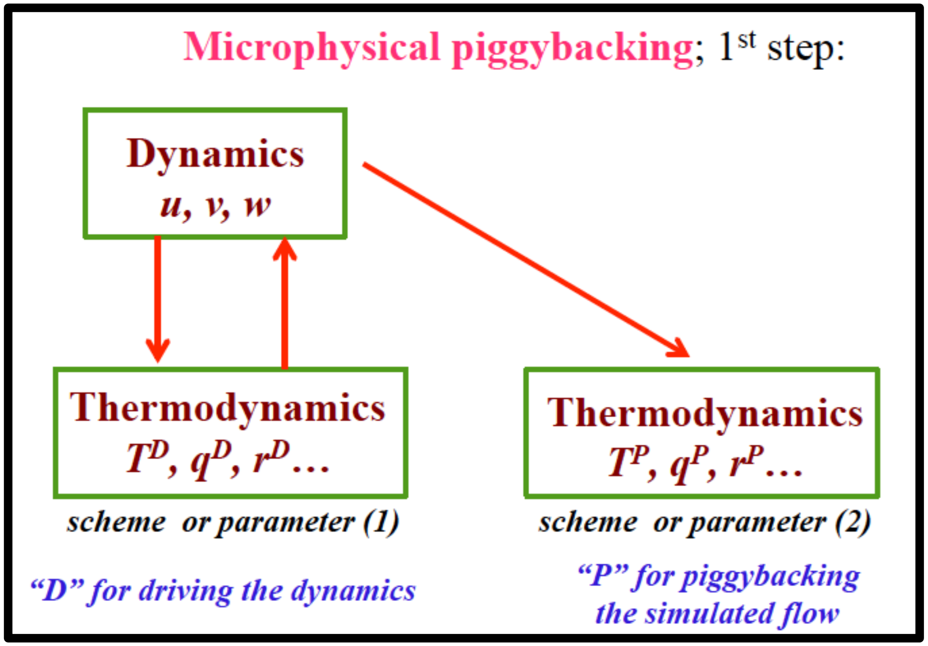
Aerosol–Cloud Interaction in Deep Convective Clouds over the Indian Peninsula Using Spectral (Bin) Microphysics

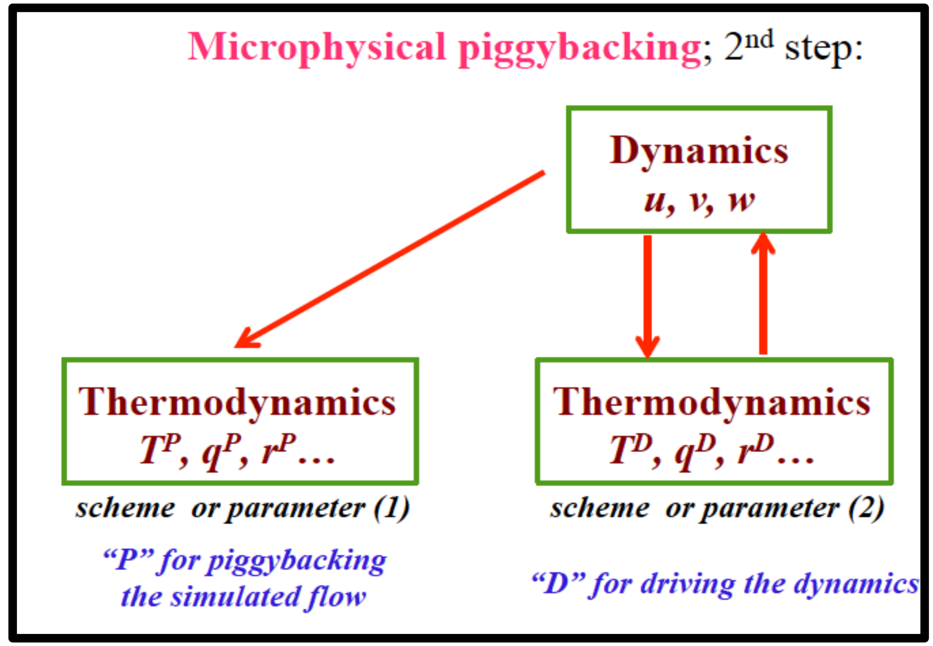
Gayatri et al. *JAS* 2017



maps of accumulated rainfall

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, 2017: Modeling condensation in deep convection. *J. Atmos. Sci*., **74**, 2247-2267.

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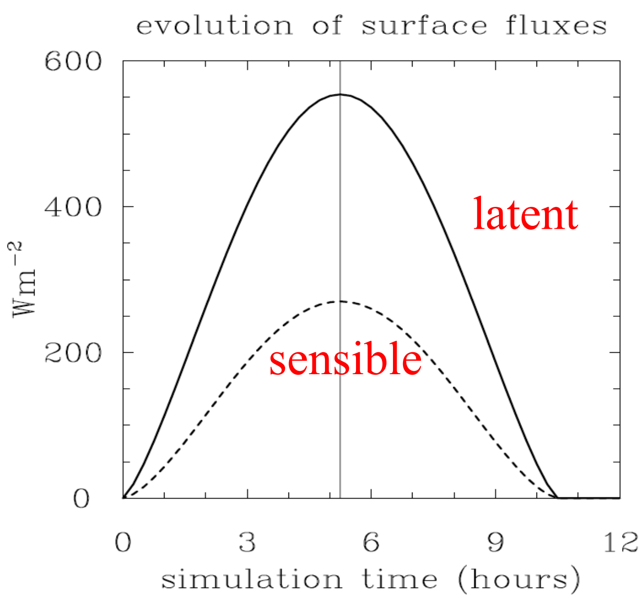
Q. J. R. Meteorol. Soc. (2006), **132**, pp. 317–344 doi: 10.1256/qj.04.147

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]



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.

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

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

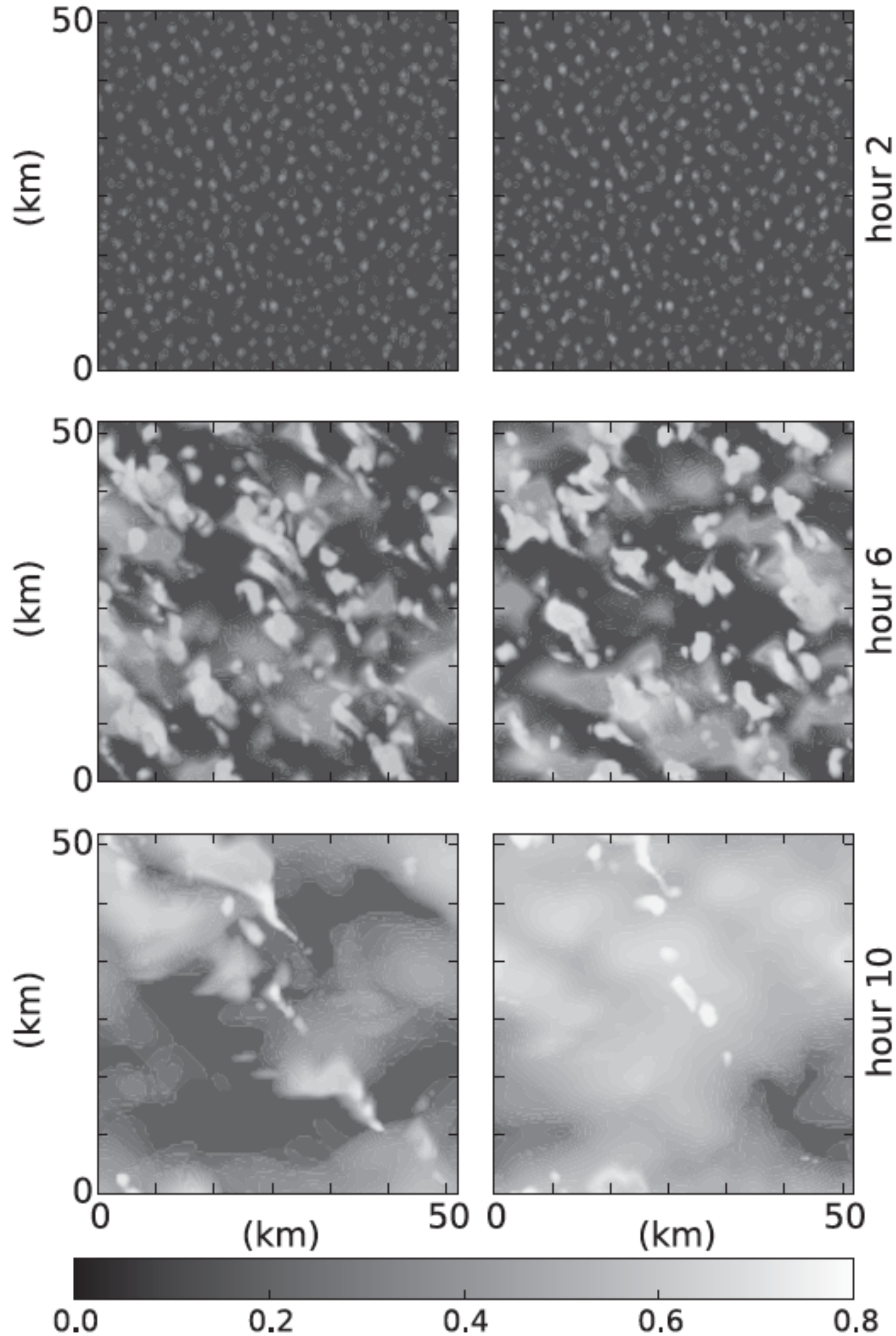
N_t is the total aerosol number — **PRI, pristine: 100 mg $^{-1}$**
POL, polluted: 1000 mg^{-1}

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)

D-PRI
(pristine)



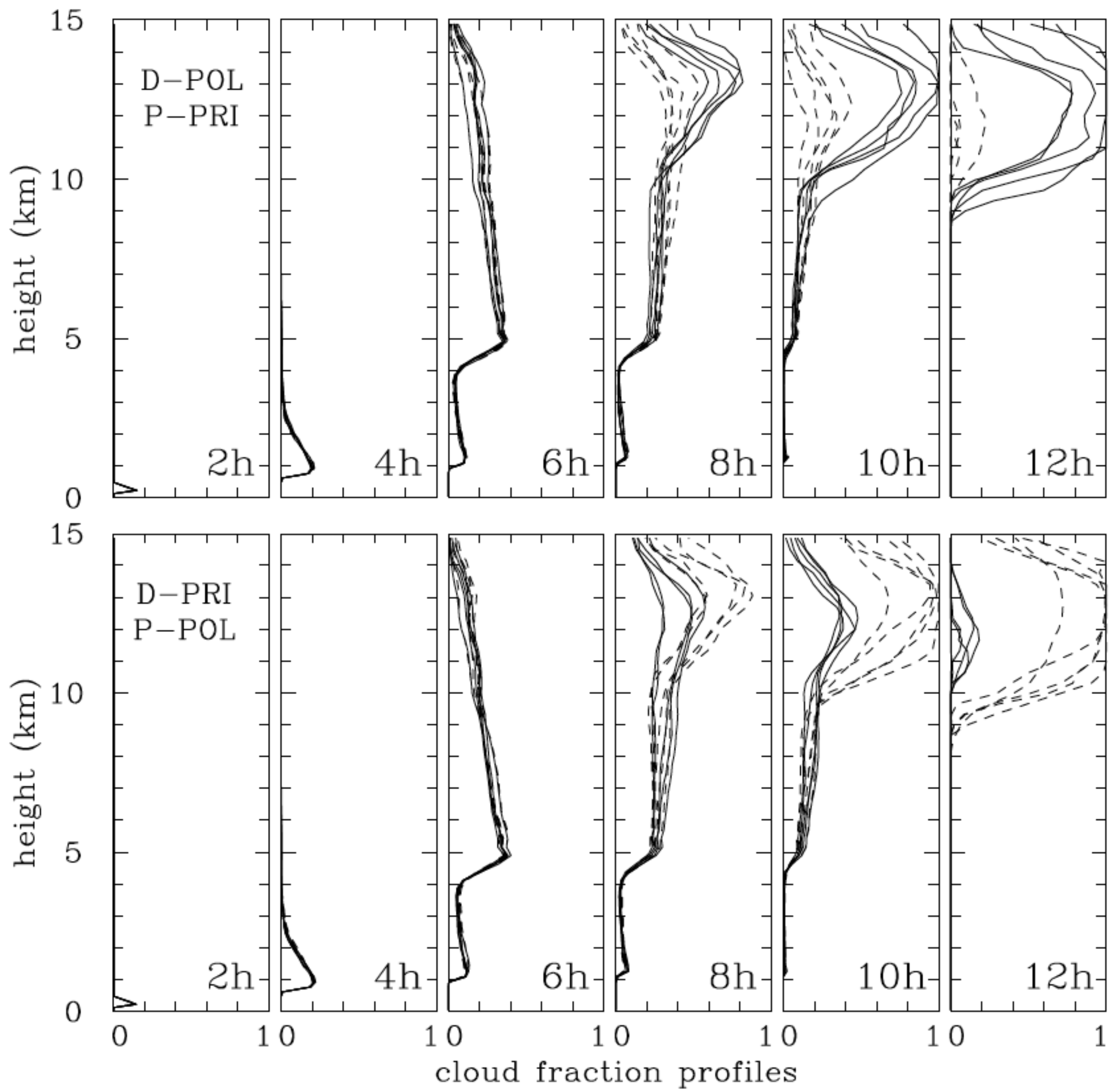
D-POL
(polluted)

FIG. 2. Albedo at hours (top)–(bottom) 2, 6, and 10 for two simulations from (left) D-PRI and (right) D-POL ensembles.

solid lines: driving set
dashed lines: piggybacking set

POL drives,
PRI piggybacks

PRI drives,
POL piggybacks

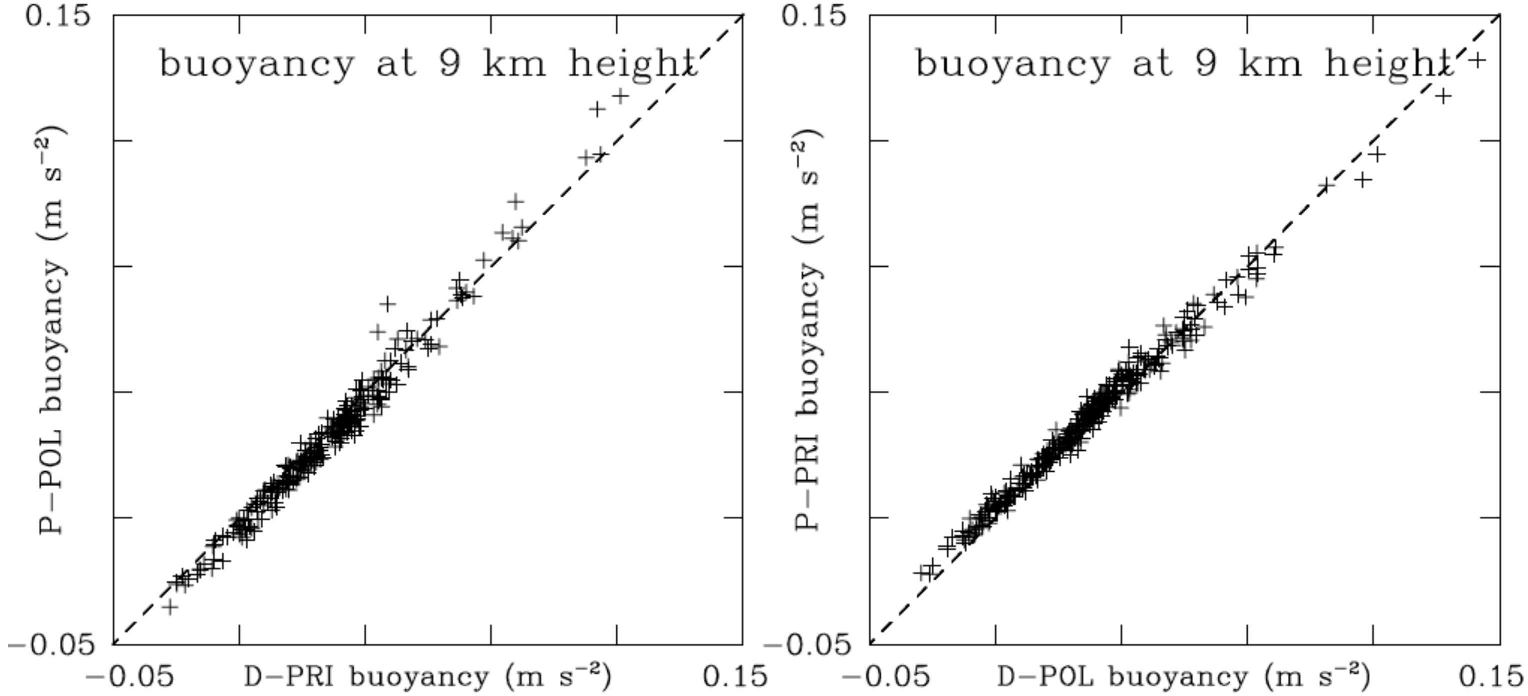


Comparing buoyancy between driving and piggybacking sets (hour 6):

D-PRI/P-POL

D-POL/P-PRI

1 K ≈ 0.03 m s^{-2}



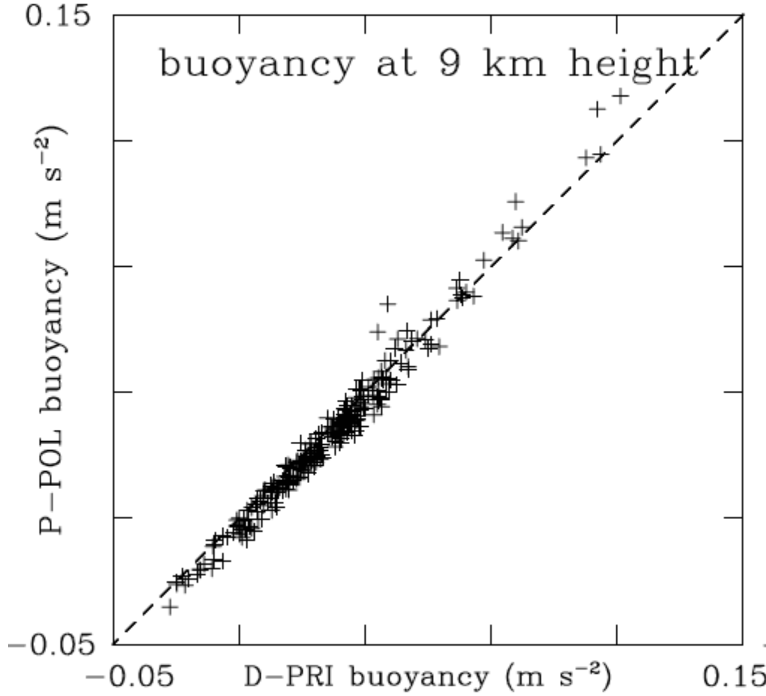
at 9 km (-27 degC)

(Rosenfeld et al. mechanism…)

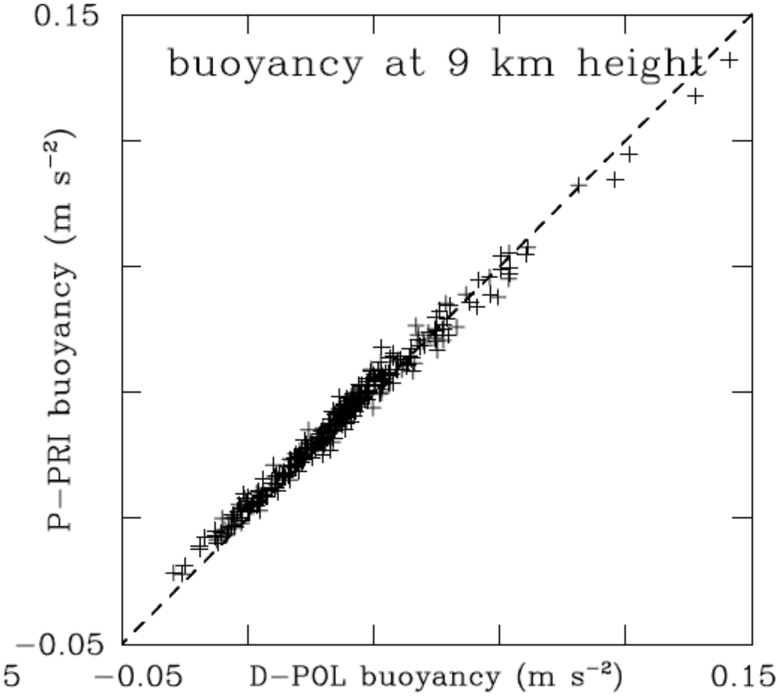
Comparing buoyancy between driving and piggybacking sets (hour 6):

1 K ≈ 0.03 m s^{-2}

D-PRI/P-POL



D-POL/P-PRI



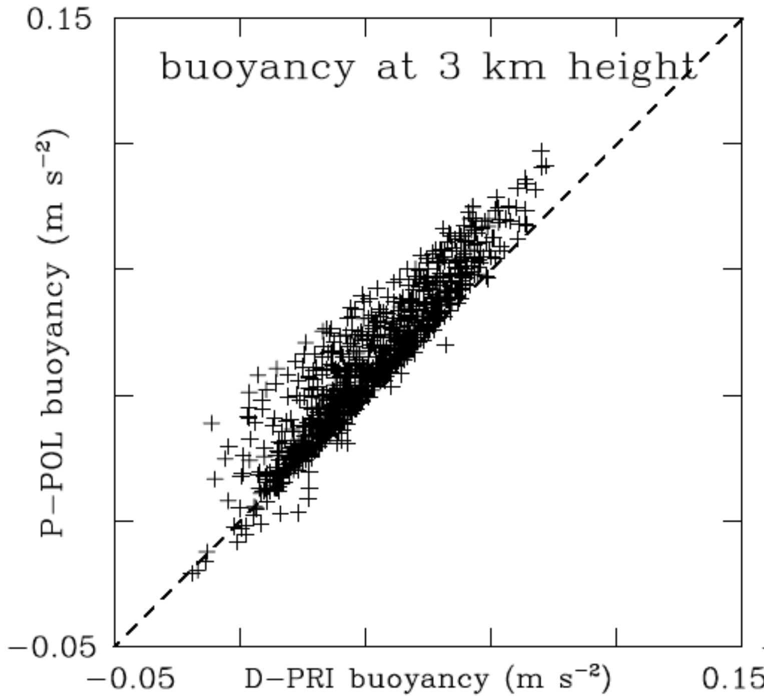
POL has slightly less buoyancy than PRI…

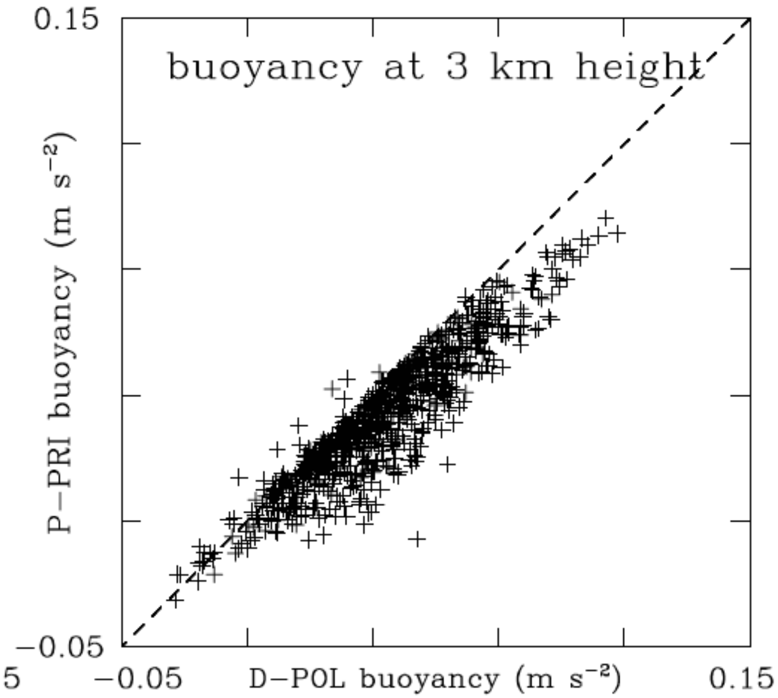
Comparing buoyancy between driving and piggybacking sets (hour 6):

D-PRI/P-POL

D-POL/P-PRI

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



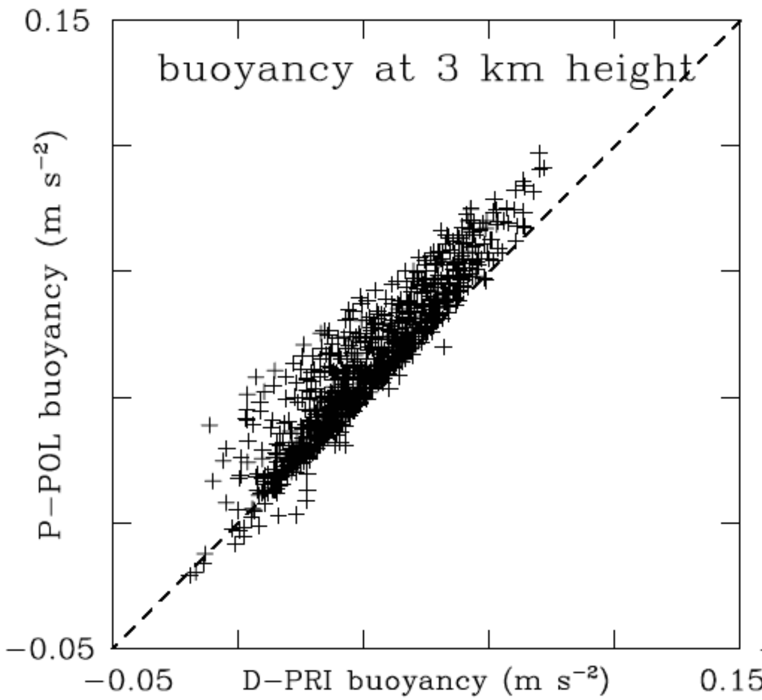


at 3 km (9 degC)

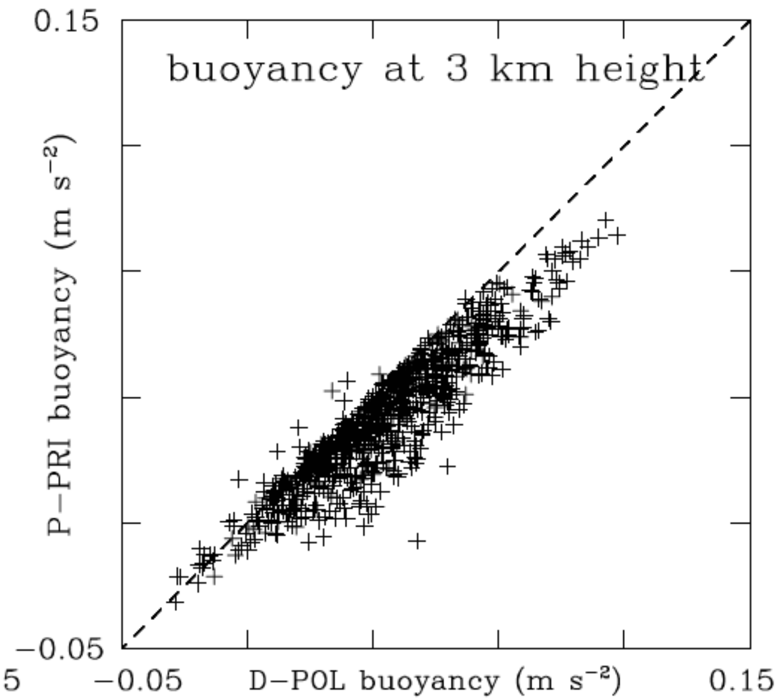
Comparing buoyancy between driving and piggybacking sets (hour 6):

1 K ≈ 0.03 m s^{-2}

D-PRI/P-POL



D-POL/P-PRI



POL can have more buoyancy than PRI…

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

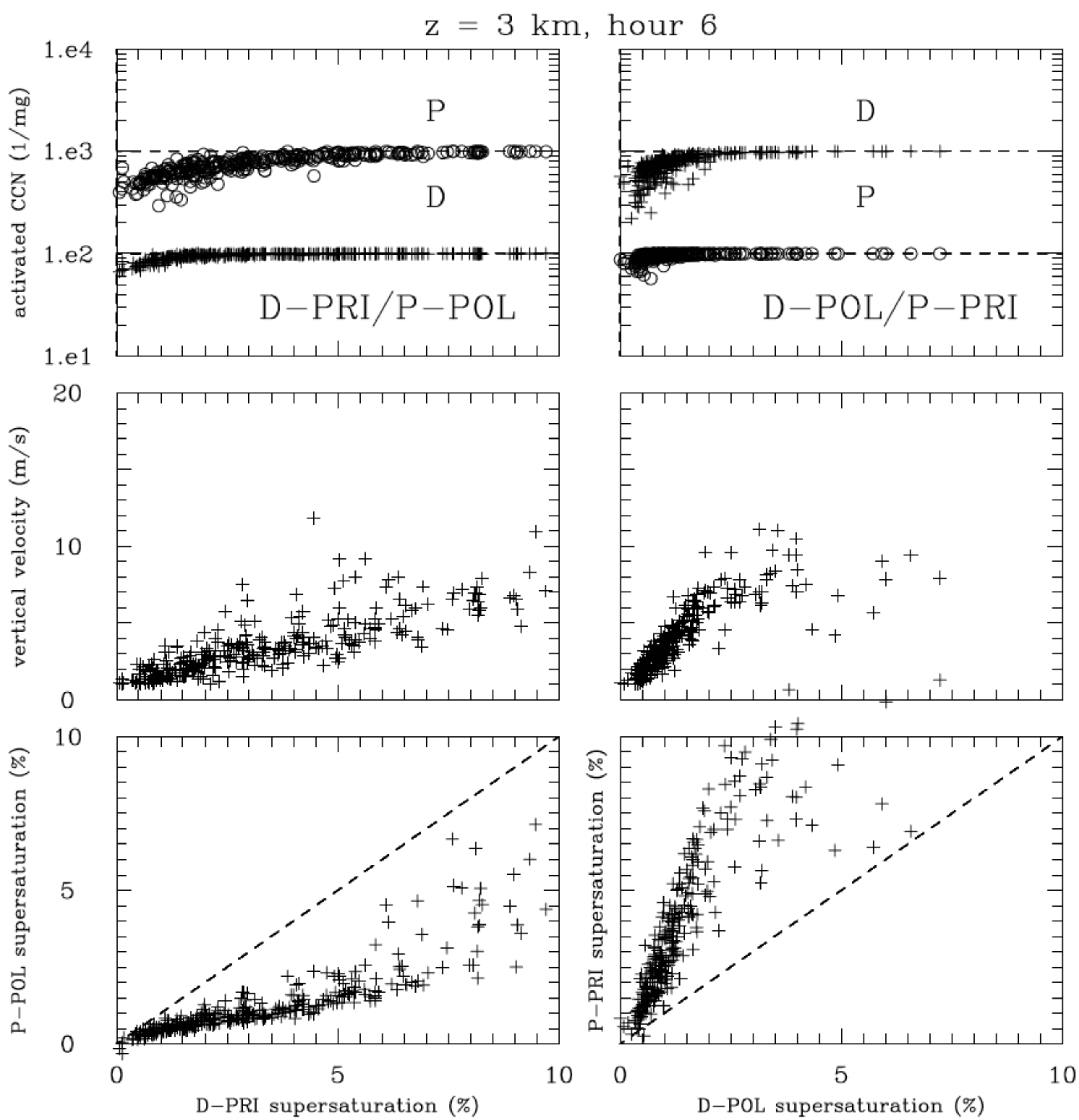
activated CCN

All CCN is activated even for the strongest updrafts…

updraft velocity

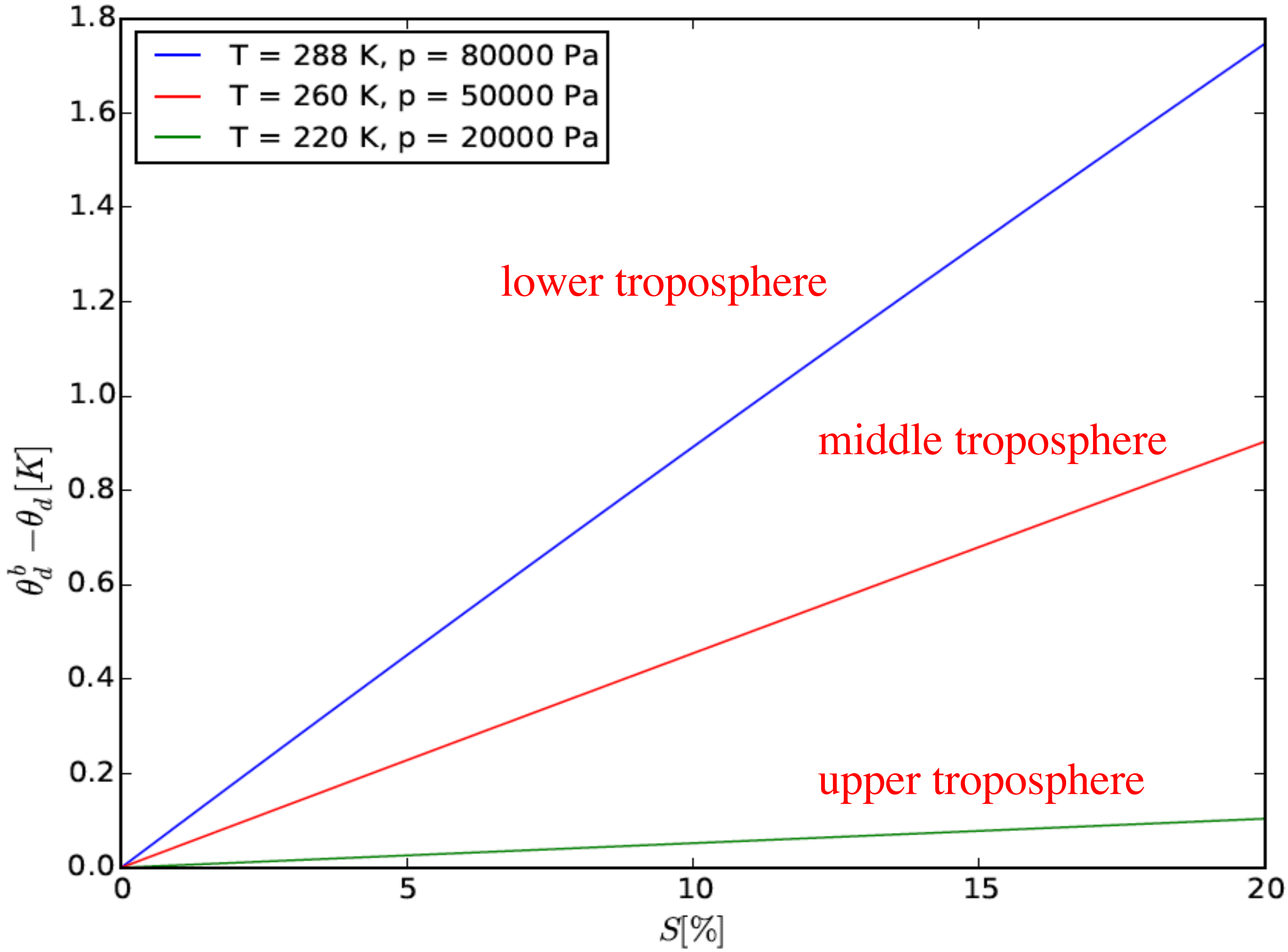
supersaturation

Supersaturations are large, especially in PRI



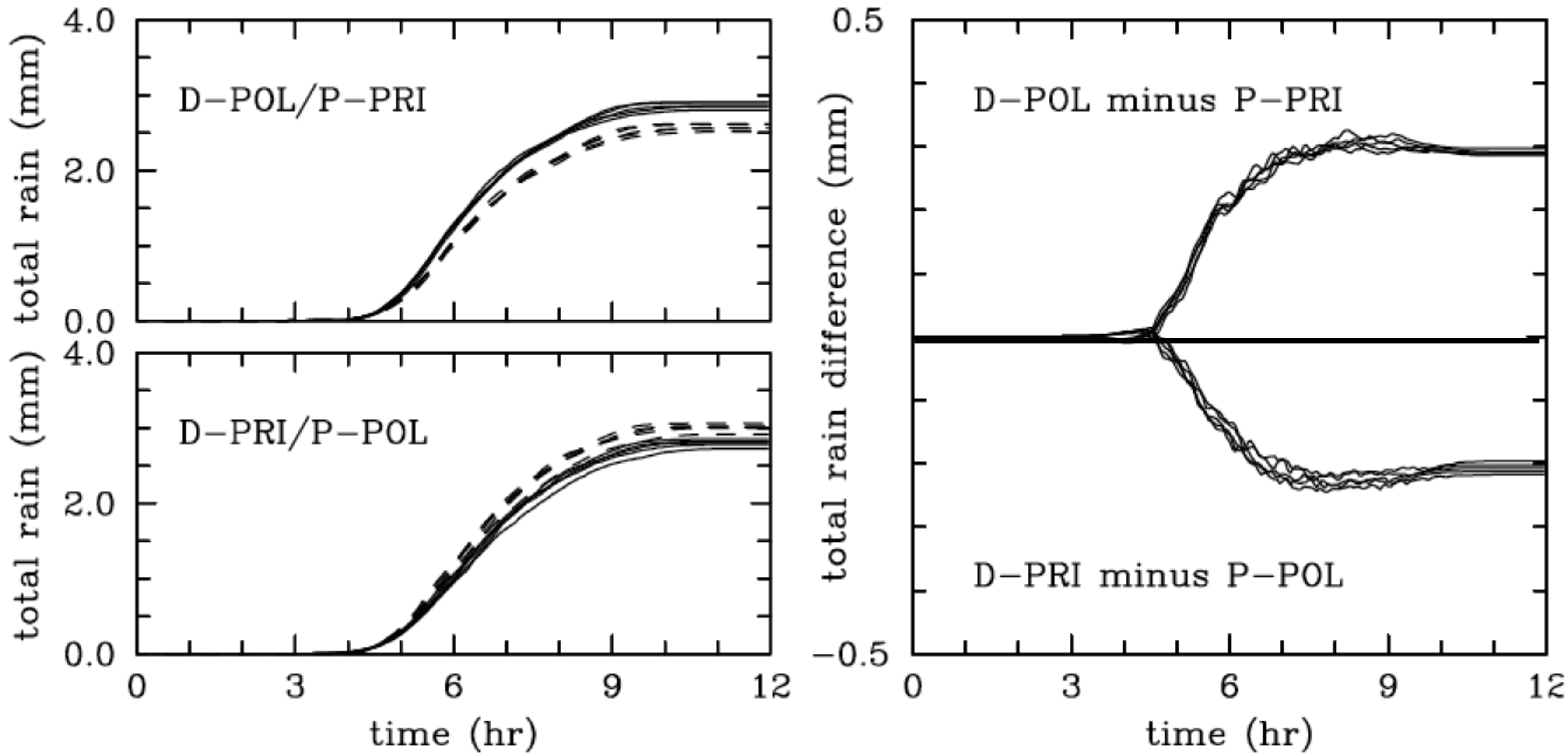
$$\theta_d = \theta(1 + \varepsilon q_v - q_c - q_r - q_{id} - q_{ir})$$

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



Impact of finite supersaturations on cloud buoyancy in deep convection

solid lines: driving set
dashed lines: piggybacking set



solid lines: driving set
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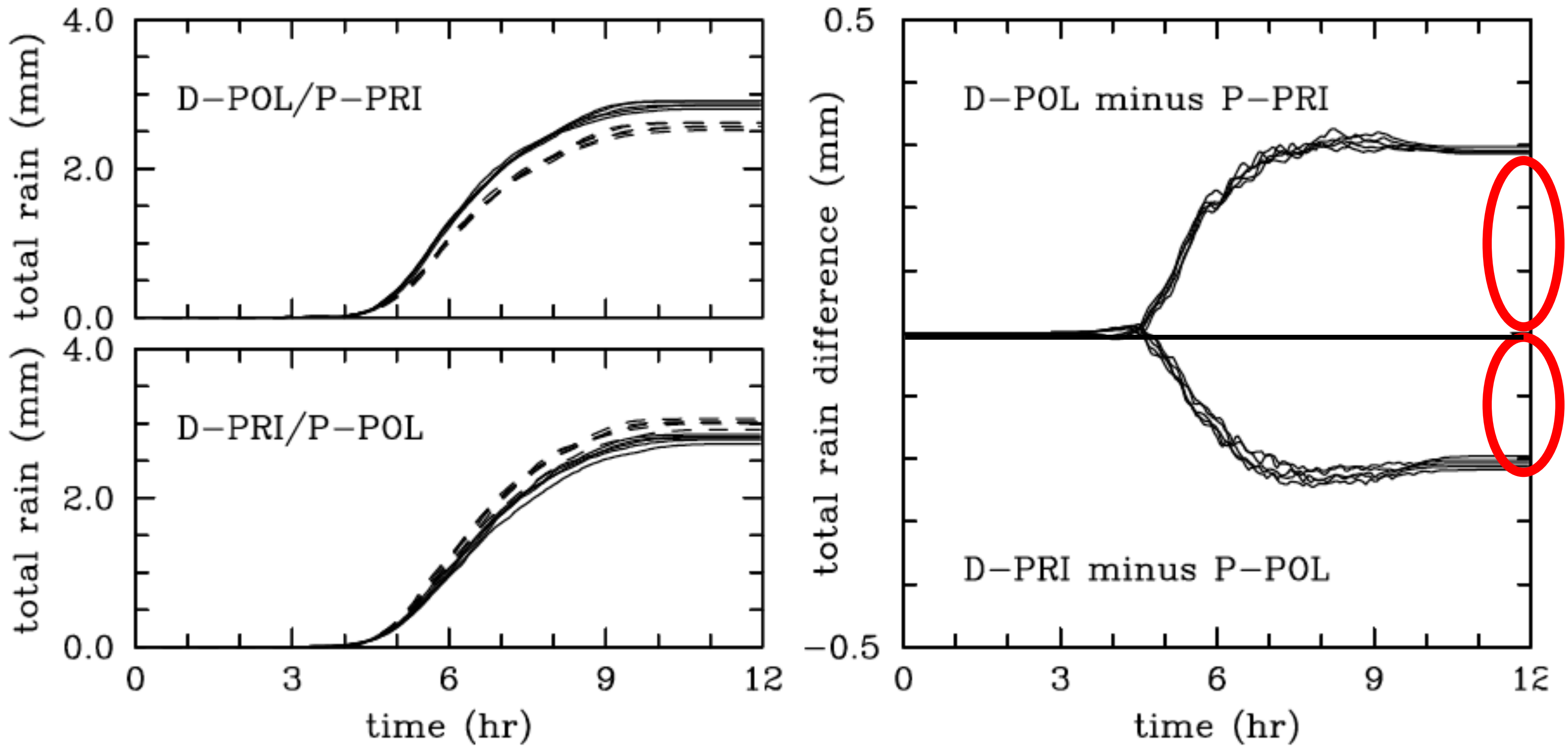


Impact on the cloud dynamics!

This can be shown by looking at the updraft statistics (no time to show that, see Grabowski and Morrison *JAS* 2016).

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**

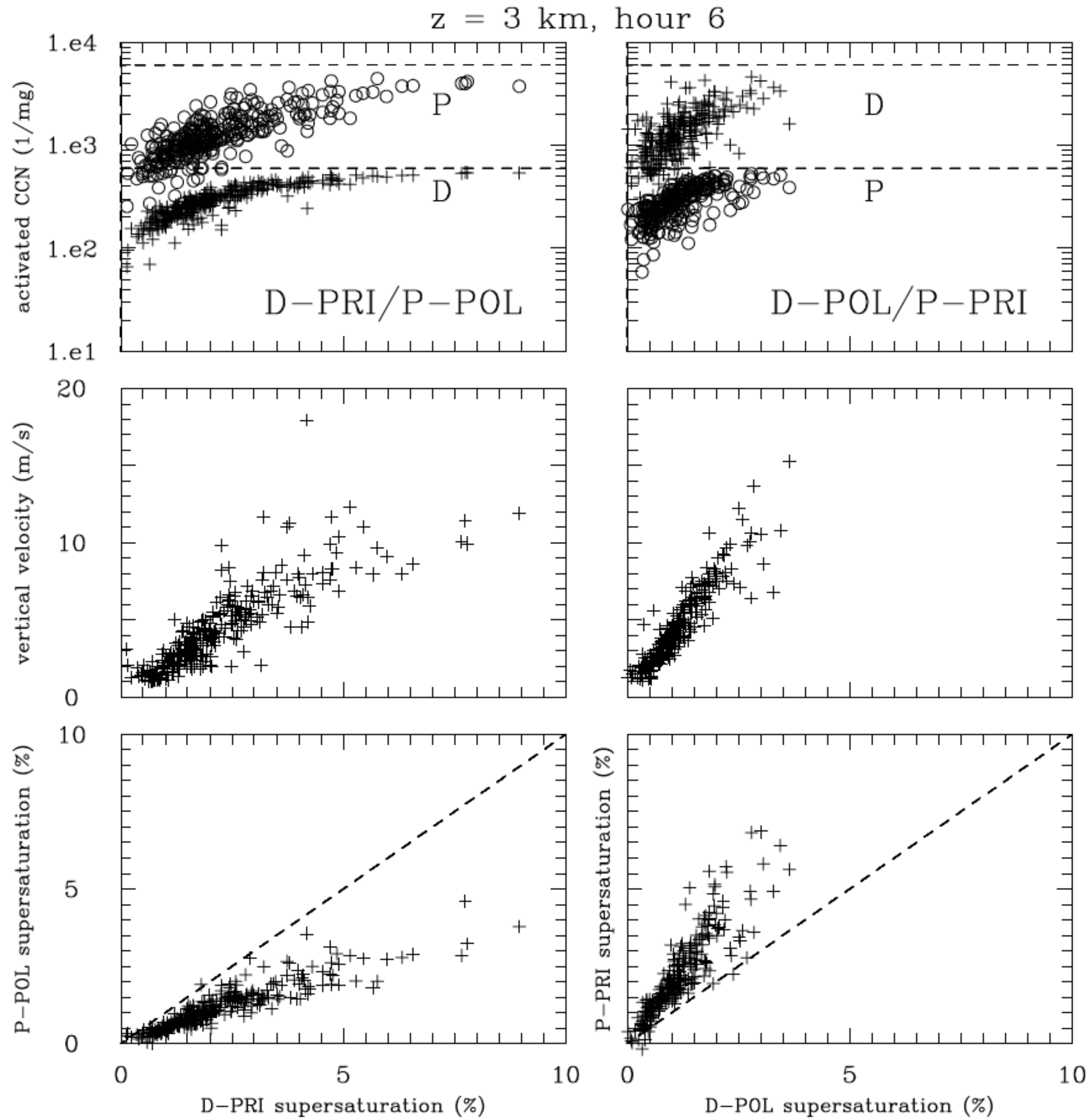
r_{d0} is the geometric mean radius of the dry particles **0.05 + 0.01 µm**

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

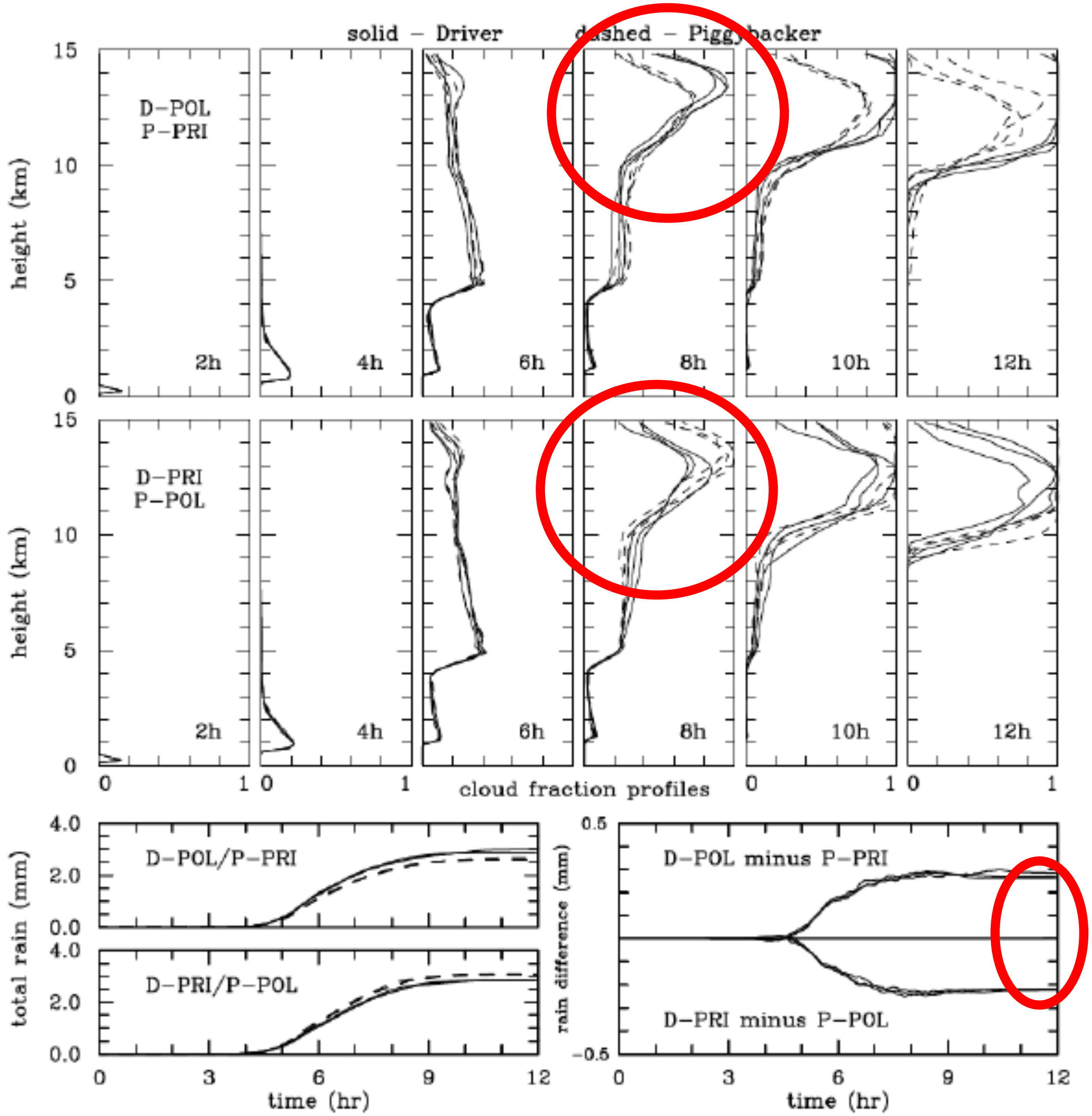
Hour 6, z = 3 km (9 degC), points with w > 1 m/s, Q > 1 g/kg

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…

The piggybacking methodology allows confident assessment of the impact of cloud microphysics on cloud simulation.

Piggybacking clarifies the dynamic basis of convective invigoration in polluted environments.

POL versus PRI simulations with 2-moment bulk scheme:

- **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.**

Can the impact of aerosols on deep convection be isolated from the effects of meteorology in atmospheric observations?

Wojciech W. Grabowski

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NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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ASR
Atmospheric System Research

U.S. DEPARTMENT OF ENERGY
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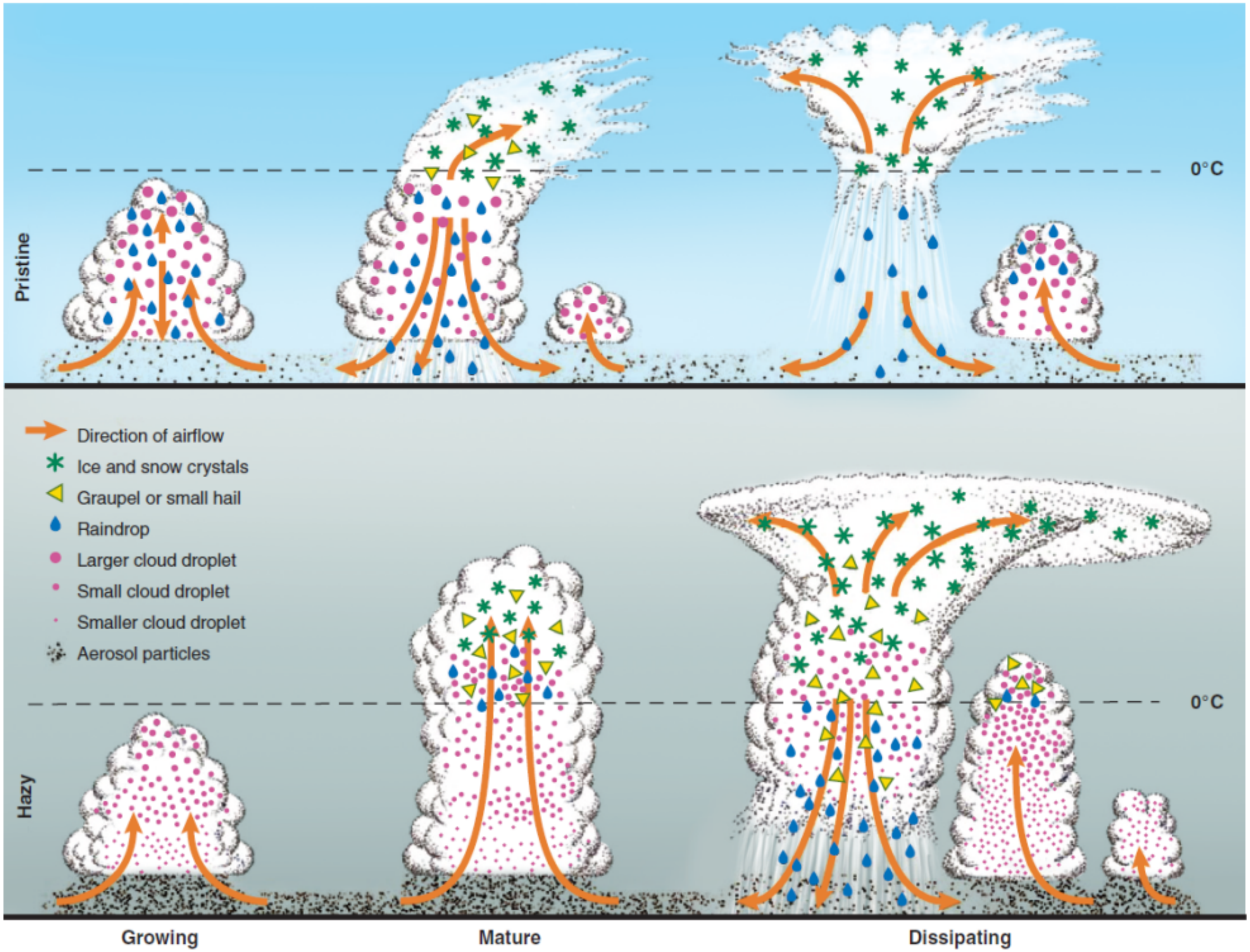
clean

polluted



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

Are atmospheric observations accurate enough to exclude meteorological factors?

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

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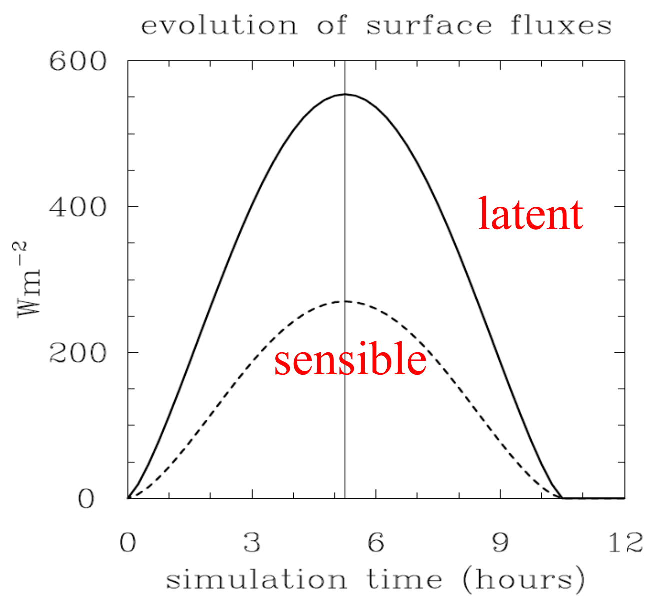


The argument:

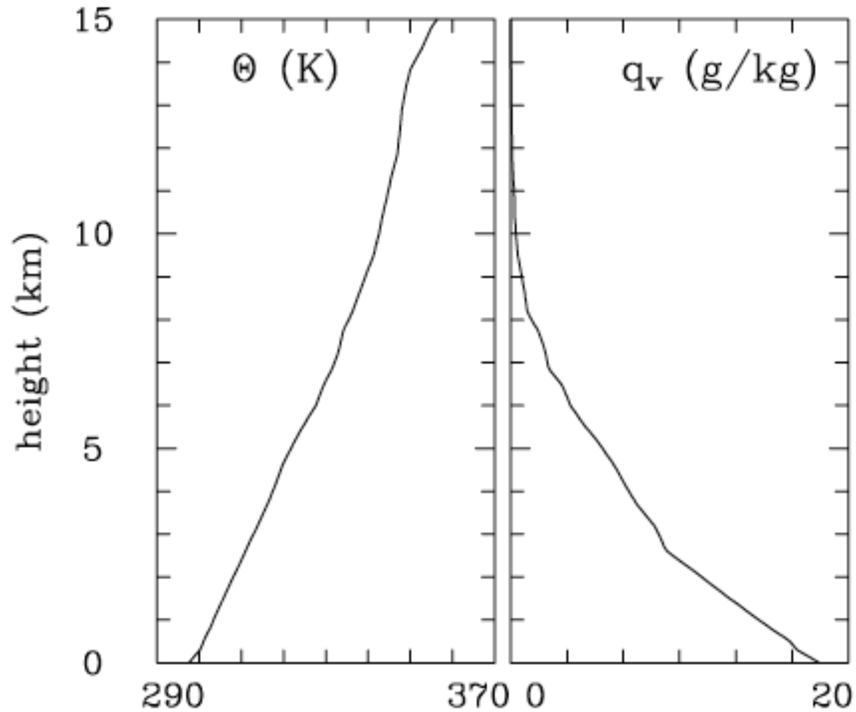
If there are other factors that affect convection ("meteorology"), then the impact can be wrongly interpreted as aerosol effects…

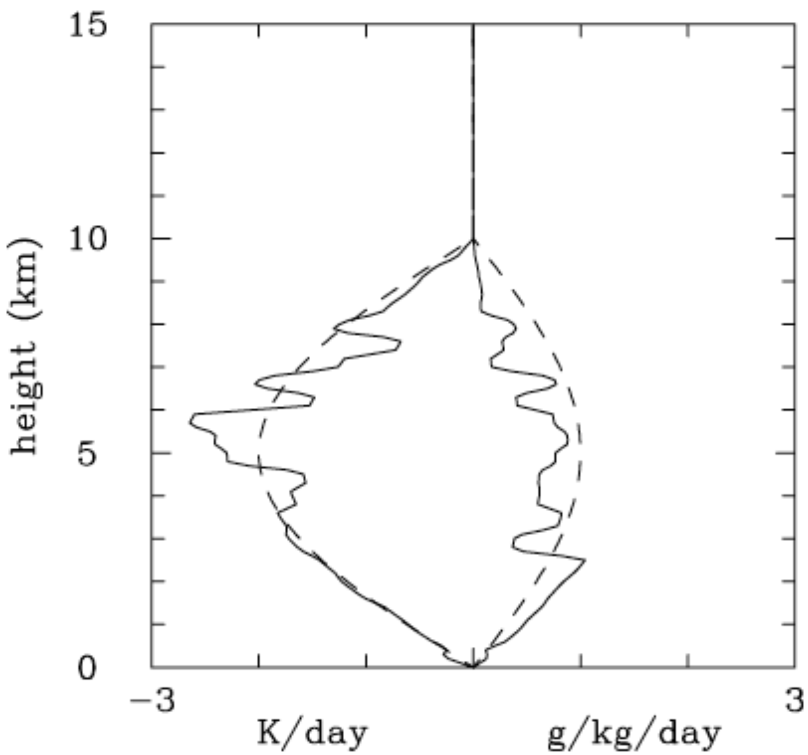
The modeling idea:

Compare simulations with and without changes in the environment ("meteorology") in which convection develops. The changes are small and thus difficult to detect in observations:

additional forcing
modified surface fluxes
modified temperature profile
modified RH profile

simulations with the two aerosol modes (more realistic?)



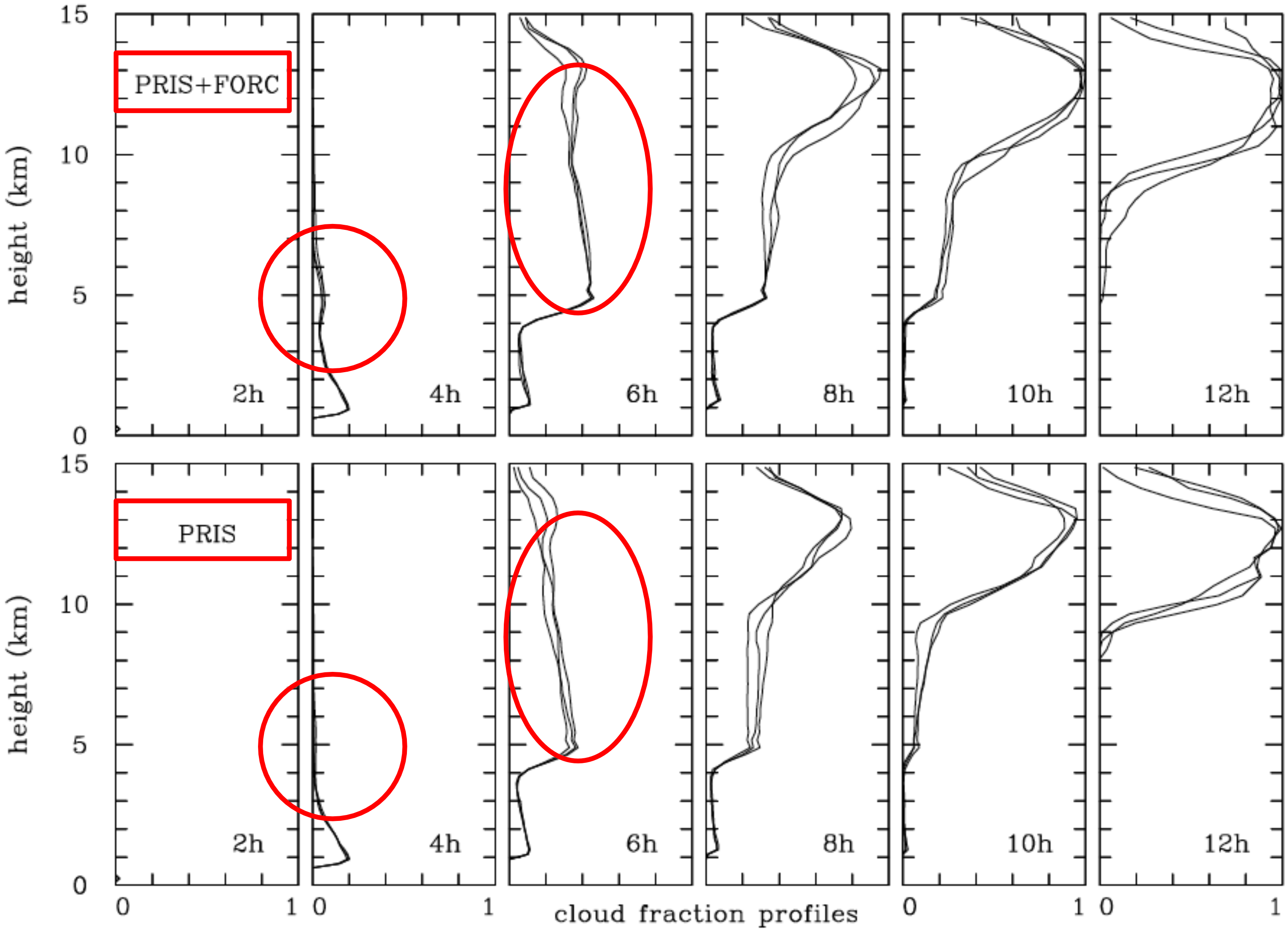


$$w = w_o \sin(\pi z/L)$$

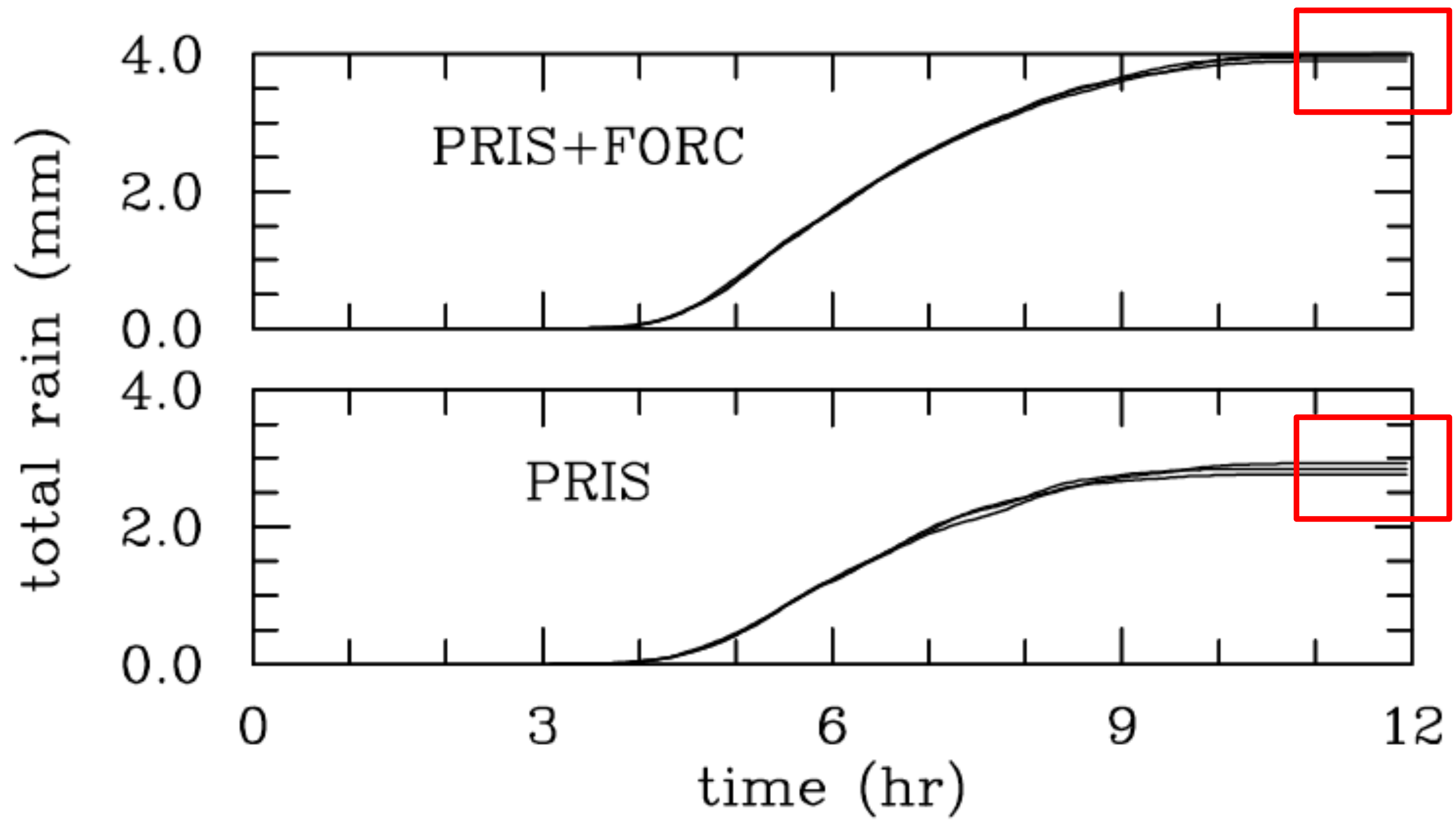
$$0 < z < L$$

$$w_o = 0.5 \text{ cm/s} \quad L = 10 \text{ km}$$

vertical: 0.5 cm/s over 5 km
corresponds to
horizontal: 0.5 m/s over 500 km

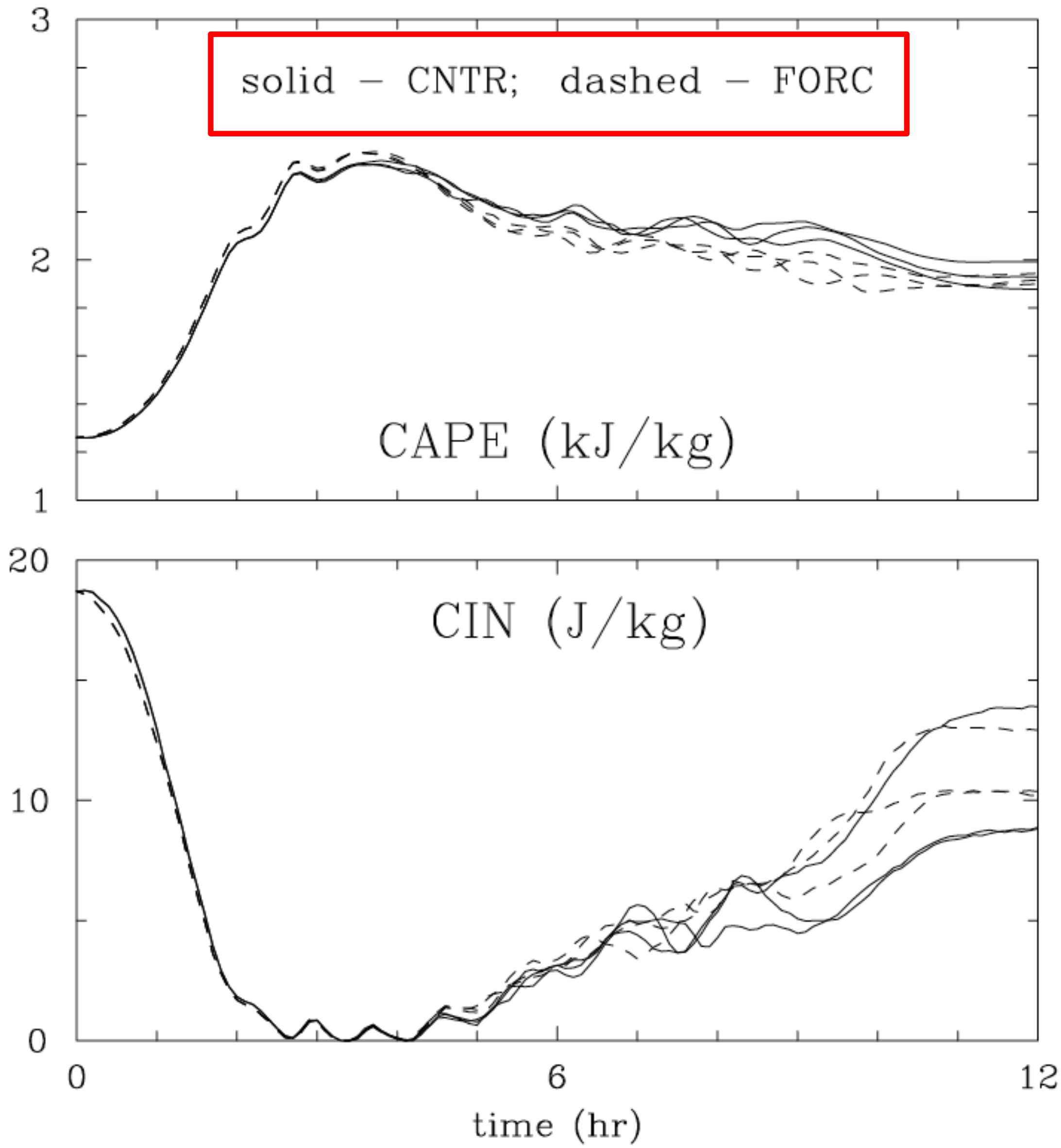


…small but noticeable impact on cloudiness...



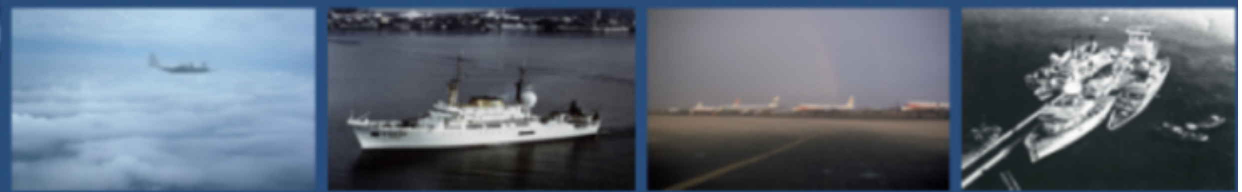
…a significant impact on surface precipitation...

So if you did not know about the ascent, you may attribute the change to aerosols!...



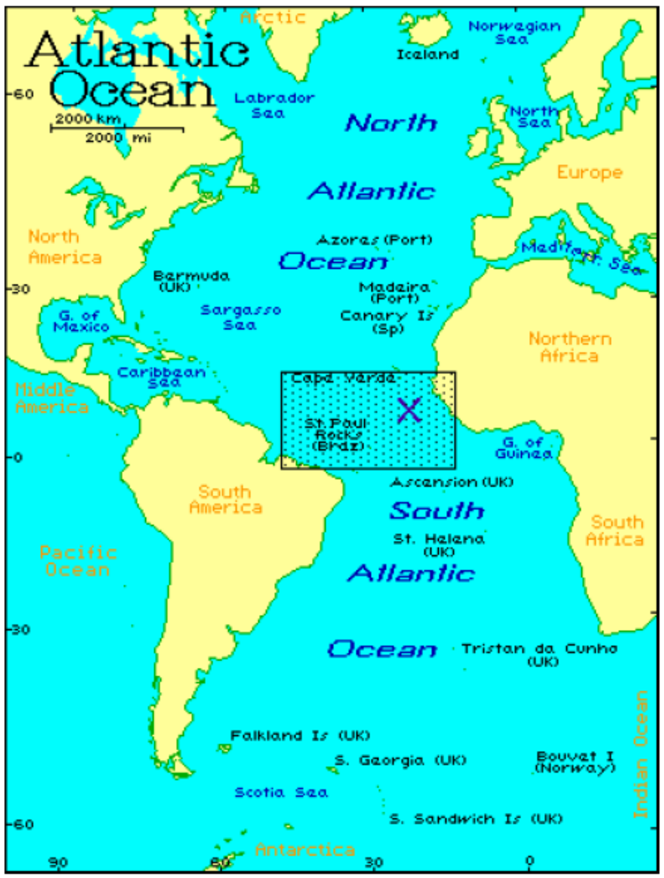
…the impact on CAPE and CIN is insignificant …

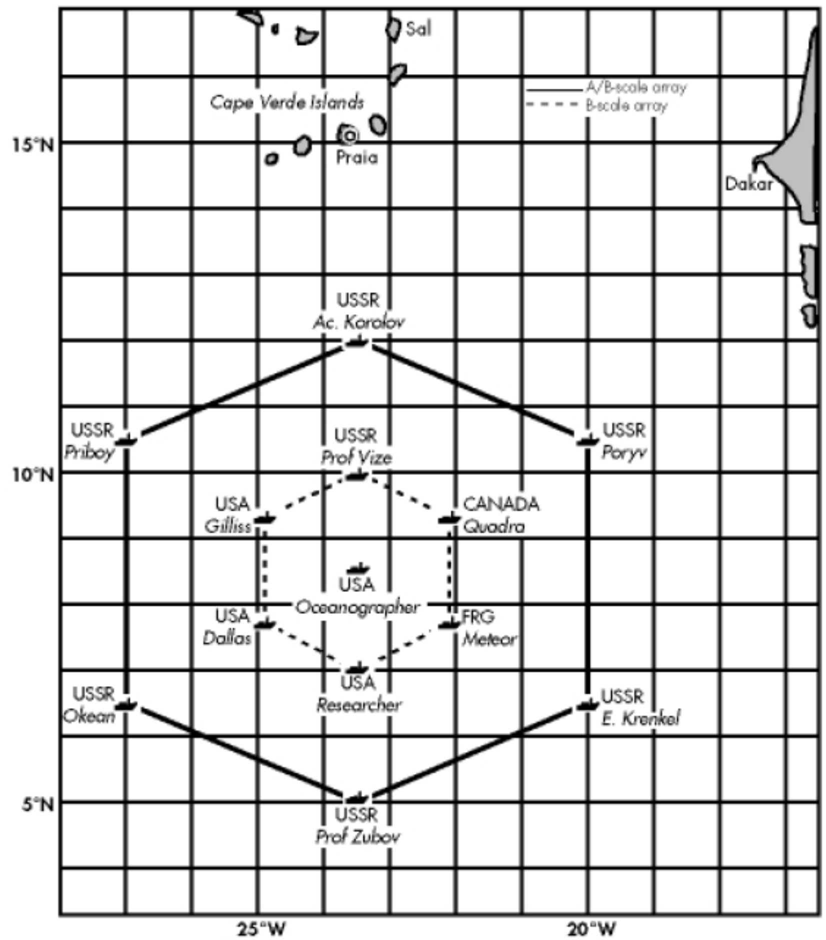
Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE)

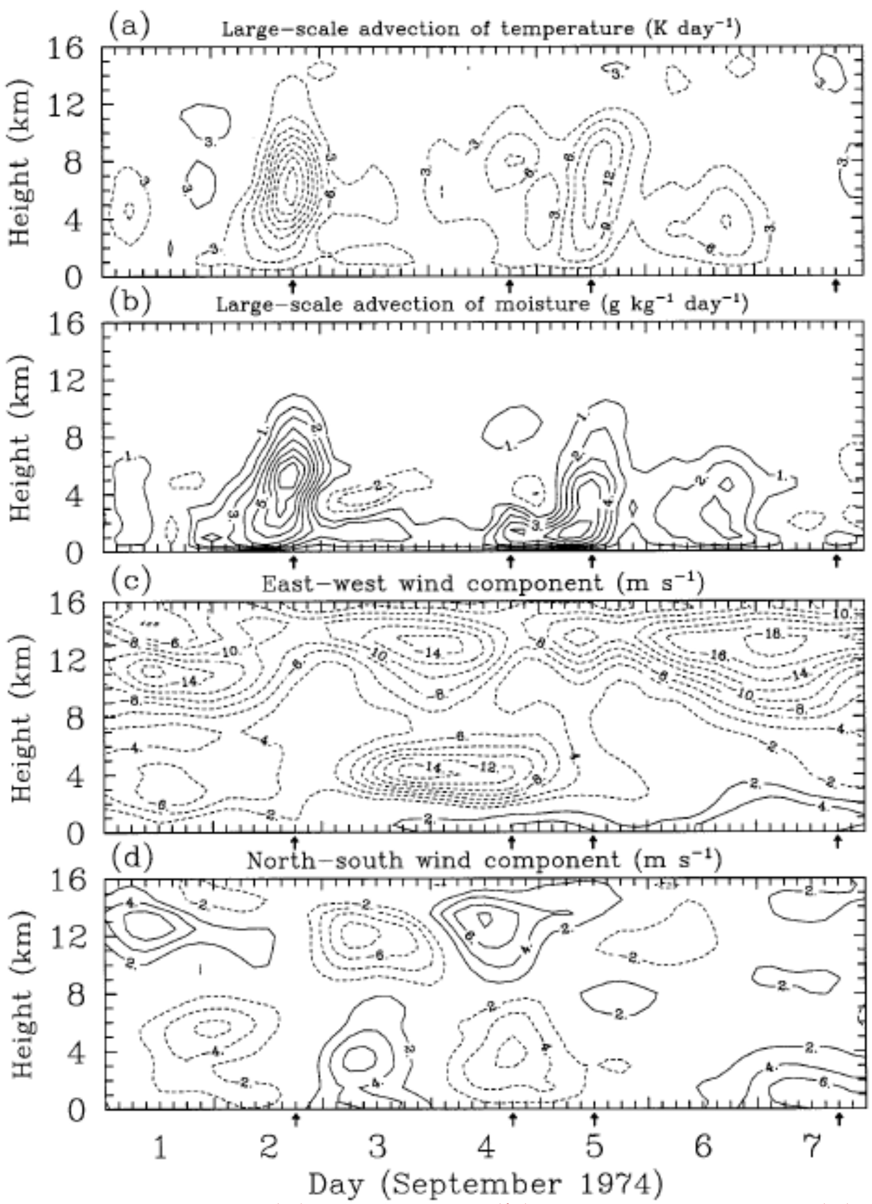


June 15, 1974 to September 23, 1974

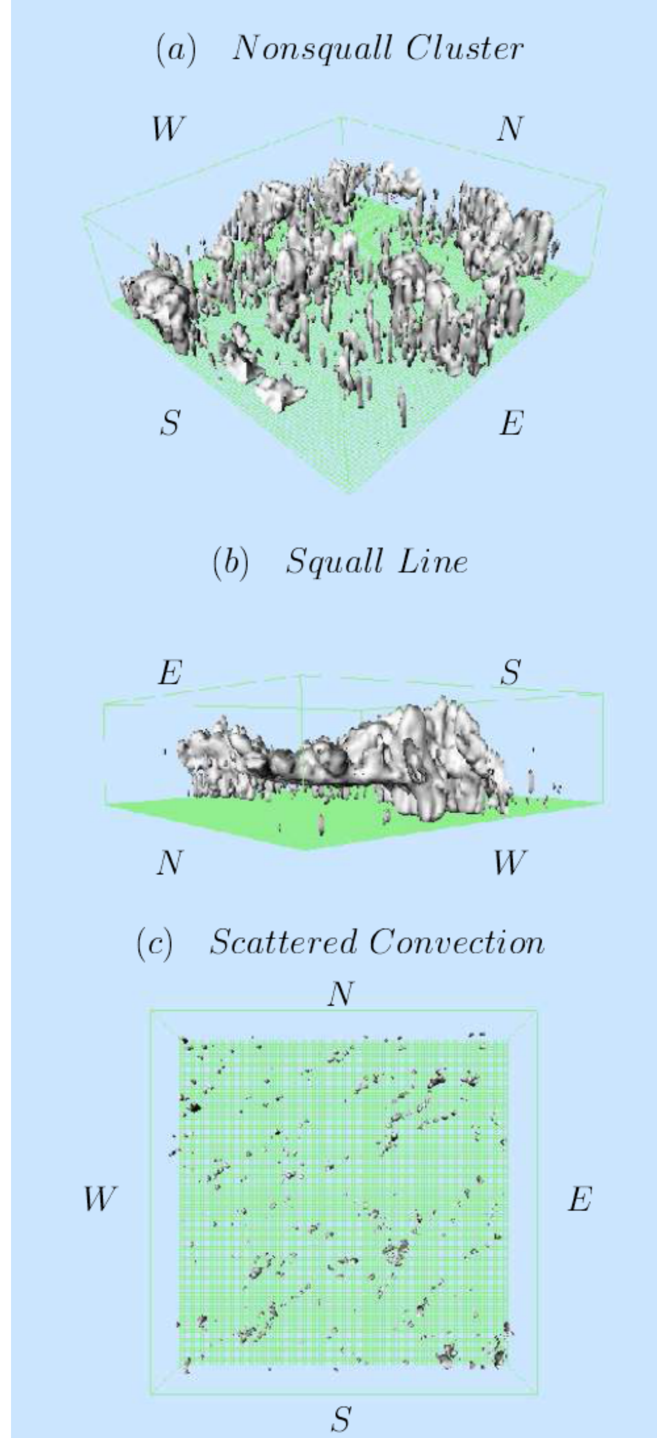
Project Location: Atlantic Ocean





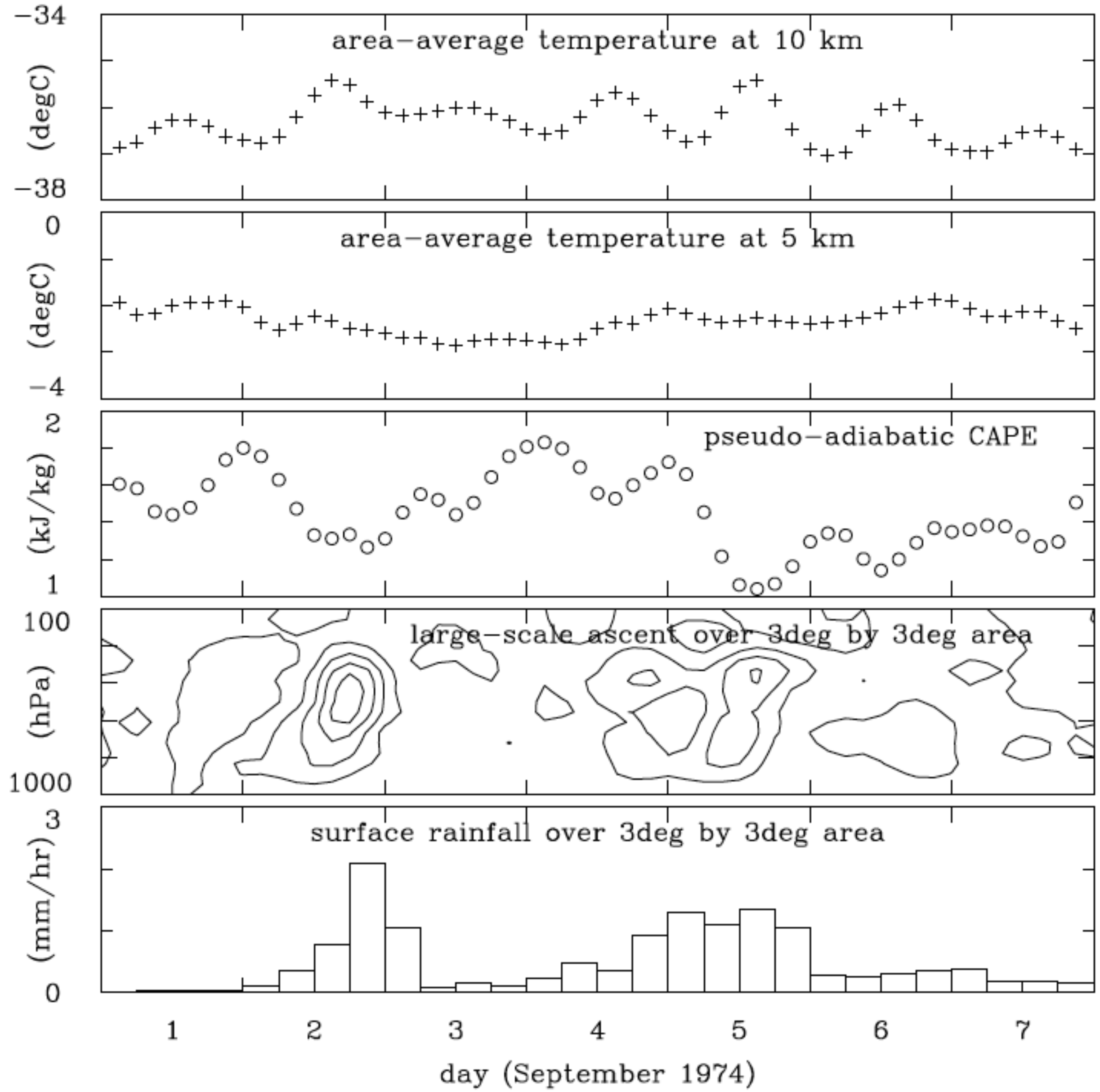


(a) (b) (c)



Grabowski et al. (*JAS* 1996, 1998a,b)

GATE sounding and surface precipitation data



Observations alone cannot provide support for the convection invigoration in polluted environments. The key issue is that correlations between modified aerosols and modified clouds seen in observations do not imply causality.

Separation of aerosol impact from the impacts of meteorology (e.g., different advective tendencies of temperature and moisture that drive cloud dynamics) is virtually impossible using current measurement capabilities.

I strongly believe that the convection invigoration is a myth, at least in the way it is presented in papers by Danny Rosenfeld and his entourage (e.g., Rosenfeld et al. *Science* 2008, Fan et al. *Science* 2018).

Only time will tell who is right and who is wrong…