Physical parameterization: Cloud microphysics

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Physical parameterizations (FE14)

The role of cloud microphysics

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.

Clouds in ICON

- Grid-scale clouds (microphysics scheme)
  Parameterization of resolved clouds and precipitation. Cloud variables are treated by prognostic equations including advection.
- Subgrid convective clouds (convection scheme)
  Convection is parameterized and diagnosed based on the large-scale environmental conditions. No advection, no history.
- Cloud cover scheme
  Combines grid-scale, convective, and diagnostic subgrid stratiform clouds to totals values that are passed to the radiation.

- Note that ICON does not allow subgrid stratiform clouds to form precipitation. All prognostic clouds have a cloud fraction of 1. This is different from other models like, for example, the IFS.

Saturation adjustment

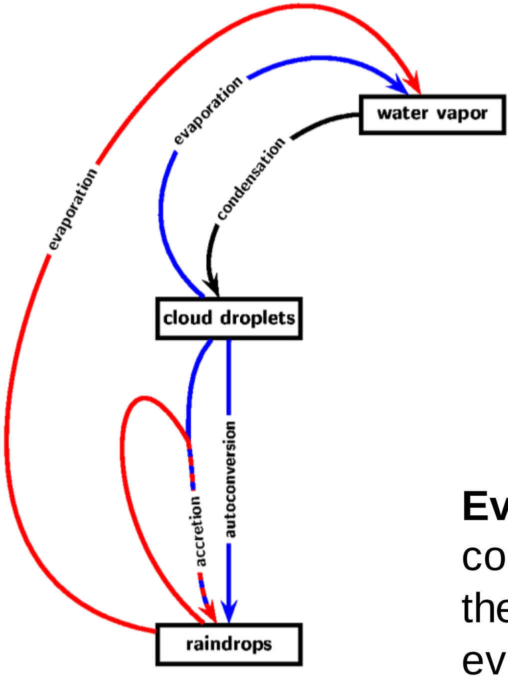
- We assume that water vapor and liquid water are in thermodynamic equilibrium
- After advection and diffusion the model is not in thermodynamic equilibrium. We have to adjust the thermodynamic state, T, qv and qc, to ensure equilibrium.
- From energy or enthalpy conservation we can derive an equation for the new temperature T_1:

$$c_v(T_1 - T_0) + (q_{sat}(T_1) - q_{v,0}) = 0$$

where $q_{sat}(T_1)$ is the saturation mixing ratio. In ICON this equation is solved by a Newton iteration.

- This approach has been used in cloud-resolving models since the 1960s. Most global models use a different approach and apply a subgrid diagnostic.

Cloud microphysical processes



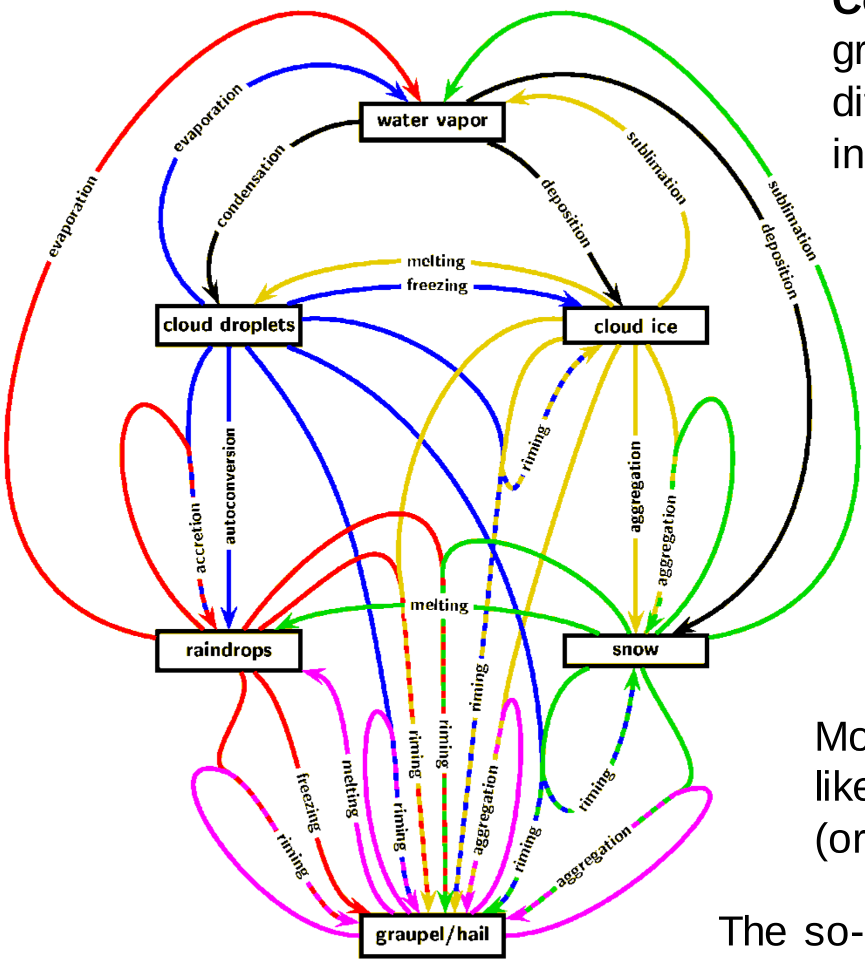
Evaporation and condensation of cloud droplets are parameterized by the saturation adjustment scheme.

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

We define the drop size distribution ***f(x)*** as the number of drops per unit volume in the mass range [x,x+dx].
For f(x) we can then derive the following budget equation for warm-rain processes

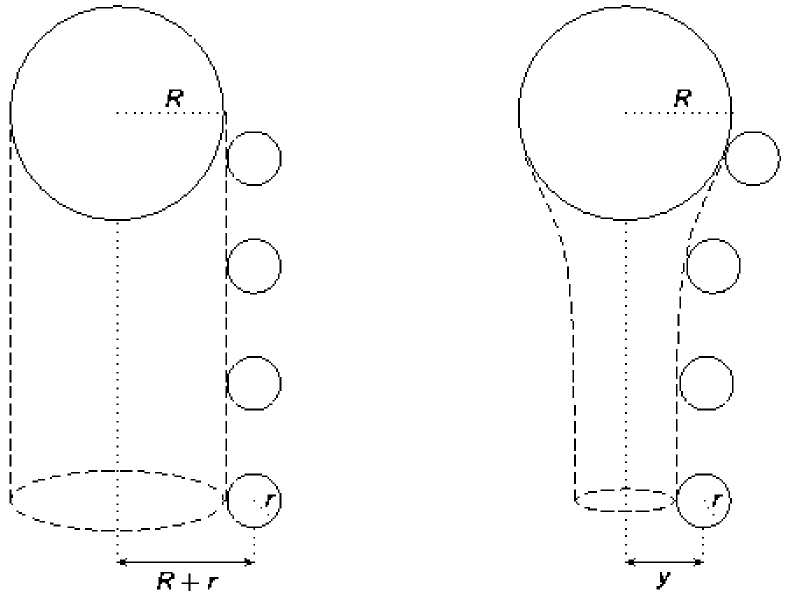
$$\frac{\partial f(x,\vec{r},t)}{\partial t} + \nabla \cdot [\vec{v}(\vec{r},t) f(x,\vec{r},t)] + \frac{\partial}{\partial z}[v_s(x) f(x,\vec{r},t)] + \frac{\partial}{\partial x}[\dot{x} f(x,\vec{r},t)] = \sigma_{coal}$$

with

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

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 the rain formation process.

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):

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

$x \in \{m,D\}$

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):

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

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	■	□	■	□	■	□	■	□	■	□	■	□

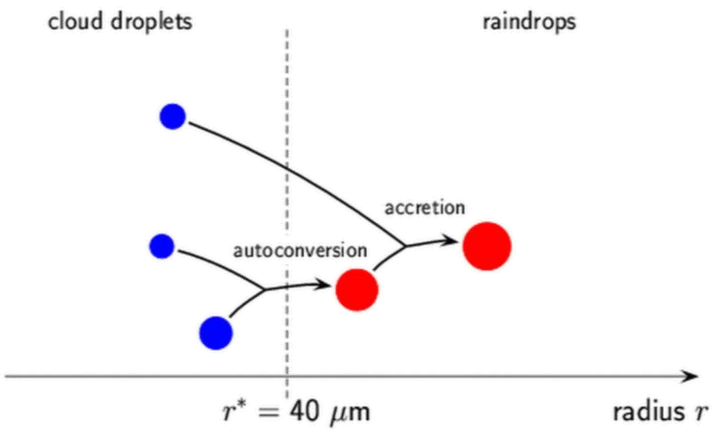
N = number densities, L = mixing ratios

🡐 ICON one-moment schemes (gscp=1 and 2) are similar to Lin et al. (1983) and Rutledge and Hobbs (1984).

🡐 ICON two-moment scheme has hail (introduced by U. Blahak and H. Noppel in 2008)

Two-moment schemes are becoming more and more the standard in research and are even an option for NWP. A three-moment scheme has been published by Milbrandt and Yau (2005). A recent development are prognostic properties schemes for ice microphysics (Morrison & Milbrandt, P3 scheme).

Kessler‘s warm phase scheme



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

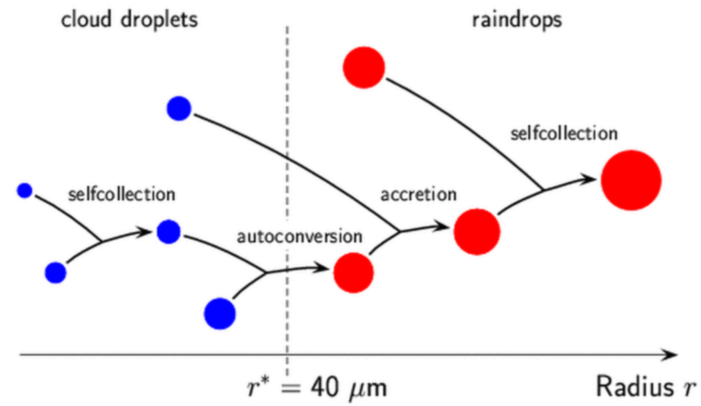
autoconversion rate:

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

„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

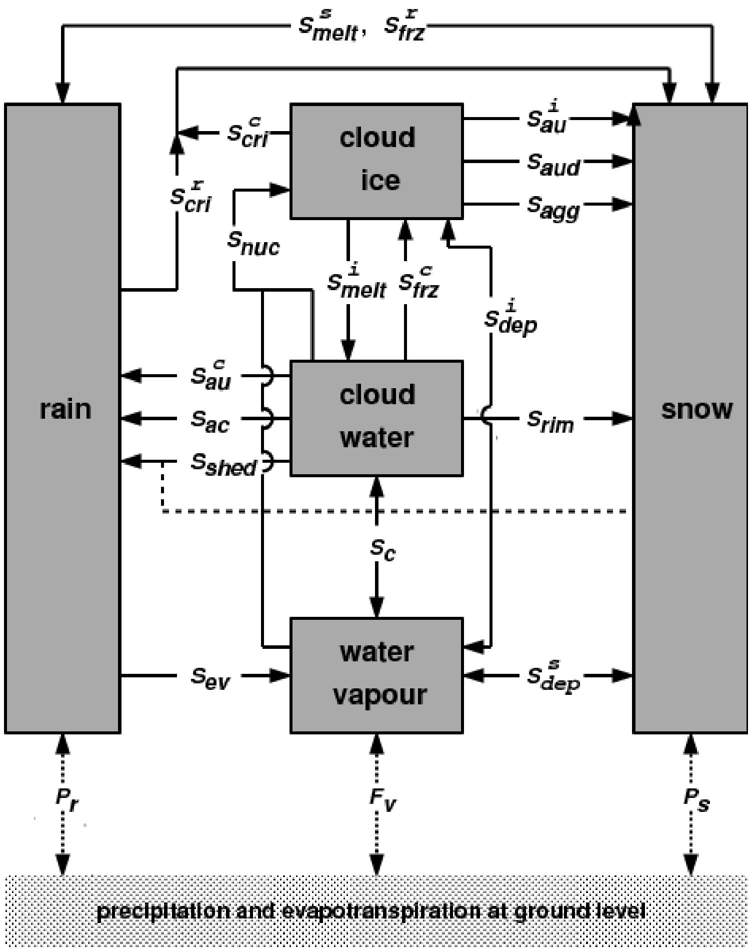
$$\left.\frac{\partial L_r}{\partial t}\right|_{au} = \frac{k_c}{20\, x^*} \frac{(\nu+2)(\nu+4)}{(\nu+1)^2} L_c^2\ \bar{x}_c^2 \left[1 + \frac{\Phi_{au}(\tau)}{(1-\tau)^2}\right]$$

with a universal function

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

A one-moment version of this autoconversion scheme is implemented in the all microphysics schemes of ICON (even in the so-called Kessler scheme).

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

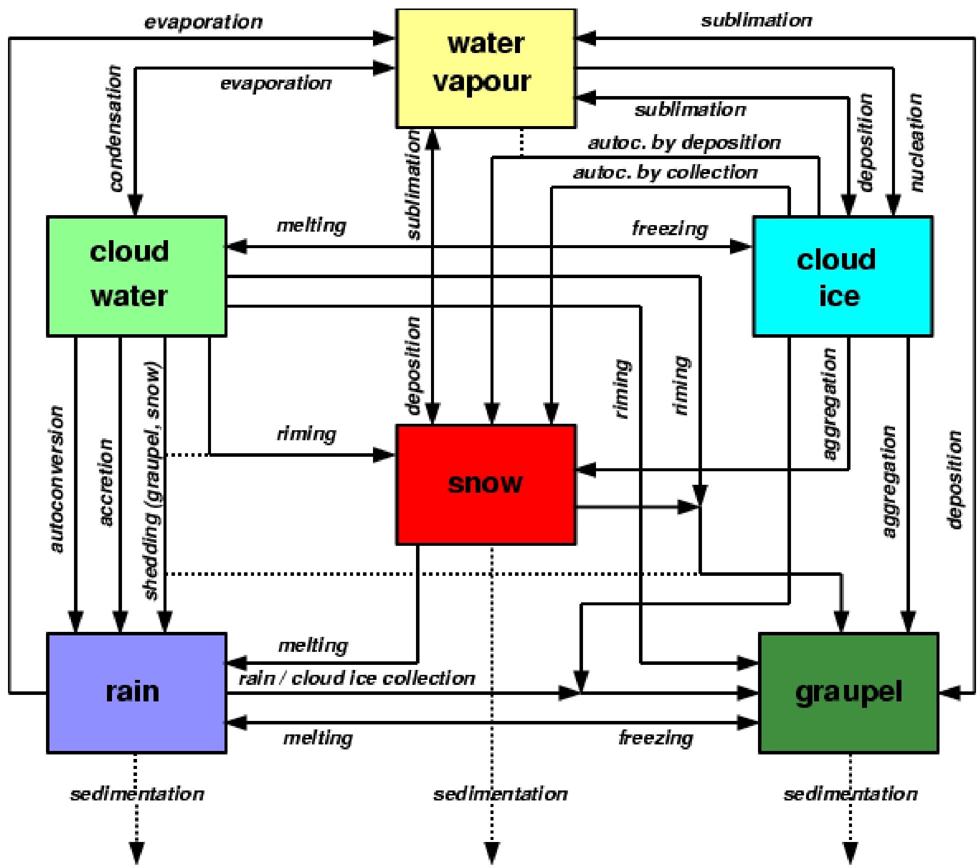


subroutine: gscp_cloudice

namelist setting: itype_gscp=1

- 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 and coarser.
- Only stratiform clouds, graupel formation is neglected.

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



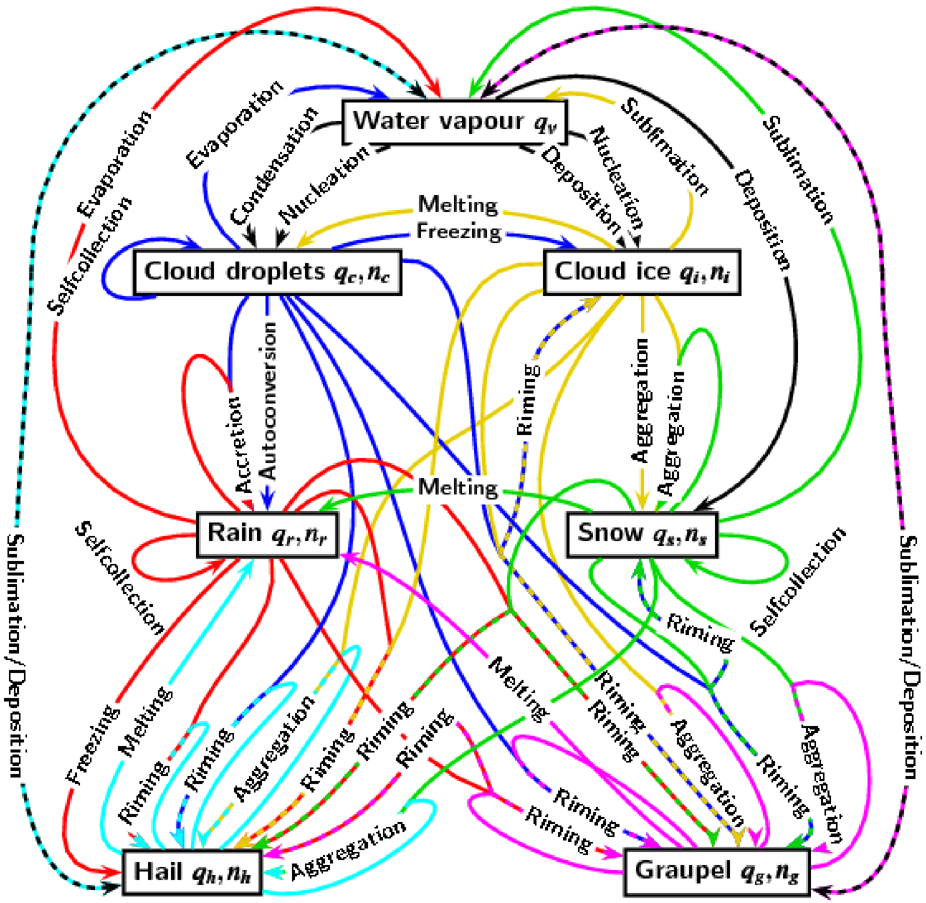
subroutine: gscp_graupel

namelist setting: inwp_gscp=2

- 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

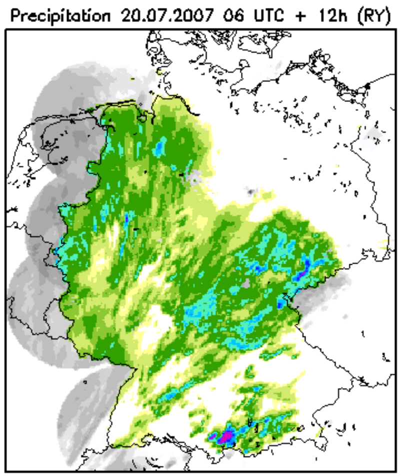


subroutine: two_moment_mcrph
namelist setting: inwp_gscp=4

- 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.

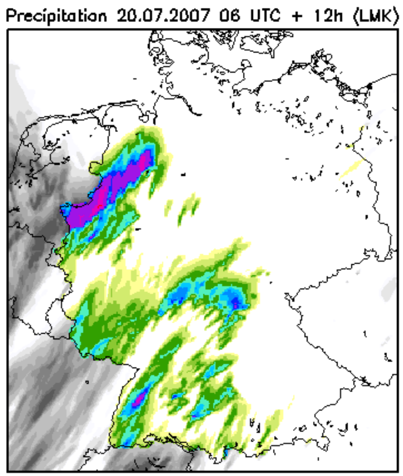
Case study 20 Juli 2007:
Cold Front / Squall Line

Radar (RY)



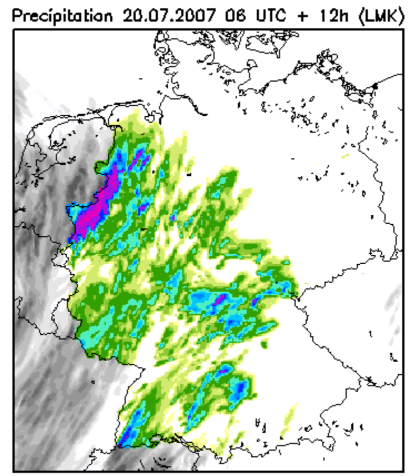
AVG: 3.4 mm

ONE-MOMENT



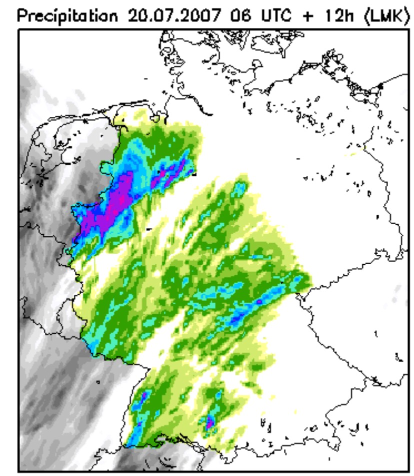
AVG: 2.8 mm

SB-CLEAN

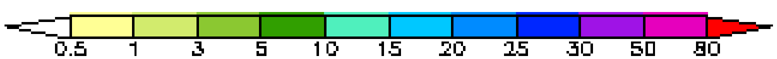


AVG: 3.4 mm

SB-POLLUTED



AVG: 3.5 mm

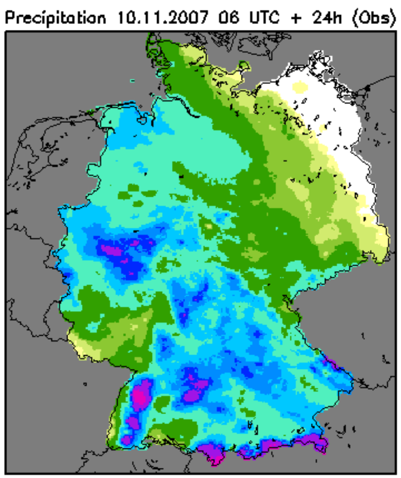


accumulated precip in mm

- ➔ More intense squall line with two-moment scheme
- ➔ Aerosol effect can slightly modify the intensity and spatial distribution.

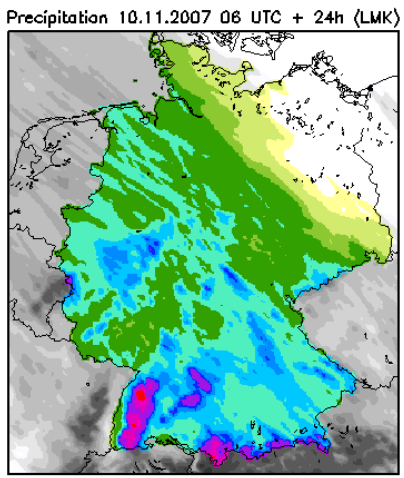
Case study 11 Nov 2007

Gauges (REGNIE)



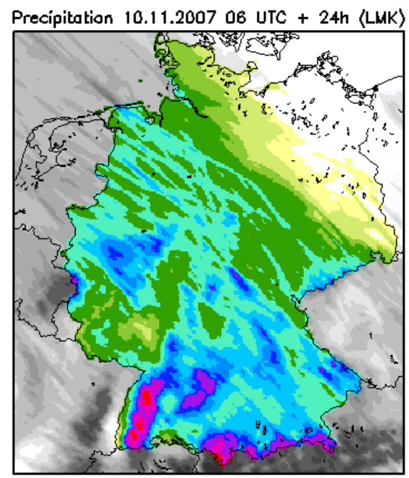
AVG: 11.7 mm

ONE-MOMENT



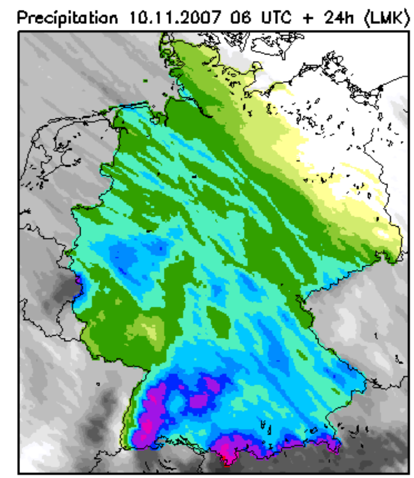
AVG: 10.7 mm

SB-CLEAN

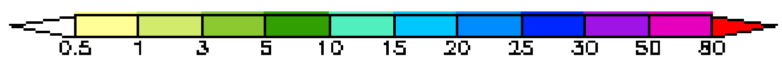


AVG: 11.4 mm

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.

ICON namelist parameters:

inwp_gscp: main switch for microphysics schemes

inwp_gscp=1: operational cloud ice scheme
inwp_gscp=2: graupel scheme
inwp_gscp=3: two-moment cloud ice (does not work)
inwp_gscp=4: two-moment scheme
inwp_gscp=5: two-moment scheme with progn. CCN and IN (only idealized cases).

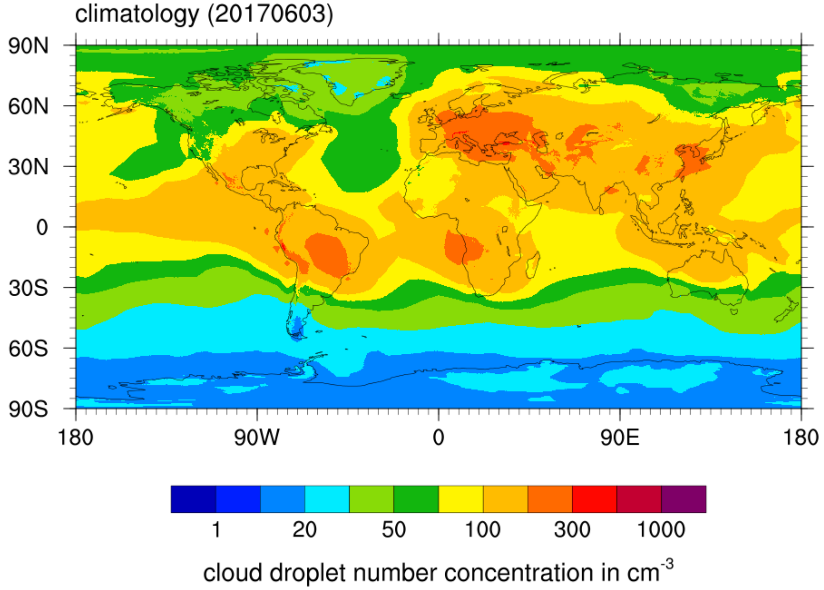
qi0: Threshold for cloud ice autoconversion (default zero)
qc0: Threshold for cloud water autoconversion (zero, not used!)

mu_rain: Shape parameter of gamma distribution of rain
mu_snow: Shape parameter of gamma distribution of snow

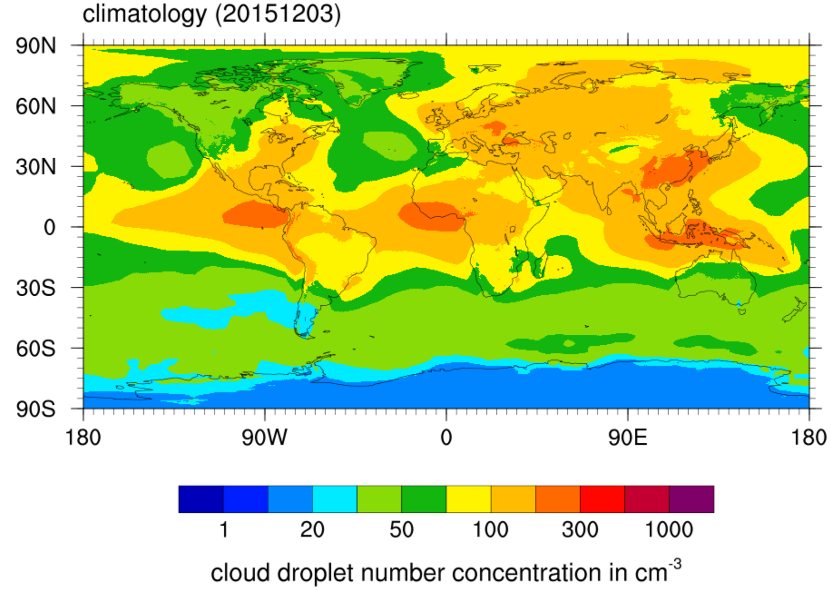
icpl_aero_gscp: switch for coupling of microphysics with aerosol climatology (activation and autoconversion of cloud droplets), only for inwp_gscp=1 and 2. Default 0, but 1 operationally.

Cloud droplet number derived from aerosol-climatology

June



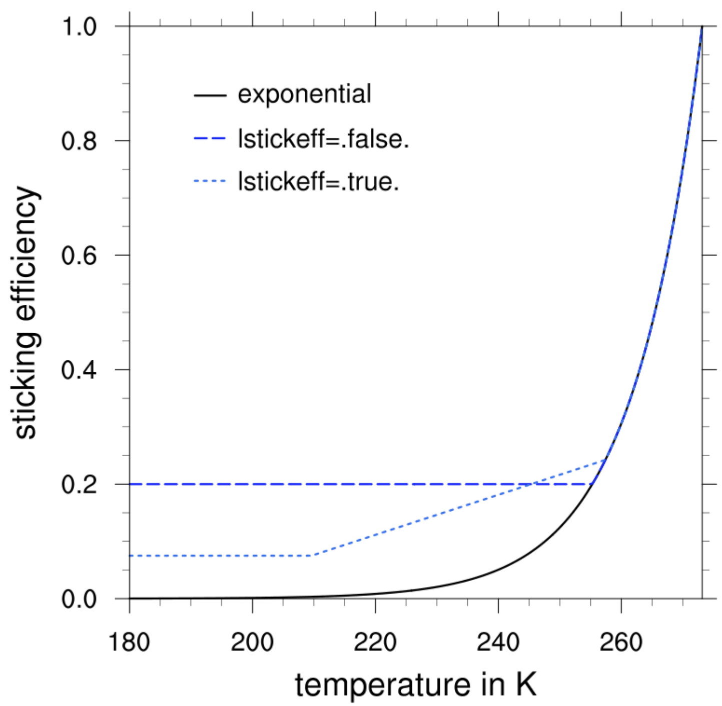
December



With icpl_aero_gscp=1 this is used in the grid-scale microphysics.
With icpl_aero_conv=1 the same field is used in the convection scheme.

Some internal switches in gscp=1:

lstickeff = .true./.false.   modification of sticking efficiency (ice-ice, ice-snow)



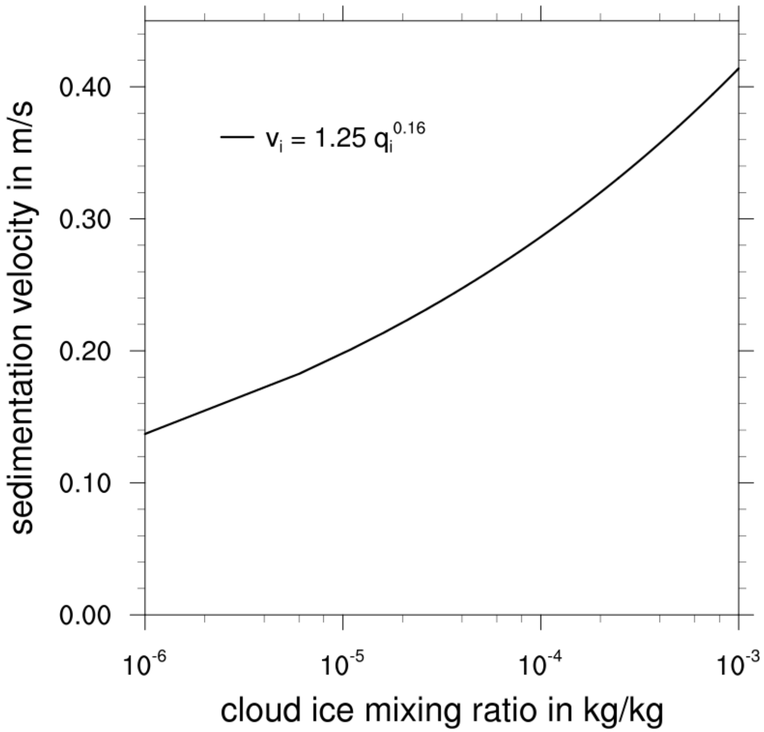
Reduced sticking efficiency leads to an increase in QI. This is necessary for the radiation budget in the tropics.

Switch is .false. by default, but this modification is also part of lorig_icon, which is .true.

The constant minimum value can be chosen by the namelist parameter tune_zceff_min (in nwp_tuning_nml)

Some internal switches in gscp=1:

lsedi_ice = .true./.false. switch for sedimentation of cloud ice



Switch is .false. by default, but this modification is also part of lorig_icon, which is .true.

The pre-factor of the power law can be modified with tune_zvz0i in nwp_tuning_nml. The original value given in the literature is a factor 3 larger.

An important parameter is the pre-factor of the snow fallspeed, tune_v0snow, also in nwp_tuning_nml.

The End