Untangling microphysical impacts on moist convection applying a novel modeling methodology

Wojciech W. Grabowski

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Microphysical piggybacking…

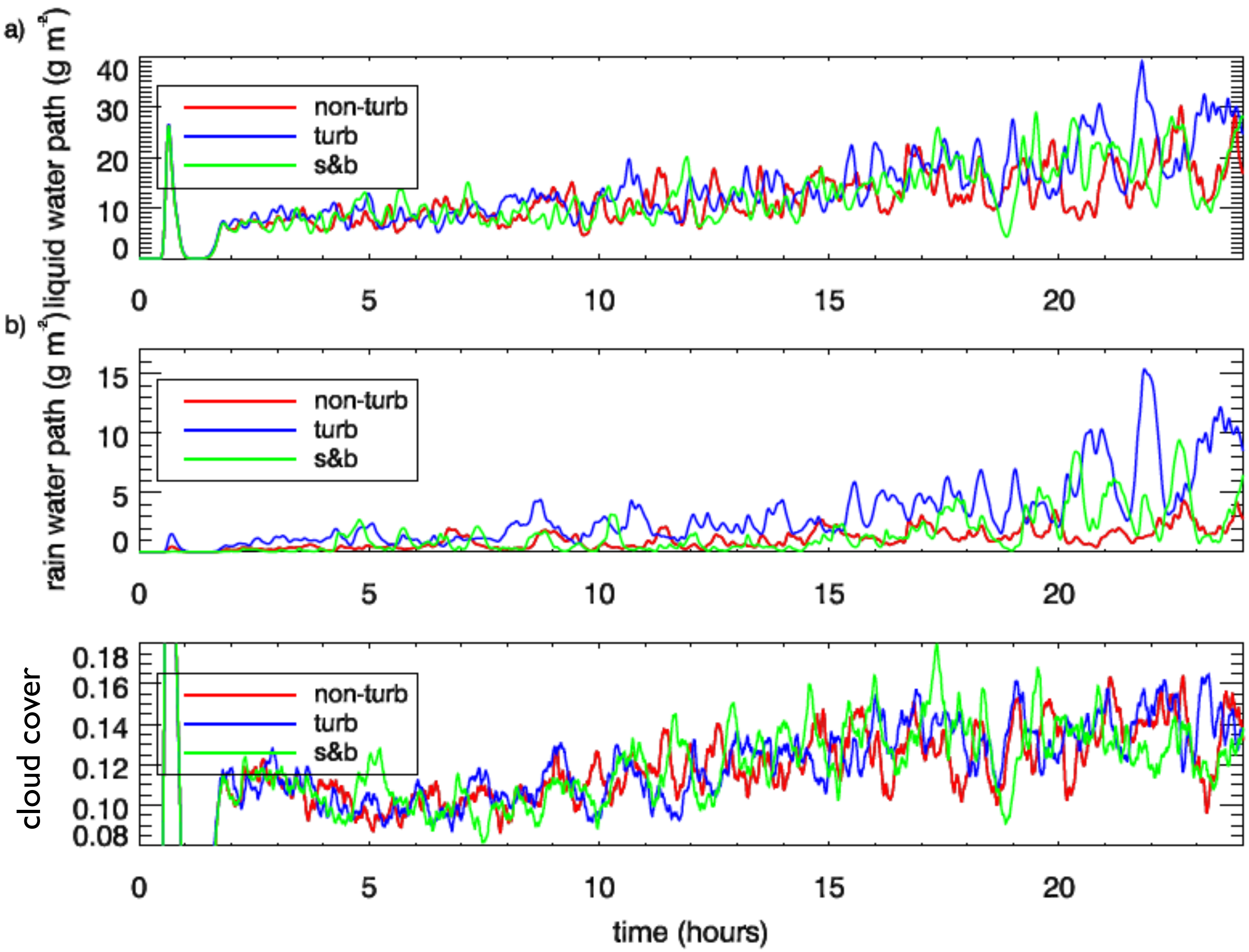
Grabowski, W. W., 2014: Extracting microphysical impacts in large-eddy simulations of shallow convection. *J. Atmos. Sci*. **71**, 4493-4499.

Grabowski W. W., 2015: Untangling microphysical impacts on deep convection applying a novel modeling methodology *J. Atmos. Sci*. (in press).

Grabowski W. W., and D. Jarecka, 2015: Modeling condensation in shallow nonprecipitating convection. *J. Atmos. Sci*. (submitted).

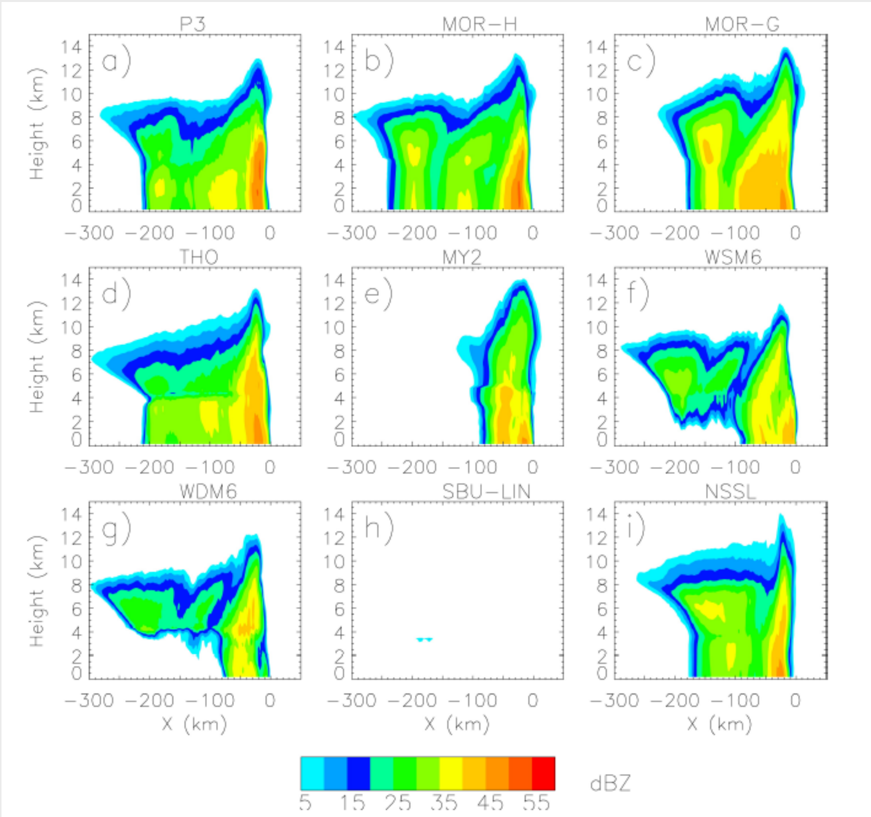
Since microphysics feed back on the cloud dynamics, numerical simulations diverge after a relatively short time. Separating physical effects from natural variability is difficult…

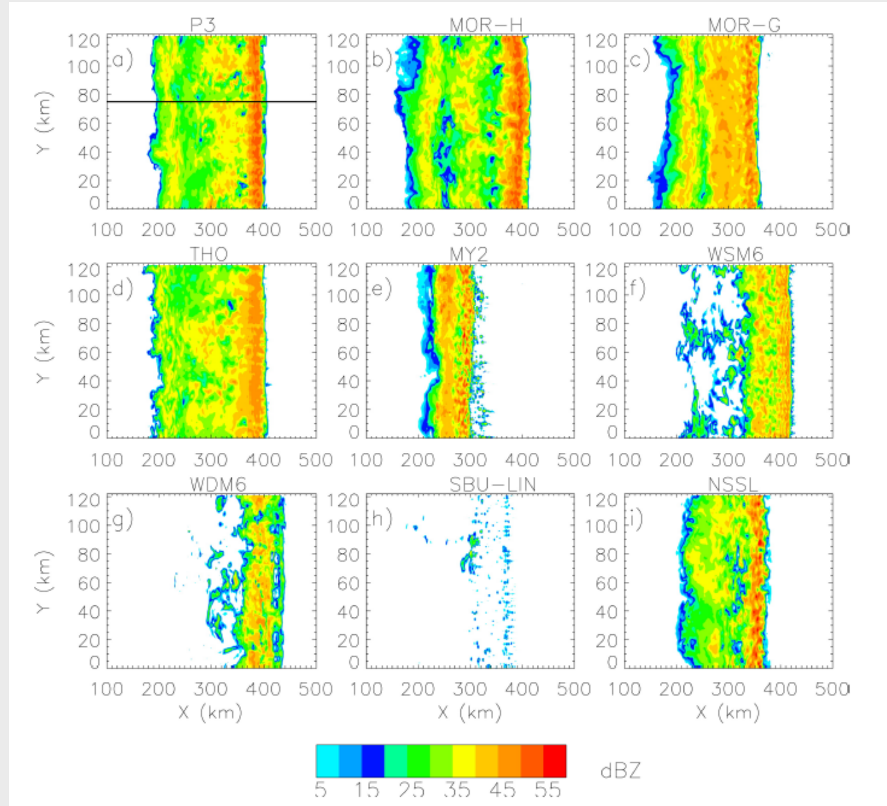
shallow convection



Franklin *ACP* 2014

deep convection (squall line)

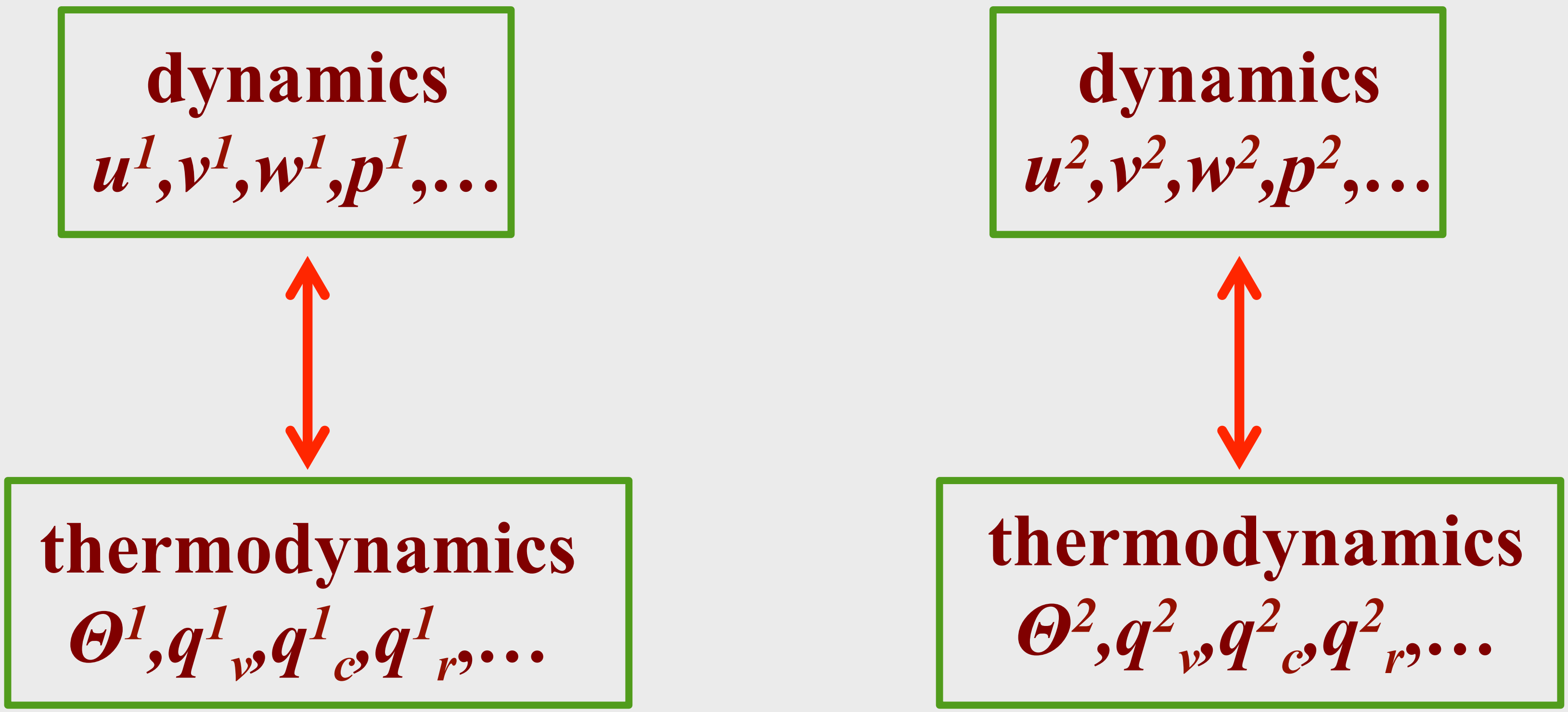




microphysics alone or microphysics plus dynamics?

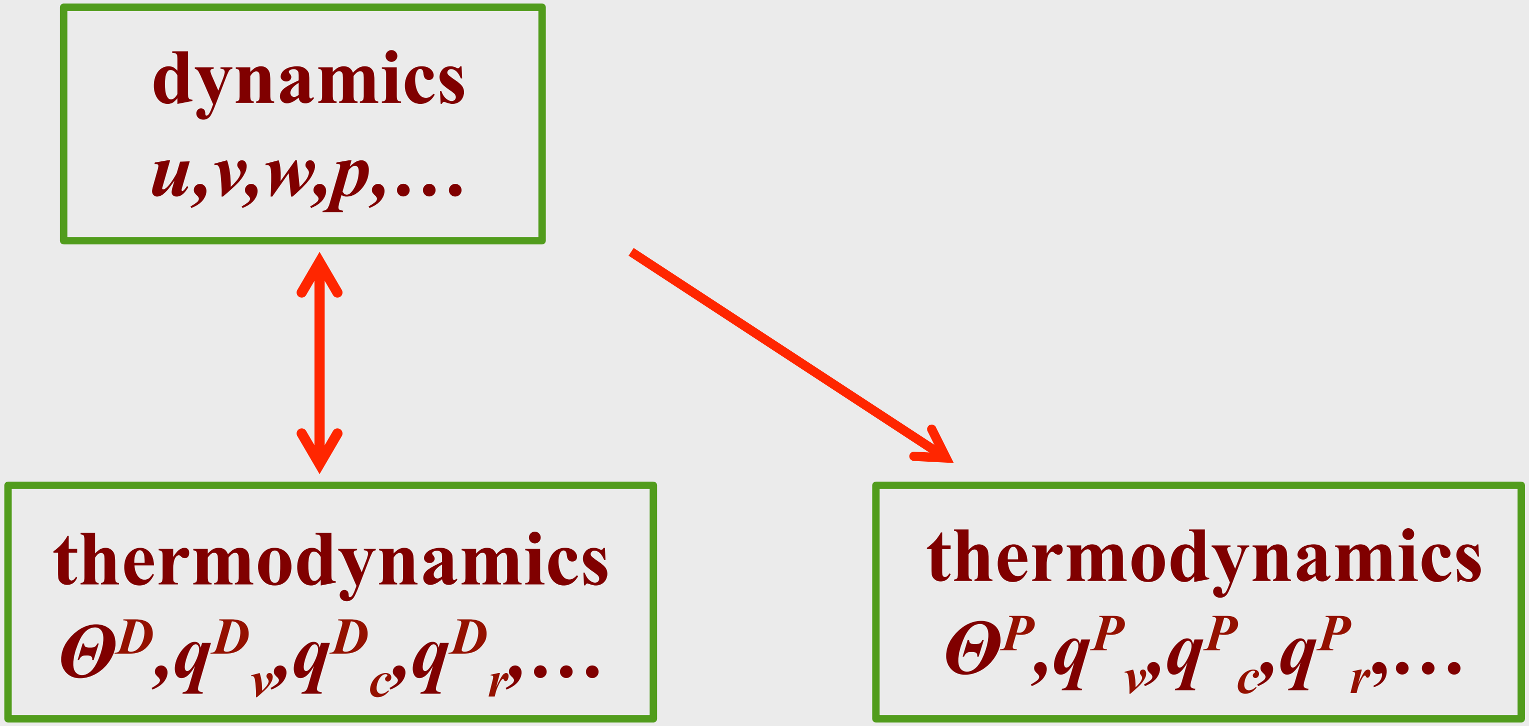
Morrison et al. *JAS* 2015

The traditional approach: two (many?) simulations…



scheme 1 ***scheme 2***

The new methodology; 1st step:



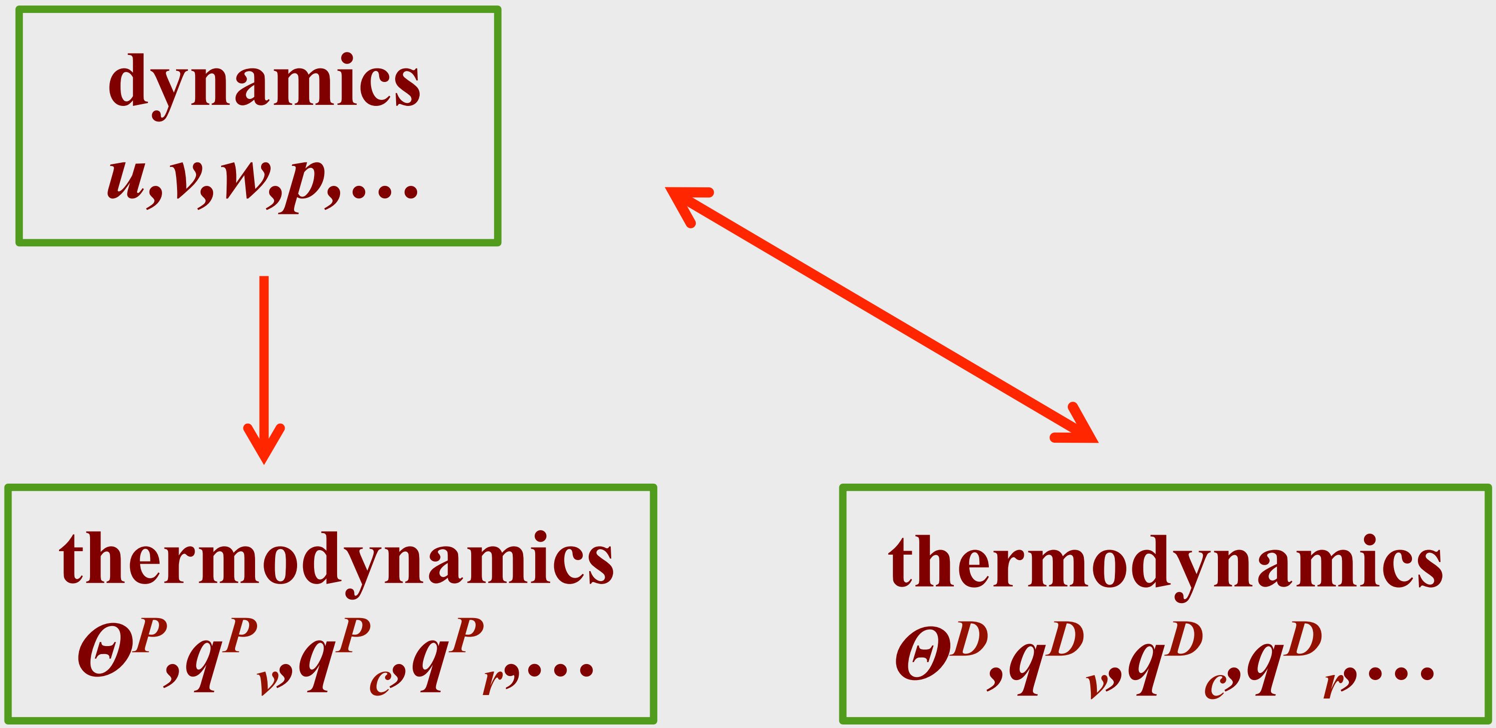
scheme 1

"D" for driving the dynamics

scheme 2

"P" for piggybacking the simulated flow

The new methodology; 2nd step:



scheme 1

"P" for piggybacking
the simulated flow

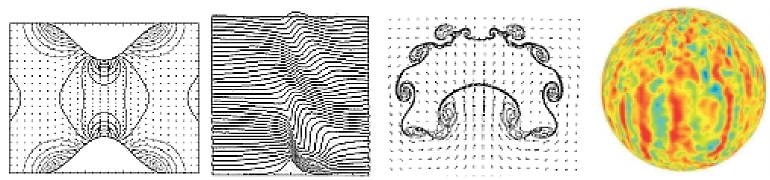
scheme 2

"D" for driving
the dynamics

http://www2.mmm.ucar.edu/eulag/

email us

Eulag
Research Model
for Geophysical Flows



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Upcoming Events

Past Events

What is New in Eulag?

Public Notice

EULAG is a numerical solver for all-scale geophysical flows. The underlying anelastic equations are either solved in an EULerian (flux form), or a LAGrangian (advective form) framework.

EULAG model is an ideal tool to perform numerical experiments in a virtual laboratory with time-dependent adaptive meshes and within complex, and even time-dependent model geometries. These abilities are due to the unique model design that combines the nonoscillatory forward-in-time (NFT) numerical algorithms and a robust elliptic solver with generalized coordinates. The code is written as a research tool with numerous options controlling the numerical accuracy and to allow for a wide range of numerical sensitivity tests. These capabilities give the researcher confidence in the numerical solutions of his/her problem. The formulation of the model equations allow for various derivatives of the code including codes for stellar atmospheres, ocean currents, sand dune propagation or biomechanical flows. EULAG is a fully parallelized code and is easily portable between different platforms.

All the model developments and details of the numerical algorithms are documented in a number of peer reviewed papers by Piotr Smolarkiewicz and his colleagues. The EULAG modeling system is developed and supported by

Current announcements:

"Eulerian vs. Lagrangian methods for cloud microphysics" , Warsaw on April 20-22, 2015. - workshop aimed at bring together researchers working on modelling cloud microphysics.

Past events:

4th International EULAG Workshop on Forward-in-time Differencing for Earth-System Models, 20-24 October 2014 in Mainz, Germany

3rd International EULAG Workshop held 25th -28th June 2012 in Loughborough UK.

2nd EULAG Model Users' Workshop took place in Sopot, Poland, 13-16 September 2010.

1st EULAG Model Users' Workshop was held in Bad T�lz, Germany 6-10 October 2008. The workshop offered tutorials covering essential physical, mathematical and numerical aspects of EULAG and provided a forum to exchange information and ideas among EULAG users.

Special issues:

The special issue of the **Acta Geophysica**: **Special volume 59 (6), 2011: Modeling Atmospheric Circulations with Sound-Proof Equations** The papers collected in the present volume of Acta Geophysica

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)
- explicit microphysics;
- 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…

Part I: Shallow convection.

Effect of cloud droplet concentration on drizzle/rain from shallow cumulus field

bulk microphysics (Grabowski 1998) with autoconversion depending on the cloud droplet concentration: 70 versus 100 per cc

A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

A. Pier Siebesma,[a] Christopher S. Bretherton,[b] Andrew Brown,[c] Andreas Chlond,[d] Joan Cuxart,[e]
Peter G. Duynkerke,[f*] Hongli Jiang,[g] Marat Khairoutdinov,[h] David Lewellen,[i] Chin-Hoh Moeng,[j]
Enrique Sanchez,[k] Bjorn Stevens,[l] and David E. Stevens[m]

JAS 2003

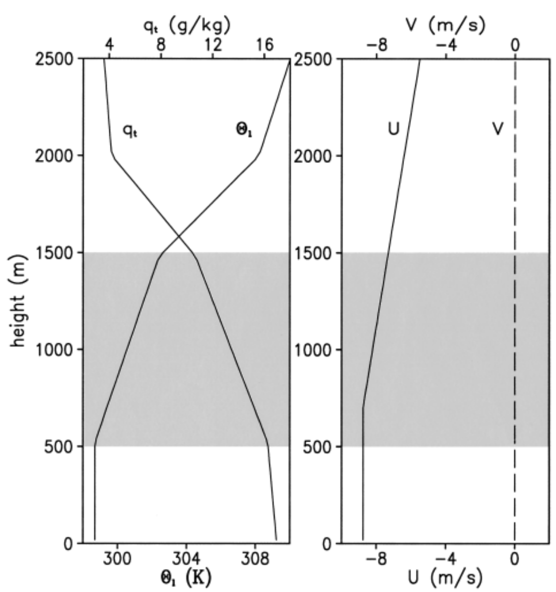
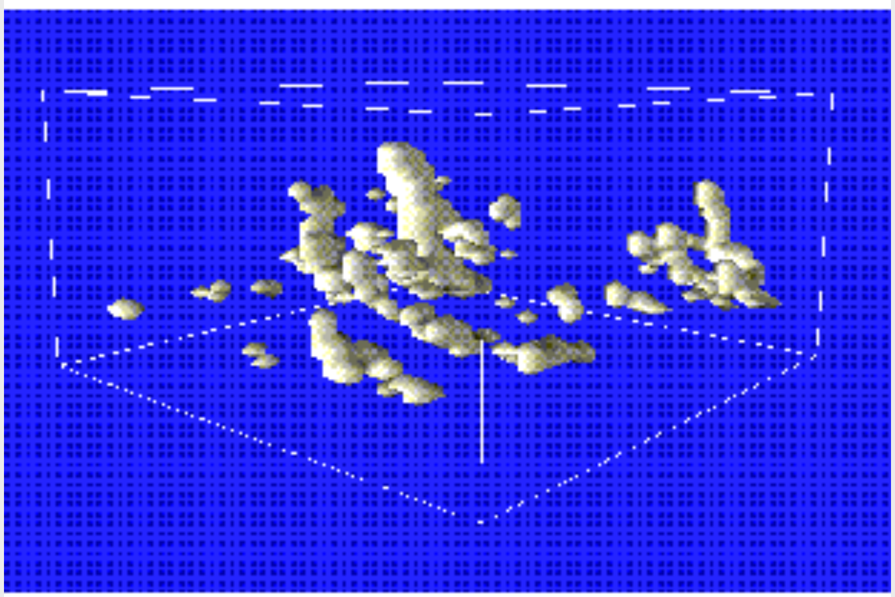


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.

$\Delta x = \Delta y = 100$m; $\Delta z = 40$m



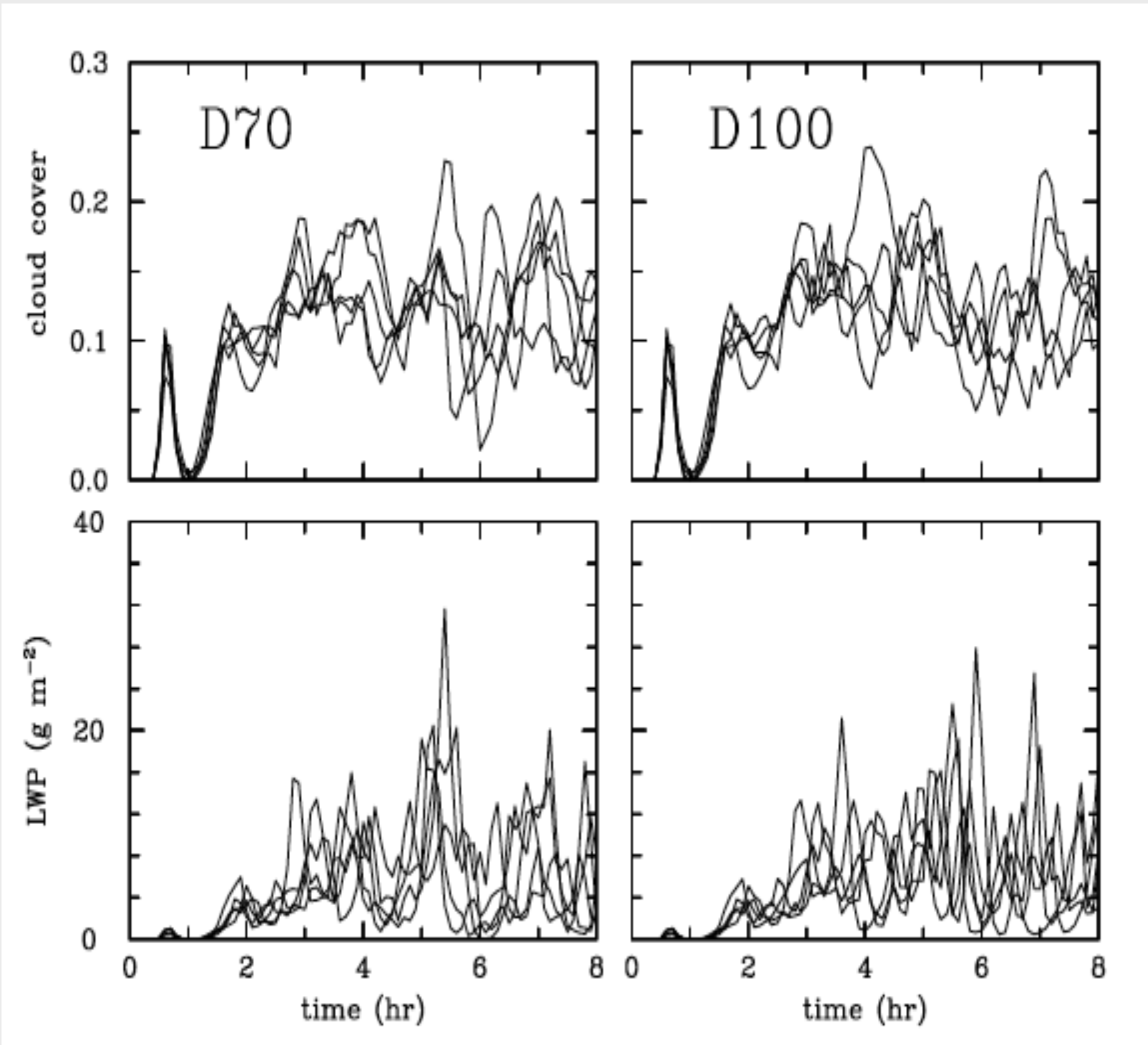
The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

Simulations:

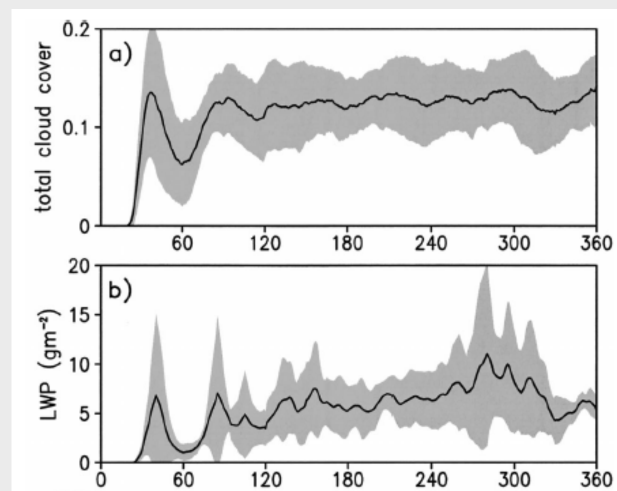
ensemble of 5 simulations driven by 70 per cc – D70, P100
ensemble of 5 simulations driven by 100 per cc – D100, P70

- look at D simulations only (traditional approach)
- look at D/P simulations (the new methodology)

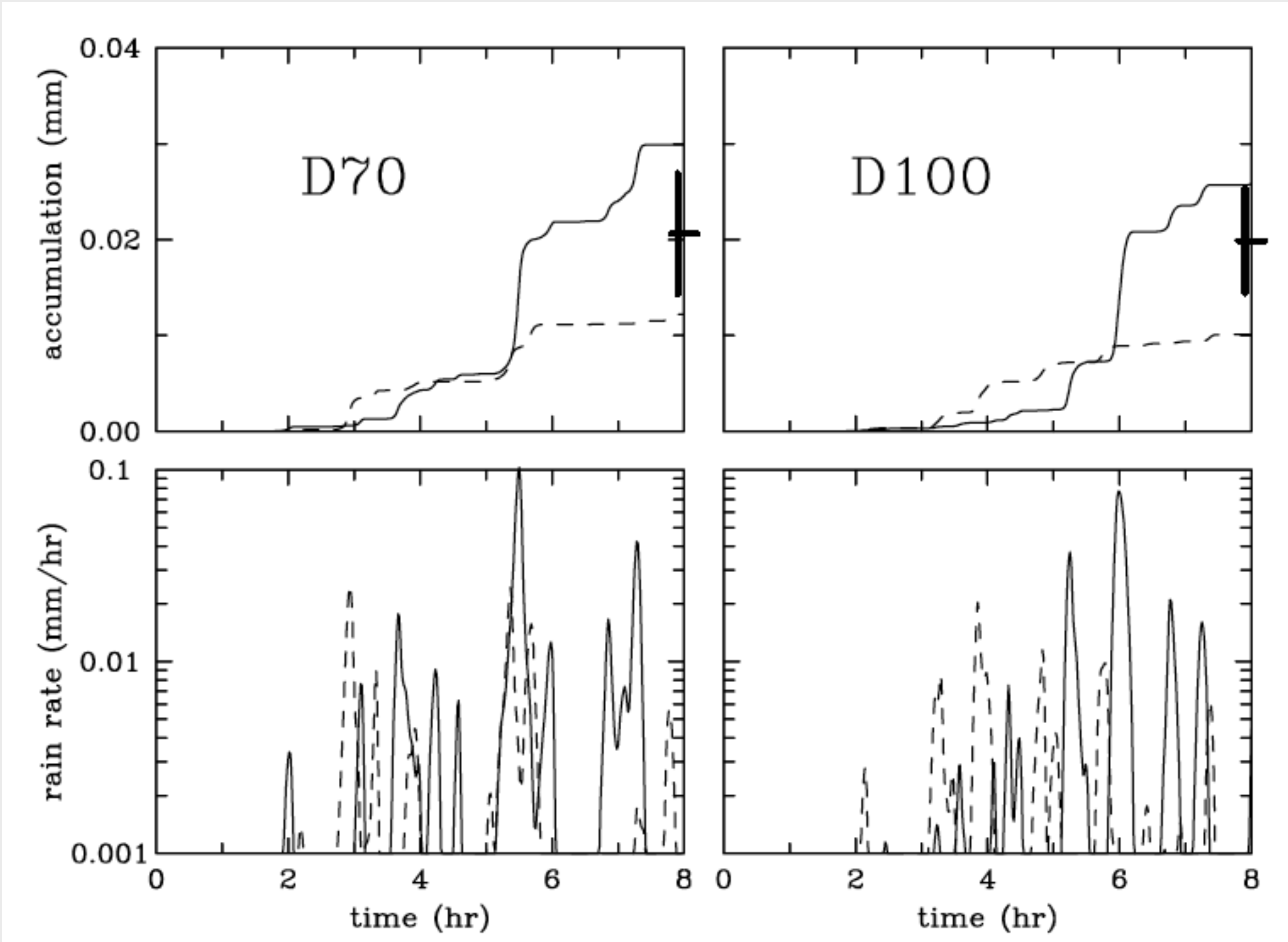
Comparison of two D simulation ensembles (5 members):



Siebesma et al. *JAS* 2003



Comparison of two D simulation ensembles (5 members):



	8-hr rain accumulations (in units of 0.01 mm)	ensemble mean, st. dev.
D70	2.54, 1.72, 2.99, 1.81, 1.22	2.06, 0.63
D100	1.01, 1.97, 1.96, 2.58, 2.43	1.99, 0.55

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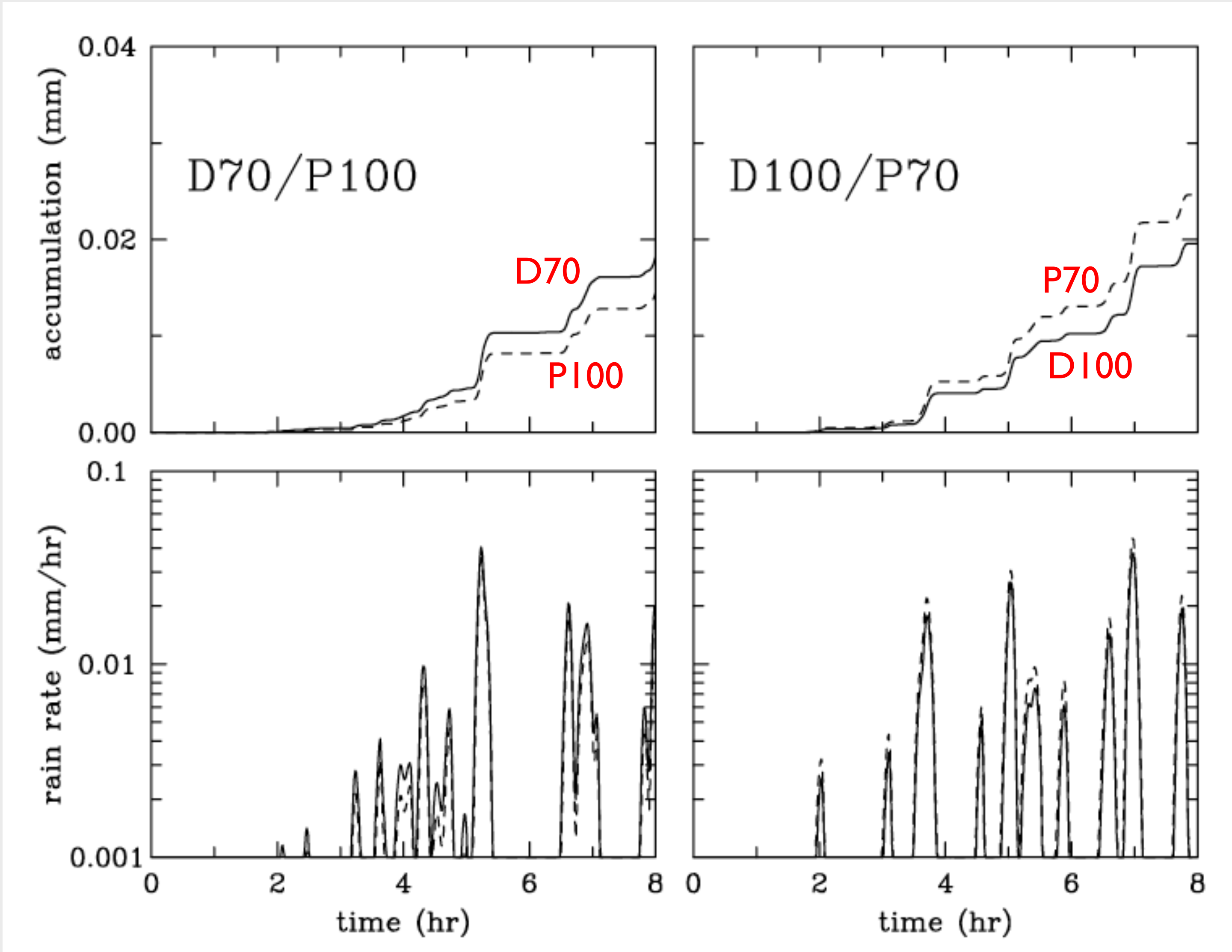
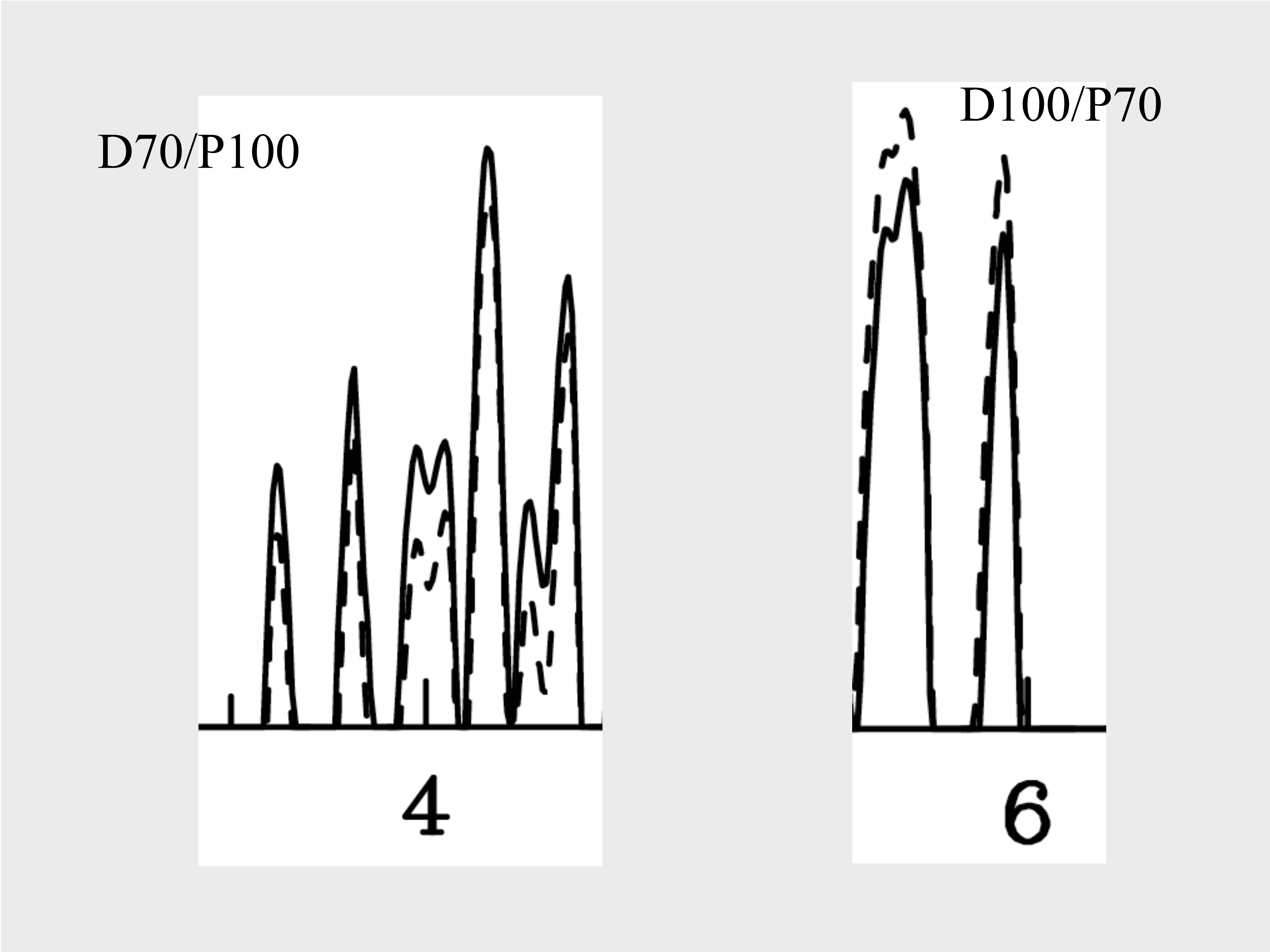
D100	1.01, 1.97, 1.96, 2.58, 2.43	1.99, 0.55

The difference is consistent with the expected effect of droplet concentration on surface rainfall from shallow convection, but the confidence is low: the difference is much smaller that the standard deviations among ensemble members…

Comparison of two D/P simulations:




D70/P100
4
D100/P70
6

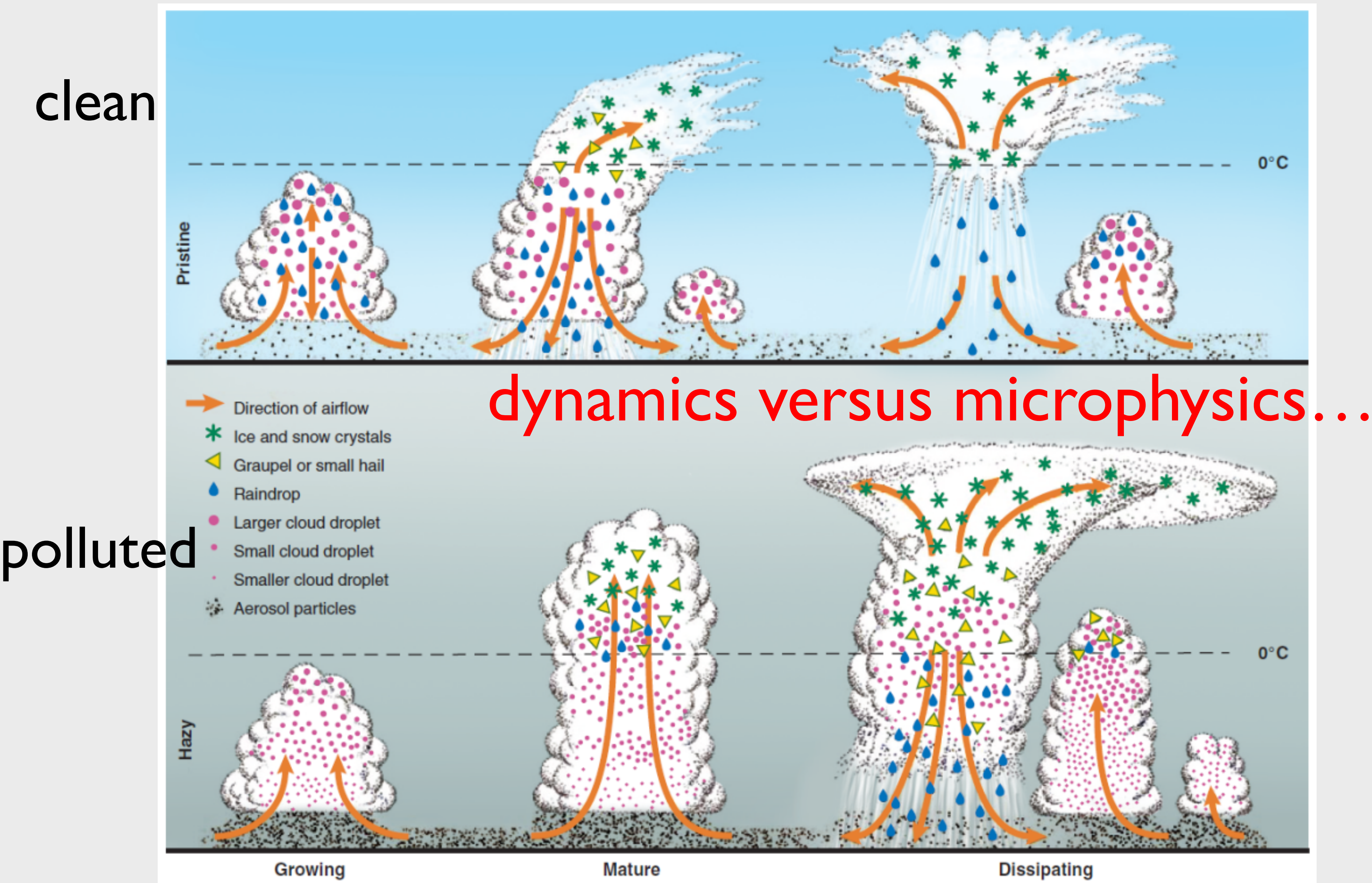
	8-hr rain accumulations (in units of 0.01 mm)	ensemble mean, st. dev.	D-P mean, st. dev.
D70	2.54, 1.72, 2.99, 1.81, 1.22	2.06, 0.63	0.41, 0.08
D100	1.01, 1.97, 1.96, 2.58, 2.43	1.99, 0.55	-0.43, 0.07
P100	2.06, 1.33, 2.48, 1.44, 0.94		
P70	1.32, 2.38, 2.46, 3.04, 2.91		

Applying the piggybacking methodology, the effect of droplet concentration is estimated with significantly higher confidence…

	8-hr rain accumulations (in units of 0.01 mm)	ensemble mean, st. dev.	D-P mean, st. dev.
D70	2.54, 1.72, 2.99, 1.81, 1.22	2.06, 0.63	0.41, 0.08
D100	1.01, 1.97, 1.96, 2.58, 2.43	1.99, 0.55	-0.43, 0.07
P100	2.06, 1.33, 2.48, 1.44, 0.94		
P70	1.32, 2.38, 2.46, 3.04, 2.91		

The fact that differences are almost the same suggests negligible impact on cloud dynamics…

Part II: Deep convection.



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

Cloud buoyancy: the potential density temperature

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

latent heating increases the temperature…

…but condensate loading reduces the buoyancy

Cloud buoyancy: the potential density temperature

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

latent heating increases the temperature…

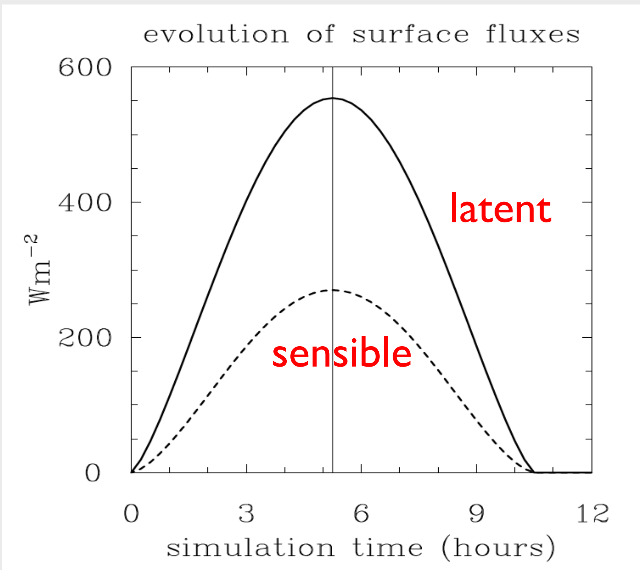
…but condensate loading reduces the buoyancy

The two almost perfectly balance each other…

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]



Current simulations:

Extended to 12 hrs
50 x 50 km^2 horizontal domain, 400 m gridlength
24 km deep domain, 81 levels, stretched grid

1. Contrasting simulations applying different microphysical schemes: separating dynamical and microphysical effects.

2. Contrasting simulations assuming clean and polluted conditions (with droplet concentration of 100/1,000 per cc for pristine/polluted) and the same microphysical scheme: exploring dynamical basis of deep convection invigoration in polluted environments.

Two microphysics schemes:

Grabowski 1998 (G98) – simple ice: SIM

Grabowski 1999 (G99) – more complex ice: IAB

G98

$$\frac{\partial \rho_o \theta}{\partial t} + \nabla \cdot (\rho_o \mathbf{u} \theta) = \frac{L_v \theta_e}{c_p T_e}(\mathrm{CON} + \mathrm{DEP}) + D_\theta, \quad (1a)$$

$$\frac{\partial \rho_o q_v}{\partial t} + \nabla \cdot (\rho_o \mathbf{u} q_v) = -\mathrm{CON} - \mathrm{DEP} + D_{q_v}, \quad (1b)$$

$$\frac{\partial \rho_o q_c}{\partial t} + \nabla \cdot (\rho_o \mathbf{u} q_c) = \mathrm{CON} - \mathrm{ACC} - \mathrm{AUT} + D_{q_c}, \quad (1c)$$

$$\frac{\partial \rho_o q_p}{\partial t} + \nabla \cdot [\rho_o (\mathbf{u} - V_T \mathbf{k}) q_p] = \mathrm{ACC} + \mathrm{AUT} + \mathrm{DEP} + \mathrm{D}_{q_p}. \quad (1d)$$

q_c – cloud condensate

q_p – precipitation

freezing/melting not considered: saturation adjustment applies always latent heat of condensation, even at cold temperatures

G99

$$\frac{\partial \rho_o \theta}{\partial t} + \nabla(\rho_o u \theta) = \mathscr{F}_\theta \equiv \frac{L_v \theta_e}{c_p T_e}(\mathrm{COND} - \mathrm{REVP}) + \frac{L_s \theta_e}{c_p T_e}(\mathrm{DEPA} + \mathrm{DEPB} + \mathrm{HOMA1}) + \frac{L_f \theta_e}{c_p T_e}(\mathrm{RIMA} + \mathrm{RIMB} + \mathrm{HOMA2} + \mathrm{HETA} + \mathrm{HETB1} - \mathrm{MELA} - \mathrm{MELB}) \quad (1a)$$

$$\frac{\partial \rho_o q_v}{\partial t} + \nabla(\rho_o u q_v) = \mathscr{F}_{q_v} \equiv -\mathrm{COND} + \mathrm{REVP} - \mathrm{DEPA} - \mathrm{DEPB} - \mathrm{HOMA1} \quad (1b)$$

$$\frac{\partial \rho_o q_c}{\partial t} + \nabla(\rho_o u q_c) = \mathscr{F}_{q_c} \equiv \mathrm{COND} - \mathrm{AUTC} - \mathrm{RCOL} - \mathrm{RIMA} - \mathrm{RIMB1} - \mathrm{HOMA2} - \mathrm{HETA} \quad (1c)$$

$$\frac{\partial \rho_o q_r}{\partial t} + \nabla[\rho_o (u - V_r k) q_r] = \mathscr{F}_{q_r} \equiv -\mathrm{REVP} + \mathrm{AUTC} + \mathrm{RCOL} + \mathrm{MELA} + \mathrm{MELB} - \mathrm{HETB1} - \mathrm{RIMB2} \quad (1d)$$

$$\frac{\partial \rho_o q_A}{\partial t} + \nabla[\rho_o (u - V_A k) q_A] = \mathscr{F}_{q_A} \equiv \mathrm{HOMA} + \mathrm{HETA} + \mathrm{DEPA} + \mathrm{RIMA} - \mathrm{MELA} - \mathrm{HETB2} \quad (1e)$$

$$\frac{\partial \rho_o q_B}{\partial t} + \nabla[\rho_o (u - V_B k) q_B] = \mathscr{F}_{q_B} \equiv \mathrm{HETB} + \mathrm{DEPB} + \mathrm{RIMB} - \mathrm{MELB} \quad (1f)$$

q_c - cloud water

q_r - rain

q_{iA} - ice A

q_{iB} - ice B

freezing/melting included

Single-moment bulk schemes…

Warm-rain representation the same in both…

G98	G99

G98

$$\frac{\partial \rho_o \theta}{\partial t} + \nabla \cdot (\rho_o \mathbf{u} \theta) = \frac{L_v \theta_e}{c_p T_e}(\mathrm{CON} + \mathrm{DEP}) + D_\theta, \qquad (1a)$$

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$$\frac{\partial \rho_o q_p}{\partial t} + \nabla \cdot [\rho_o (\mathbf{u} - V_T \mathbf{k}) q_p] = \mathrm{ACC} + \mathrm{AUT} + \mathrm{DEP} + \mathrm{D}_{q_p}. \qquad (1d)$$

q_c – cloud condensate

q_p – precipitation

freezing/melting not considered: saturation adjustment applies always latent heat of condensation, even at cold temperatures

G99

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$$\frac{\partial \rho_o q_v}{\partial t} + \nabla(\rho_o u q_v) = \mathscr{F}_{q_v} \equiv -\mathrm{COND} + \mathrm{REVP} - \mathrm{DEPA} - \mathrm{DEPB} - \mathrm{HOMA1} \qquad (1b)$$

$$\frac{\partial \rho_o q_c}{\partial t} + \nabla(\rho_o u q_c) = \mathscr{F}_{q_c} \equiv \mathrm{COND} - \mathrm{AUTC} - \mathrm{RCOL} - \mathrm{RIMA} - \mathrm{RIMB1} - \mathrm{HOMA2} - \mathrm{HETA} \qquad (1c)$$

$$\frac{\partial \rho_o q_r}{\partial t} + \nabla[\rho_o(u - V_r k) q_r] = \mathscr{F}_{q_r} \equiv -\mathrm{REVP} + \mathrm{AUTC} + \mathrm{RCOL} + \mathrm{MELA} + \mathrm{MELB} - \mathrm{HETB1} - \mathrm{RIMB2} \qquad (1d)$$

$$\frac{\partial \rho_o q_A}{\partial t} + \nabla[\rho_o(u - V_A k) q_A] = \mathscr{F}_{q_A} \equiv \mathrm{HOMA} + \mathrm{HETA} + \mathrm{DEPA} + \mathrm{RIMA} - \mathrm{MELA} - \mathrm{HETB2} \qquad (1e)$$

$$\frac{\partial \rho_o q_B}{\partial t} + \nabla[\rho_o(u - V_B k) q_B] = \mathscr{F}_{q_B} \equiv \mathrm{HETB} + \mathrm{DEPB} + \mathrm{RIMB} - \mathrm{MELB} \qquad (1f)$$

q_c - cloud water

q_r - rain

q_{iA} - ice A

q_{iB} - ice B

freezing/melting included

Two microphysics schemes:

Grabowski 1998 (G98) – simple ice: SIM

Grabowski 1999 (G99) – more complex ice: IAB

Two collections of simulations:

C1: 12 piggybacking simulations with SIM and IAB:

3 pristine ensemble members for D-SIM/P-IAB and 3 for D-IAB/P-SIM

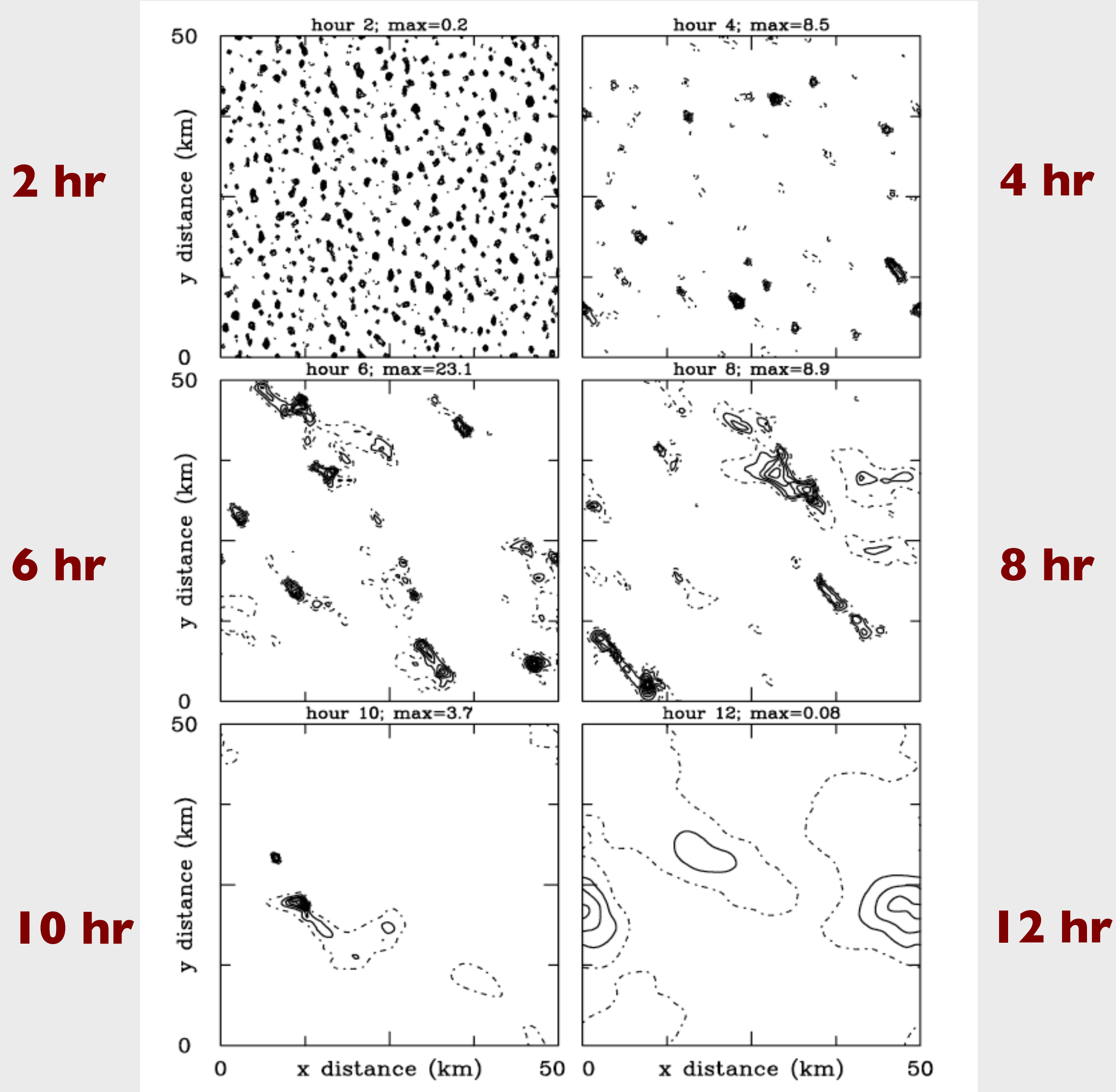
3 polluted ensemble members for D-SIM/P-IAB and 3 for D-IAB/P-SIM

C2: 12 piggybacking simulations with polluted and pristine:

3 SIM ensemble members for D100/P1000 and 3 for D1000/P100

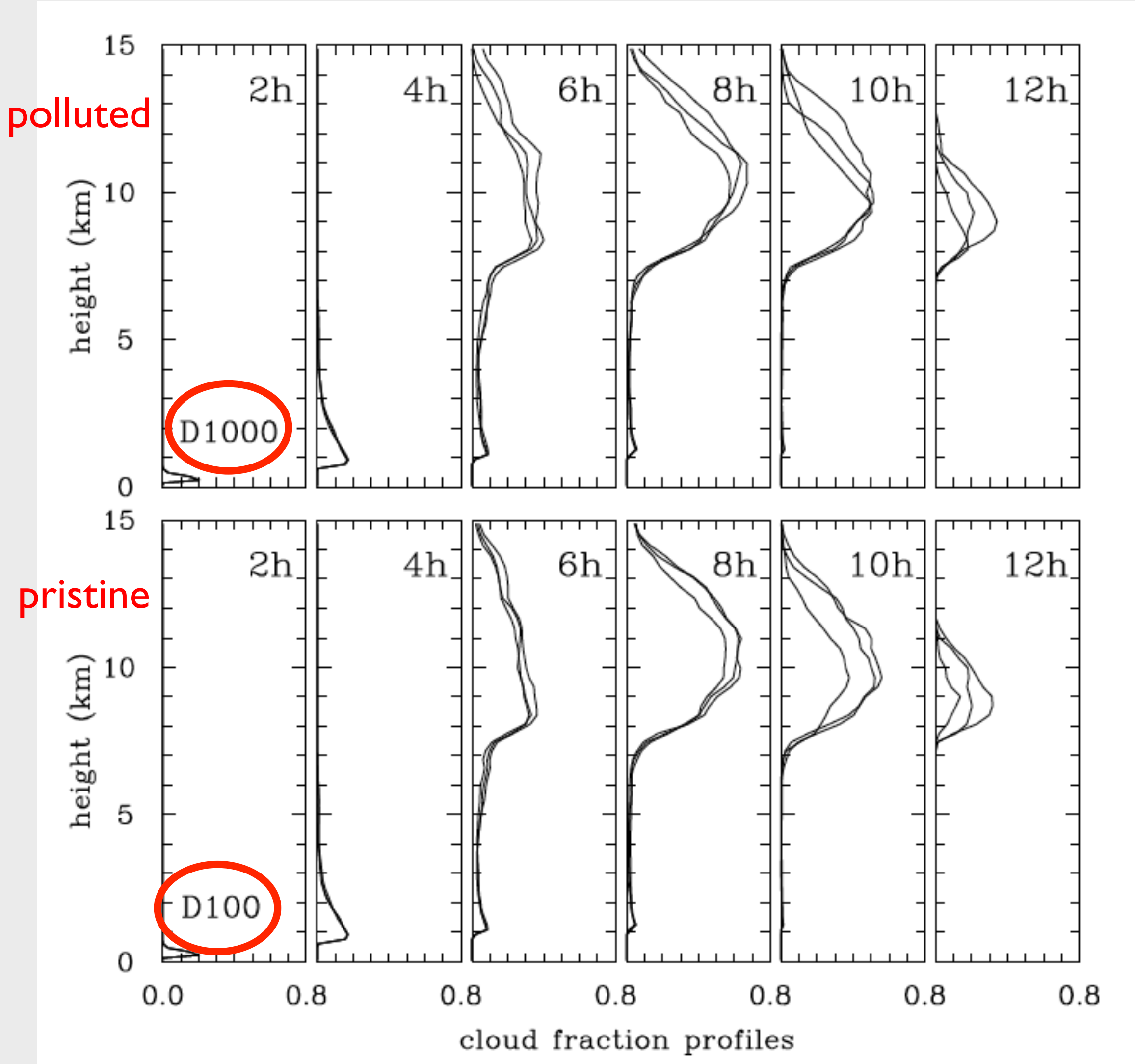
3 IAB ensemble members for D100/P1000 and 3 for D1000/P100

Example of model results: maps of the total water path (liquid plus ice); a single simulations from IAB ensemble

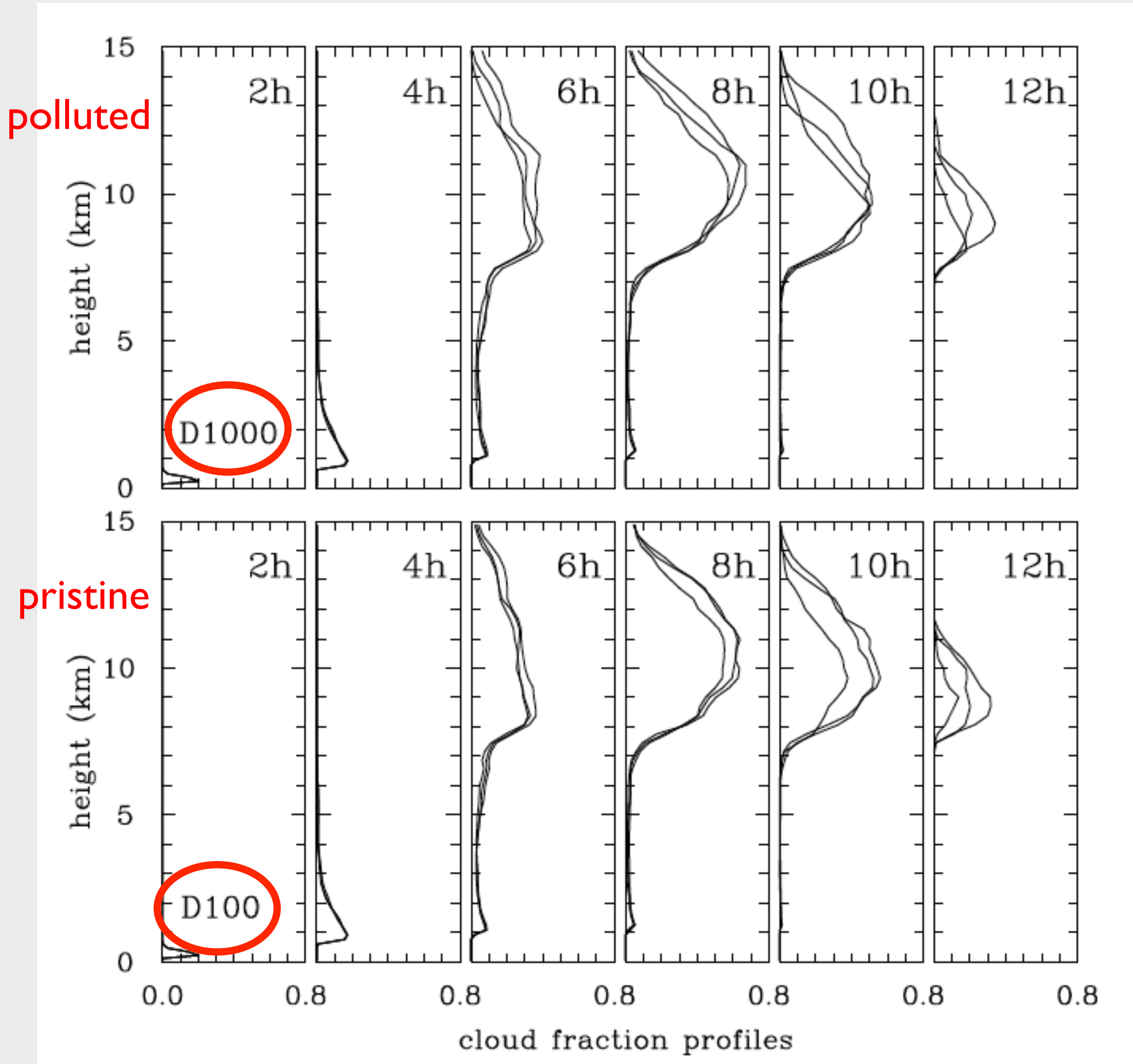


contour interval: 0.1 x maximum

Example of model results: cloud fraction profiles from IAB ensemble

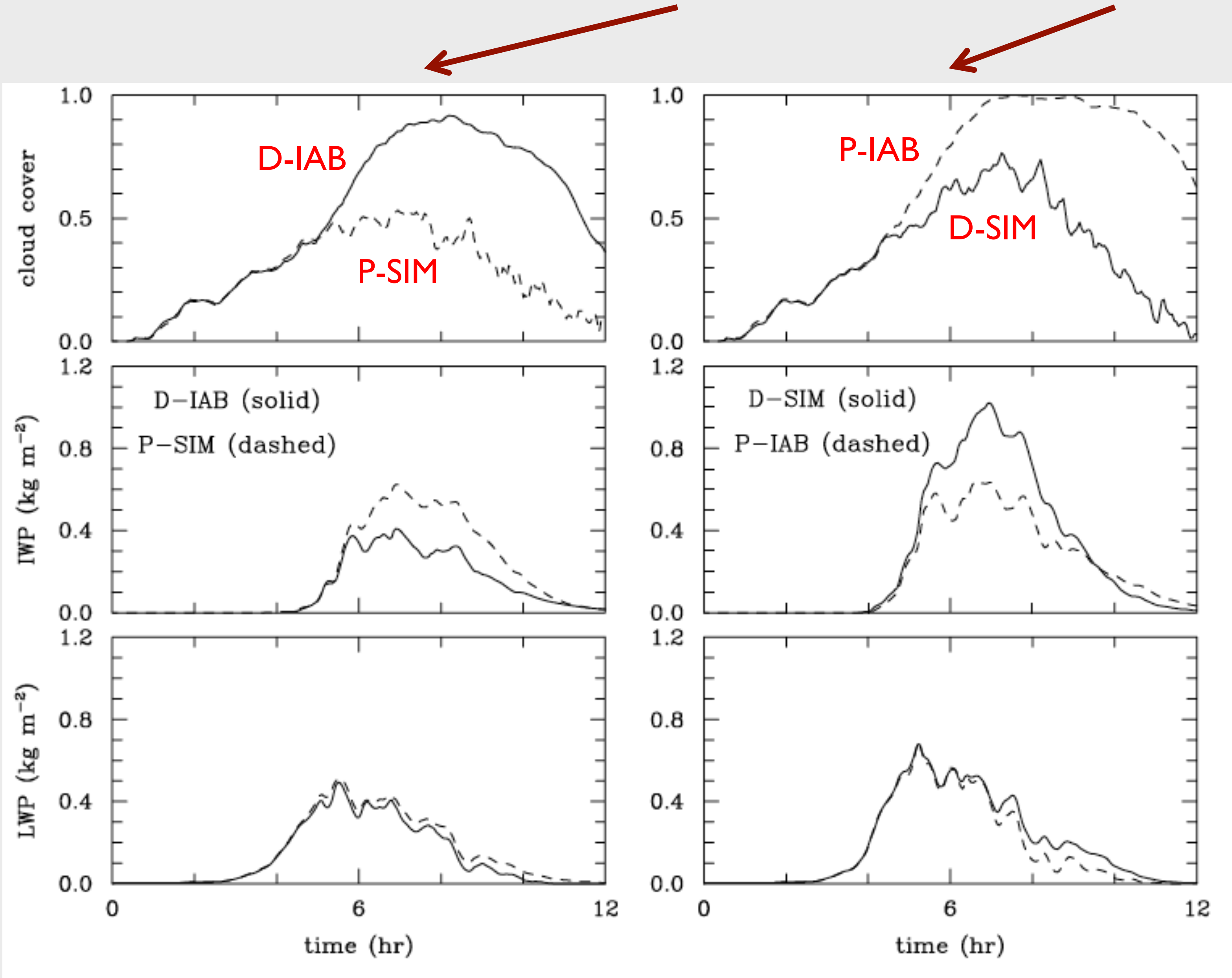


Example of model results: cloud fraction profiles from IAB ensemble

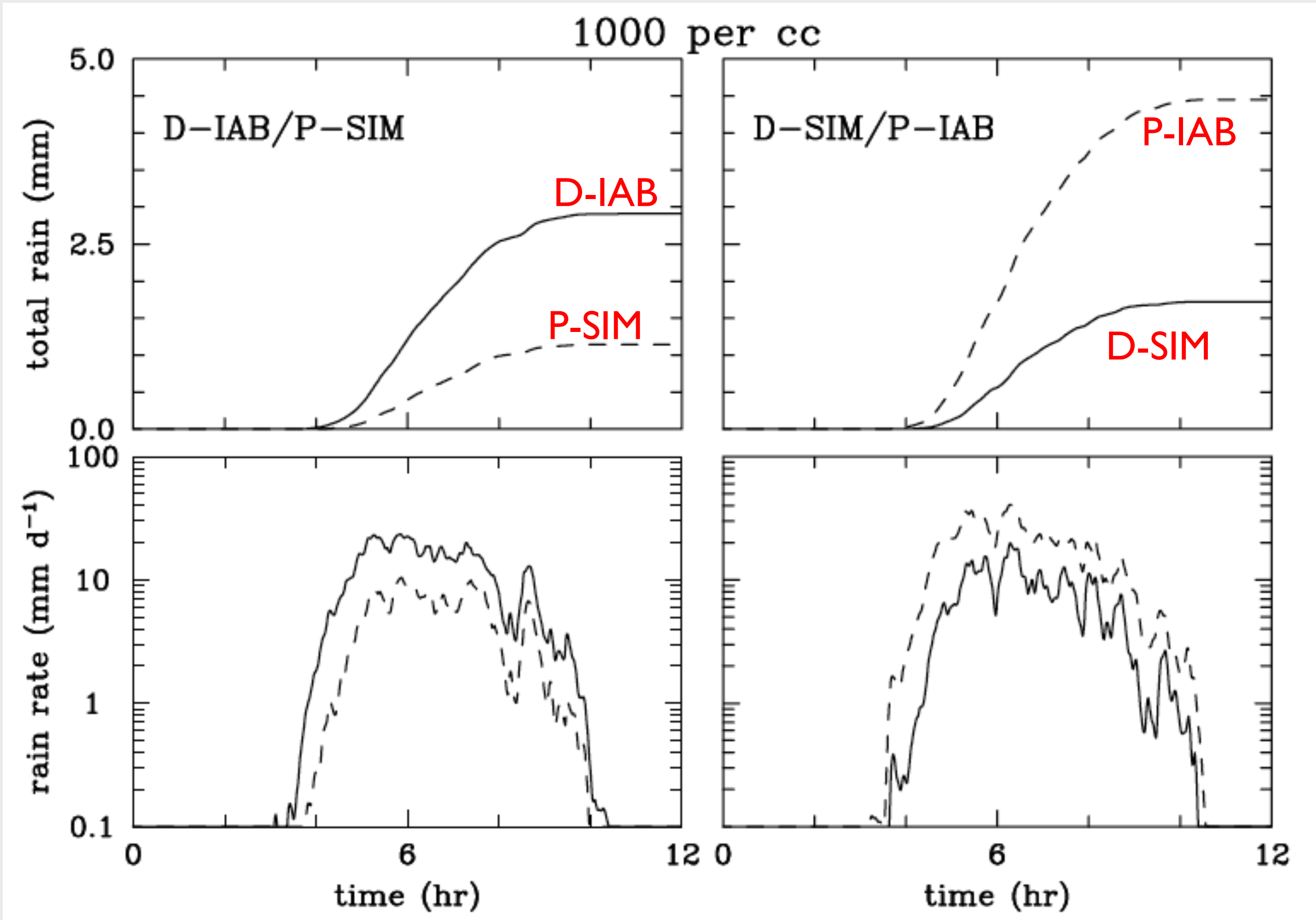


Droplet concentration seems to have an insignificant effect…

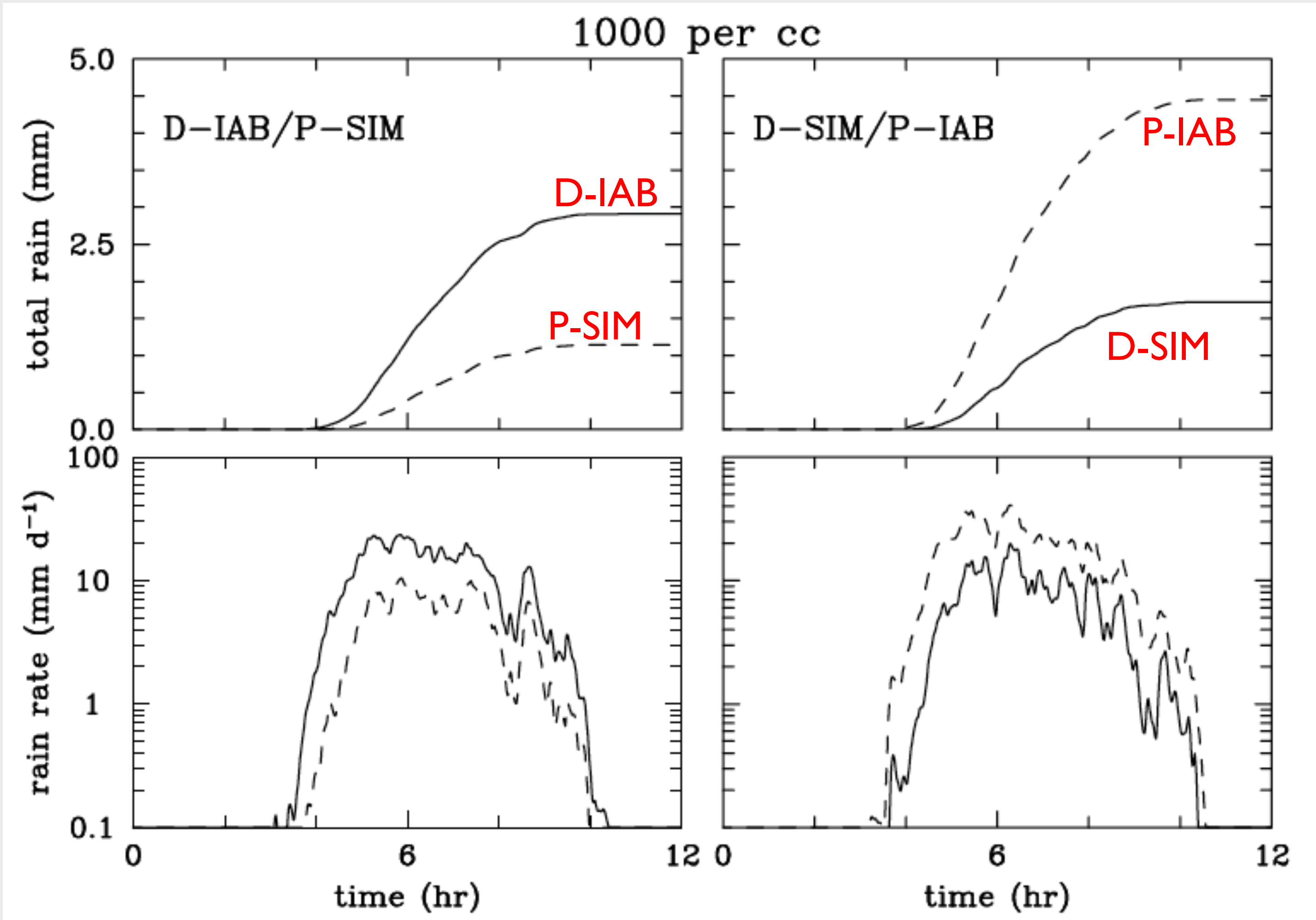
Piggybacking with different schemes: D-IAB/P-SIM versus D-SIM/P-IAB



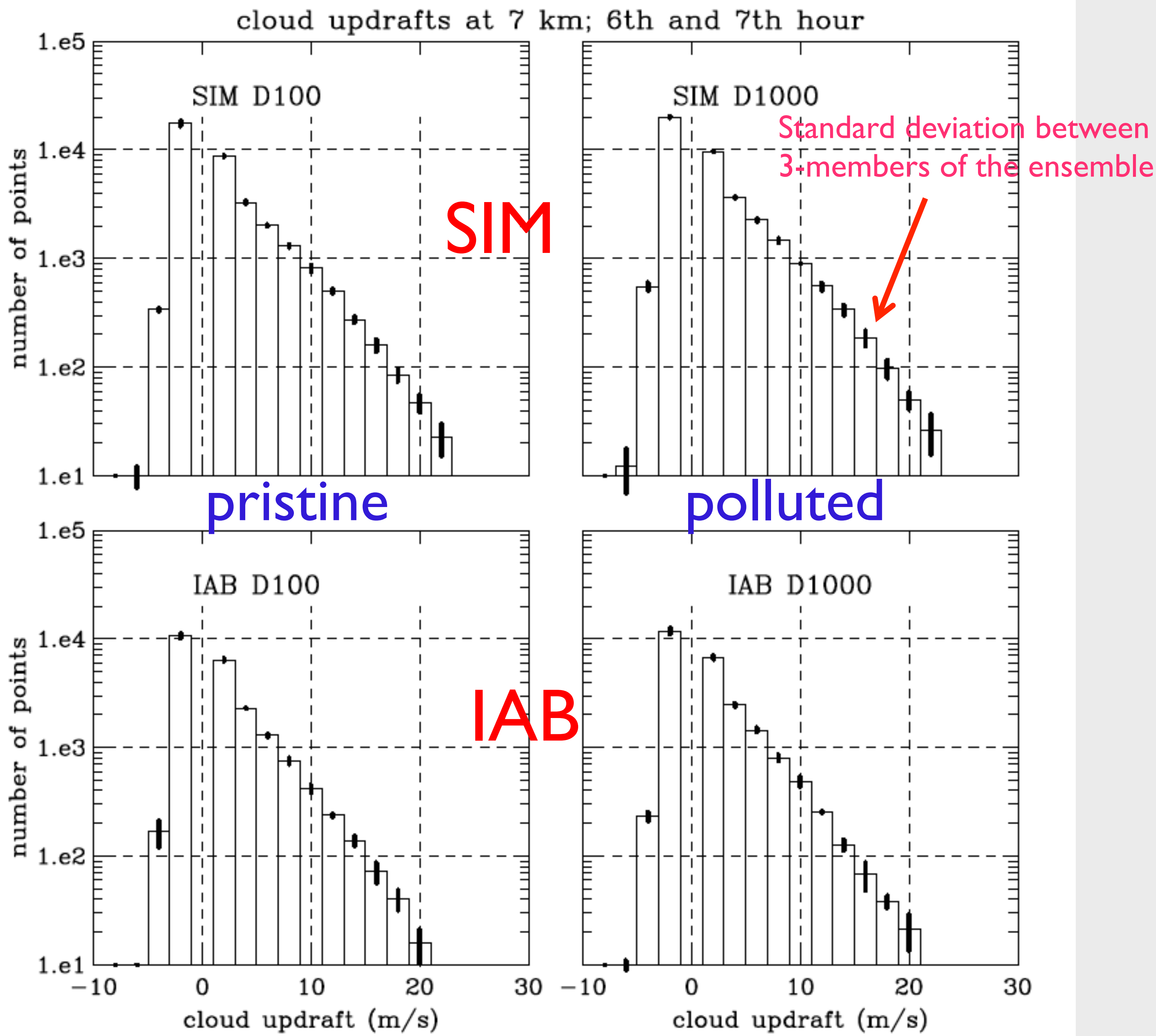
Piggybacking with different schemes: D-IAB/P-SIM versus D-SIM/P-IAB

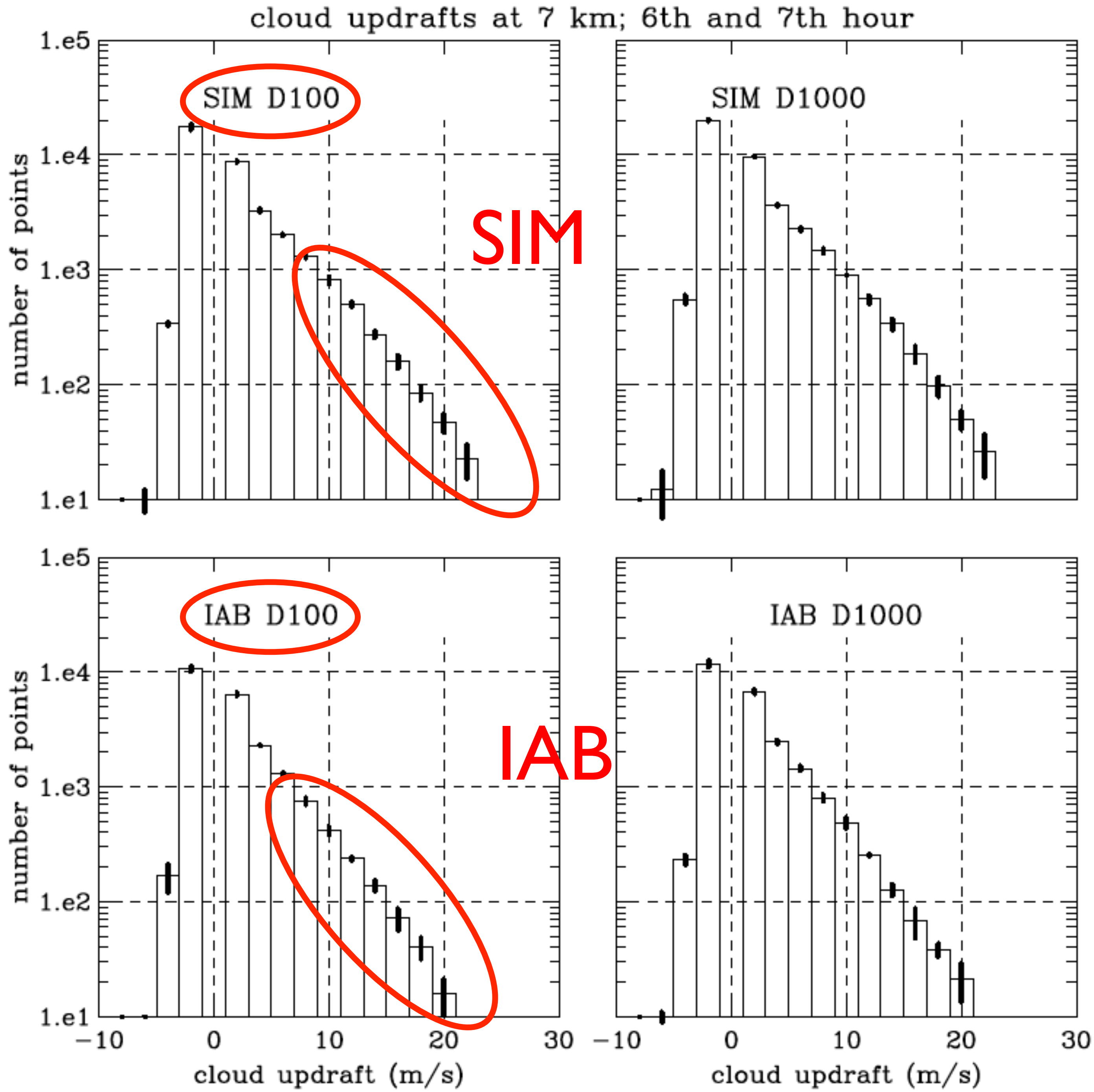


Piggybacking with different schemes: D-IAB/P-SIM versus D-SIM/P-IAB



Differences between left and right panel suggest modified dynamics between SIM and IAB driving…


cloud updrafts at 7 km; 6th and 7th hour
SIM D100
SIM D1000
Standard deviation between
3 members of the ensemble
SIM
IAB
pristine
polluted
IAB D100
IAB D1000
number of points
cloud updraft (m/s)
1.e5
1.e4
1.e3
1.e2
1.e1
−10
0
10
20
30



cloud updrafts at 7 km; 6th and 7th hour
SIM D100
SIM D1000
IAB D100
IAB D1000
SIM
IAB
number of points
1.e5
1.e4
1.e3
1.e2
1.e1
−10
0
10
20
30
cloud updraft (m/s)

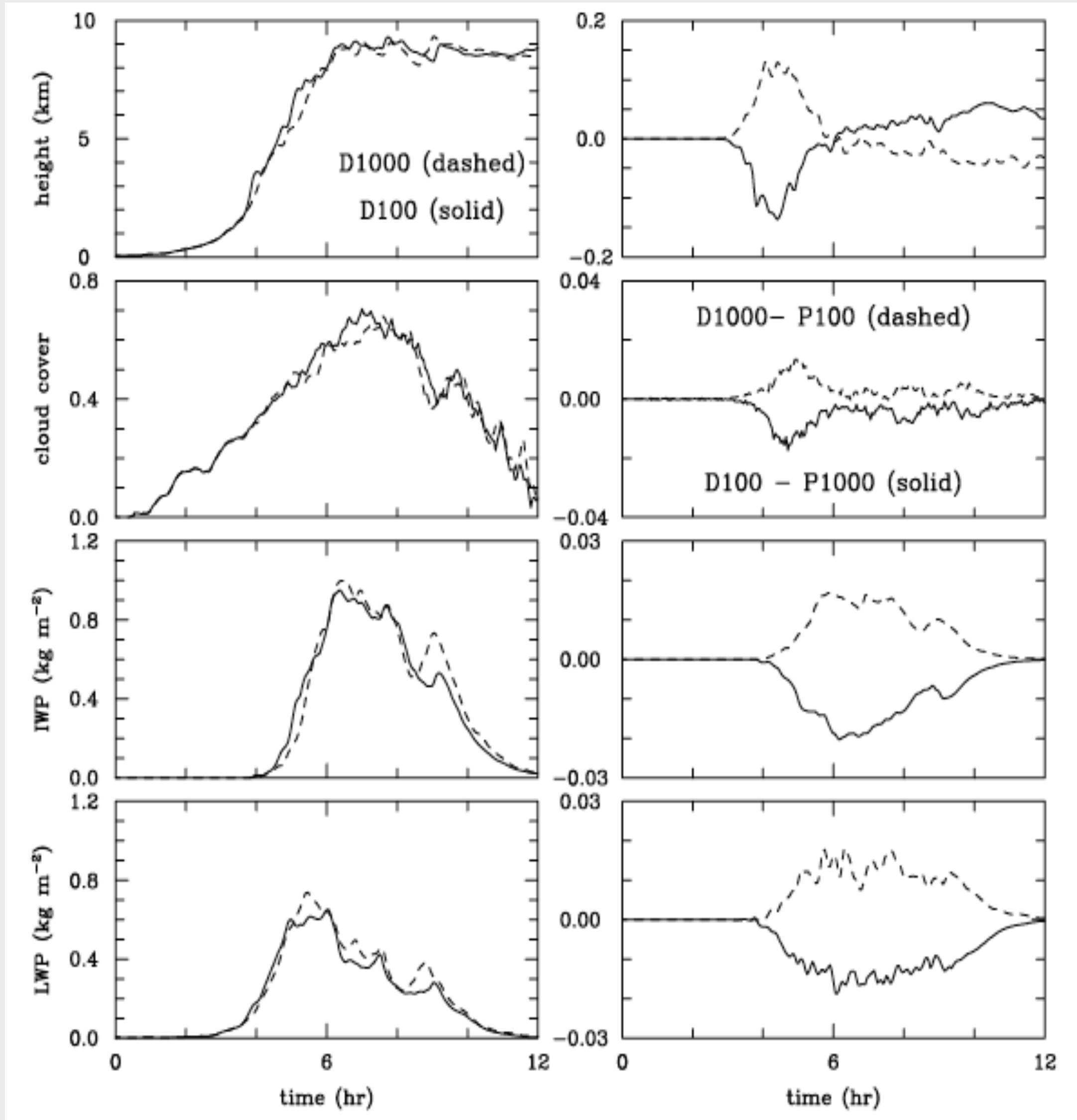
SIM

height of the center of mass of the condensate field

cloud cover

liquid water path

ice water path



D100; D1000

D100 – P1000
D1000 – P100

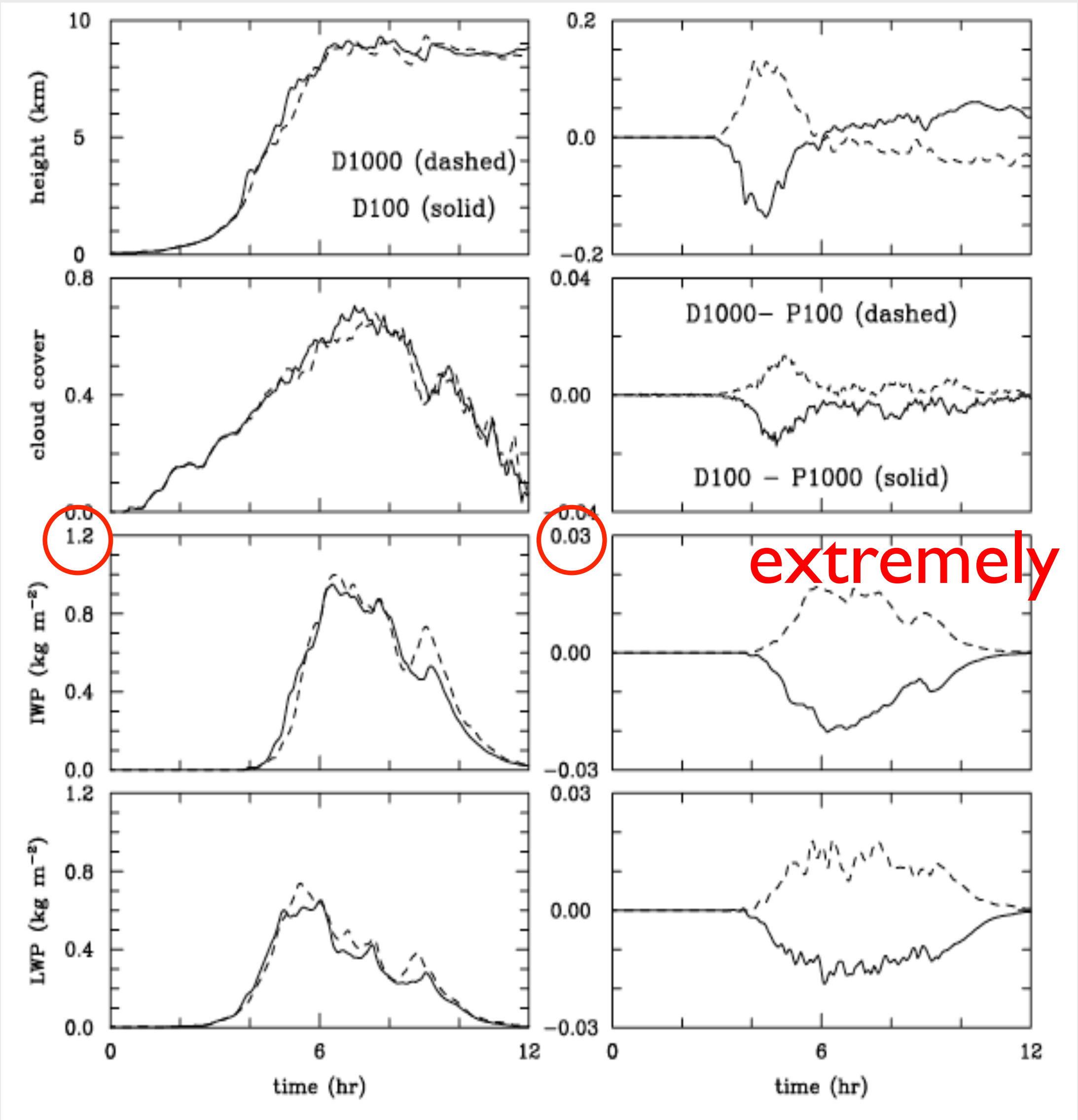
SIM

height of the center of mass of the condensate field

cloud cover

liquid water path

ice water path

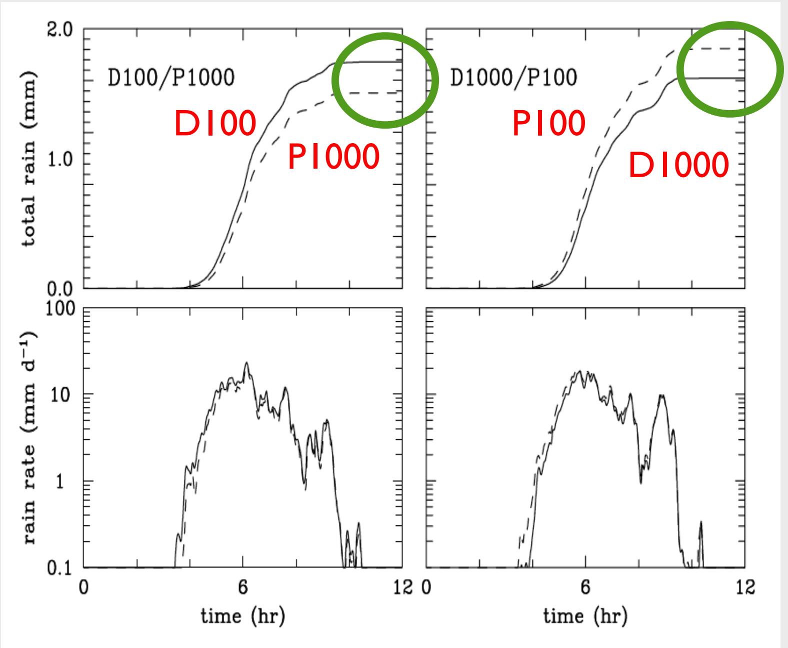


extremely accurate!

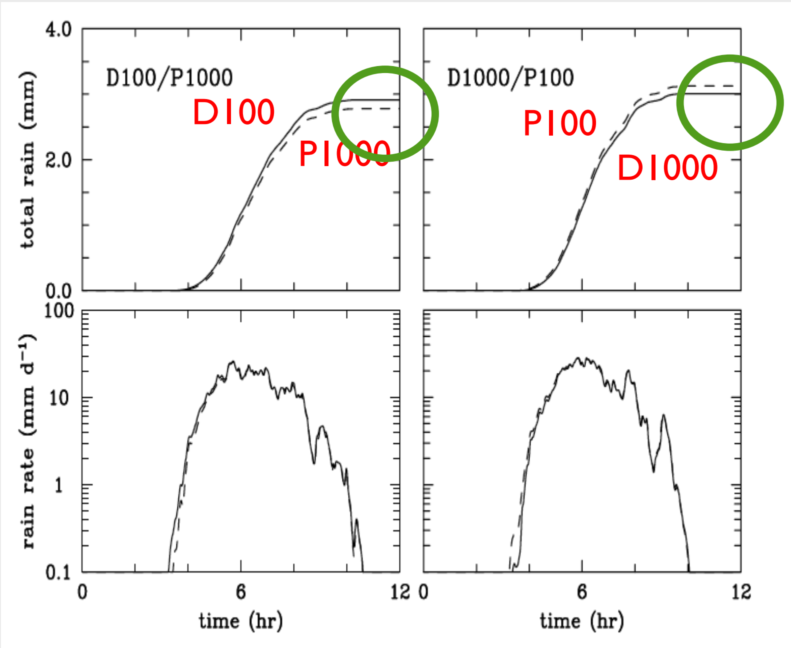
D100; D1000

D100 – P1000
D1000 – P100

SIM

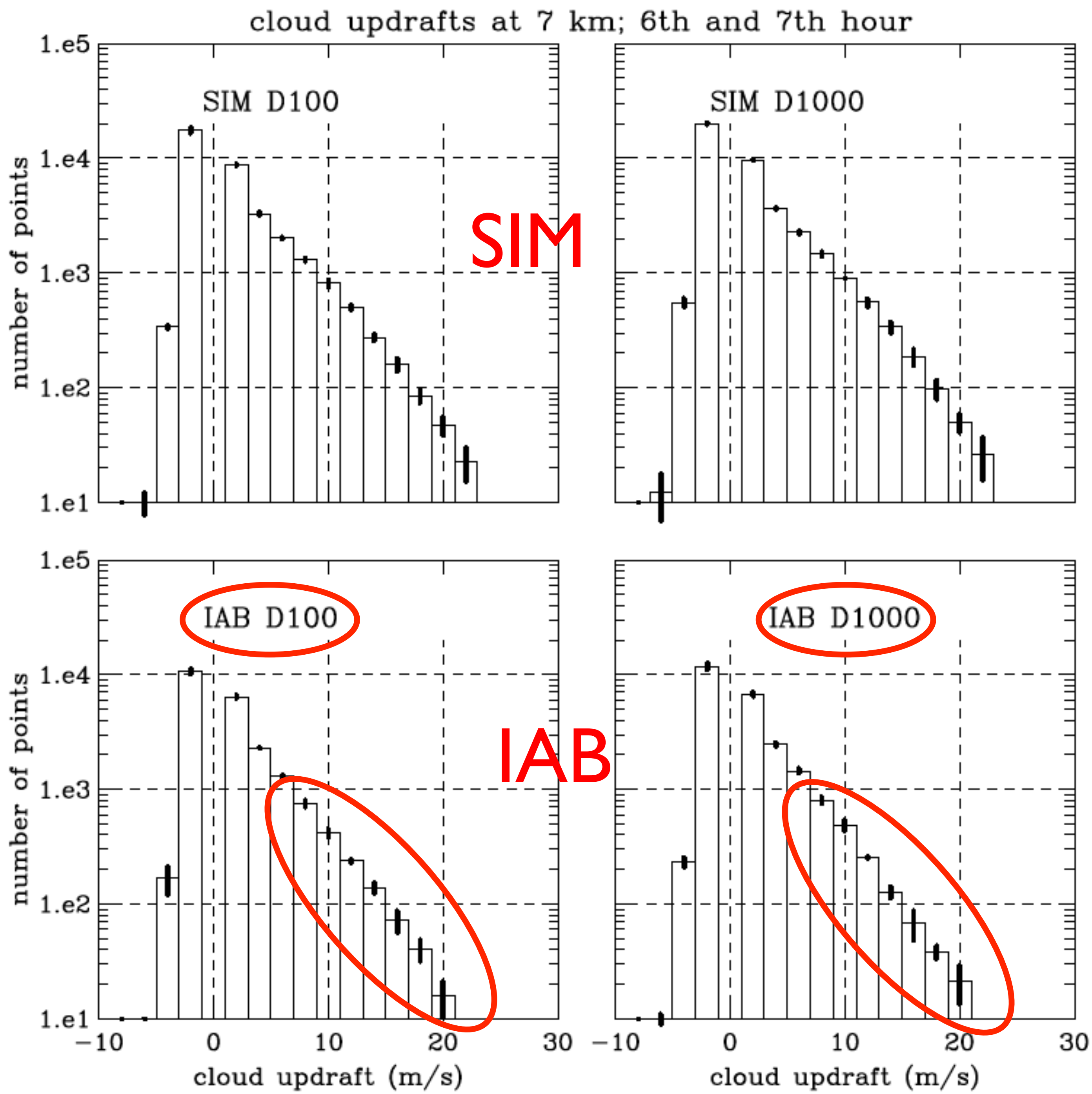


IAB



Pristine simulations still produce more rain…

Differences (D-P and P-D) are similar (except for the sign)…



cloud updrafts at 7 km; 6th and 7th hour
SIM D100
SIM D1000
SIM
IAB D100
IAB D1000
IAB
number of points
cloud updraft (m/s)
1.e5
1.e4
1.e3
1.e2
1.e1
−10
0
10
20
30

IAB

	12-hr rain accumulations (mm)	D ensemble mean, st. dev.
D100	2.91, 3.03, 2.79	2.91, 0.10
D1000	3.01, 2.90, 2.91	2.94, 0.09

IAB

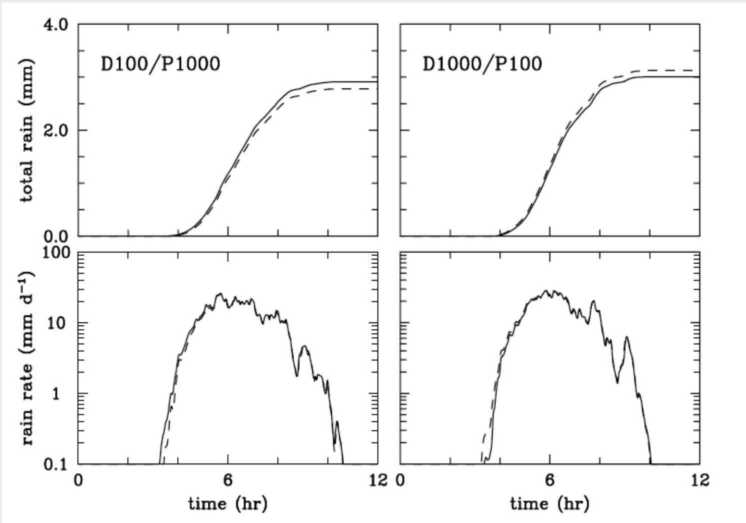
	12-hr rain accumulations (mm)	D ensemble mean, st. dev.
D100	2.91, 3.03, 2.79	2.91, 0.10
D1000	3.01, 2.90, 2.91	2.94, 0.09

?

IAB

	12-hr rain accumulations (mm)	D ensemble mean, st. dev.	D-P ensemble mean, st. dev.
D100	2.91, 3.03, 2.79	2.91, 0.10	0.12, 0.01
D1000	3.01, 2.90, 2.91	2.94, 0.09	-0.12, 0.01
P1000	2.78, 2.92, 2.67		
P100	3.12, 3.02, 3.03		

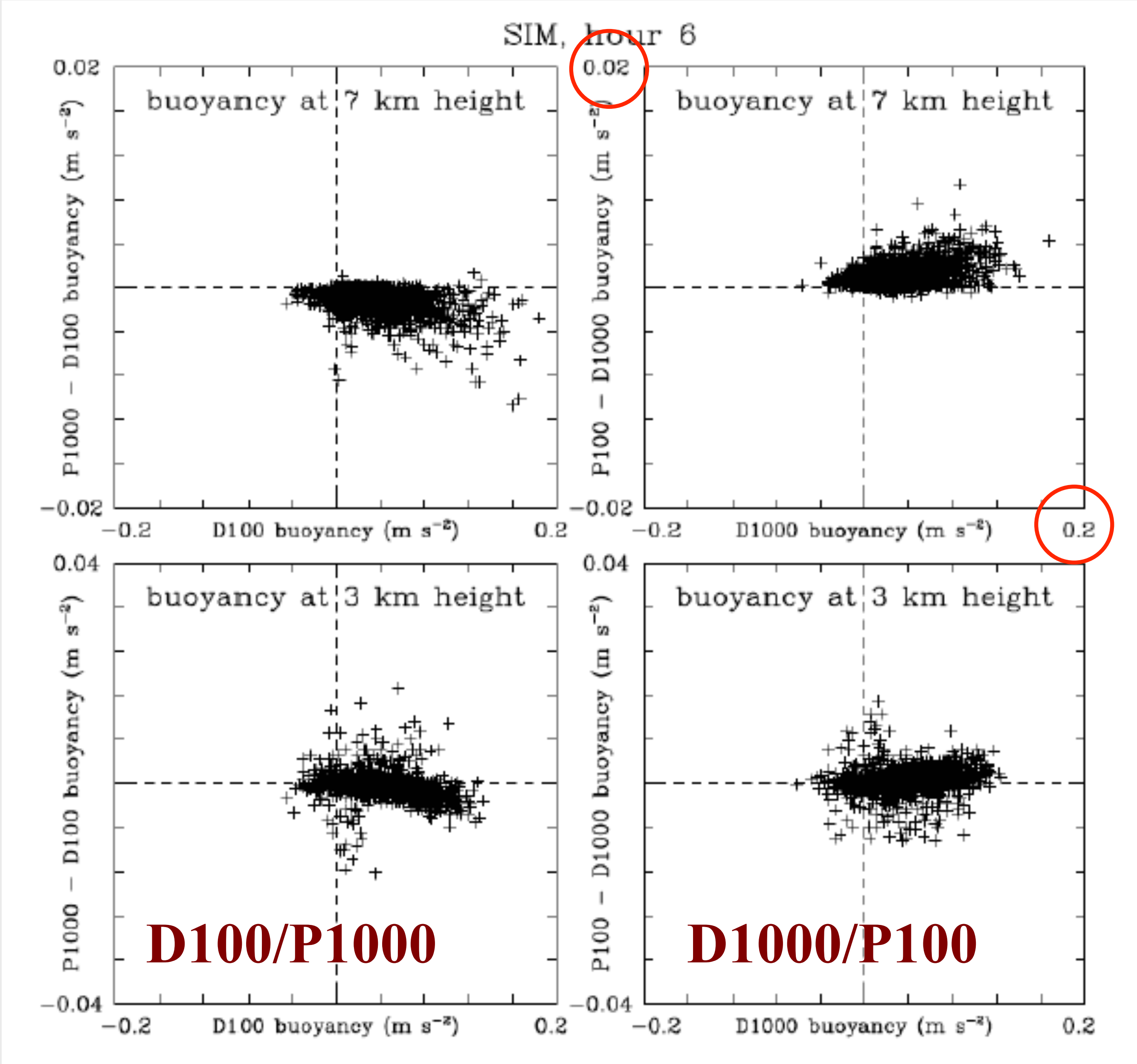
!



Comparing cloud updraft buoyancies in SIM D/P simulation:

7 km;
-12 degC

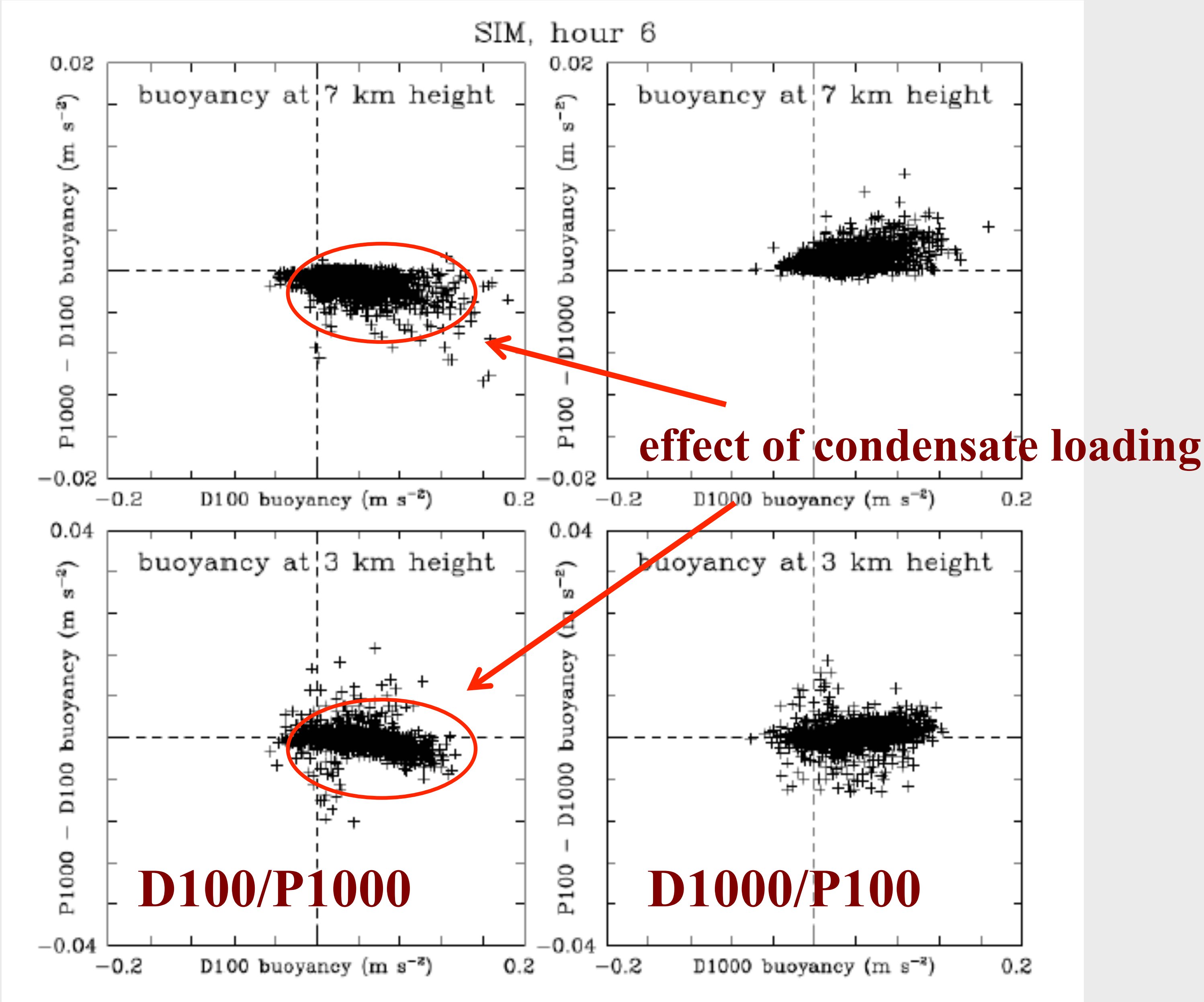
3 km;
9 degC



Comparing cloud updraft buoyancies in SIM D/P simulation:

7 km;
-12 degC

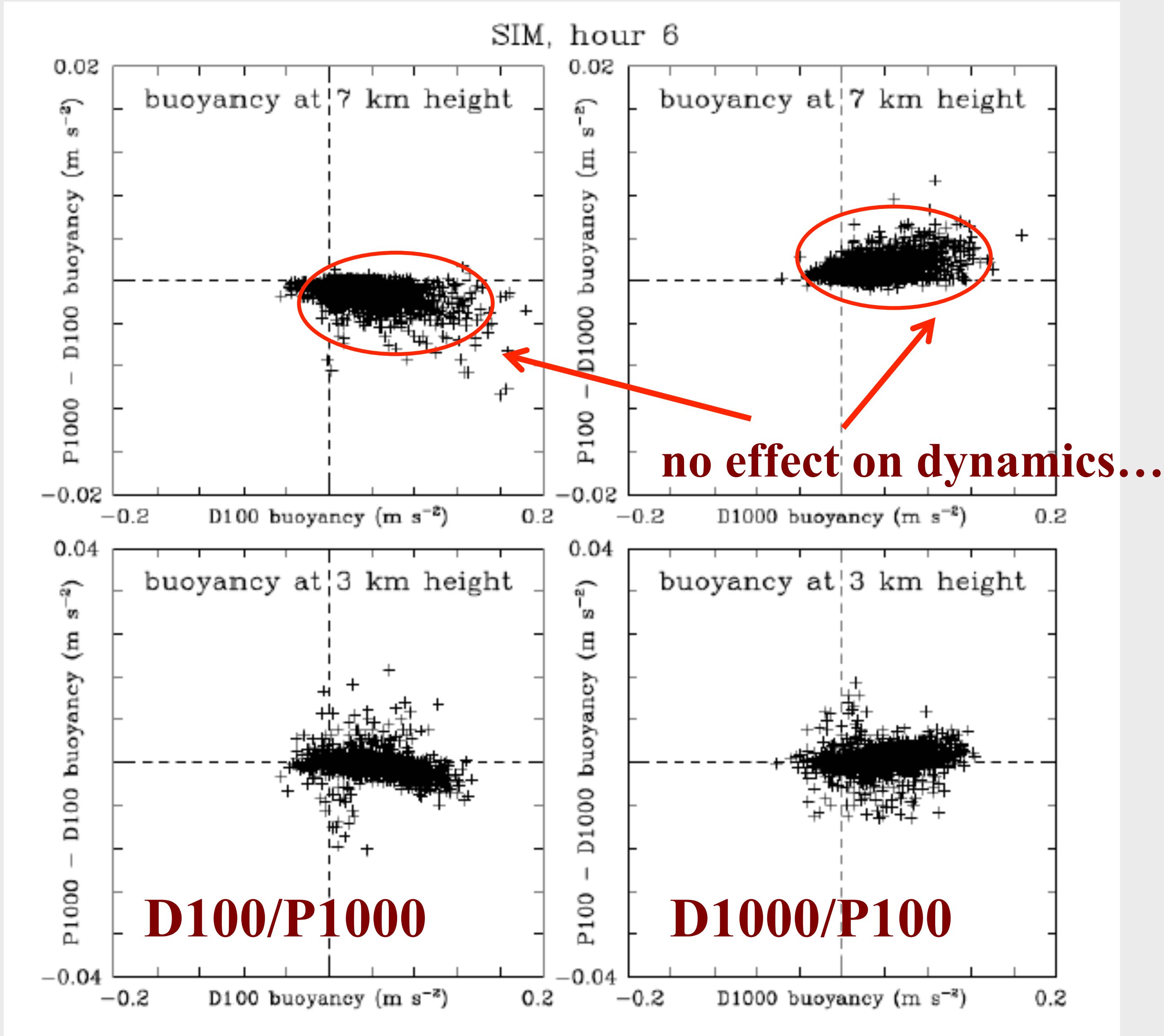
3 km;
9 degC



Comparing cloud updraft buoyancies in SIM D/P simulation:

7 km;
-12 degC

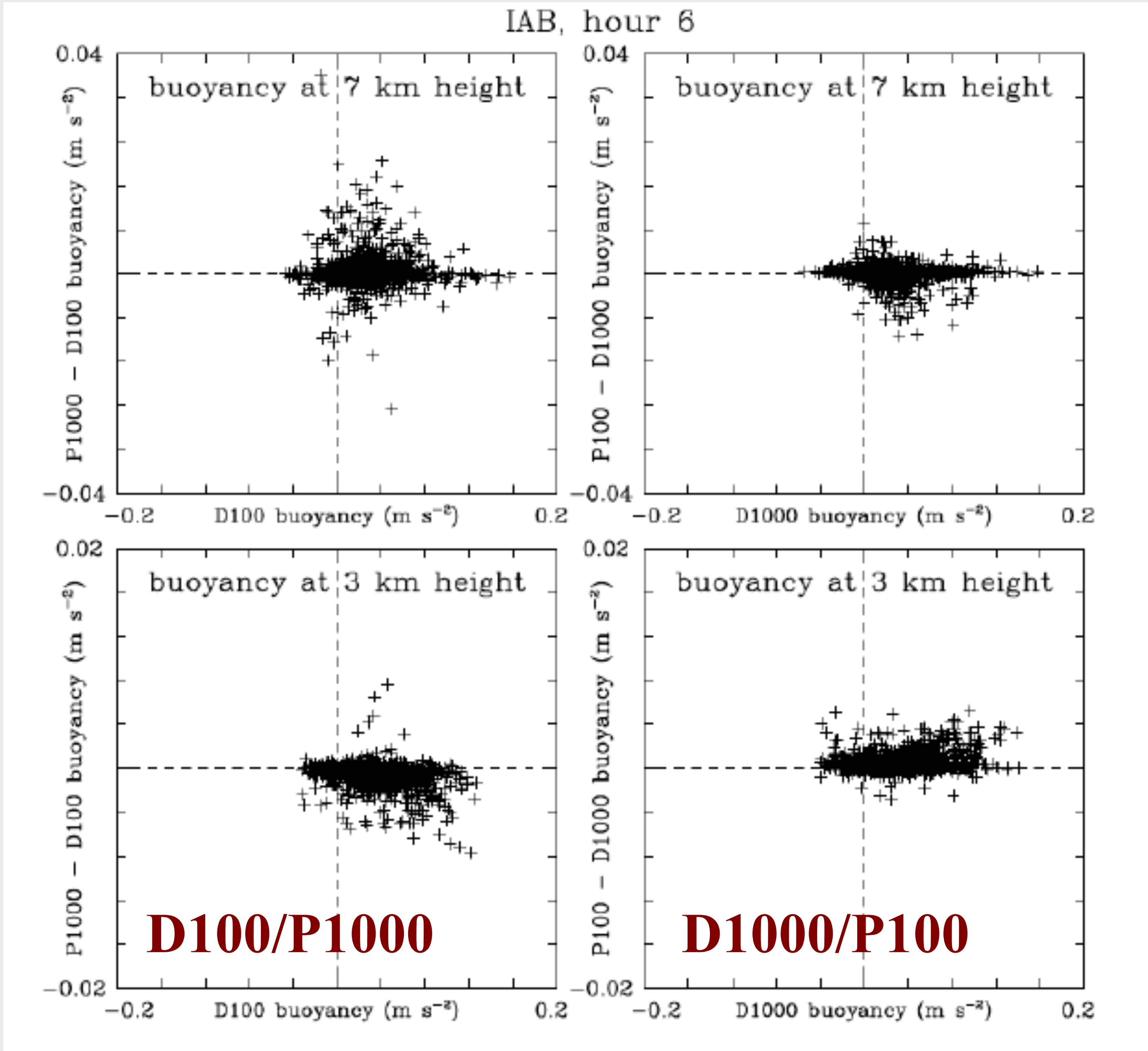
3 km;
9 degC



Comparing cloud updraft buoyancies in IAB D/P simulation:

7 km;
-12 degC

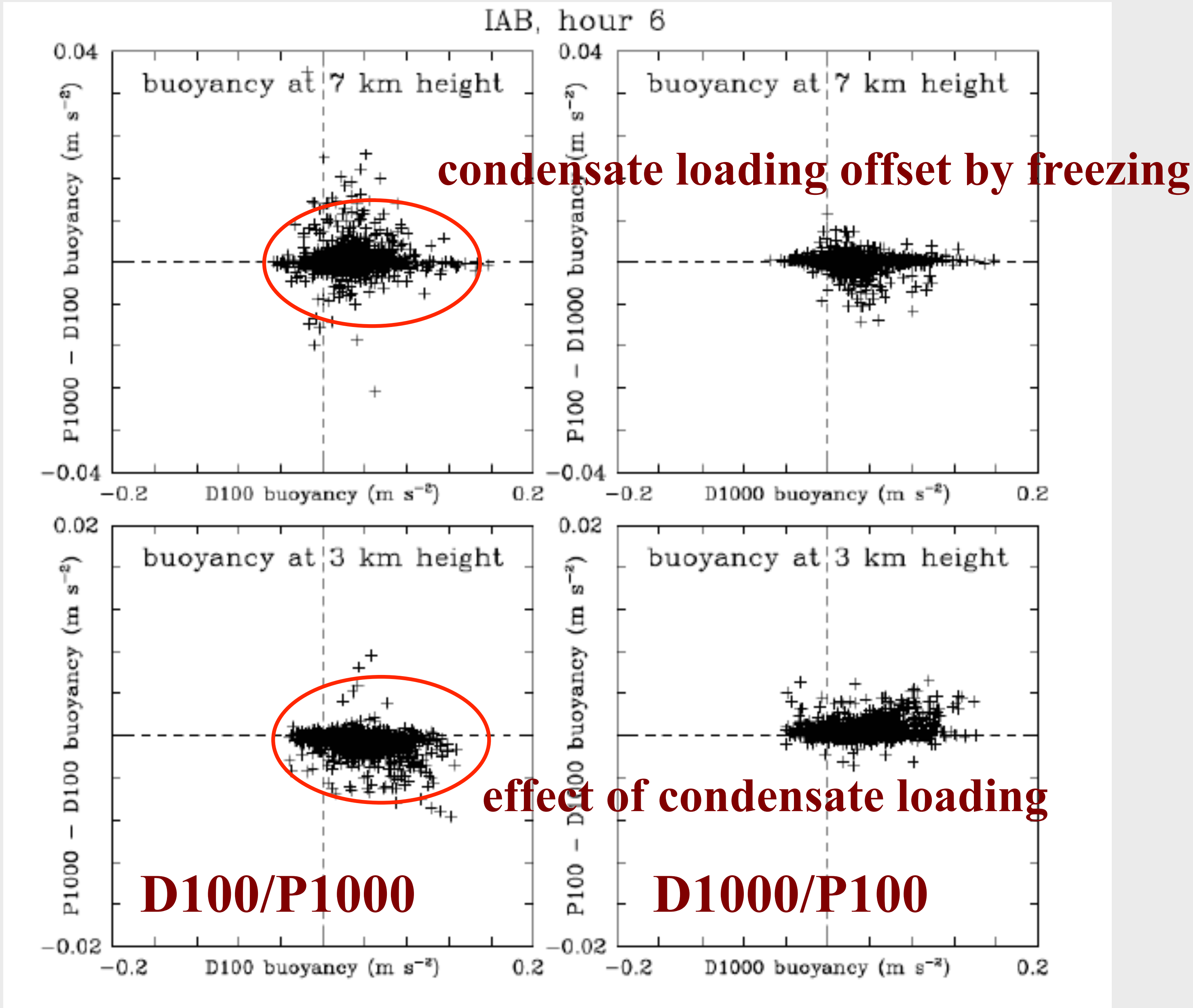
3 km;
9 degC

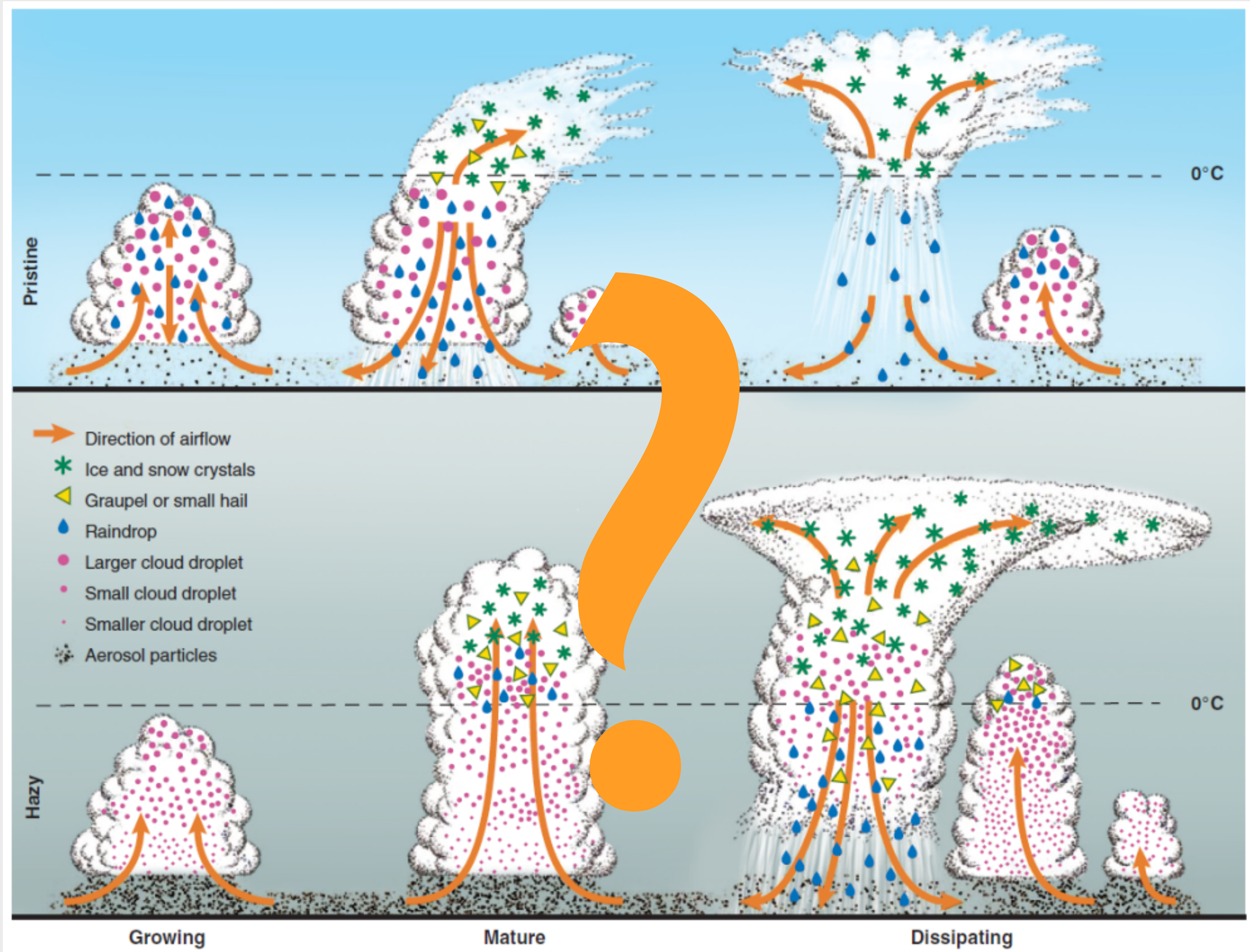


Comparing cloud updraft buoyancies in IAB D/P simulation:

7 km;
-12 degC

3 km;
9 degC





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

Conclusions:

1. **The piggybacking methodology allows confident assessment of impacts of cloud microphysical parameterizations. It decouples their effect from the impact on cloud dynamics.**

2. **Contrasting D/P and P/D simulations allows investigating the impact on the dynamics. The fact that the D-P differences are similar (except for the sign) between D/P and P/D implies small impact on the cloud dynamics as in the collection C2. Large differences imply significant impact as in the collection C1.**

3. **For shallow convection, the methodology allows assessing microphysical impacts with unprecedented accuracy.**

4. **For deep convection, the methodology calls into question the dynamic basis of convective invigoration in polluted environments.**