Aerosol-cloud-precipitation interactions

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NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH
ASR
Atmospheric System Research
U.S. DEPARTMENT OF ENERGY
Office of Science

Fan, J., Y. Wang, D. Rosenfeld, and X. Liu, 2016: Review of aerosol–cloud interactions: Mechanisms, significance, and challenges. *J. Atmos. Sci*., **73**, 4221–4252.

Tao, W.-K., J.-P. Chen, Z. Li, C. Wang, and C. Zhang, 2012: Impact of aerosols on convective clouds and precipitation. *Rev. Geophys*., **50**, RG2001, doi:10.1029/2011RG000369.

These papers include several hundred references…

What determines the concentration of cloud droplets?

To answer this, one needs to understand formation of cloud droplets, that is, the activation of cloud condensation nuclei (CCN) .

This typically happens near the cloud base, when the rising air parcel approaches saturation.

Saturation ratio:

Saturated water vapor pressure over an aqueous solution droplet with radius *r*

Saturated water vapor pressure over plain water surface

Surface tension (Kelvin) effect

Solute (Raoult) effect

$$\frac{e_r}{e_\infty} = 1 + \frac{a}{r} - \frac{b}{r^3}$$

$$a = \frac{2\sigma}{\rho_l R_v T} \qquad b = \frac{4 i m_s M_v}{3\pi \rho_l M_s}$$

σ - surface tension

ρ_l - water density

R_v – gas constant for water vapor

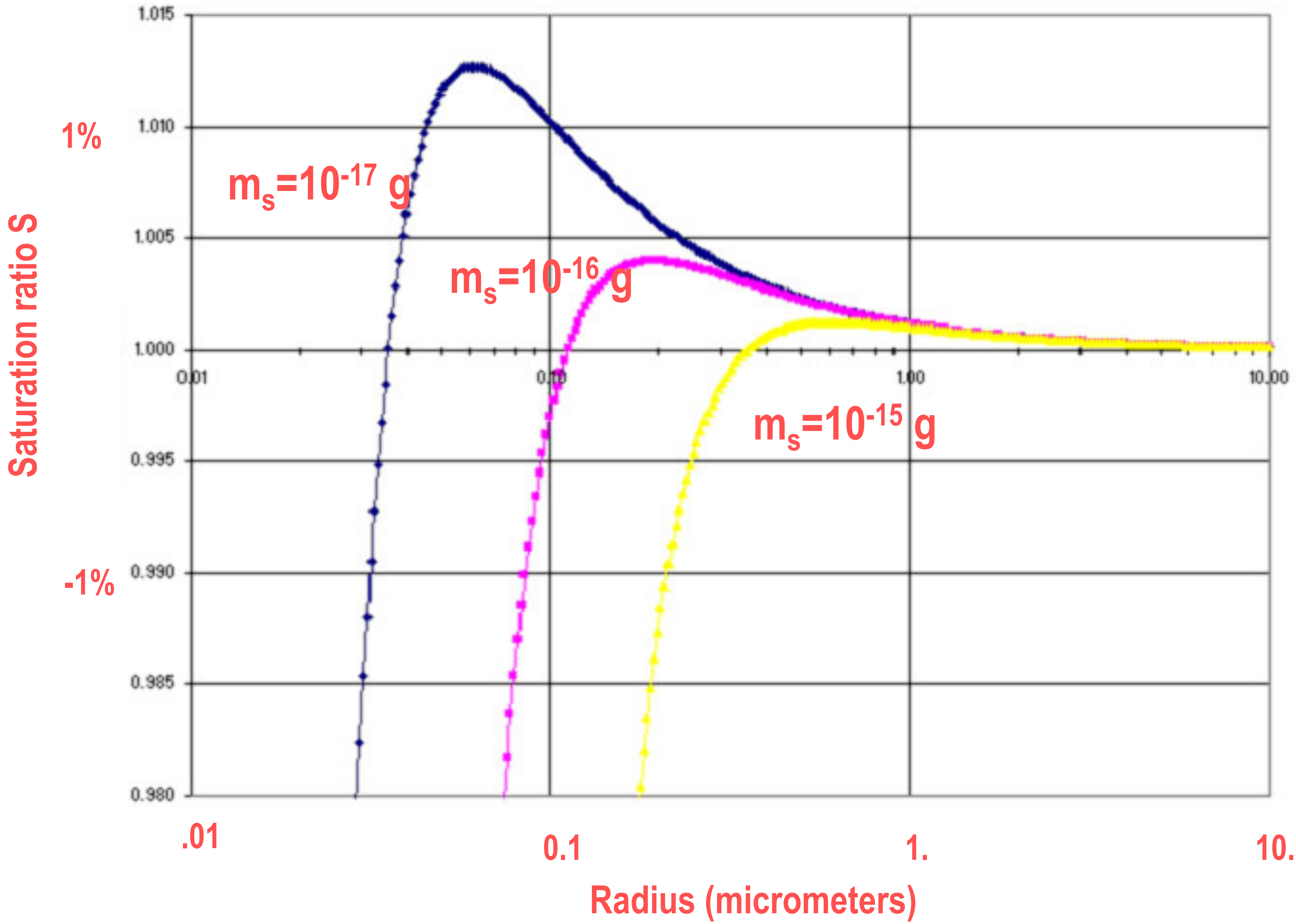
T – air temperature

i – van't Hoff factor

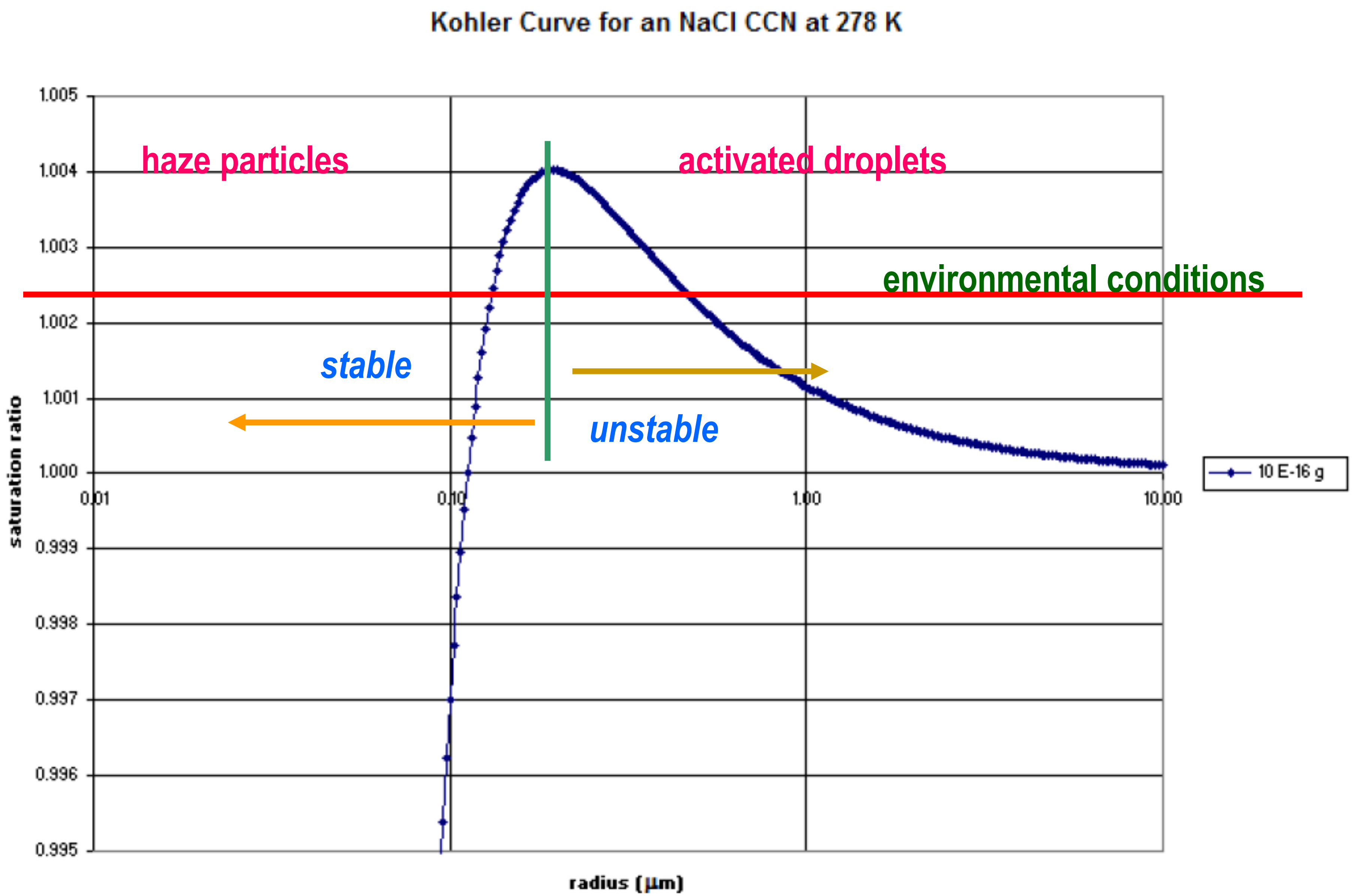
m_s – mass of solute

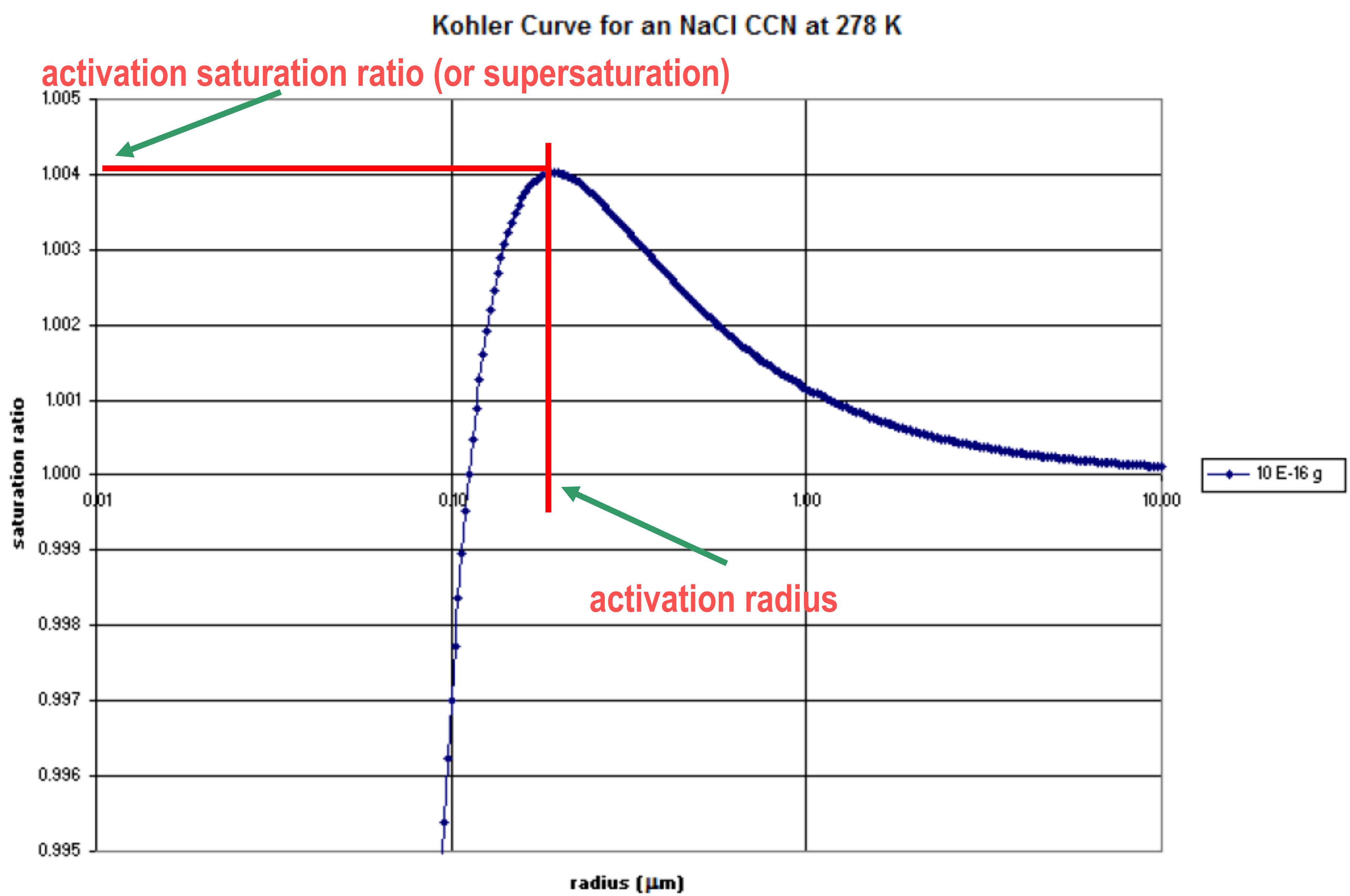
M_v – molar mass of water

M_s – molar mass of solute



Saturation ratio S
1%
-1%
1.015
1.010
1.005
1.000
0.995
0.990
0.985
0.980
0.01
0.10
1.00
10.00
$m_s=10^{-17}$ g
$m_s=10^{-16}$ g
$m_s=10^{-15}$ g
.01
0.1
1.
10.
Radius (micrometers)


Kohler Curve for an NaCl CCN at 278 K
haze particles
activated droplets
environmental conditions
stable
unstable
saturation ratio
1.005
1.004
1.003
1.002
1.001
1.000
0.999
0.998
0.997
0.996
0.995
0.01
0.10
1.00
10.00
radius (µm)
10 E-16 g

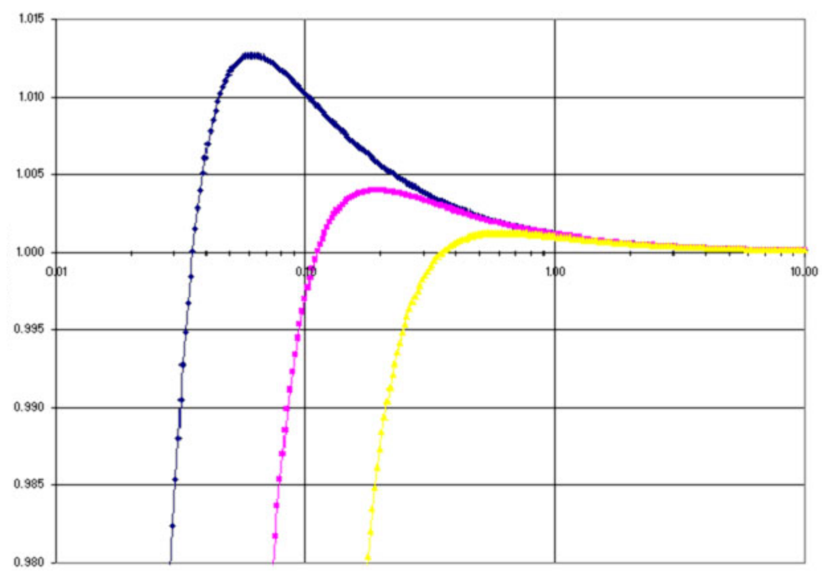


Kohler Curve for an NaCl CCN at 278 K
activation saturation ratio (or supersaturation)
activation radius
saturation ratio
radius (µm)
10 E-16 g
1.005
1.004
1.003
1.002
1.001
1.000
0.999
0.998
0.997
0.996
0.995
0.01
0.10
1.00
10.00

CCN, soluble salt particles, have different sizes.

Large CCN are nucleated first, activation of smaller ones follows as the supersaturation builds up.

Once sufficient number of CCN is activated, supersaturation levels off, and activation is completed.



Twomey CCN activation:

N - total concentration of activated droplets

S – supersaturation ($S = q_v/q_{vs} - 1$)

$$N = a\,S^b$$

a, b – parameters characterizing CCN

$0 < b < 1$ (typically, $b=0.5$)

$a \sim 100\ cm^{-3}$ maritime/clean

$a \sim 1{,}000\ cm^{-3}$ continental/polluted

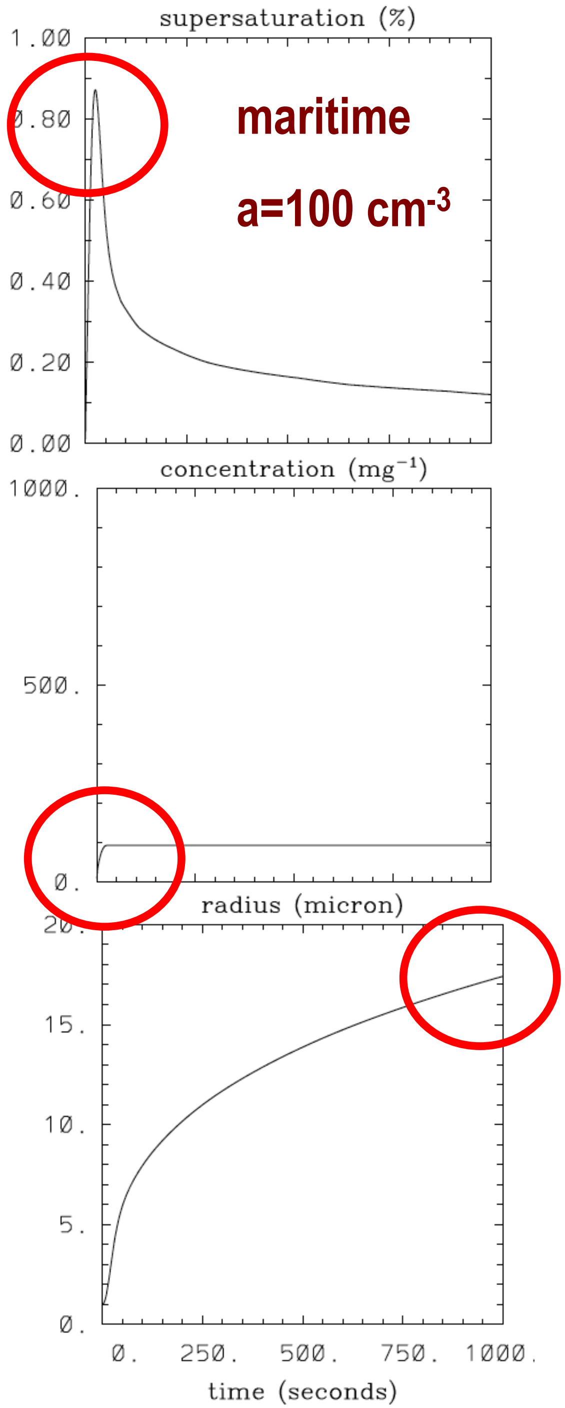
Computational example:

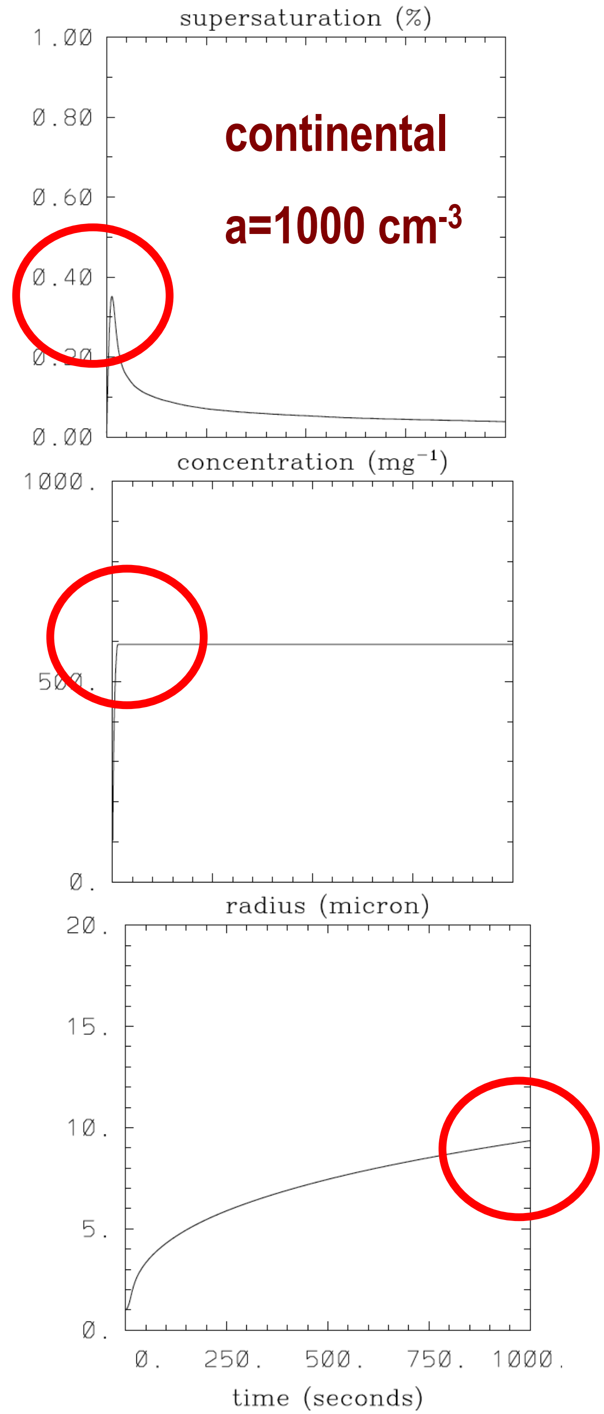
Nucleation and growth of cloud droplets in a parcel of air rising with vertical velocity of 1 m/s;

Contrasting continental/polluted and maritime/pristine aerosols

a~100 cm^{-3} maritime/clean

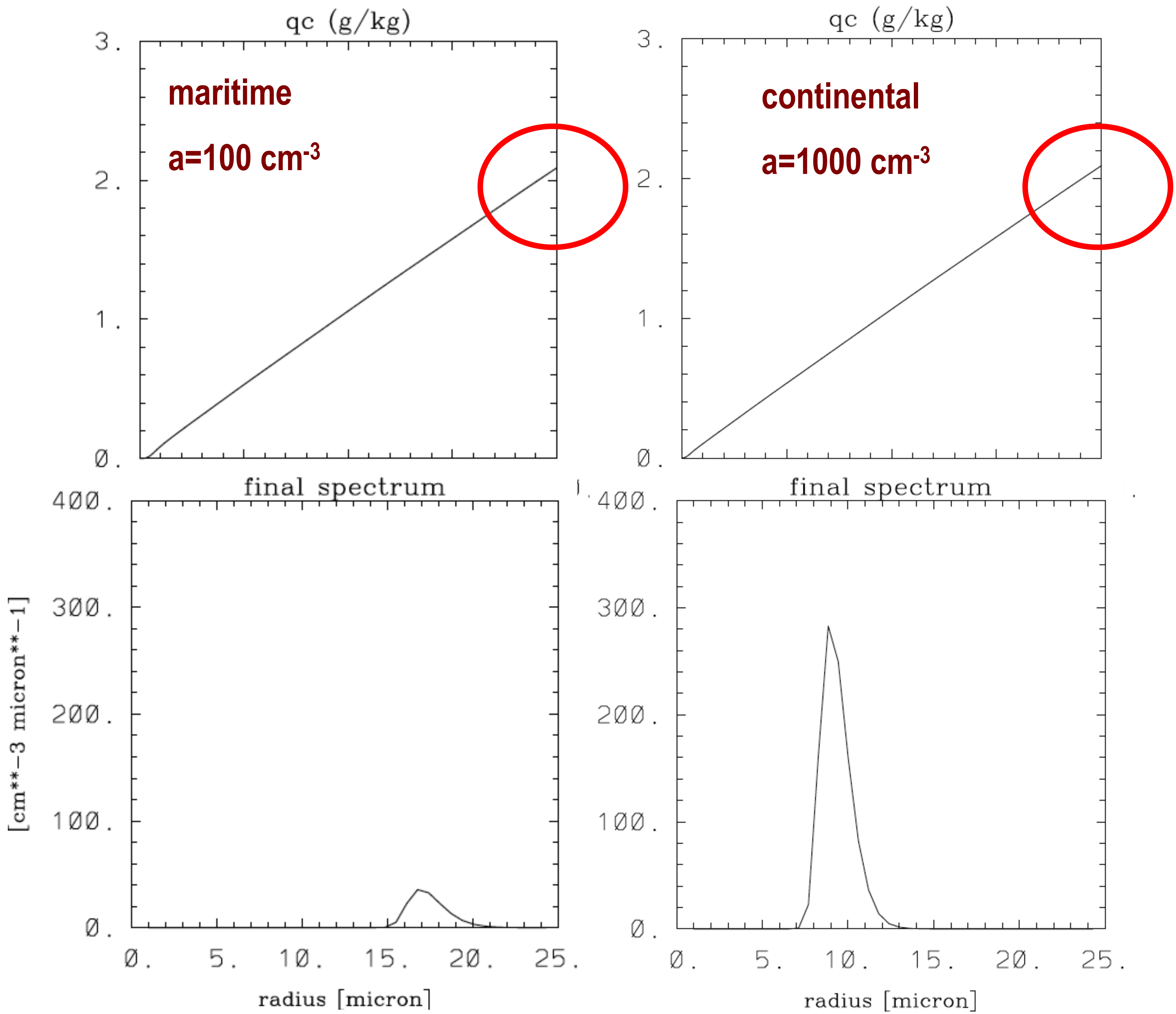
a~1,000 cm^{-3} continental/polluted

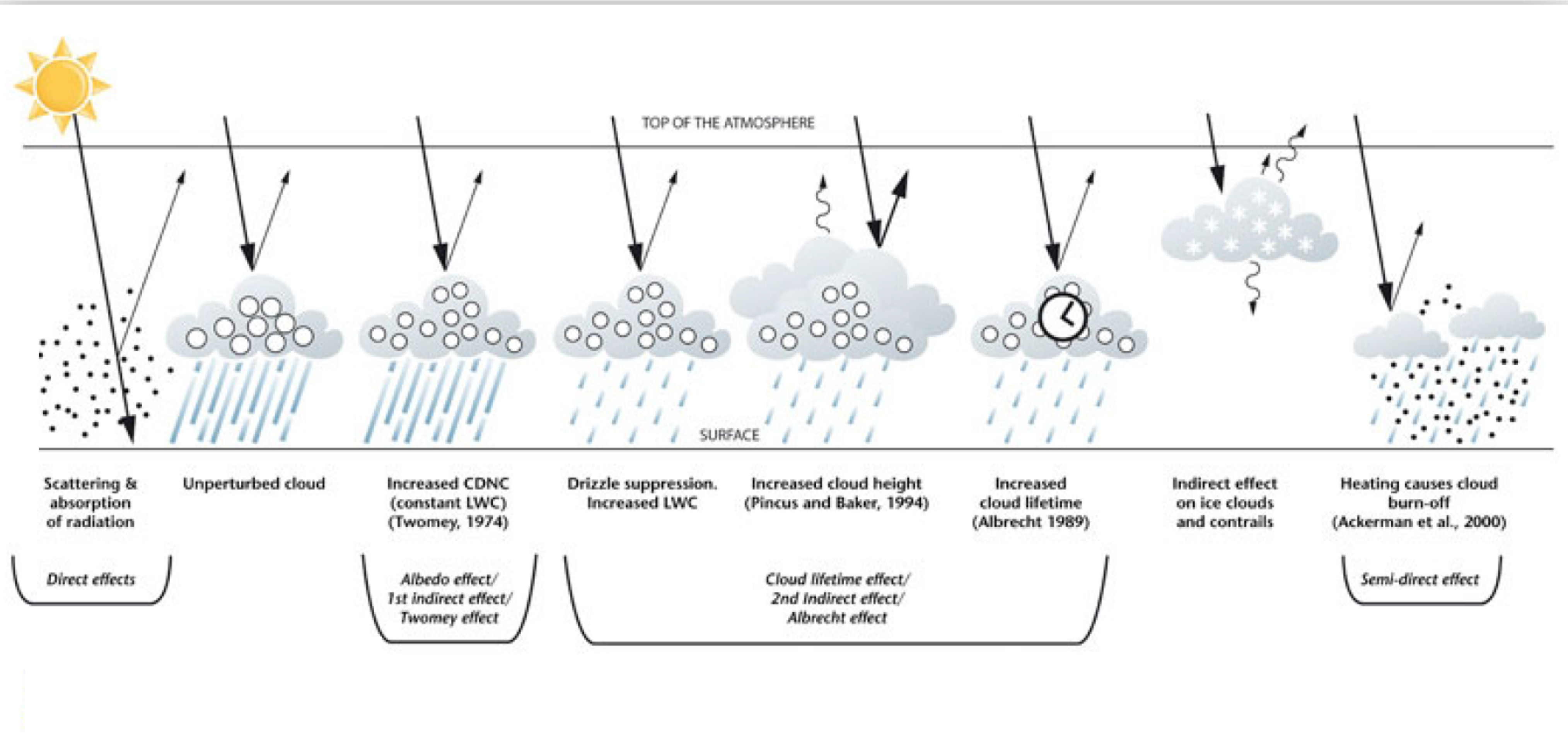

supersaturation (%)
maritime
a=100 cm-3
concentration (mg-1)
radius (micron)
time (seconds)


supersaturation (%)
continental
a=1000 cm-3
concentration (mg-1)
radius (micron)
time (seconds)

$$N = a\,S^b$$

$$b = 0.5$$

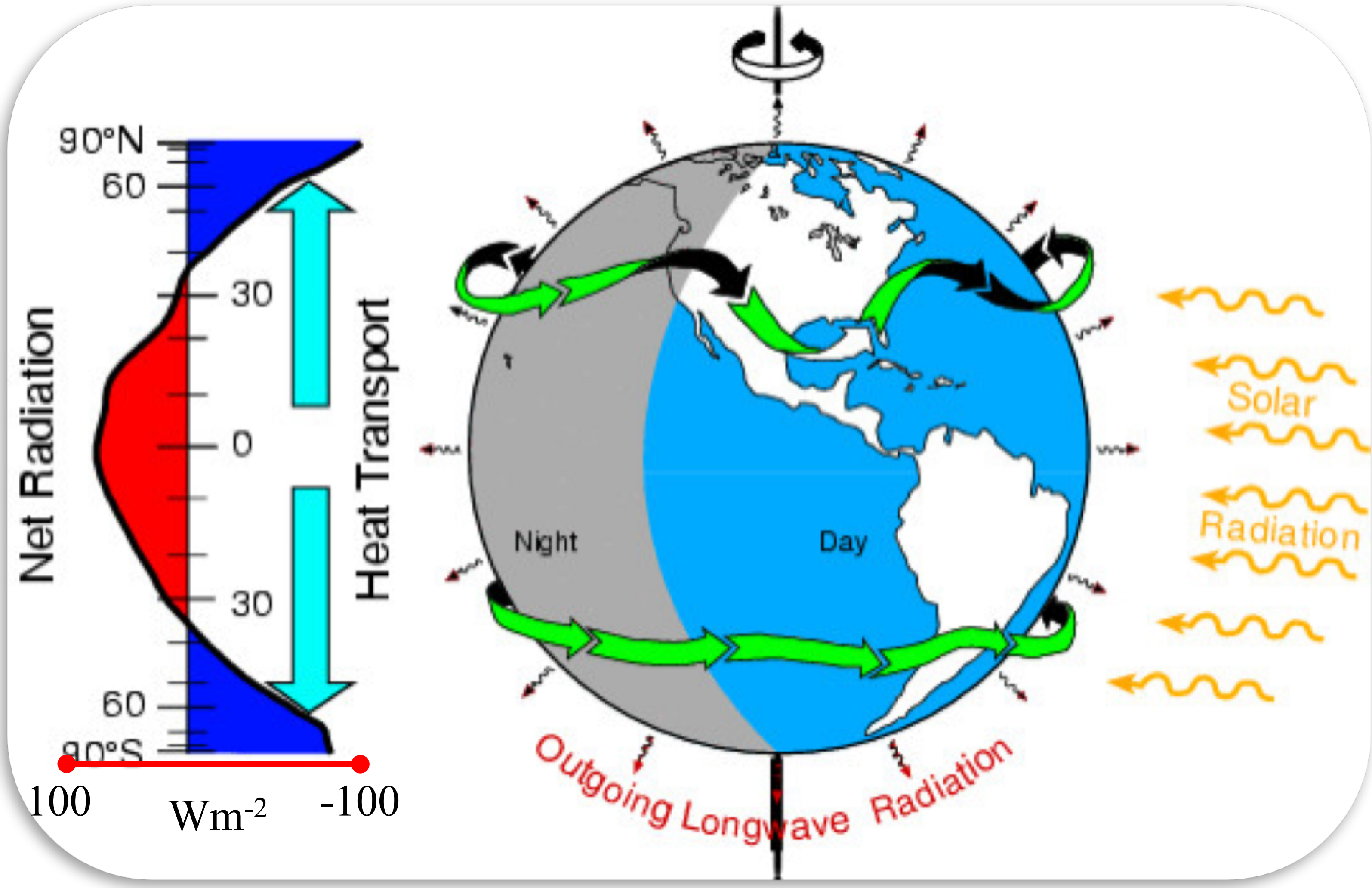

qc (g/kg)
maritime
a=100 cm-3
continental
a=1000 cm-3
final spectrum
[cm**-3 micron**-1]
radius [micron]
3.
2.
1.
0.
400.
300.
200.
100.
0.
5.
10.
15.
20.
25.

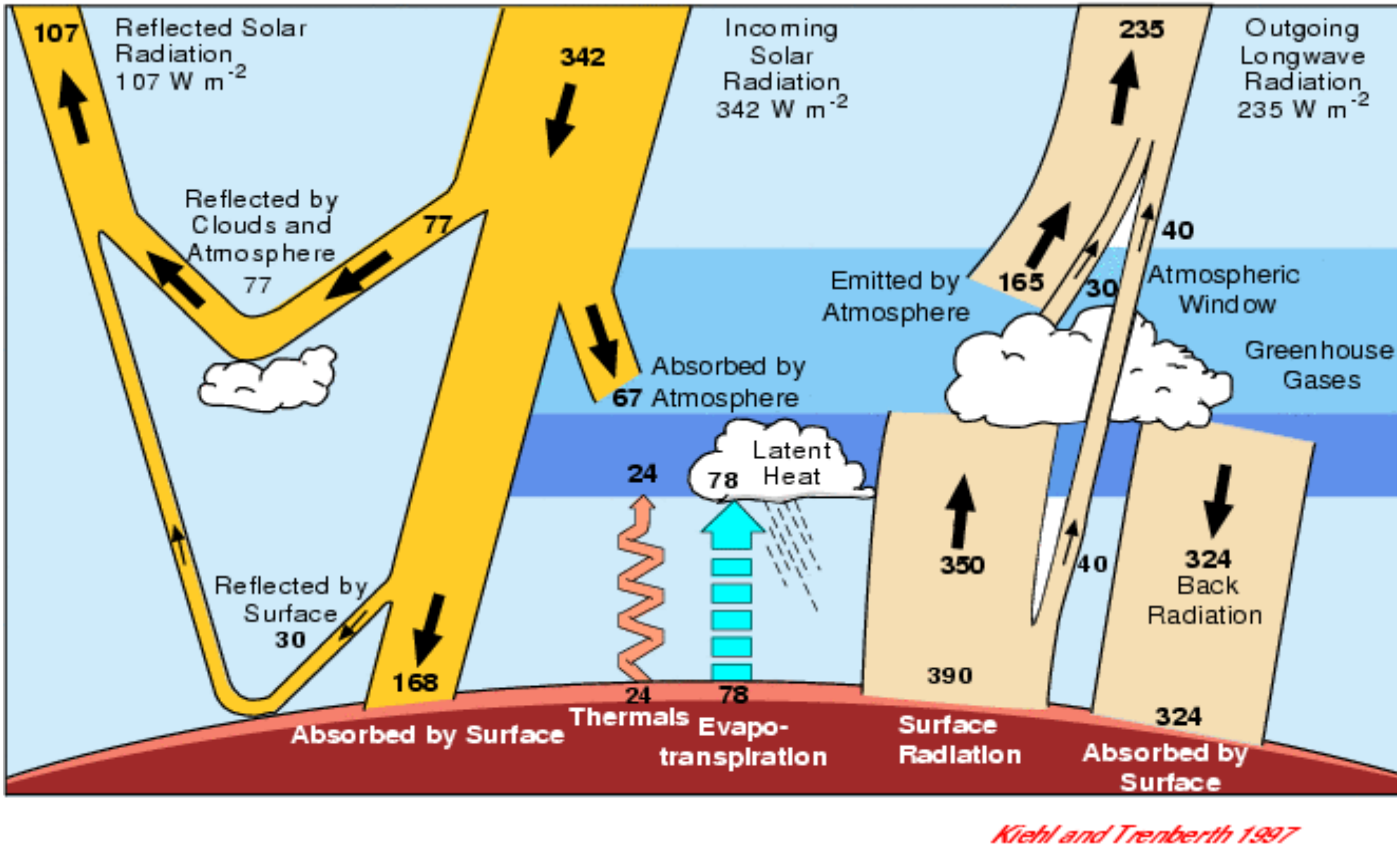


[IPCC Fourth Assessment Report]

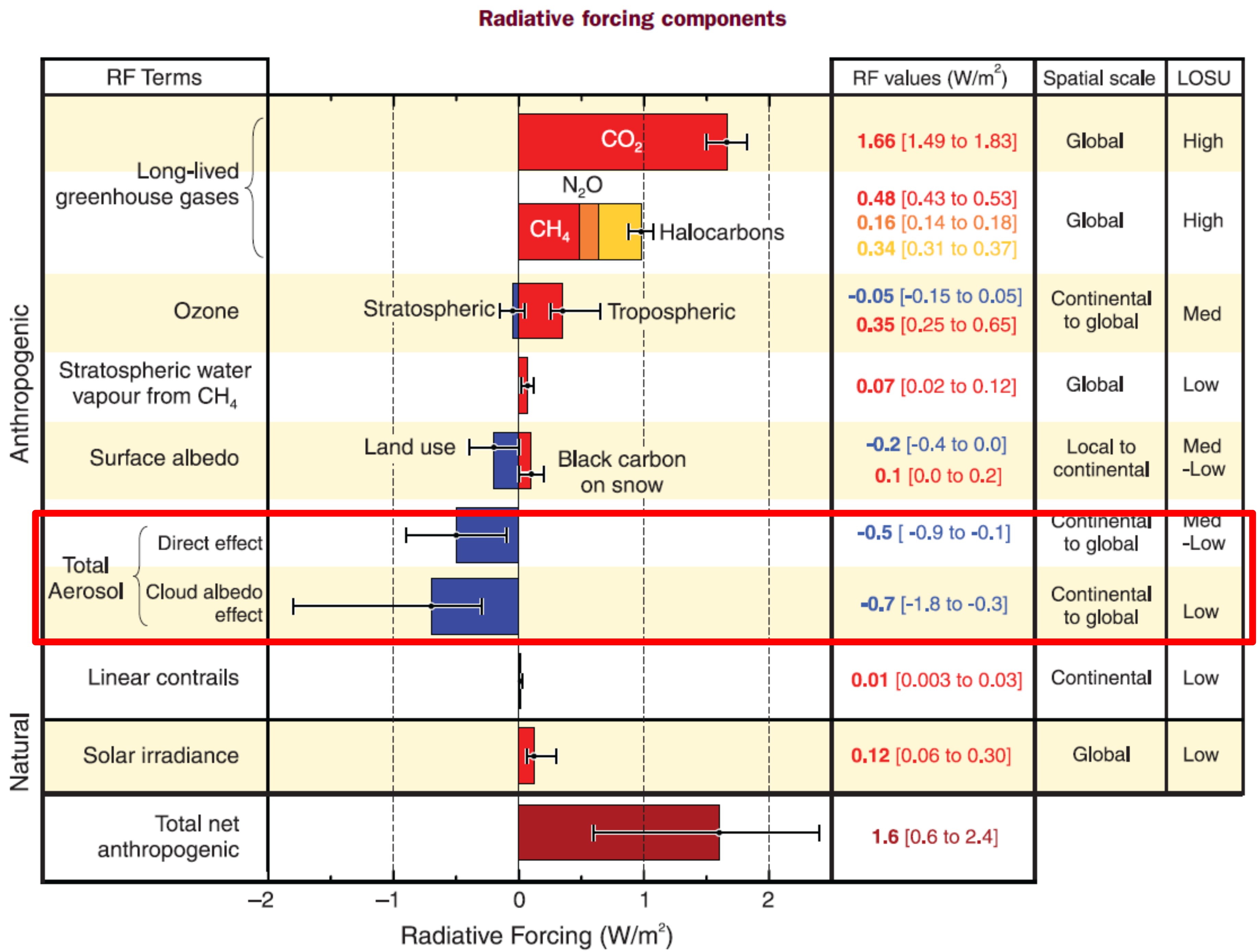
Global versus local effects…

Top-of-atmosphere net (solar minus Earth longwave) radiative flux





The Earth annual and global mean energy budget



IPCC 2007; Synthesis Report

Global versus local effects…

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

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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

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Revised: 5 December 2011 – Accepted: 8 January 2012 – Published: 16 January 2012

2008, 2009, 2010 summers (JJA) convection-permitting (~3 km gridlength) 48-hour hindcasts using COSMO-DE

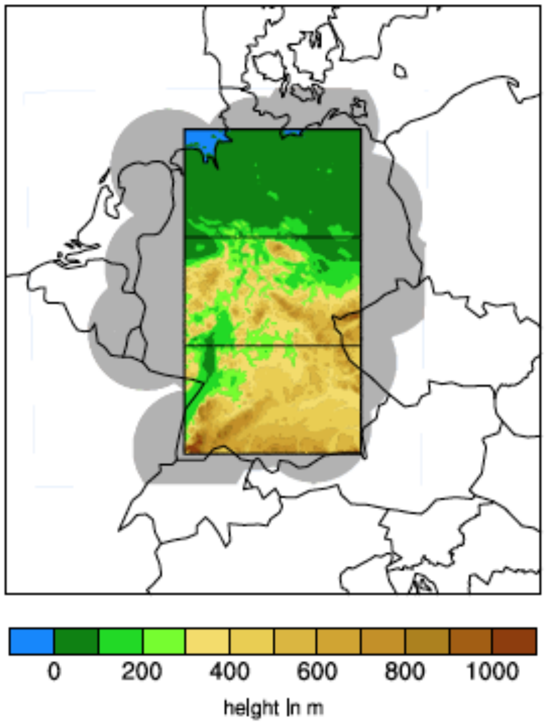


Fig. 1. COSMO-DE model domain, with insertions of coverage of the German radar composite (grey), and the three evaluation sub-domains with the model orography.

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	2009	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	–	–

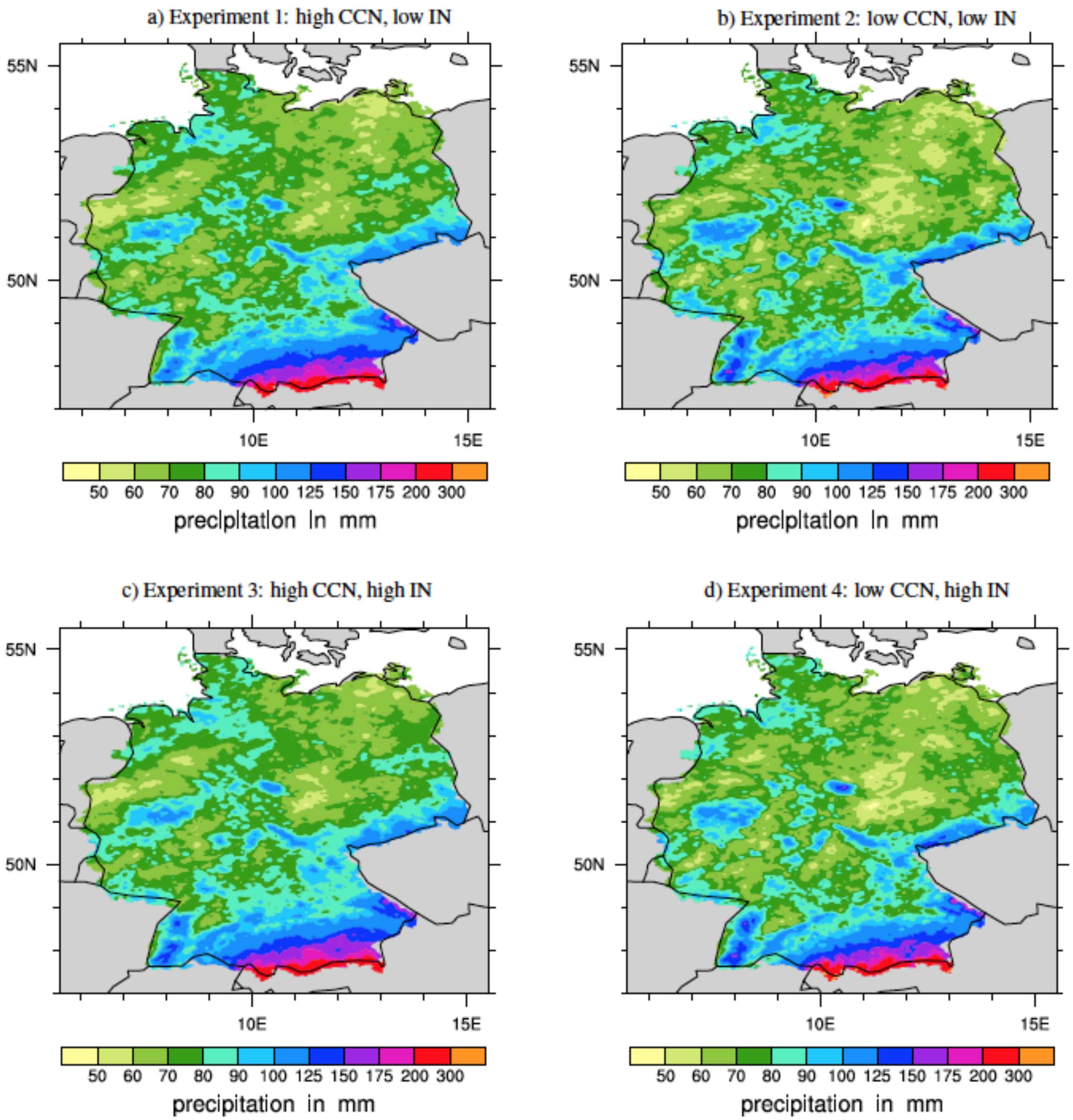


Fig. 5. Monthly mean precipitation amount of JJA 2008–2010 for experiments 1–4 combined from 06:00–18:00 h hindcasts initialized at 00:00 and 12:00 UTC.

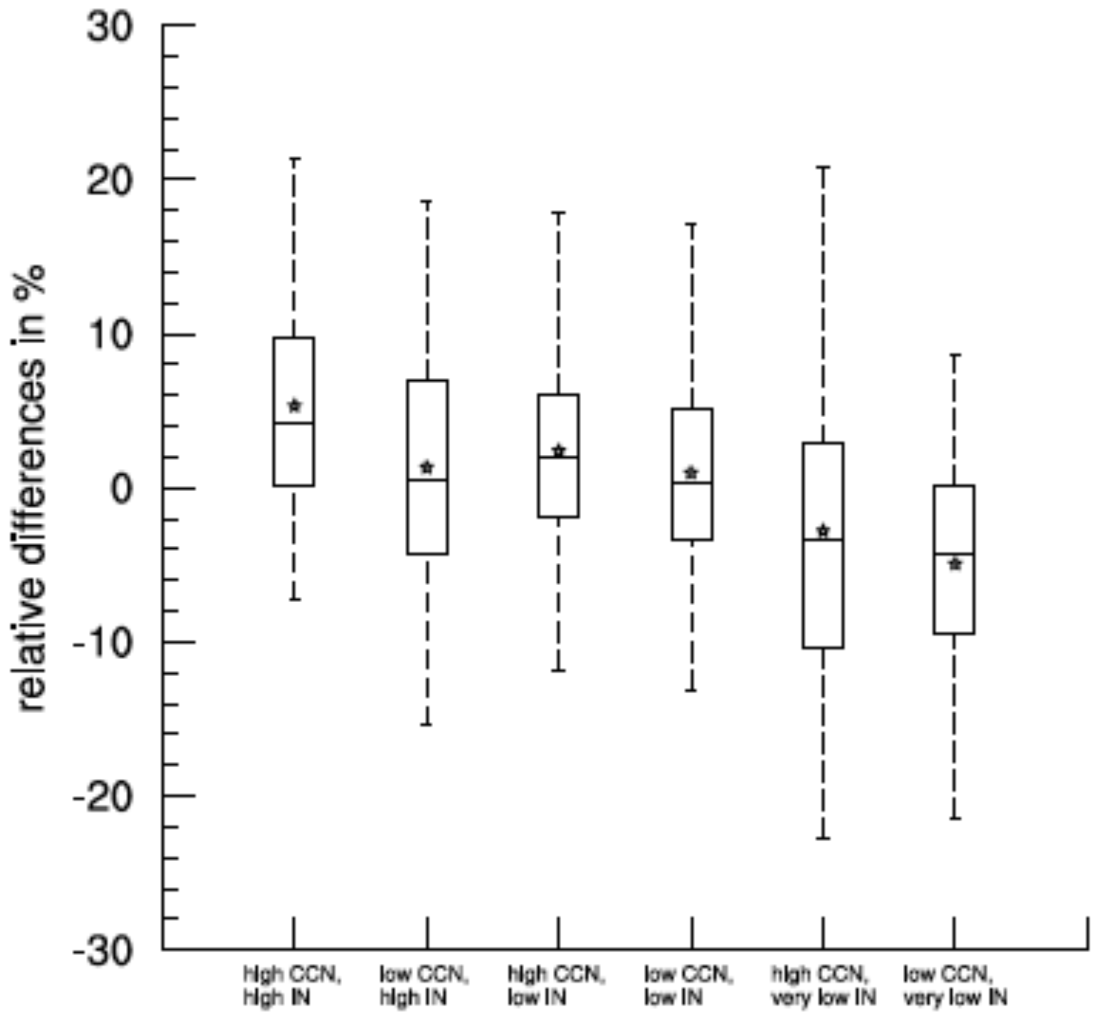
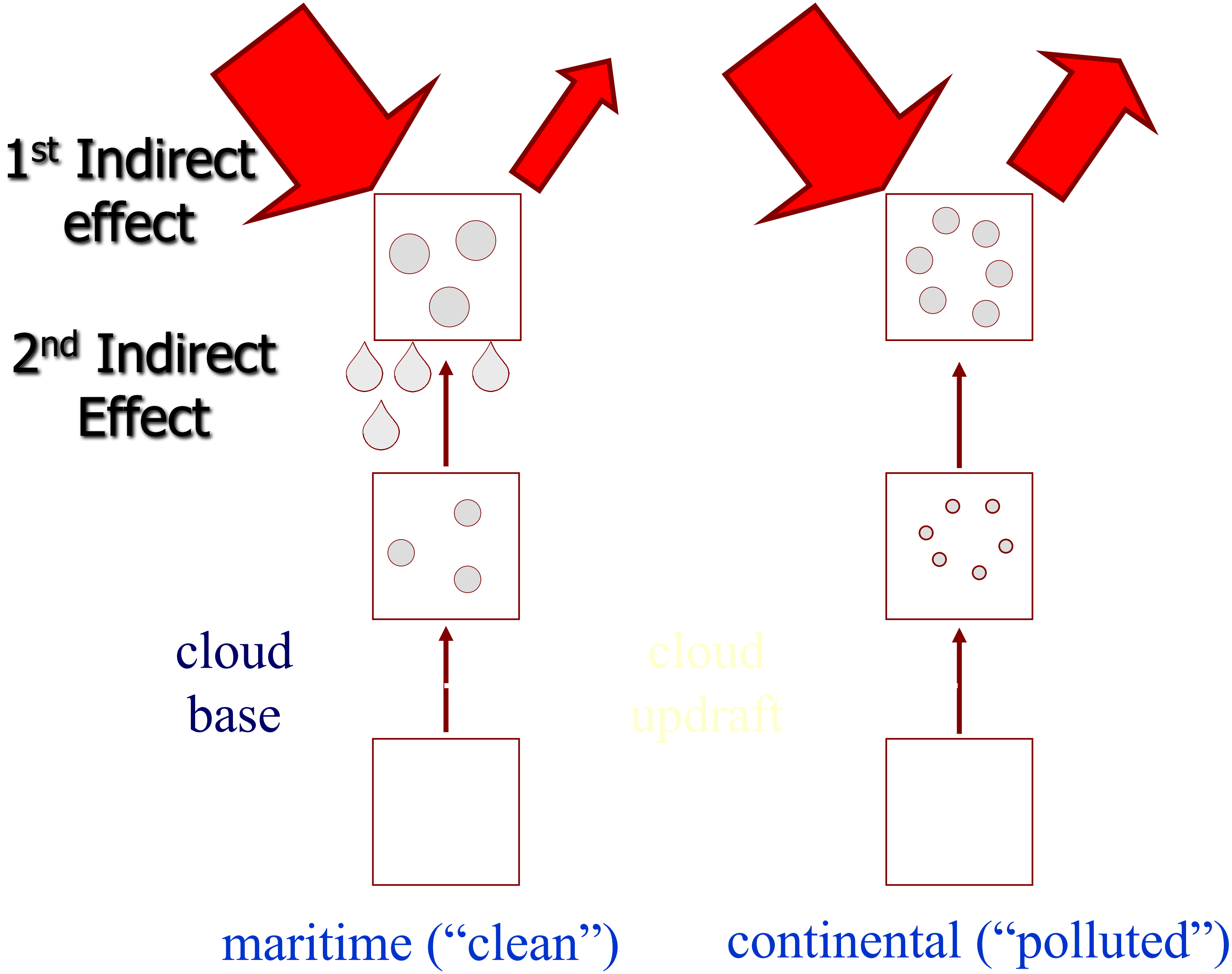
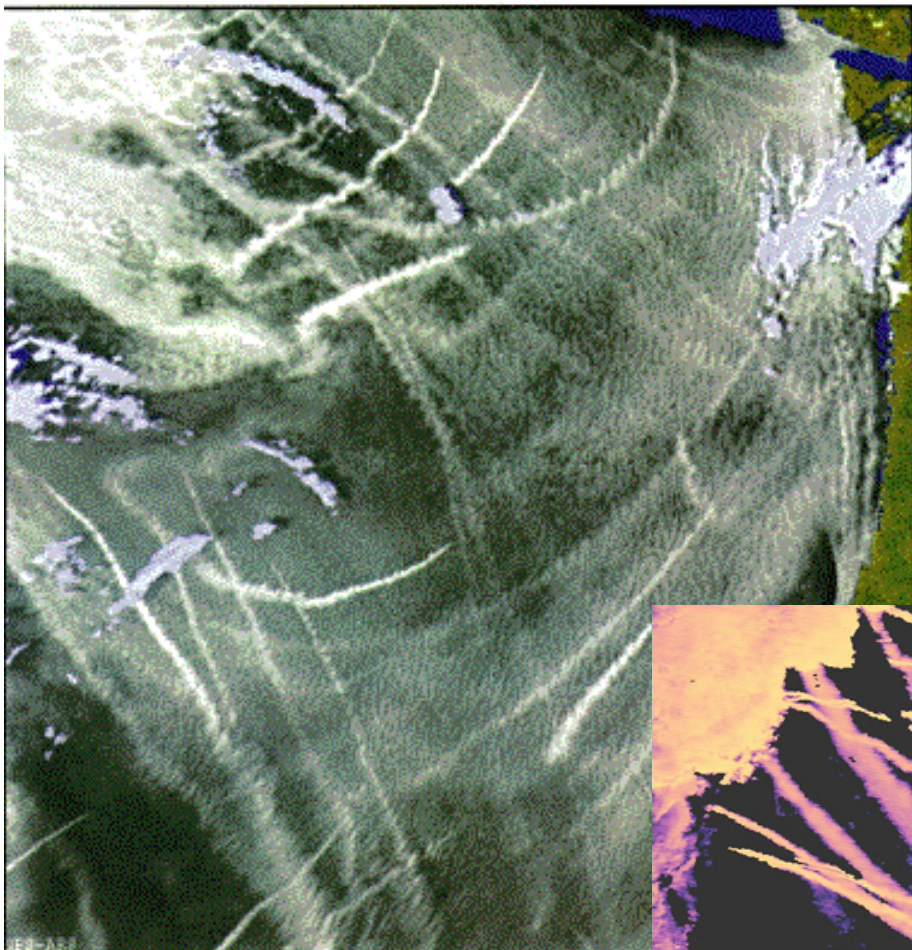


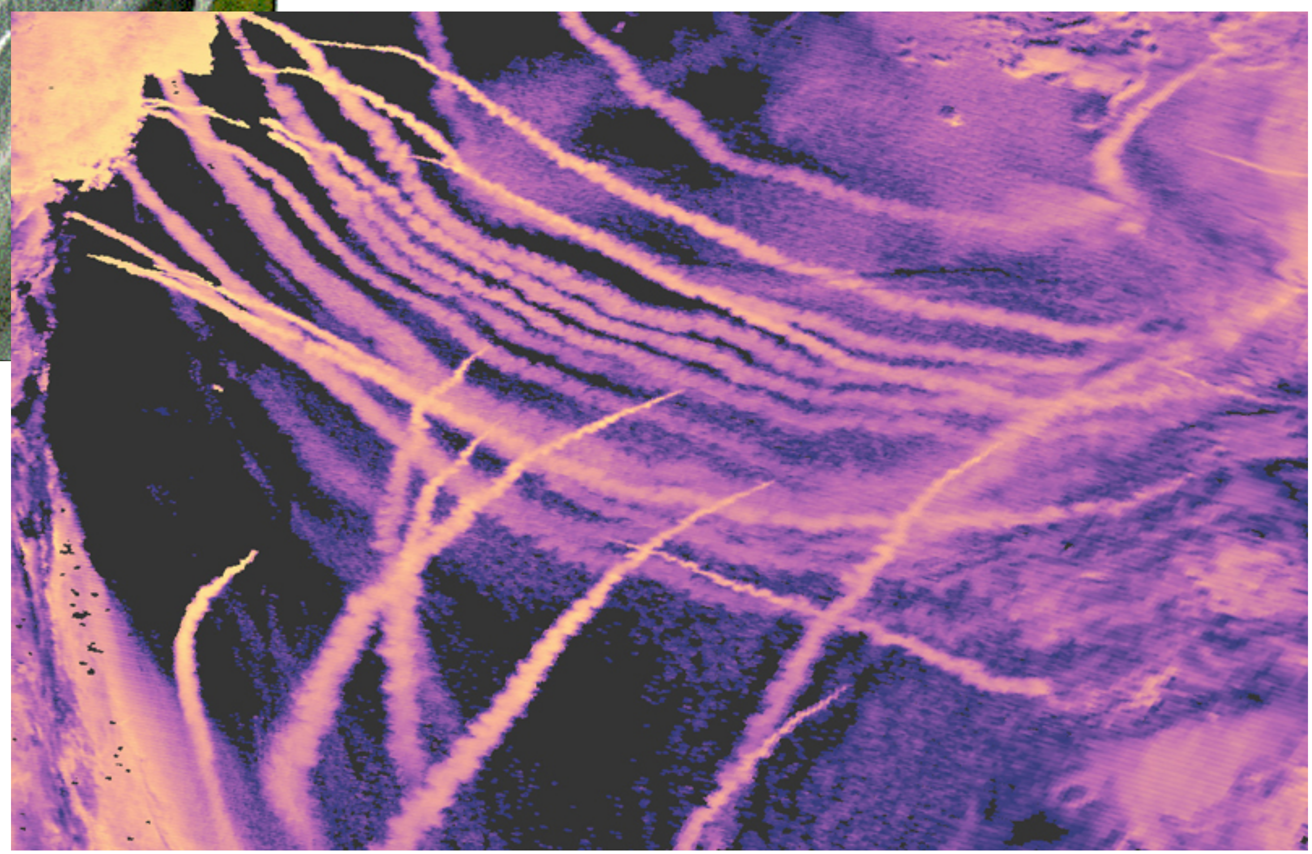
Fig. 9. Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008–2010. Shown are anomalies relative to the mean of Exps. 1–6. The precipitation data has been averaged over either one of the three subdomains. The bottom and top of the boxes are the lower and upper 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.

Indirect aerosol effects (warm rain only)





Ship tracks: spectacular example of indirect effects caused by ship exhausts acting as CCN (long-lasting, feedback on cloud dynamics?)

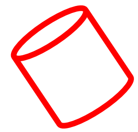


Why indirect aerosol effect are so uncertain and difficult to quantify?

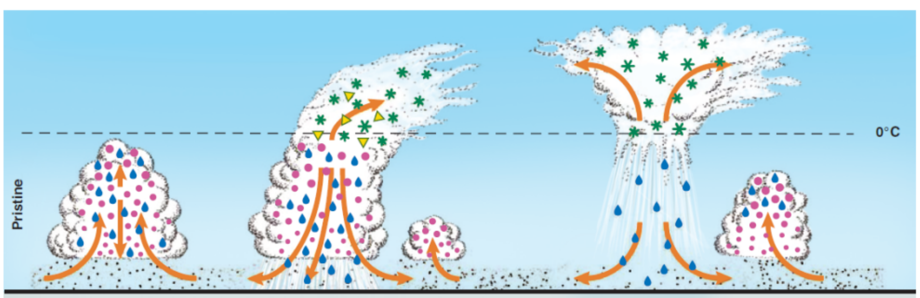
Because they are a $(\text{parameterization})^2$ problem for current global climate models: parameterized microphysics in parameterized clouds!

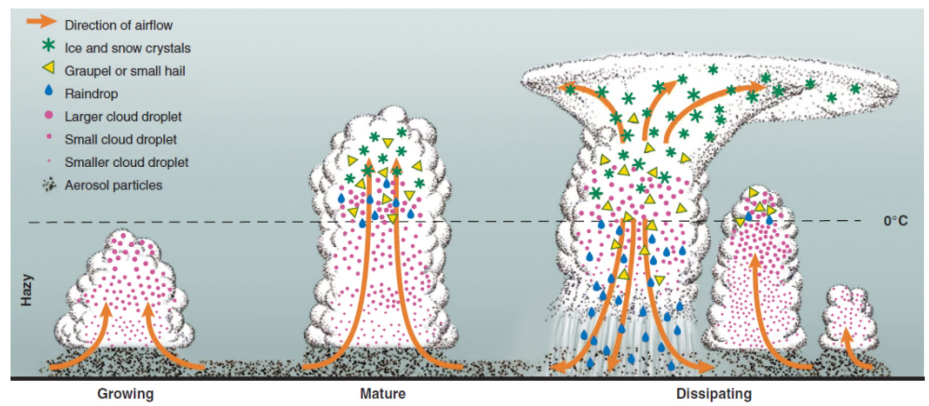
Because observations cannot distinguish with confidence the impact of aerosols from the impact on meteorological conditions: correlation versus causality

correlation versus causality:



satellites observing aerosols and clouds…



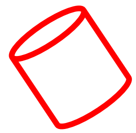


clean

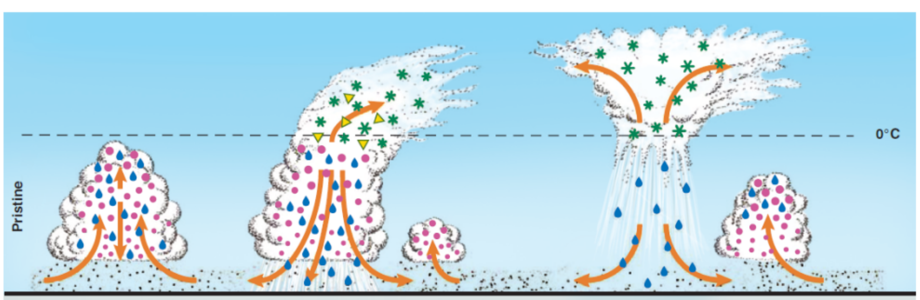
polluted

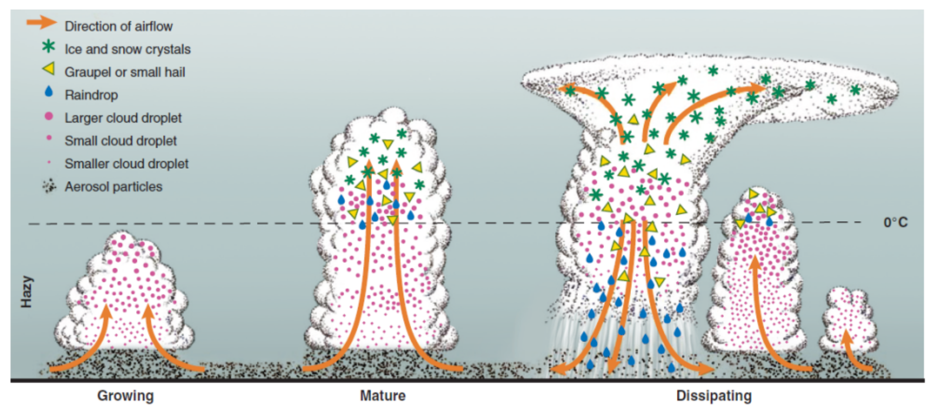
correlation versus causality:

If clouds correlate with aerosol, this does not imply that aerosols are solely responsible for changing clouds…



satellites





clean

polluted

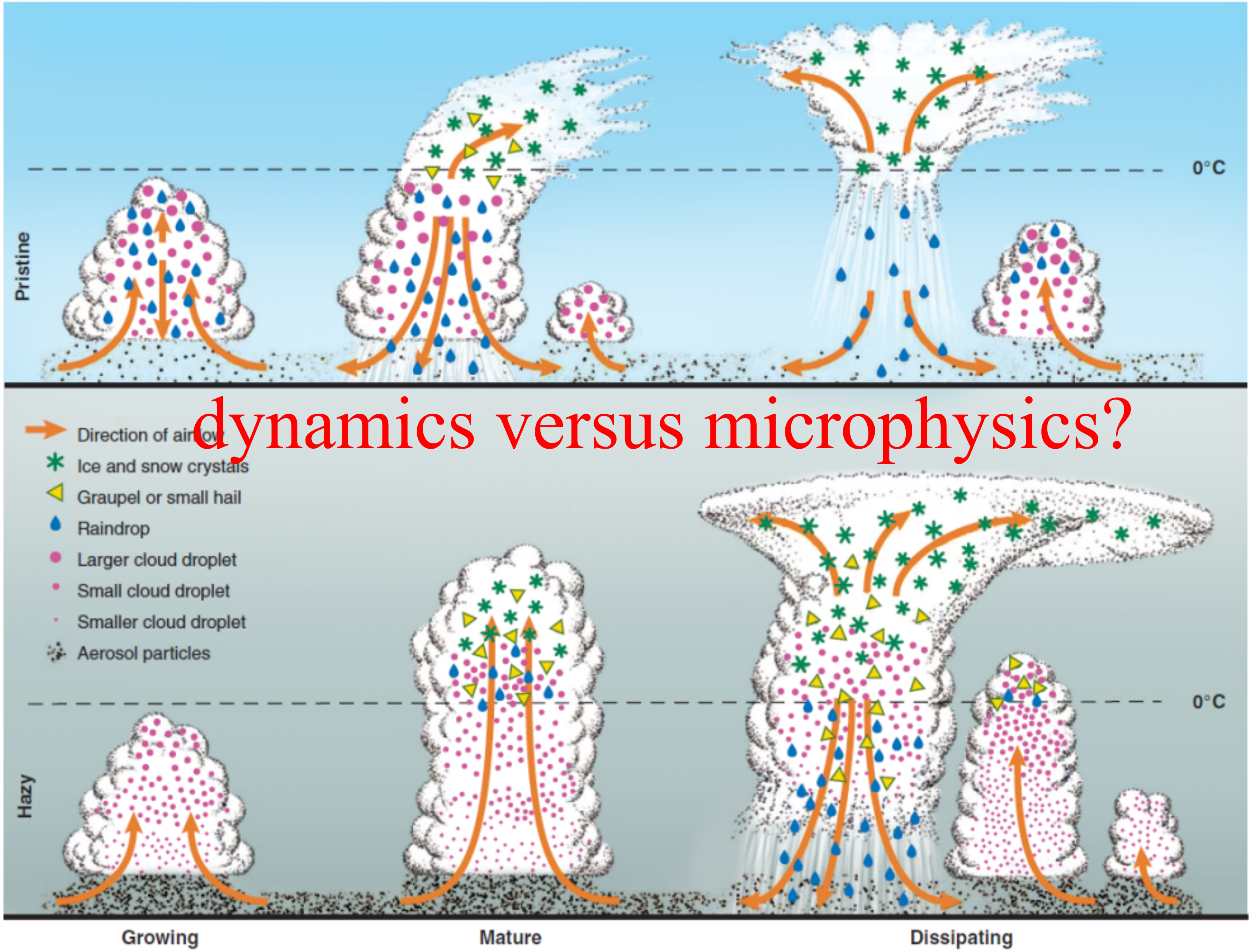
If clouds correlate with aerosol, this does not imply that aerosols are solely responsible for changing clouds…

Clouds and aerosol can simply vary together (for instance, because of the large-scale advection patterns…).

If I drive to the office in the morning and there is more accidents at that time, am I responsible for the increase?

clean

polluted

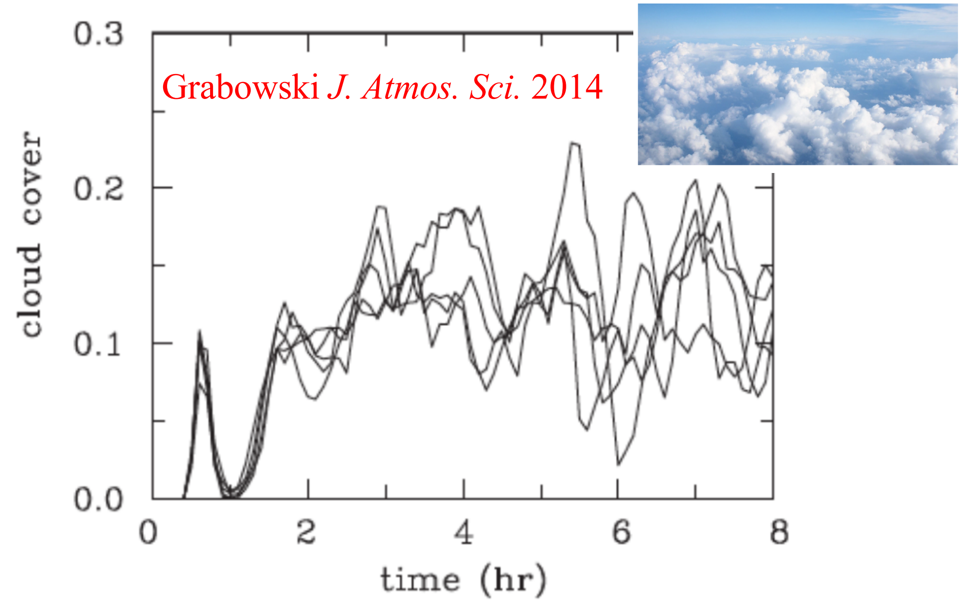


dynamics versus microphysics?

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

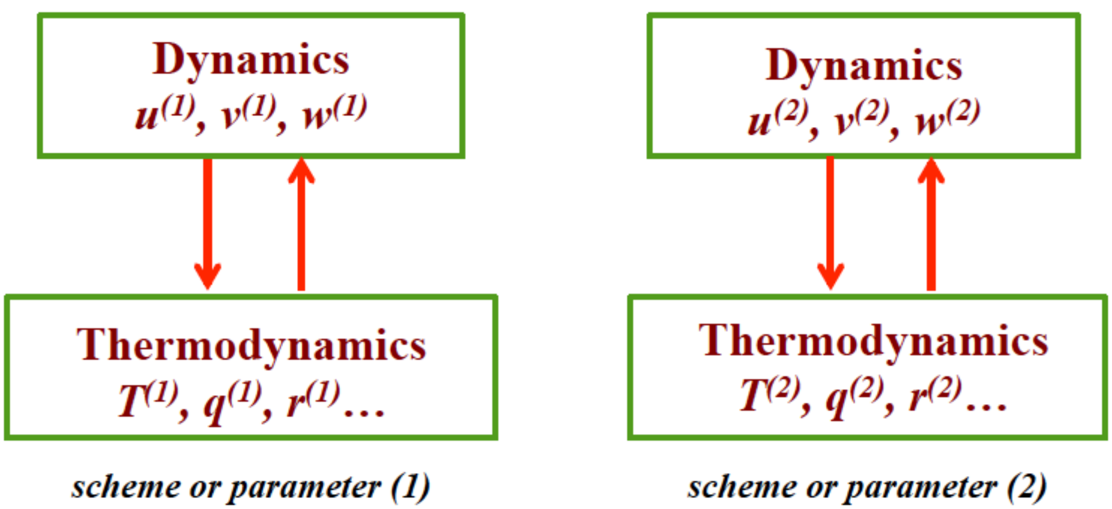
Methodology:

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



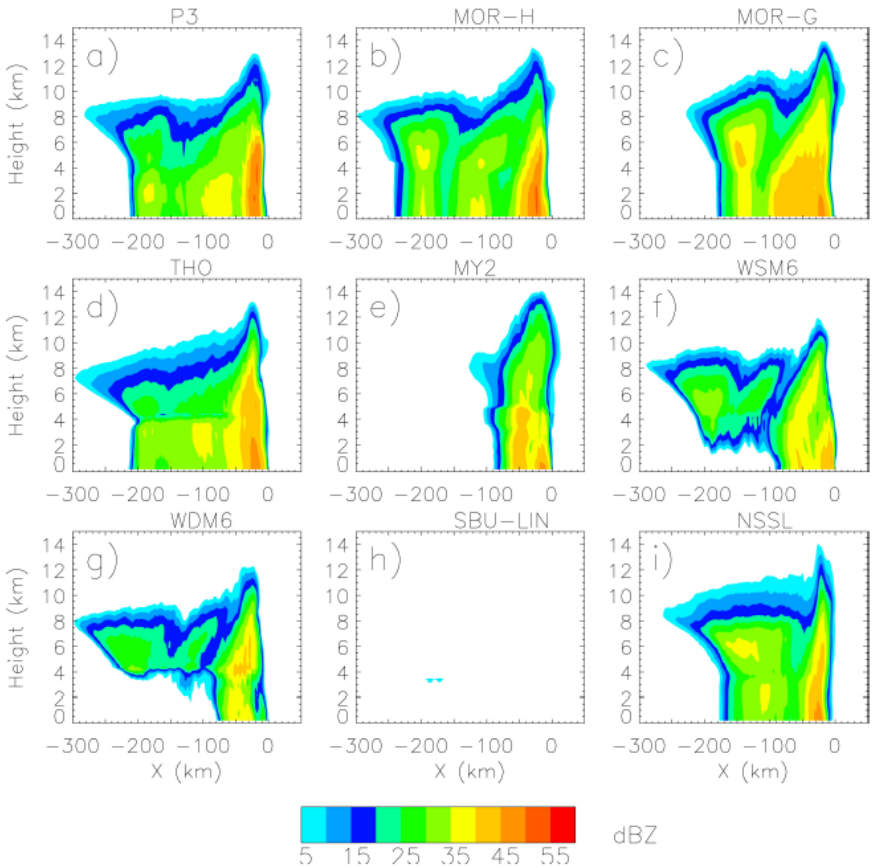
Evolution of cloud cover in 5 simulations of shallow cumulus cloud field. The only difference is in random small temperature and moisture perturbations at t=0.

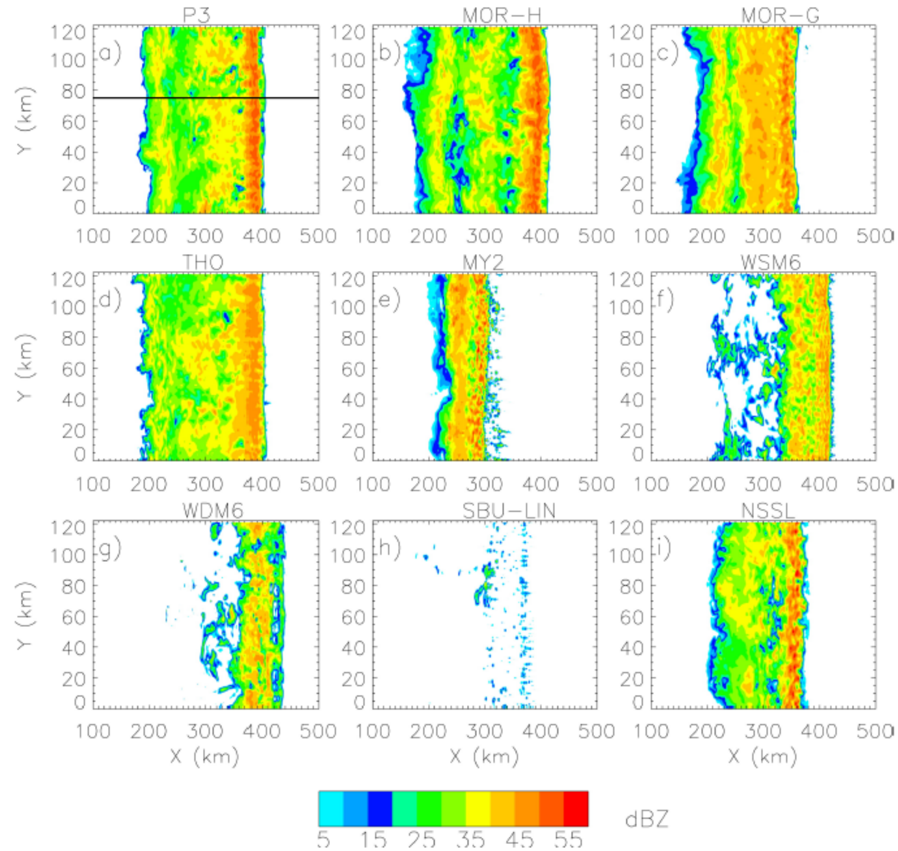
Traditional approach: parallel simulations with different microphysical schemes or scheme parameters



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

squall line simulations with different microphysics schemes:

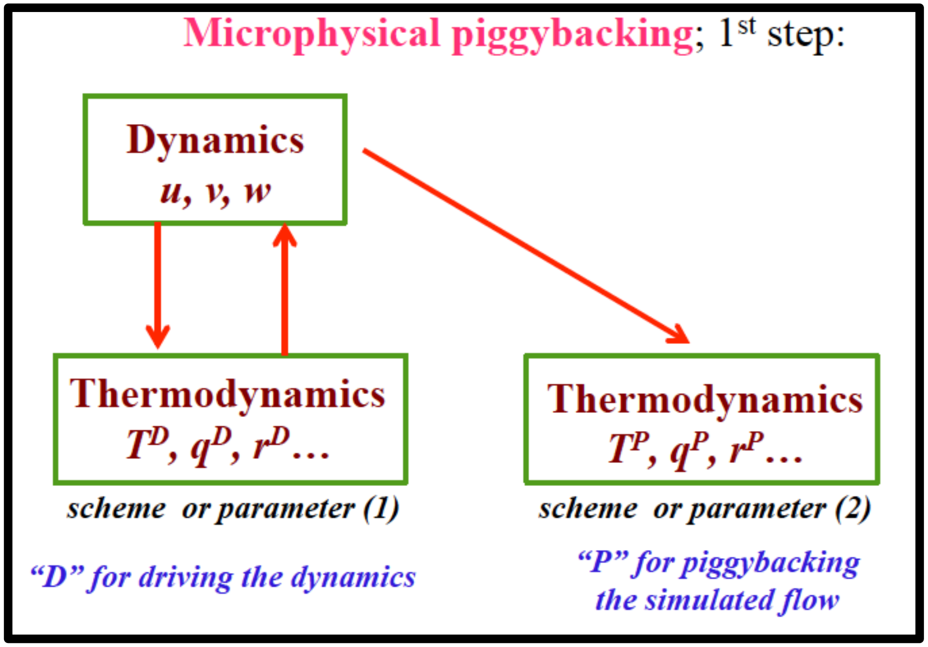


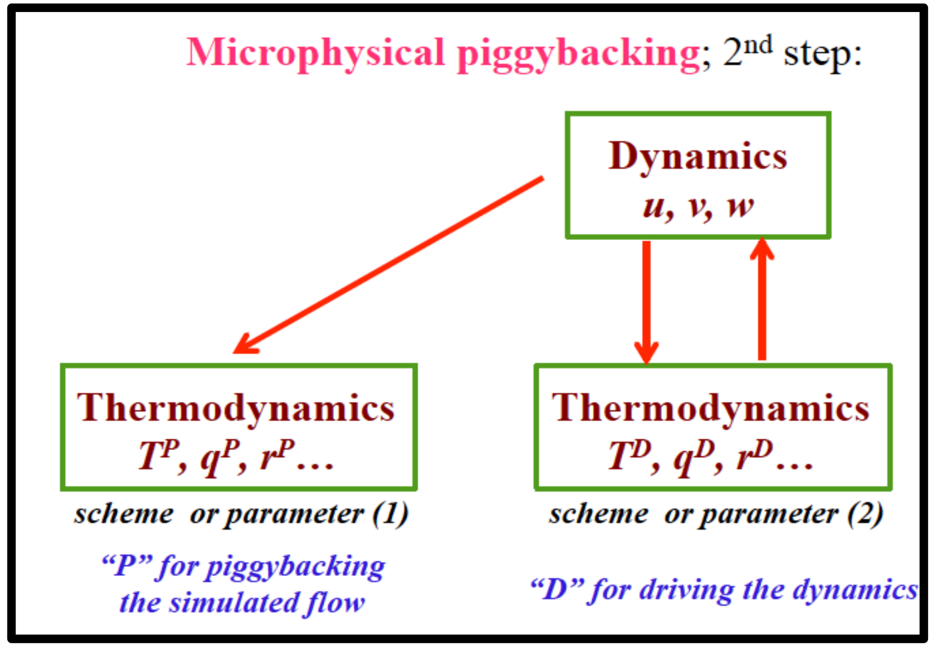


microphysics alone or microphysics plus dynamics?

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

3D babyEULAG: a simple anelastic toy model targeting moist convection (shallow – LES; deep – CSRM; etc):

- no topography;
- no subgrid-scale model (i.e., ILES);
- stretched vertical grid;
- periodic (horizontal), rigid lid (top and bottom boundaries);
- single-thread

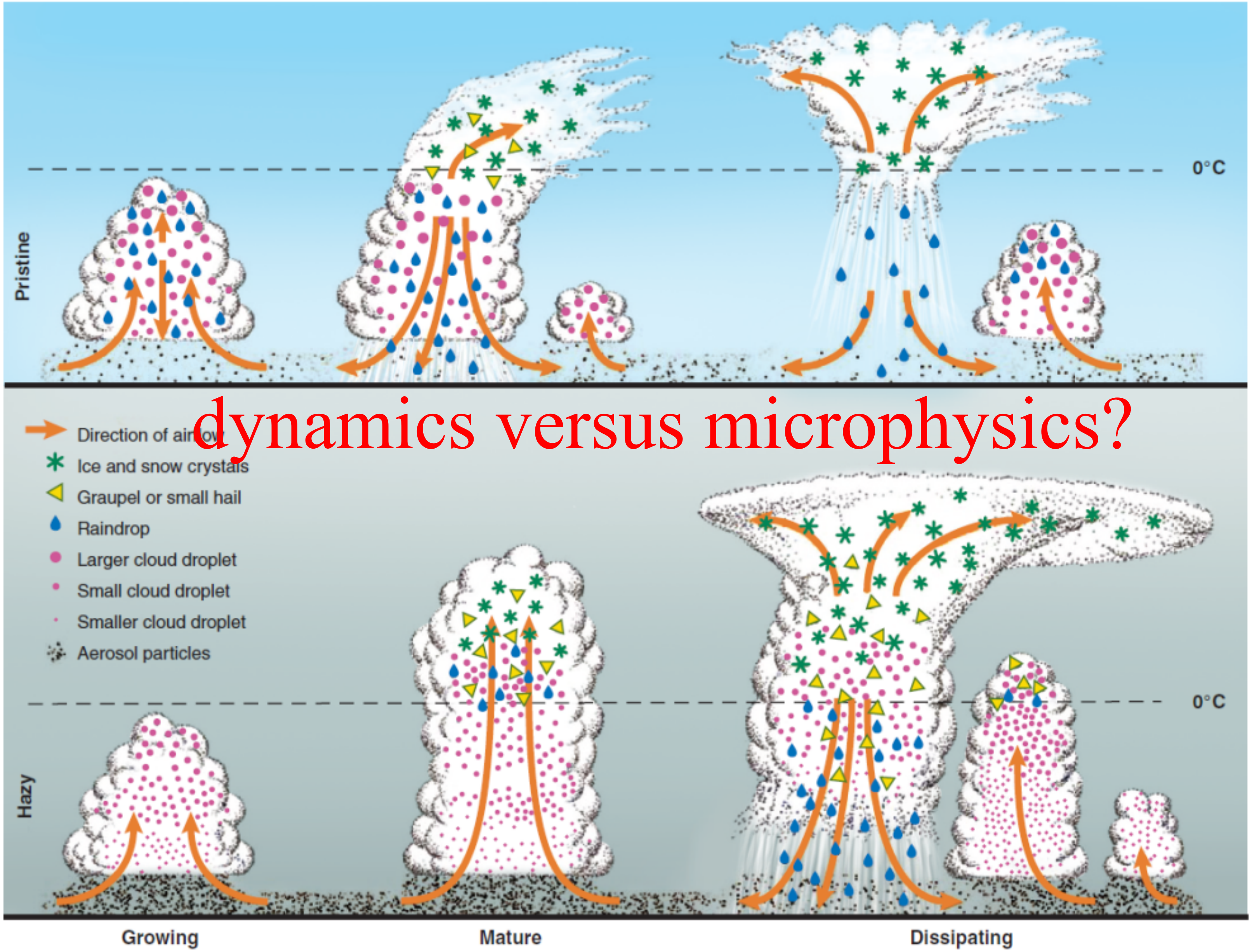
Fortran 77 code, ~3k lines, ~300 lines in the main program

To be run on a laptop or a desktop PC

My experience (Mac): 100^3 grid-point LES/CSRM runs not much slower than real time…

clean

polluted



dynamics versus microphysics?

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

Cloud buoyancy: the potential density temperature

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

$\varepsilon = 0.61$

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)

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…

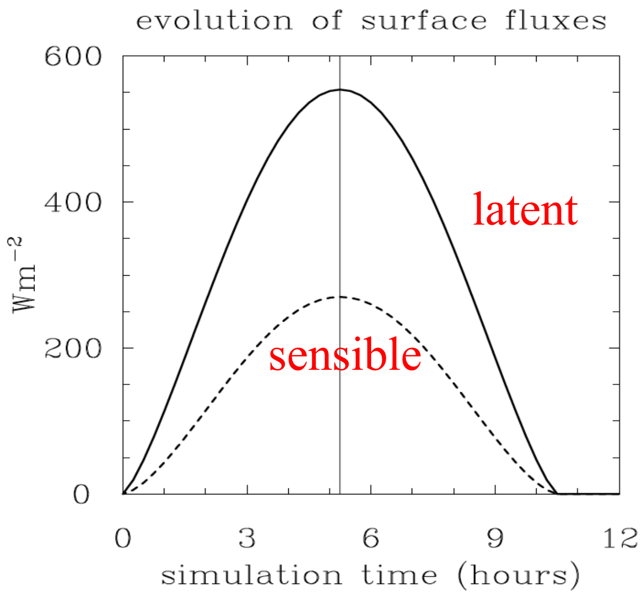
Finite supersaturation impacts Θ, q_v, and q_c:

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

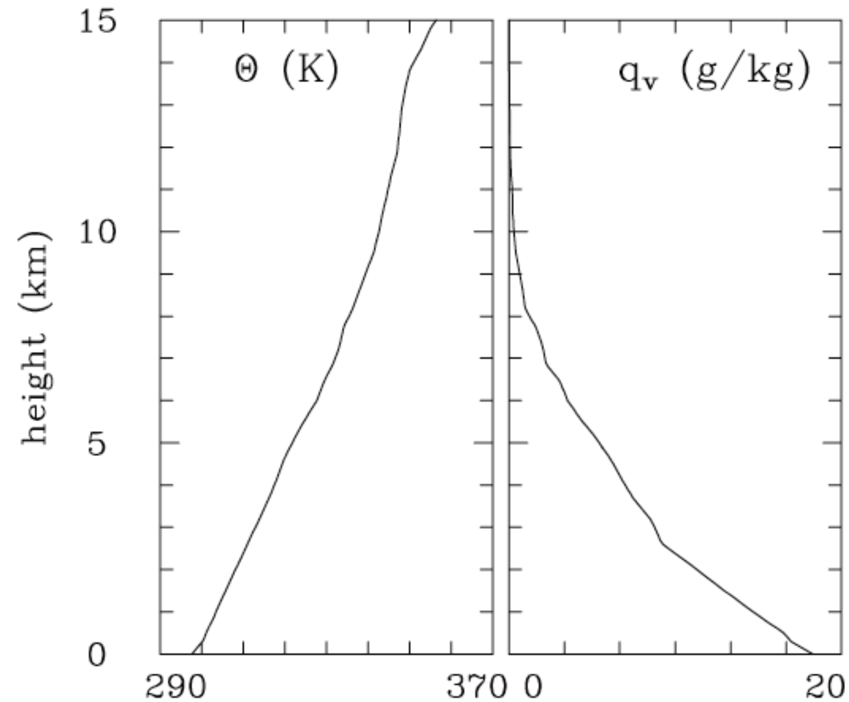
Q. J. R. Meteorol. Soc. (2006), **132**, pp. 317–344 doi: 10.1256/qj.04.147

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

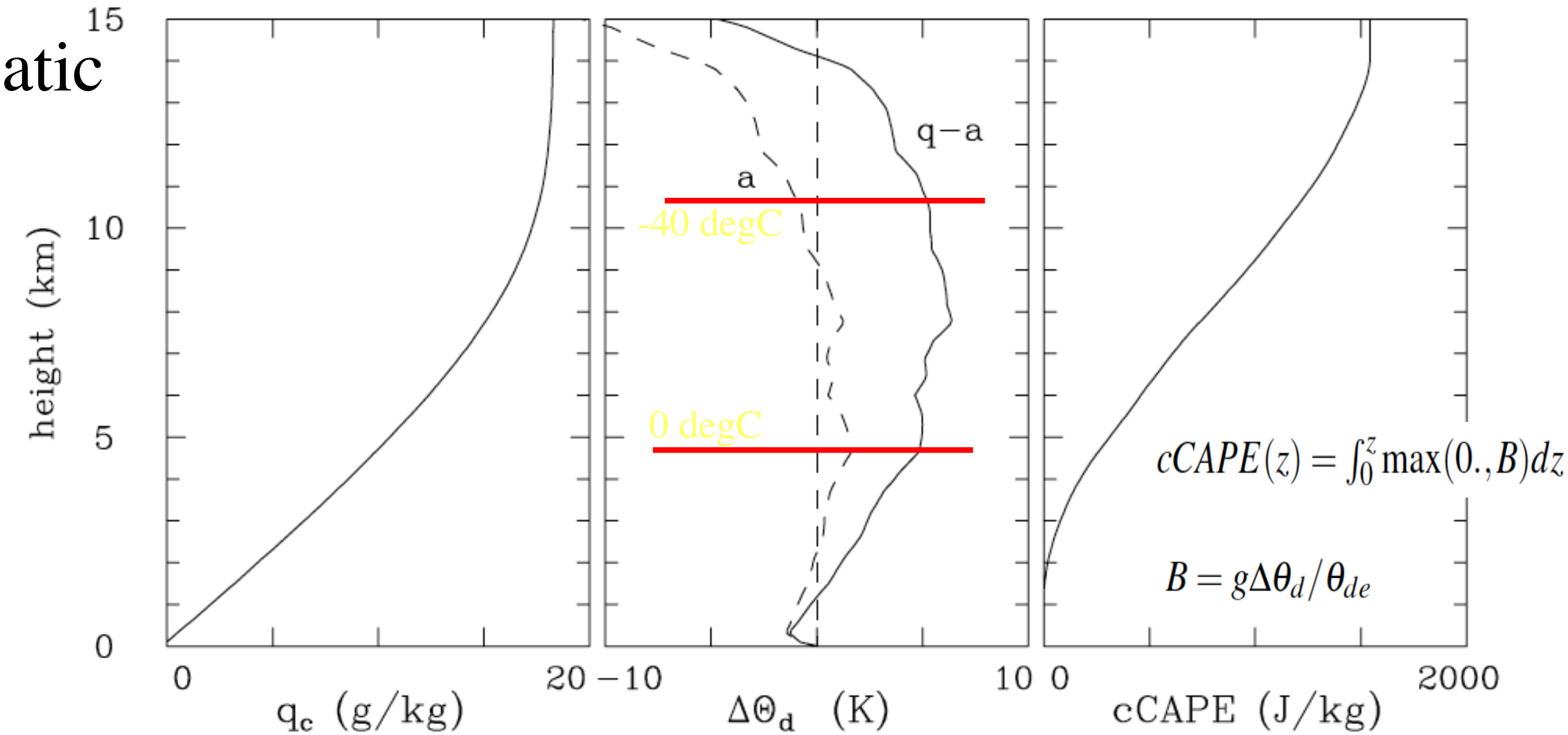
By W. W. GRABOWSKI[1]*, P. BECHTOLD[2], A. CHENG[3], R. FORBES[4], C. HALLIWELL[4], M. KHAIROUTDINOV[5], S. LANG[6], T. NASUNO[7], J. PETCH[8], W.-K. TAO[6], R. WONG[8], X. WU[9] and K.-M. XU[3]



LBA sounding



(pseudo) adiabatic parcel analysis



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.

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

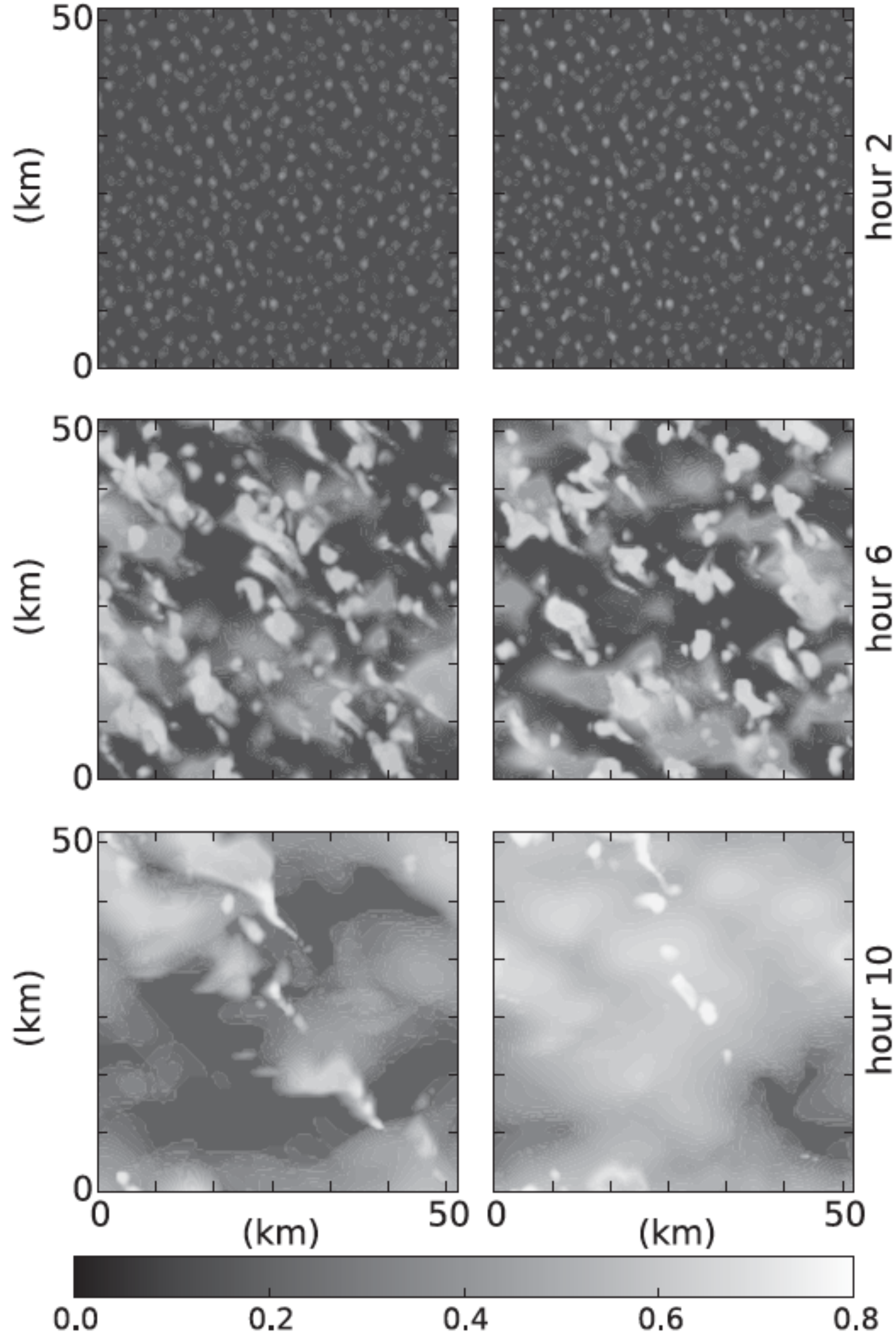
PRI, pristine: 100 mg $^{-1}$
POL, polluted: 1000 mg^{-1}

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)



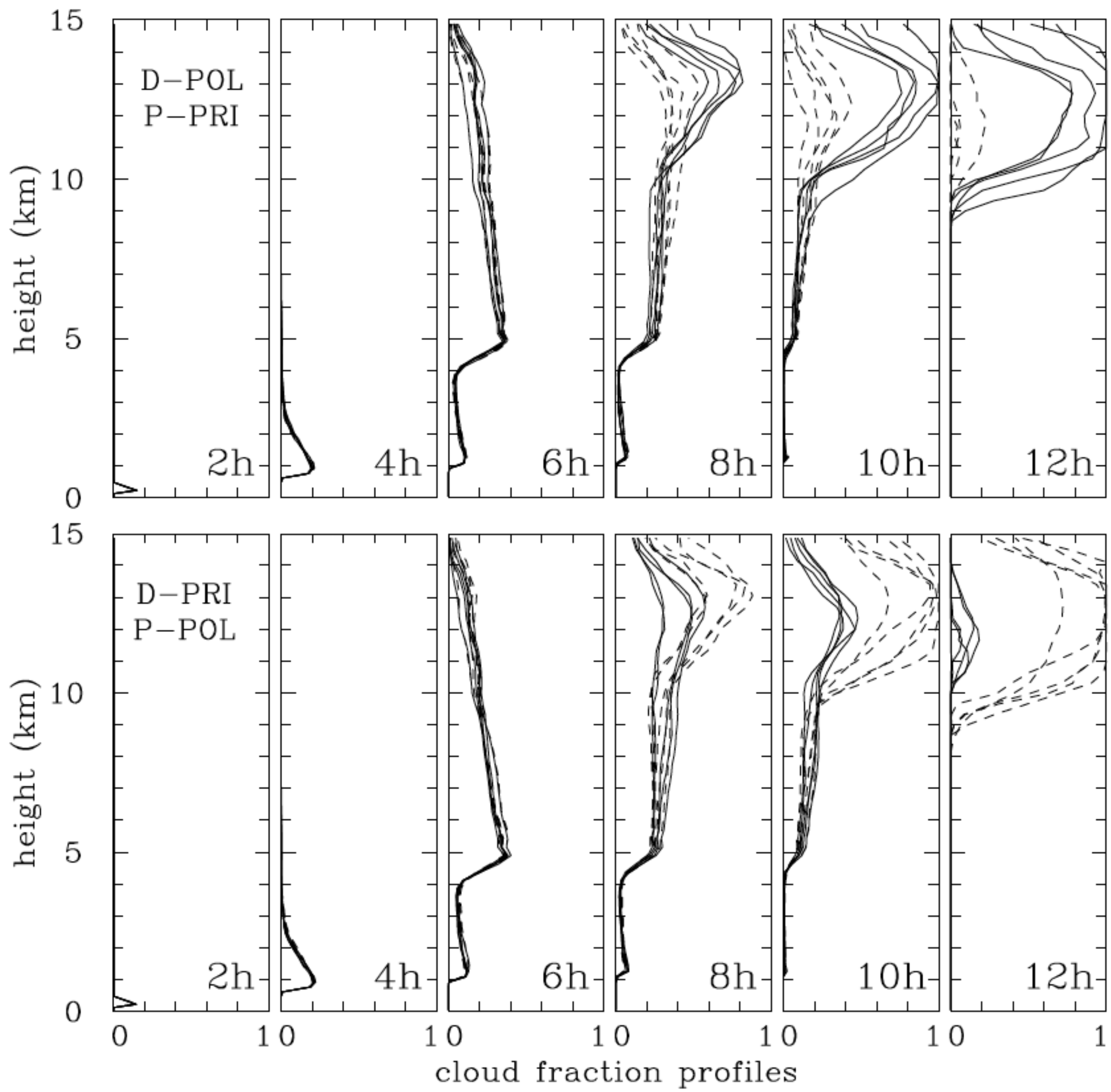
D-POL
(polluted)

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

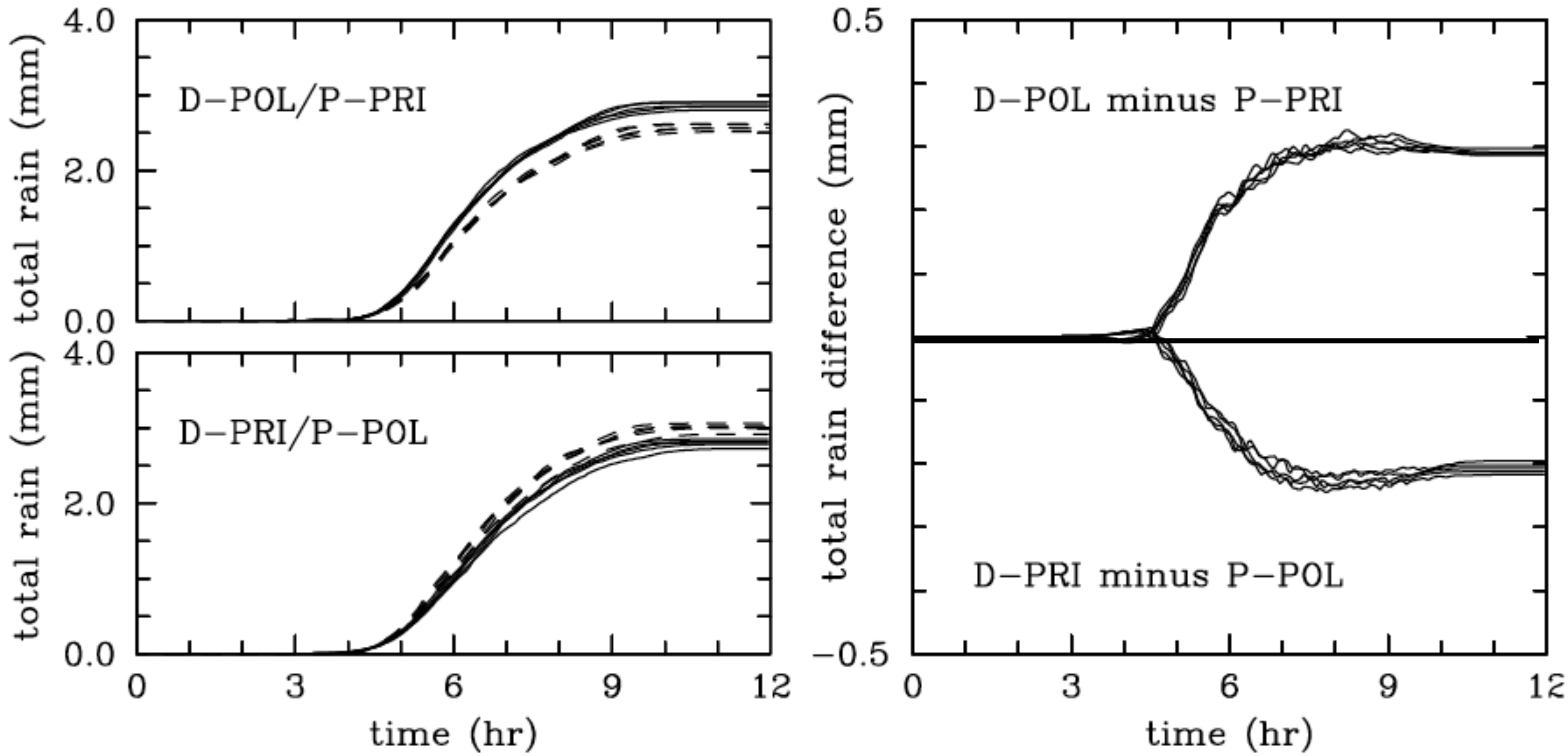
solid lines: driving set
dashed lines: piggybacking set

POL drives,
PRI piggybacks

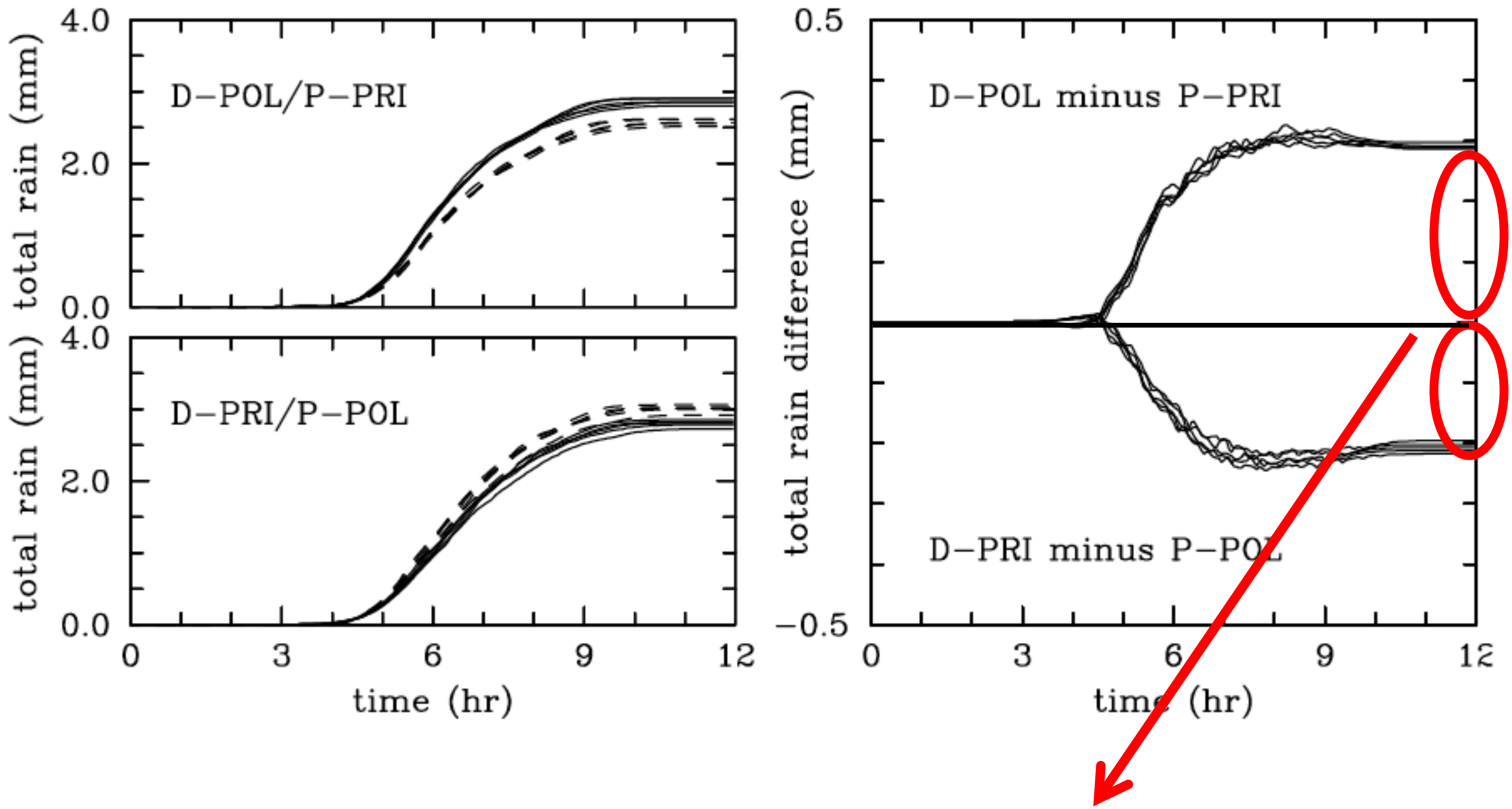
PRI drives,
POL piggybacks



solid lines: driving set
dashed lines: piggybacking set



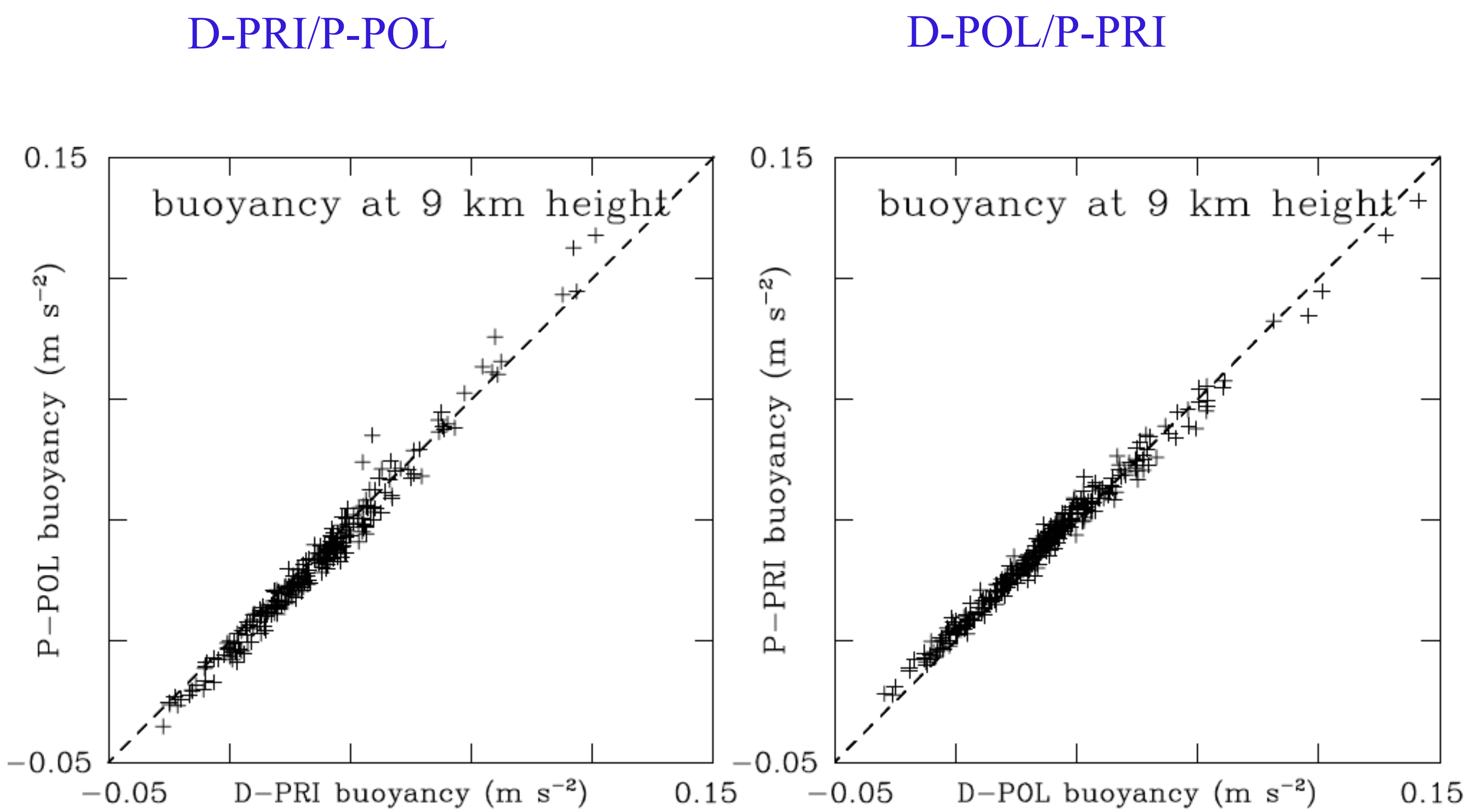
solid lines: driving set
dashed lines: piggybacking set



impact on the cloud dynamics?

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

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

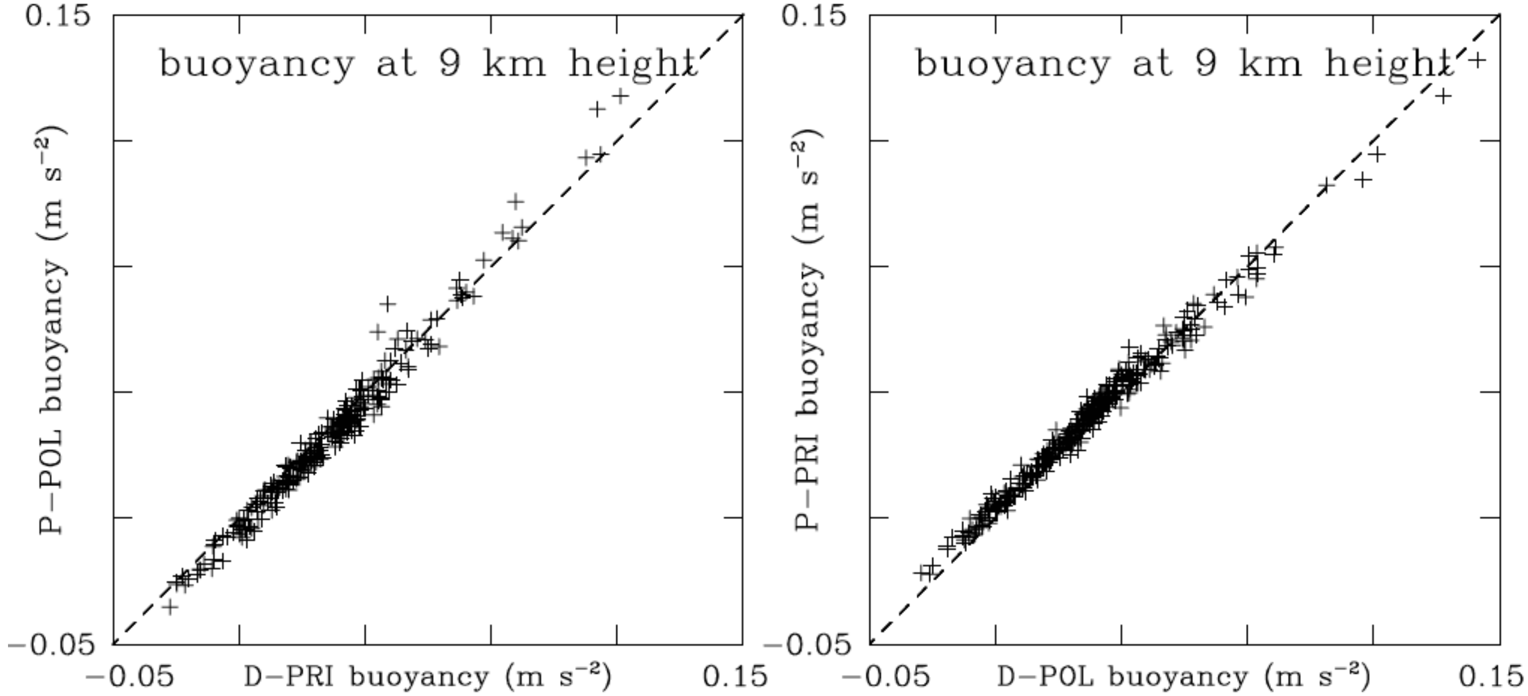


at 9 km (-27 degC)
(Rosenfeld et al. mechanism…)

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

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

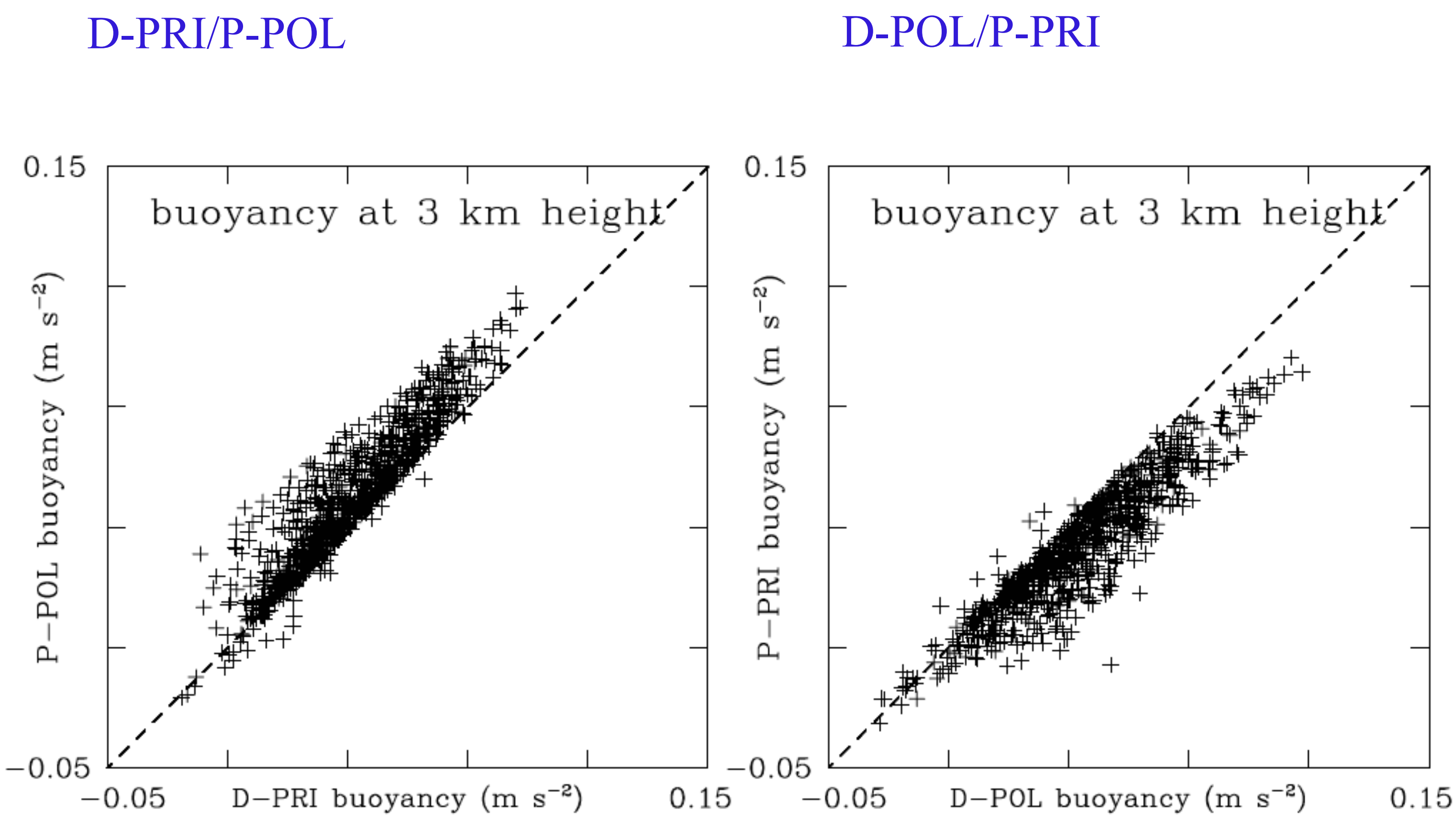
1 K ≈ 0.03 m s^{-2}



POL has slightly less buoyancy than PRI…

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

1 K ≈ 0.03 m s^{-2}



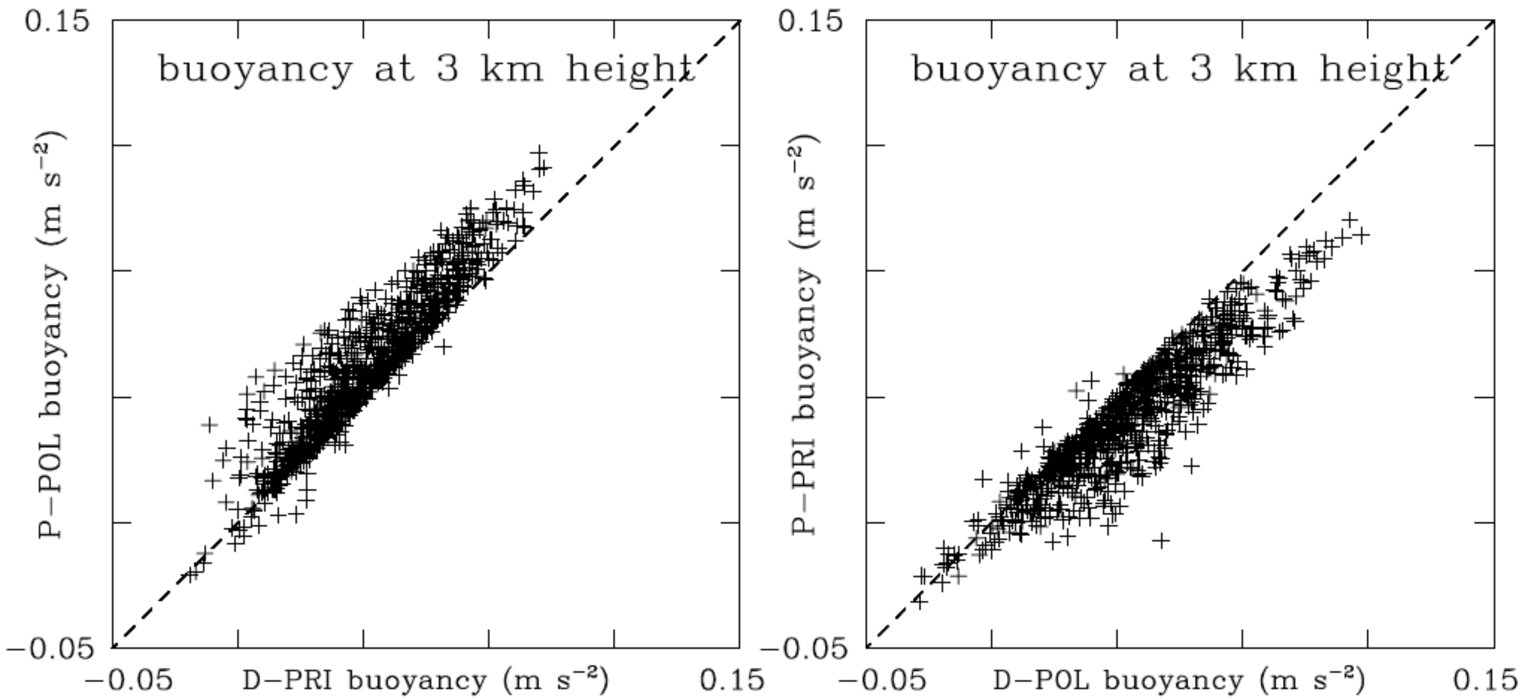
at 3 km (9 degC)

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

D-PRI/P-POL

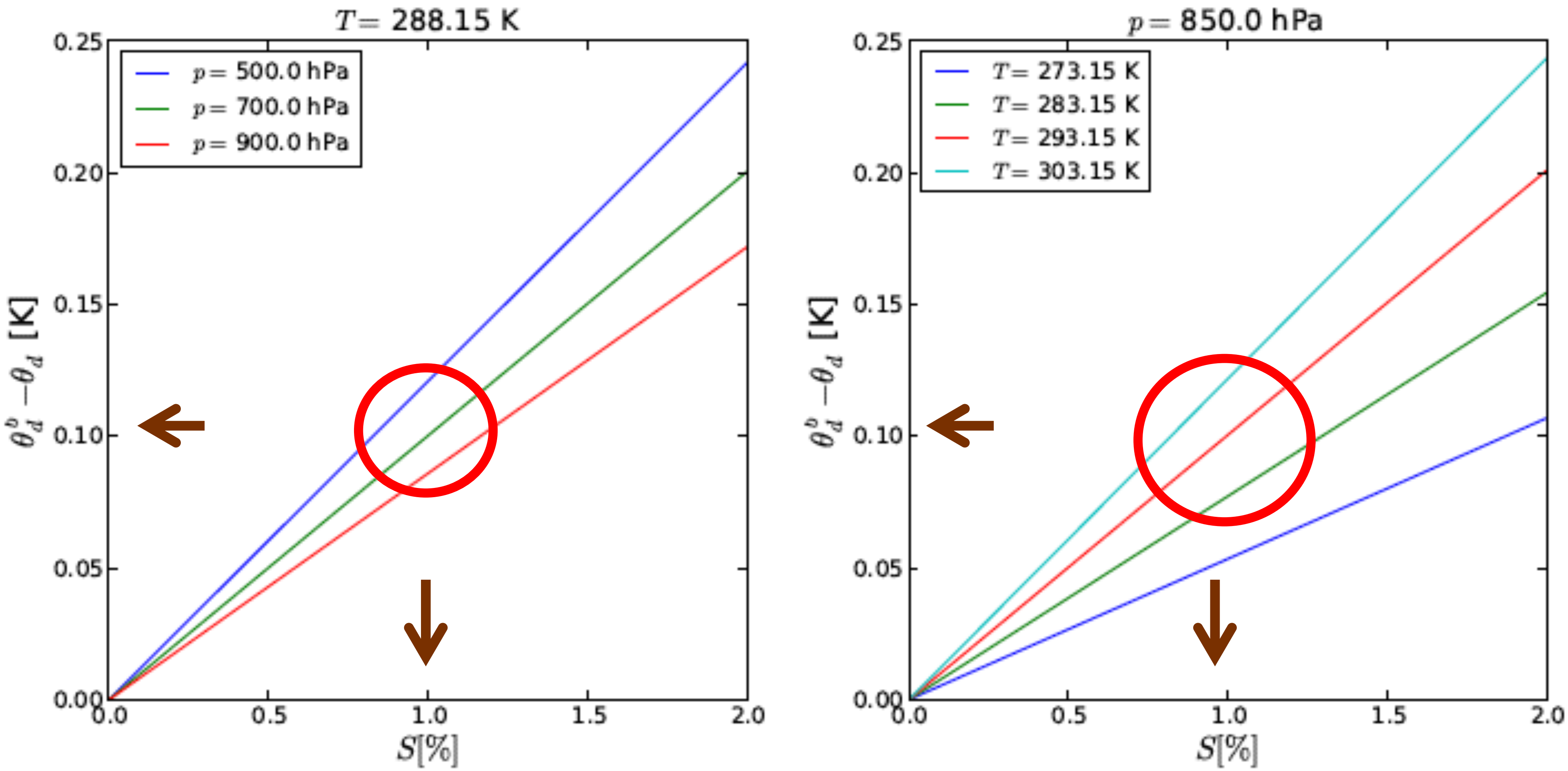
D-POL/P-PRI

1 K ≈ 0.03 m s^{-2}



POL can have significantly more buoyancy than PRI…

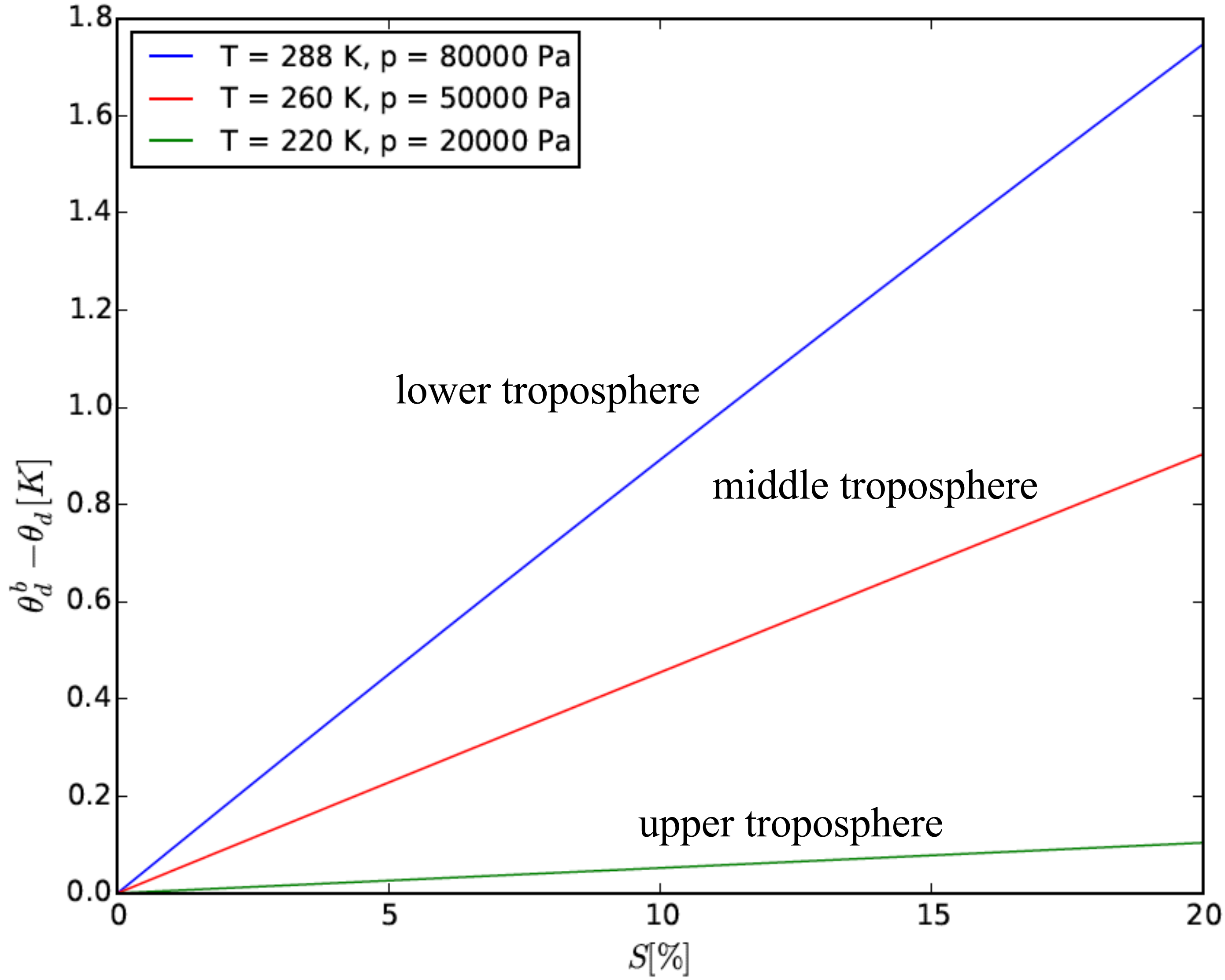
Comparing Θ_d with finite supersaturation with Θ_d at S=0, Θ_d^b



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, Θ_d^b

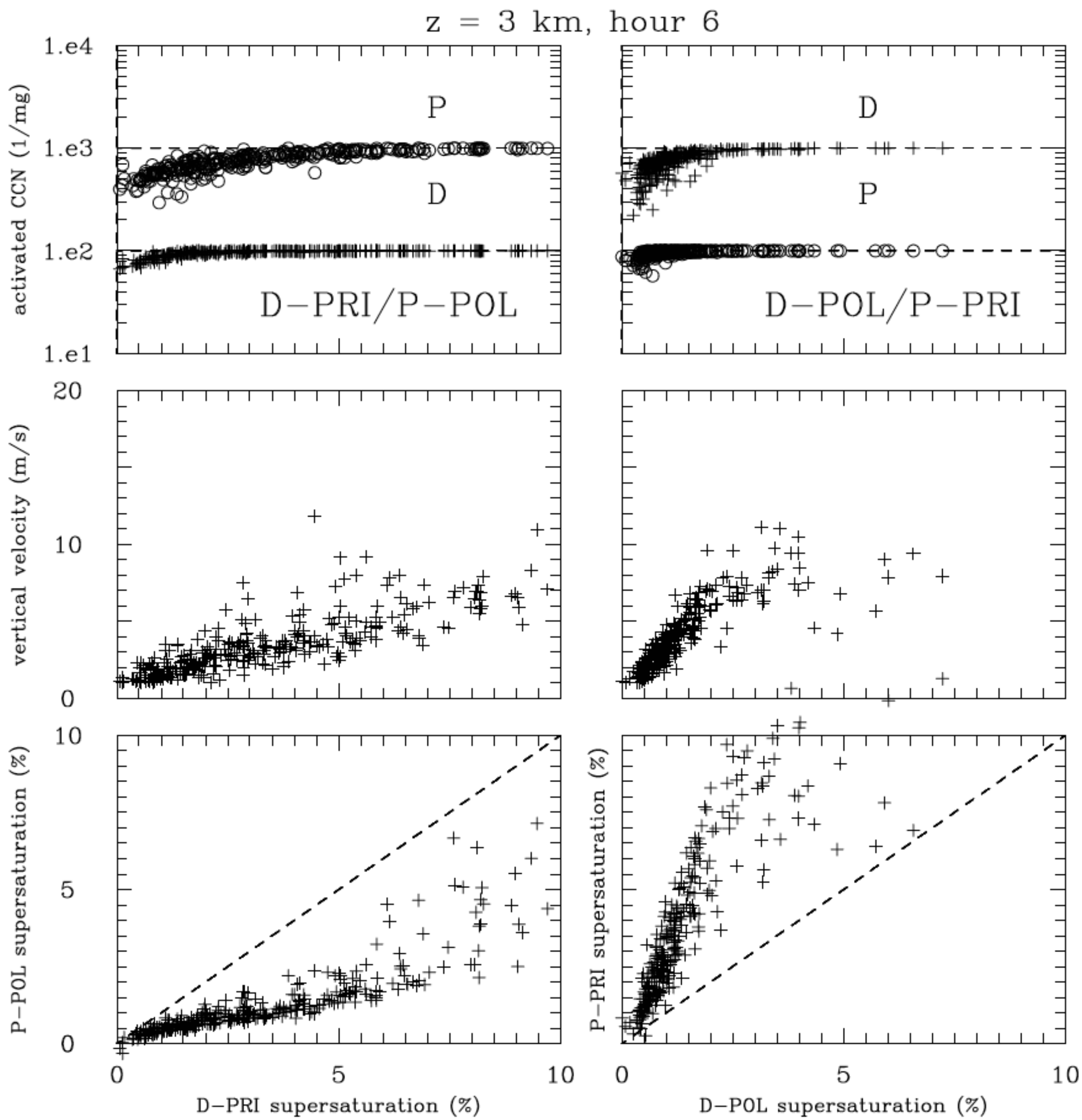


Hour 6, z = 3 km (9 degC), points with w > 1 m/s, Q > 1 g/kg

activated CCN

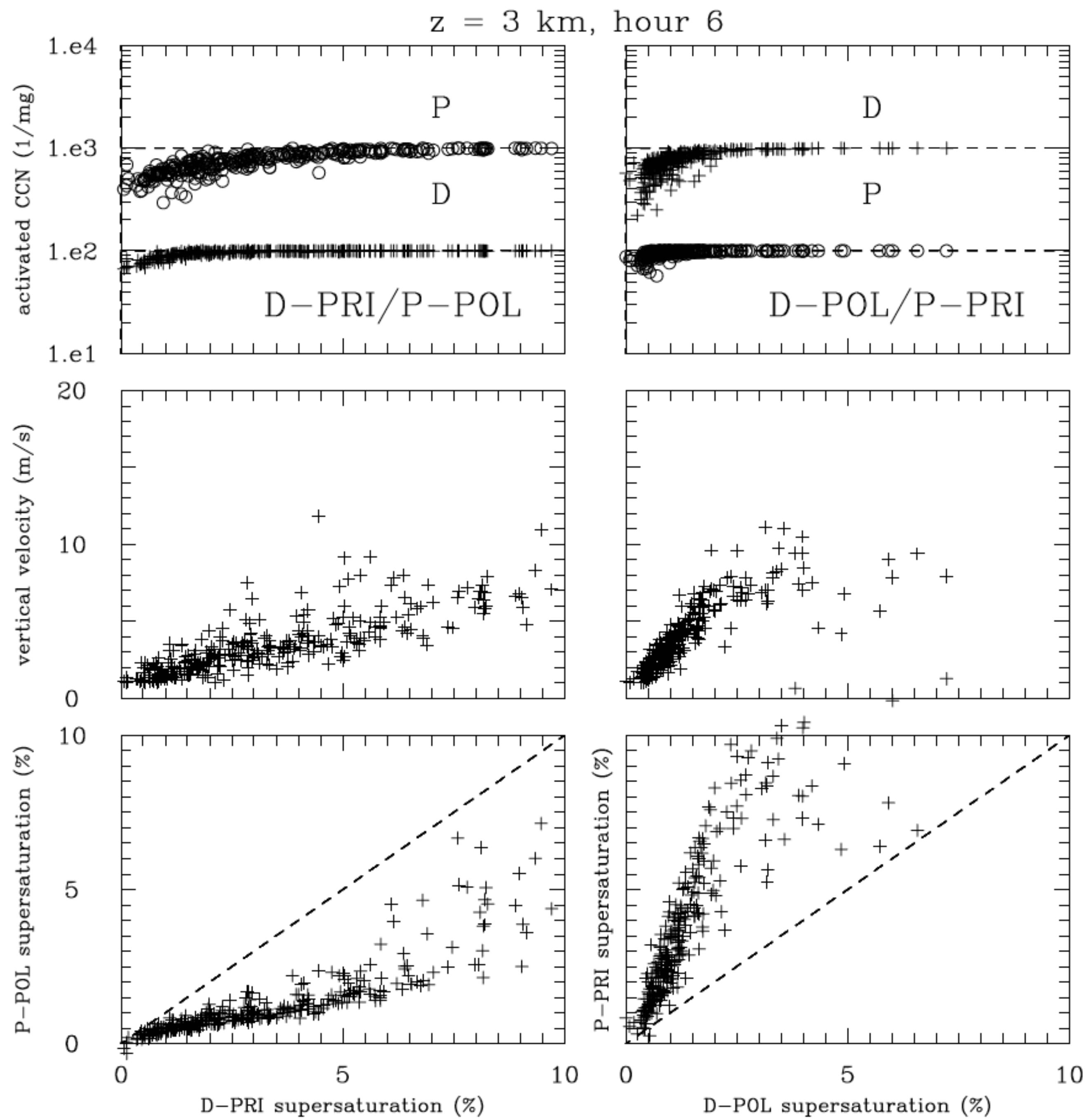
updraft velocity

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}

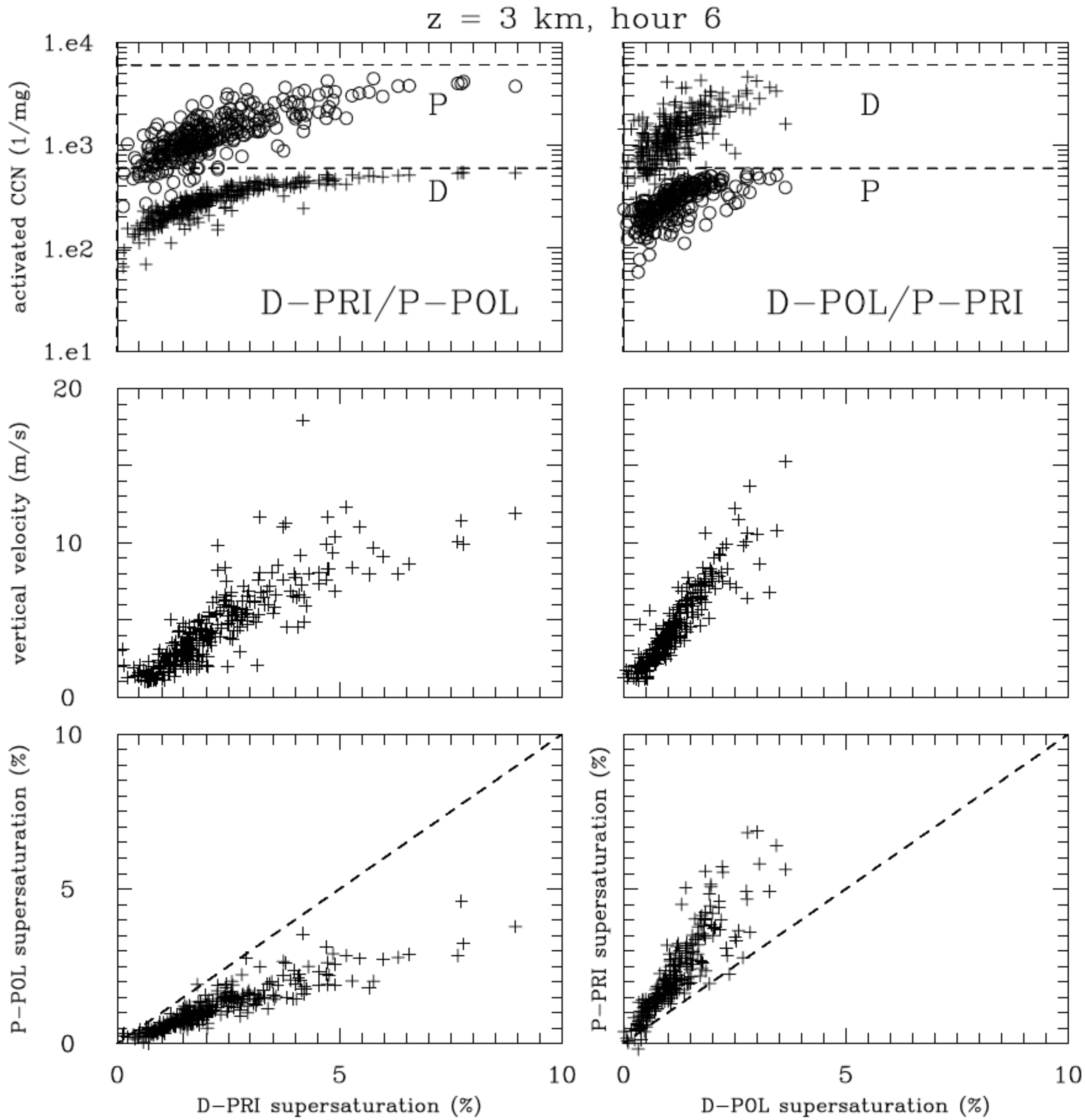
σ_d is the standard deviation **2.0**

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

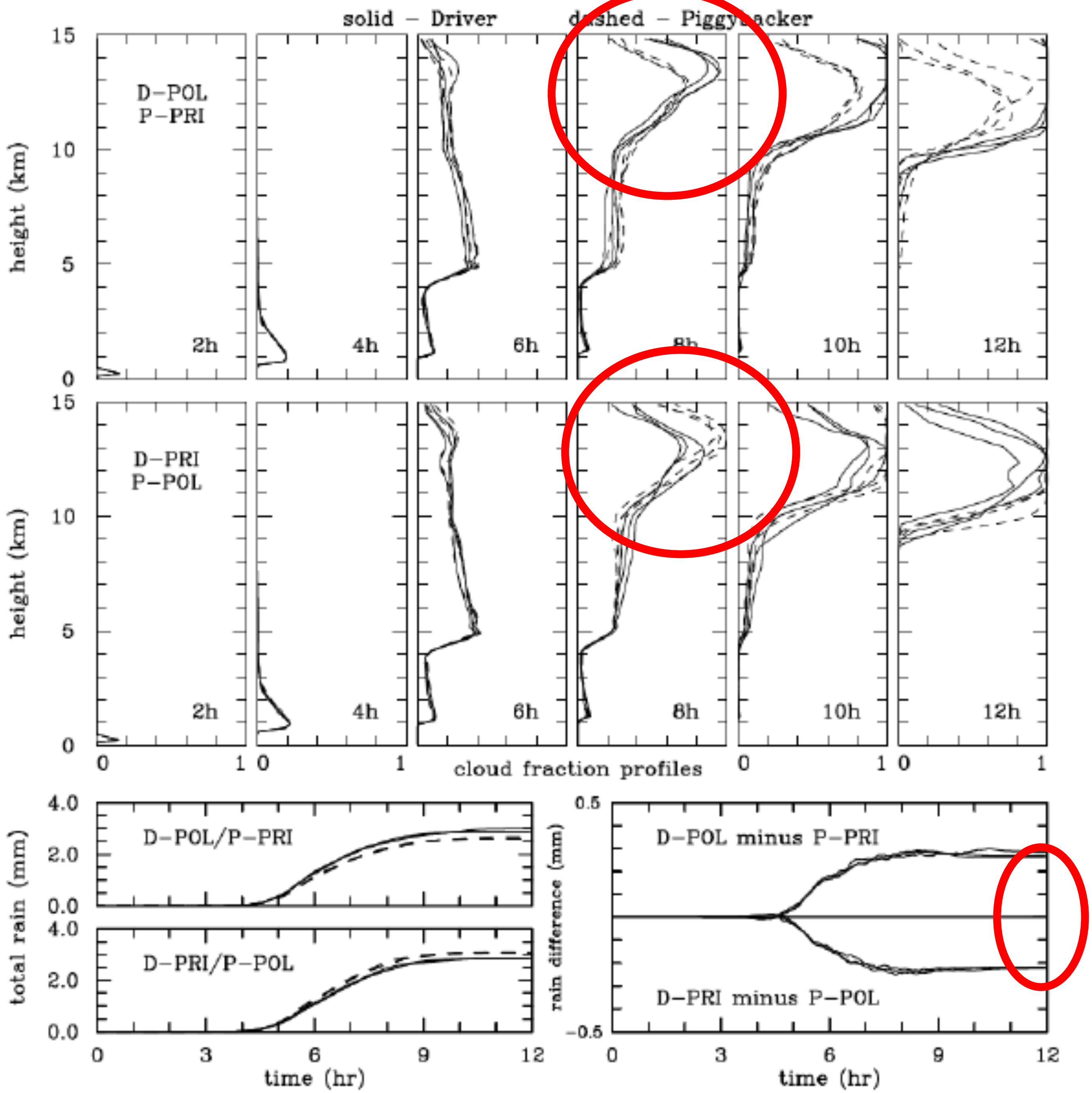
Not all CCN is activated even for the strongest updrafts…



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…



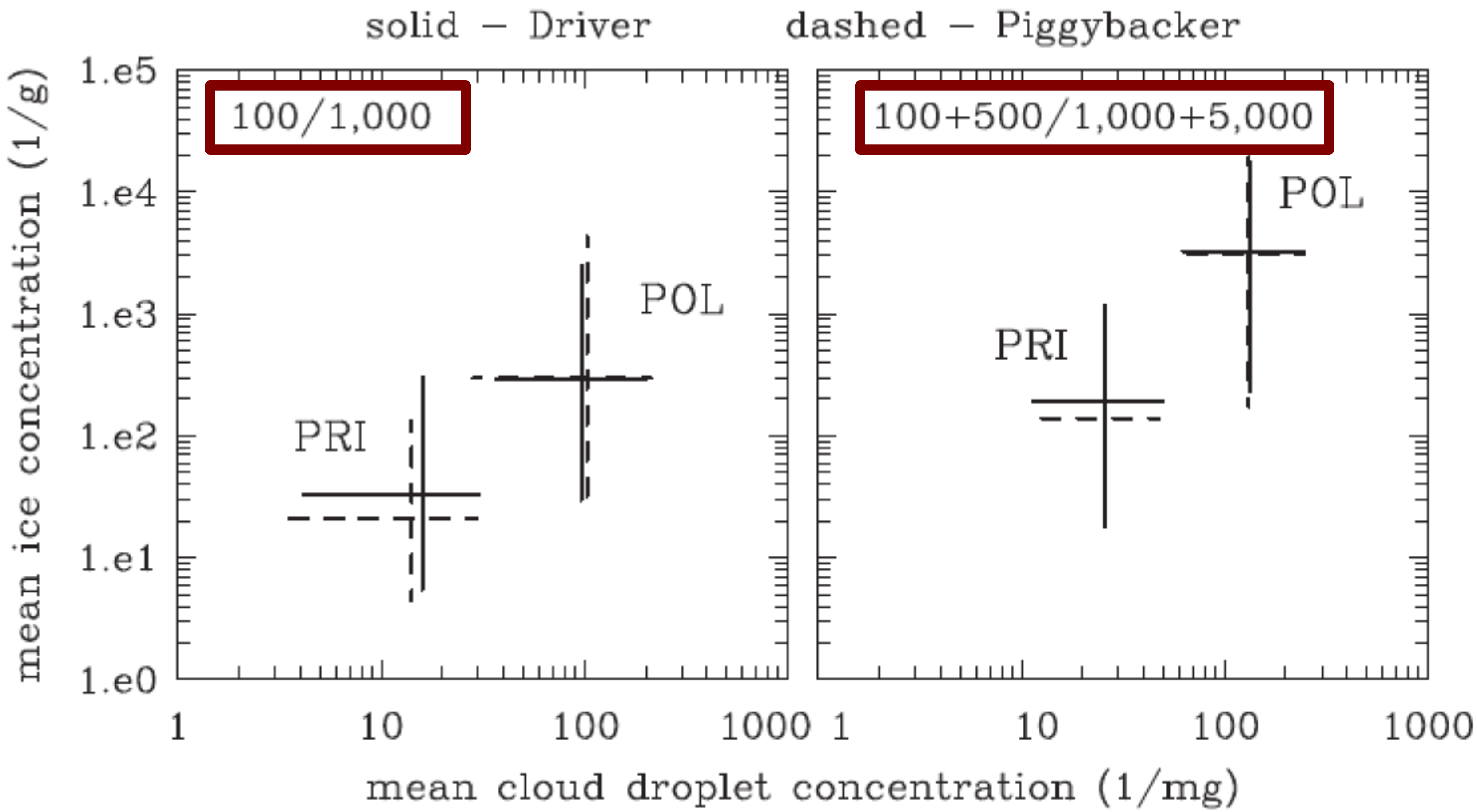
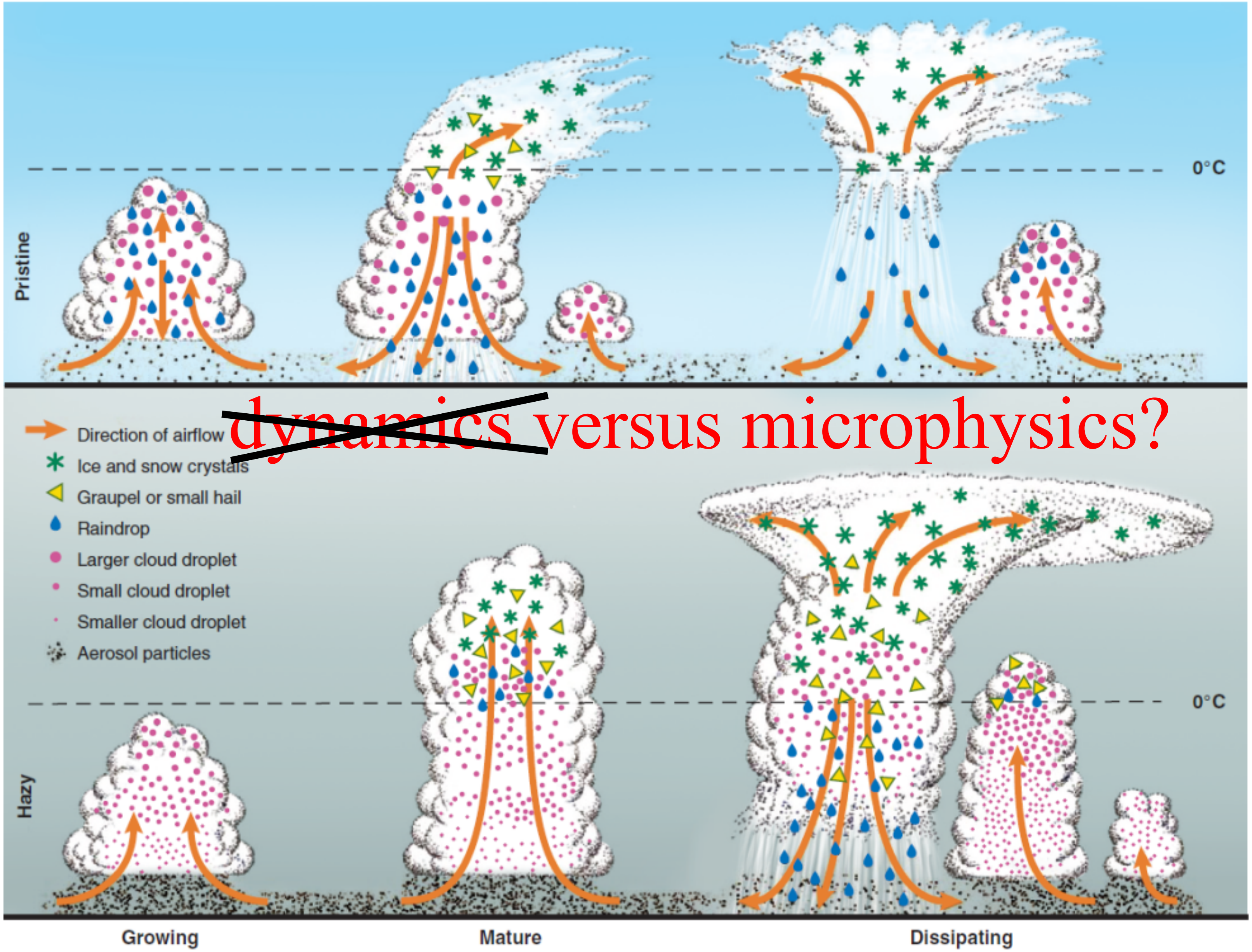


FIG. 14. Mean ice crystal concentration in the upper troposphere as a function of the mean cloud droplet concentration below the freezing level in deep convective columns for simulations with (left) a single CCN mode and (right) two CCN modes. Each cross represents the range from the 10th to 90th percentiles, 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.

clean

polluted



~~dynamics~~ versus microphysics?

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

Summary:

Aerosol-cloud-precipitation interactions include multitude of aspects and concern both global and local weather and climate. They are typically referred to as the "indirect aerosol effects". Only small fraction of those aspects were highlighted in this lecture. The review papers provide more complete overview of the problem.

Observations alone cannot provide support for conceptual models of indirect aerosol effects, like 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 with current measurement capabilities.

Separation of aerosol impact from meteorology is possible though modeling. One approach is to consider extended (weeks and months) NWP simulations as in Seifert et al. Another one is the piggybacking approach that allows clear separation of microphysical and dynamical impact of aerosols. The latter shows a *small* modification of deep convection *dynamics* and a *significant microphysical* impact on convective anvils.