Representing microphysical processes in cloud models

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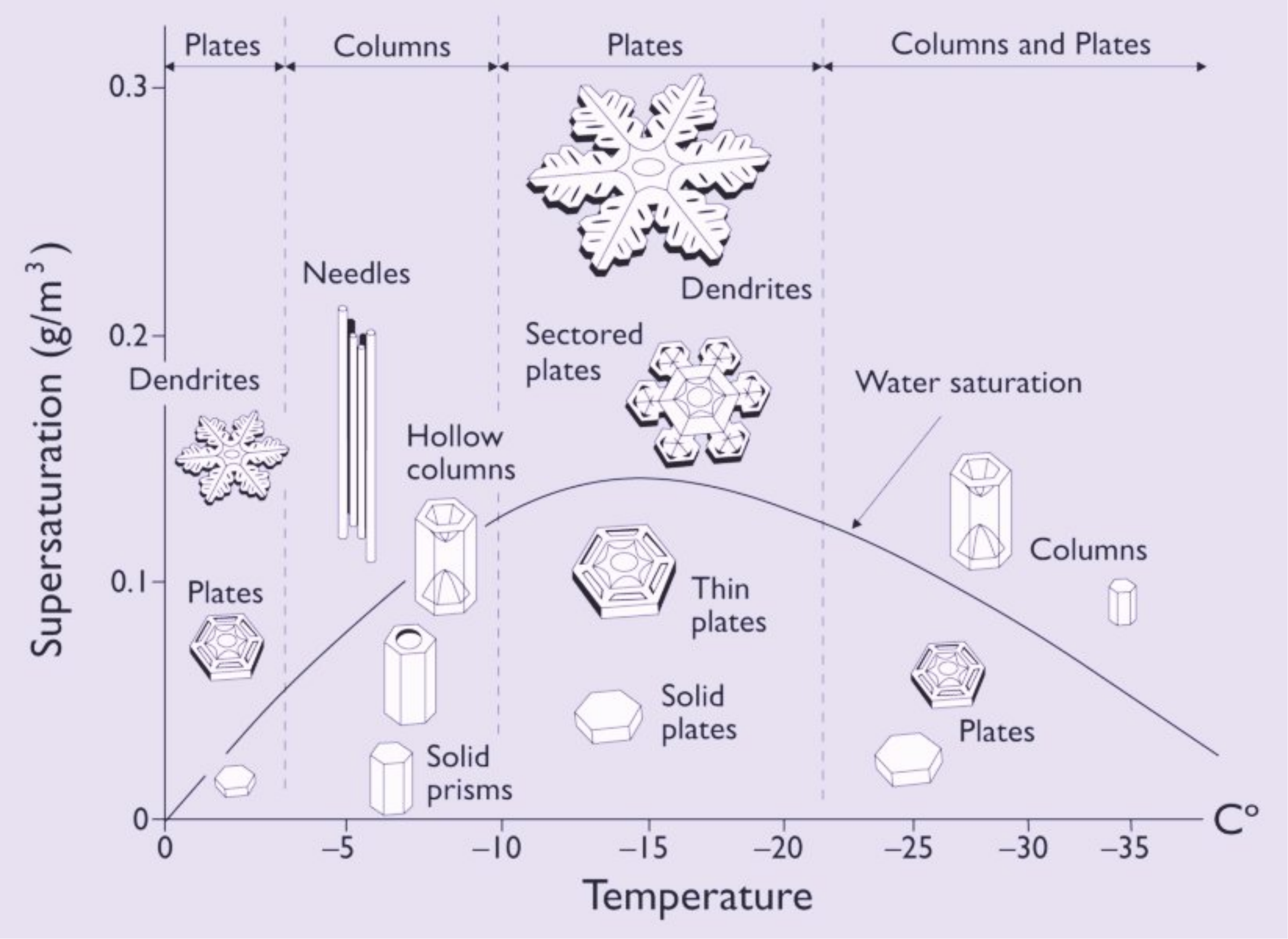
Representing microphysical processes in models

- Why do we need to represent clouds in models?
- Grid-scale precipitation vs. parameterized
- Parameterization approaches
- Evaluation of parameterizations

Grid-scale precipitation vs. parameterized

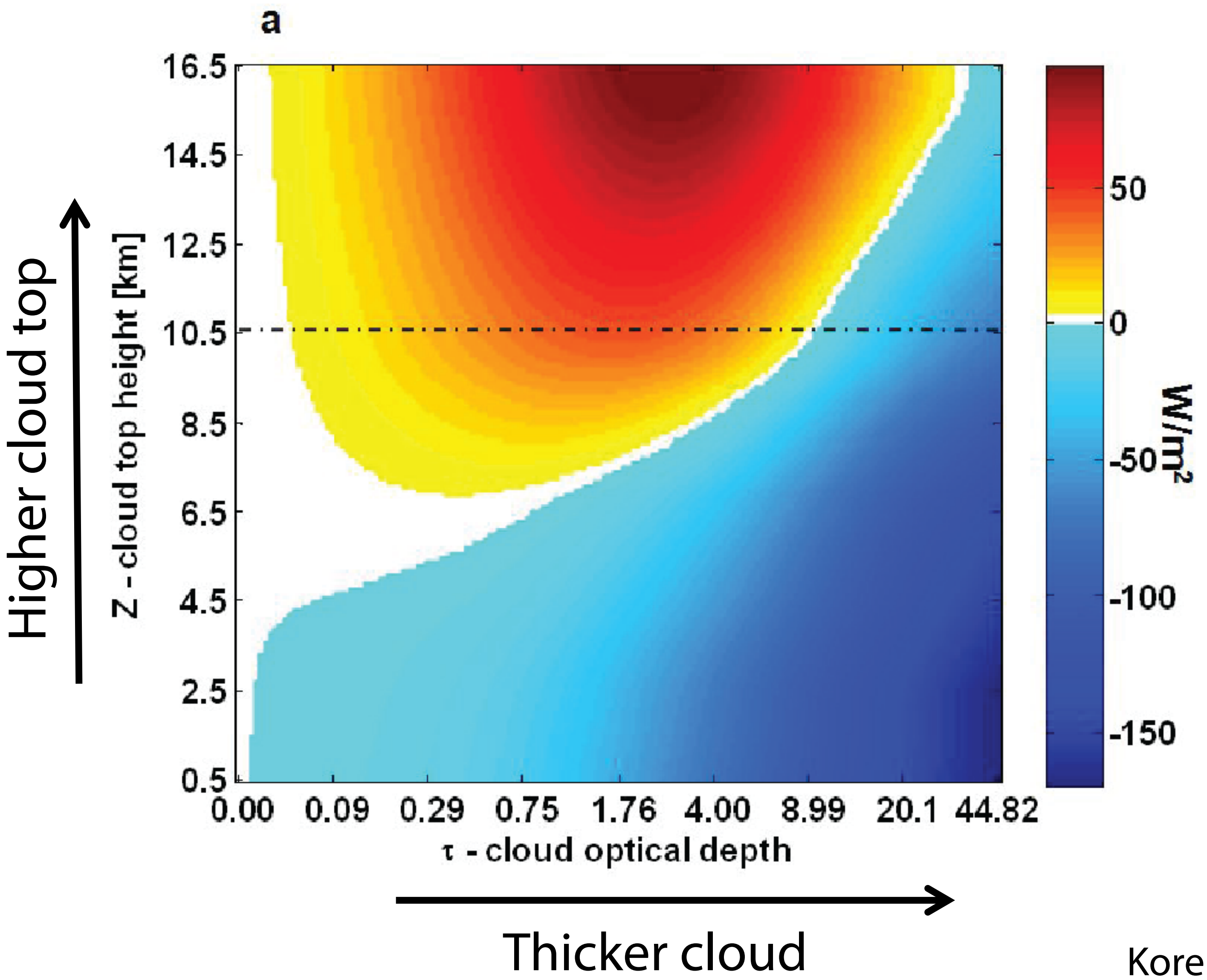
Let's ignore the ice phase for now…



Why do we care about clouds?

Why do clouds present such a challenge to climate models?

- High clouds and low clouds affect the climate differently



Koren et al. (2010)

Low clouds in climate models

Cloud-top height

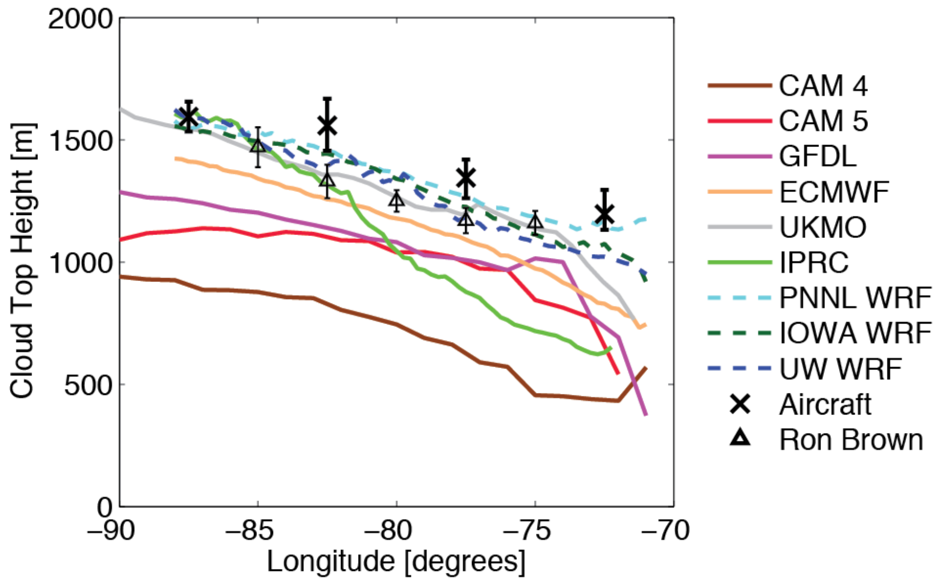


Figure 4. Model-mean cloud-top height along 20° S compared with mean cloud top measured using cloud radar from C-130 flights (Bretherton et al., 2010). Mean observations of R/V *Ron Brown* from 2001 to 2008 (de Szoeke et al., 2012) are plotted as triangles with bars as standard deviation.

Liquid water

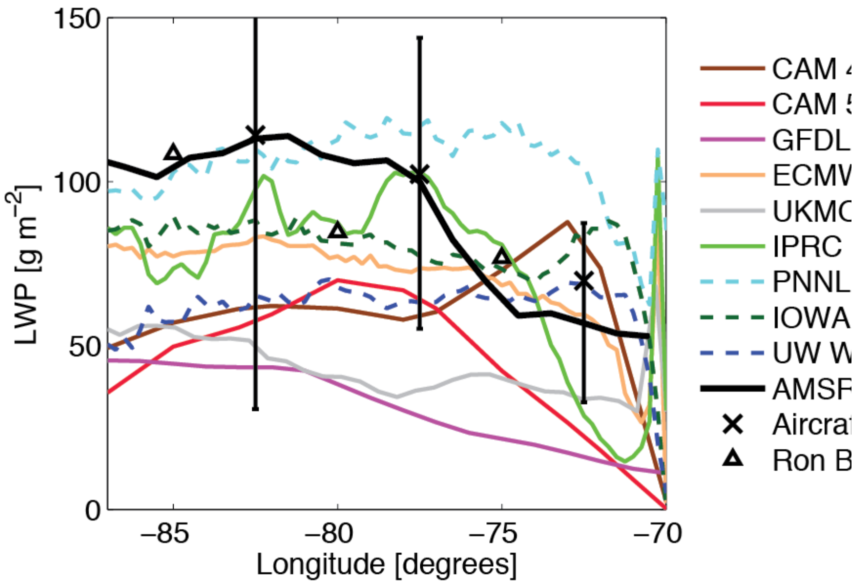
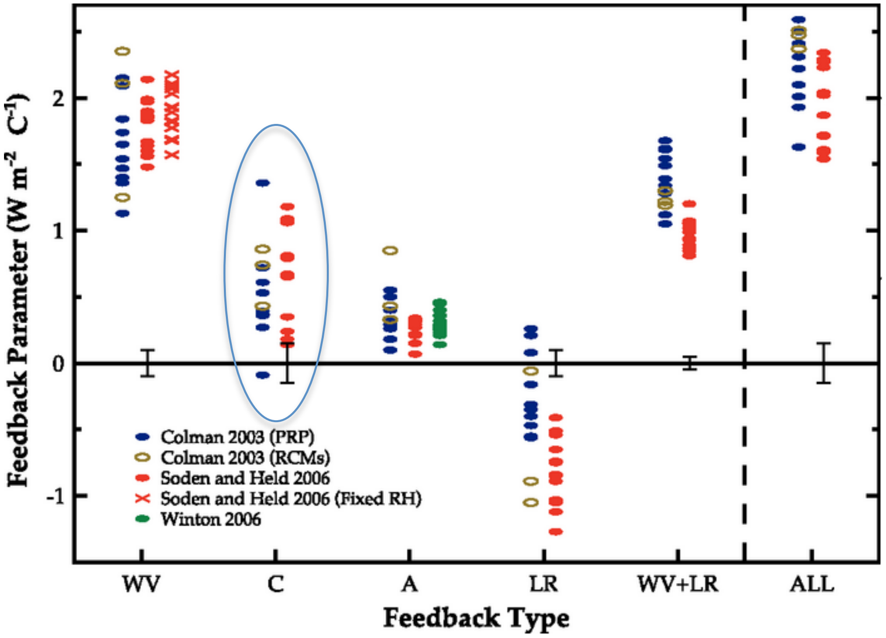


Figure 3. Grid-box mean LWP along 20° S compared with
E satellite mean of day and night passes and mean LWP fr
crowave radiometer on the C-130 (Zuidema et al., 2012). Err
represent interquartile ranges of aircraft leg means. Also plo
triangles are mean values measured by the R/V *Ron Brow*
2001 to 2008 (de Szoeke et al., 2012).

Wyant et al. (2015)

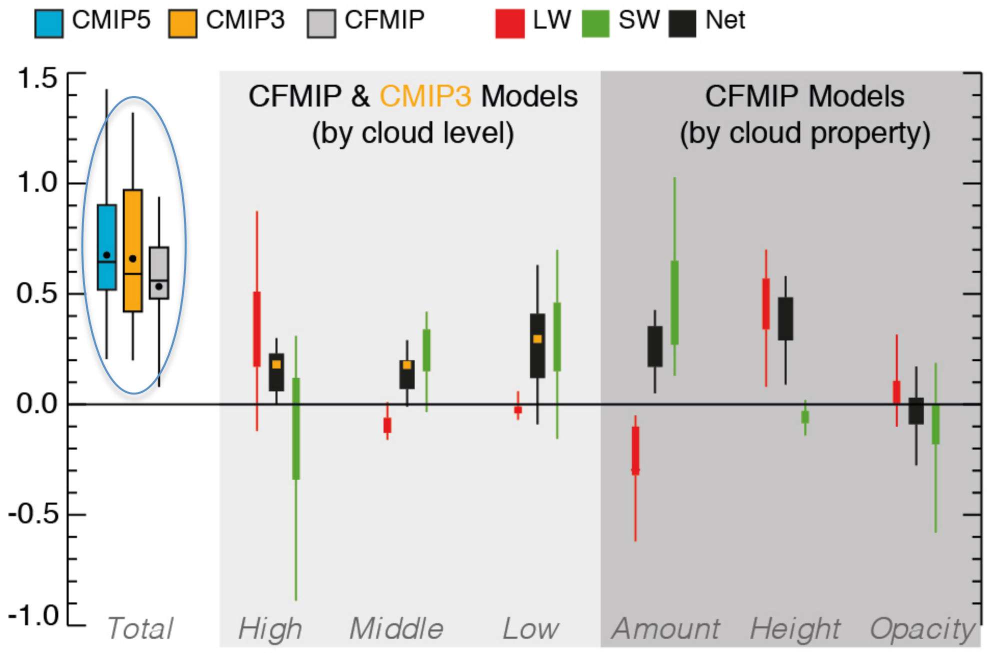
Cloud feedbacks in climate models

AR4 — 2007



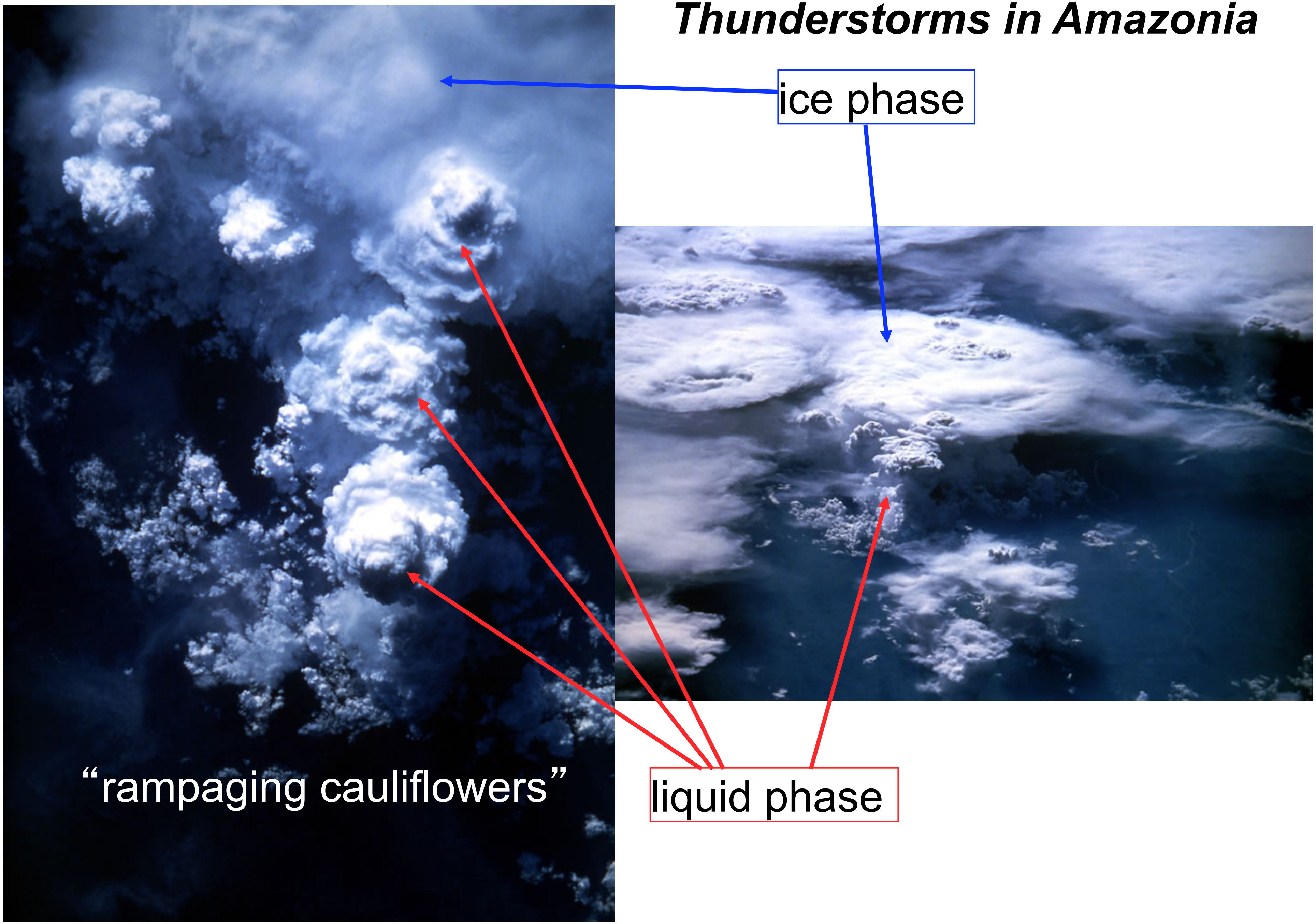
Bony et al. (J. Climate, 2006)

AR5 — 2013



IPCC AR5 (2013)

Thunderstorms in Amazonia

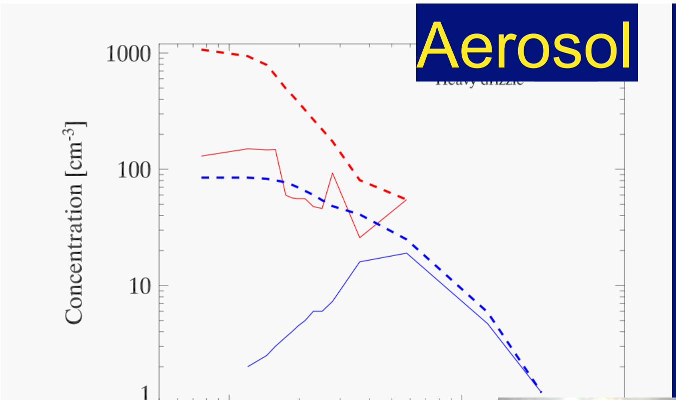


ice phase

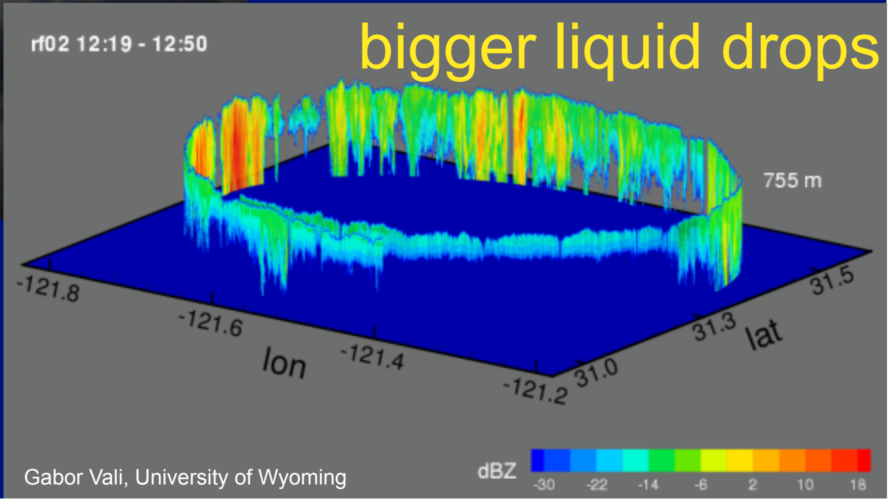
liquid phase

“rampaging cauliflowers”

Aerosol–cloud–precipitation


Aerosol

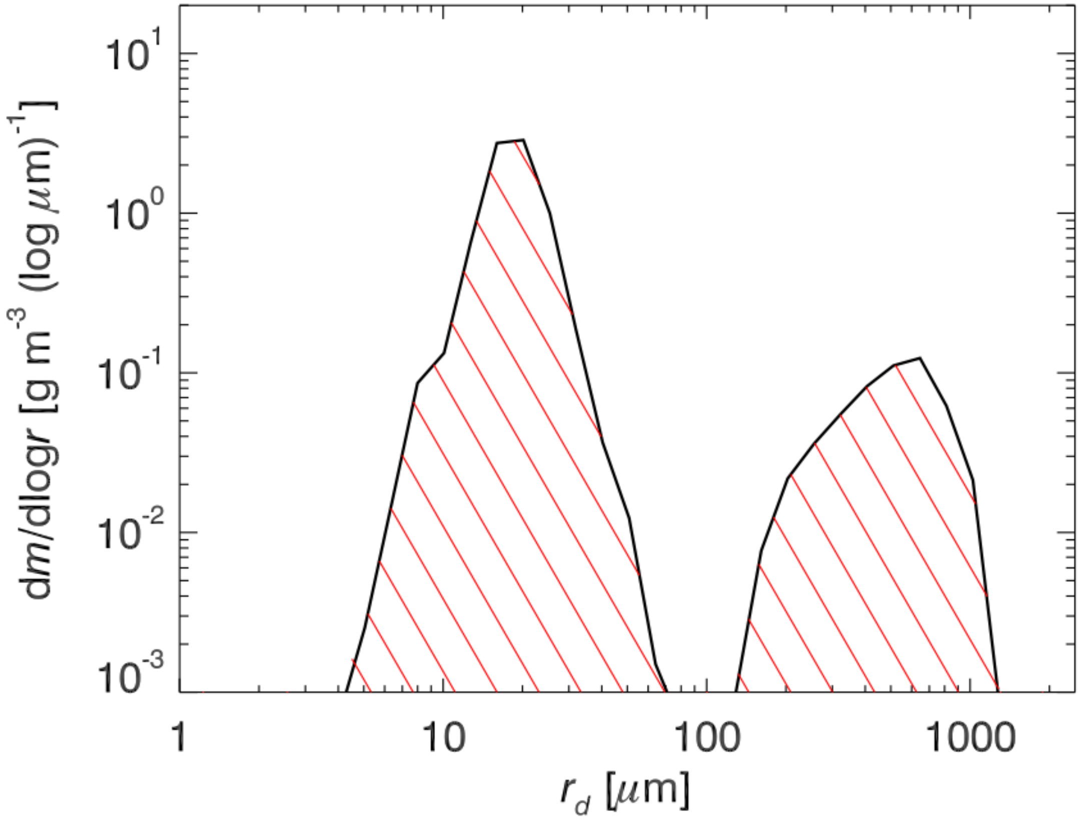

liquid drops


bigger liquid drops

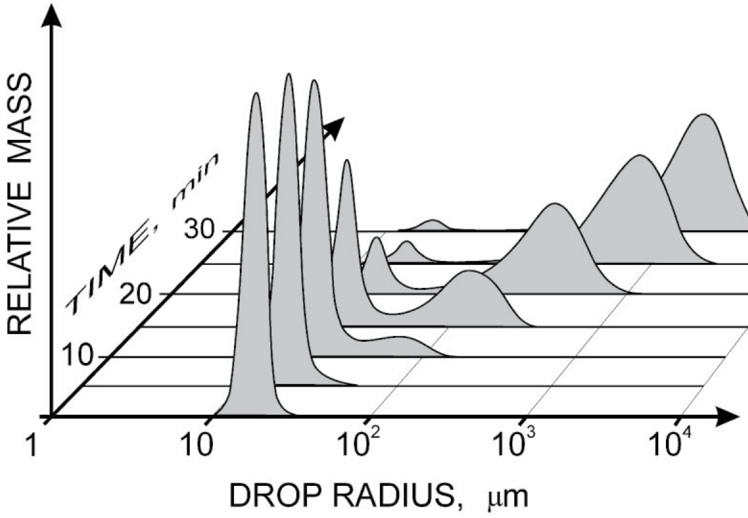
Gabor Vali, University of Wyoming

How do we represent the evolution of drop spectra?

Instantaneous spectrum:



Evolution of spectrum:



From Berry and Reinhardt (1974), adapted from Shaw (2003)

Microphysical parameterizations

Ideally, the following processes should be represented (warm-rain only here):

1. Nucleation
2. Condensational growth
3. Coalescence
4. Droplet breakup
5. Evaporation

Three different parameterization philosophies:

- Simple saturation adjustment
- Size-resolving (bin) microphysics
- Bulk microphysics

Simple saturation adjustment

Requirement for condensation:

$$q_v - q_{vs}(T, p) > 0$$

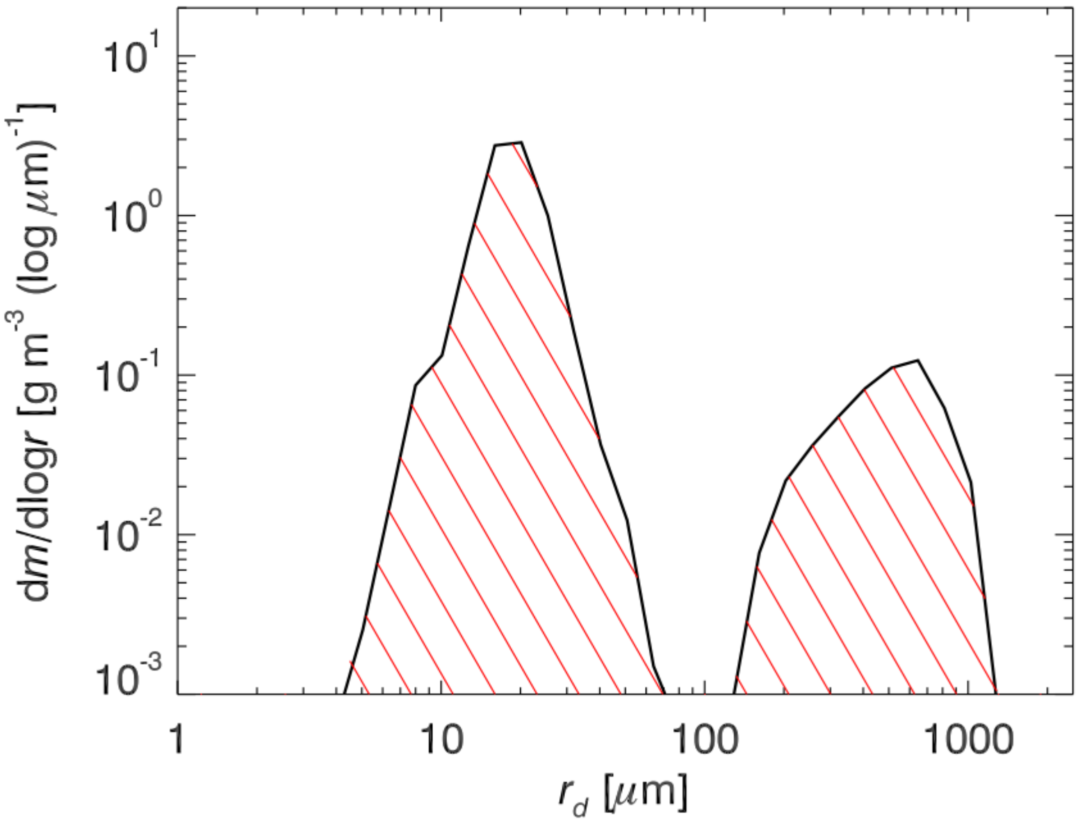
Iteratively determine temperature, q_v, and condensate.

- Represents all drop characteristics by a single mass parameter (mixing ratio)
- Does not explicitly represent nucleation
- Does not explicit represent condensation
- Ignores coalescence

Advantages: simple, cheap, OK (sorta) for nonprecipitating liquid clouds

Disadvantages: naïve, no precip., no information about drop size

Size-resolving (bin) microphysics



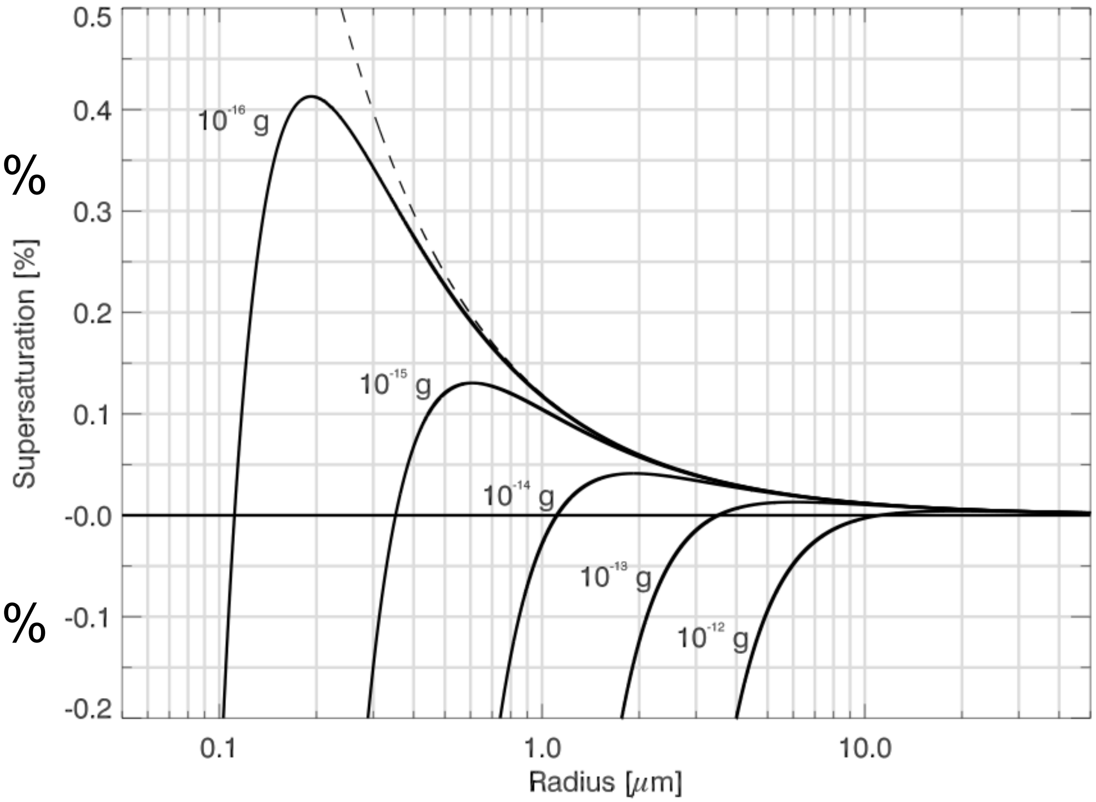
- Discretized drop size distribution
  34 mass-doubling bins
  1 μm – 2 mm
- Discretized aerosol distribution
  19 bins
  0.0076 μm – 7.6 μm

Size-resolving (bin) microphysics — nucleation

Köhler equation

$$S - \frac{2\sigma}{\rho_w R_v T_r} + \frac{2\rho_n M_w r_n^3}{\rho_w M_n r^3} = 0$$

RH > 100%



RH < 100%

Size-resolving (bin) microphysics — condensation

- Diffusion equation for droplet growth
- Flux of vapor to the droplet balanced by flux of latent heat away from droplet

Equation for droplet growth:

$$\frac{\mathrm{d}r^2}{\mathrm{d}t} = \frac{2(S-1)}{\left[\left(\frac{L}{R_v T} - 1\right)\frac{L\rho_l}{KT} + \frac{\rho_l R_v T}{D e_s(T)}\right]}$$

Size-resolving (bin) microphysics — condensation

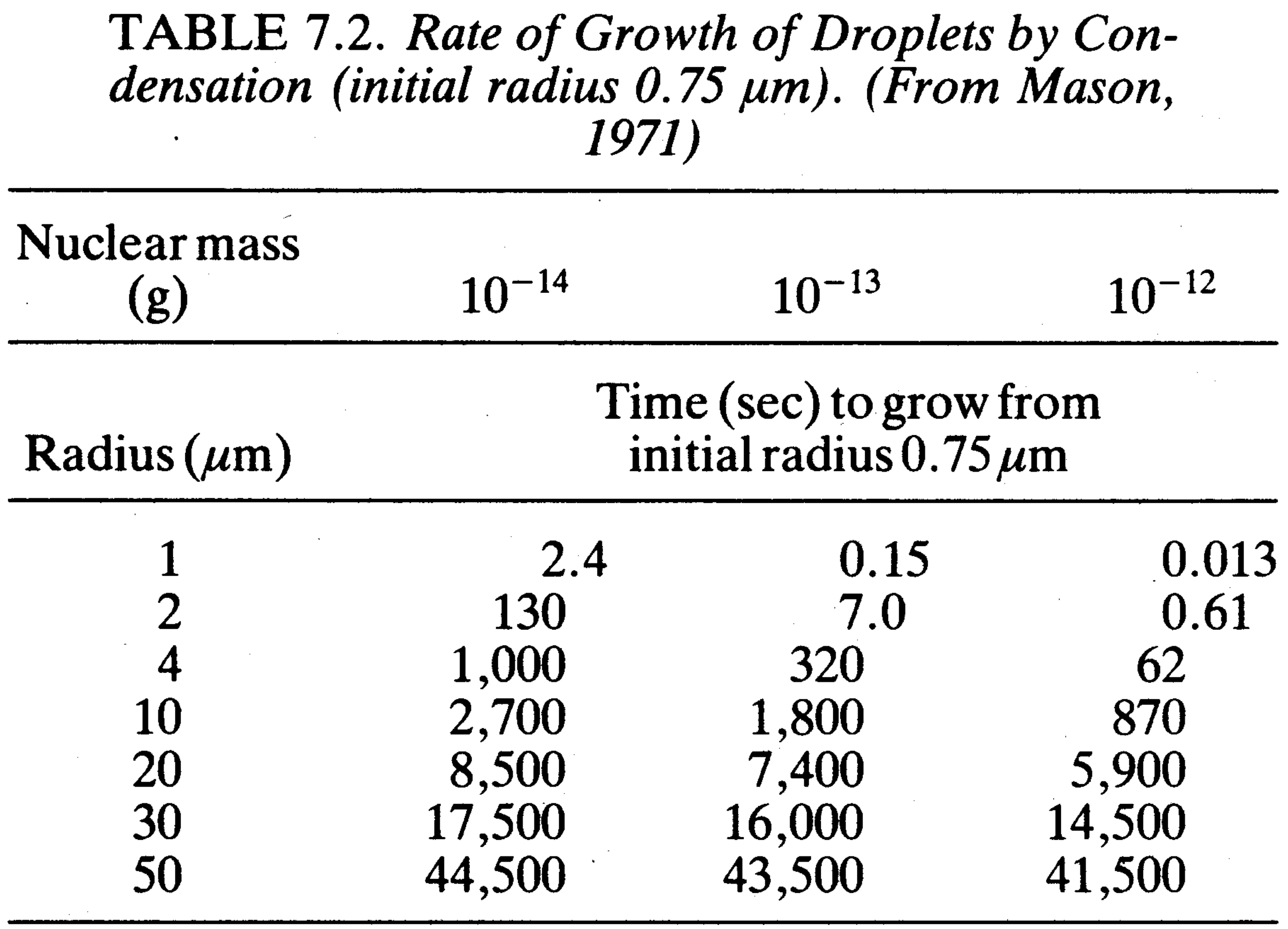


TABLE 7.2. *Rate of Growth of Droplets by Condensation (initial radius 0.75 μm). (From Mason, 1971)*

Nuclear mass (g)	10^{-14}	10^{-13}	10^{-12}
Radius (μm)	Time (sec) to grow from initial radius 0.75 μm		
1	2.4	0.15	0.013
2	130	7.0	0.61
4	1,000	320	62
10	2,700	1,800	870
20	8,500	7,400	5,900
30	17,500	16,000	14,500
50	44,500	43,500	41,500

Size-resolving (bin) microphysics — coalescence

Stochastic collection equation (rate equation for each bin)

$$\frac{\partial N(m)}{\partial t} = \frac{1}{2}\int_0^m N(m-m')K(m-m',m')N(m')\mathrm{d}m' - \int_0^\infty N(m)K(m,m')N(m')\mathrm{d}m'$$

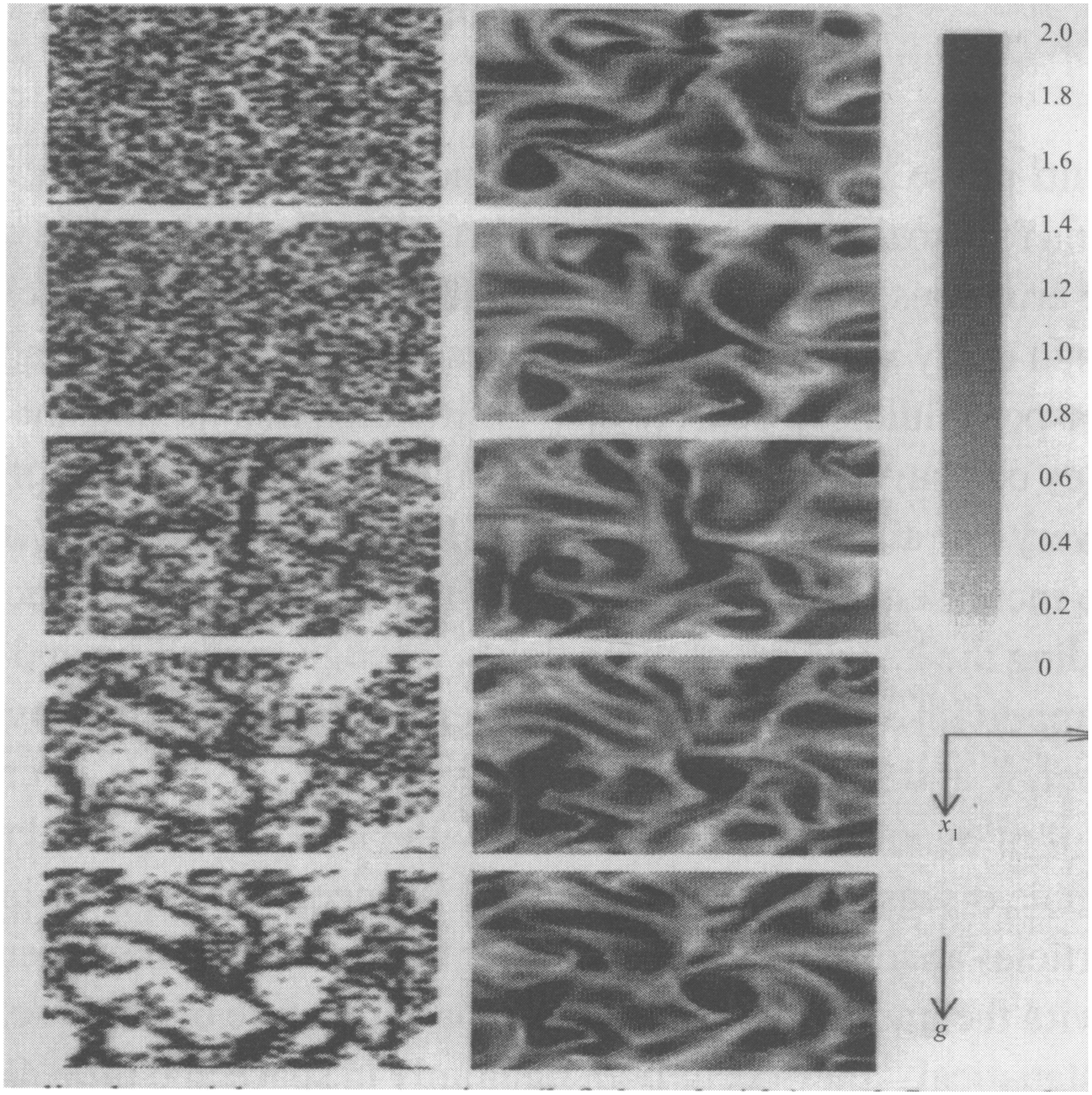
Collection kernel (gravitational)

$$K(m,m') = \pi[r(m)+r(m')]^2|v(m)-v(m')|E(r,r')$$

Terminal fall speed

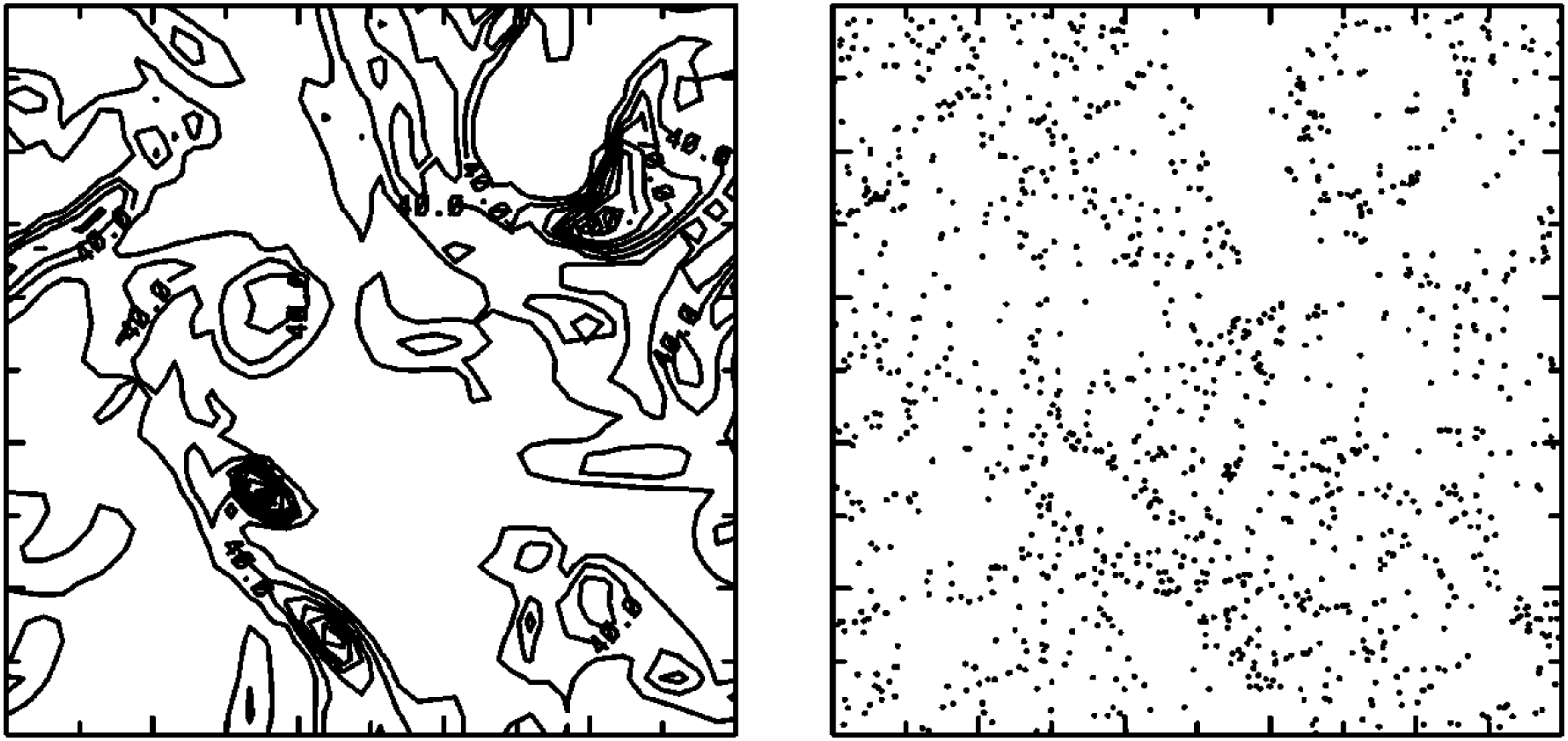
$v = k_1 r^2 \quad \text{for } r < 40\ \mu\text{m}$	cloud; small drizzle
$v = k_2 r \quad \text{for } 40\ \mu m < r < 0.6\ \text{mm}$	large drizzle; small rain drops
$v = k_3 r^{1/2} \quad \text{for } r > 0.6\ \text{mm}$	rain drops

Where do the 20 μm drops come from?



Wang and Maxey (1993)

Turbulence and droplet clustering

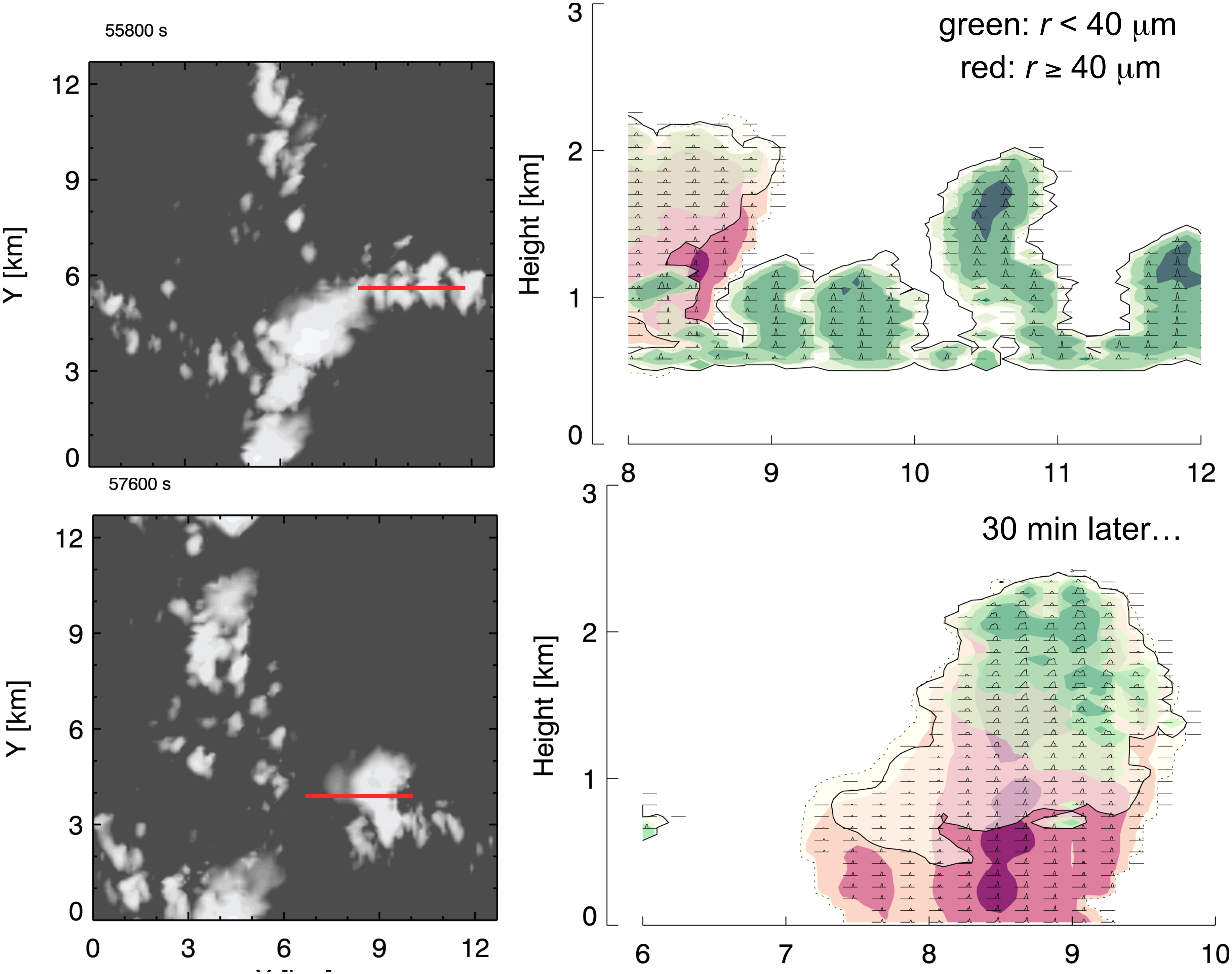


Vaillancourt et al. (2002)

Size-resolving (bin) microphysics

Example from the Rain in Cumulus over the Ocean (RICO) field campaign

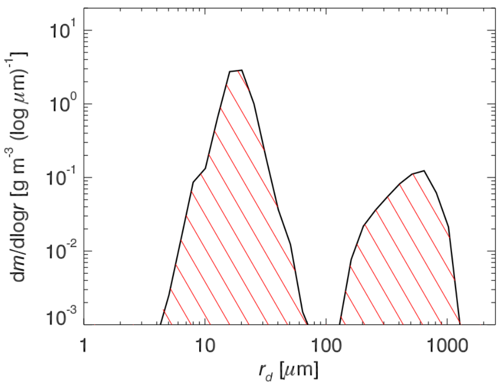
photo by Bjorn Stevens

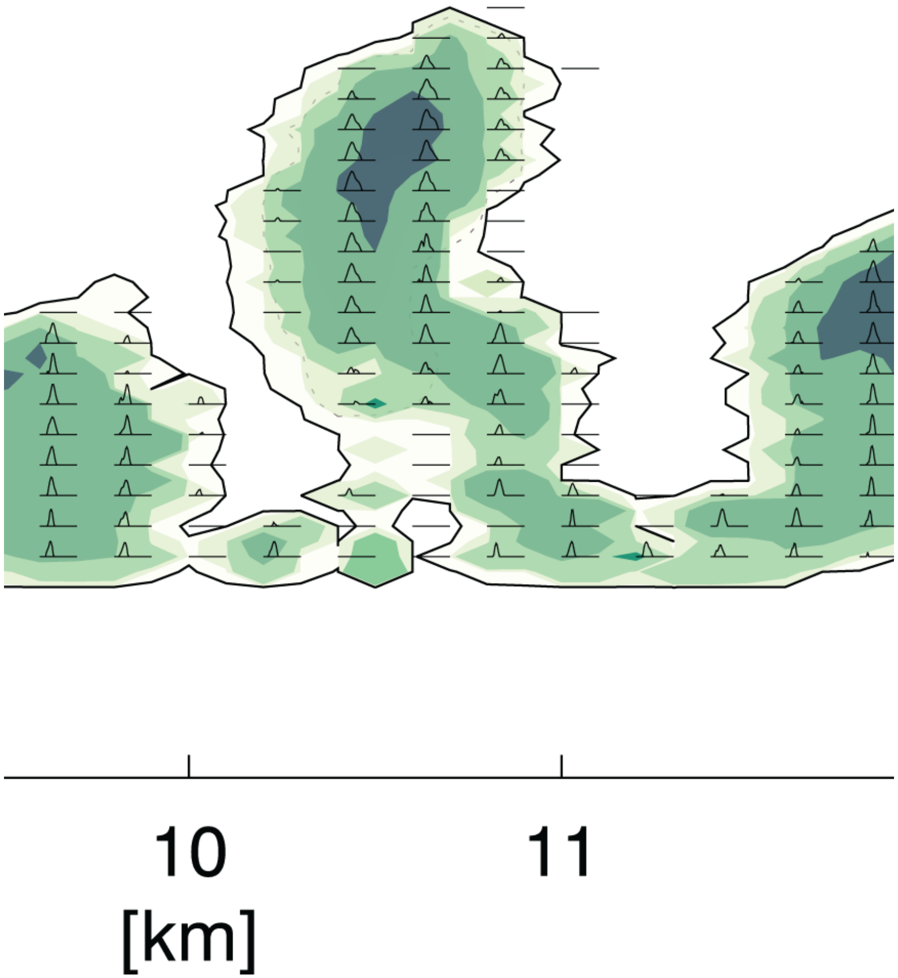


green: $r < 40$ µm
red: $r \geq 40$ µm

30 min later…

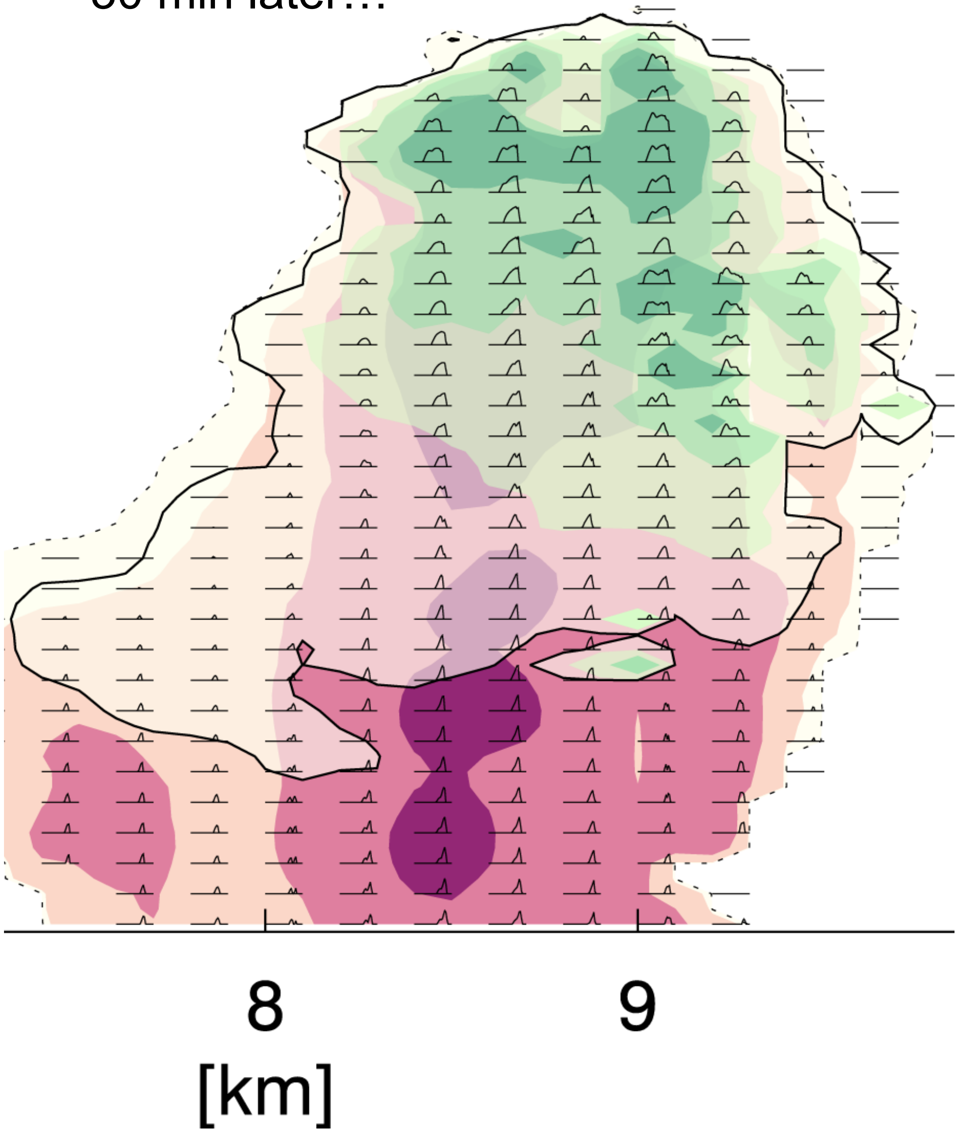
$t = t_0$



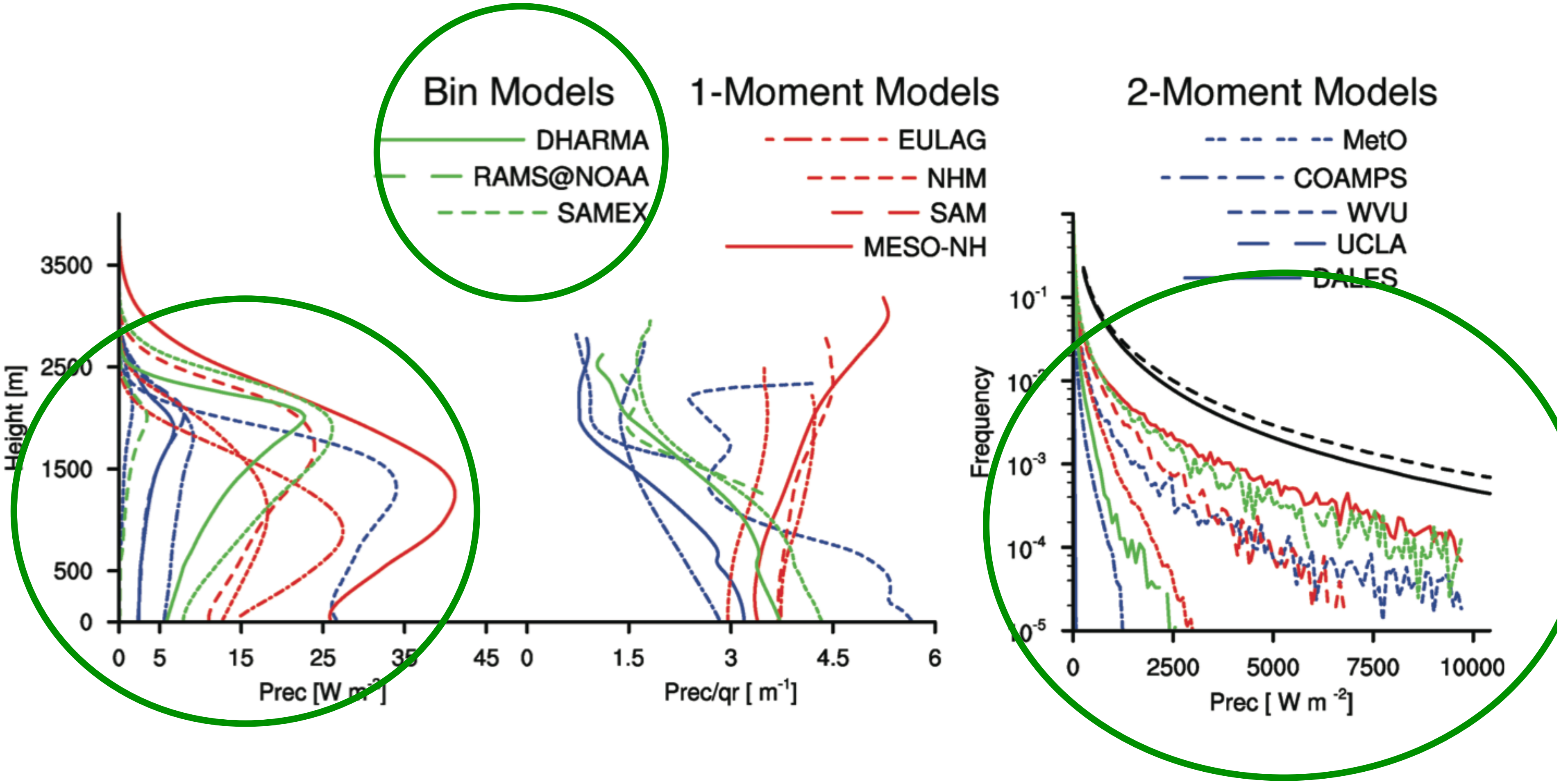


green: $r < 40$ μm
red: $r \geq 40$ μm

30 min later…



Is more complicated always better?



van Zanten et al. (2011)

Bin microphysics — summary

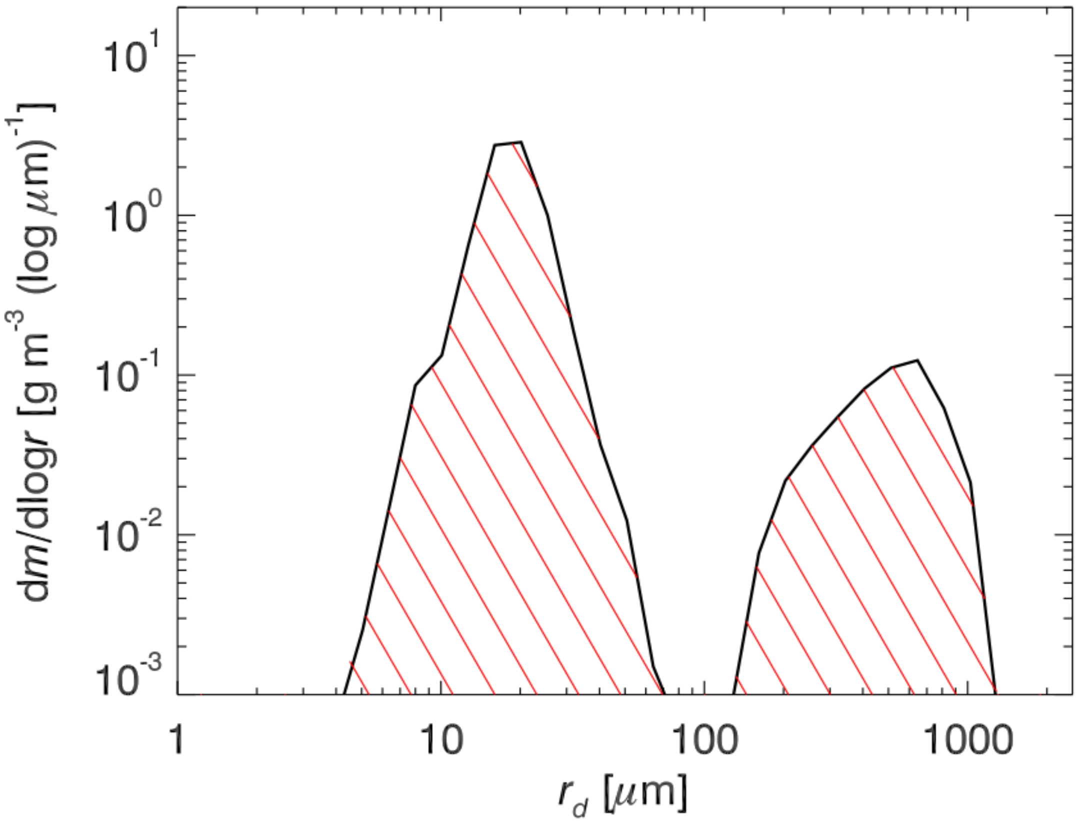
Advantages:

- Represents the fundamental physics of the precipitation process
- Spectral output can be compared with spectral observations (foreshadowing)
- Since we have the DSD, 'forward' calculations can be performed, enabling direct comparison with surface-based remotely sensed observations

Disadvantages:

- Numerically expensive
- Numerically 'challenging' — is the drop broadening we see in the spectra real, or is it a numerical artifact?
- Different bin models don't necessarily converge to one another

Bulk microphysics

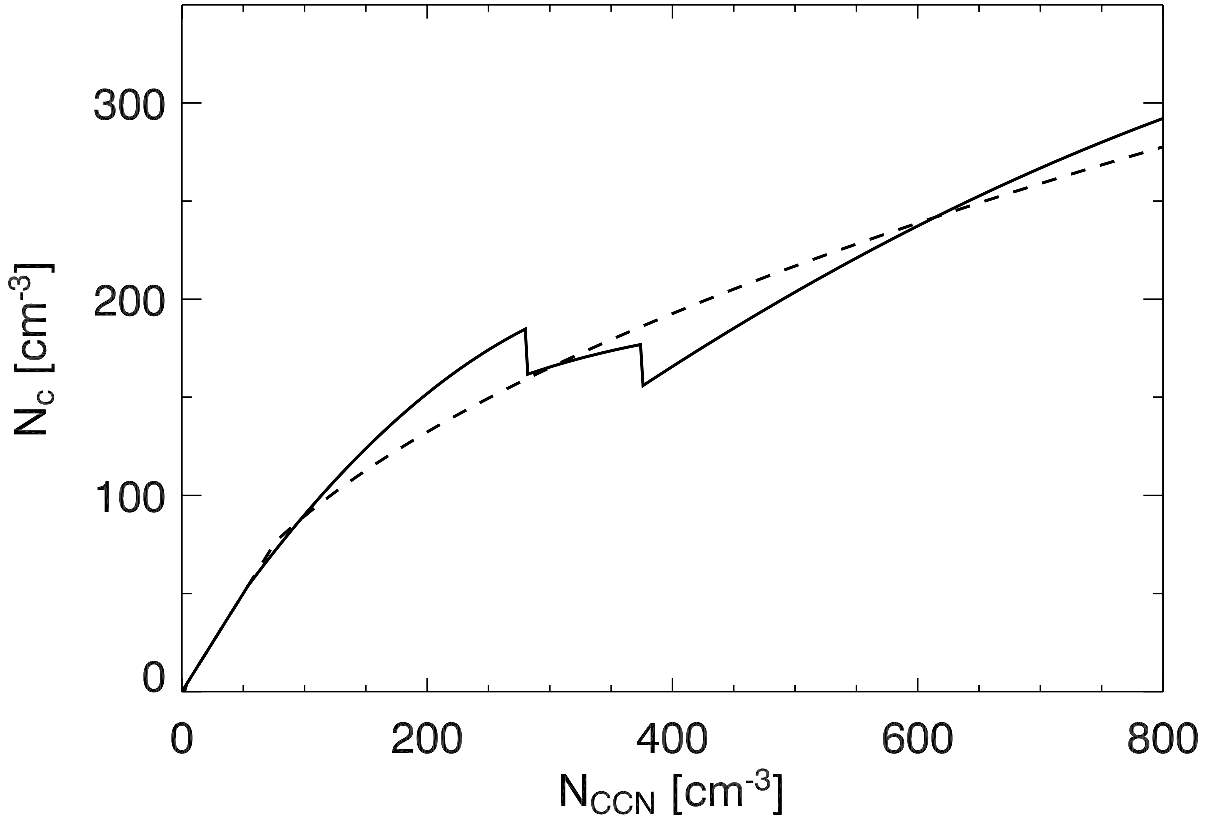


- Partition the condensate into partial moments of the DSD
- Precipitating and nonprecipitating components
- Make some assumptions about DSD of precipitating drops

Bulk microphysics — nucleation and condensation

Sometimes empirically based:

$$
\begin{array}{ll}
N_c = -1.15\times10^{3} N_{CCN}{}^{2} + 0.963 N_{CCN} + 3.5 & 54 \le N_{CCN} \le 280 \\
N_c = 197.0(1 - e^{-6.13\times10^{-3} N_{CCN}}) & 280 < N_{CCN} < 375 \\
N_c = -2.10\times10^{-4} N_{CCN}{}^{2} + 0.568 N_{CCN} - 27.9 & 375 \le N_{CCN} \le 1500
\end{array}
$$



Usually employ simple saturation adjustment

Bulk microphysics — collision-coalescence

Collection of cloud droplets by falling precipitation

For a single drop, the increase of mass of the falling drop is

$$\frac{dM}{dt} = \frac{\pi}{4} v_D \rho_a q_l \varepsilon$$

But we have a whole spectrum of precipitation drops. Let's assume M-P:

$$n(D) = N_0 e^{-\lambda D}$$

Integrate the accretion formula over the DSD:

$$\frac{dq_r}{dt} = \frac{\pi}{4} q_l \varepsilon N_0 \int_0^\infty v_D D^2 e^{-\lambda D} dD$$

Bulk microphysics — collision-coalescence

But the terminal velocity is a function of size:

$$\frac{dq_r}{dt} = \frac{\pi}{4} q_l \varepsilon N_0 \int_0^\infty [k(g\frac{\rho_l}{\rho_a})^{1/2} D^{1/2}] D^2 e^{-\lambda D} dD$$

Yuck. Simplify…

$$\frac{dq_r}{dt} = k(g\frac{\rho_l}{\rho_a})^{1/2} \frac{\pi}{4} q_l \varepsilon N_0 \int_0^\infty D^{5/2} e^{-\lambda D} dD$$

This can be integrated analytically. Yay!

$$\frac{dq_r}{dt} = k(g\frac{\rho_l}{\rho_a})^{1/2} \frac{\pi}{4} q_l \varepsilon N_0 \frac{\Gamma(7/2)}{\lambda^{7/2}}$$

Bulk microphysics — collision-coalescence

We need an expression for the slope parameter. Try to express it in terms of model variables. Mixing ratio is just the 3rd moment of the DSD:

$$q_r = \frac{\rho_l}{\rho_a}\frac{\pi}{6}N_0\int_0^\infty D^3 e^{-\lambda D}dD$$

which also can be analytically integrated:

$$q_r = \frac{\rho_l}{\rho_a}\frac{\pi}{6}N_0\frac{\Gamma(4)}{\lambda^4}$$

solve for the slope parameter and substitute into previous equation…

Bulk microphysics — collision-coalescence

$$\frac{dq_r}{dt} = k_1 g^{1/2} \frac{\rho_a}{\rho_l}^{3/8} \varepsilon N_0^{1/8} q_c q_r^{7/8}$$

$$\sim q_c q_r$$

This was all made possible because we assumed a ‘nice’ DSD.

Bulk microphysics — another approach

- Apply multiple nonlinear regression to the thousands of DSDs from simulations to obtain these conversion rates
- Bulk drizzle parameterizations (Khairoutdinov and Kogan 2000; Kogan 2013)
- Prognostic equations for q_c, N_c, q_r, N_r, and N_{CCN}
- 2-moment

$$\left.\frac{\partial q_r}{\partial t}\right|_{auto} = 1350 q_c^{2.47} N_c^{-1.79} \qquad \left.\frac{\partial q_r}{\partial t}\right|_{acc} = 67(q_c q_r)^{1.15}$$

$$V_{q_r} = 0.007 r_{vr} - 0.1 \qquad V_{N_r} = 0.012 r_{vr} - 0.2$$

Bulk microphysics

Advantages:

- Represents some aspects of fundamental physics
- Conceptually straightforward (usually)
- Can mimic reasonable response to aerosol concentrations
- Can account for cloud processing of aerosol
- Can be numerically inexpensive

Disadvantages:

- Only appropriate when the assumptions hold
- Oftentimes tuned for specific cases or phenomena
- Can be numerically expensive, depending on complexity

Evaluation of microphysical parameterizations

Forward calculation vs. inverse/retrievals?

Forward calculation:

model cloud fields → forward model → synthetic observations

Inverse calculation:

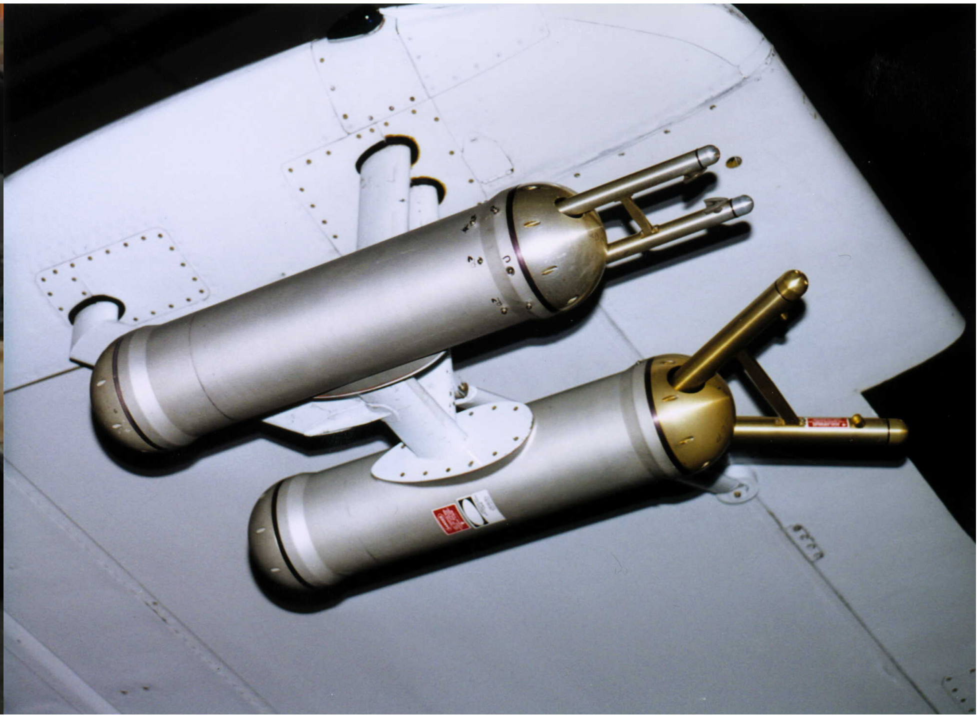
Remotely sensed observations → retrieval → retrieved geophysical quantities

Evaluation of microphysical parameterizations: cloud observations

FSSP

FSSP (NCAR/RAL)

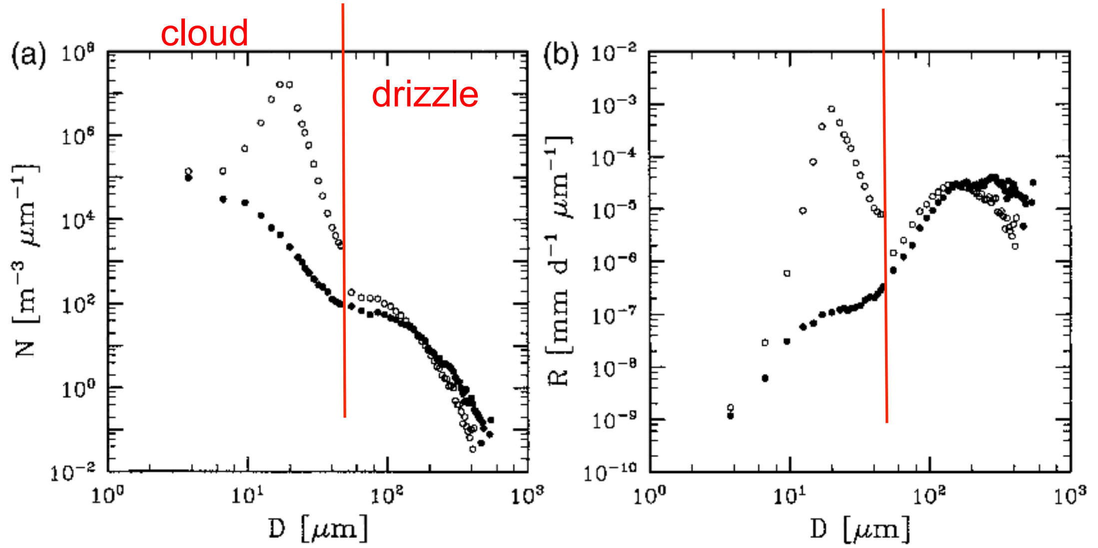
2DC and 2DP



2DC and 2DP (NCAR/RAF)

Evaluation of microphysical parameterizations

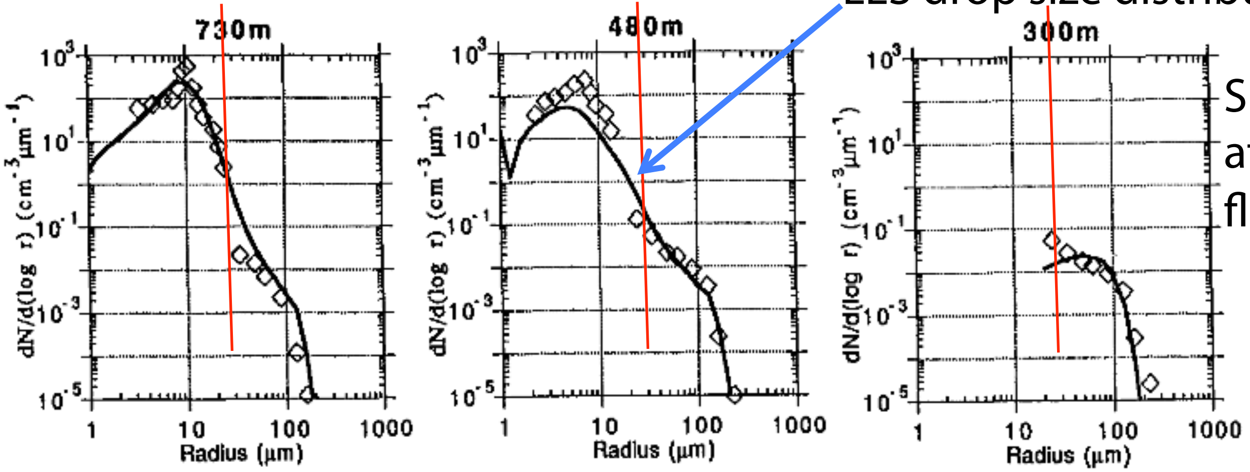
Drop size distributions for cloud and drizzle modes



Droplet spectra from DYCOMS RF07 (VanZanten et al. 2005)

FIG. 4. (a) Leg-averaged drop concentration *N* and (b) drizzle rate *R* as function of the drop diameter *D* with regard to the second CT leg (open circles) and first SC leg (closed circles) of RF07.

LES drop size distribution

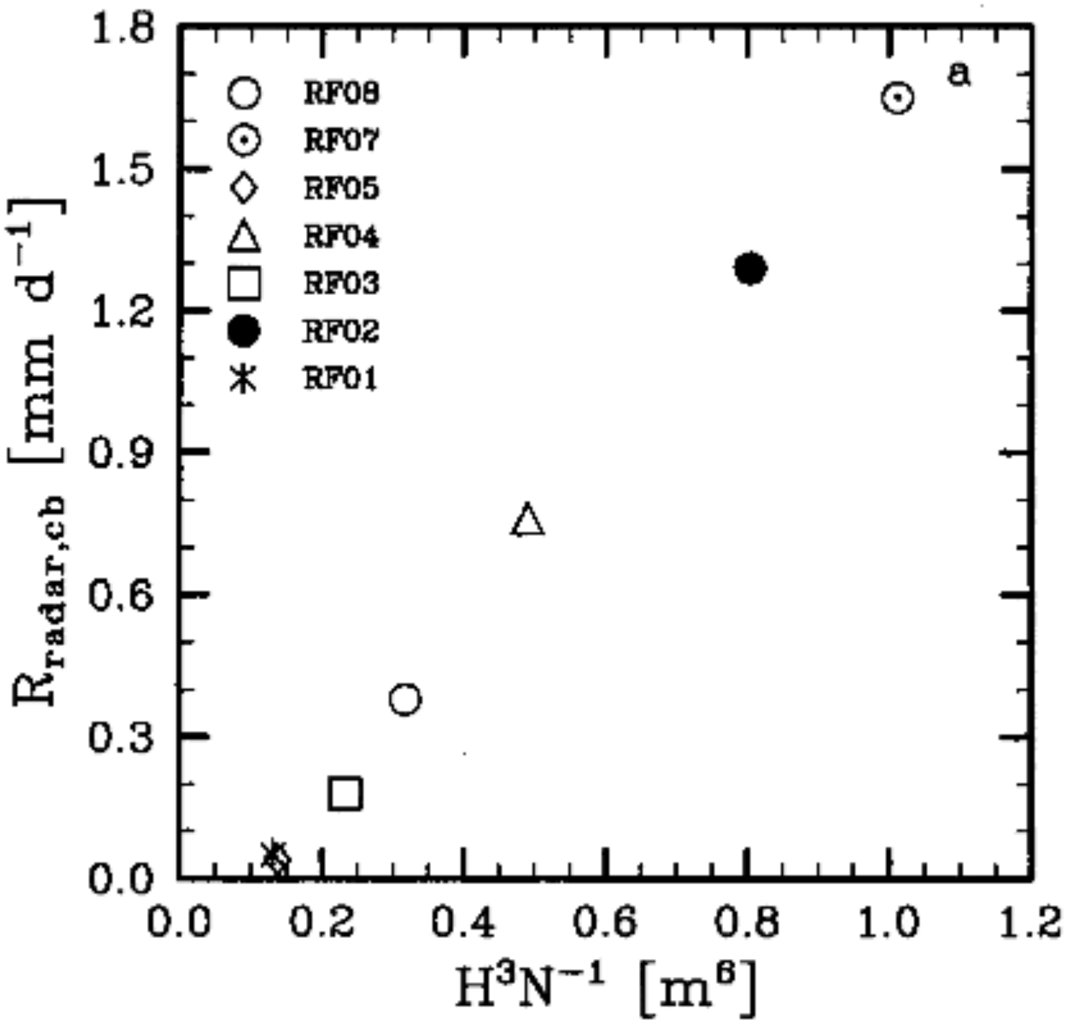


Simulated and observed spectra at three different heights from flight 526 (Kogan et al. 1995)

FIG. 7. Comparison of droplet spectra simulated in the case N (solid lines) with the measurements from Nicholls (1984) (diamonds) at different heights above the surface: (a) 730, (b) 480, and (c) 300 m.

Precipitation process scalings

vanZanten and Stevens (2005)



Scalings:

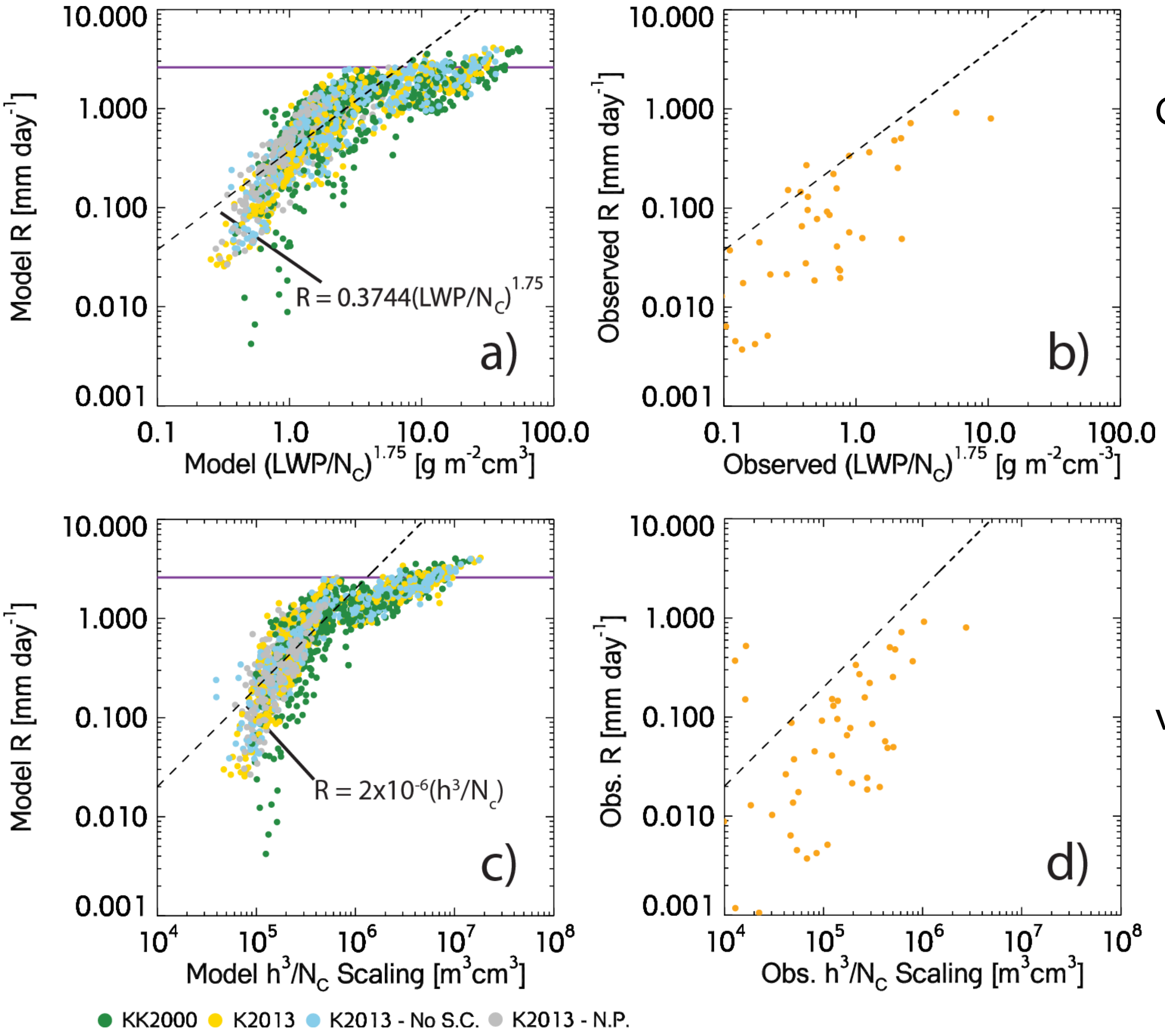
H^3/N [vanZanten et al (2005)]

H^4/N [Pawloska and Brenguier (2003)]

$(\mathrm{LWP}/N)^{1.75}$ [Comstock et al. (2004)]

… where H is cloud depth

Precipitation process scalings (drizzle rate)

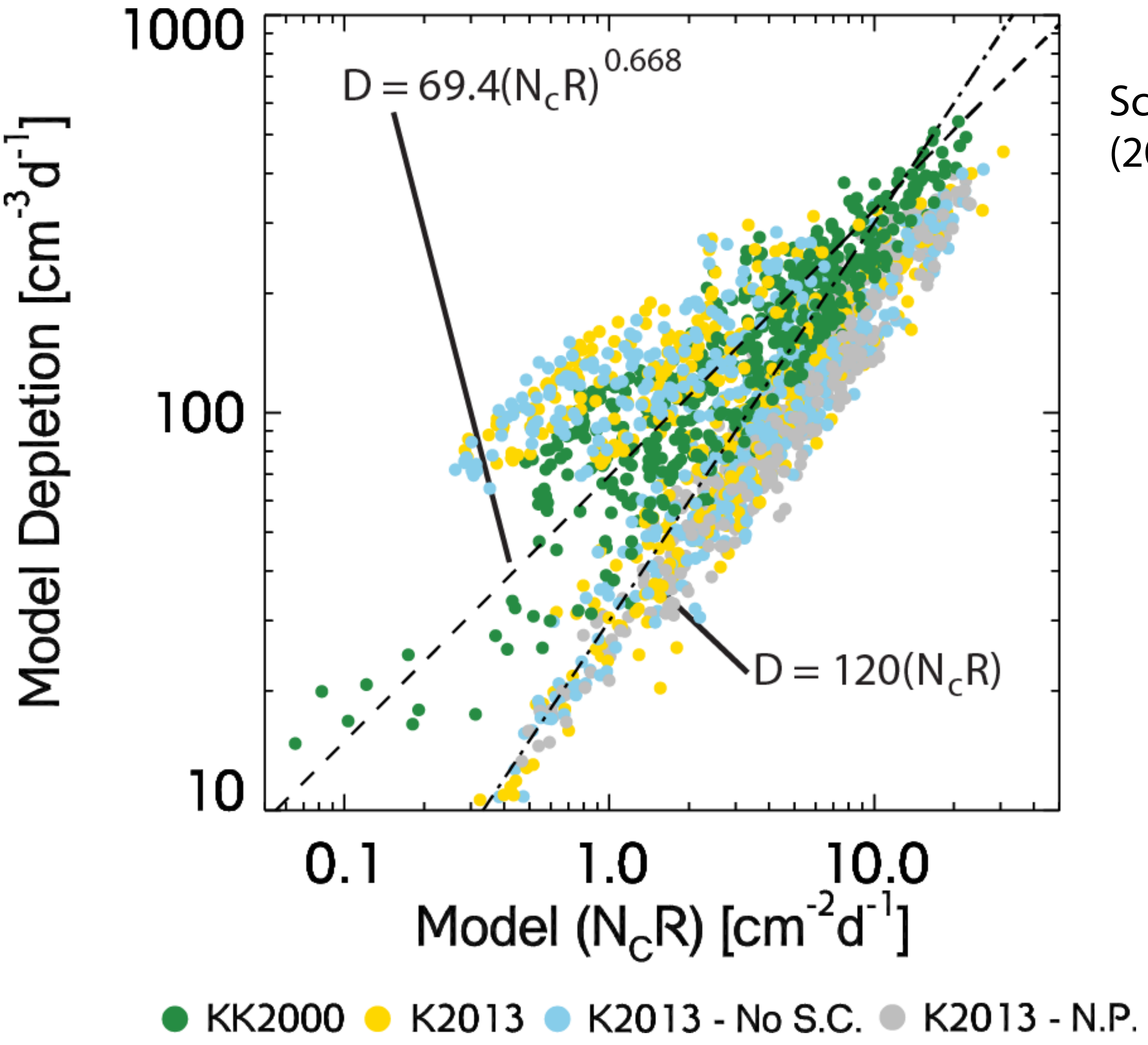


Comstock et al. (2004)

van Zanten et al. (2005)

Nelson et al. (2015, in review)

Precipitation process scalings (coalescence scavenging)

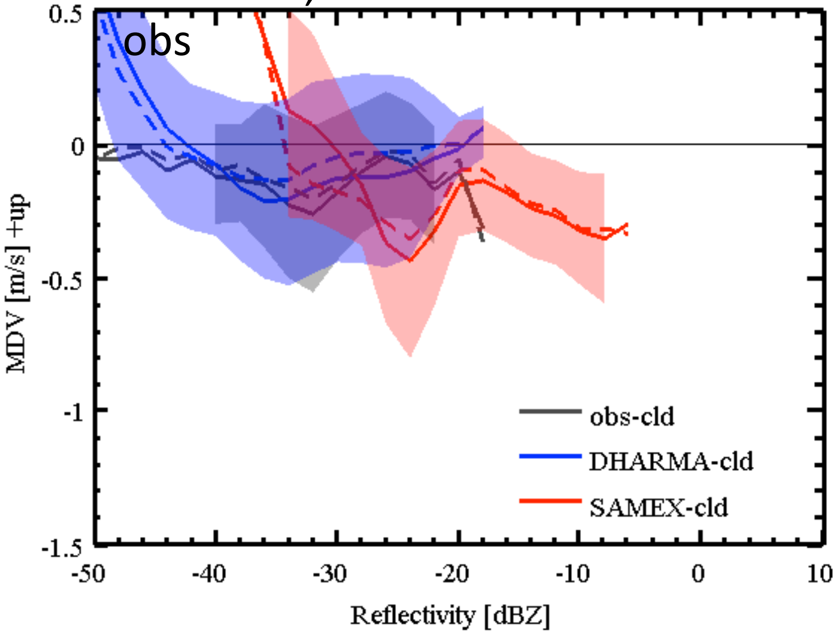


Scalings from Mechem et al. (2006) and Wood (2006)

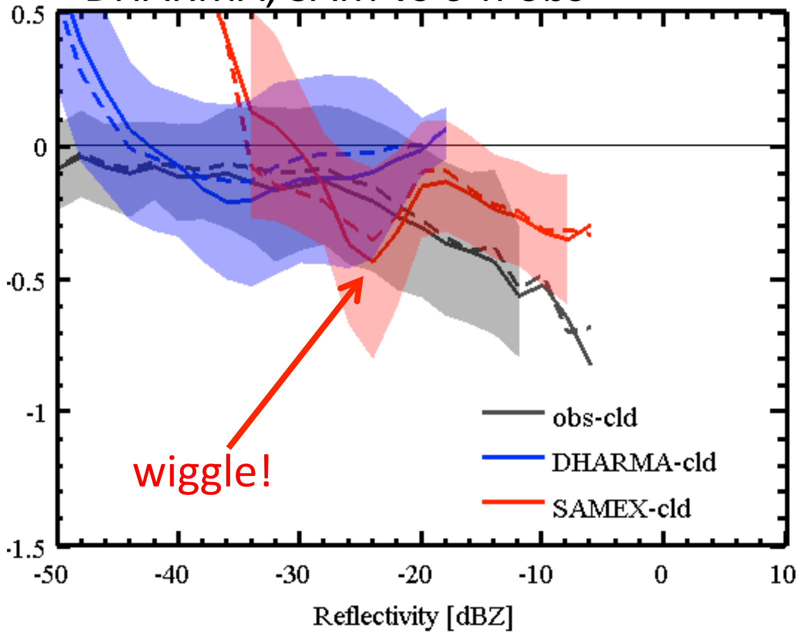
Nelson et al. (2015, in review)

Results: Mean Doppler velocity vs reflectivity

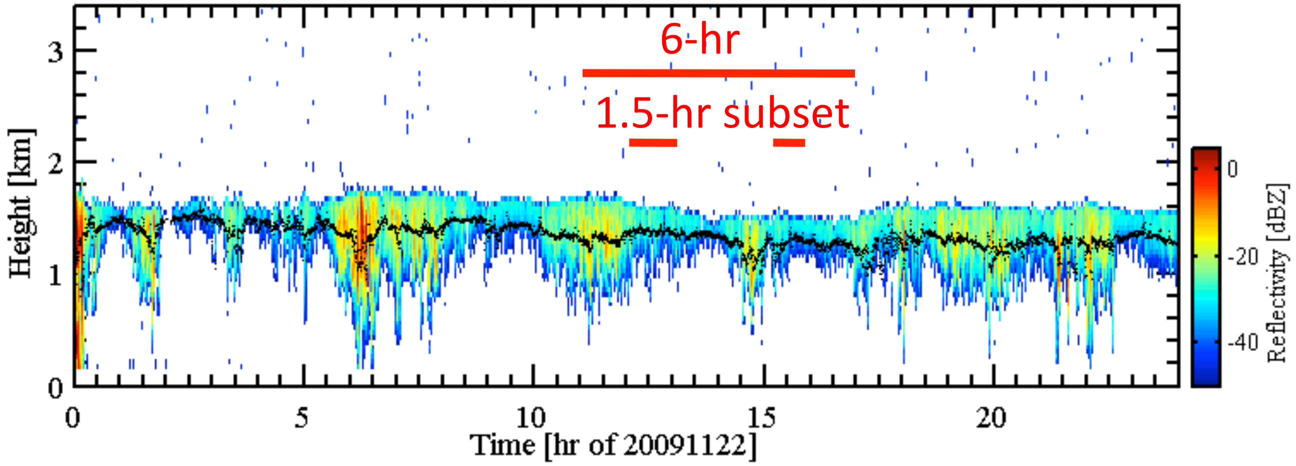
DHARMA, SAM vs 1.5-h subset obs



DHARMA, SAM vs 6-h obs



wiggle!

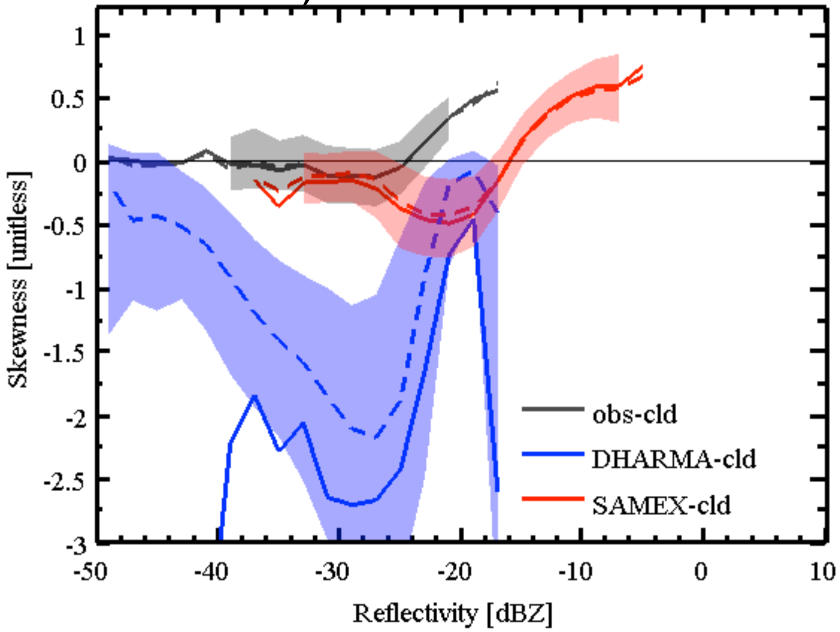


6-hr

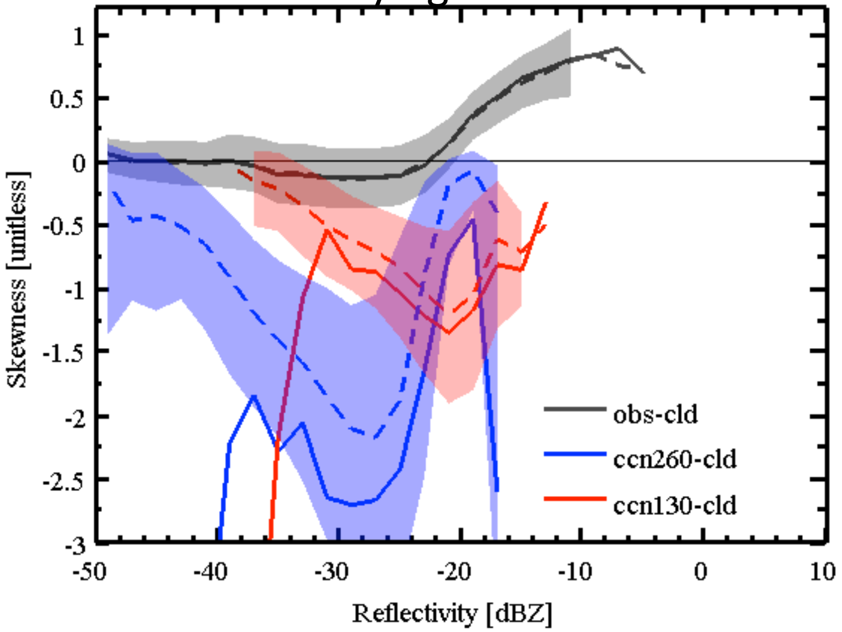
1.5-hr subset

Results: Doppler velocity skewness vs reflectivity

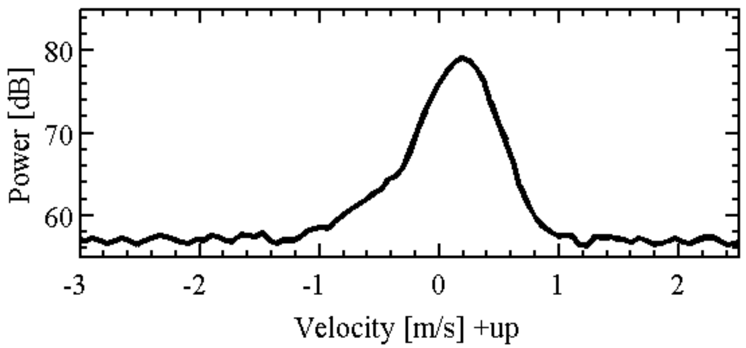
DHARMA, SAM vs subset obs



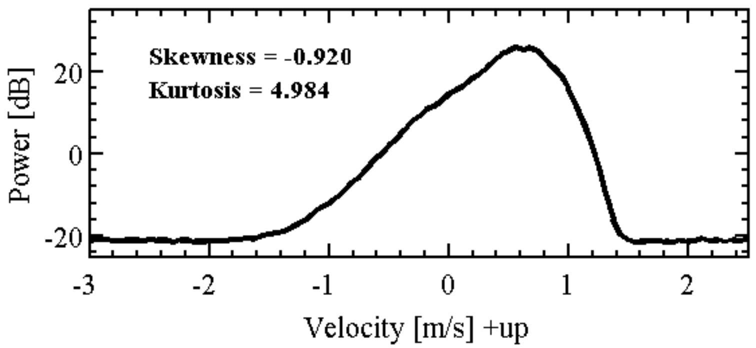
DHARMA varying CCN vs 6-h obs



Example of observed Doppler spectrum



Example of simulated Doppler spectrum



Discussion — model evaluation

Which is more useful for model evaluation/validation, forward calculation or retrievals (the inverse calculation)?

Discussion — What governs BL cloud precipitation processes?

Is it…..

Aerosol?

Lower aerosol concentrations ("cleaner") → fewer, larger cloud droplets → more efficient collision efficiency → greater precipitation production

Or is it…..

Meteorology?

Deeper (or moister) cloud → more liquid water → larger cloud droplets → greater precipitation production