Hans-Ertel-Zentrum für Wetterforschung
Deutscher Wetterdienst

HErZ-CC LES course

The microphysics lecture

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Overview

→ microstructure of clouds

→ cloud processes

→ bulk parameterization

→ warm rain: autoconversion / accretion

→ sedimentation

→ more details on sedimentation and evaporation

→ turbulence effects on warm rain

→ ice particle fall speeds

→ ice nucleation

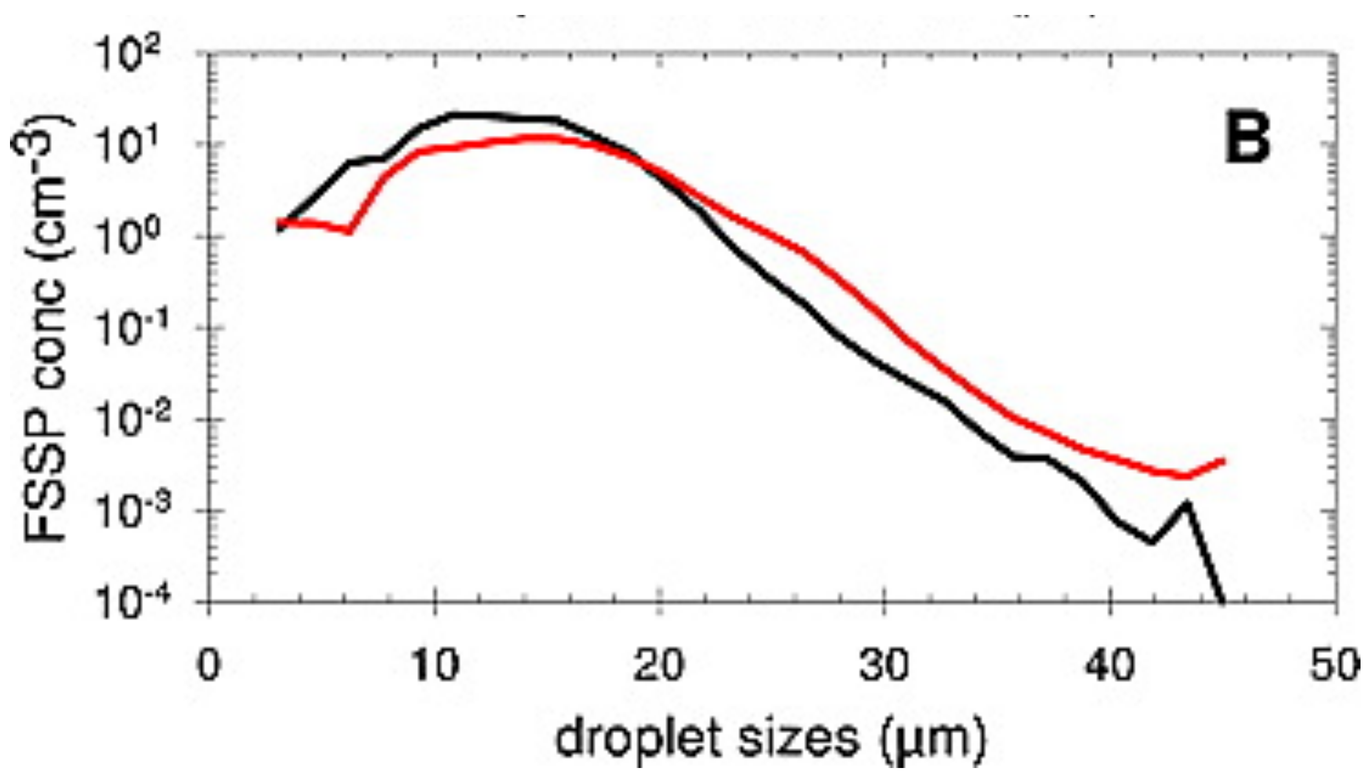
→ glacitation of clouds

→ UCLA-LES microphysics schemes

Microstructure of liquid clouds

Liquid clouds are characterised by small micrometer sized droplet. Typical drops sizes range from 1-2 µm and a few tens of micrometers.

Drop size distributions in maritime shallow clouds

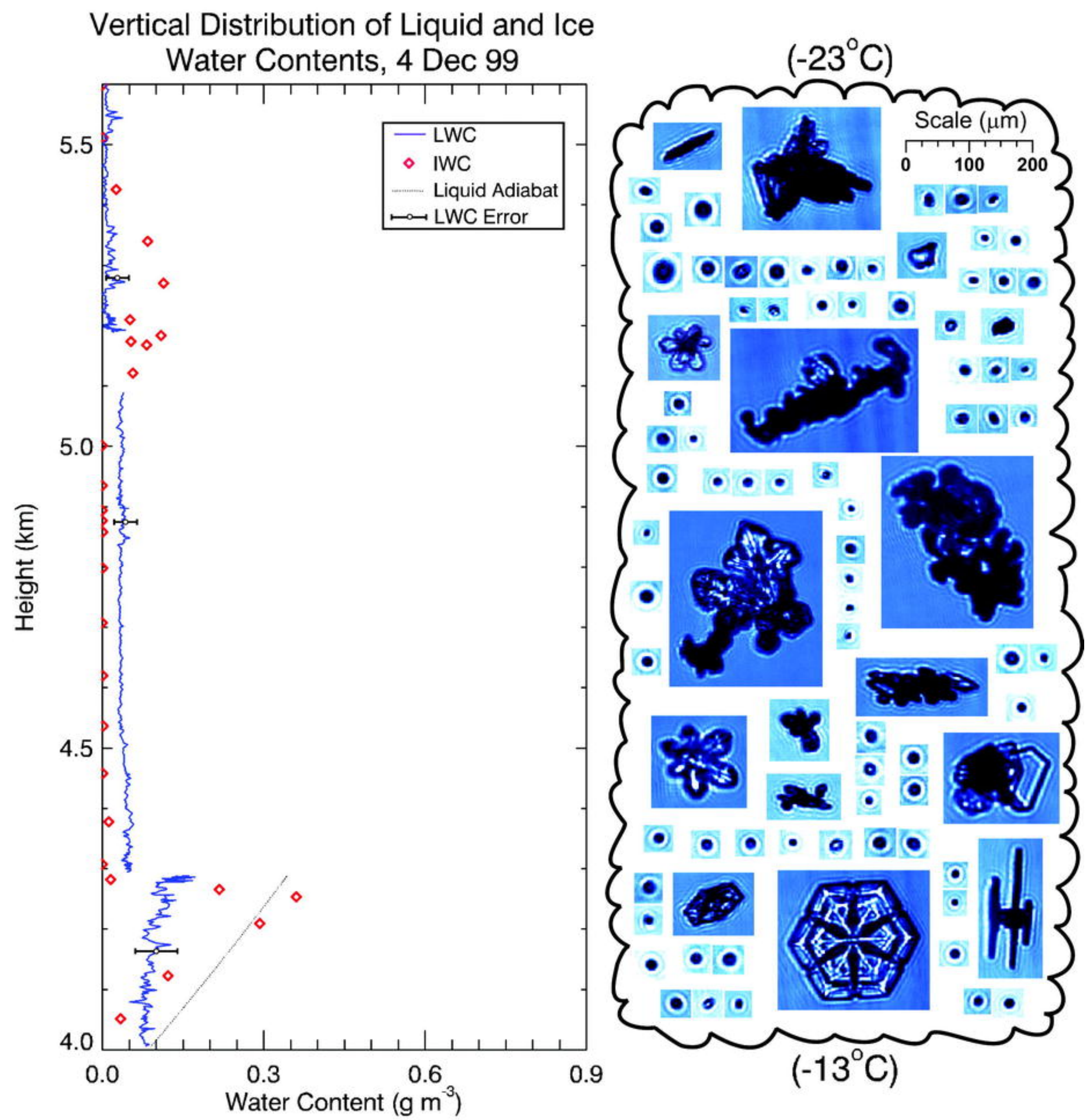


(from Hudson and Noble, 2009, JGR)

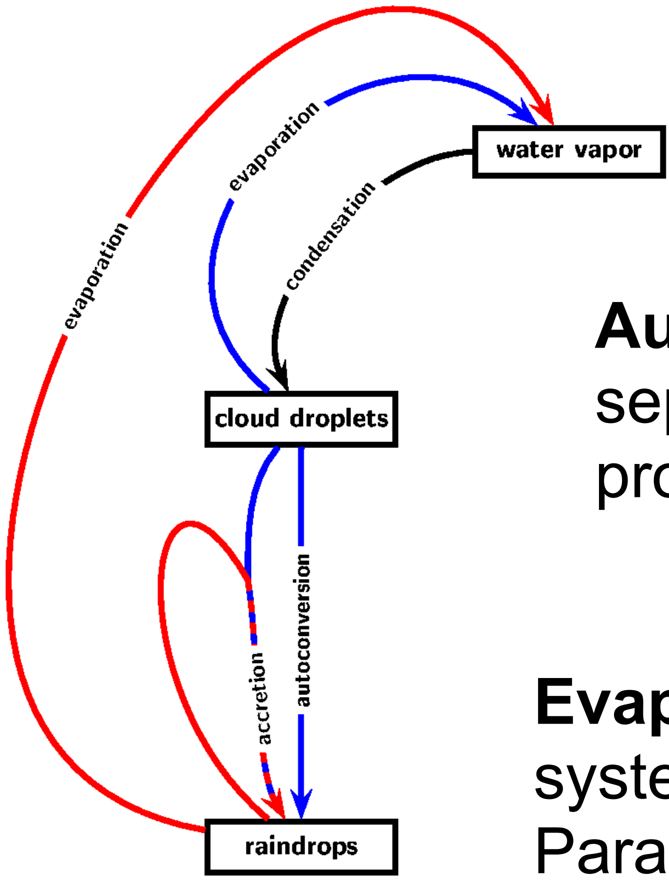
Microstructure of mixed-phase clouds

In mixed-phase clouds we find small liquid droplet coexisting with ice particles of different shapes and sizes.

Here an example of measurements with a Cloud Particle Imager (CPI) by Fleishhauer et al. (2002).



Cloud microphysical processes



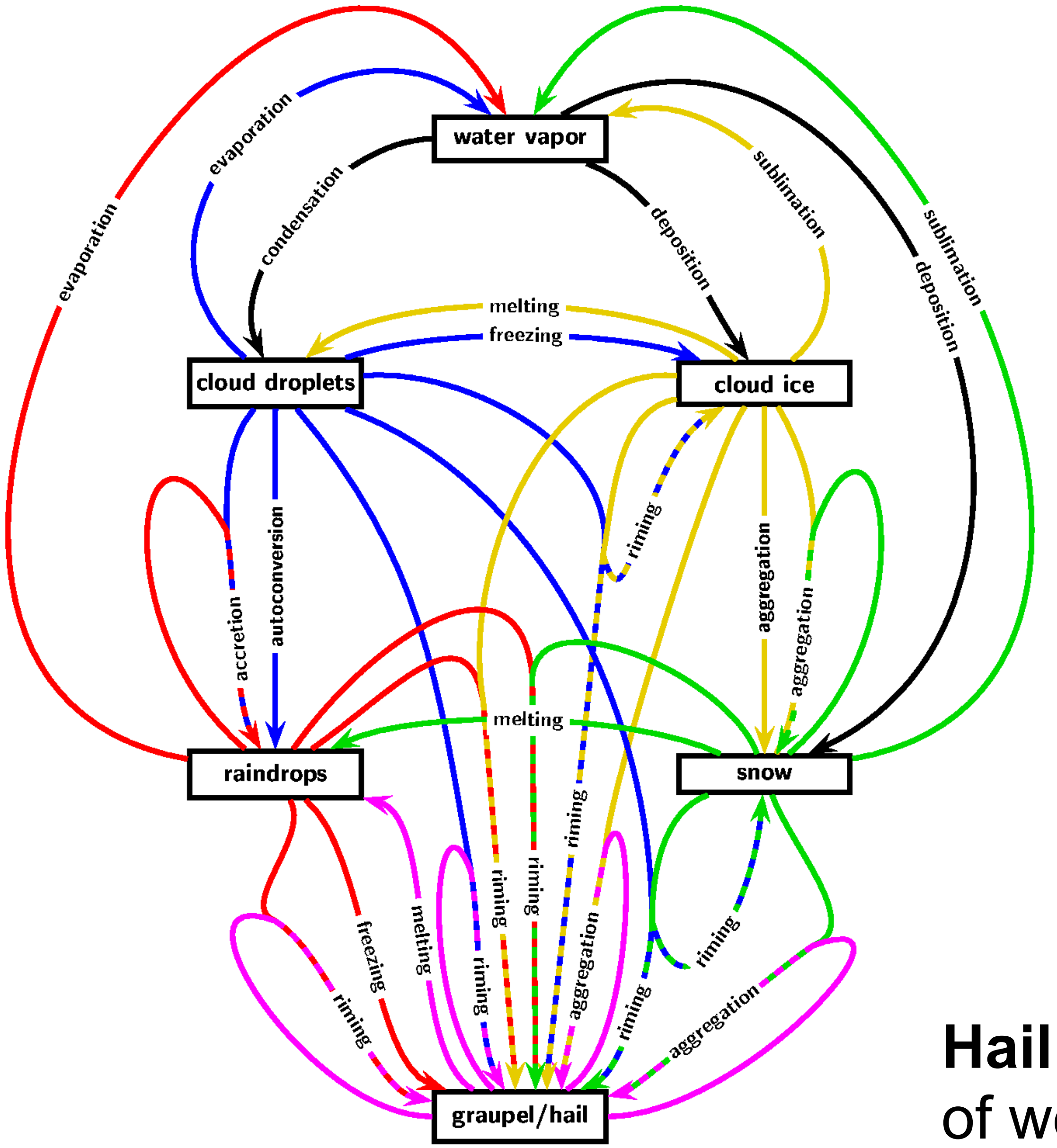
Evaporation and condensation of cloud droplets are usually parameterized by a saturation adjustment scheme.

Autoconversion is an artificial process introduced by the separation of cloud droplets and rain. Parameterization of the process is quite difficult and many different schemes are available.

Evaporation of raindrops can be very important in convective systems, since it determines the strength of the cold pool. Parameterization is not easy, since evaporation is very size dependent.

Even for the warm rain processes a lot of things are unknown or in discussion for decades, like effects of **mixing / entrainment** on the cloud droplet distribution, effects of **turbulence** on coalescence, **coalescence efficiencies, collisional breakup** or the details of the **nucleation** process. In most cloud models these problems are neglected or parameterized in a quite simple and ad-hoc way.

Cloud microphysical processes



Conversion processes, like snow to graupel conversion by riming, are very difficult to parameterize but very important in convective clouds.

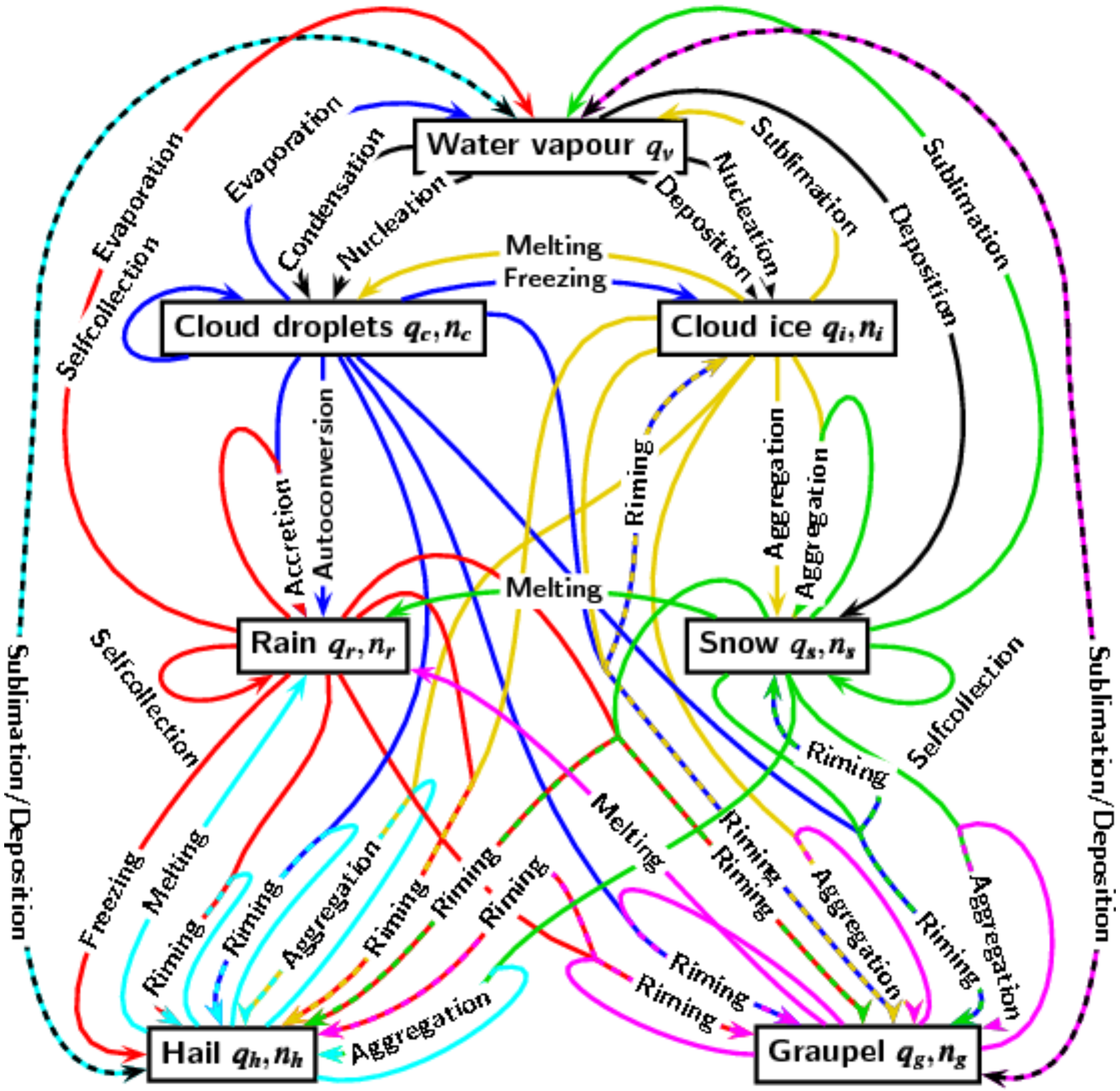
Especially for snow and graupel the particle properties like **particle density** and **fall speeds** are important parameters. The assumption of a constant particle density is questionable.

Aggregation processes assume certain collision and sticking efficiencies, which are not well known.

Hail processes is especially complicated because of wet growth, partial melting or shedding.

The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood

Cloud microphysical processes



This is the level=5 scheme in UCLA-LES

... but secondary processes, like Hallet-Mossop, are not included in the diagram.

Spectral formulation of cloud microphysics

The particle size distribution ***f(x),*** with some measure of particle size ***x***, is explicity calculated from

$$\frac{\partial f(x,\vec{r},t)}{\partial t} + \nabla \cdot [\vec{v}(\vec{r},t) f(x,\vec{r},t)] + \frac{\partial}{\partial z}[v_s(x) f(x,\vec{r},t)] + \frac{\partial}{\partial x}[\dot{x} f(x,\vec{r},t)] = \sigma_{coal} + \sigma_{break}$$

with

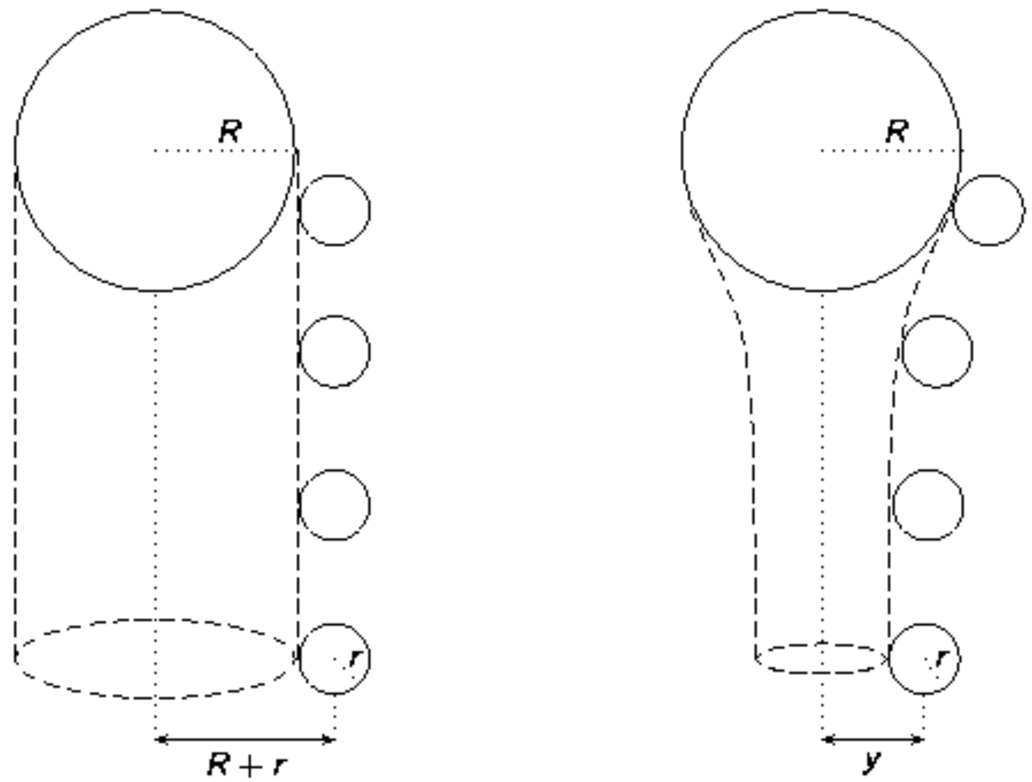
$$\sigma_{coal} = \frac{1}{2}\int_0^x f(x-x',\vec{r},t)\, f(x',\vec{r},t)\, K(x-x',x')\, dx' - \int_0^\infty f(x,\vec{r},t)\, f(x',\vec{r},t)\, K(x,x')\, dx'$$

and

$$\sigma_{break} = \frac{1}{2}\int_0^\infty \int_0^x f(x',\vec{r},t)\, f(x'',\vec{r},t)\, B(x',x'')\, P(x;x',x'')\, dx'\, dx'' - \int_0^\infty f(x,\vec{r},t)\, f(x',\vec{r},t)\, B(x,x')\, dx'.$$

The gravitational collision-coalescence kernel

$$K(x,y) = \pi\,[r(x)+r(y)]^2\,|v(x)-v(y)|\,E_{coll}(x,y)\,E_{coal}(x,y)$$

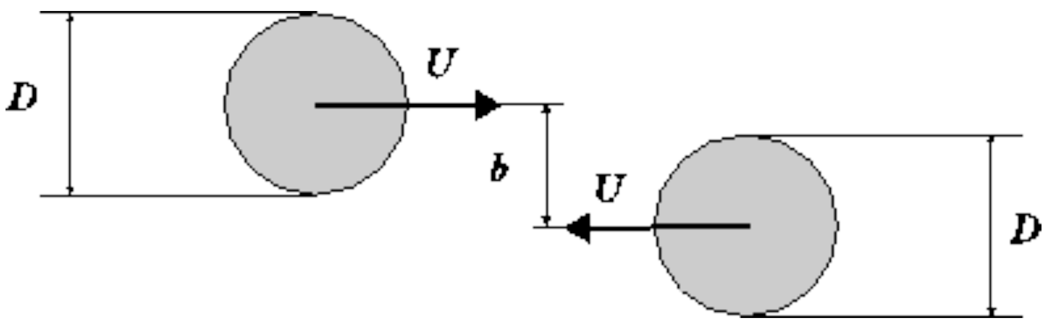


collision efficiency:

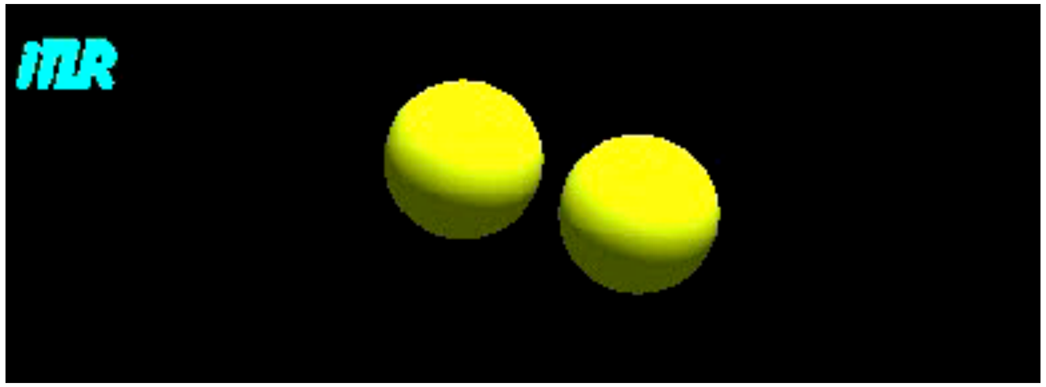
$$E_{coll} = \frac{y^2}{(R+r)^2}$$

The effects of in-cloud turbulence on the collision frequency is a current research topic. Recent results indicate that turbulence can significantly enhance the rain formation process.

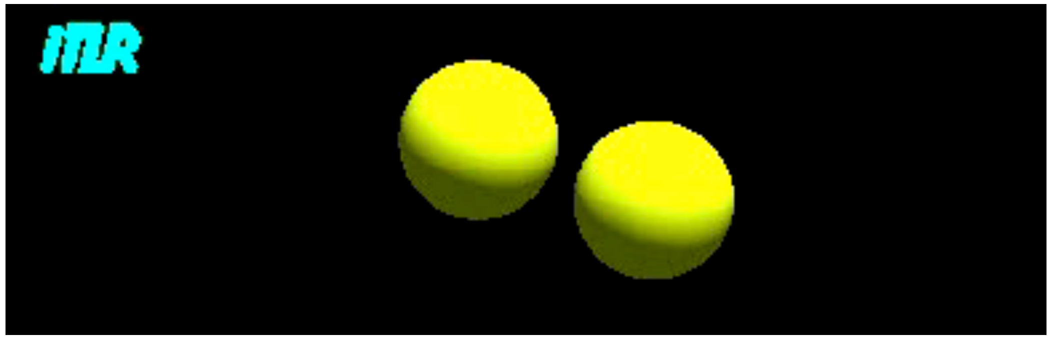
Collisional breakup



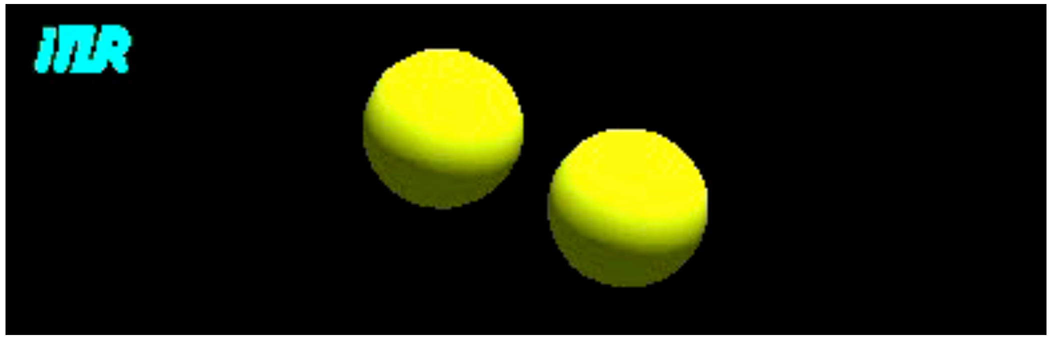
DNS by University Stuttgart



coalescence



no coalescence
(rebound)



collisional breakup
(filament type)

Bulk microphysical schemes

Instead of ***f(x)*** only moments of the size distribution are explicitly predicted like the liquid water content:

$$L = \frac{\pi \rho_w}{6} \int_0^\infty D^3 f(D) dD$$

or the number concentration of particles:

$$N = \int_0^\infty f(D) dD$$

maybe even a third one, like the sixth moment (reflectivity)

Bin vs. bulk microphysics

Spectral bin model (100-500 variables):

$$\frac{\partial f(x)}{\partial t} + \nabla \cdot [\mathbf{v}\, f(x)] + \frac{\partial}{\partial z}[v_T(x)\, f(x)] = \mathcal{F}(x)$$

Two-moment bulk model (8-12 variables):

$$\frac{\partial N}{\partial t} + \nabla \cdot [\mathbf{v}\, N] + \frac{\partial}{\partial z}[v_N(\bar{x})\, N] = N\, \mathcal{G}(\bar{x})$$

$$\frac{\partial L}{\partial t} + \nabla \cdot [\mathbf{v}\, L] + \frac{\partial}{\partial z}[v_L(\bar{x})\, L] = L\, \mathcal{H}(\bar{x}), \qquad \bar{x} = L/N$$

One-moment bulk model (3-5 variables):

$$\frac{\partial L}{\partial t} + \nabla \cdot [\mathbf{v}\, L] + \frac{\partial}{\partial z}[\tilde{v}_L(L)\, L] = \mathcal{S}(L)$$

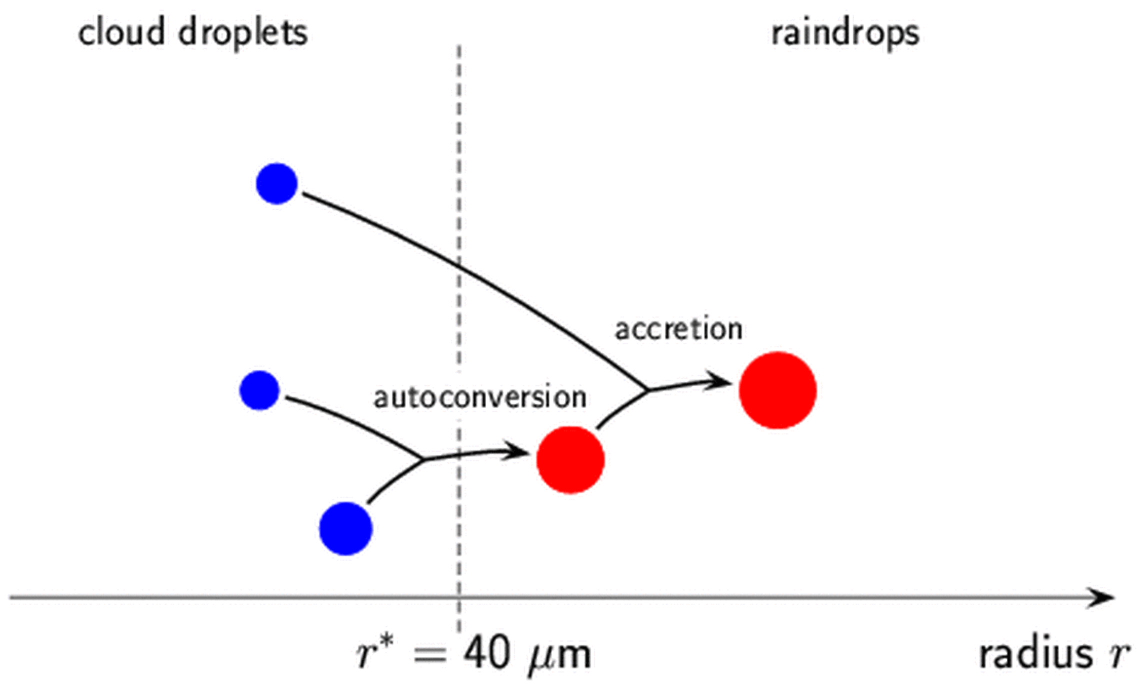
UCLA-LES level=3 and level=5 are a two-moment schemes

UCLA-LES level=4 is a mix of one- and two-moment scheme

Note: cloud droplets are single moment in all UCLA-LES schemes, number is prescribed.

Kessler‘s warm phase scheme

In 1969 Kessler published a very simple warm rain parameterization which is still used in many bulk schemes.



autoconversion rate:

$$\left.\frac{\partial L_r}{\partial t}\right|_{au} = \begin{cases} k\,(L_c - L_0), & \text{if } L_c > L_0 = 0.5 \text{ g m}^{-3} \\ 0, & \text{else} \end{cases}$$

„As we know, water clouds sometimes persist for a long time without evidence of precipitation, but various measurements show that cloud amounts > 1 g/m³ are usually associated with production of precipitation. It seems reasonable to model nature in a system where the rate of cloud autoconversion increases with the cloud content but is zero for amounts below some threshold.“

(E. Kessler: *On the Distribution and Continuity of Water Substance in Atmospheric Circulation*, *Meteor. Monogr.* , 1969)

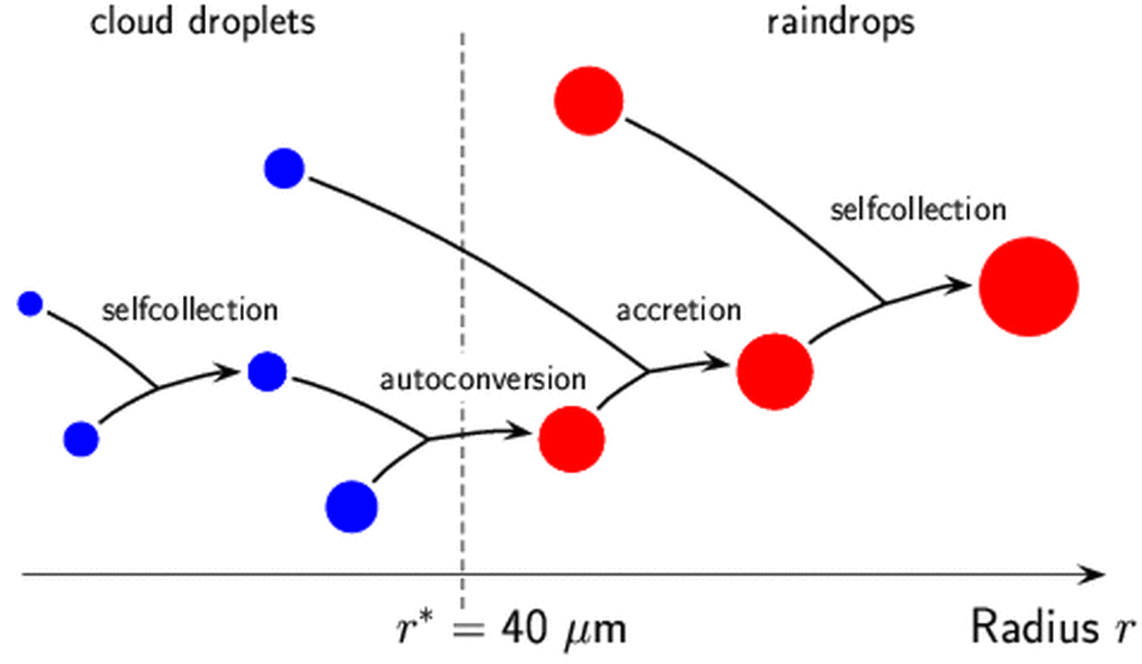
A two-moment warm phase scheme

Assuming a Gamma distribution for cloud droplets

$$f_c(x) = A x^{\nu} e^{-Bx}$$

the following autoconversion can be derived from the spectral collection equation

$$\left.\frac{\partial L_r}{\partial t}\right|_{au} = \frac{k_c}{20\, x^*} \frac{(\nu+2)(\nu+4)}{(\nu+1)^2} L_c^2\, \bar{x}_c^2 \left[1 + \frac{\Phi_{au}(\tau)}{(1-\tau)^2}\right]$$



with a universal function.

$$\Phi_{au}(\tau) = 600\tau^{0.68}(1-\tau^{0.68})^3$$

The universal function parameterizes the time evolution, i.e. the broadening, of the cloud droplet distribution during the rain formation process.

Seifert and Beheng (2001), Atmos. Res.

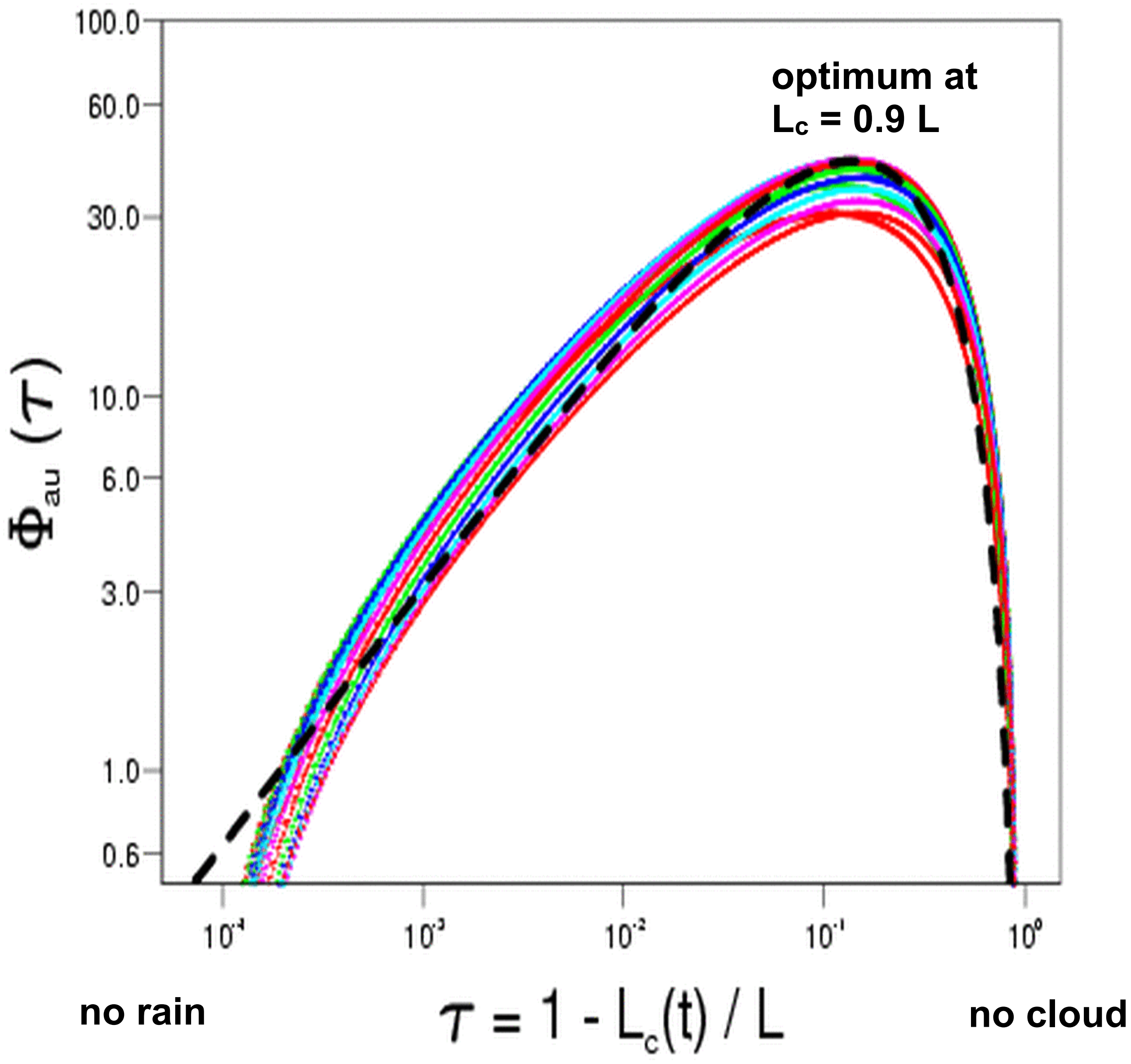
A two-moment warm phase scheme

The colored lines represent solutions of the spectral collection equation for various initial conditions.

The dashed line is the fit:

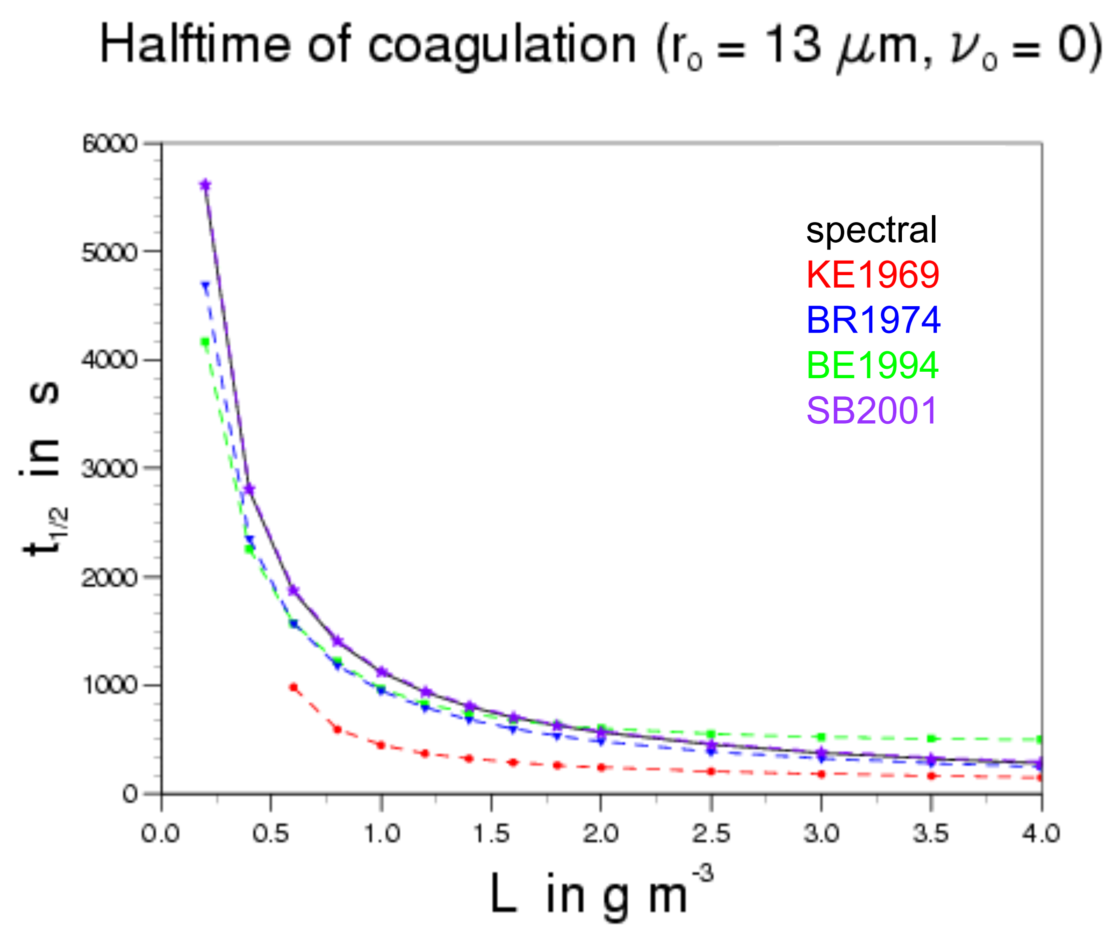
$$\Phi_{\mathrm{au}}(\tau) = 600\tau^{0.68}(1 - \tau^{0.68})^3$$

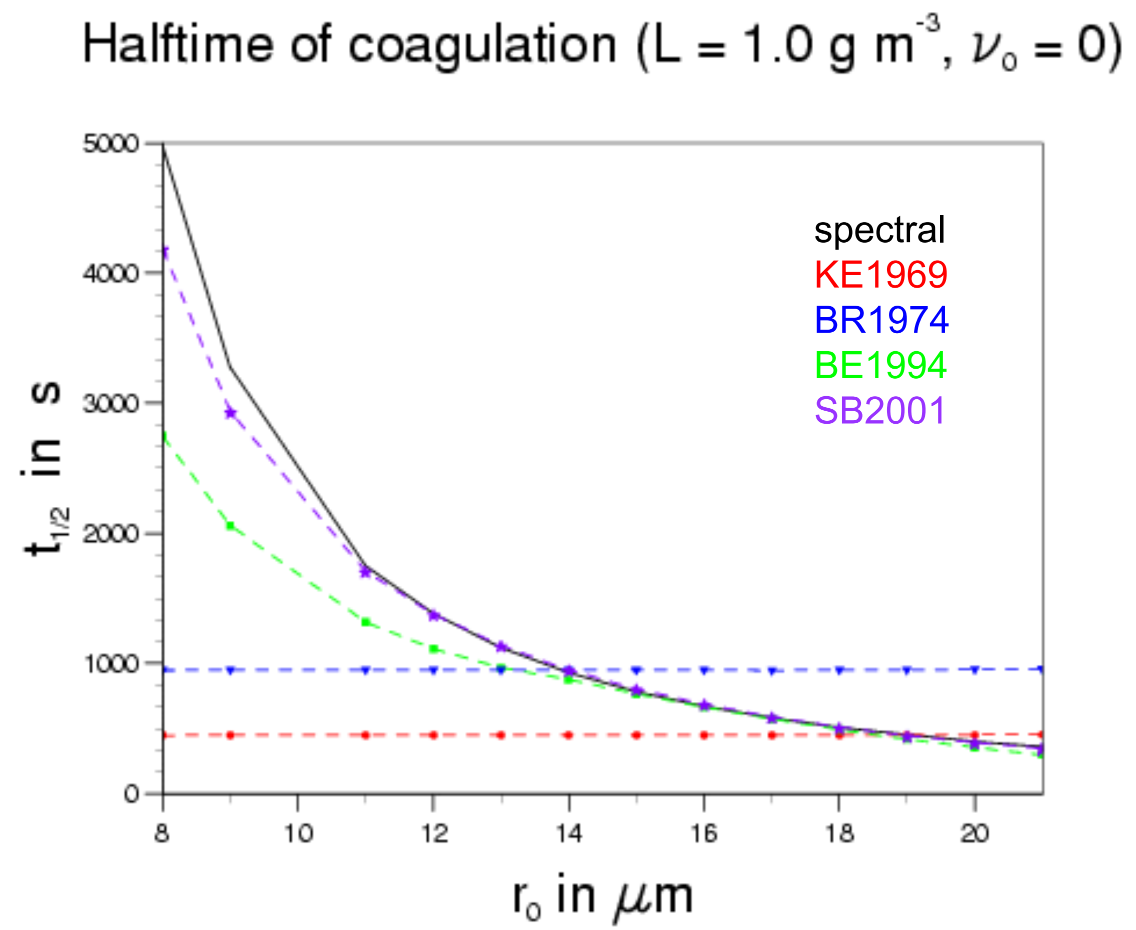
This function describes the **broadening of the cloud droplet size distribution** by collisions between cloud droplets.



Seifert and Beheng (2001), Atmos. Res.

A comparison of warm phase autoconversion schemes





- For high LWC the differences between the schemes are usually small
- For low LWC the differences are larger and the effects of drop size or cloud droplet number concentration on coalescence, can be important.

Sedimentation as an example for bulk process schemes

$$\frac{\partial f(D)}{\partial t} + \frac{\partial}{\partial z}\left[v(D) f(D)\right] = 0$$

with f(D) number density size distribution (unit m^{-4}).

Now we integrate for the (bulk) mass density (liquid water content)

$$L = \frac{\pi \rho_W}{6} \int_0^\infty D^3 f(D) dD$$

and find

$$\frac{\partial L}{\partial t} + \frac{\partial}{\partial z}\left[v_L L\right] = 0$$

with the mass weighted fall velocity

$$v_L = \frac{\int_0^\infty D^3 f(D) v(D) dD}{\int_0^\infty D^3 f(D) dD}$$

… use the fundamental parameterization assumption

Now we assume that $f(D)$ can be described by an exponential distribution

$$f(D) = N_0 \, \exp(-\lambda D) \text{ with } N_0 = \text{const.}$$

All moments of this distribution are then given by

$$\mathcal{M}_n = \int_0^\infty D^n f(D) dD = \frac{\Gamma(n+1)}{\lambda^{n+1}}$$

or, more specific, for the liquid water content we find

$$L = \frac{\pi \rho_\mathcal{W}}{6} \int_0^\infty D^3 f(D) dD = \pi \rho_\mathcal{W} \lambda^4$$

… and specify a fall speed....

A power-law for the particle fall speed

$$v(D) = \alpha \left(\frac{D}{D_0} \right)^{\frac{1}{2}}$$

leads to the following sedimentation velocity:

$$v_L = \frac{\int_0^\infty D^3 f(D) v(D) dD}{\int_0^\infty D^3 f(D) dD} = \frac{N_0 \; \alpha}{6} \Gamma \left(\frac{9}{2} \right) \left(\frac{L}{\pi \rho_{\mathcal{W}}} \right)^{\frac{1}{8}} = \tilde{\alpha} L^{\frac{1}{8}}$$

Note: This was just a one-moment scheme!

An interesting result for sedimentation:

Spectral microphysics:

$$\frac{\partial f(D)}{\partial t} + \frac{\partial}{\partial z}\left[v(D) f(D)\right] = 0$$

One-moment scheme:

No gravitational sorting!

$$\frac{\partial L}{\partial t} + \frac{\partial}{\partial z}\left[v_{L}(L) L\right] = 0$$

Two-moment scheme:

Has gravitational sorting!

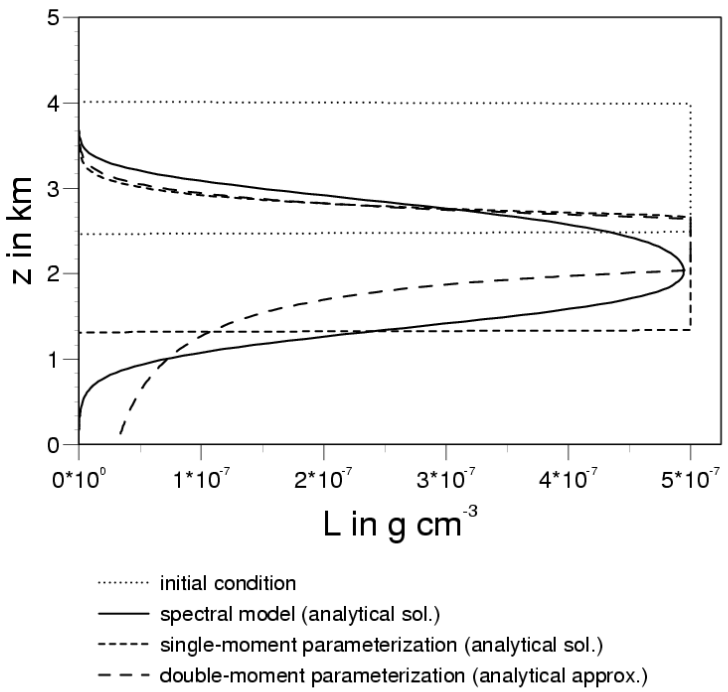
$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial z}\left[v_1(\bar{x})\, N\right] = 0$$

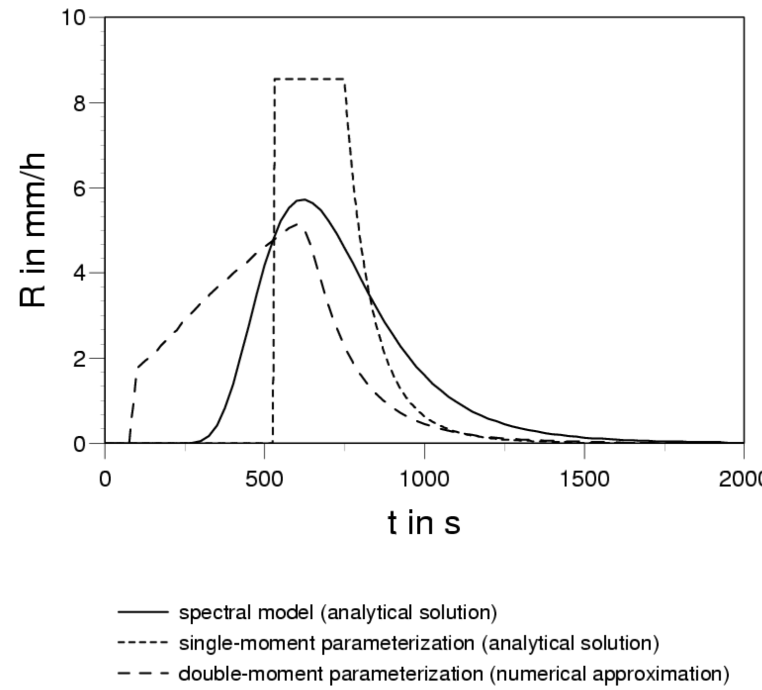
$$\frac{\partial L}{\partial t} + \frac{\partial}{\partial z}\left[v_2(\bar{x})\, L\right] = 0$$

Note: A linear PDE is parameterized by a nonlinear PDE!!

An idealized rainfall experiment

Sedimentation of a layer of raindrops as described by the spectral equation, a one-moment scheme and a two-moment scheme.





Both parameterizations have serious problems with this simple test!

Wacker and Seifert (2001), Atmos. Res.

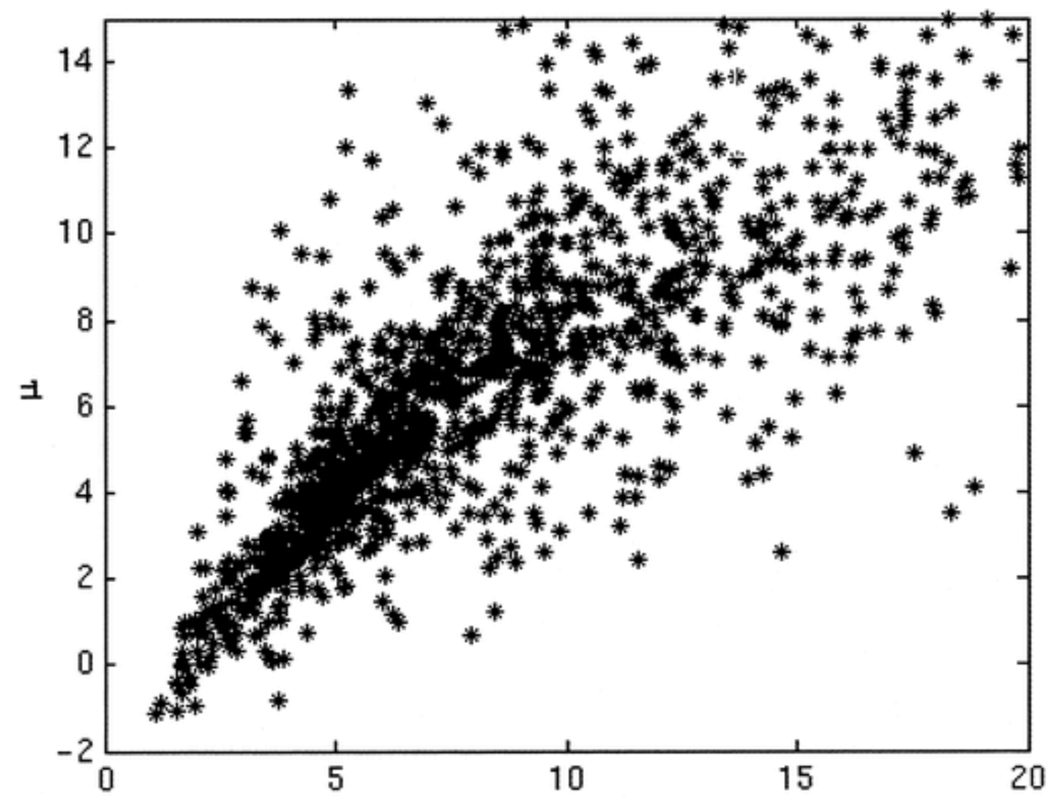
When you are stuck: Look at the real thing!

Especially in convective precipitation the raindrop size distribution f(D) is highly variable and not necessarily exponential. A better description is a Gamma distribution:

$$f(D) = N_0\, D^{\mu}\, \exp(-\lambda D)$$

Problem: μ and N_0 are highly variable and have a strong impact on evaporation and sedimentation

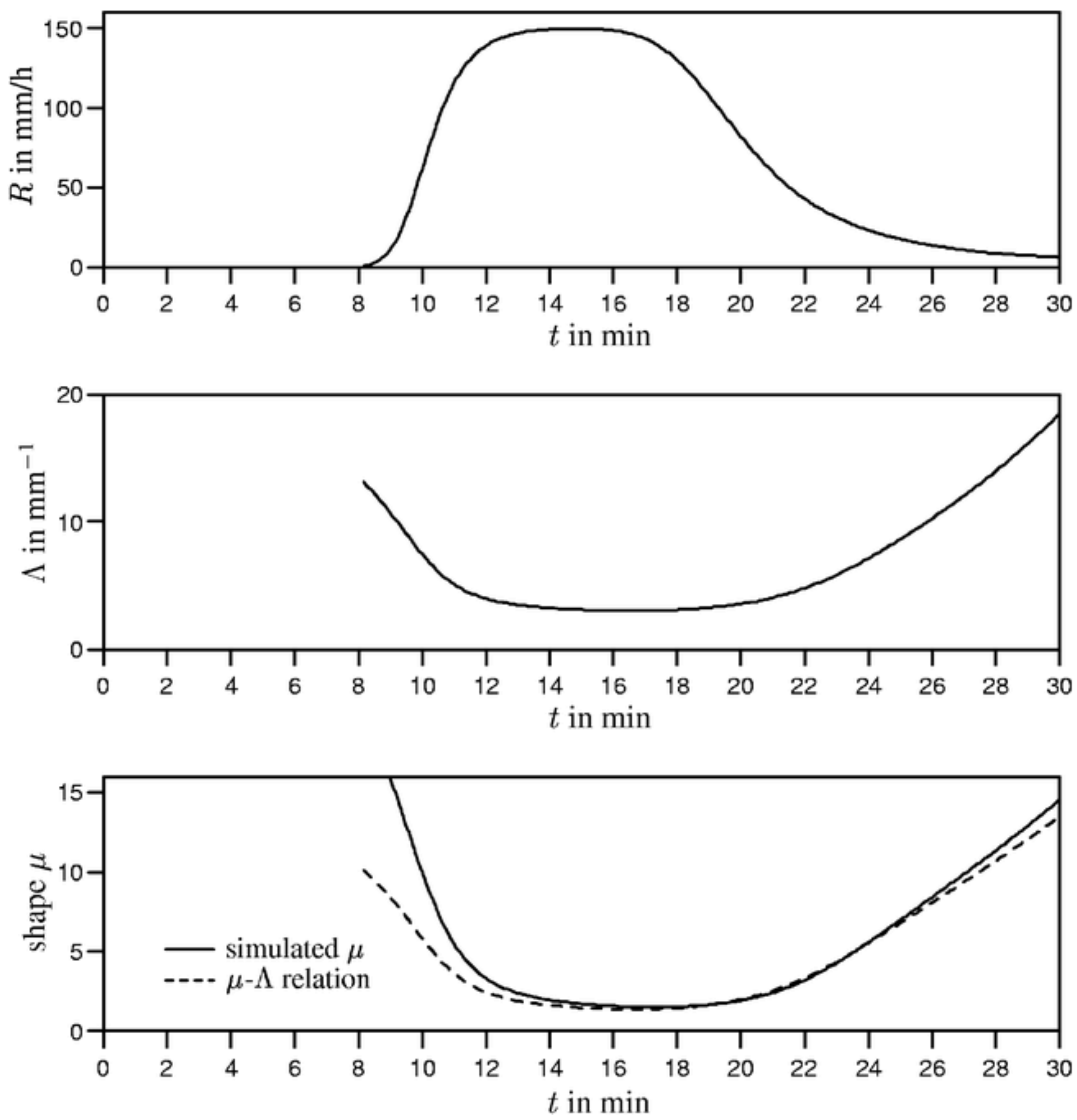
Zhang et al. (2001) measured μ vs. λ



$\lambda = \lambda(q_r)$ in mm^{-1}

Two-moment schemes do not necessarily solve (all) our problems!
.... but we can help them out.

Another idealized rainfall experiment



Simulation using a 1D rainshaft model with a homogenous cloud as initial condition.

The shape of the raindrop size distribution can be parameterized as a function of the slope parameter

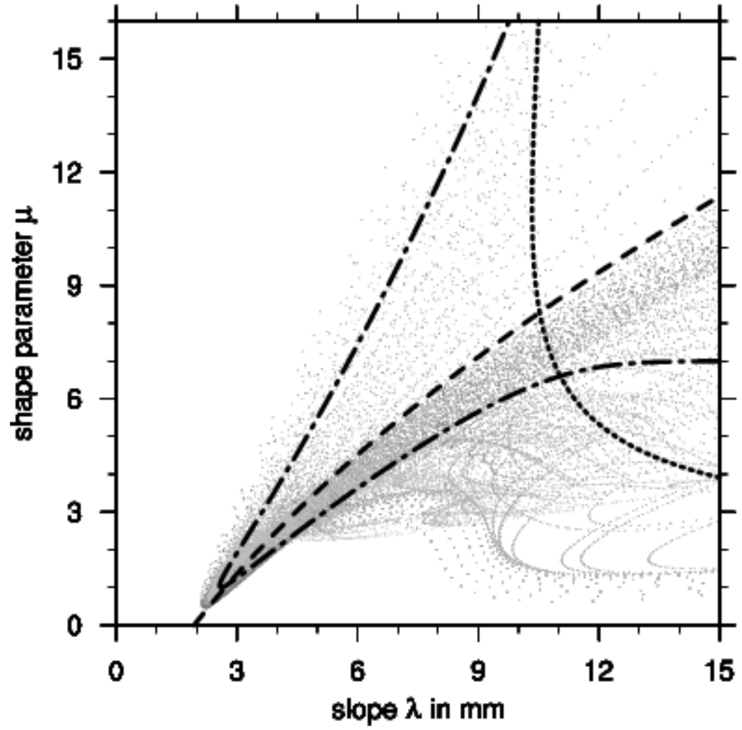
$$f(D) = N_0 \, D^{\mu} \, \exp(-\lambda D)$$

with $\mu = \mu(\lambda)$

YES! We can simulate the empirical relationship with a quit simple bin model.

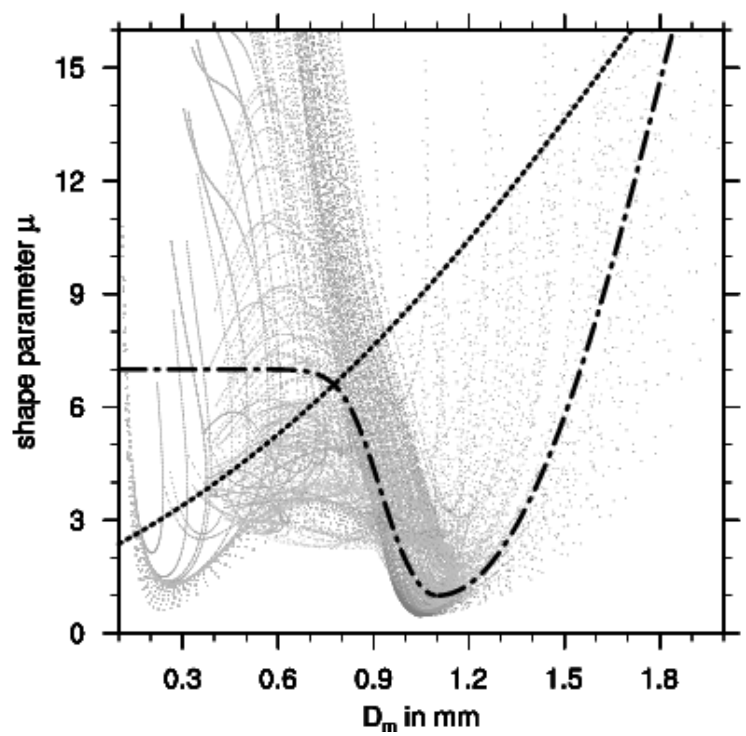
Seifert (2005), JAM

The shape parameter of the raindrop distribution



Adding evaporation to the problem leads to more scatter in the μ-λ-relation.
Using a μ-D-relation instead of μ-λ allows to distinguish large and small mean diameters

$$\mu = \begin{cases} 6\tanh\{[c_1 (D_m - D_{eq})]^2\} + 1, & D_m \leq D_{eq} \\ 30\tanh\{[c_2 (D_m - D_{eq})]^2\} + 1, & D_m > D_{eq} \end{cases}$$

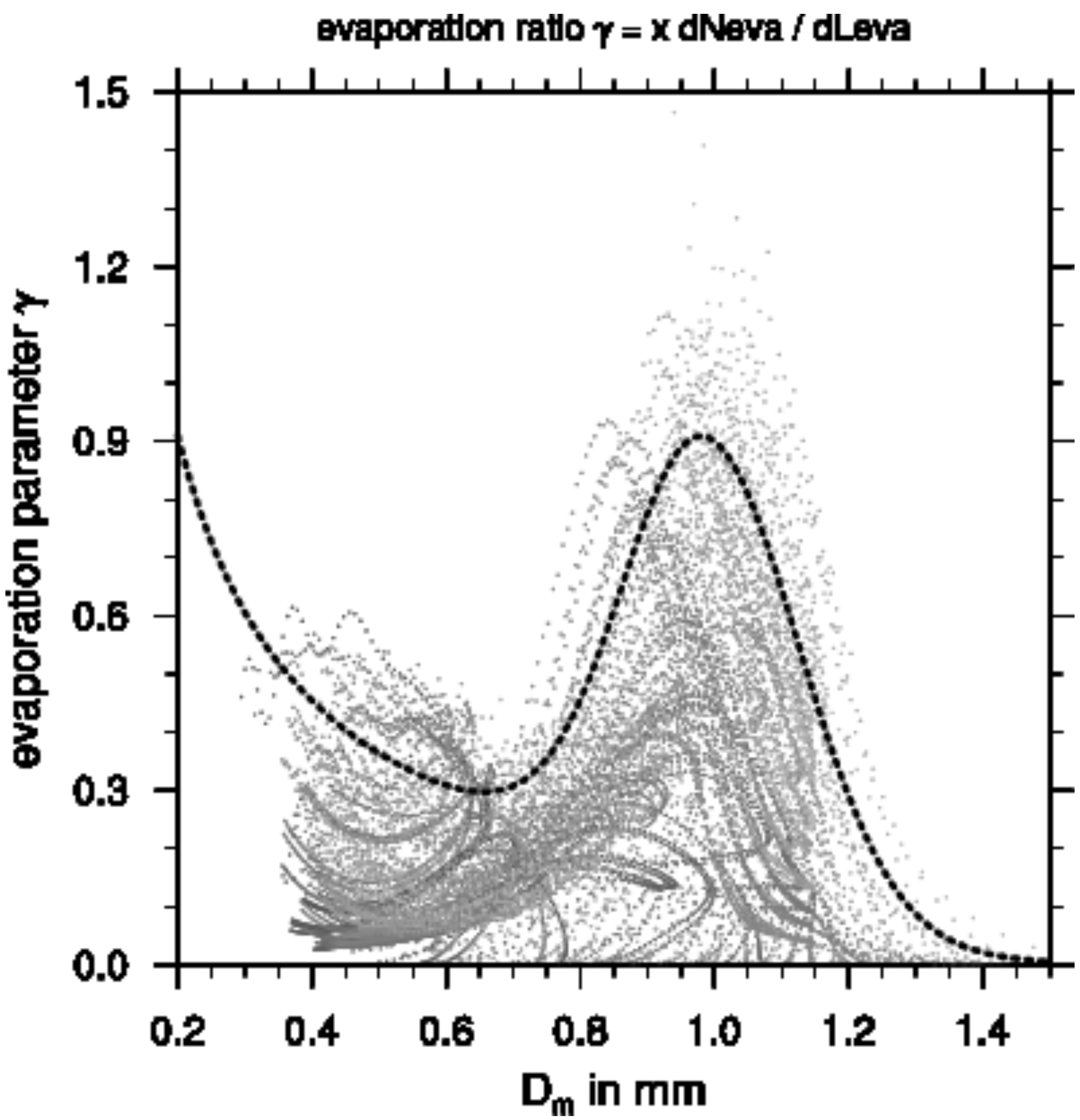


- Low μ for D ≈ 1 mm:
  „breakup/coalescence regime“
- Large μ for D >> 1 mm:
  „gravitational sorting regime“
- Large uncertainty for small mean diameters:
  evaporation, gravitational sorting,…

Not yet in UCLA-LES level=3 or 4, only level=5

Seifert (2008), JAS

The size effect of evaporation



Using the spectral bin model, an empirical parameterization of the size effect of evaporation can be derived:

$$\left.\frac{\partial N_r}{\partial t}\right|_{\mathrm{eva}} = \gamma \; \frac{N_r}{L_r} \; \left.\frac{\partial L_r}{\partial t}\right|_{\mathrm{eva}}$$

with

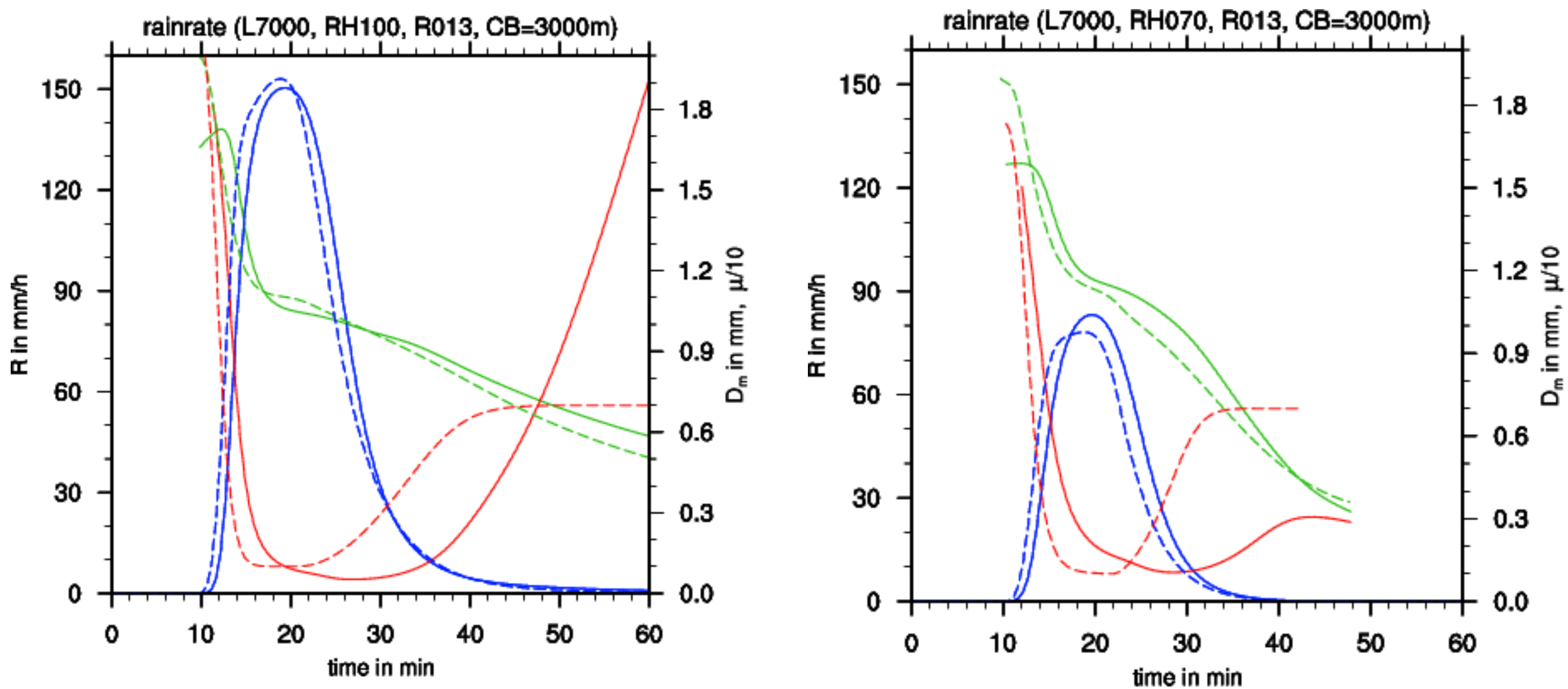
$$\gamma = \frac{D_{eq}}{D_m} \exp(-0.2\mu)$$

Not yet in UCLA-LES level=3 or 4, only level=5

Seifert (2008), JAS

Results of the revised two-moment scheme in a 1D rainshaft model

Comparison of the spectral bin and the two-moment bulk model for an strong rain event (rain rate **R**, mean diameter $\mathbf{D_m}$ and shape parameter $\boldsymbol{\mu}$)



Note: No overshooting or any other artifacts in rainrate

Seifert (2008), JAS

Microphysics sensitivities in UCLA-LES

Columns are cloud droplet number concentration, liquid water path, rain water path, cloud cover, inversion height, surface rain rate, max. rain rate and number of raindrops

N_c	Microphysics	$\mathcal{L}$	$\mathcal{R}$	C	z_i	R	R_{mx}	N_R
35	SB	13.0	16.8	0.13	2183	36.5	53.1	25.9
70		17.4	17.3	0.14	2368	42.3	50.1	16.9
105		20.0	6.5	0.17	2477	11.6	19.1	10.4
140		19.8	3.9	0.18	2494	8.1	11.4	7.5
35	KK	14.7	30.5	0.11	2271	37.5	86.7	16.9
70		20.3	3.1	0.18	2506	2.3	9.0	5.0
105		20.5	1.4	0.18	2527	1.8	4.4	3.4
140		20.9	0.4	0.19	2508	0.3	1.1	3.0

Name	Microphysics	$\mathcal{L}$	$\mathcal{R}$	C	z_i	R	R_{mx}	N_R
S01	SB	17.4	17.3	0.14	2368	42.3	50.1	16.9
S02	SB-$\mu = 0$	16.6	6.8	0.16	2357	18.0	24.9	14.9
S03	SB-$\mu = 5$	18.9	19.4	0.15	2368	31.0	53.6	18.4
S04	SB-$\mu = 10$	18.3	22.7	0.15	2401	42.4	60.2	16.7
S05	(SB, SB, KK)	16.8	20.8	0.13	2431	40.3	56.4	16.8
S06	SB (no SC)	22.8	38.1	0.17	2452	27.6	85.9	64.0
S07	(SB, KK, SB)	20.4	20.3	0.15	2273	42.9	99.3	57.0
S08	KK	20.3	3.1	0.18	2506	2.3	9.0	5.0
S09	(SB, KK, KK)	22.4	55.6	0.16	2348	18.1	95.5	58.3
S10	(KK, SB, SB)	18.9	1.6	0.18	2505	2.7	7.0	3.9
S11	S03 with Breakup	16.2	19.6	0.13	2335	36.5	53.0	16.7
S12	S11 with Ventilation	14.7	15.6	0.11	2336	23.0	62.9	21.6

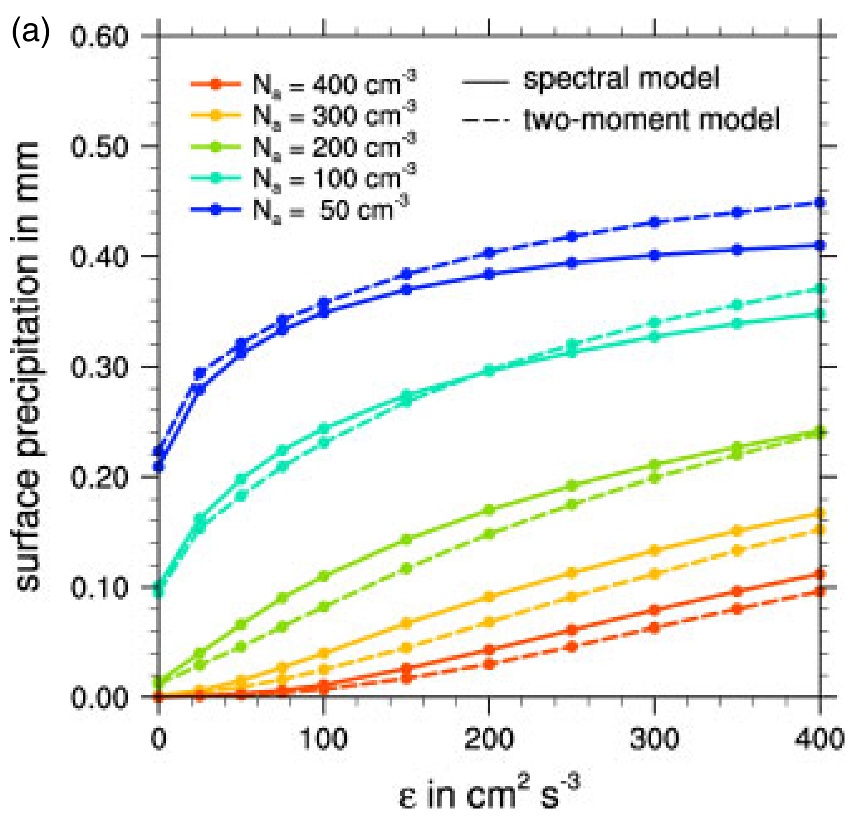
Read the paper!

Stevens and Seifert (2008), Journal of the Meteorological Society of Japan

Turbulence effect on warm rain

Turbulence can enhance the collision frequency of droplet. This can be included in the SB warm rain scheme and is included in UCLA-LES.

rainshaft model



UCLA-LES RICO simulations

Table II. Sensitivity to turbulence-enhanced coalescence (T), versus no turbulence enhancement (NT), for cloud droplet number concentrations N_c = 70, 140 and 300 mg^{-1}. NT-140-hr and T-140-hr represent simulations with doubled horizontal resolution (grid spacing of 50 m).

Run	L (gm^{-2})	R (gm^{-2})	z_i (m)	C	R_{sfc} (W m^{-2})	R_{max} (W m^{-2})	N_r (dm^{-3})
NT-70	18.6	7.0	2418	0.17	8.6	16.6	19.7
T-70	19.3	22.2	2358	0.15	43.3	51.6	26.6
NT-140	18.9	0.8	2449	0.17	0.8	2.0	8.7
T-140	19.7	8.3	2422	0.17	13.2	18.8	14.9
NT-140-hr	21.1	1.0	2422	0.21	1.1	2.6	8.9
T-140-hr	21.9	3.9	2399	0.21	4.9	9.9	10.9
NT-300	20.2	0.0	2442	0.17	0.0	0.0	4.7
T-300	18.3	0.4	2438	0.16	0.4	0.9	6.4

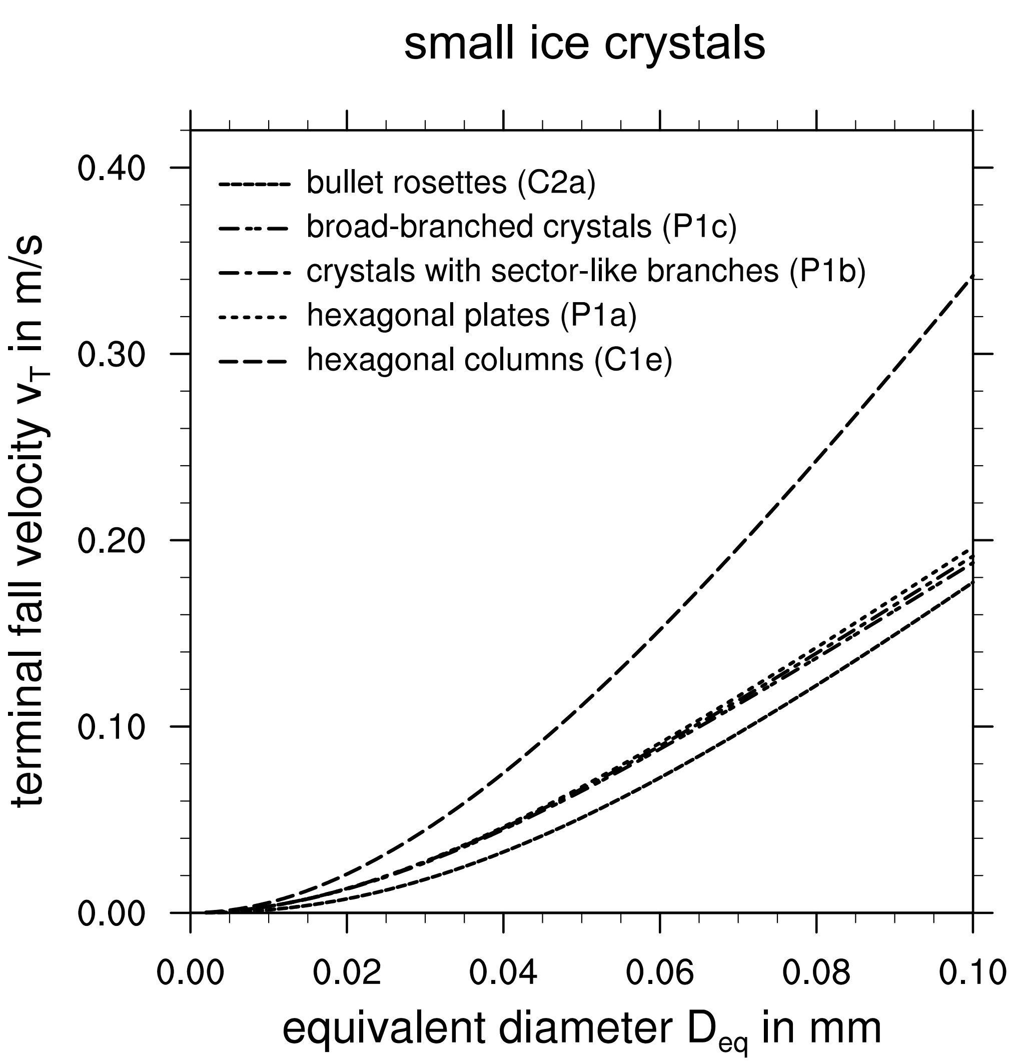
Variables are cloud (liquid) water path L, rain water path R, inversion height z_i, fraction of cloudy columns C, rain-drop number concentrations averaged over raining regions N_r, surface rain rate R_{sfc}, and the maximum rain-rate R_{max} within the (domain-averaged) profile of rain-rate.
All variables are averaged over the last four hours of each simulation.
A rain rate of 29 W m^{-2} corresponds to 1 mm day^{-1}.

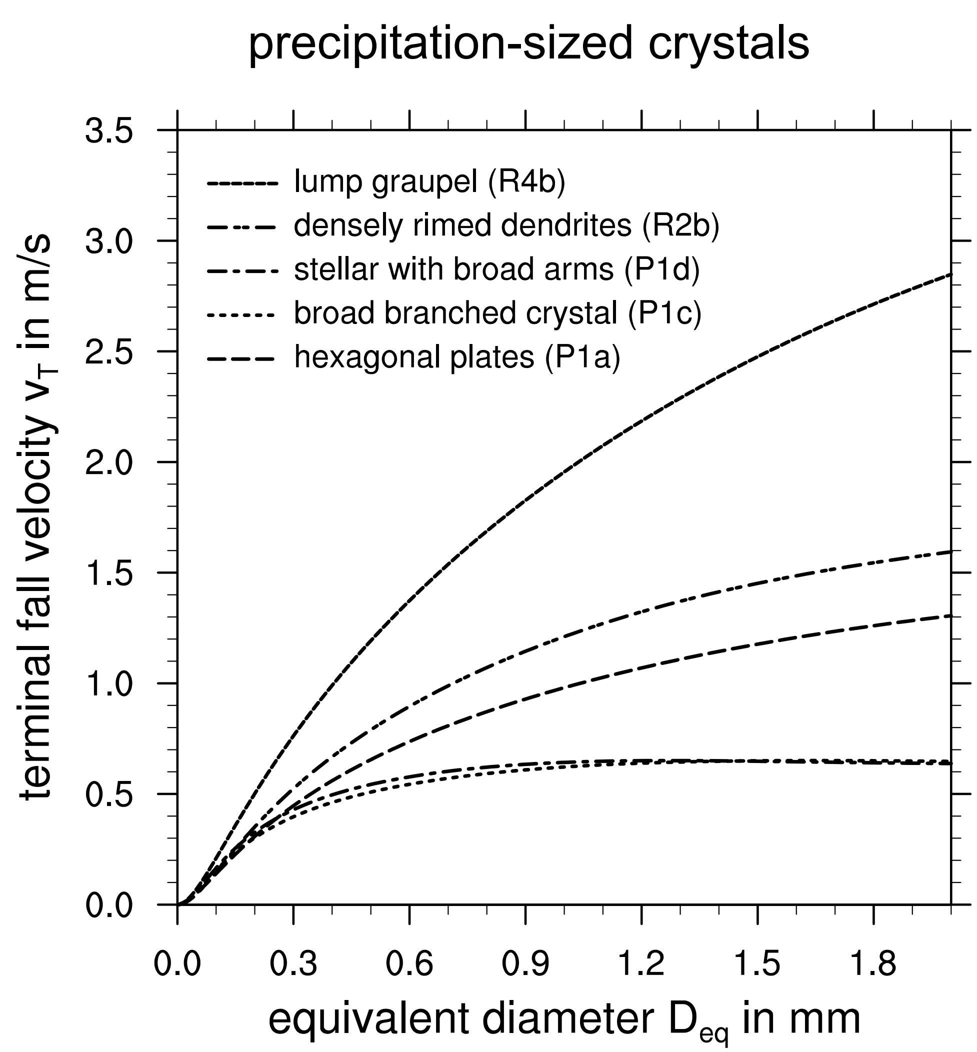
Again, read the paper!

Seifert, Nuijens and Stevens (2010), QJ

Ice particle fall speeds

- For the parameterization of sedimentation and growth rates the terminal fall velocity of the particles is of greatest importance





- Often used for ‚tuning', because actual particles habits for a case are usually not known and can hardly be predicted.

Ice nucleation

- ➔ Homogeneous nucleation from vapor: Does not occur in the atmosphere!
- ➔ Homogeneous freezing of cloud droplets: at about -37 C, can occur in stron deep convective updrafts
- ➔ Homogeneous freezing of liquid aerosols: colder than -37, but below RH=100 %, may be the main mechanism for cirrus formation. Does still need high ice supersaturation of 140-170 %.
- ➔ Heterogeneous freezing: needs ice nuclei (IN), for each specific IN strongly temperature and RH dependent. Usually we don‘t know the IN distribution and have to make ad-hoc choices, e.g., climatology.
- ➔ Different modes of heterogeneous nucleation: immersion freezing, deposition nucleation, contact nucleation, etc.
- ➔ The importance of different substances, e.g., soot, dust, or organics is still under debate. Aerosol age, and aerosol processing does play a role (also for CCN).

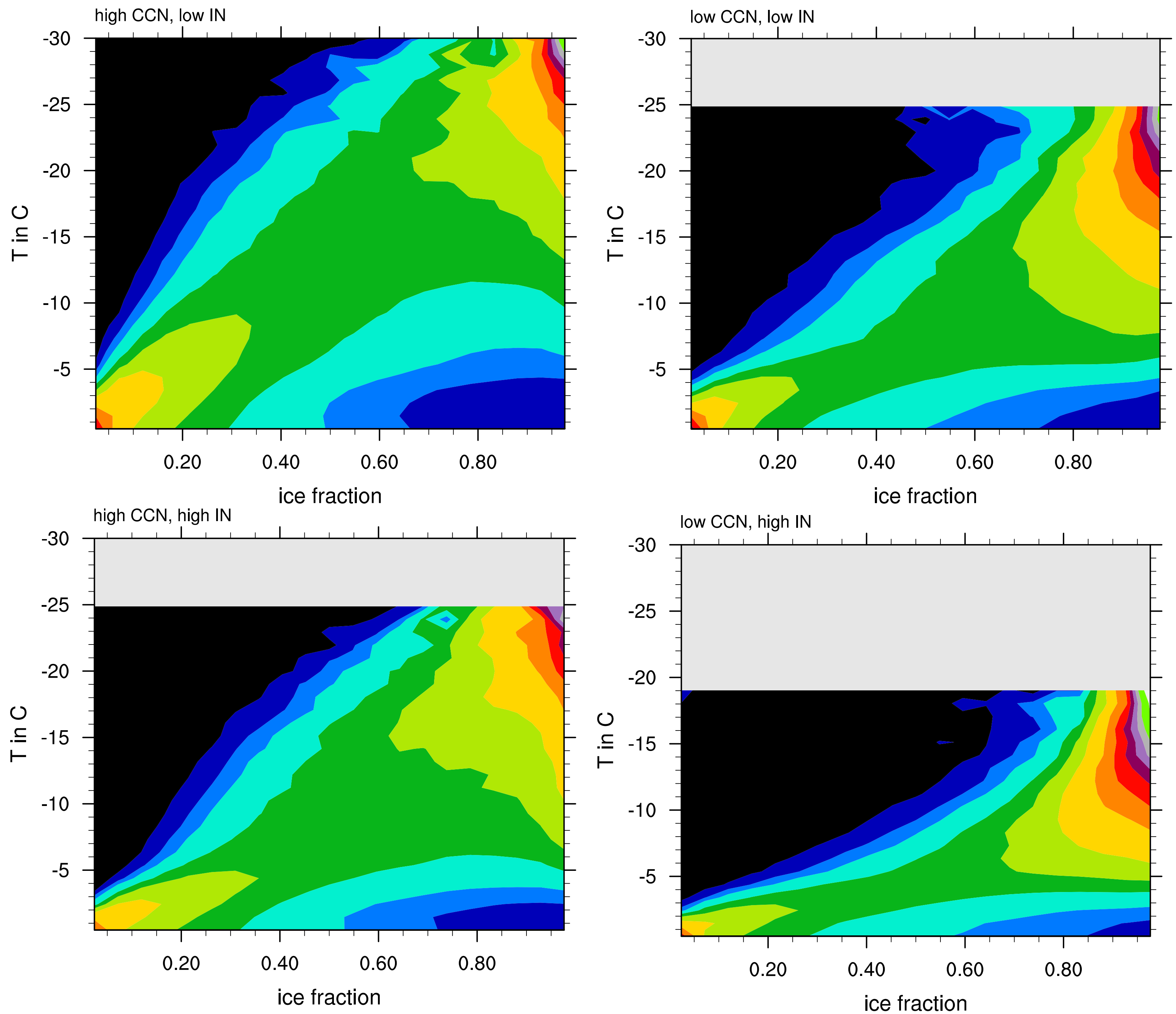
My personal advice: Stay away from ice clouds, if you can!

If you can not for some reason, then make at least sure that your results are not overly dependent on your IN choices, and get some f**** observations.**

Glaciation of clouds

PDF of IWC/TWC as a function of temperature

- ➔ more IN lead to a more efficient glaciation
- ➔ less CCN lead to a more efficient glaciation, because large drizzle drops or rain have a higher freezing probability
- ➔ Therefore your choices of CCN and IN matter for the cloud dynamics



Seifert et al. (2011), ACPD

UCLA-LES microphysics schemes

level=2: Pure condensation

level=3: Bjorn‘s warm rain scheme based on SB 2001

- two-moment rain as described in Stevens and Seifert (2008).
- *Code is short and easy to understand.*

level=4: Thijs‘ mixed-phase scheme

- one-moment snow and graupel, two-moment rain and ice,
- works fine for bubble convection, but not yet tuned for other cases.
- *Code is well organized, but not documented*

level=5: Axel‘s two-moment mixed-phase scheme with hail,

- everything two-moment, well tested on 1-3 km grids, i.e. COSMO model,
- but not much experience with LES cases.
- Scheme is very modular, many choices, more extensions, i.e. process parameterizations, are available, e.g. more ice nucleation or CCN activation schemes.
- *Code got quite messy recently and may be a bit confusing, but the structure is still okay. Several published papers that describe the schemes.*