Atmospheric aerosols, cloud microphysics, and climate

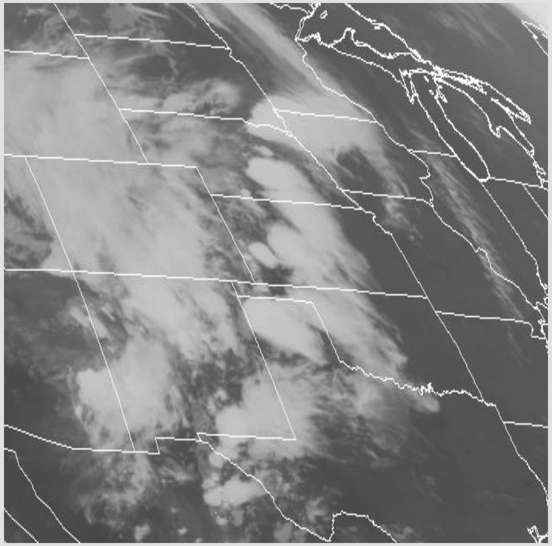
Wojciech W. Grabowski

National Center for Atmospheric Research,
Boulder, Colorado, USA

Clouds and climate: the range of scales...

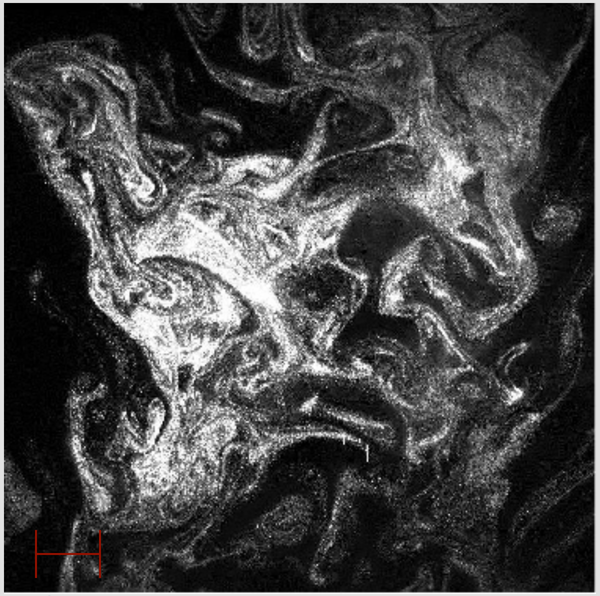
1,000 km

Mesoscale convective systems over US



Small cumulus clouds

Mixing in laboratory cloud chamber



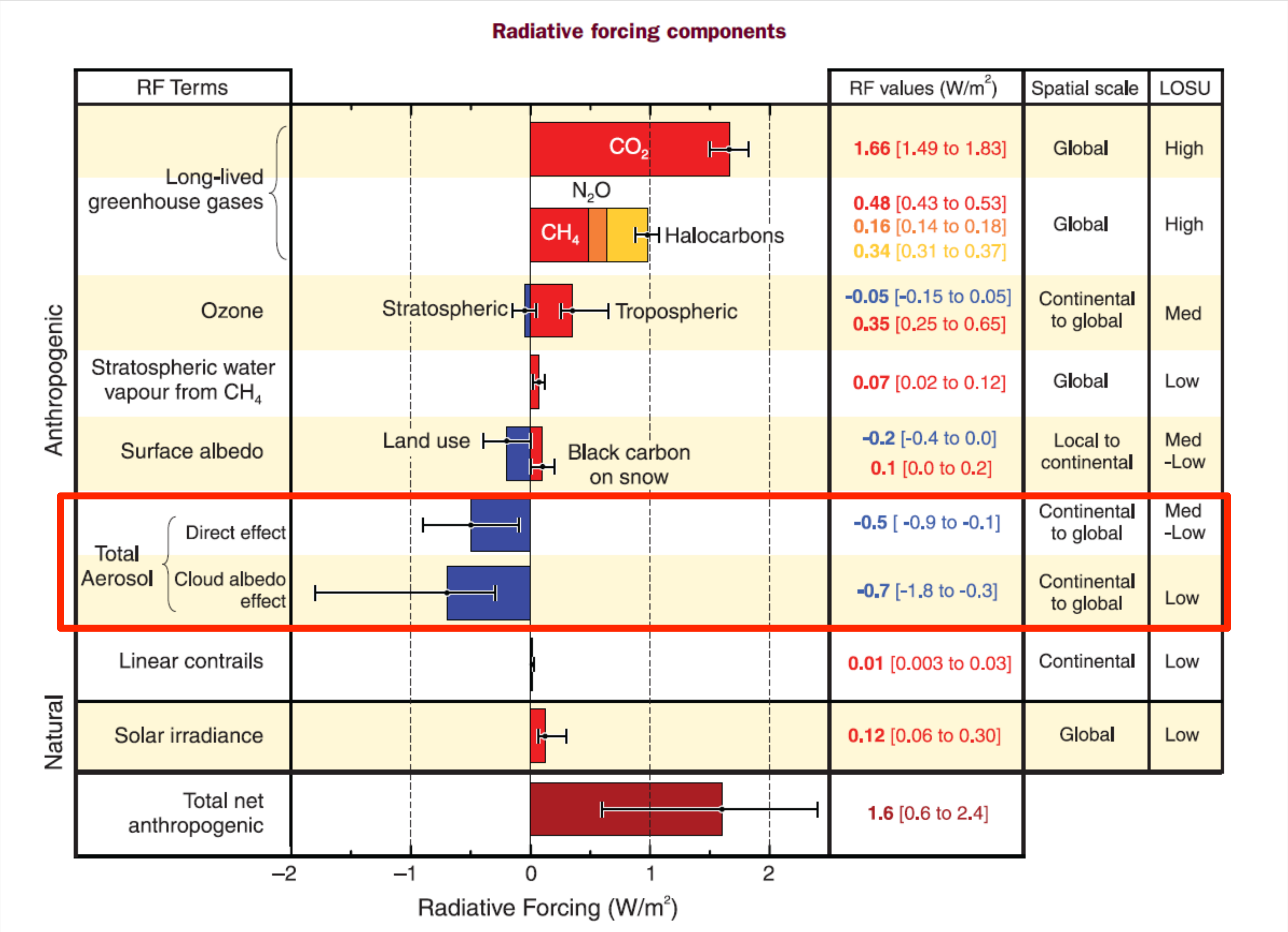
10 cm

Why do we care about aerosols in the climate system?

Direct impact on the transfer of solar and Earth thermal radiation of suspended aerosols;

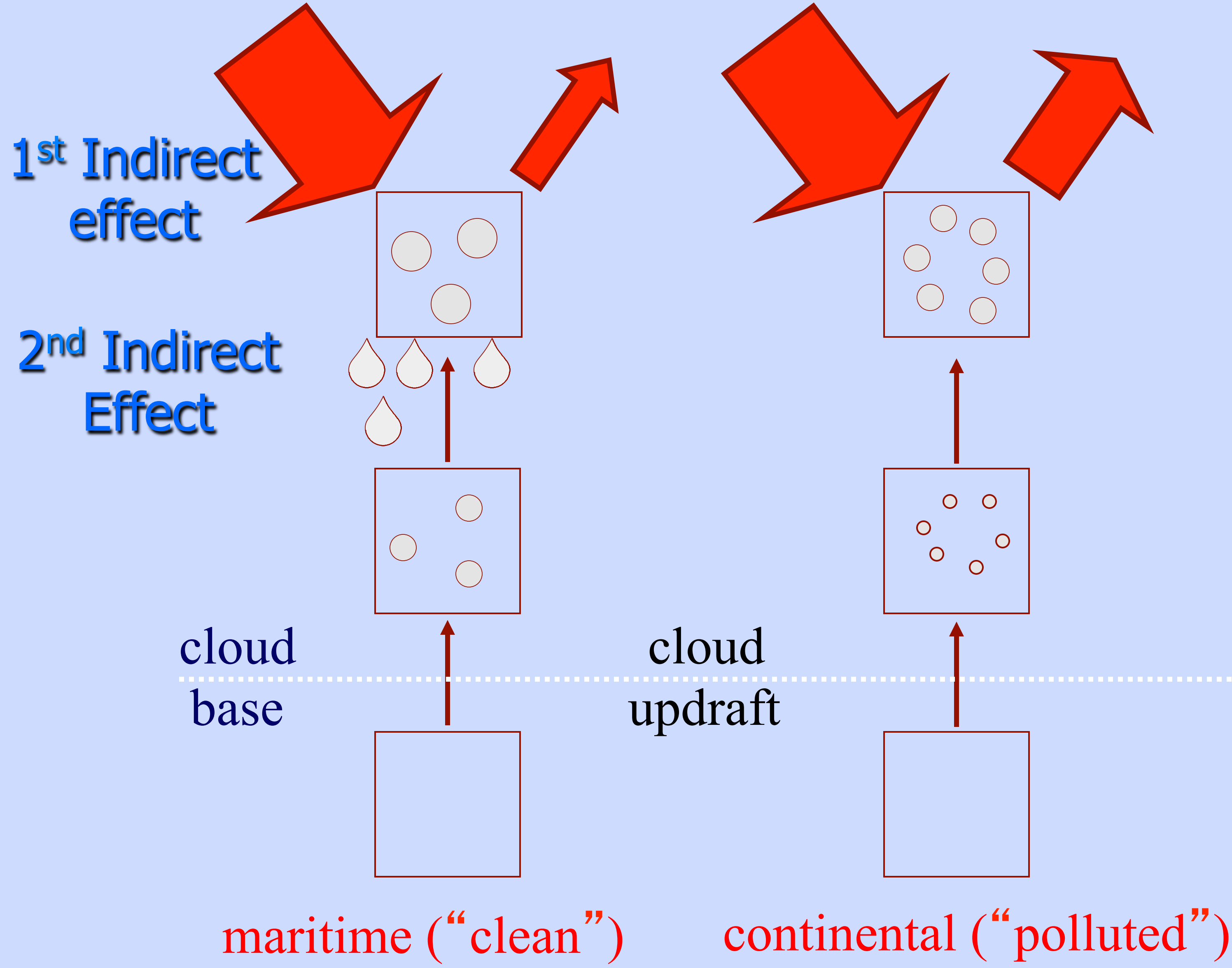
Indirect effects: impact on cloud processes (and thus on radiation and hydrological cycle);

Sink of many important chemical species.

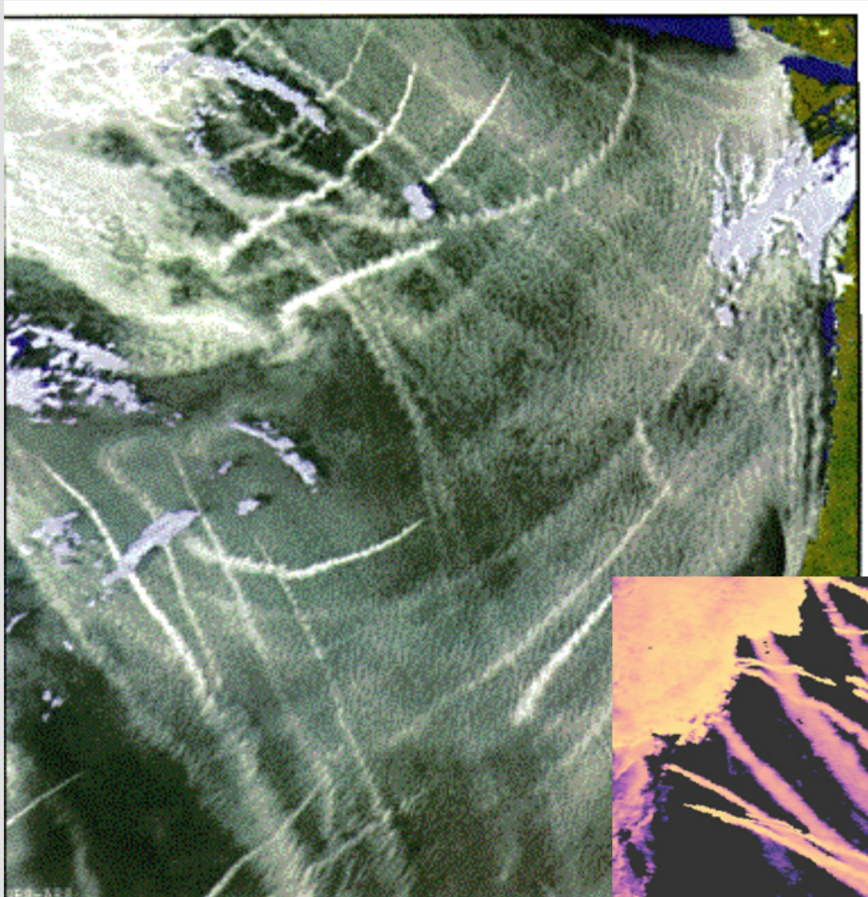


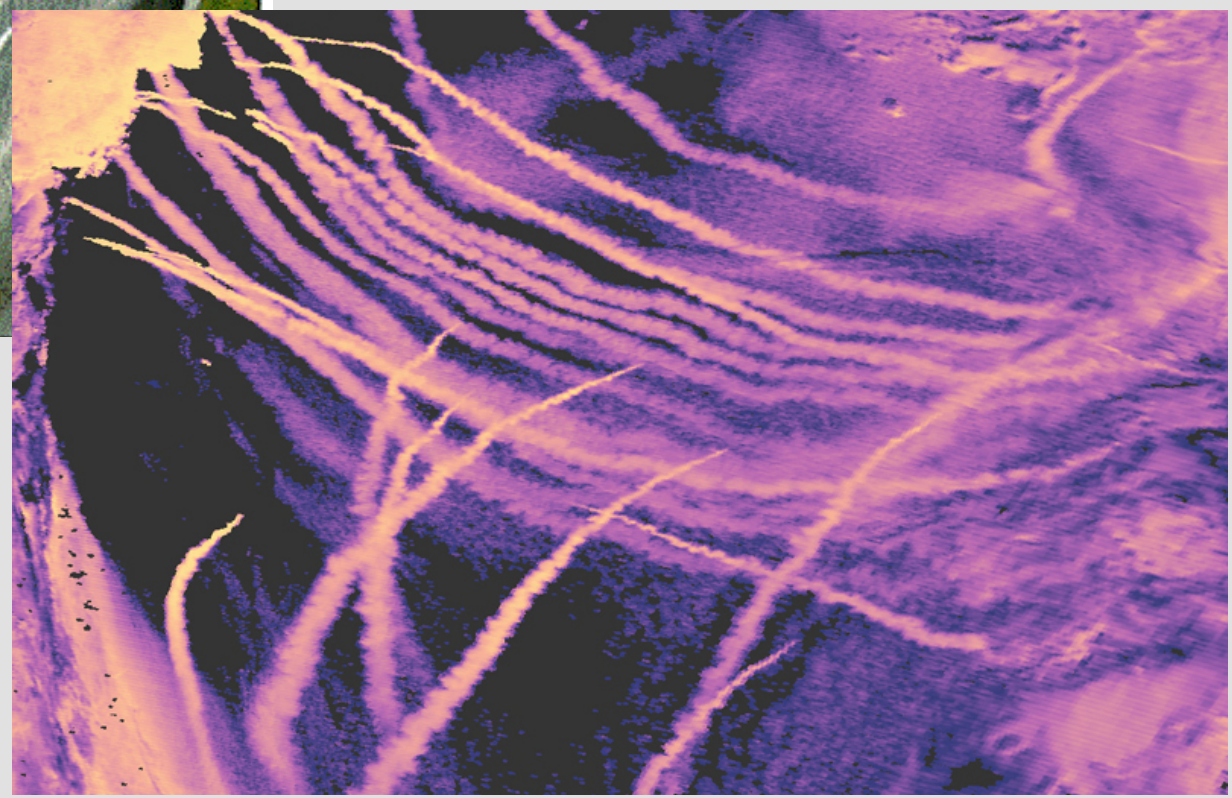
IPCC 2007; Synthesis Report

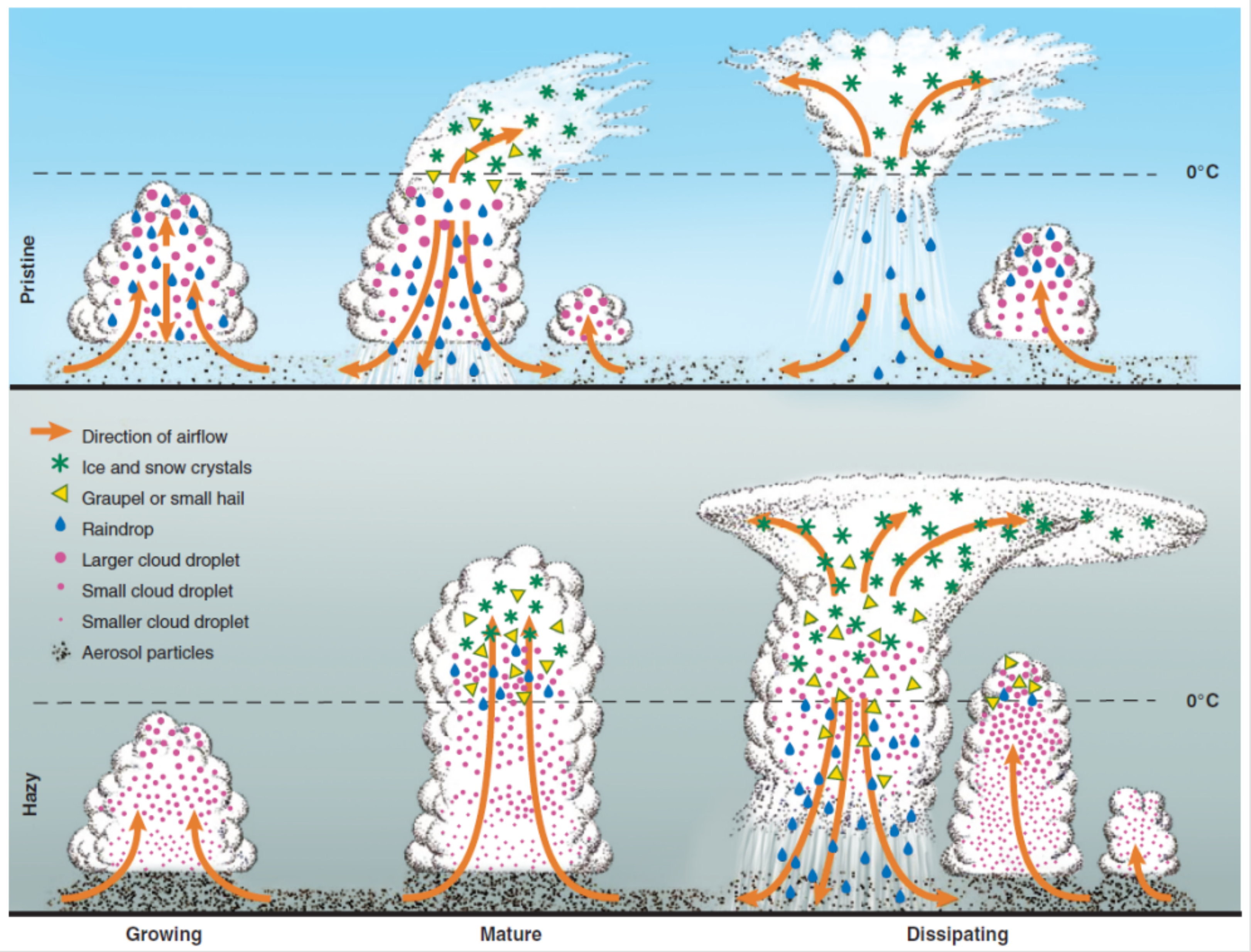
Indirect aerosol effects (warm rain only)



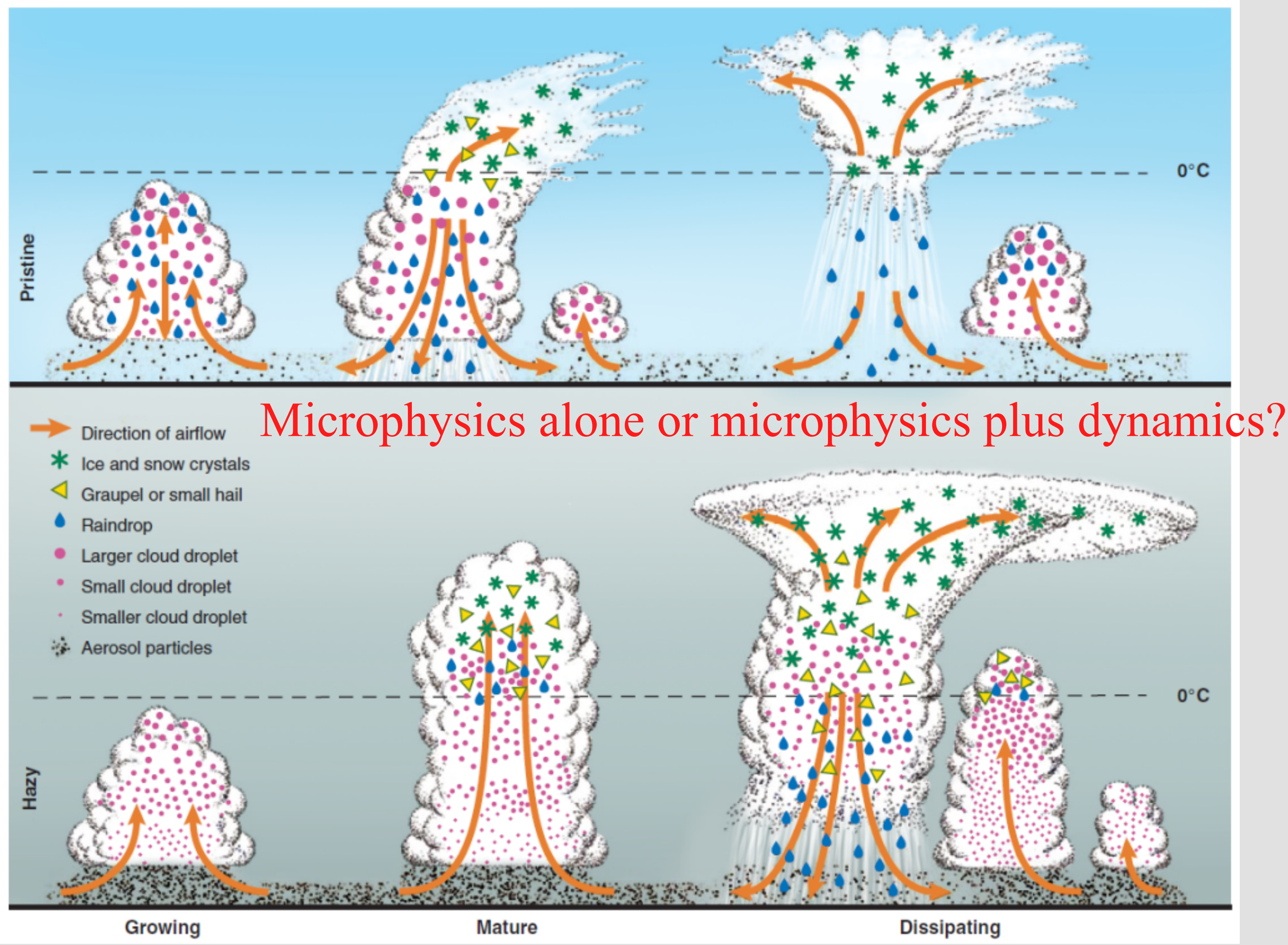
Ship tracks: spectacular example of indirect effects caused by ship exhausts acting as CCN (long-lasting, feedback on cloud dynamics?)







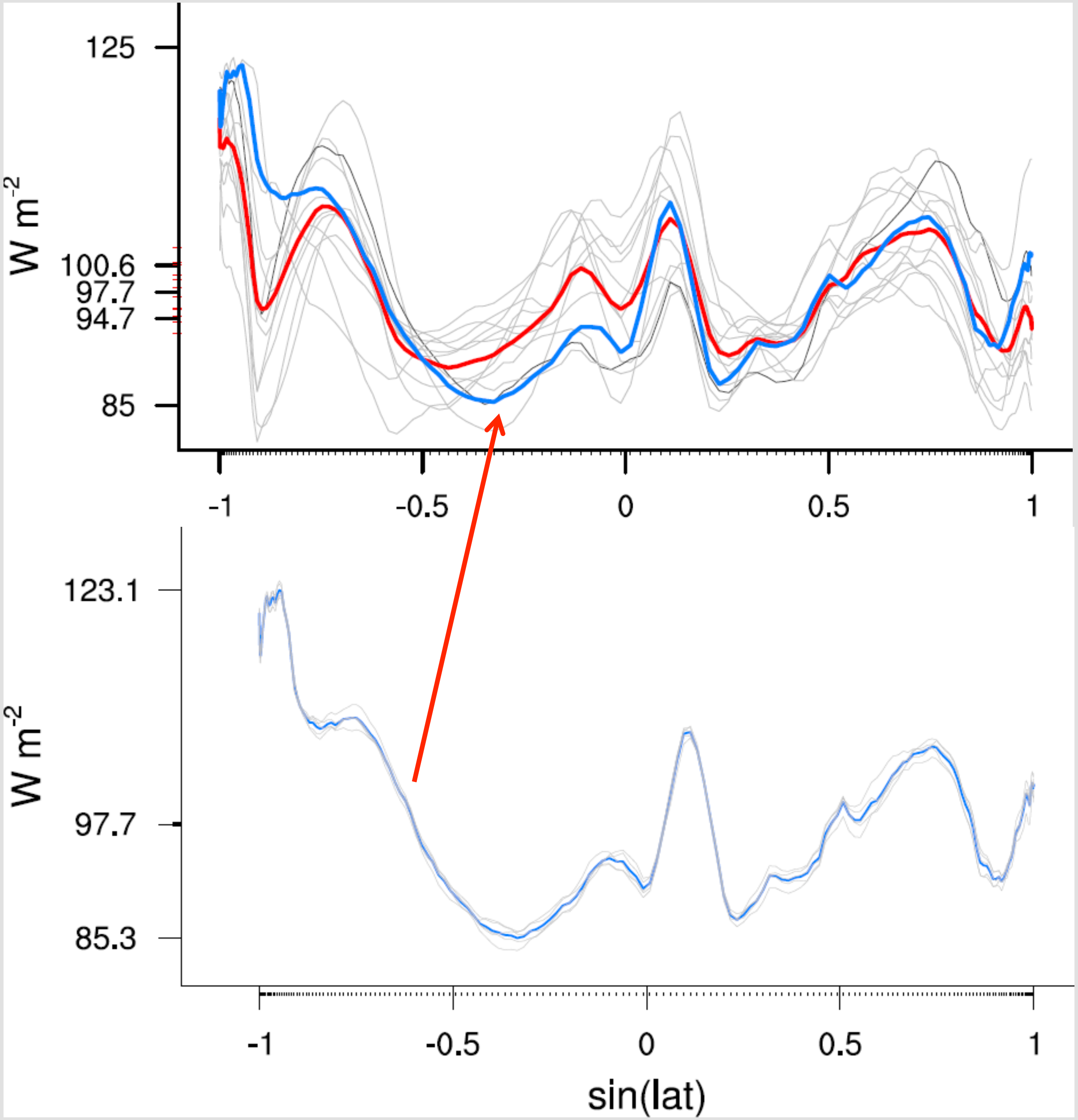
Rosenfeld et al. *Science*, 2008
"Flood or Drought: How Do Aerosols Affect Precipitation?"



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

Why indirect aerosol effects 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!



Simulated year-to-year variability of meridional distribution of reflected solar radiation from IPCC model ensemble.

Annual variability of observed reflected solar radiation from satellite (CERES): 4 years of data.

…parameterized clouds…

(courtesy of Bjorn Stevens)

Issues:

-Current observational techniques do not allow untangling relationships between aerosols and clouds on spatial and temporal scales relevant to climate:

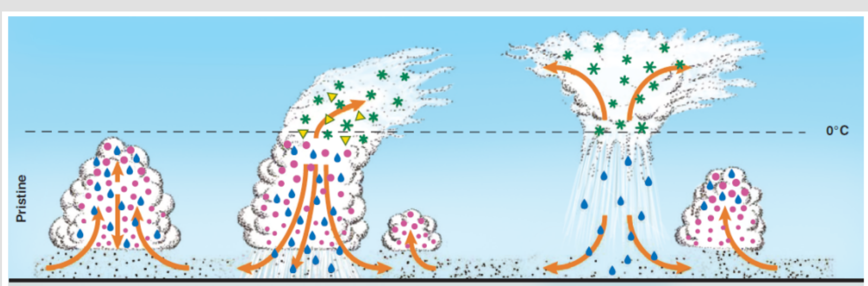
correlation versus causality

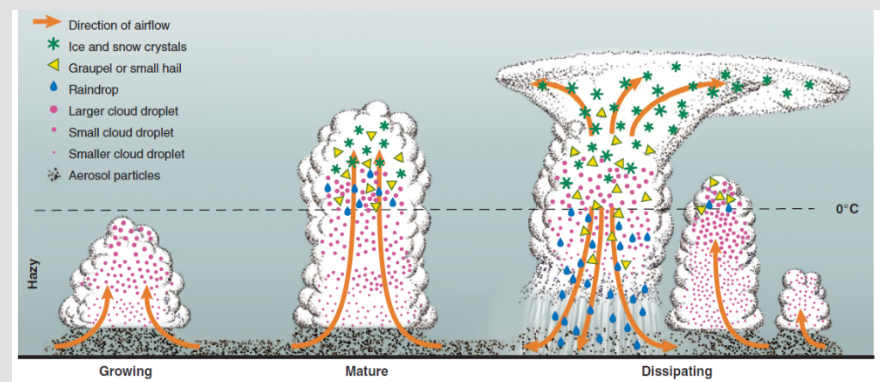
-Traditional general circulation models misrepresent the impact of aerosols on climate

dynamic response at wrong scales

correlation versus causality:

satellites observing aerosols and clouds…





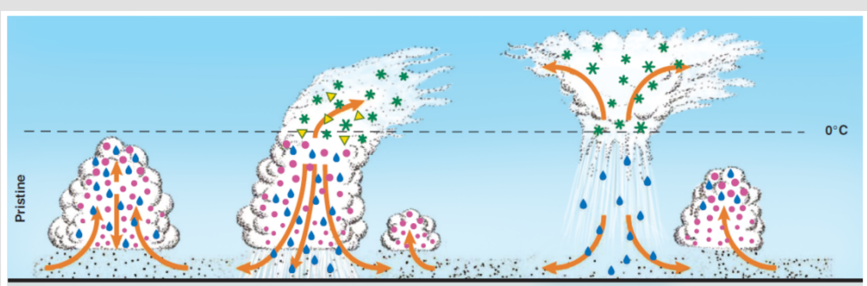
clean

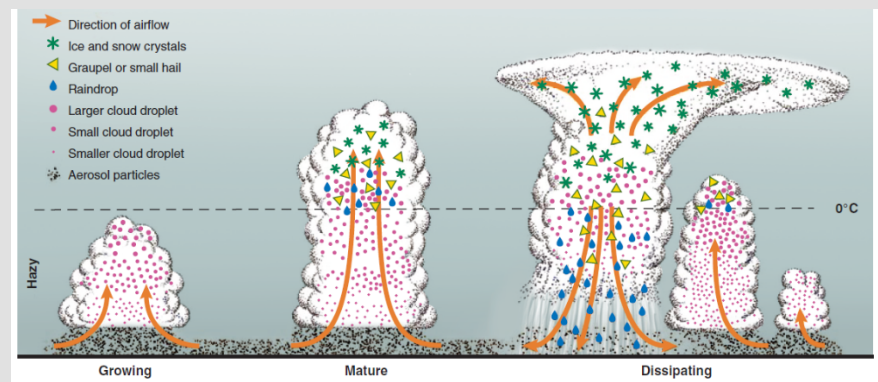
polluted

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 are more accidents at that time, am I responsible for the increase?

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…).

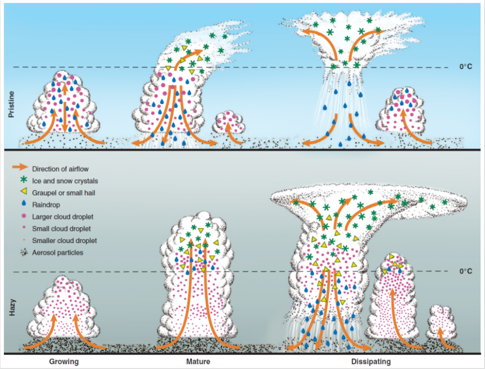
If I drive to the office in the morning and there is more accidents at that time, am I responsible for the increase?

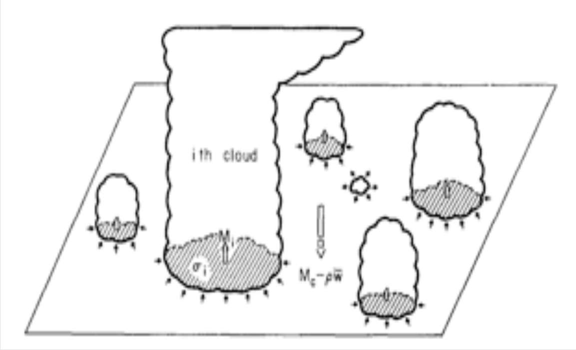
And - perhaps more importantly - these large-scale advection patterns (“meteorology”) have by far more significant impact on clouds…

single-cloud reasoning

versus

cloud-ensemble reasoning

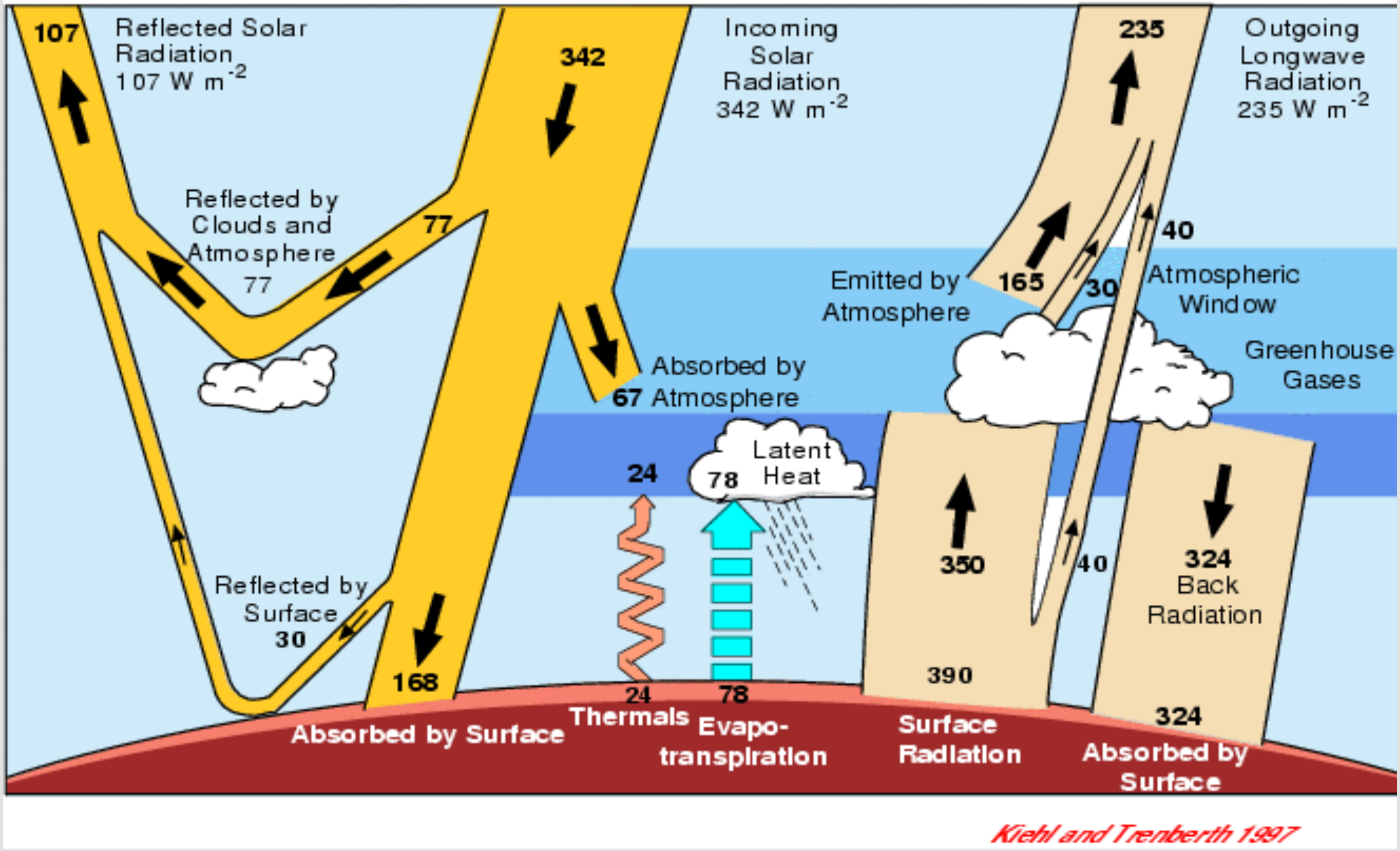




Arguably, only the cloud-ensemble reasoning is appropriate once climate implications are considered.

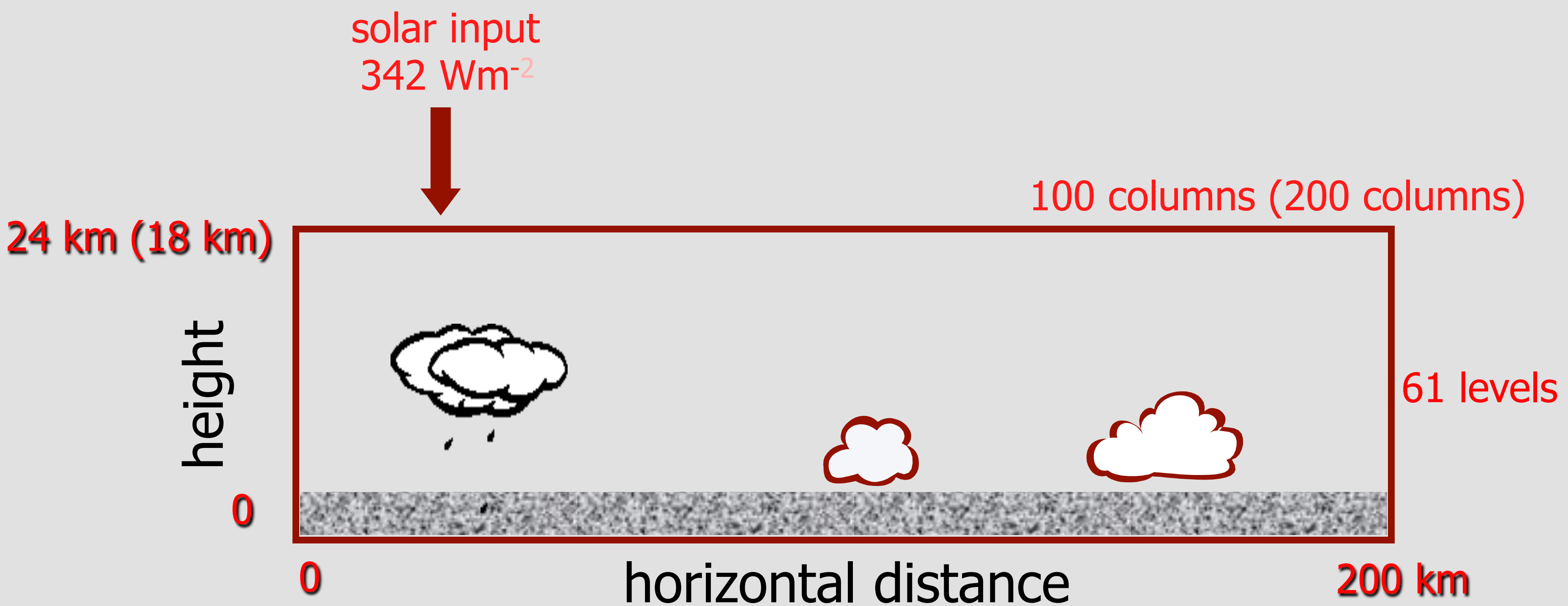
Another way to think about the problem: single-process reasoning (e.g., microphysics) versus the system-dynamics approach. Only the latter includes all the feedbacks and forcings in the system.

Convective-radiative quasi-equilibrium is the simplest system that includes interactions between clouds and their environment (“system-dynamics approach”).



The Earth annual and global mean energy budget

Radiative-convective quasi-equilibrium mimicking planetary energy budget using a 2D cloud-resolving model



Surface temperature = 15° C
Surface “relative humidity” = 85%
Surface albedo = 0.15

Grabowski *J. Climate* 2006, Grabowski and Morrison *J. Climate* 2011

Numerical model:

- Dynamics: 2D babyEULAG model (used as the super-parameterization model; Grabowski 2001) with simple bulk microphysics (warm-rain plus ice; Grabowski 1998)
- Radiation: NCAR's Community Climate System Model (CCSM) (Kiehl et al 1994) in the Independent Column Approximation (ICA) mode
- 100 columns (Δx=2km) and 61 levels (stretched; 12 levels below 2 km; top at 24 km)

Grabowski *J. Climate* 2006

Simulations with the double-moment bulk microphysics:

Warm-rain scheme of Morrison and Grabowski (JAS 2007, 2008a) predicts concentrations and mixing ratios of cloud water and rain water; relatively sophisticated CCN activation scheme, contrasting pristine and polluted CCN spectra, and better representation of the homogeneity of subgrid-scale mixing.

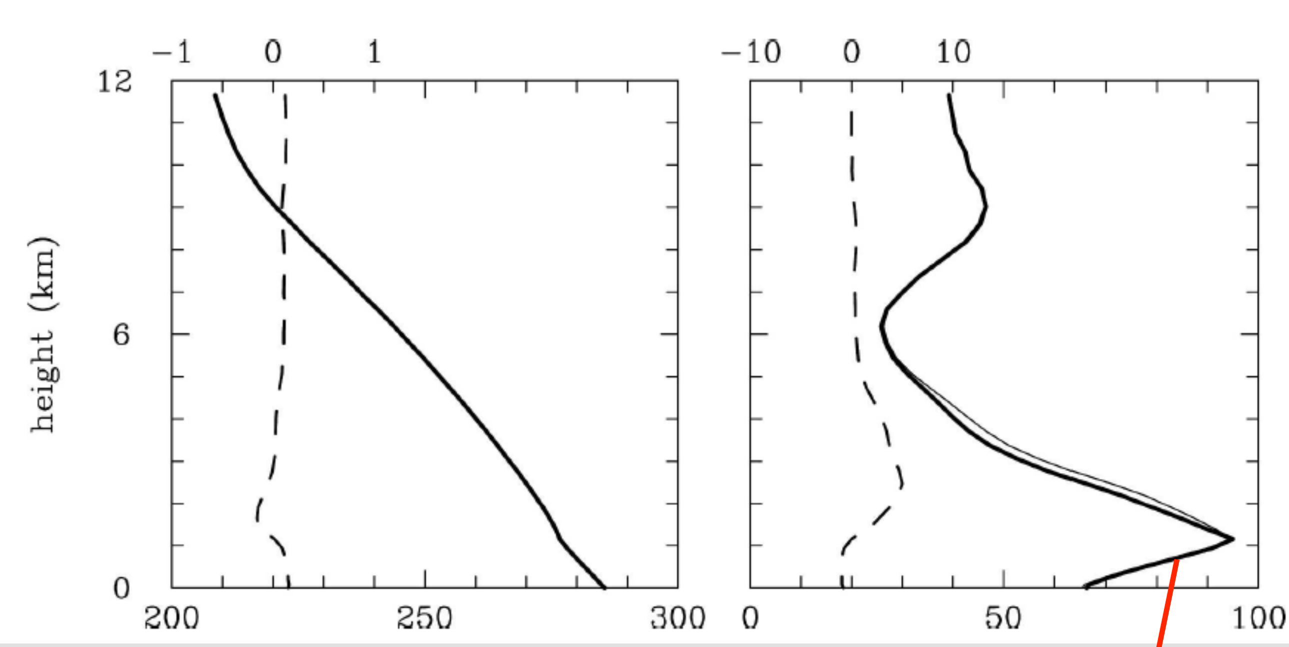
Ice scheme of Morrison and Grabowski (JAS 2008b) predicts concentrations and two mixing ratios of ice particles to keep track of mass grown by diffusion and by riming; heterogeneous and homogeneous ice nucleation with the same IN characteristics for pristine and polluted conditions.

No direct aerosol effects, as in Grabowski (2006).

Grabowski
***J. Climate* 2006**

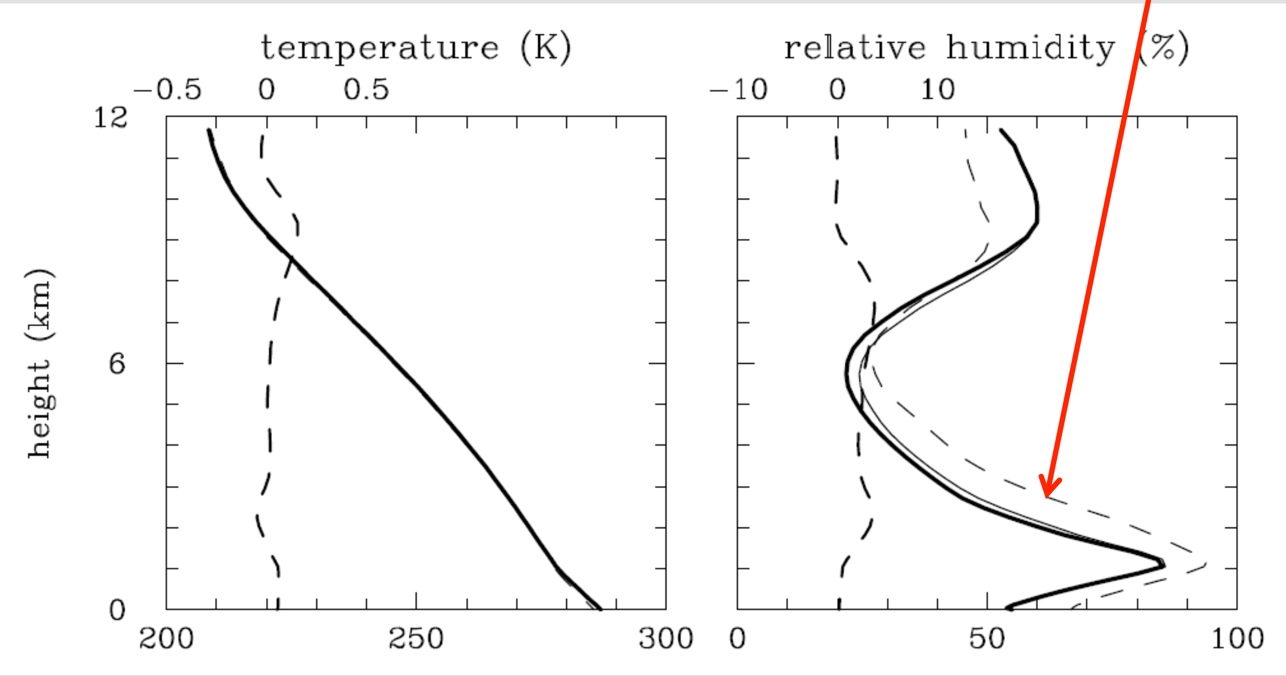
pristine: N_c=100 per cc
polluted: N_c=1,000 per cc

Thin: polluted
Thick: pristine
Dashed: polluted-pristine



Grabowski and Morrison
***J. Climate* 2011**

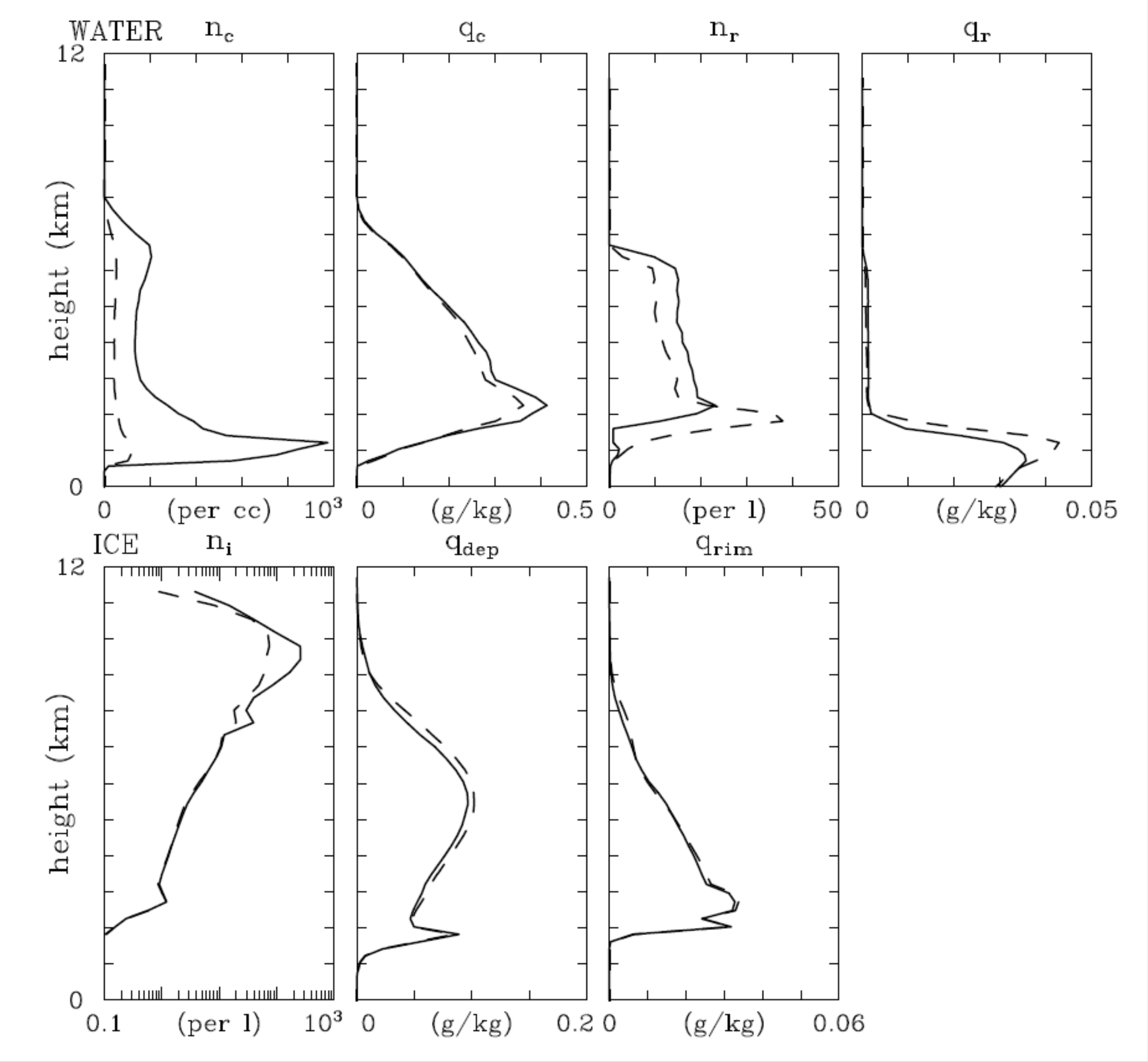
pristine: N_{CCN}=200 per cc
polluted: N_{CCN}=2,000 per cc



Cloud water and drizzle/rain fields

Solid: polluted
Dashed: pristine

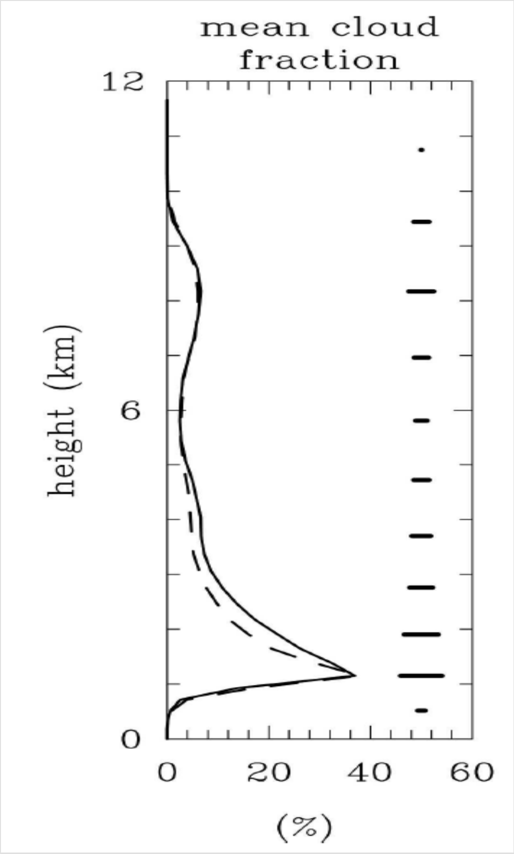
Ice field

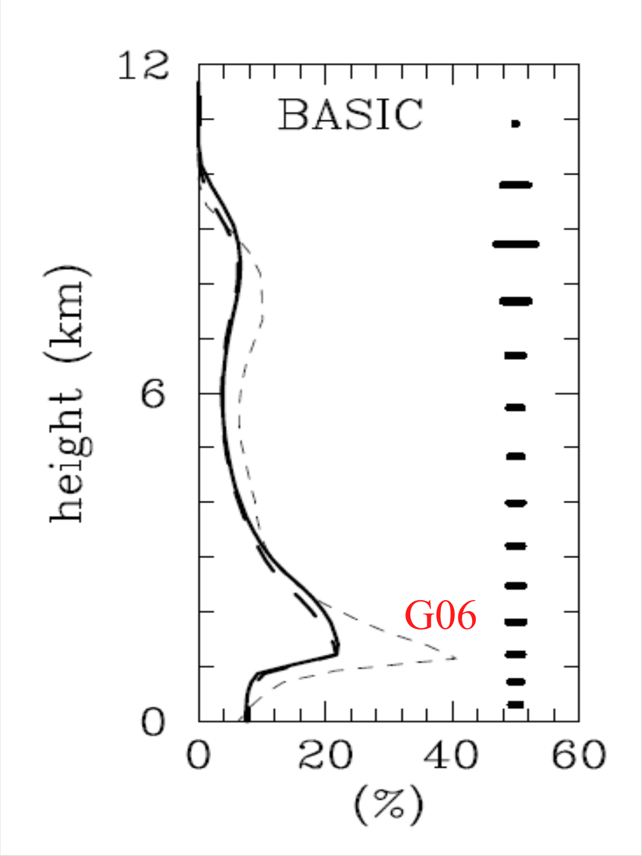


Grabowski and Morrison
***J. Climate* 2011**

Grabowski
***J. Climate* 2006**

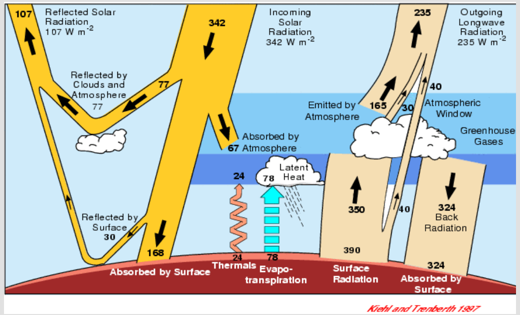
Grabowski and Morrison
***J. Climate* 2011**





Solid: polluted
Dashed: pristine
Horizontal bars: standard deviation of temporal evolution
(measure of statistical significance of the difference)

	PRISTINE	PRISTINE	POLLUTED	POLLUTED	KT97
	h	ei	h	ei	
Net TOA shortwave flux ($W\,m^{-2}$)	256 (3)	257 (3)	247 (4)	248 (5)	235
G06 results	*225 (12)*	*245 (6)*	*201 (10)*	*225 (9)*	
TOA albedo	0.25 (0.01)	0.25 (0.01)	0.28 (0.01)	0.27 (0.01)	0.31
G06 results	*0.34 (0.03)*	*0.28 (0.03)*	*0.41 (0.03)*	*0.34 (0.03)*	
OLR ($W\,m^{-2}$)	251 (4)	252 (4)	247 (8)	246 (12)	235
G06 results	*242 (3)*	*243 (3)*	*240 (3)*	*242 (3)*	
Radiative cooling of troposphere ($W\,m^{-2}$)	-94 (4)	-94 (4)	-93 (8)	-91 (12)	-102
G06 results	*-101 (4)*	*-100 (5)*	*-101 (4)*	*-99 (4)*	
Solar flux absorbed at surface ($W\,m^{-2}$)	202 (4)	204 (3)	193 (5)	194 (6)	168
G06 results	*163 (11)*	*184 (8)*	*141 (12)*	*164 (10)*	
Surface net longwave ($W\,m^{-2}$)	96 (2)	96 (2)	93 (3)	93 (3)	66
G06 results	*73 (5)*	*73 (6)*	*70 (5)*	*73 (5)*	
Surface sensible heat flux ($W\,m^{-2}$)	10 (1)	10 (1)	9 (1)	9 (1)	24
G06 results	*20 (2)*	*20 (1)*	*19 (1)*	*18 (2)*	
Surface latent heat flux ($W\,m^{-2}$)	84 (1)	84 (1)	82 (1)	81 (1)	78
G06 results	*73 (2)*	*73 (2)*	*75 (2)*	*74 (2)*	
Surface precipitation ($W\,m^{-2}$)	83 (19)	83 (21)	82 (20)	81 (20)	78
G06 results	*69 (33)*	*70 (29)*	*72 (28)*	*70 (32)*	
Surface energy budget ($W\,m^{-2}$)	13 (3)	15 (3)	9 (4)	11 (5)	0
G06 results	*-2 (7)*	*17 (5)*	*-23 (9)*	*-2 (7)*	

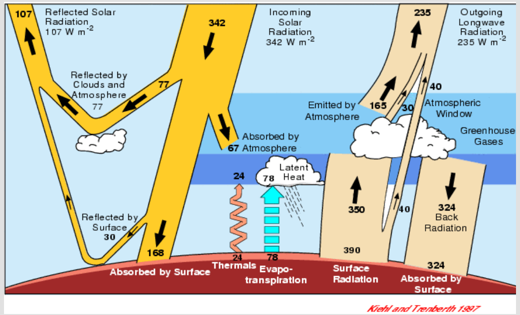


Interpretation (without going into details that make the difference between G06 and GM11 interesting):

1. Radiative cooling virtually the same in PRISTINE and POLLUTED simulations;

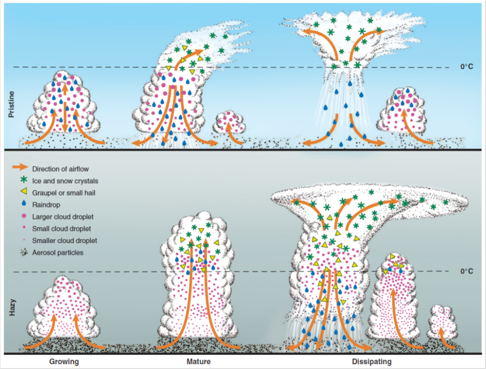
2. Thus, the surface heat flux (latent plus sensible) has to be the same. Bowen ratio practically does not change….

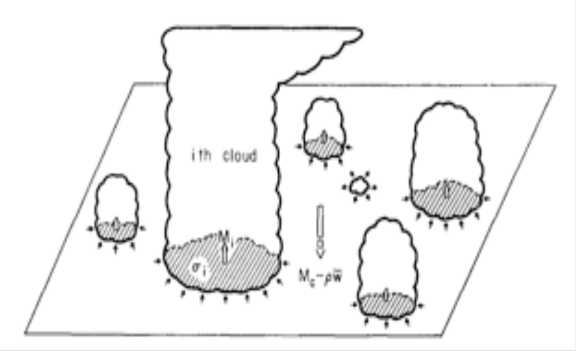
3. Thus, the surface precipitation has to stay the same. Apparently its mean (ensemble-averaged) vertical distribution does not change either because of feedbacks in the system…



How are these results relevant to the indirect effects in the climate system?

single-cloud reasoning versus cloud-ensemble reasoning





local (or regional) effects versus global effects

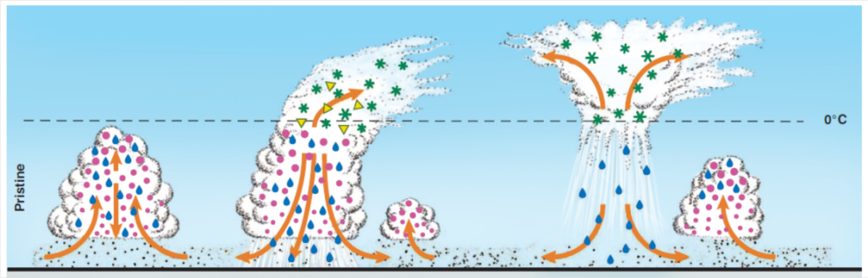
If such a picture is correct, then the biggest challenge for understanding the effects of aerosol on climate is to quantify possibly significant local effects versus relatively insignificant global effects.

The key point is that for the local effects, the “meteorology” (i.e., large-scale processes) are most likely by far more important. This is why separating aerosol effects from “meteorology” is very difficult…

This points to the multiscale aspect of the problem…

dynamic response at wrong scales:

Climate models are good at large-scale circulations…



…and they have to parameterize cloud-scale processes.

A simple heuristic argument:

Small-scale atmospheric dynamics is about hydrodynamic instabilities. Such instabilities typically are most active at the smallest scales (e.g., KH and RT instabilities without viscosity).

So any impact of aerosols is first be felt and processed at small-scales. Only what is left is available to affect large-scale circulations.

This is not how traditional GCMs are working…

…unless we can design parameterizations that can respond in the right way, which is difficult: $(\text{parameterization})^2$ problem.

Current GCMs project small-scale effects into large-scale dynamics…

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Superparameterization (SP) and Multiscale Modeling Framework (MMF) to the rescue!

Cloud-Resolving Convection Parameterization (CRCP)
(super-parameterization, SP)

Grabowski and Smolarkiewicz, *Physica D* 1999

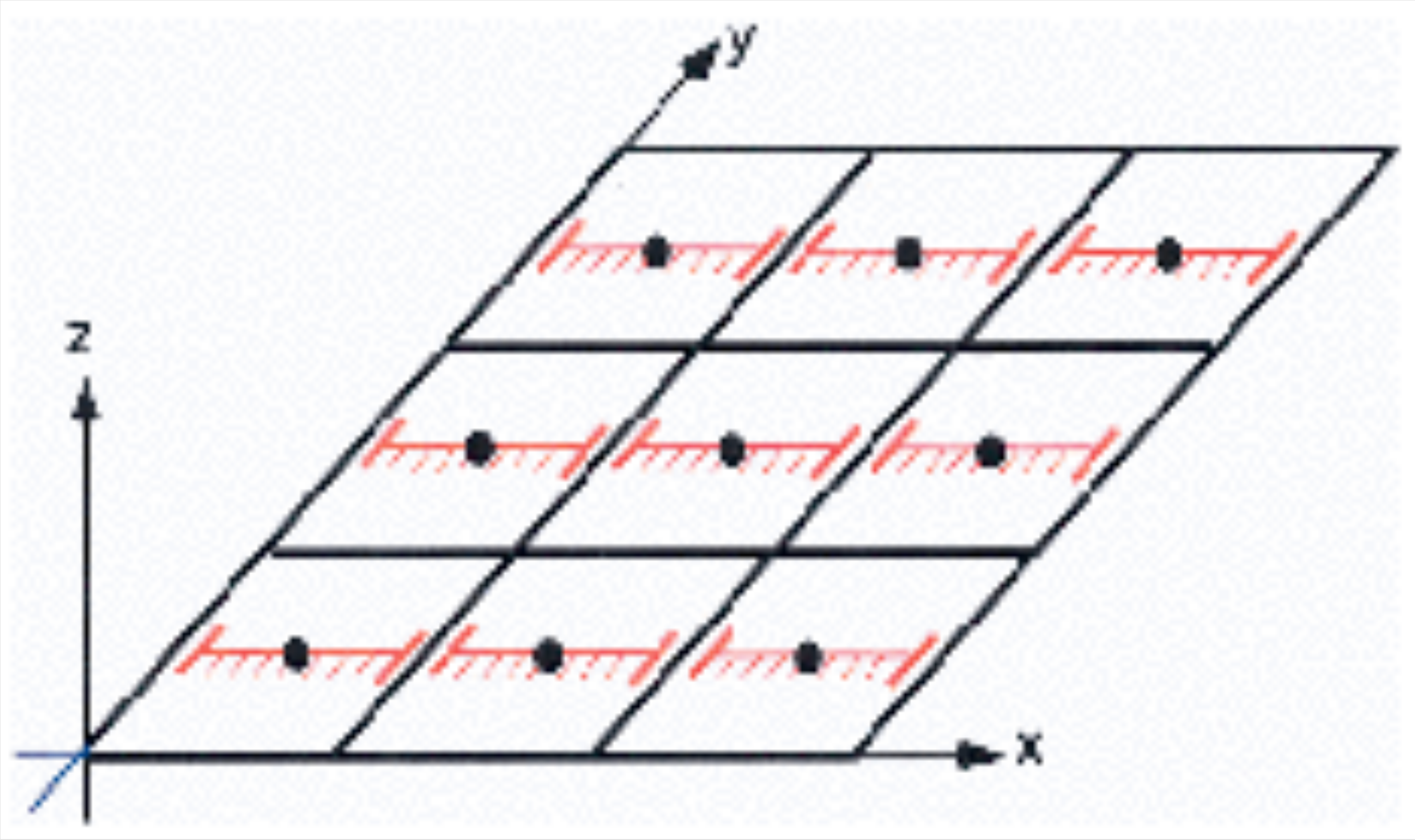
Grabowski, *JAS* 2001; Khairoutdinov and Randall *GRL* 2001;

Randall et al., *BAMS* 2003

The idea is to represent subgrid scales of the 3D large-scale model (horizontal resolution of 100s km) by embedding periodic-domain 2D CRM (horizontal resolution around 1 km) in each column of the large-scale model

Another (better?) way to think about CRCP: CRCP involves hundreds or thousands of 2D CRMs interacting in a manner consistent with the large-scale dynamics

Original CRCP proposal



- CRCP is a "parameterization" because scale separation between large-scale dynamics and cloud-scale processes is assumed; cloud models have periodic horizontal domains and they communicate only through large scales.
- CRCP is "embarrassingly parallel": a climate model with CRCP can run efficiently on 1000s of processors.
- CRCP is a physics coupler: most (if not all) of physical (and chemical, biological, etc.) processes that are parameterized in the climate model can be included into CRCP framework.

NSF Science and Technology Center was created in 2006…

http://cmmap.colostate.edu

The effects of anthropogenic aerosols as simulated by the SP-CAM with two-moment microphysics

Marat Khairoutdinov

State University of New York @ Stony Brook
Long Island, New York

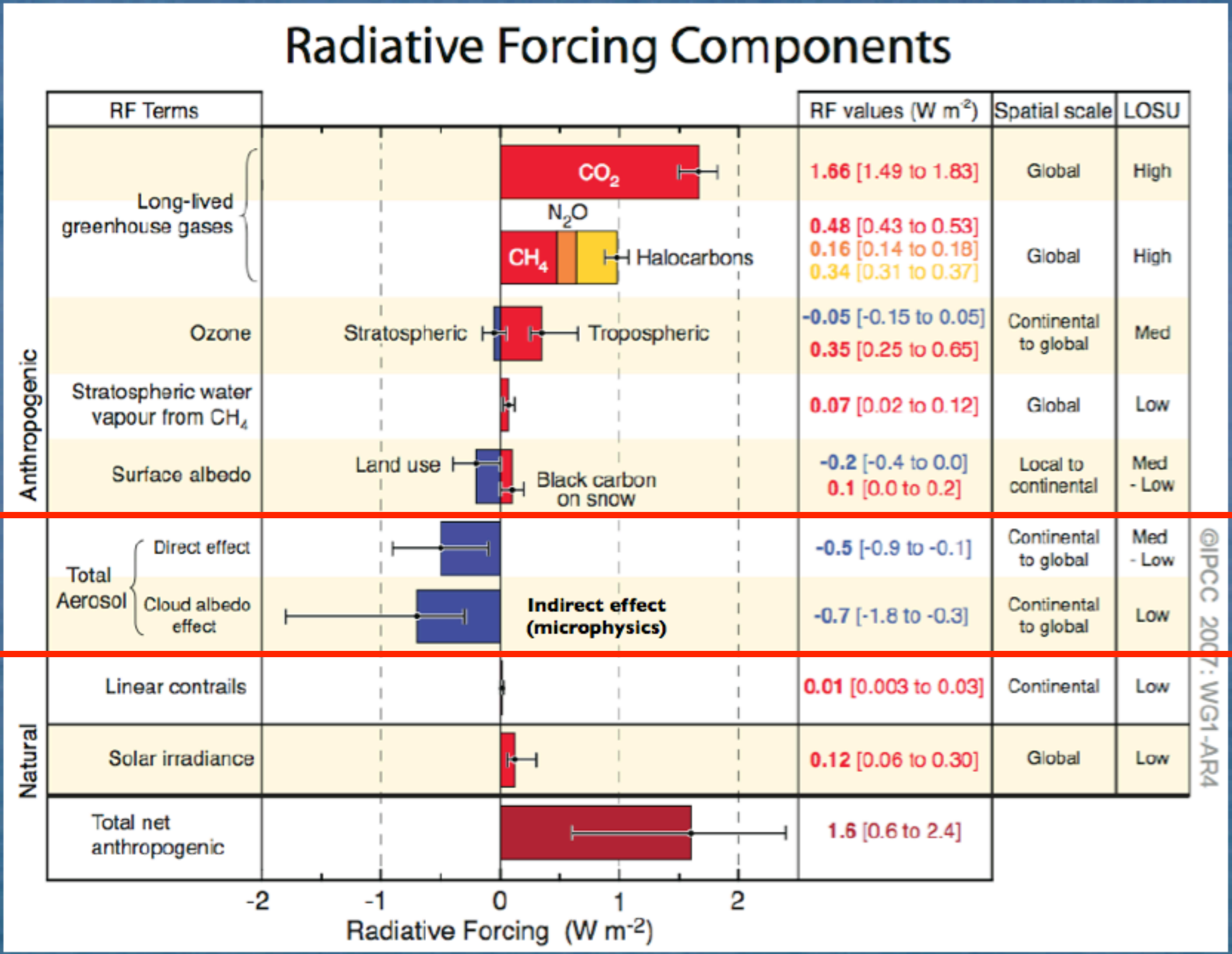
Wojciech Grabowski
Hugh Morrison

National Center for Atmospheric Research
Boulder, Colorado

Center for Multiscale Modeling of Atmospheric Processes
CMMAP
Reach for the sky.

Industrial Era Climate Change

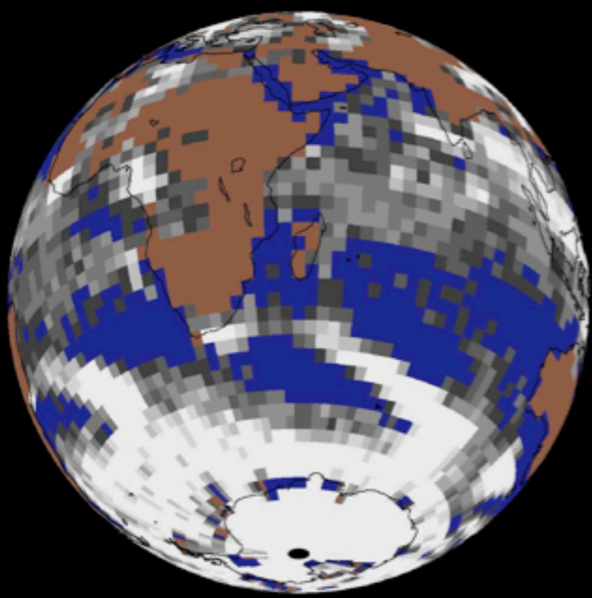
Source: IPCC 4th Assessment Report (AR4)

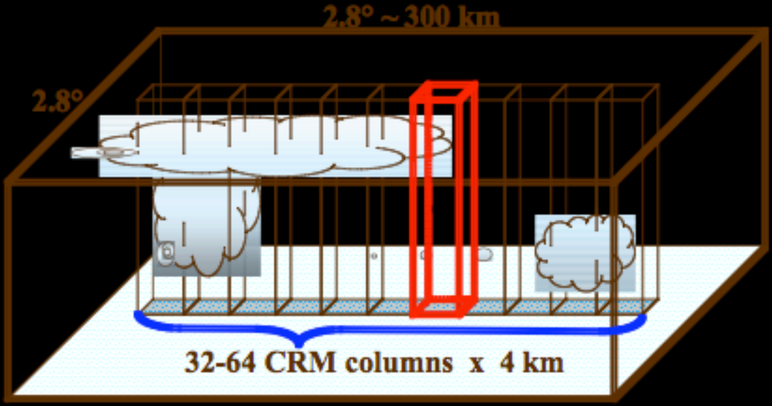


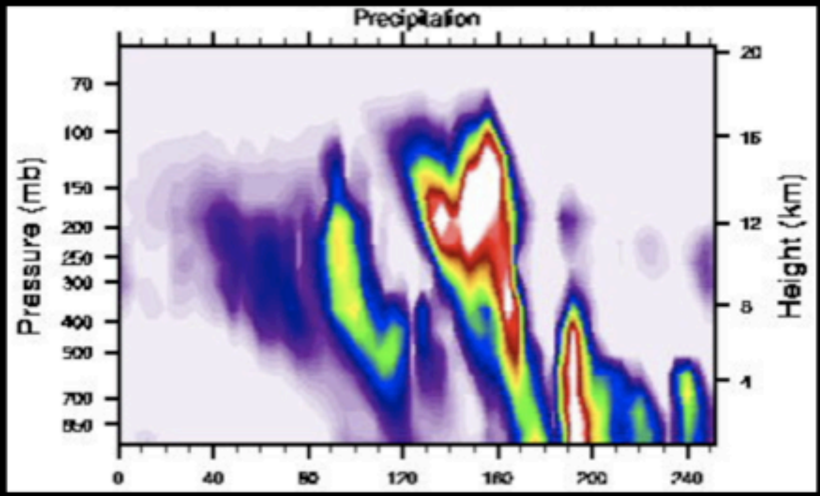
Super-parameterized CAM: SP-CAM

Multiscale Modeling Framework (MMF)

A copy of a CRM (a.k.a. "super-parameterization") is run in each column of CAM GCM.







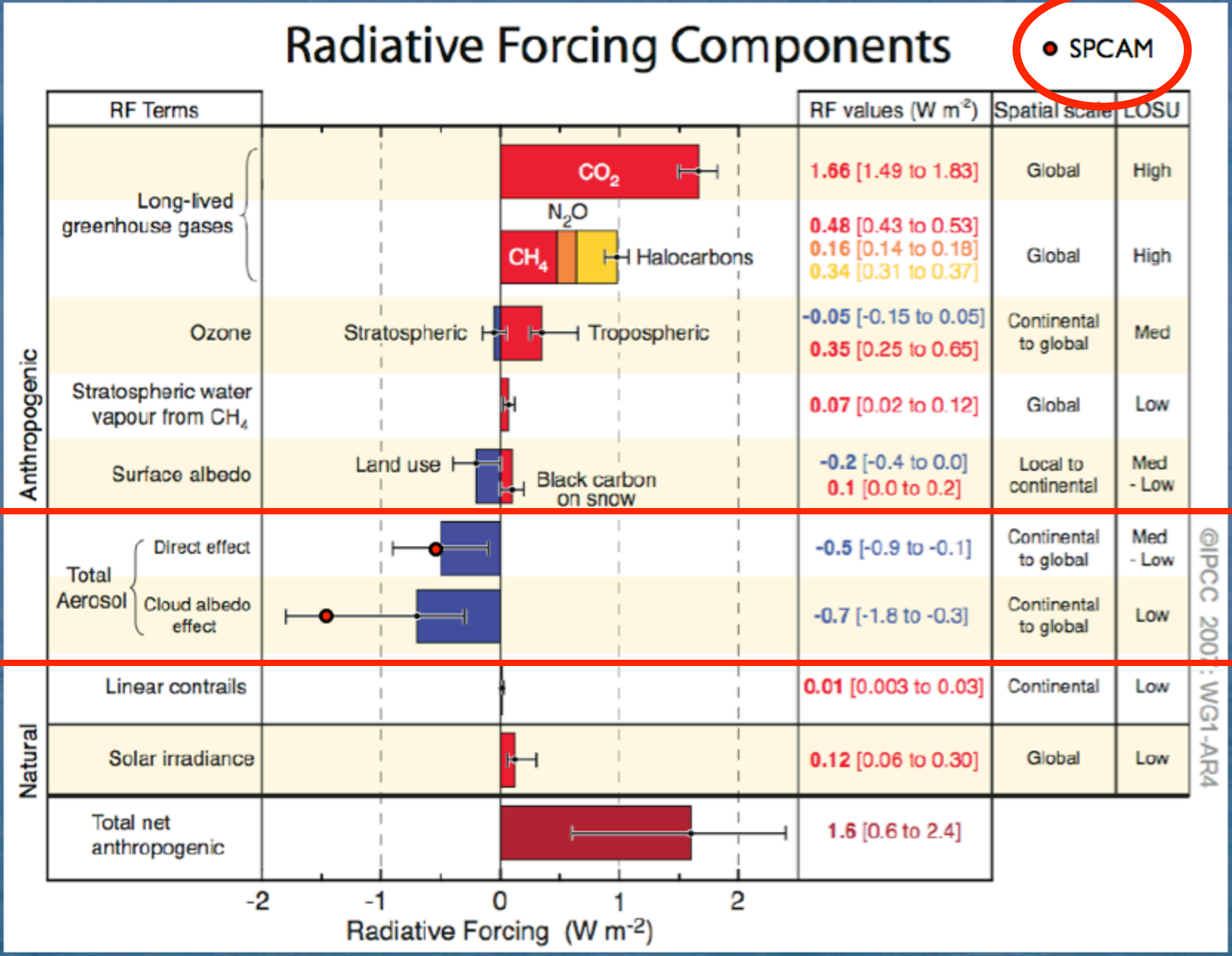
Each column of this has this

Bulk Microphysics Schemes in System for Atmospheric Modeling - SAM CRM used as super-parameterization in SP-CAM

Original One-Moment (Khairoutdinov and Randall 2003)	Two-Moment (Morrison et al. 2005) Thanks to Peter Blossey for implementing it in SAM
• 2 prognostic microphysics variables: total non-precipitating and precipitating water mixing ratios; • Cloud liquid and ice water, rain, graupel and snow are diagnosed as f(T); • Autoconversion to rain by simple Kessler formula; • Cloud drop effective radius is prescribed •No indirect aerosol effect is included.	• 10 prognostic microphysics variables; • Prognostic mixing ratio and concentration for 5 categories of water; • Autoconversion depends on water content and concentration (KK 2000); •Cloud Condensation nuclei (CCN) spectrum is prescribed; •Cloud droplet effective radius is computed; •Indirect aerosol effects are included.

IPCC 4th Assessment Report (AR4)

Industrial Era Climate Change

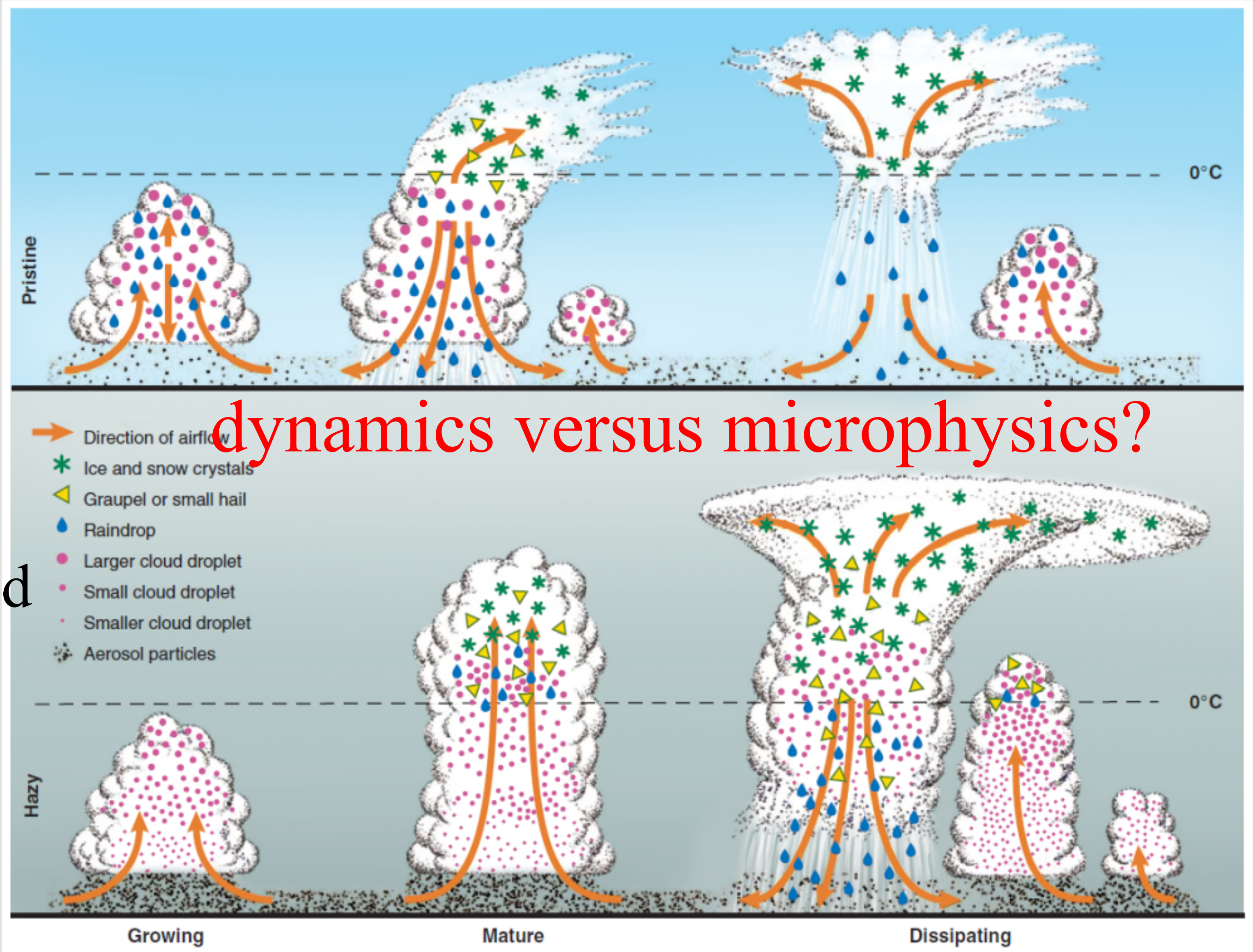


Summary

- Two-moment microphysics capable of representing indirect aerosol effects is implimented in SP-CAM;
- The presence of anthropogenic sulfate aerosol tends to strengthen the Hadley cell and increase mid-latitude cyclone activity, redistributing precipitation without changing the net;
- Anthropogenic sulfate aerosol effect (feedback) is estimated to be
    - Direct: -0.6 W/m^2;
    - Indirect: -1.5 W/m^2

clean

polluted

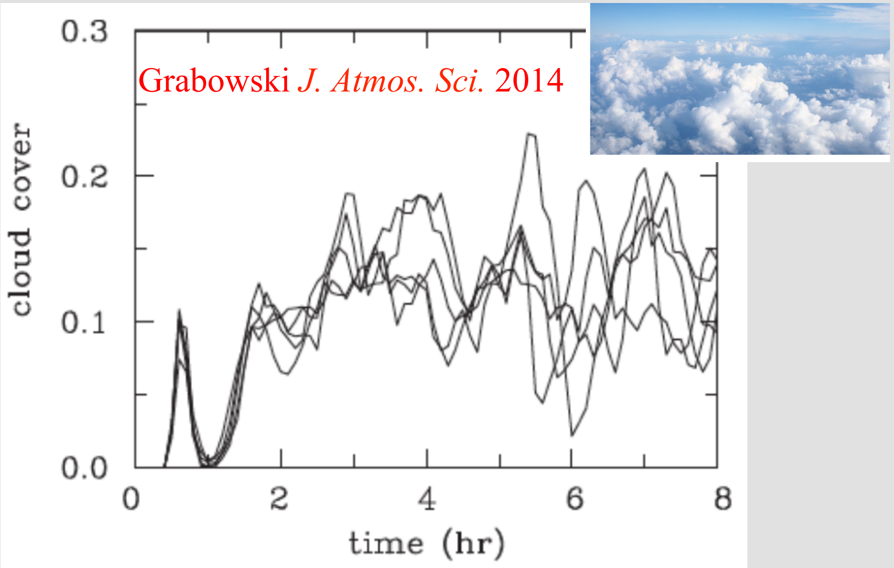


Rosenfeld et al. *Science*, 2008

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

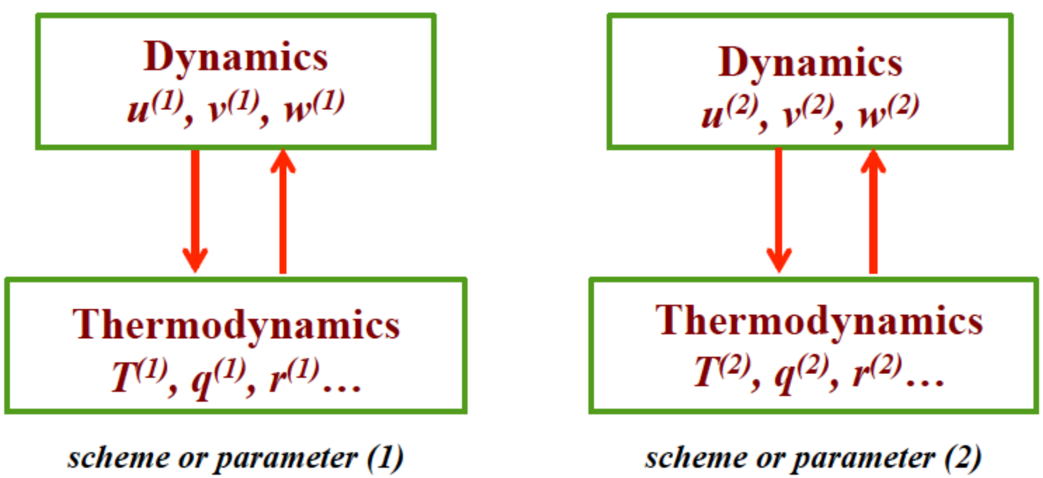
Methodology:

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



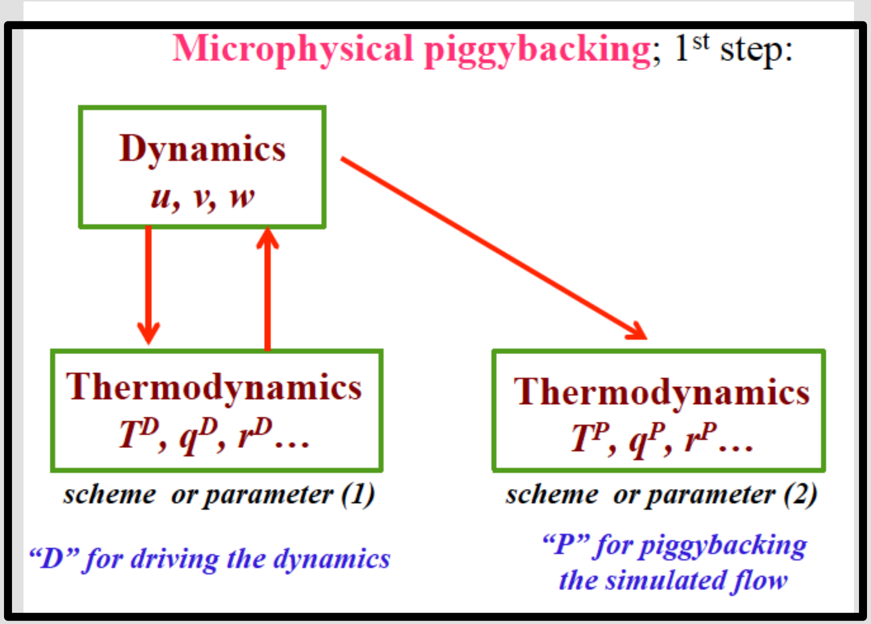
Evolution of cloud cover in 5 simulations of shallow cumulus cloud field. The only difference is in random small temperature and moisture perturbations at t=0.

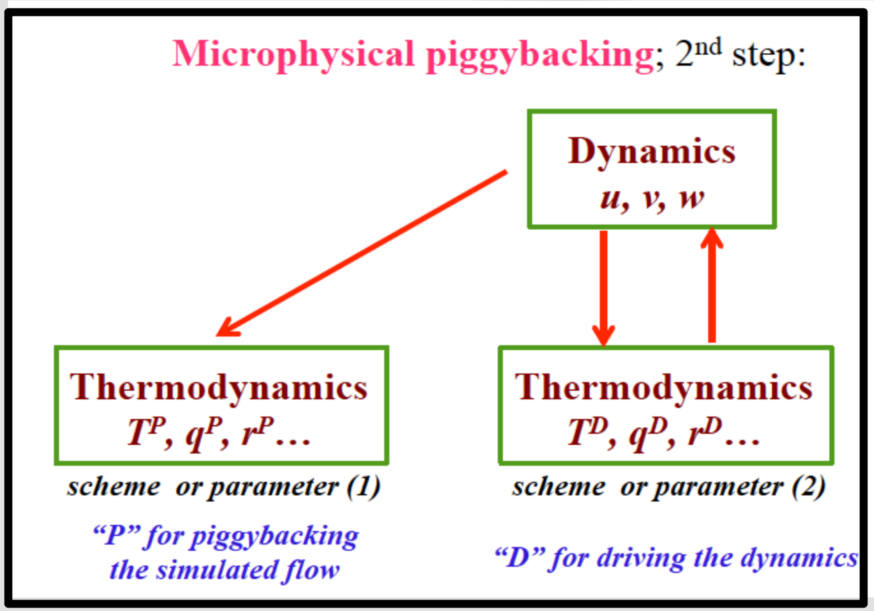
Traditional approach: parallel simulations with different microphysical schemes or scheme parameters



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

Novel modeling methodology*: the piggybacking*





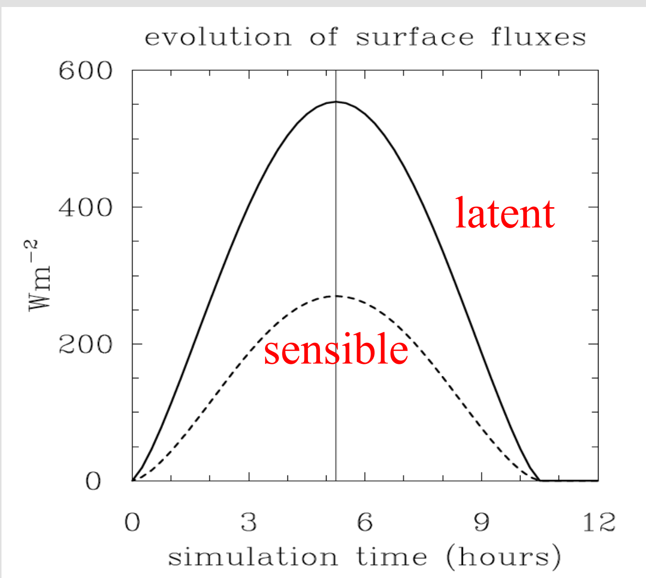
The novel piggybacking methodology is being applied in modeling studies that investigate the impact of cloud microphysics on cloud dynamics, see references below.

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*. (in press).

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 IN for POL and PRI

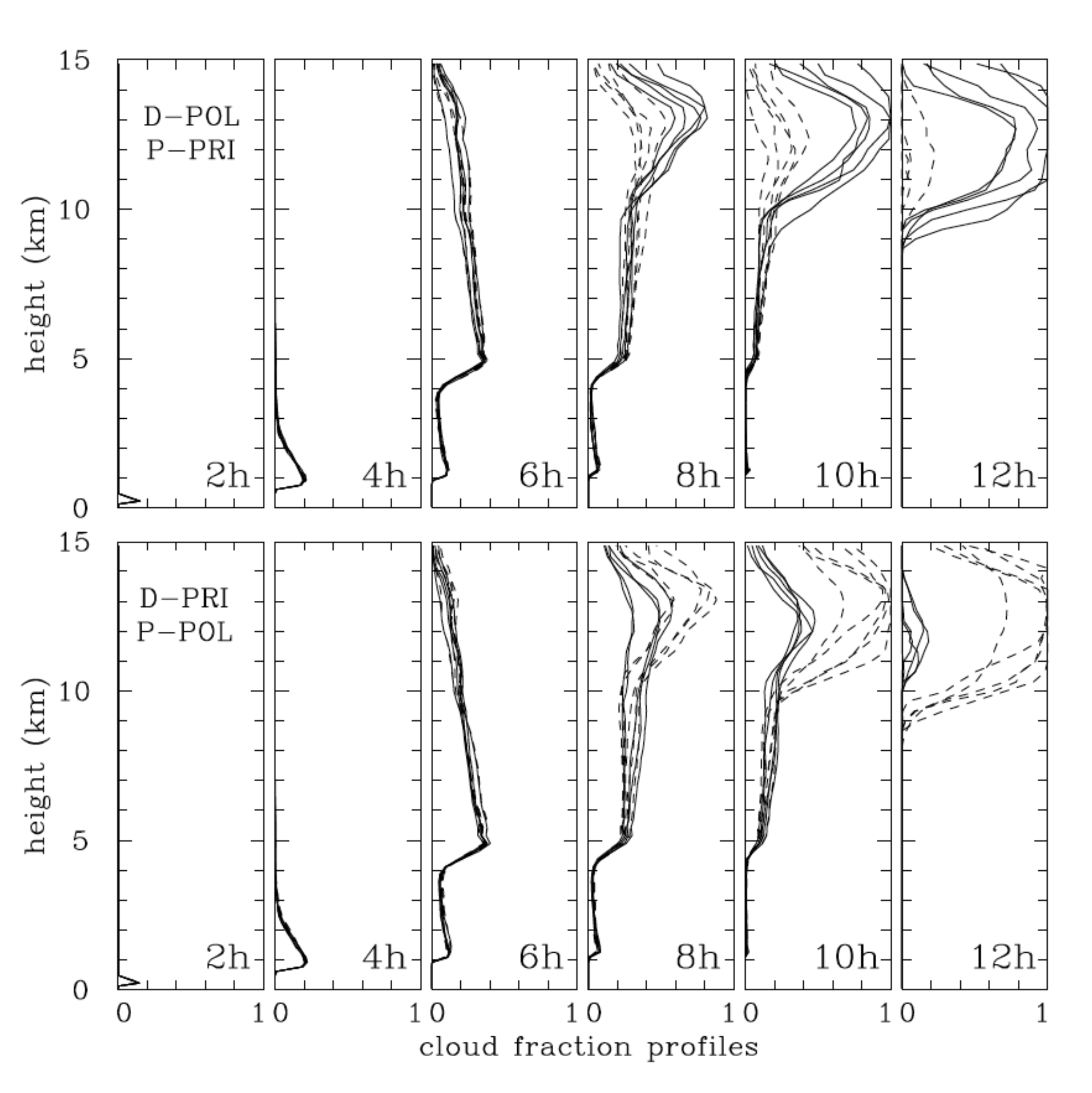
Piggybacking: D-PRI/P-POL: PRI drives, POL piggybacks
D-POL/P-PRI: POL drives, PRI piggybacks

Five-member ensemble for each

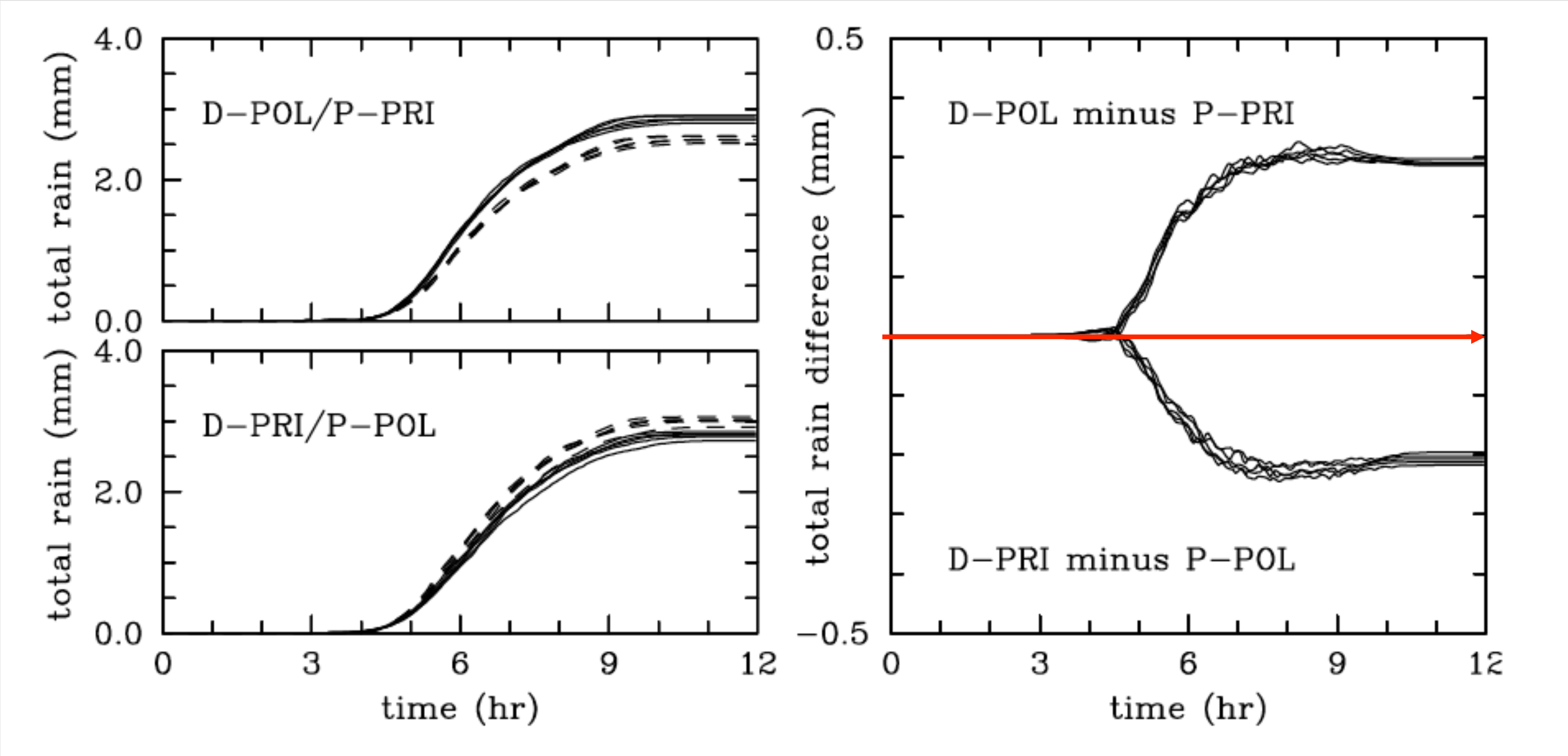
solid lines: driving set
dashed lines: piggybacking set

POL drives,
PRI piggybacks

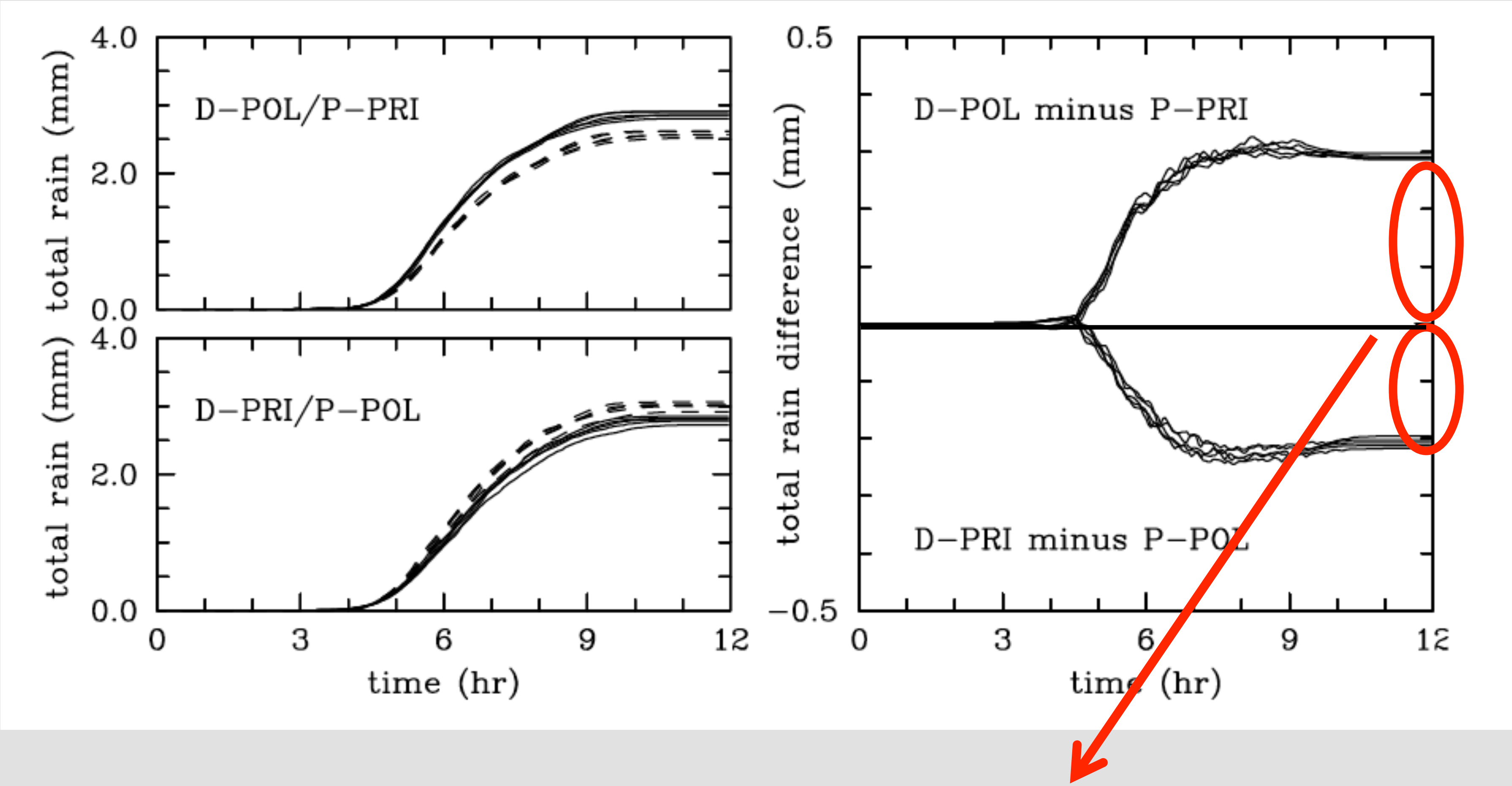
PRI drives,
POL piggybacks



solid lines: driving set
dashed lines: piggybacking set



solid lines: driving set
dashed lines: piggybacking set

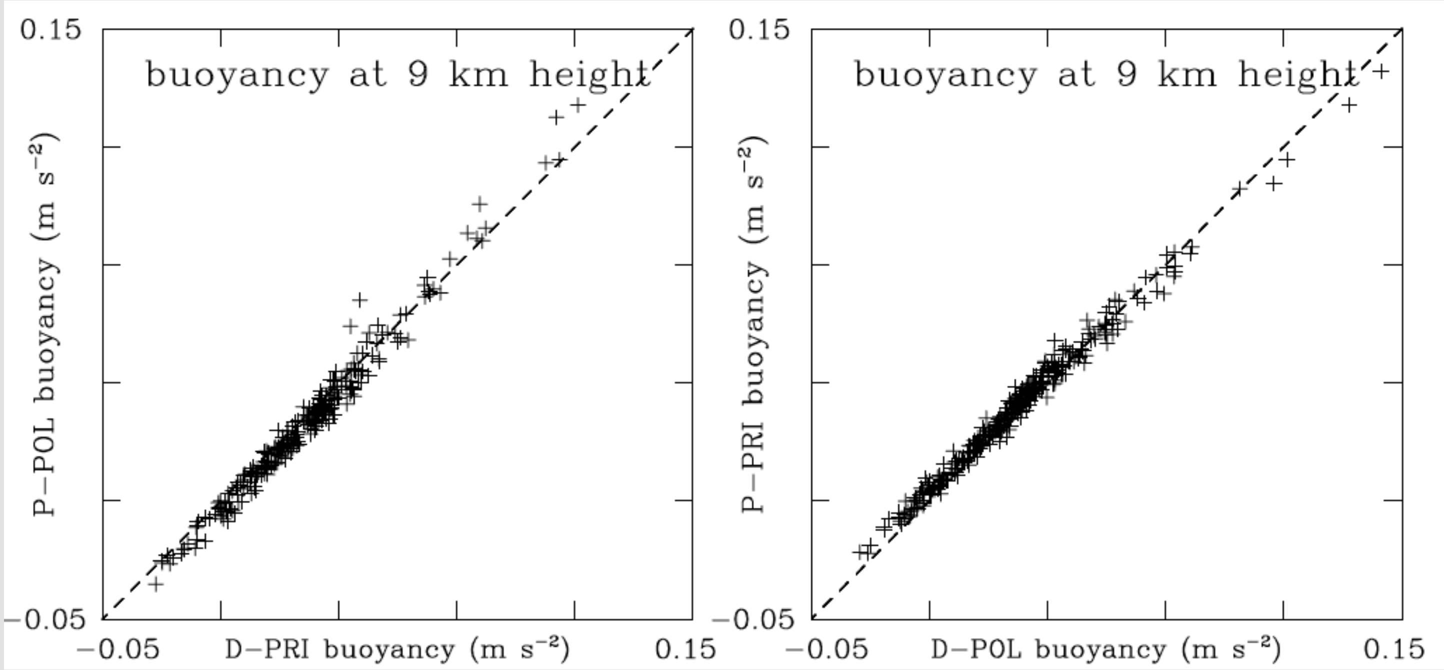


impact on the cloud dynamics?

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

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

1 K ≈ 0.03 m s^{-2}



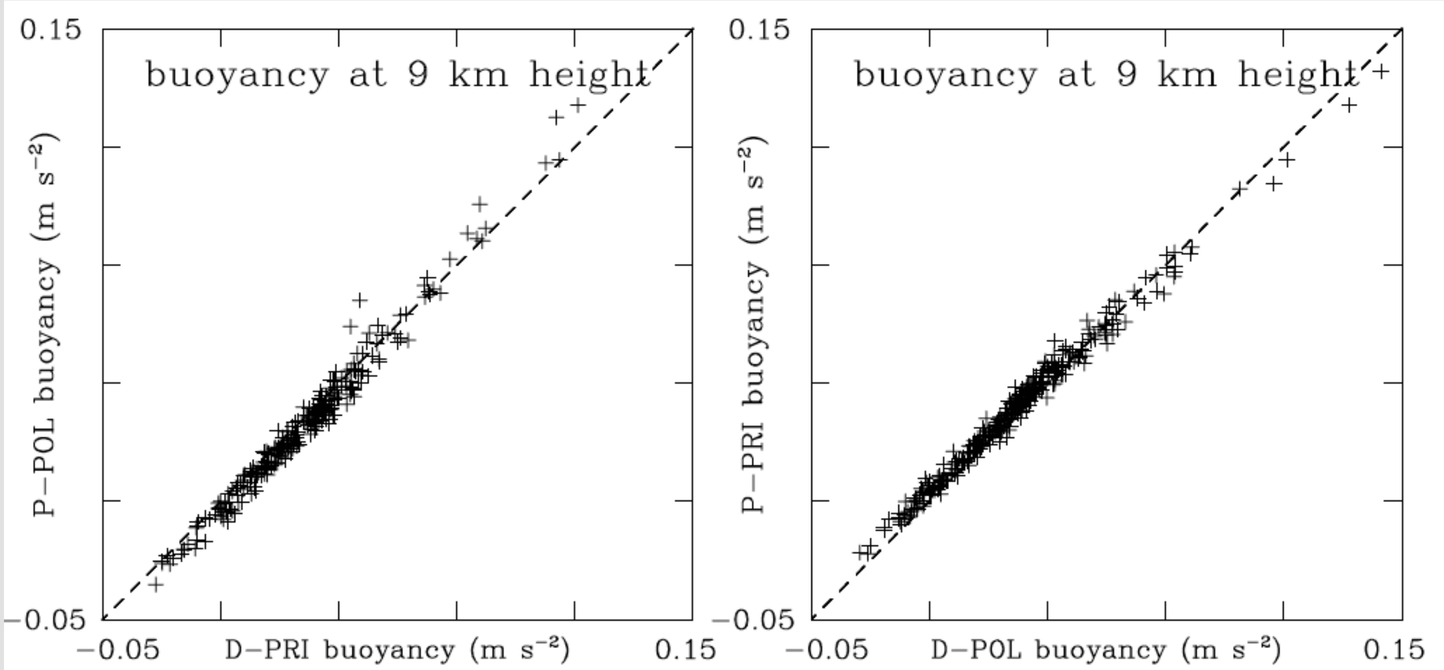
at 9 km (-27 degC)

(Rosenfeld et al. mechanism…)

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

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

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



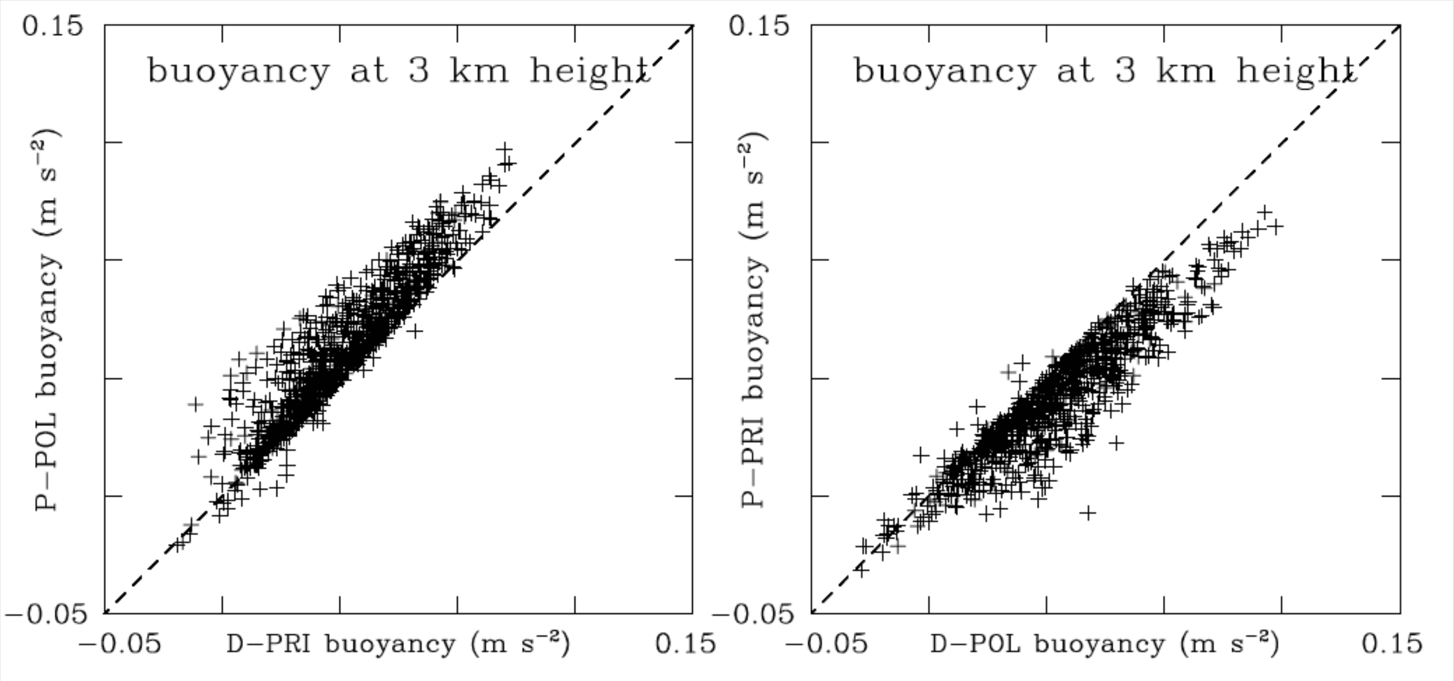
at 9 km (-27 degC)

POL has slightly less buoyancy than PRI…

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

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

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

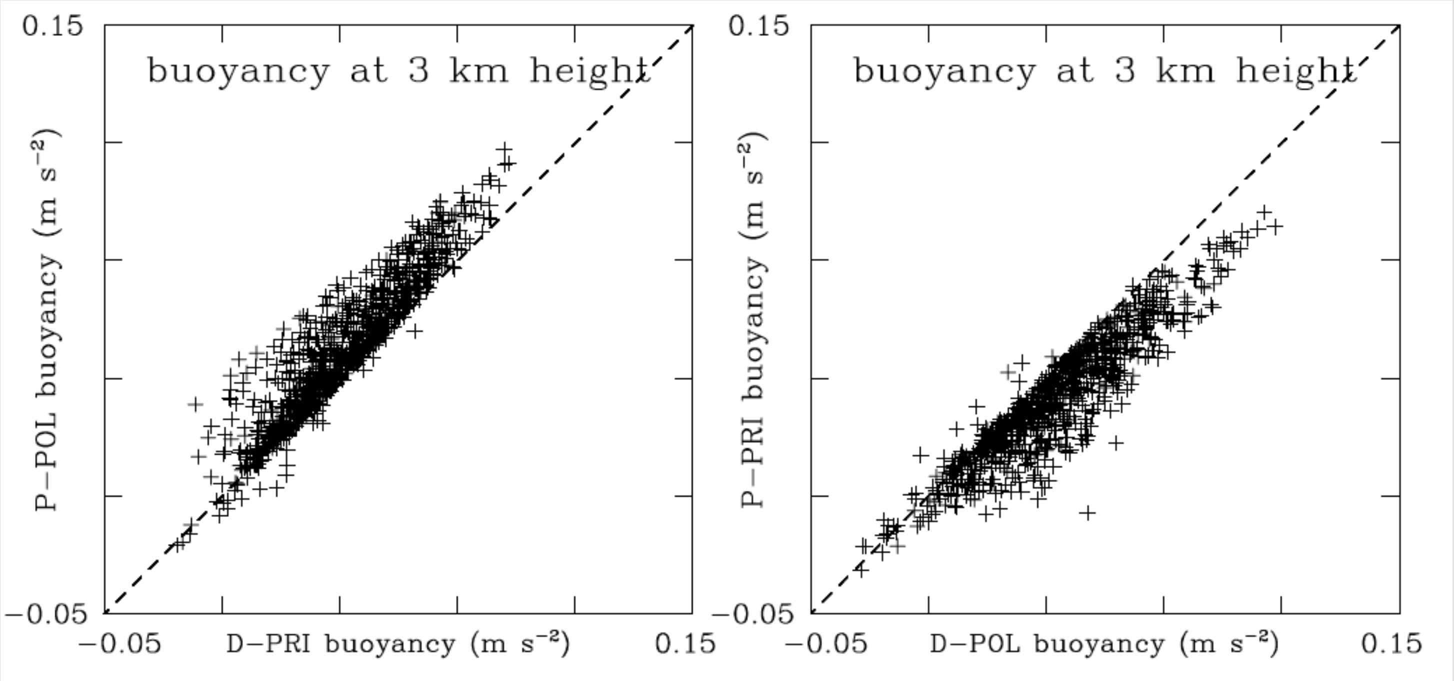


at 3 km (9 degC)

Comparing buoyancy between driving and piggybacking sets (hour6):

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

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



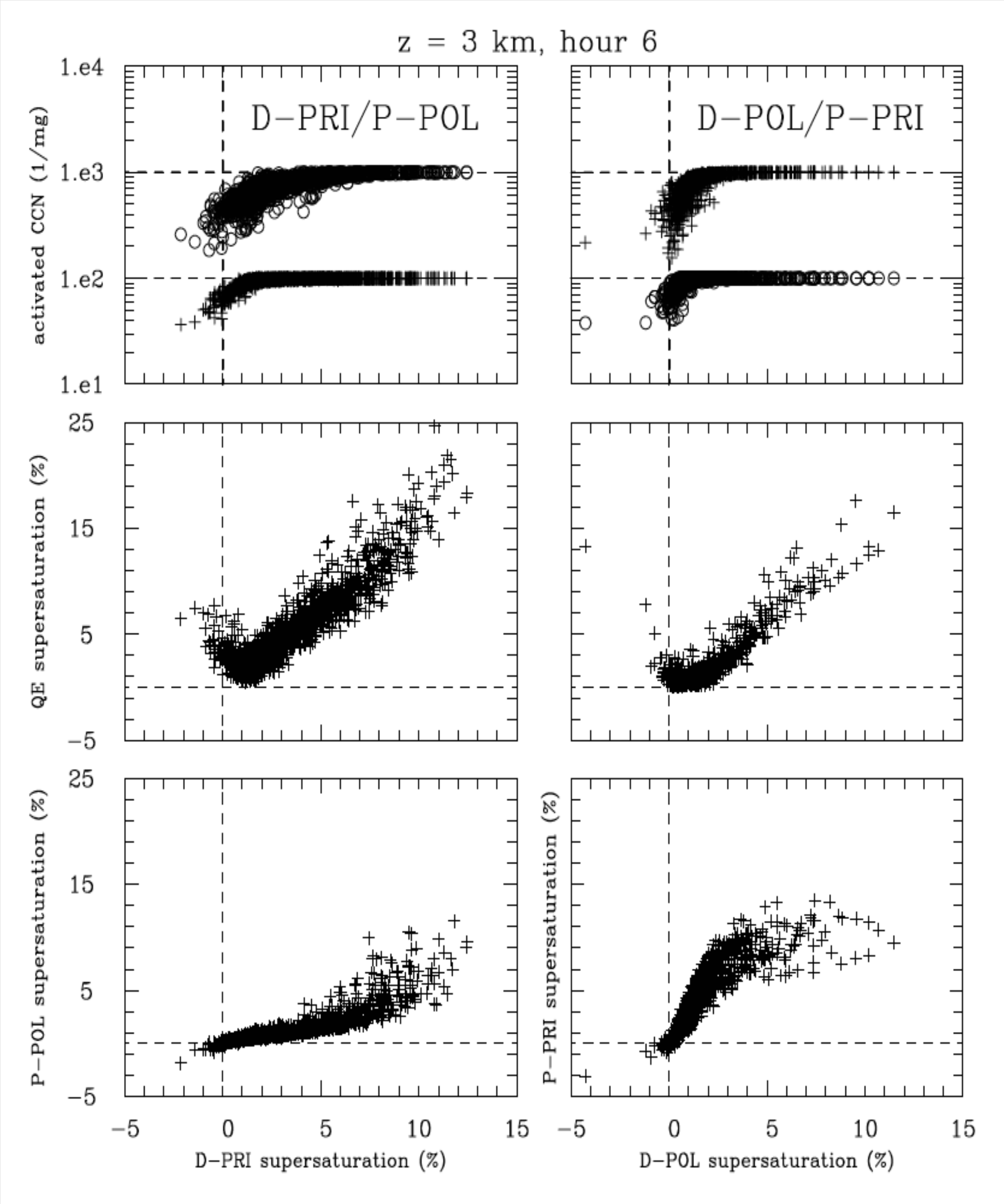
at 3 km (9 degC)

POL can have significantly more buoyancy than PRI…

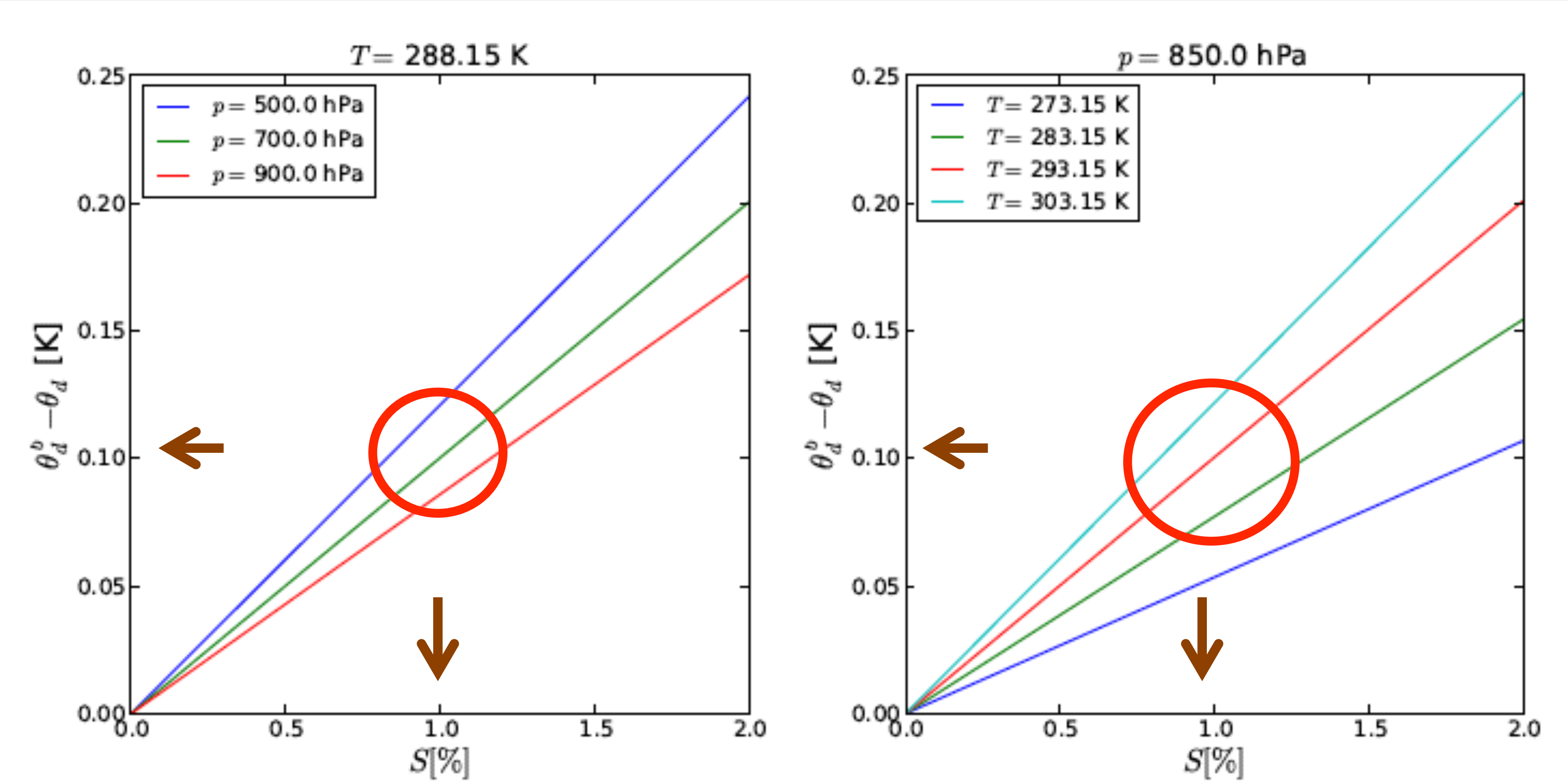
Local supersaturation, QE supersaturation, and activated CCN

$$S_{qe} \sim w\,\tau$$

$$\tau \sim (N_c r_c + N_r r_r)^{-1}$$



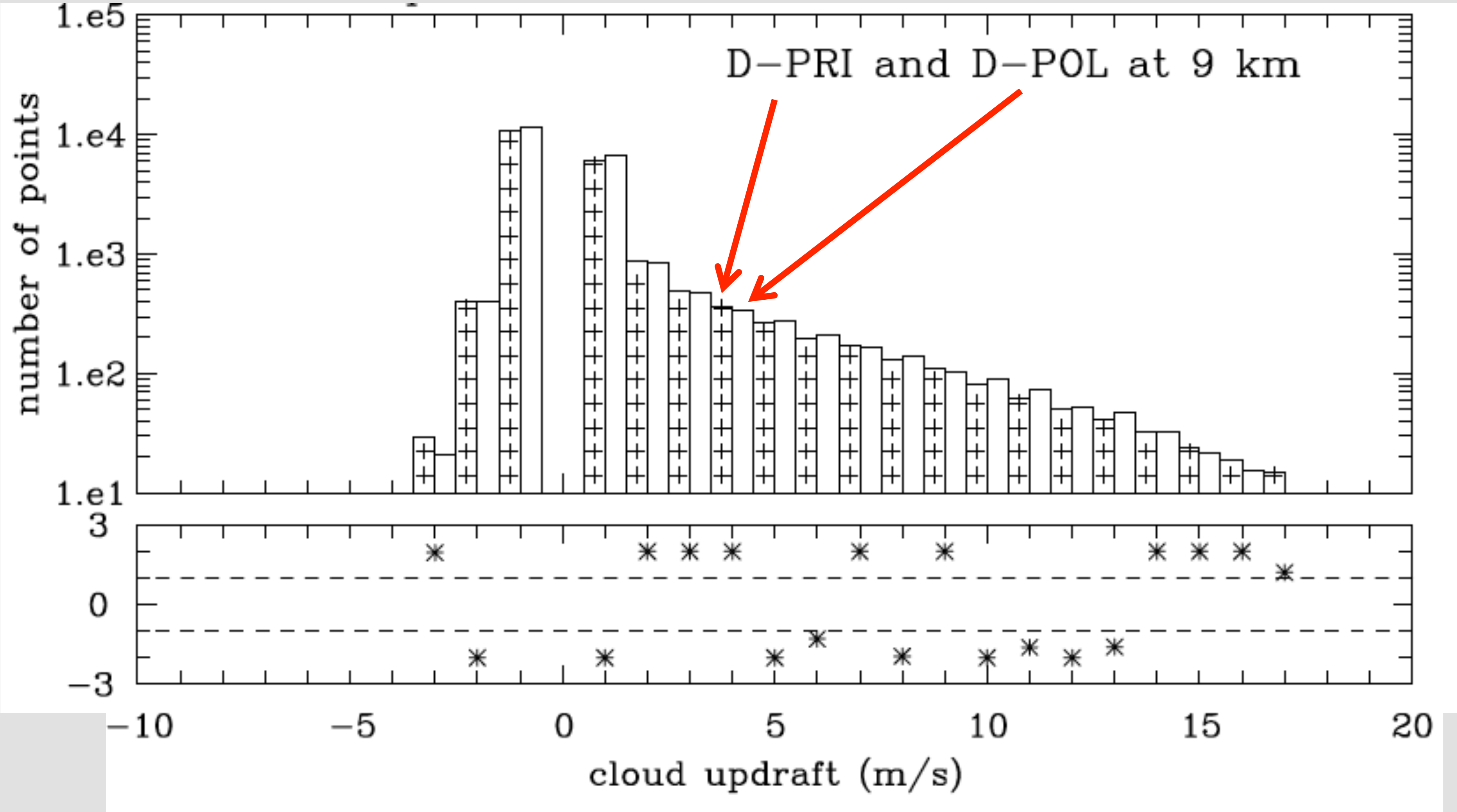
Comparing Θ_d with finite supersaturation with Θ_d at S=0, $\Theta_d^{\,b}$



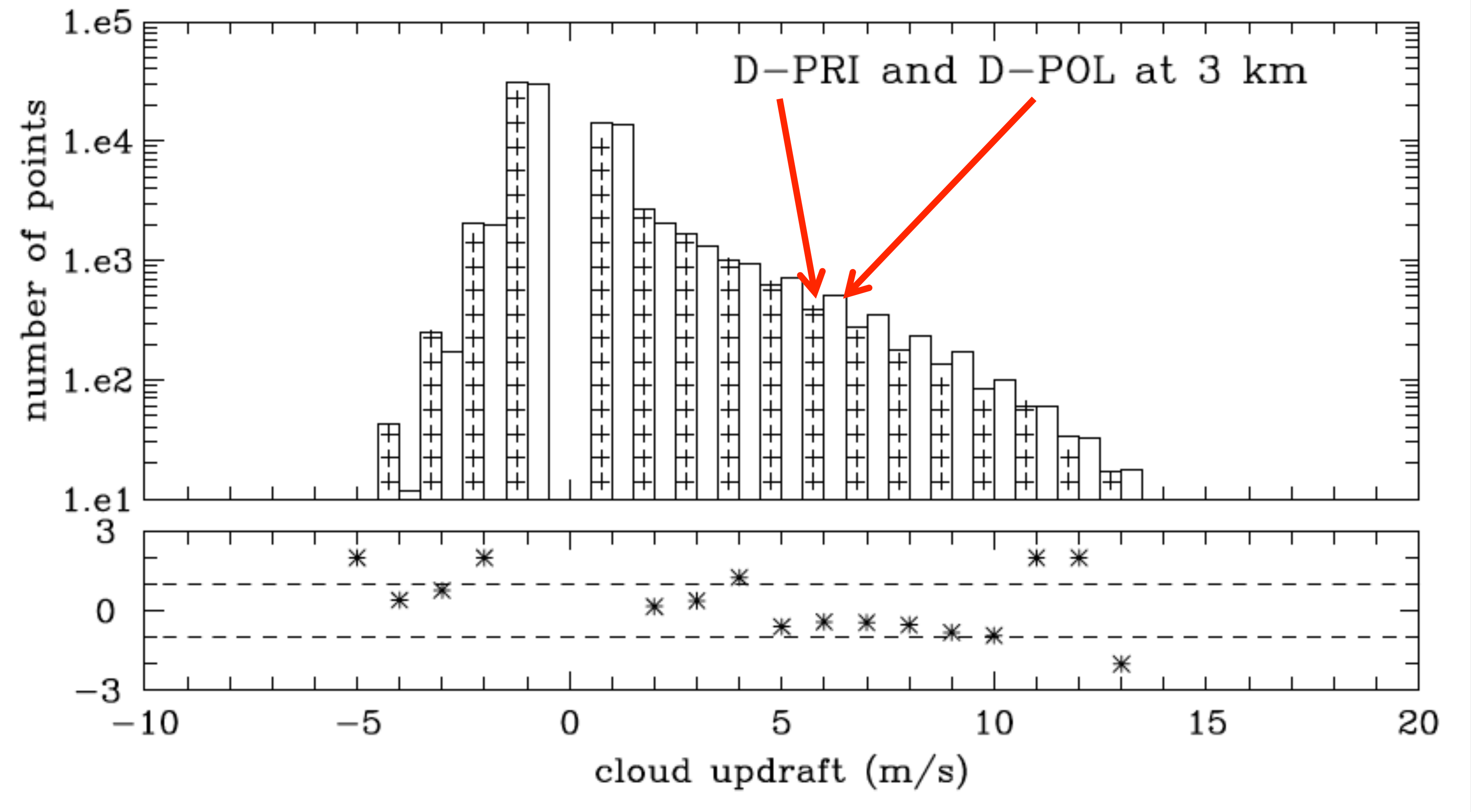
10% supersaturation ≈ 1 K density temperature reduction

Grabowski and Jarecka (*JAS*, 2015)

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**,
measure of statistical significance of the D-PRI and D-POL difference



Conclusions:

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

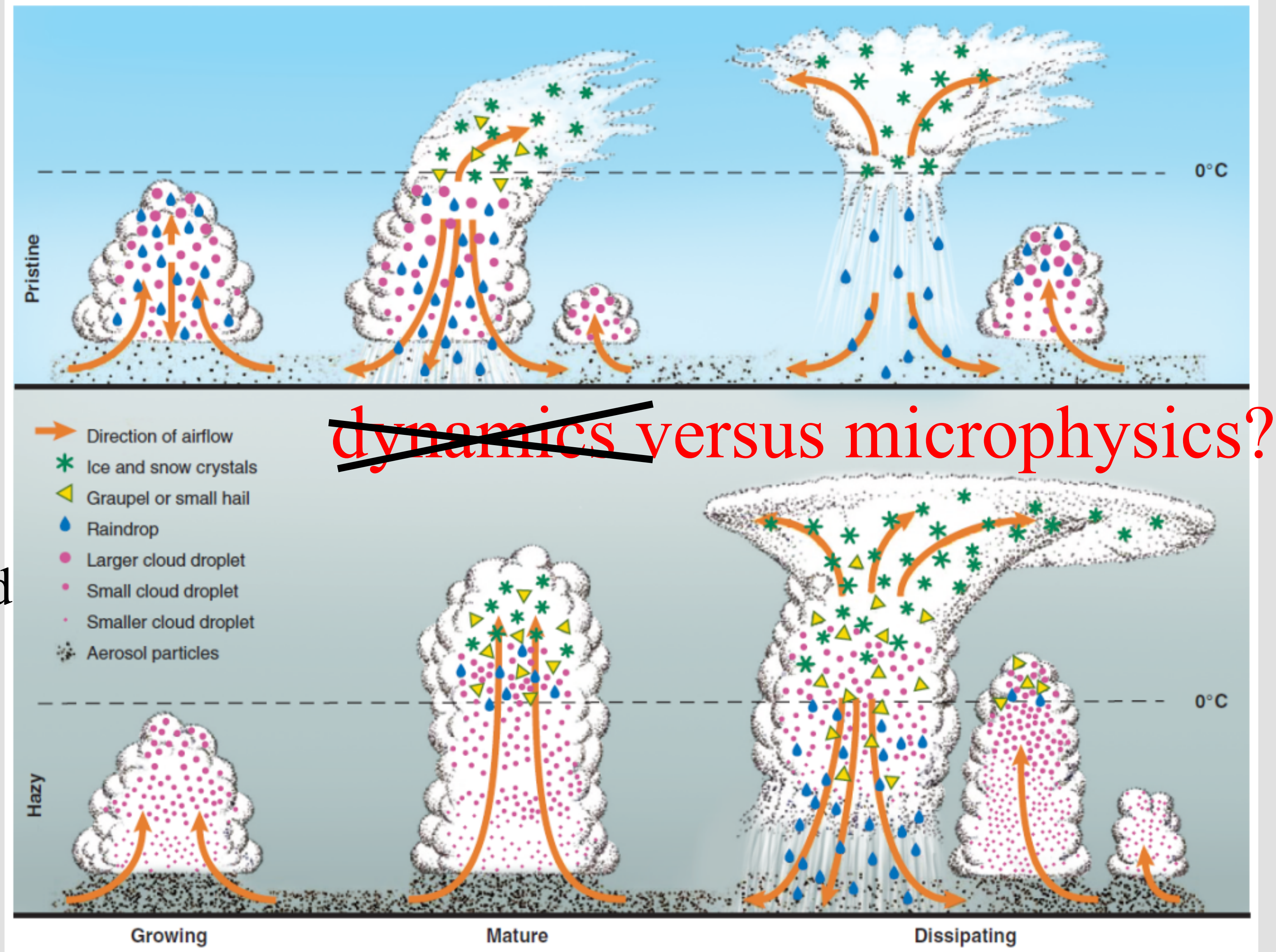
- single-moment bulk schemes: no dynamical effect, 5-15% more surface rain in pristine cases;

- double-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.

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

clean

polluted



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

Concluding comments:

The effect of clouds on the climate system is one of the most difficult aspects of the climate research. It involves multiscale interactions between dynamics (from global to small-scale turbulence), cloud microphysics, radiative transfer, and surface processes.

Indirect impact of atmospheric aerosols (i.e., through modifications of cloud and precipitation processes) is one of the least understood aspects of the climate change. Estimates from traditional climate models are uncertain because of the "$(\text{parameterization})^2$" problem (parameterized microphysics in parameterized clouds).

Concluding comments:

Superparameterization approach as well as cloud-resolving general circulation models (the latter still way to expensive for climate simulations) provide valuable alternatives to advance the climate science in general, and effects of aerosols in particular.

Microphysical piggybacking allows confident separation microphysical effects of aerosols from the impact on cloud dynamics (i.e., “convective invigoration”). For deep convection, piggybacking shows strong microphysical effect and a rather small dynamical impact.