Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Physical Parameterizations I: Cloud Microphysics and Subgrid-Scale Cloudiness

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Outline

- Motivation
- Some fundamentals about clouds and precipitation
- Basic parameterization assumptions
- Overview of microphysical processes
- Some words about warm phase autoconversion schemes
- An example: Sedimentation velocity
- The microphysics schemes of the COSMO model
- Sub-grid cloudiness
- Summary

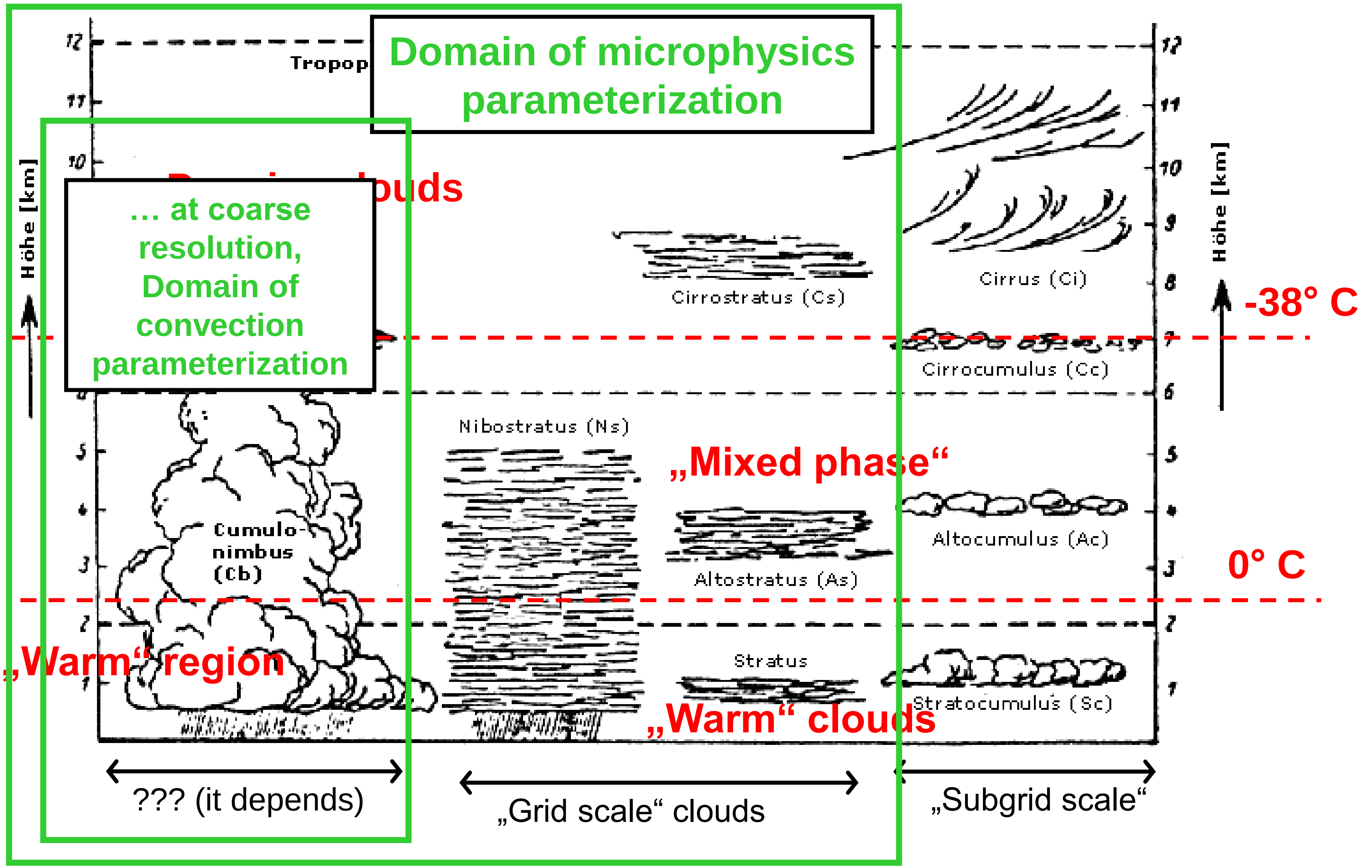
Motivation

Cloud microphysical schemes have to describe the formation, growth and sedimentation of water particles (hydrometeors). They provide the latent heating rates for the dynamics.

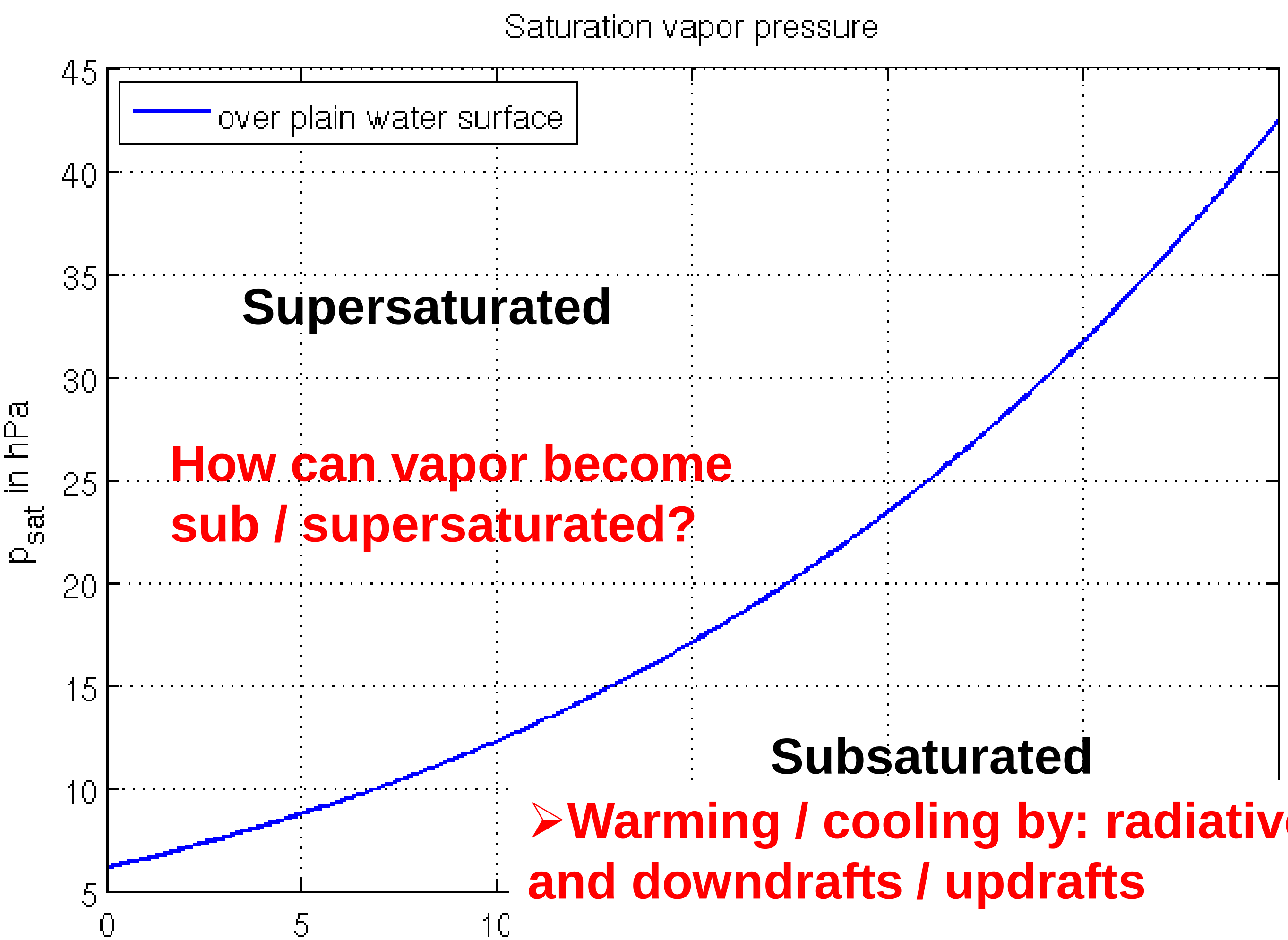
Cloud microphysical schemes are a central part of every model of the atmosphere. In numerical weather prediction they are important for quantitative precipitation forecasts.

In climate modeling clouds are crucial due to their radiative impact, and aerosol-cloud-radiation effects are a major uncertainty in climate models.

Basic cloud classification

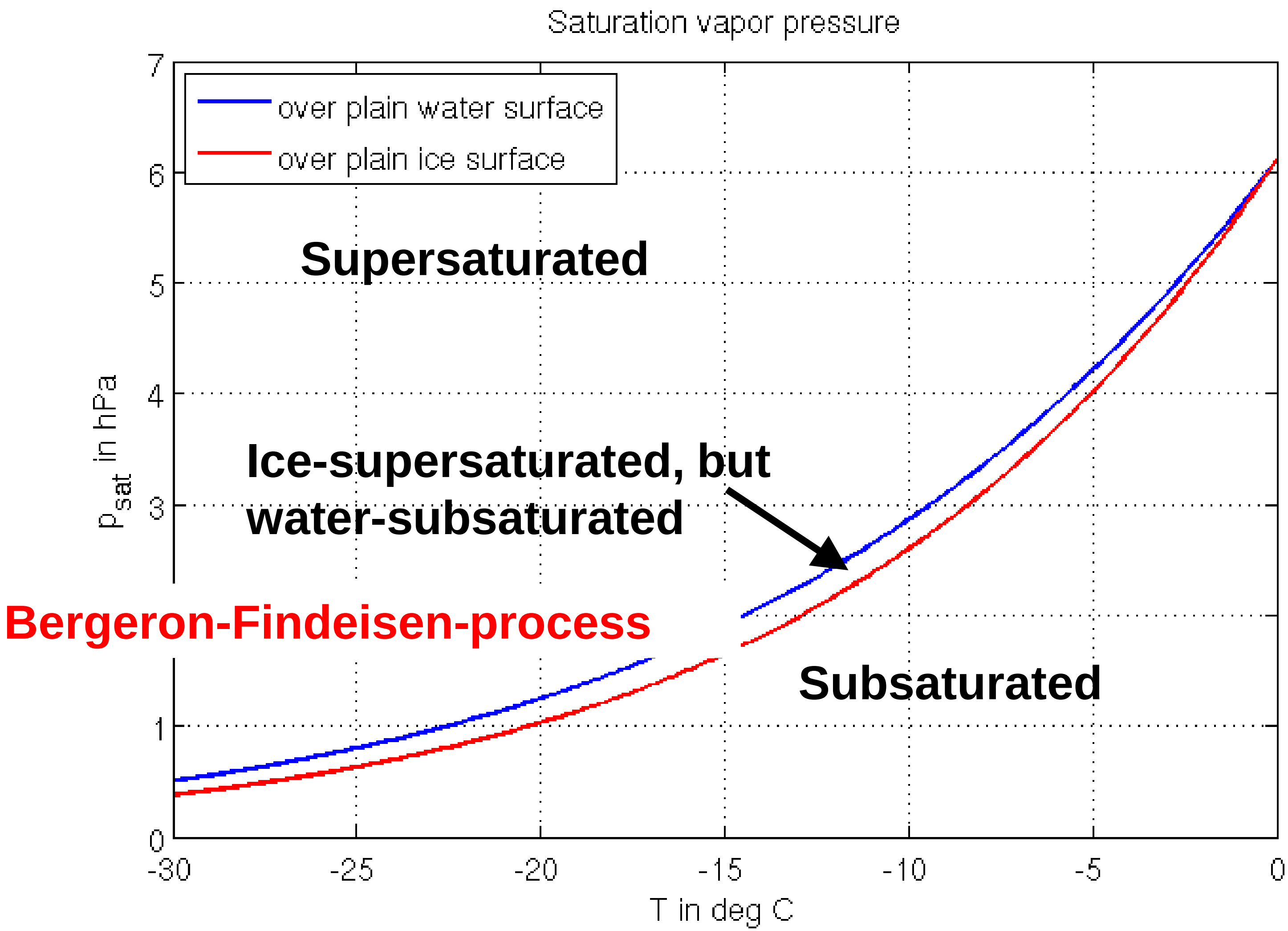


Equilibrium between water vapor and liquid/ice – Saturation vapor pressure



- ➢**Warming / cooling by: radiative effects and downdrafts / updrafts**
- ➢**Mixing of nearly saturated warmer and cooler air**

Equilibrium between water vapor and liquid/ice – Saturation vapor pressure



Prerequisites for the formation of cloud particles

- „Enough“ supersaturation + condensation nuclei = cloud droplets

  What is „enough“?

  → Köhler-theory, „non-activated / activated“ CN

  → Larger CN are activated first and can grow to cloud droplets by diffusional growth

- Ice particles: supersaturation w.r.t ice + ice nuclei (IN)

  Different modes: homogeneous / heterogeneous nucleation

- These processes are representet only very simplistically in operational cloud microphysics parameterizations!

Description by size distributions

Clouds are an ensemble of differently sized particles, which can be liquid or solid with different „habits“ (polydisperse, heterogeneous system).

$f(D) =$ Number of particles in size interval $[D, dD]$

Common *ansatz* for this *particle size distribution:*

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

Gamma-Distribution

Transformation to particle mass m using $f(D)\, dD \;=\; f(m)\, dm$:

$$\text{if} \quad m \;\sim\; a_{geo}\, D^{b_{geo}} \qquad \left(\text{Sphere:} \quad m \;=\; \frac{\pi}{6}\rho_{bulk}\, D^3\right)$$

$$\Rightarrow \boxed{f(m) \;=\; \hat{N}_0\, m^{\hat{\mu}}\; \exp -\hat{\lambda}\, m} \qquad (\textit{ansatz} \text{ conserved!})$$

Size distribution and its „moments“

Instead of ***f(x)***, usually some moments of the size distribution are explicitly predicted by operational NWP models:

$$\mathcal{M}_n = \int_0^\infty D^n f(D) dD$$

3rd moment = water content

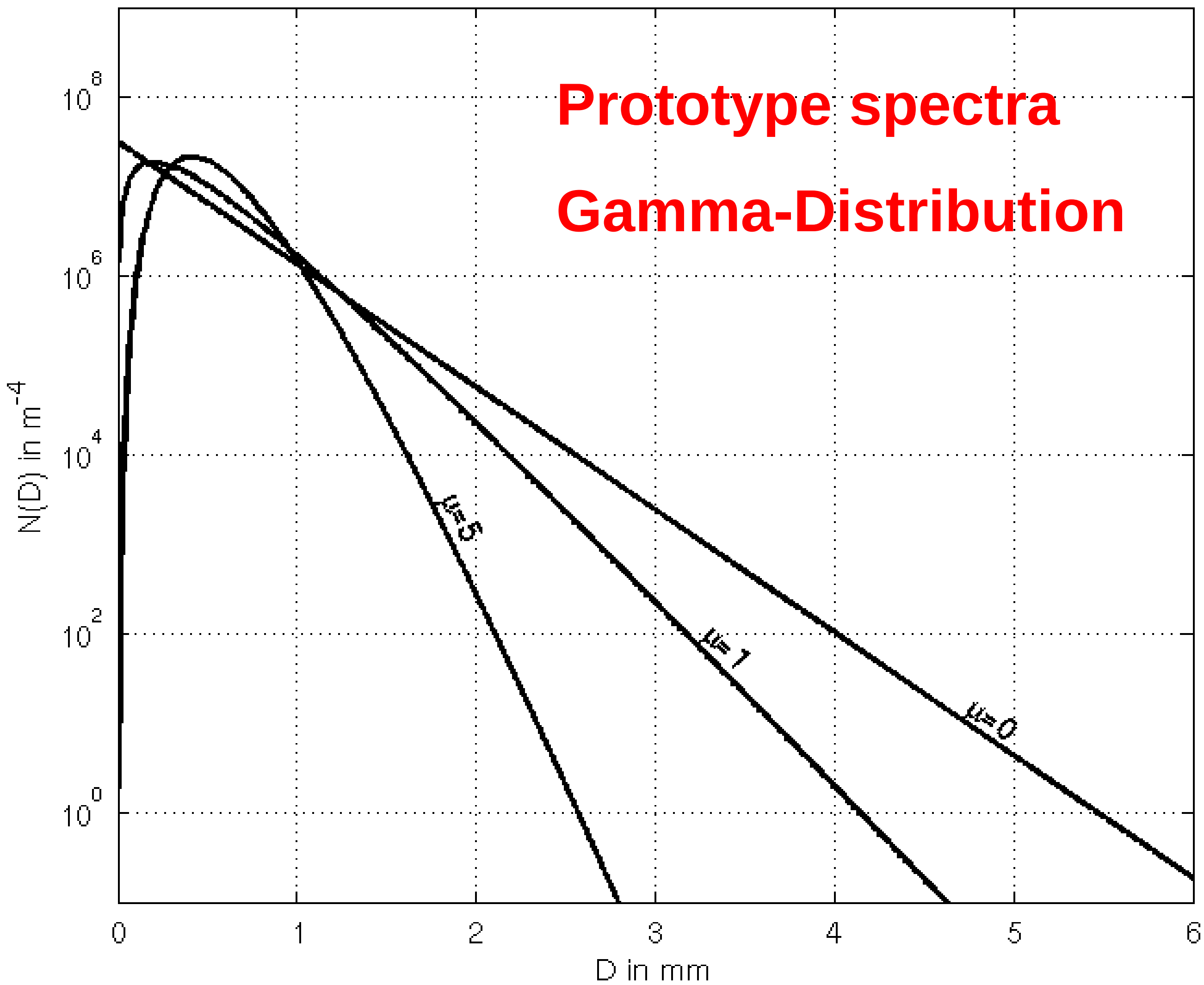
$$L = \frac{\pi \rho_w}{6} \int_0^\infty D^3 f(D) dD$$

or the 0th moment = number concentration of particles:

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

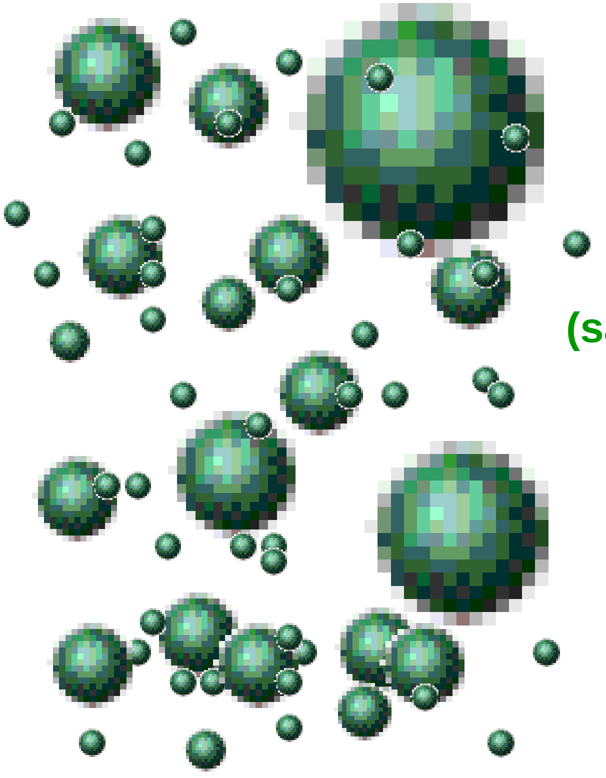
maybe even a third one, like the sixth moment (reflectivity)

Description by size distributions



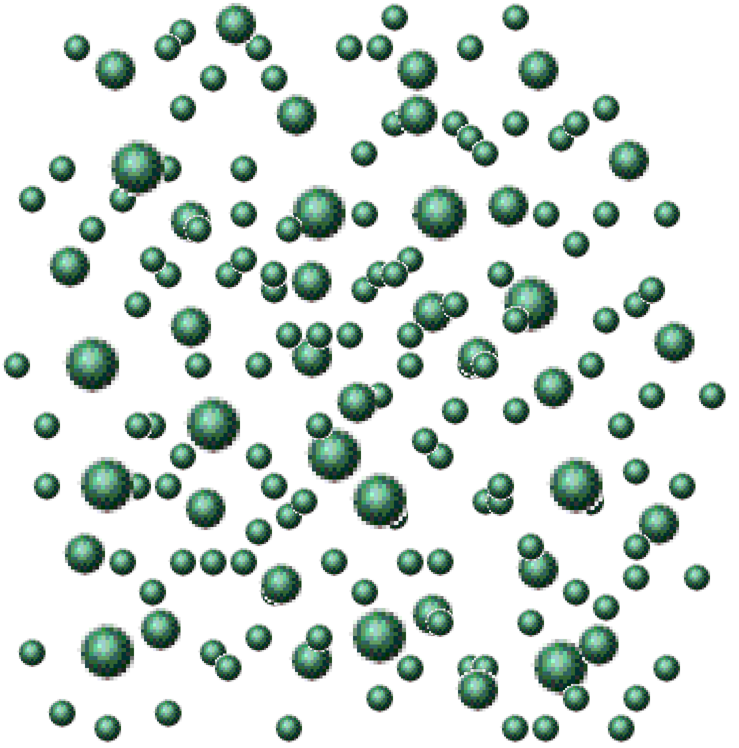
Description by size distributions

Lower value of N_0



(same total mass)

Higher value of N_0



Why using the gamma-Distribution *ansatz*?

First, it fits observed distributions reasonably well.

Second, it is mathematically attractive for **computation of moments** with the help of the **gamma-function *Γ(x)***:

Definition: $\int_0^\infty t^{x-1} e^{-t} dt = \Gamma_{(x)}$

Recursion: $\Gamma_{(x+1)} = x\,\Gamma_{(x)}$

Relation to faculty: $\Gamma_{(0)} = \Gamma_{(1)} = 1 \;\Rightarrow\; \Gamma_{(n+1)} = n!$

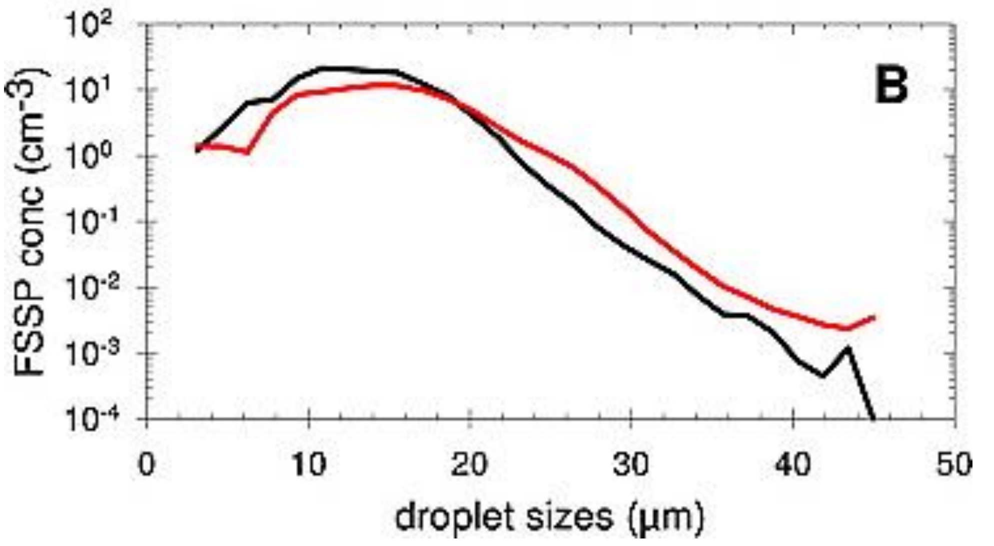
$$\boxed{\mathcal{M}_n = \int_0^\infty D^n \boxed{f(D)}\, dD = \int_0^\infty D^n \boxed{N_0 D^\mu e^{-\lambda D}}\, dD = N_0 \frac{\Gamma_{\left(\frac{\mu+n+1}{\nu}\right)}}{\lambda^{\frac{\mu+n+1}{\nu}}}}$$

For computational purposes, there is a very good approximation of ***Γ(x),*** see, e.g., Press et al. (2001), *Numerical Recipes in Fortran 77, Cambridge University Press*

Microstructure of warm clouds

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

Drop size distributions in maritime shallow clouds

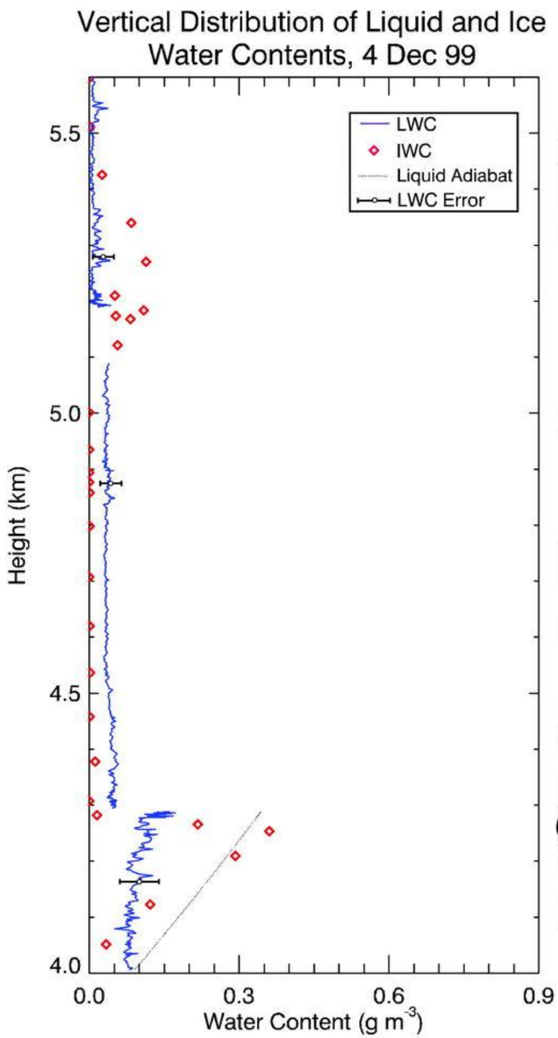


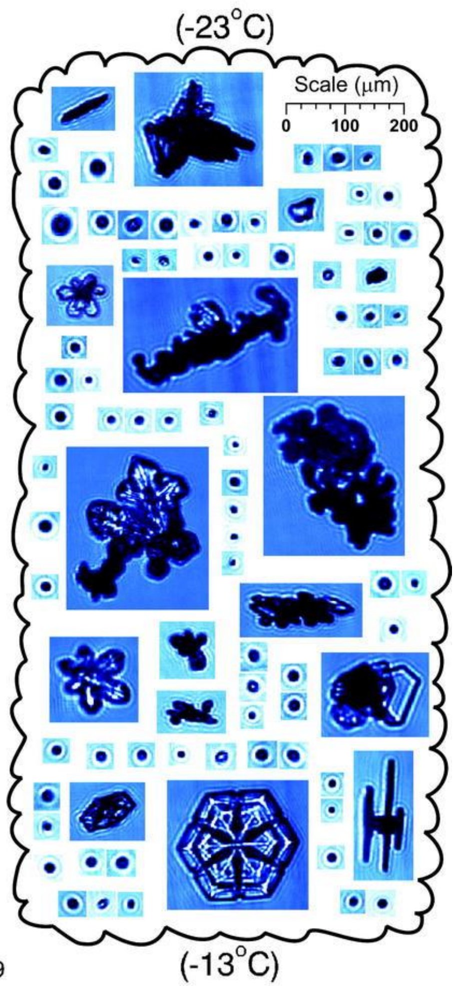
(from Hudson and Noble, 2009, JGR)

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).





Microstructure of rain and snow

The classical measurements of Marshall and Palmer (1948) show that the raindrop size distribution can be parameterized by an inverse exponential with a constant intercept parameter.

Similar results apply to snow, graupel and hail.

THE DISTRIBUTION OF RAINDROPS WITH SIZE

By J. S. Marshall and W. McK. Palmer[1]
McGill University, Montreal

(Manuscript received 26 January 1948)

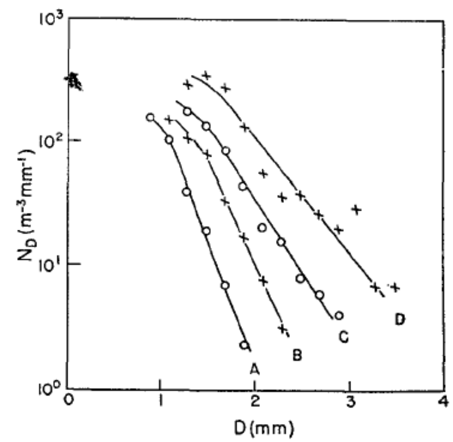


FIG. 1. Distribution of number versus diameter for raindrops recorded at Ottawa, summer 1946. Curve A is for rate of rainfall 1.0 mm hr^{-1}, curves B, C, D, for 2.8, 6.3, 23.0 mm hr^{-1}. $N_D \delta D$ is the number of drops per cubic meter, of diameter between D and $D + \delta D$ mm. Multiplication by 10^{-5} will convert N_D to the units of equation (2).

Except at small diameters, both sets of experimental observations can be fitted (fig. 2) by a general relation,

$$N_D = N_0 e^{-\Lambda D}, \qquad (1)$$

where D is the diameter, $N_D \delta D$ is the number of drops of diameter between D and $D + \delta D$ in unit volume of space, and N_0 is the value of N_D for $D = 0$.

It is found that

$$N_0 = 0.08 \text{ cm}^{-4} \qquad (2)$$

Cloud -> precipitation (1)

Depositional growth (good approximation):

$$\dot{m} \sim D\, d_v(T)\, f_v(D)\, S$$
$$\dot{D} \sim D^{-1}\, d_v(T)\, f_v(D)\, S$$

d_v: Diffusivity of water vapor in air

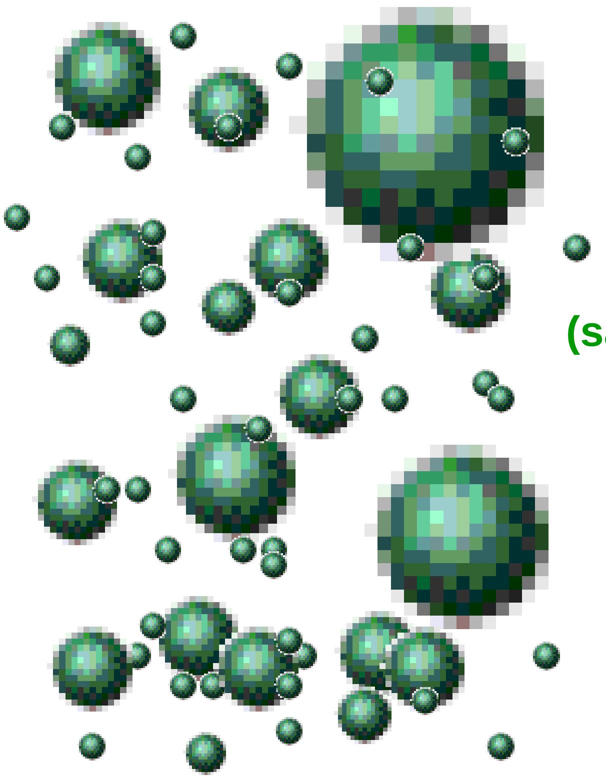
f_v: Ventilation factor, roughly $\sim \sqrt{D}$

Important for „small“ particles < 20-30 µm

Associated latent heat release -> coupling to the dynamics (T-equation)

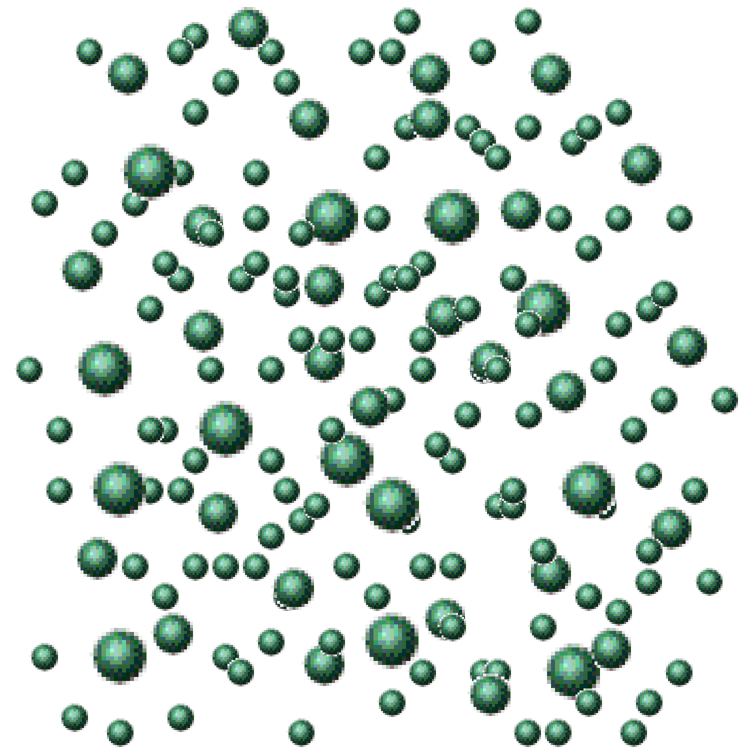
Description by size distributions

Lower evaporation



(same total mass)

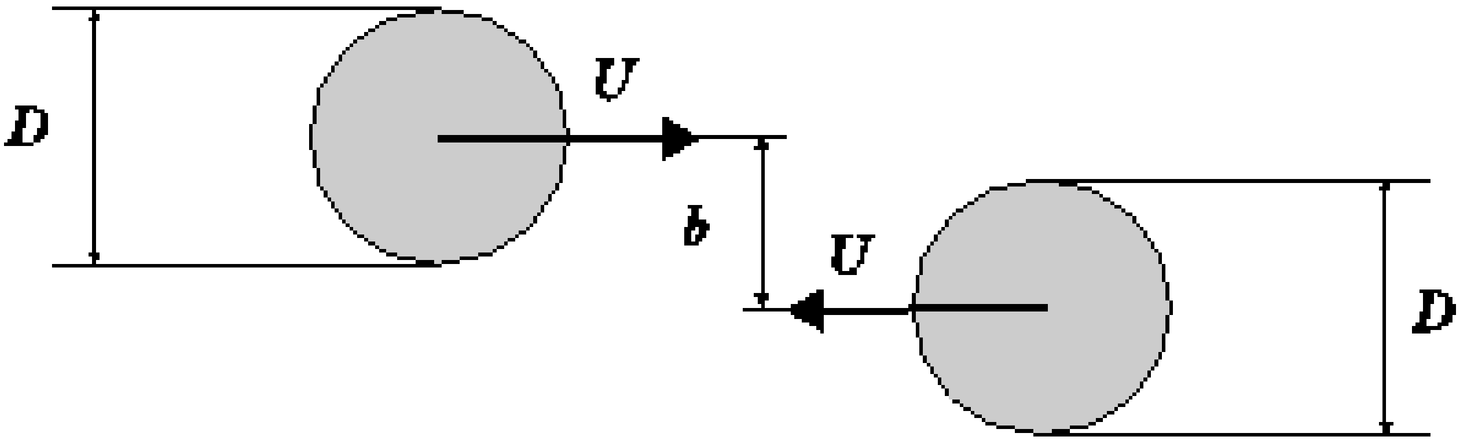
Higher evaporation



Very roughly: dQw ~ total drop surface area per volume

Cloud -> precipitation (2)

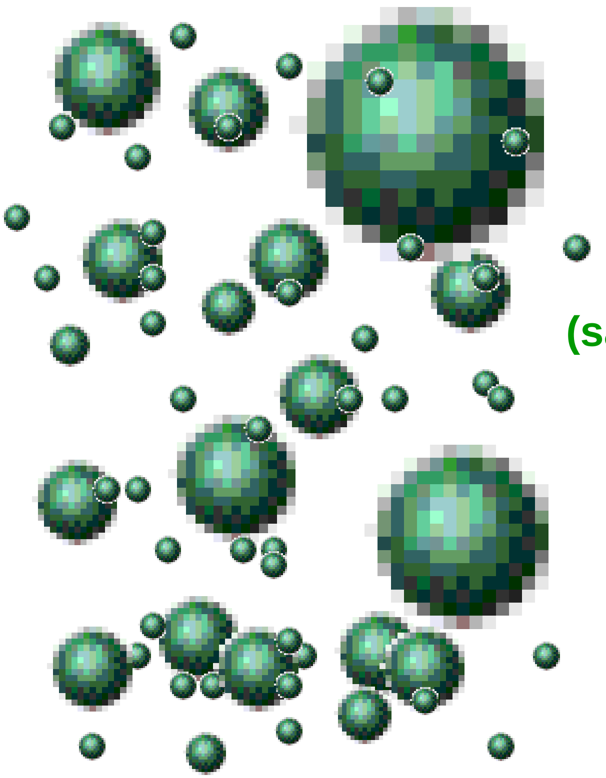
Particle collisions (mostly binary collisions)



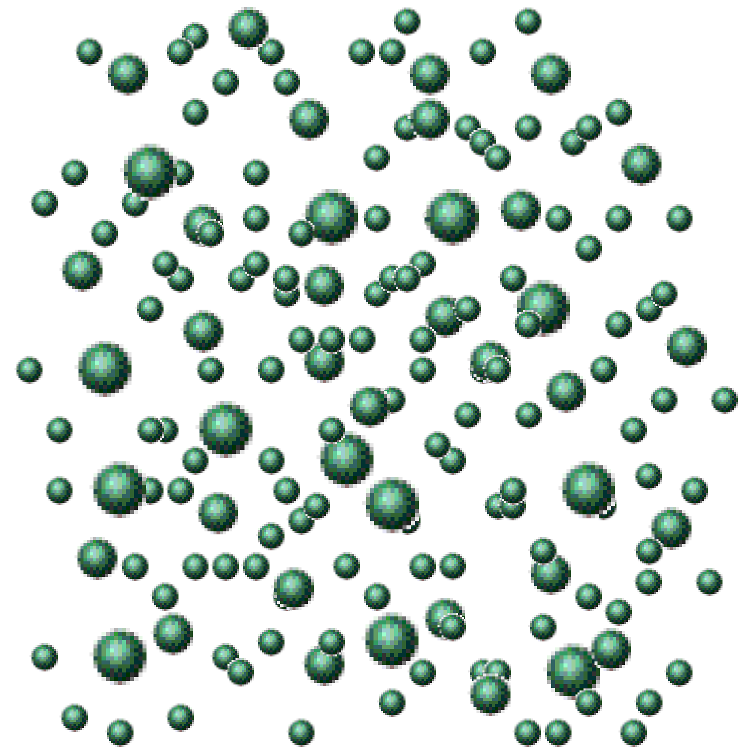
Important for „larger“ particles > 20-30 µm

Description by size distributions

Higher collision rates **Lower collision rates**



(same total mass)



Very roughly: collision rate ~ N * mean fall speed difference * mean cross-sectional area

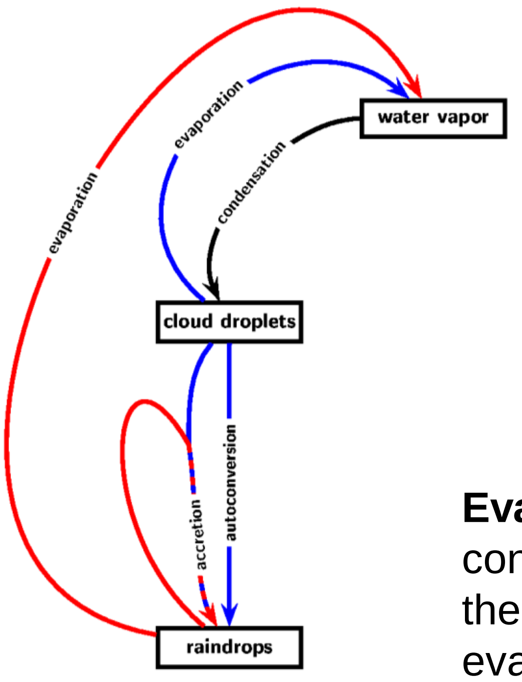
Basic parameterization assumptions

1. The various types of hydrometeors are simplified to a few categories, e.g., cloud droplets, raindrops, cloud ice, snow, graupel etc.

2. We assume thermodynamic equilibrium between cloud droplets and water vapor. Therefore the condensation/evaporation of cloud droplets can be treated diagnostically, i.e., by the so-called saturation adjustment.
   In Contrast, depositional growth/decay of ice particles is treated explicitly.

Technical comment: The saturation adjustment, **`subroutine satad`**, is called at several points in the COSMO code, e.g., within the dynamics and at the end of the microphysics scheme.

Cloud microphysical processes



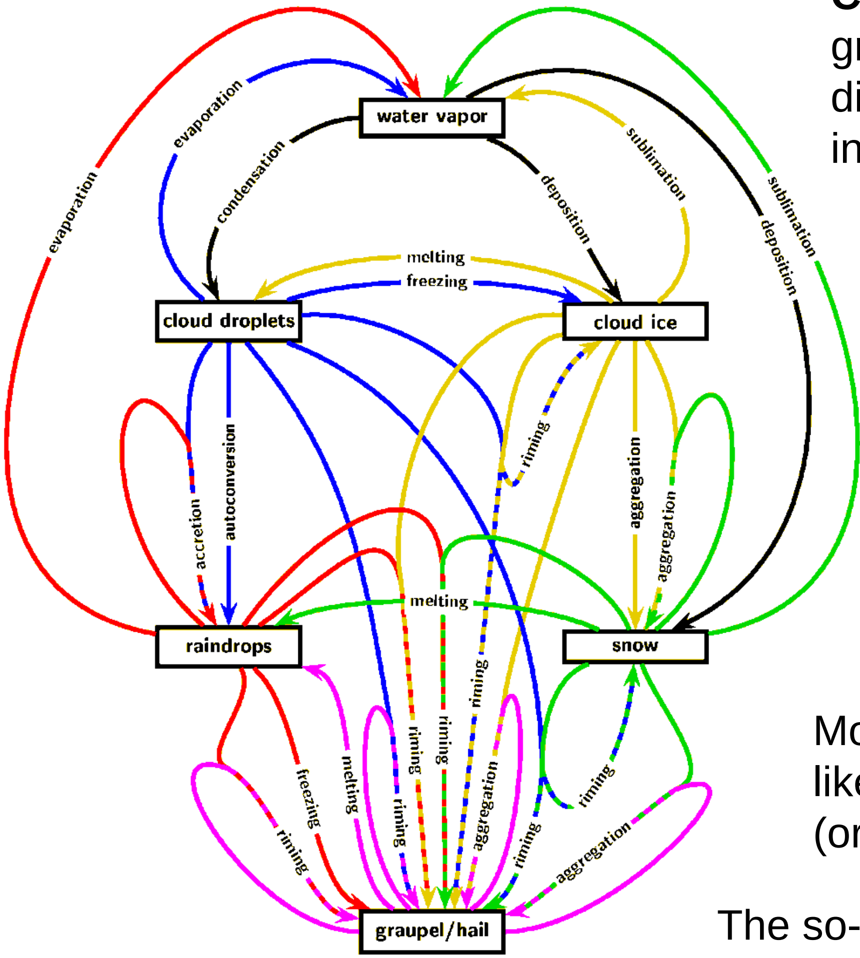
Evaporation and condensation of cloud droplets are usually parameterized by a saturation adjustment scheme.

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 cloud models these problems are usually neglected.

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.

Most schemes do not include **hail processes** like wet growth, partial melting or shedding (or only very simple parameterizations).

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

Spectral formulation of cloud microphysics for droplets (a one-class system):

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

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

with

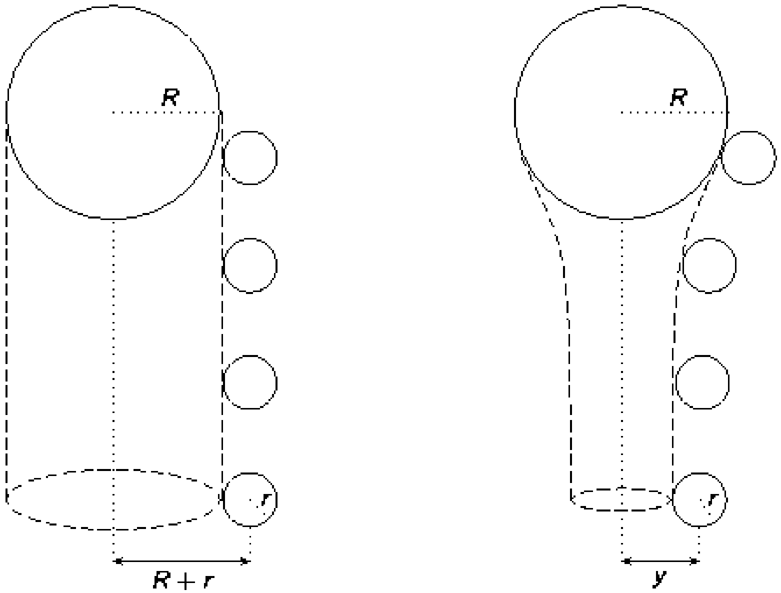
$$\sigma_{coal} = \frac{1}{2}\int_0^x f(x-x',\vec{r},t)\, f(x',\vec{r},t)\, K(x-x',x')\, dx' - \int_0^\infty f(x,\vec{r},t)\, f(x',\vec{r},t)\, K(x,x')\, dx'$$

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

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



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

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

Spectral formulation of cloud microphysics in a multi-class system:

For each species j, one spectral equation (breakup omitted):

$$\frac{\partial f_j(\vec{r},t,x)}{\partial t} + \nabla \cdot \left(\vec{v}(\vec{r},t) f_j(\vec{r},t,x) \right) + \frac{\partial}{\partial z}\left(v_{sj}(x) f_j(\vec{r},t,x) \right) + \frac{\partial}{\partial x}\left(\dot{x} f_j(\vec{r},t,x) \right) = \sum_{k=1}^{N} \sigma_{jk} \qquad j = 1 \ldots N$$

$\sigma_{jk} \neq \sigma_{kj}$ (meaning: species j kollides with another species k)

Collision terms $\boldsymbol{\sigma_{jk}}$: Example: rain (2) + graupel (5) = graupel (5)

$$\sigma_{25} = \left.\frac{\partial f_r(x_r)}{\partial t}\right|_{coll,gr} = -\int_0^\infty f_r(x_r)\, f_g(x_g)\, K_{gr}(x_r, x_g)\, dx_g$$

$$\sigma_{52} = \left.\frac{\partial f_g(x_g)}{\partial t}\right|_{coll,gr} = +\int_0^{x_g} f_g(x_g - x_r)\, f_r(x_r)\, K_{gr}(x_g - x_r, x_r)\, dx_r - \int_0^\infty f_g(x_g)\, f_r(x_r)\, K_{gr}(x_g, x_r)\, dx_r$$

with the „geometric“ collision kernel (assuming $E_{coal} = 1$)

$$K_{gr}(x_g, x_r) = \frac{\pi}{4}\left(D_g^2(x_g) + D_r^2(x_r) \right) \left| v_g(x_g) - v_r(x_r) \right| \, E_{gr}(x_g, x_r)$$

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

Set of equations solved **per species** for different scheme types:

Spectral bin model **(~ 50 – 100 variables)**

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

x discretized in N bins;
one equation solved per bin;
x ∈ {m,D}

Two-moment bulk model **(2 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 **(1 variable)**

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

Most currently available schemes in the official COSMO model are one-moment bulk schemes. One two-moment scheme is available and used for research and COSMO-ART!

Increasing complexity of bulk microphysics models over the last decades

	cloud		rain		ice		snow		graupel		hail	
	N	L	N	L	N	L	N	L	N	L	N	L
Kessler, 1969; Berry, 1968		□		□								
Wisner et al., 1972		□		□								□
Lin et al., 1983		□		□		□		□				□
Rutledge & Hobbs, 1984		□		□		□		□		□		
Cotton et al., 1986		□		□	■	□		□		□		
Mölders et al., 1995		□		□		□						
Kong & Yau, 1997		□		□		□						
Murakami, 1990		□		□	■	□	■	□		□		
Ferrier, 1994		□		□	■	□	■	□	■	□	■	□
Reisner et al., 1998		□		□	■	□	■	□	■	□		
Meyers et al., 1997		□	■	□	■	□	■	□	■	□	■	□
Ziegler, 1985	■	□	■	□		□		□			■	□
Cohard & Pinty, 2000	■	□	■	□								
Seifert & Beheng, 2002	■	□	■	□	■	□	■	□	■	□		

N = number densities, L = mixing ratios

← COSMO schemes are similar to Lin et al. (1983) and Rutledge and Hobbs (1984).

Two-moment schemes are becoming more and more the standard in research and are even an option for NWP. Even the first three-moment scheme has been published by Milbrandt and Yau (2005). A quite different approach has been recently introduced by Gilmore and Straka who use about 100 different ice categories.

Parameterization of sedimentation:

An example how to derive bulk microphysics equations

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

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

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

… and find the sedimentation velocity v_L for liquid water:

For the fall speed we can assume

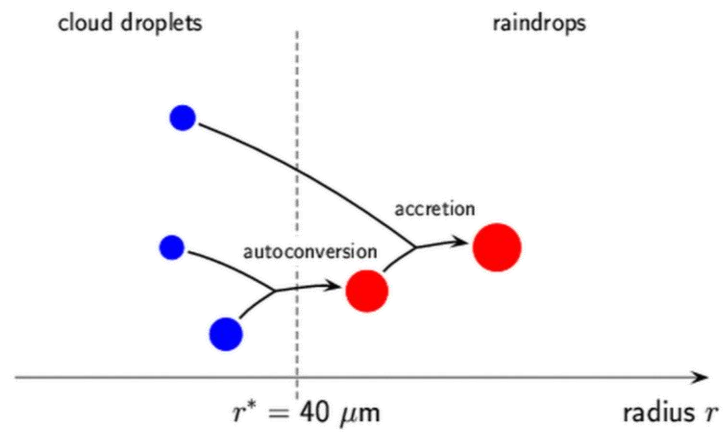
$$v(D) = \alpha \left(\frac{D}{D_0} \right)^{\frac{1}{2}}$$

which leads to

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

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:

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

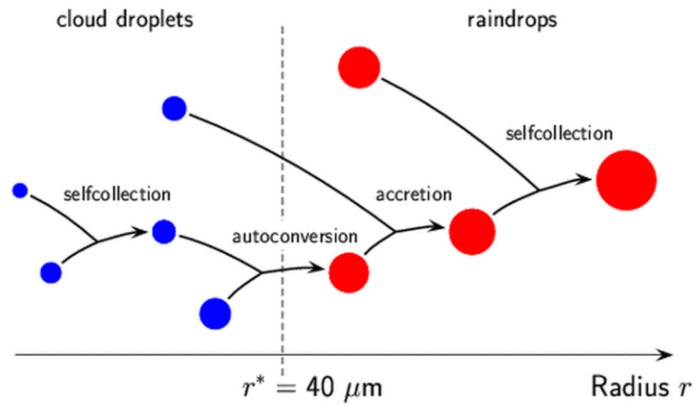
„As we know, water clouds sometimes persist for a long time without evidence of precipitation, but various measurements show that cloud amounts > 1 g/m³ are usually associated with production of precipitation. It seems reasonable to model nature in a system where the rate of cloud autoconversion increases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

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



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

A one-moment version of this autoconversion scheme is now implemented in the microphysics schemes of COSMO 4.0

Solid (ice) particles

Mass content L_x ($x \in \{i, s, g\}$) in kg m^{-3}:

$$L_x \ = \ \int_0^\infty m(D)\, f(D)\, dD$$

with

$$m(D) = a_{geo}\, D^{b_{geo}} \qquad \text{and} \qquad f(D) = N_0 \exp\left(-\lambda\, D\right)$$

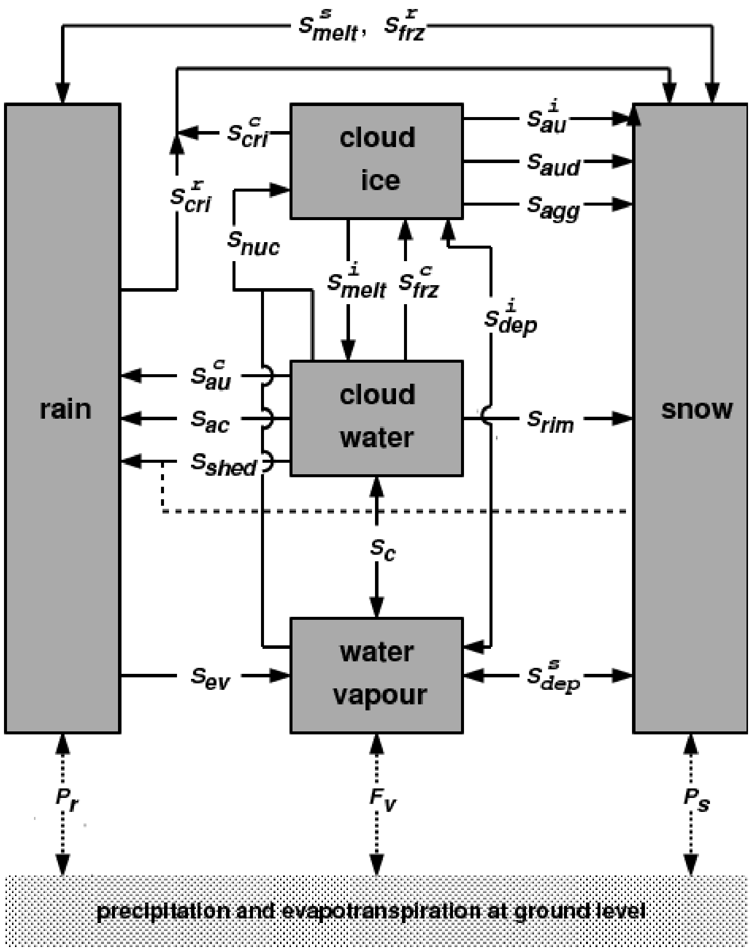
it follows

$$L_x \ = \ a_{geo} \int_0^\infty D^{b_{geo}}\, f(D)\, dD \ = \ N_0 \frac{\Gamma(b_{geo} + 1)}{\lambda^{b_{beo}+1}}$$

Typical values: Snow flakes $b_{geo} \sim 2.0$

Graupel $b_{geo} \sim 3.0$

The COSMO two-category ice scheme
(also known as the ‘cloud ice scheme’)



subroutine: hydci_pp

namelist setting: itype_gscp=3
lprogprec=.true.
(both default in COSMO)

- Includes cloud water, rain, cloud ice and snow.
- Prognostic treatment of cloud ice, i.e., non-equilibrium growth by deposition.
- Developed for the 7 km grid, e.g., DWD’s COSMO-EU.
- Only stratiform clouds, graupel formation is neglected.

The COSMO two-category ice scheme

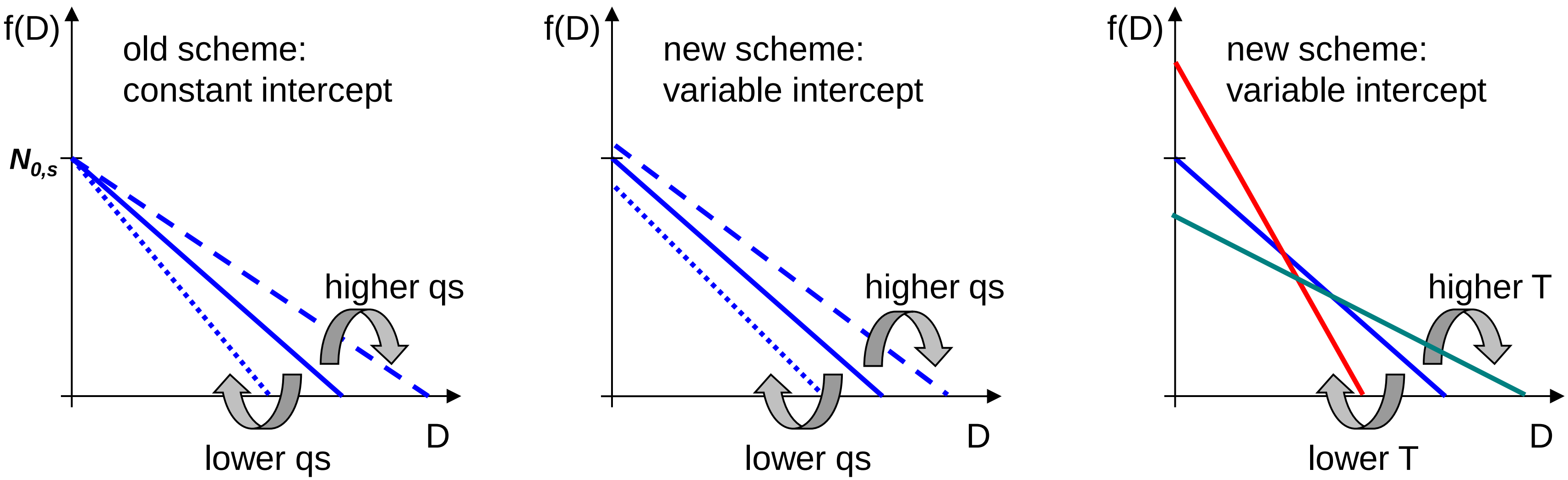
Various freezing modes depending on temperature and humidity:

1. Heterogenous freezing of raindrops:
   $T < 271.15$ K and $qr > 0$
2. Heterogenous condensation freezing nucleation:
   $T \leq 267.15$ K and water saturation
3. Heterogenous deposition nucleation:
   $T < 248.15$ K and RHi > 100 % (ice supersaturation)
4. Homogenous freezing of cloud droplets:
   $T \leq 236.15$ K and $qc > 0$

For parameterizing (2) and (3), a number concentration of ice nuclei is assumed, which depends on T:

$$N_i(T) = N_0^i \exp\{\, 0.2\,(T_0 - T)\}\,, \qquad N_0^i = 1.0 \cdot 10^2 m^{-3}$$

Variable snow intercept parameter N_{0s}



- The snow size distribution can now adjust to different conditions as a function of temperature and snow mixing ratio.
- This will (hopefully) give more accurate estimates of the various microphysical process rates.

Variable snow intercept parameter N_{0s}: An empirical parameterization

Using a parameterization of Field et al. (2005, QJ) based on **aircraft measurements** all moments of the snow PSD can be calculated from the mass moment:

$$\mathcal{M}_n = a(n, T_c)\mathcal{M}_2^{b(n,T_c)}$$

Why M_2?

$m_s \sim D^2$!

Assuming an exponential distribution for snow, $N_{0,s}$ can easily be calculated using the 2nd moment, proportional to q_s, and the 3rd moment:

$$N_0 = \frac{27}{2}\frac{\mathcal{M}_2^4}{\mathcal{M}_3^3} = \frac{27}{2}\,a(T)\,\mathcal{M}_2^{4-3b(T)}$$

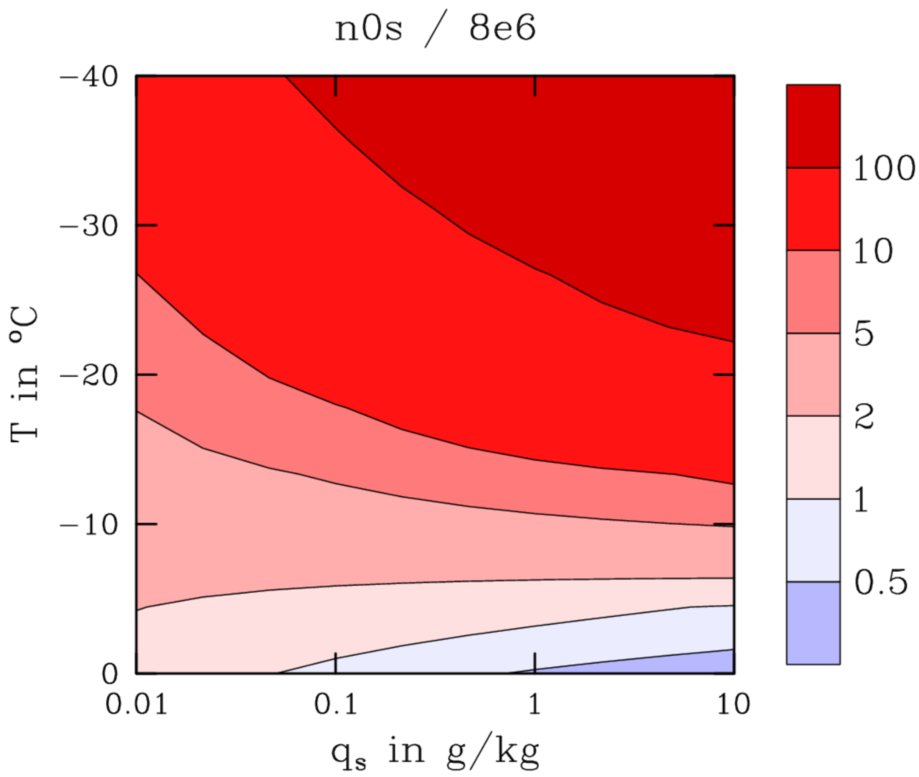
Now we have parameterized N_0 as a function of temperature and snow mixing ratio.

Variable snow intercept parameter (continued)

$$N_0 = \frac{27}{2}\,\frac{\mathcal{M}_2^4}{\mathcal{M}_3^3} = \frac{27}{2}\,a(T)\,\mathcal{M}_2^{4-3b(T)}$$

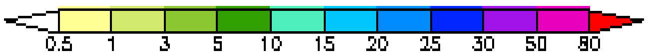
The dominant effect is the temperature dependency, which represents the size effect of aggregation, i.e. on average snow flakes at warmer temperature are larger.

This dependency has already been pointed out be Houze et al. (1979, JAS) and is parameterized in many models using $\boldsymbol{N_{0,s}(T)}$.

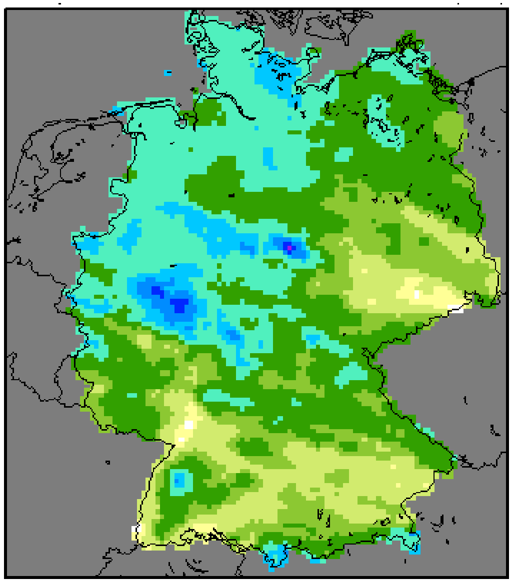


Accumulated precipitation
11.01.07 00 UTC, 06h - 30h

accumulated precipitation in mm

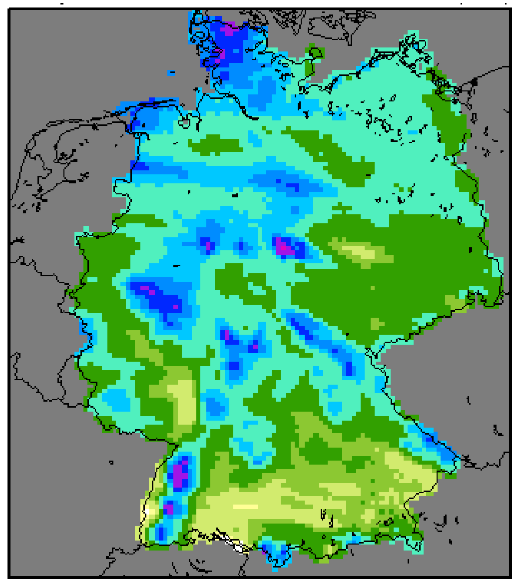


Surface observations



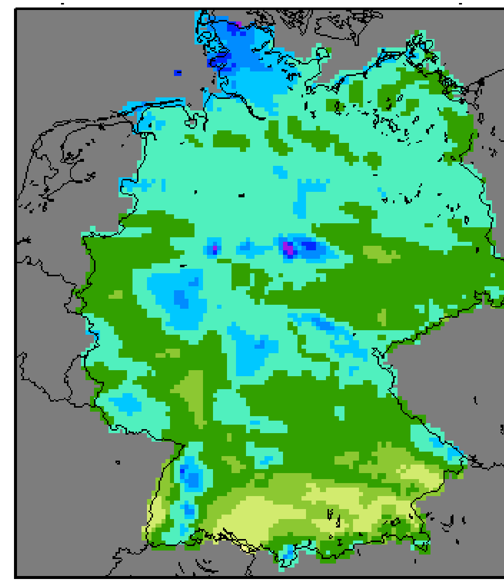
mean: 8.1 mm
max: 31.5 mm

old microphysics



mean: 11.5 mm
max: 50.7 mm

current microphysics

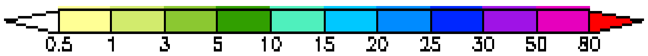


mean: 10.3 mm
max: 36.7 mm

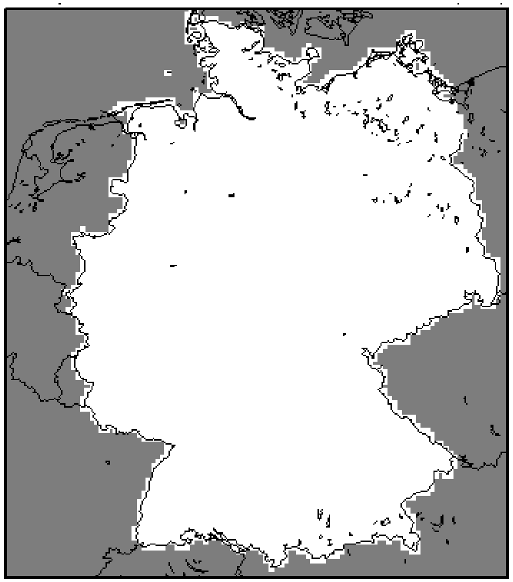
- Orographic precipitation falls out slower leading to decreased precipitation amounts at mountain tops and more horizontal advection into the lee

Accumulated precipitation
22.12.06 00 UTC, 06h - 30h

accumulated precipitation in mm

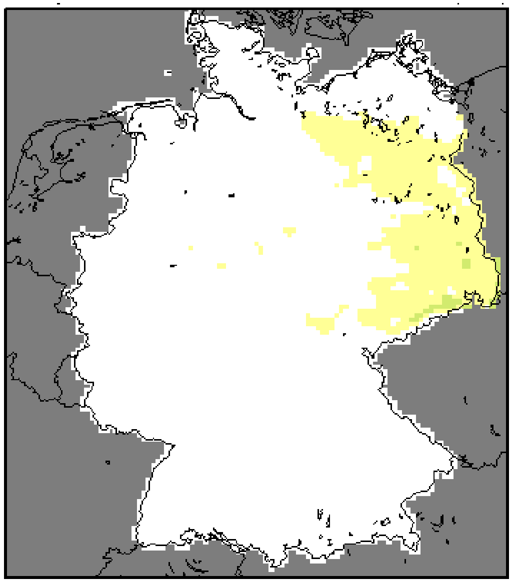


Surface observations



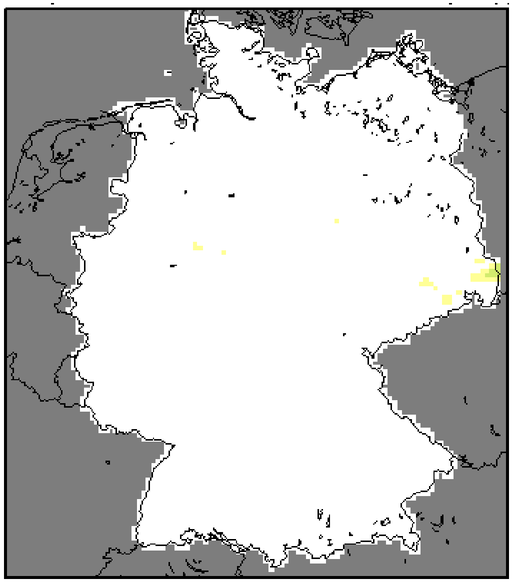
mean: 0.002 mm
max: 0.45 mm

old microphysics



mean: 0.17 mm
max: 2.1 mm

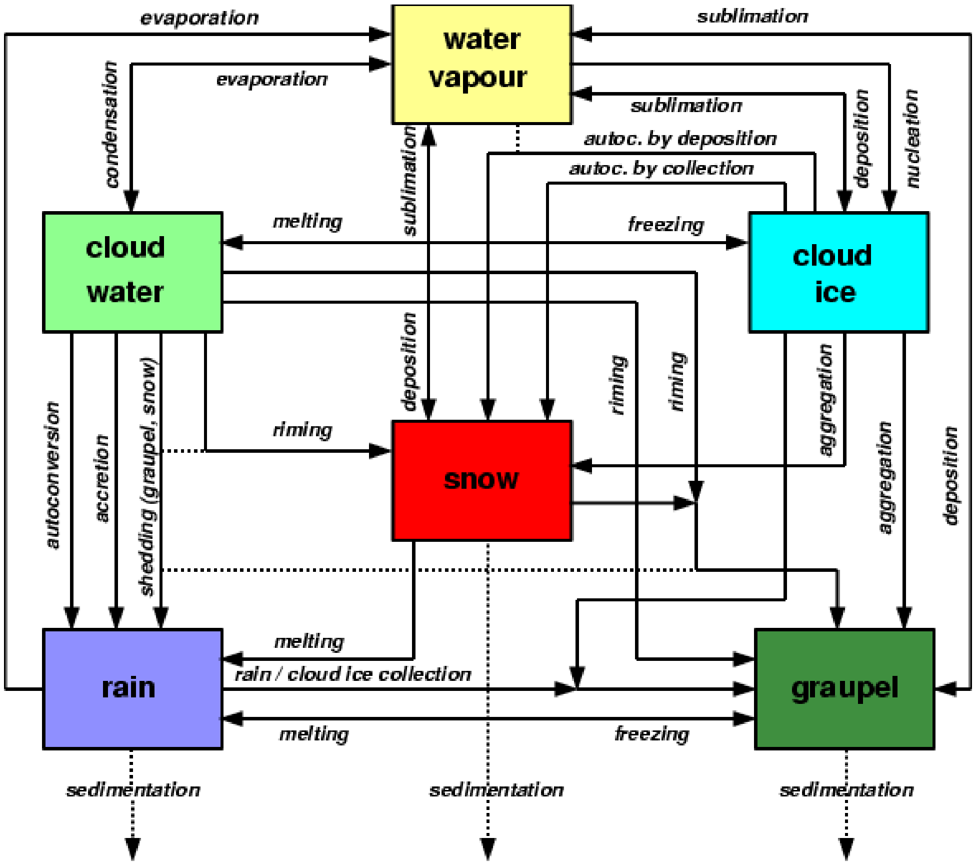
current microphysics



mean: 0.01 mm
max: 1.65 mm

- Wrong forecasts of widespread drizzle are considerably reduced by the highly non-linear SB2001 autoconversion scheme

The COSMO three-category ice scheme
(also known as the 'graupel scheme')



subroutine: hydci_pp_gr

namelist setting:

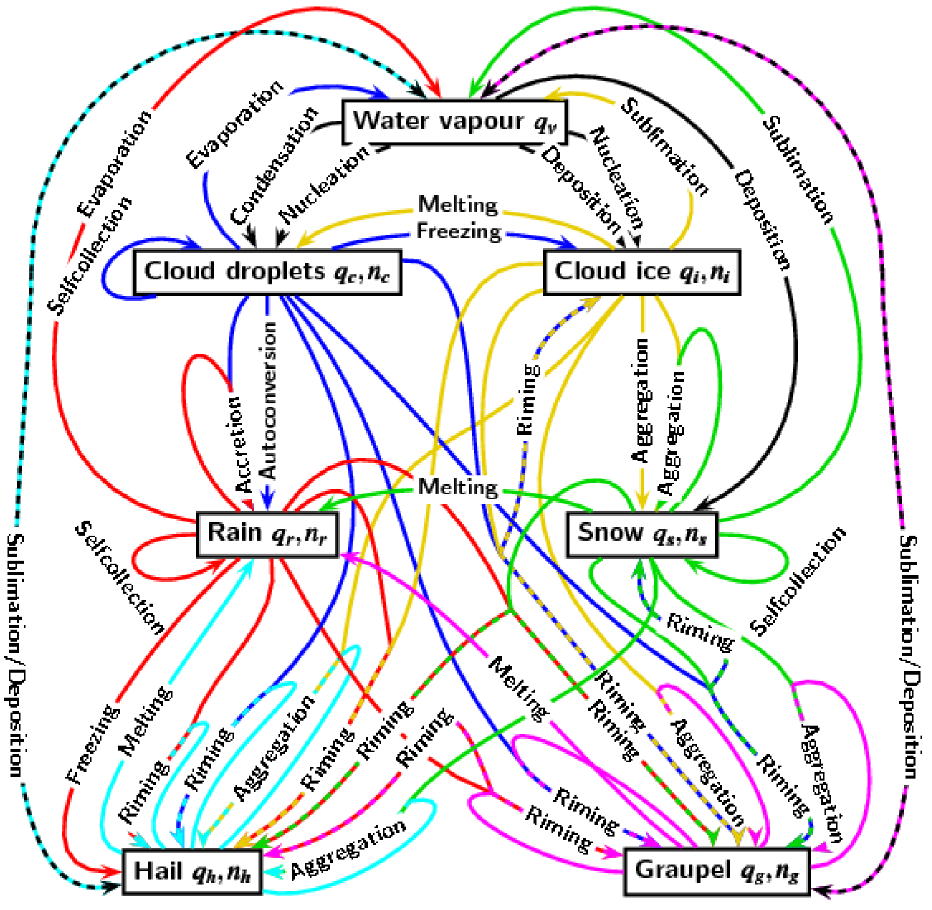
itype_gscp=4

lprogprec=.true.

- Includes cloud water, rain, cloud ice, snow and graupel.
- Graupel has much higher fall speeds compared to snow
- Developed for the 2.8 km grid, e.g., DWD's convection-resolving COSMO-DE.

- Necessary for simulation without parameterized convection. In this case the grid-scale microphysics scheme has to describe all precipitating clouds.

A two-moment microphysics scheme in the COSMO model

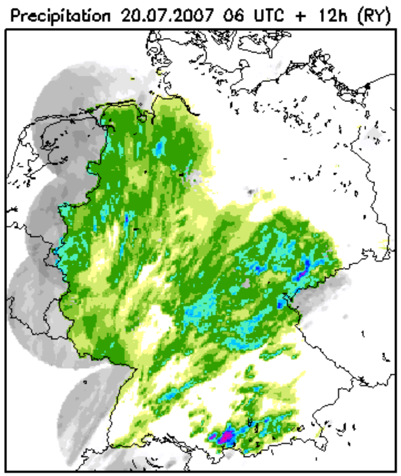


- Prognostic number concentration for all particle classes, i.e. explicit size information.
- Prognostic hail.
- Aerosol-cloud-precipitation effects can be simulated
- Using 12 prognostic variables the scheme is computationally expensive and not well suited for operational use.
- Works well with COSMO-ART

Available since COSMO 5.0

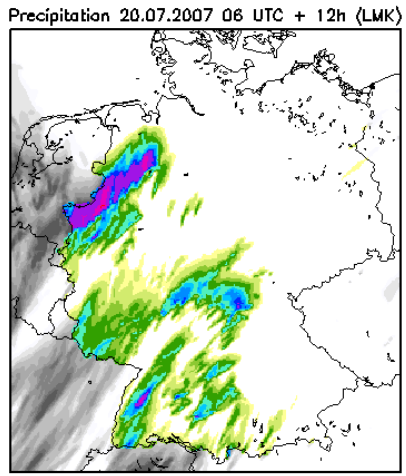
Case study 20 Juli 2007:
Cold Front / Squall Line

Radar (RY)



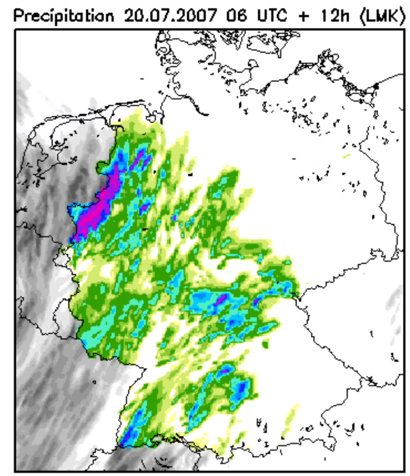
AVG: 3.4 mm

ONE-MOMENT



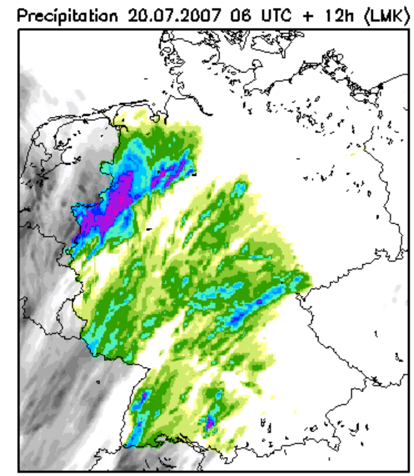
AVG: 2.8 mm

SB-CLEAN

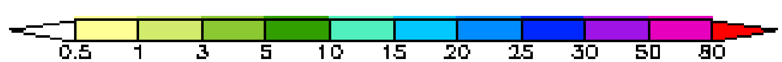


AVG: 3.4 mm

SB-POLLUTED



AVG: 3.5 mm



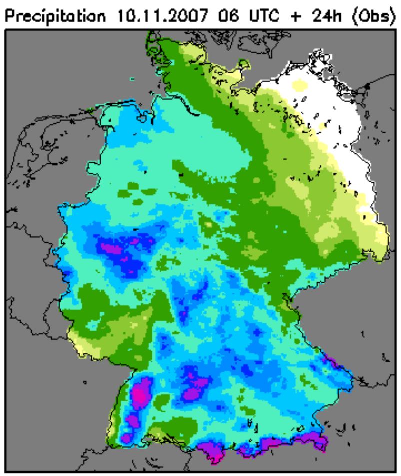
accumulated precip in mm

➔ More intense squall line with two-moment scheme

➔ Aerosol effect can slightly modify the intensity and spatial distribution.

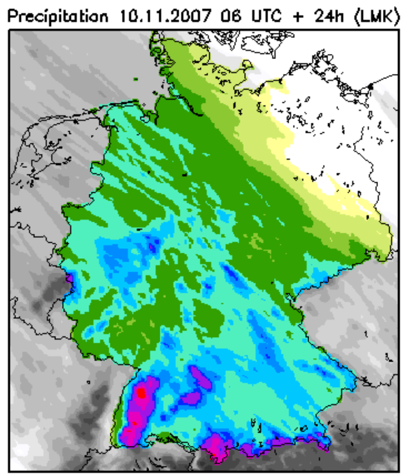
Case study 11 Nov 2007

Gauges (REGNIE)



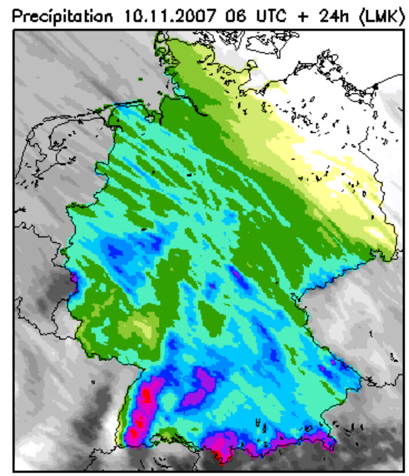
AVG: 11.7 mm

ONE-MOMENT



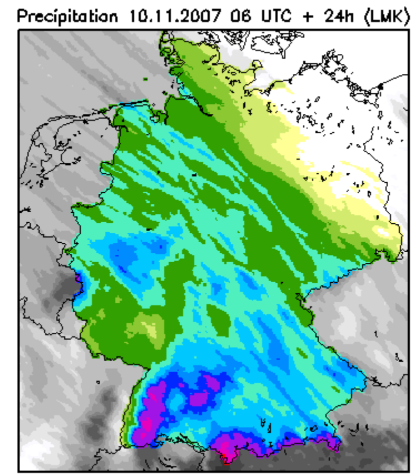
AVG: 10.7 mm

SB-CLEAN

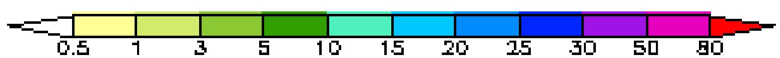


AVG: 11.4 mm

SB-POLLUTED



AVG: 11.0 mm



accumulated precip in mm

- ➔ Only weak sensitivity to cloud microphysics. No significant difference between one- and two-moment scheme.
- ➔ Orographic precipitation enhancement is weaker for ‘polluted’ aerosol assumptions.

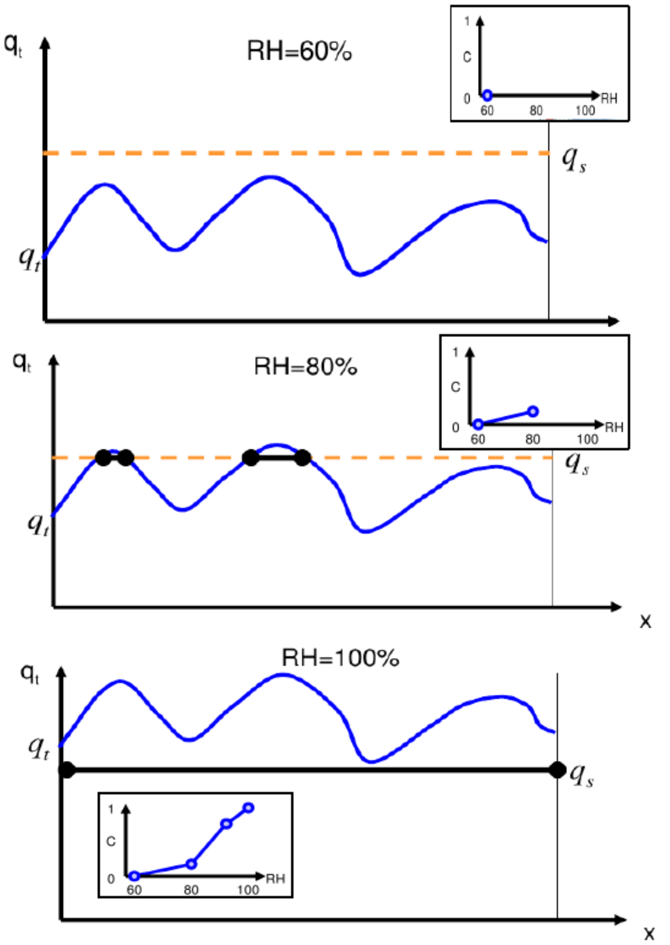
Parameterization of cloud cover

Within a grid box fluctuations in temperature and moisture can lead to sub-grid clouds.

The figure shows fluctuations of the total mixing ratio. For $\boldsymbol{q_t}$ exceeding the saturation mixing ratio $\boldsymbol{q_s}$, clouds form by condensation.

This leads to an empirical parameterization of fractional cloud cover ***C*** as a function of relative humidity ***RH***.

The COSMO model uses a RH-based scheme in the radiation schoeme.

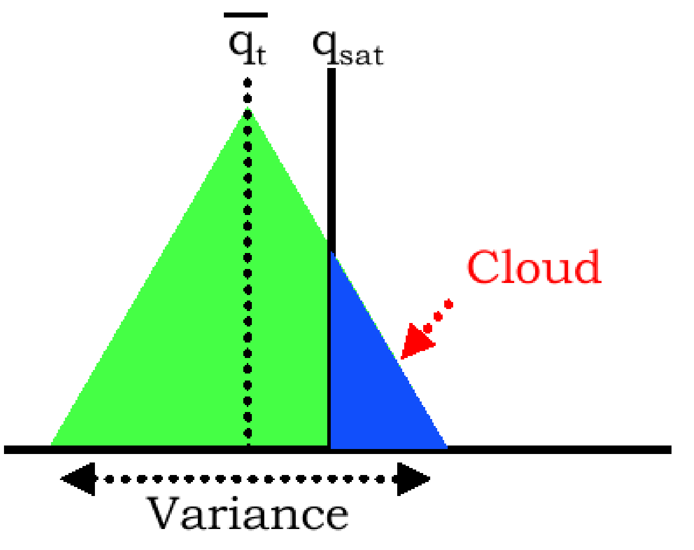


Parameterization of cloud cover

A slightly more sophisticated concepts are PDF-based schemes. Using assumptions about the sub-grid variability of $\boldsymbol{q_t}$, one can derive the cloud fraction from

$$C = \int_{q_s}^{\infty} G(q_t)\, dq_t$$

where $\boldsymbol{G(q_t)}$ is the PDF of $\boldsymbol{q_t}$



Piecewise linear PDF of qt, and the diagnosed cloud fraction

PDF-based schemes are also known as statistical cloud schemes **(Sommeria and Deardorff 1978).** **The COSMO model uses a statistical cloud scheme within the turbulence model to parameterize effects of phase changes (latent heat release) by boundary layer clouds.**

The COSMO cloud cover scheme for Radiation

(subroutine: organize_radiation)

First, stratiform sub-grid clouds are estimated as a function of the total water mass fraction $q_t = q_v + q_c + q_i$ and

$$\alpha_{sgs} = 0.95 - 0.8\,\sigma\,(1-\sigma)(1+\sqrt{3}(\sigma - 0.5))$$

with $\sigma = p/p_s$ wherein p are pressure and surface pressure, respectively. The sub-grid stratiform cloud fraction is then parameterized by

Stratiform sub-grid clc

$$\mathcal{N}_{sgs} = \max\left\{0, \min\left[1, \left(\frac{q_t}{q_{sat}} - \alpha_{sgs}\right)(1-\alpha_{sgs})^{-1}\right]\right\}^2 .$$

Generalized relative humidity RH_g

with

$$q_{sat} = q_{sat,l}\,(1-f_{ice}) + q_{sat,i}\,f_{ice}$$

and

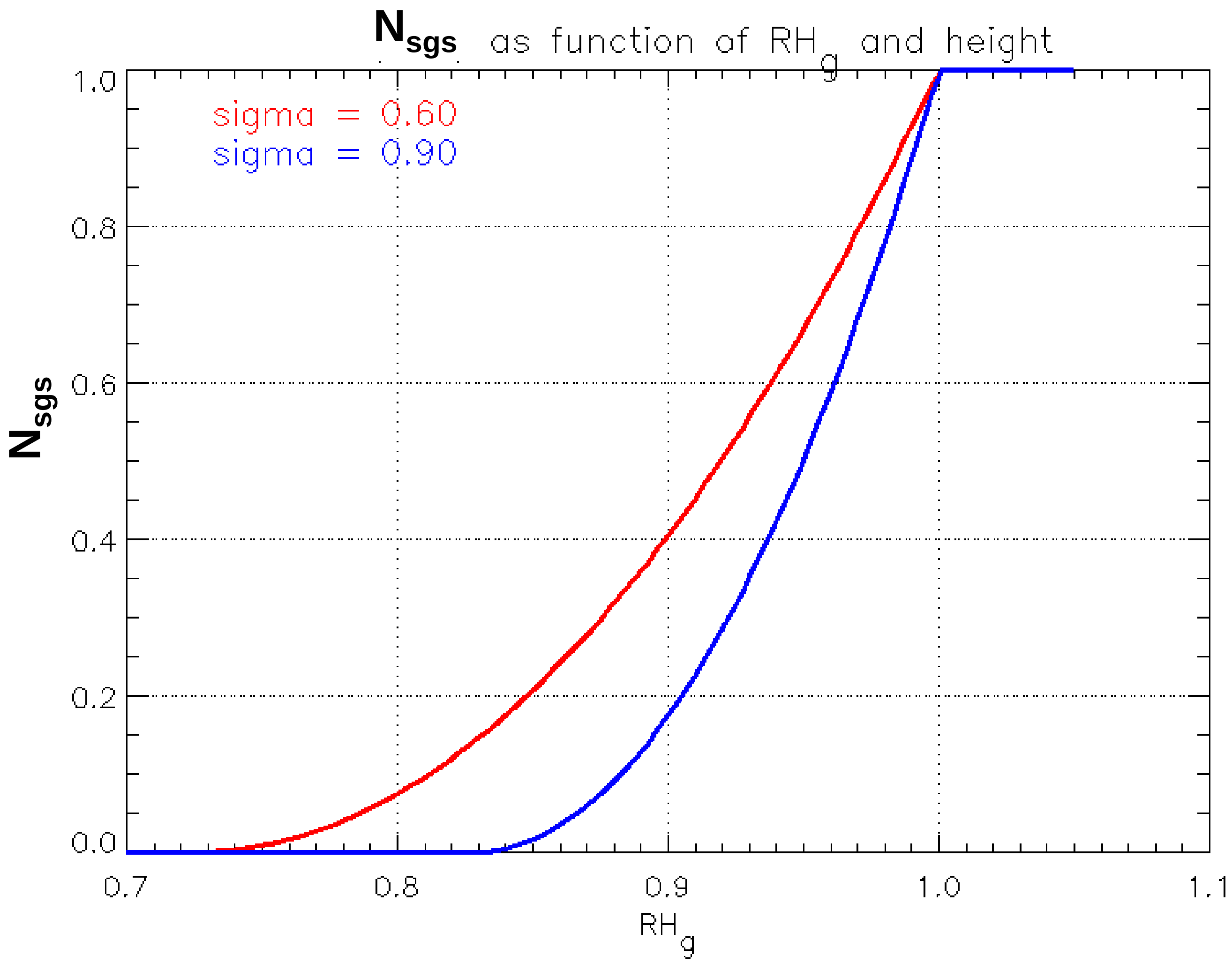
$$f_{ice} = 1 - \min\left[1, \max\left(0, \frac{T_C - (-25)}{(-5)-(-25)}\right)\right]$$

Here T_C is the temperature in degree Celcius. Note that for unstable conditions, i.e. $\partial\theta/\partial z < 0$, the stratiform cloud fraction is set to zero.

Using the grid-scale mass fractions q_c and q_i, the stratiform cloud cover is calculated by:

$$\mathcal{N}_{strat} = \begin{cases} 1, & \text{if } q_c > 0 \\ 1, & \text{if } q_i > 10^{-7} \\ \mathcal{N}_{sgs}, & \text{else.} \end{cases}$$

The COSMO cloud cover scheme for Radiation



sigma = P / PS

The COSMO cloud cover scheme for Radiation

(subroutine: organize_radiation)

For convective clouds the cloud fraction is parameterized as a function of cloud depth, i.e. it is assumed that the radius of convective clouds increases with cloud depth.

$$\mathcal{N}_{con} = \min\left[1, \max\left(0.05, 0.35\,\frac{z_{top} - z_{base}}{5000\ \mathrm{m}}\right)\right]$$

Here z_{top} and z_{base} are cloud top and cloud base as parameterized within the Tiedtke convection scheme.

The COSMO cloud cover scheme for Radiation

(subroutine: organize_radiation)

For thin upper-level ice clouds ($q_{i,strat} < 0.01$ g/kg) the cloud fraction is reduced based on the estimated ice water content by:

$$\mathcal{N}_{strat,corr} = \mathcal{N}_{strat}\ \min\left[1, \max\left(0.2, \frac{q_{i,strat} - 10^{-7}}{10^{-5} - 10^{-7}}\right)\right],$$

if $q_{c,strat} > 10^{-10}$

Note that this correction is also applied if grid-scale ice clouds are present, thus due to this correction cloud fraction can be < 1 even if $q_i > 10^{-7}$.

The total cloud fraction from all three cloud types is then given by:

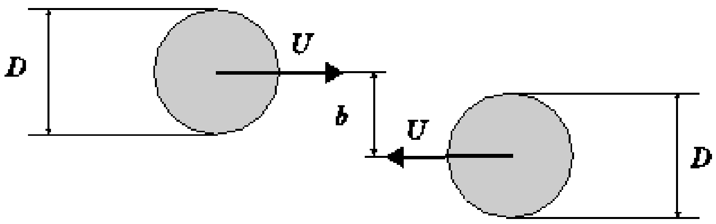
$$\mathcal{N} = \mathcal{N}_{strat,corr} + \mathcal{N}_{con}(1 - \mathcal{N}_{strat,corr})$$

Known problems of precipitation forecasts

- In older versions moist bias during winter, i.e., about 20-40% too much precipitation. Since winter 2010/2011 much better, mostly because of Runge-Kutta dynamical core.
- Smaller dry bias during summer in COSMO-EU (7 km) and COSMO-DE (2.8 km), i.e. convection is not active enough, but probably different reasons in both models.
- Luv-lee problem in COSMO-EU due to convection scheme which triggers only on the windward side of the mountains and convective precipitation is not advected.
- Too less parameterized convective precipitation in the tropics, at least in NWP mode with ~7 - 14 km resolution

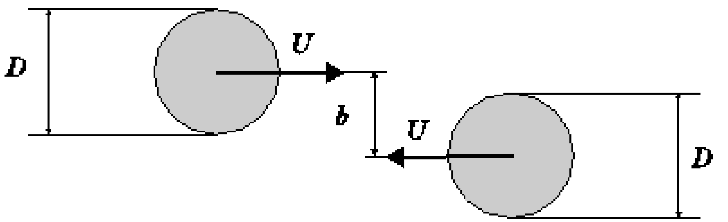
Note that these problems are not primarily caused by the microphysics scheme.

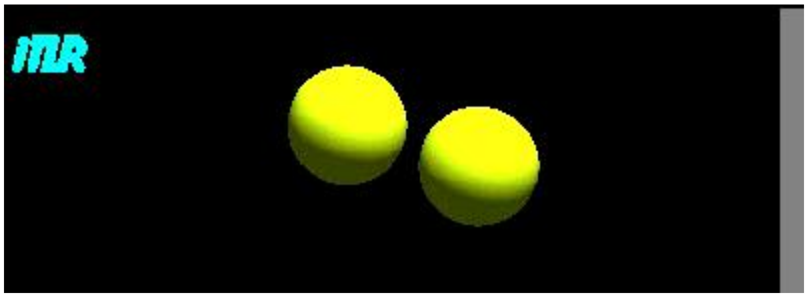
Collisional Breakup of Drops



The currently used breakup parameterizations based on the Low and List (1982) data are quite uncertain.
Spectral bin models still have problems to reproduce the observed DSDs (Seifert et al. 2005).
A promising approach to derive improved breakup parameterizations is the direct numerical simulation of individual binary droplets collisions (Beheng et al. 2006)

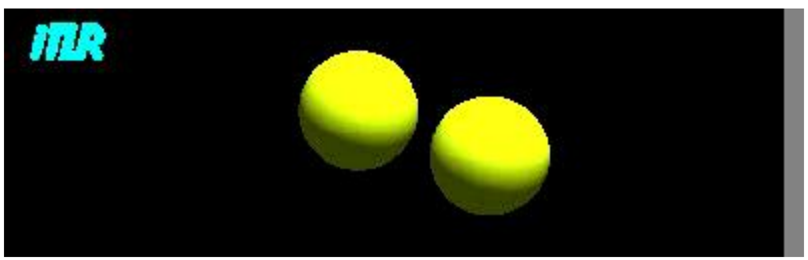
Collisional Breakup of Drops





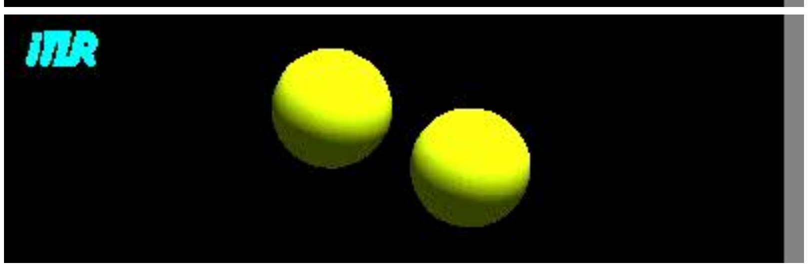
Binary droplet collision with
$We = 4\rho U^2 D/\sigma = 106$
$Re = 2UD/\nu = 100$
$B = b/D = 0.33$

coalescence!



Binary droplet collision with
$We = 4\rho U^2 D/\sigma = 106$
$Re = 2UD/\nu = 100$
$B = b/D = 0.37$

temporary coalescence!



Binary droplet collision with
$We = 4\rho U^2 D/\sigma = 106$
$Re = 2UD/\nu = 100$
$B = b/D = 0.48$

collisional breakup!

(Simulations by ITLR, University Stuttgart)

Arakawa (2004)

'Understanding requires simplifications, including various levels of "parameterizations," [...] which are quantitative statements on the statistical behavior of the processes involved. Parameterizations thus have their own scientific merits. '

The End

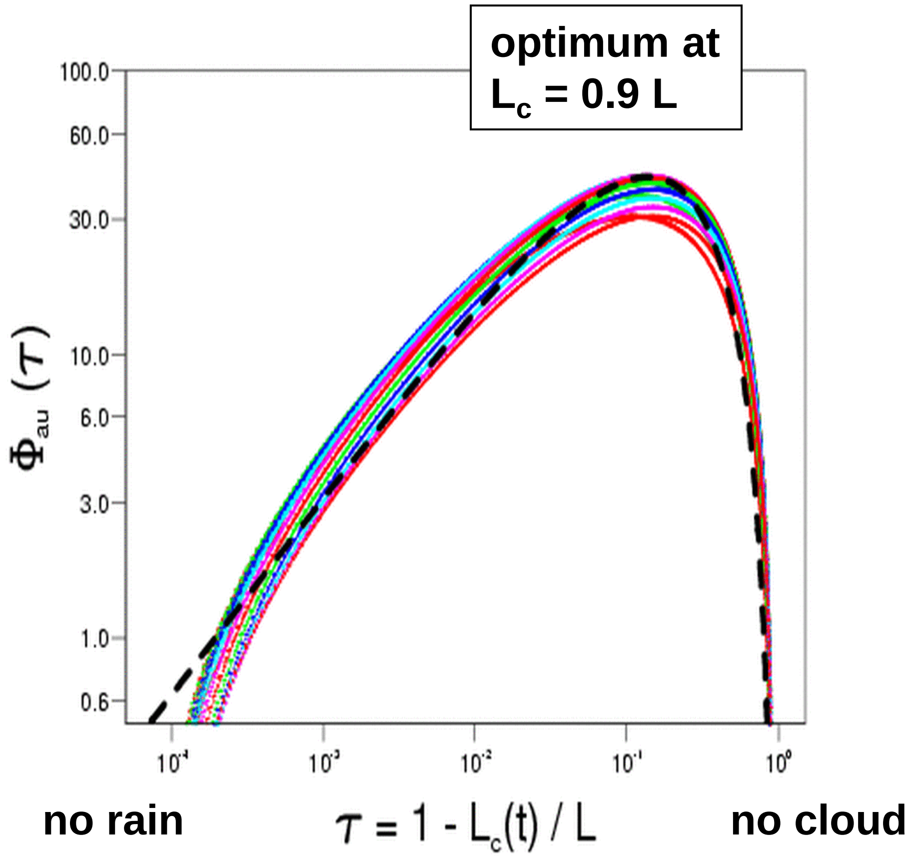
A double-moment warm phase scheme

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)

The COSMO two-category ice scheme

Although we neglect graupel as a category, riming, i.e., the collection of cloud droplets by snow is taken into account. Now, as another example, we explicitly derive …..

The parameterization of the riming rate of snow

The parameterization of the riming of snow is an example of the so-called continous growth equation. Using spectral notation, the riming rate is defined as

$$Q_{rim} = \int_0^\infty \int_0^\infty K(R,r)\, f_c(r)\, f_s(R)\, m(r)\, dr\, dR$$

with the collection kernel

$$K(R,r) = E_{cs}\, \pi\, (R+r)^2 |v_s(R) - v_c(r)|$$

Now we assume $r \ll R$ and $v_c \ll v_s$, i.e, the kernel is only a function of R,

$$K(R,r) = E_{cs}\, \pi\, R^2 v_s(R)$$

The COSMO two-category ice scheme

Then the riming rate simplifies to

$$Q_{rim} = \int_0^\infty \int_0^\infty K(R,r)\, f_c(r)\, f_s(R)\, m(r)\, dr\, dR = \int_0^\infty \int_0^\infty E_{cs}\, \pi\, R^2 v_s(R)\, f_c(r)\, f_s(R)\, m(r)\, dr\, dR$$

$$= \pi\, E_{cs} \int_0^\infty R^2\, v_s(R)\, f_s(R) \int_0^\infty f_c(r)\, m(r)\, dr\, dR = \pi\, E_{cs}\, L_c \int_0^\infty R^2\, v_s(R)\, f_s(R)\, dR$$

which is called 'continous growth equation'.

Now we can use our assumptions about the snow properties, which are

$$\begin{aligned} m_s(D) &= aD^2 && \text{(mass-size-relation)} \\ v_s(D) &= \alpha D^\beta && \text{(fall speed of snow)} \\ f_s(D) &= N_0 \exp(-\lambda D) && \text{(exponential size distribution)} \end{aligned}$$

and find

$$Q_{rim} = \frac{\pi}{4}\, E_{cs}\, L_c \int_0^\infty D^2\, v_s(D)\, f_s(D)\, dD = \frac{\pi}{4}\, E_{cs}\, L_c\, \alpha\, N_0 \int_0^\infty D^{\beta+2}\, \exp(-\lambda D)\, dD$$

$$= \frac{\pi}{4}\, E_{cs}\, L_c\, \alpha\, N_0\, \frac{\Gamma(\beta+3)}{\lambda^{\beta+3}} \overset{\beta=\frac{1}{4}}{=} \frac{\pi}{4}\, E_{cs}\, L_c\, \alpha\, N_0\, \Gamma(3.25)\, \lambda^{13/4}$$

The COSMO two-category ice scheme

And to eliminate λ we use the snow content:

$$L_s = \int_0^\infty m(D) f(D) dD = \int_0^\infty a\, D^2\ N_0 \exp(-\lambda D) dD$$

$$= a N_0 \int_0^\infty D^2\ \exp(-\lambda D) dD = a\, N_0\, \Gamma(3)\, \lambda^{-3} = 2\, a\, N_0\, \lambda^{-3} \Rightarrow \lambda = \left(\frac{L_s}{2\, a\, N_0} \right)^{-1/3}$$

Now we can eliminate λ in the riming rate and use $L_x = \rho q_x$:

$$Q_{rim} = \frac{\pi}{4} E_{cs}\ L_c\, \alpha\, N_0\ \Gamma(3.25)\ \lambda^{13/4} = \frac{\pi}{4} E_{cs}\ L_c\, \alpha\, N_0\ \Gamma(3.25)\ \left(\frac{L_s}{2\, a\, N_0} \right)^{13/12}$$

$$= \frac{\pi}{4} E_{cs}\ \rho\, q_c\ \alpha\, N_0\ \Gamma(3.25)\ \ (2\, a\, N_0)^{-13/12} (\rho q_s)^{13/12}$$

Which is identical to Eqs. (5.112) and (5.115) on p. 73 of the documentation (Part II):

$$S_{rim} = \frac{Q_{rim}}{\rho} = c_{rim} q_c\, (\rho q_s)^{13/12} \qquad \text{with} \qquad c_{rim} = \frac{\pi}{4}\ E_{cs}\, \alpha\, N_0\ \Gamma(3.25)\ \ (2\, a\, N_0)^{-13/12}$$

Diagnostic vs prognostic precipitation

subroutine: hydci vs hydci_pp
namelist setting:
  itype_gscp=3
  lprogprec=.false. vs .true.

Prognostic: Full budget equation for mixing ratios q_x $(L_x = \rho q_x)$

$$\frac{\partial q^x}{\partial t} + \mathbf{v} \cdot \nabla q^x - \frac{1}{\rho} \frac{\partial}{\partial z} (\rho q^x v_T^x) = S^x$$

Diagnostic: The first two terms are neglected and the Eq. reduce to

$$\frac{g}{\sqrt{\gamma}} \frac{\rho_0}{\rho} \frac{\partial P_r}{\partial \zeta} = S^r , \qquad \frac{g}{\sqrt{\gamma}} \frac{\rho_0}{\rho} \frac{\partial P_s}{\partial \zeta} = S^s$$

with the precipitation fluxes P_x

Diagnostic vs prognostic precipitation

Advantage of diagnostic schemes:

- Computation time is reduced
- Assumptions are well justified for horizontal grids spacing > 20 km

Problems of diagnostic schemes:

- Precipitation is directly coupled to orography (Luv/Lee problems).
- Timescales of snow formation cannot be represented properly.
- Cannot provide boundary conditions of qr, qs for prognostic schemes.
- No longer used at DWD, therefore outdated and not well tested anymore.

Recommendation: Do not use diagnostic schemes!

Diagnostic schemes eliminated in the current NWP version (but still part of the current CLM version)!

Technical comment: To save some computer time on coarse grids, you can switch off the advection of qr and qs by setting *lprogprec=.true.*, but *ltrans_prec=.false.* Doing so you can use the new subroutines and you can provide boundary conditions for nested grids.

The COSMO cloud cover- and water content scheme for Radiation

- **CLC = fct(QC, QI, generalized RH_g, convective CLC_CON)**
  - RH_g: blending in mixed-phase region between water and ice saturation, using prescribed ice fraction f_{ice} = linear ramp function of T between 0 (-5˚C) and 1 (-25˚C) (Deardorff?)
    $RH_g := (QV+QC+QI) / QV_{sat,g} = (QV+QC+QI) / (QV_{sat,water} *(1-f_{ice}) + QV_{sat,ice}*f_{ice})$
  - $CLC\_SGS = MAX (0, MIN (1, (RH_g - \xi) / (c_L - \xi)))^2$ $c_1 = 0.8$ (tuning), $c_2 = sqrt(3)$, $c_L = 1.0$
    with: $\xi = 0.95 - c_1 * \sigma * (1-\sigma) * (1 + c_2*(\sigma-0.5))$, $\sigma = p / p_s$ (height parameter)
  - But CLC_SGS = 1 for gridscale clouds (QC and/or QI > 0) ! **(dep. on RH_g see next slide)**
  - CLC_CON = 0.35*(TOP_CON-BAS_CON) / 5000.0
    (for both „shallow“ and „full“ convection parameterization)
  - Finally weighted average: CLC = CLC_SGS + CLC_CON * (1 – CLC_SGS)

- **Water contents of SGS clouds:**
  - of SGS clouds: $QC\_SGS = 0.005 * QV_{sat,g} * (1-f_{ice})$ (0.005 = 0.01 * subgr. variab. fact. 0.5)
    $QI\_SGS = 0.005 * QV_{sat,g} * f_{ice}$
  - of convective clouds: $QC\_CON = 0.01 * QV_{sat,g} * (1-f_{ice})$ $(= 2.0 \times 0.005 * QV_{sat,g} * (1-f_{ice}))$
    $QI\_CON = 0.01 * QV_{sat,g} * f_{ice}$

- **Finally: combined water contents as input for radiation:**
  - QX_RAD = QX_CON * CLC_CON + max[QX_SGS, 0.5*QX] * CLC_SGS * (1 – CLC_CON) with X ϵ {C,I}