Clouds and precipitation

Martin Köhler | Academic ICON Training | July 2025

Based on material by Alberto de Lozar and Axel Seifert

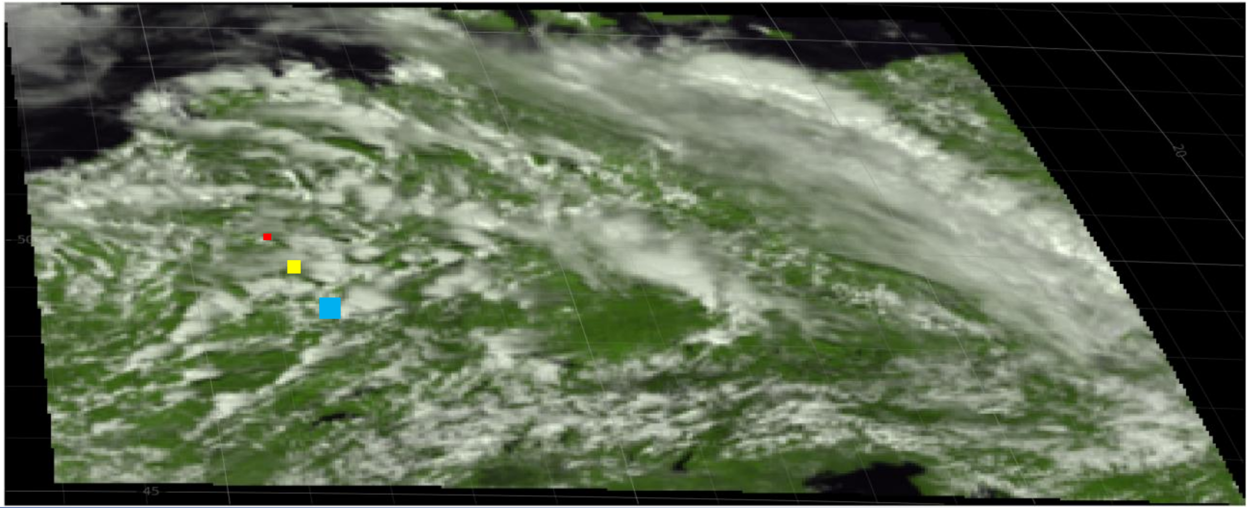
Introduction

Resolved/unresolved clouds

Clouds are characterized by a large range of length scales (D):

- Resolved clouds (D >> Δx) are given by the microphysics. Microphysics uses an all or nothing scheme, it is only active when the mean RH in a grid box is 100%.
- Unresolved clouds (D << Δx) are given by parameterizations. They allow for a cloud fraction inside the grid box. They are necessary by all NWP models.

Gridsizes:
ICON D2: 2km
ICON EU: 6.5 km
ICON: 13 km



Two different kind of clouds

It is useful to think of sub-grid clouds of two different types:

- Convective clouds. They are generated by updrafts that typically originate at the boundary layer.

- Clouds generated by turbulent fluctuations inside the grid box (like a broken stratus cloud).

Major effects of clouds

The main effects of clouds are:

- Precipitation.
- Transport of water and heat from the boundary layer to the higher levels of the atmosphere.
- Clouds are radiatively active:
    - Low clouds mostly reflect short-wave radiation.
    - High clouds warm the atmosphere by trapping long-wave radiation.
- Latent-heat release in clouds can enhance local turbulent motions.

Subgrid-clouds effects accounted by:

Convective Parameterization

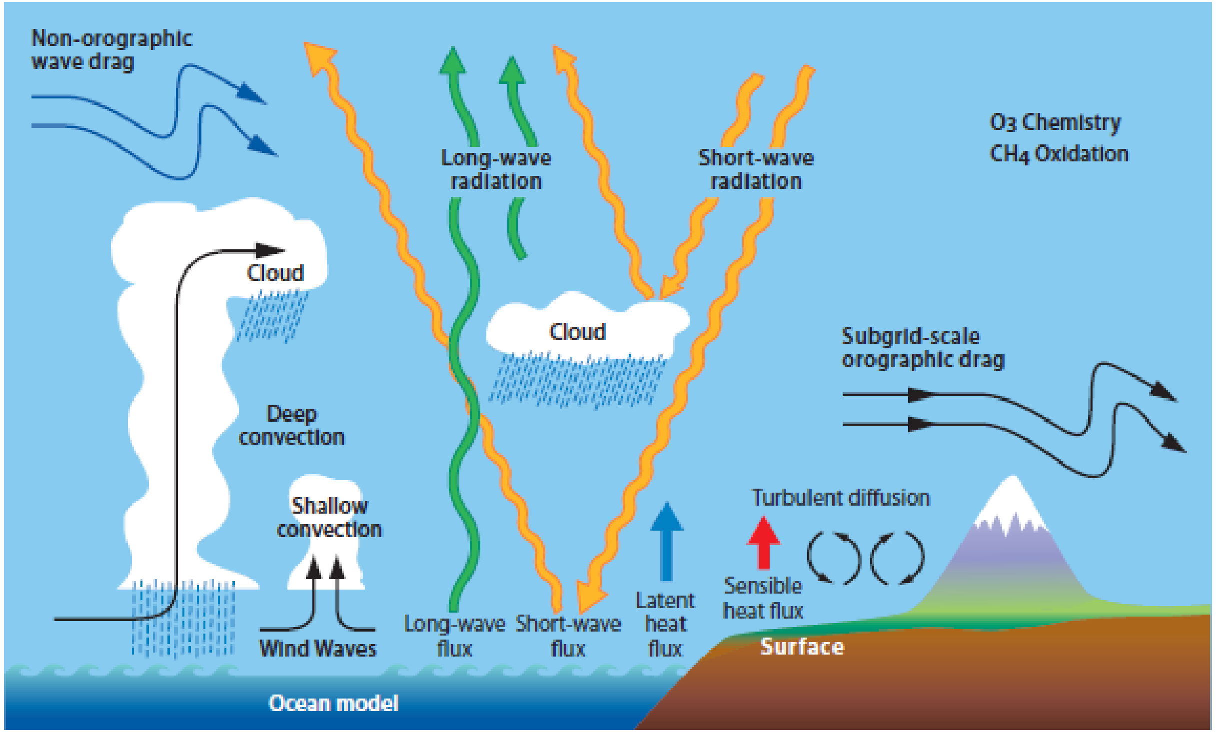
Provides information to

Cloud Parameterization

Provides information to

Turbulence Parameterization

Parametrized processes



courtesy to Anton Beljaars

Convection

Tiedtke-Bechtold parameterization in ICON

Why do we need a convection scheme?

- Convection is the most efficient way to remove atmospheric instability.
- Convection in nature is characterized by many time and length scales. The model cannot resolve all these scales
- The model will produce convection if the instability is there, but only at the scale that can be resolved. This might produce too strong convective systems.

Basics

- The convective parameterization can efficiently remove instability as it accounts for sub-grid:
  - Transport of water and heat from the boundary layer to the higher levels of the atmosphere.
  - Precipitation.
- This parameterization is only for sub-grid clouds.
- ICON uses the Tiedtke-Bechtold convection scheme.

Convection: single updraft

- The convection scheme accounts for all unresolved convective clouds inside the grid box.
- One important simplification is to treat the ensemble as a single cloud.
- The ensemble is partially recovered when averaging temporal or spatially (different realizations of the convective scheme produce different clouds).

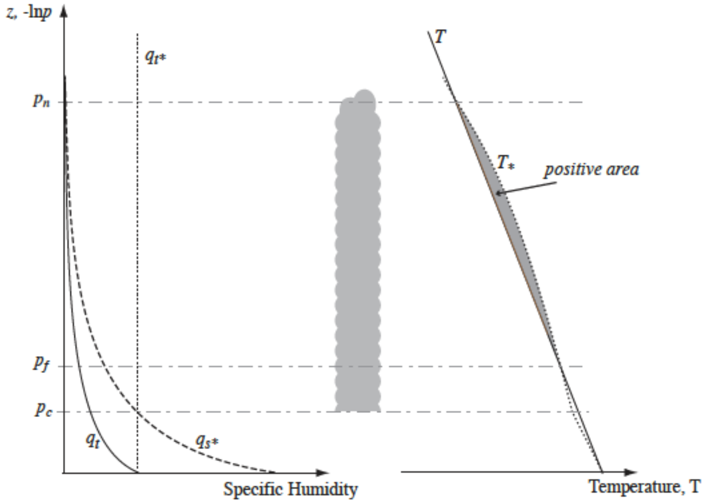
The test parcel

- When the atmosphere is conditionally unstable, a finite perturbation might produce convection.

- The scheme checks if the atmospheric is unstable by producing a test parcel at the surface with a positive temperature perturbation that propagates to the upper levels.

- Depending on the results of this first calculation the scheme decides if deep/shallow/mid-level or no convection is called: the main criteria is the resulting cloud depth.

- Mid-level-convection does not start at the surface.



Stevens, Atm. Rev. Earth Planet Sci. (2005)

It starts with a cloud-base mass-flux...

- Convection is calculated by assuming an updraft that starts at cloud base.

- At cloud base the updraft is characterized by a perturbation of the environment and a mass-flux: $M = \varrho w^c \sigma$, where w^c and σ are the velocity and fractional area of the updraft (cloud). The initial mass flux at is determined by a closure formulation.

- The updraft is integrated vertically using an entraining plume model: entrainment (ε) and detrainment (δ) models are also needed.

$$\frac{\partial M}{\partial z} = M(\varepsilon - \delta)$$

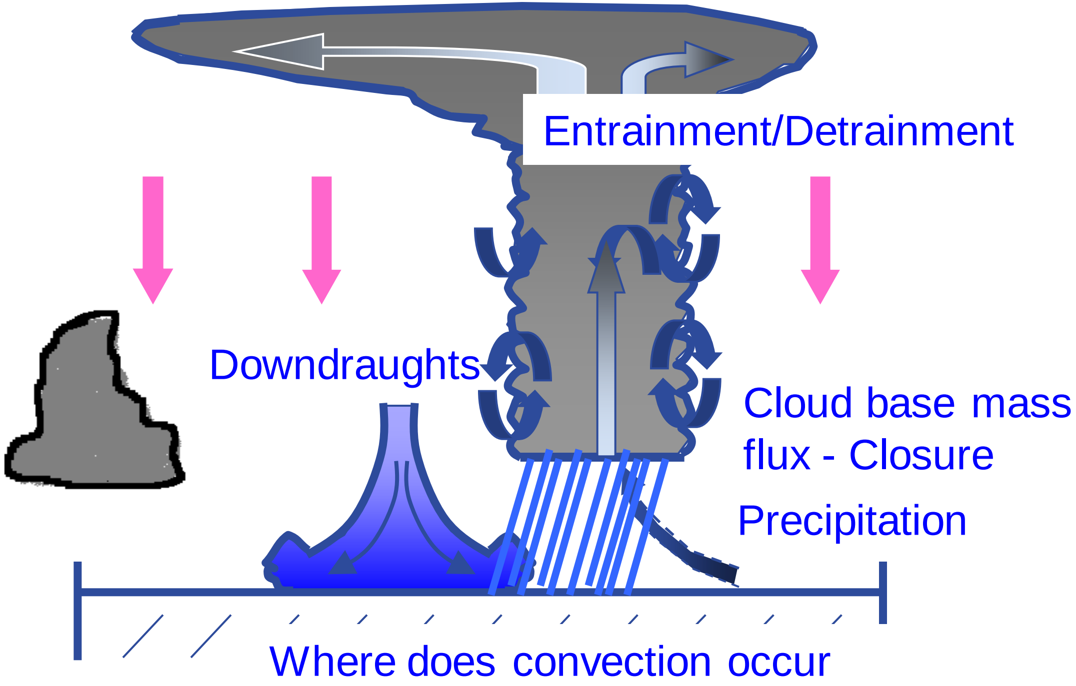
mass flux

$$\frac{\partial (M q_v^c)}{\partial z} = M(\varepsilon q_v^e - \delta q_v^c) - \text{Cond}$$

entraining plume model: it considers the mixing with the environment and condensation

... and then much more

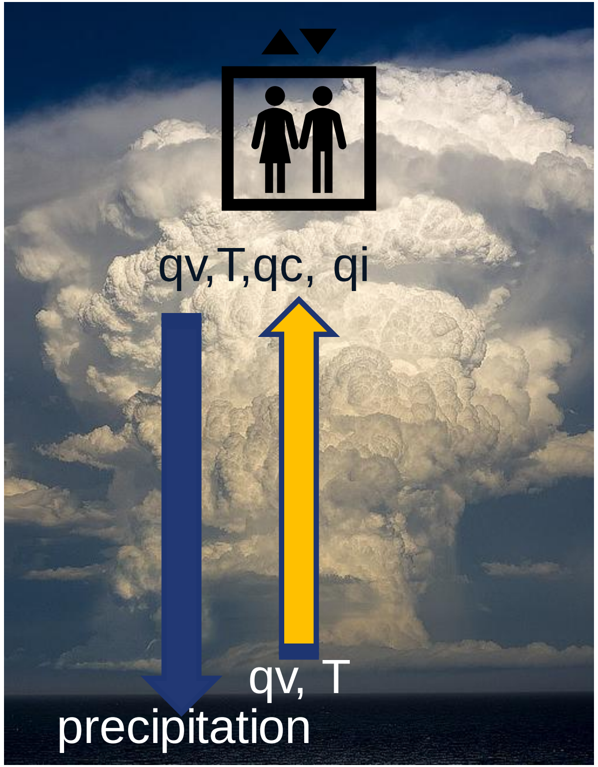
- The plume propagates until it is stopped by a strong enough inversion. Most ice/vapor/water are detrained at the inversion.
- Precipitation/evaporation is generated in the updraft accent with a simplified microphysics.
- The scheme also includes downdraughts and cold pools.
- Process details depend on the initial choice shallow/deep.



courtesy Bechtold

Some important details

- Convection works on the slow physics.
  - The scheme is called every N time steps and the tendencies are applied until the next call.
  - But all calculations are done in a single time step.
- The convective transport is non-local: water and heat and momentum are transported instantly from levels below cloud base into higher levels of the atmosphere.
- Every time it is called, the scheme decides if and how it is triggered, which might cause an intermittent behavior.
- Purely local without memory. It is not advected.



ICON Useful Namelists (convection)

entrorg	= 0.00195	Entrainment parameter
rprcon	= 0.0014	Conversion of cloud water into precipitation (microphysics).
tex/qex	= 0.125/0.0125	Excess of temperature/humidity in test parcel
lowcapefac/negpblcape	= 1.0/-500	Tuning parameters to adjust the diurnal-cycle
rhebc_land/ rhebc_ocean rhebc_land_tropic rhebc_ocean_tropic	= 0.825/0.85 = 0.70 = 0.76	RH trehsholds over land/ocean. There is a different therehold over the tropics.
rcucov/ rcucov_trop	= 0.075/0.03	Convective area fraction for evaporation (also over the tropics.

Convective-permitting simulations

- At convective-permitting/convective-resolving scales (~3 km) we aim for the model to explicitly resolve deep convection. Therefore, we switch off the convective scheme when the test parcel calculation decides for deep convection. If not, the atmosphere will be stabilized by the scheme and explicit convection will rarely happen.

- Notice that shallow convection is not resolved at those scales, and it should be parameterized. It is always a difficult question which scales should be left to be resolved.

- This choice is not obvious because:
  - If the shallow convection scheme is too active, the atmospheric instability could be strongly reduced. This results in a weak resolved convection and little precipitation.
  - If the shallow convection scheme is too passive, the atmosphere might become too unstable, causing an exaggerated deep convection.

Some suggestions

- For resolutions coarser than 5 km we recommend to use the deep-convection parameterization. The model will produce convection at the grid-scale (usually too large and thus too intense) when the parameterization is off.
- For resolutions coarser than 1km we recommend to use the shallow-convection parameterization, as omitting it or making it too weak can lead to excessive extreme rain rates (due to a too unstable atmosphere).
- We find it useful to use the shallow-convection parameterization down to a resolution of 500 m over Germany. This might be different for other domains.
- We do not recommend to have deep convection on and off in different domains in two-way nested simulations, as the thermodynamic profiles can vary significantly.

ICON

Useful Namelists

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

inwp_convection = 0 / 1	It switches off/on **all** convective parameterization (for very high resolutions ≲ 500 m it should be off).
lshallowconv_only = .true./.false.	The parametrization is switched off when model decides for deep/mid-level convection (for convection permitting ~1km).
tune_rdepths = 20000	Maximum allowed depth of shallow convection (in Pa). Deeper clouds trigger deep convection or none if lshallowconv_only = .true.
lgrayzone_deepconv = .true./.false.	Mild version of deep convection that helps to reduce the intensity of strong convective events. The parametrization is switched off when model decides for mid-level convection. Active in ICON-D2.

Cloud Microphysics

Axel Seifert

The role of cloud microphysics

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

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

3. 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 (aka cloud scheme):**
  Combines grid-scale, convective, and diagnostic subgrid stratiform clouds to total values that are passed to the radiation.
- Note that ICON does not allow subgrid stratiform clouds to form precipitation. This is different from other models like, for example, the IFS.

Grid-scale clouds through liquid 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 conservation we can derive an equation for the new temperature T_1:

$$c_{d,v}(T_1 - T_0) + \hat{L}_{\ell v}(q_{sat}(T_1) - q_{v,0}) = 0$$

  where $q_{sat}(T_1)$ is the saturation mixing ratio.

- In ICON this equation is solved by a Newton iteration, actually twice per time step. First, after the dynamics, and then again after the physics before the output is written.

Grid-scale clouds through liquid saturation adjustment

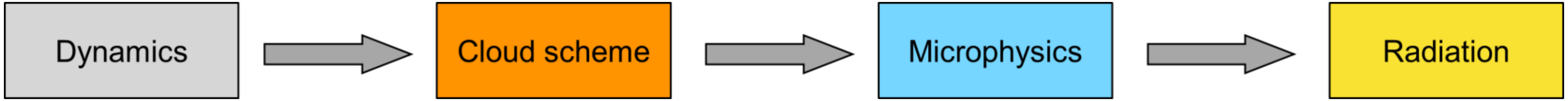
- ➔ We assume that water vapor and liquid water are in thermodynamic equilibrium
- ➔ After advection and diffusion the model is not in thermodynamic equilibrium. We have to adjust the thermodynamic state, T, qv and qc, to ensure equilibrium.

Note:

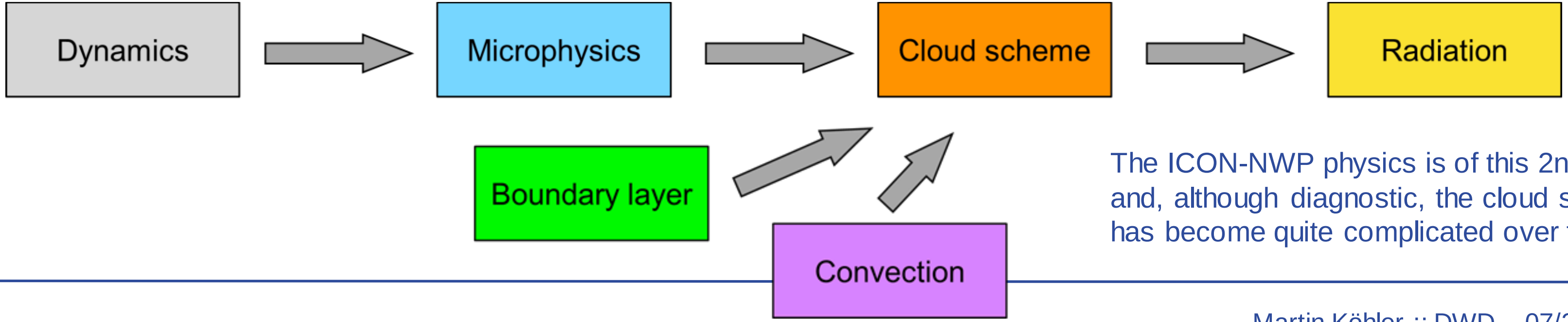
- ➔ This approach has been used in cloud-resolving models since the 1960s. Most global models use a different approach and first apply a sub-grid diagnostic, i.e., the microphysics would be calculated with the sub-grid cloud fraction.
- ➔ Therefore ICON with NWP physics should not be used with very coarse grid like R02B04.

Different approaches to clouds in NWP and climate models

Some NWP and most climate models calculate the microphysics on a sub-grid cloud fraction:

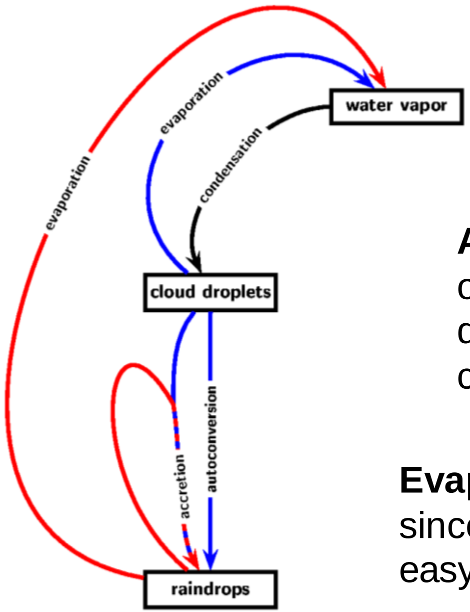


Some models that have their roots in cloud-resolving modeling use grid-box mean microphysics and a diagnostic cloud scheme afterwards:



The ICON-NWP physics is of this 2nd type and, although diagnostic, the cloud scheme has become quite complicated over the years.

Cloud microphysical processes:

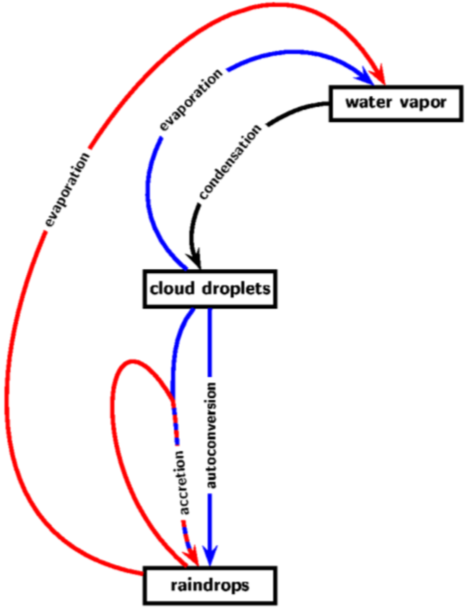


Evaporation and condensation of cloud droplets are parameterized by the saturation adjustment scheme.

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. **Accretion** is the collection of cloud droplets by raindrops.

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.

Cloud microphysical processes:



Even for the warm rain processes a lot of things are still unknown or at least uncertain, like effects of **mixing / entrainment** on the cloud droplet distribution, effects of **turbulence** on collision-coalescence, and microphysical uncertainties like **collisional breakup** or the details of the **activation** process.

In operational models many of these intricacies are usually ignored, but for climate models they can become important, because of their impact on cloud feedbacks.

Cloud microphysical processes:

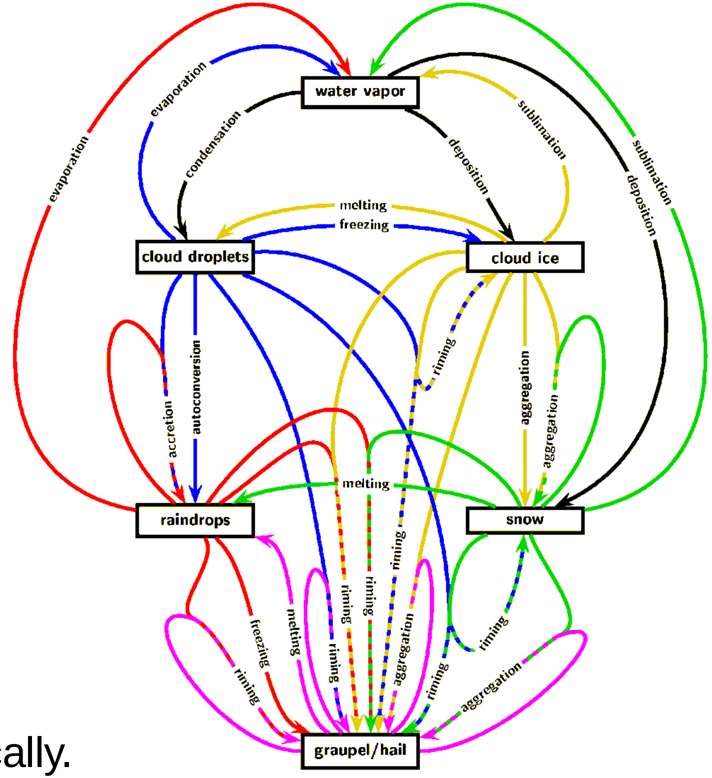
Conversion processes, like snow to graupel conversion by riming, are very difficult to parameterize but very important in convective clouds.

Especially for snow and graupel the particle properties like **particle density** and **fall speeds** are important parameters.

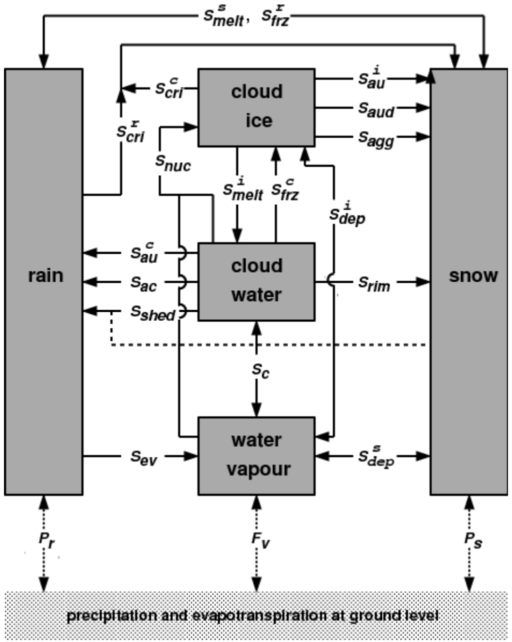
Aggregation processes assume certain collision and sticking efficiencies, which are not well known.

Most schemes do not include **hail processes** like wet growth, partial melting or shedding.

Another open question is **secondary ice production,** which can increase the number of ice particles dramatically.



The COSMO/ICON two-category ice scheme (aka‘cloud ice scheme’)

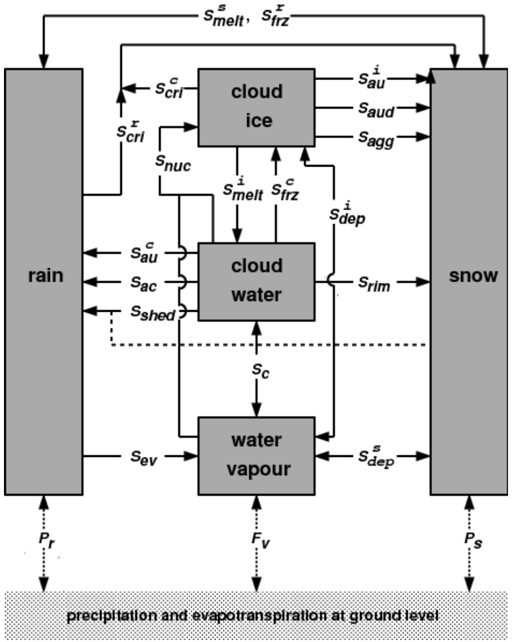


subroutine: gscp_cloudice

namelist setting: inwp_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.

ICON two-moment cloud ice scheme

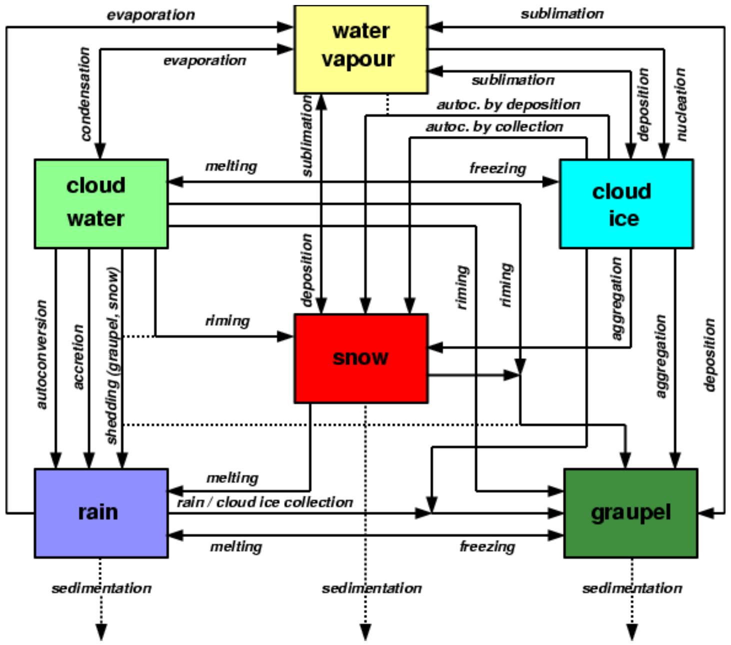


subroutine: gscp_cloudice2mom

namelist setting: inwp_gscp=3

- Extension of gscp=1 cloud ice scheme
- Includes cloud water, rain, cloud ice and snow and the number of cloud ice particles.
- Physically based ice formation by heterogeneous and homogeneous nucleation.
- Developed for the 7 km grid and coarser.
- In contrast to gscp=1 this scheme can better predict **ice supersaturation** in the upper troposphere.

The COSMO/ICON graupel scheme

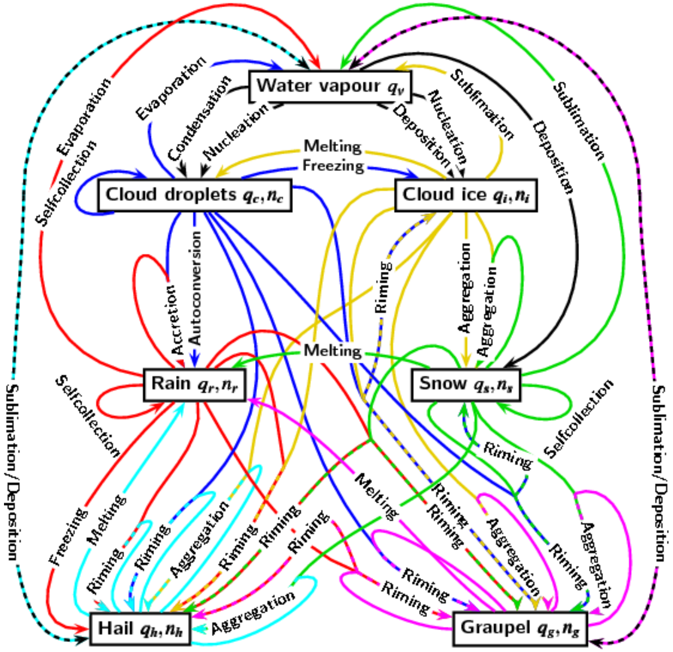


subroutine: gscp_graupel

namelist setting: inwp_gscp=2

- Includes cloud water, rain, cloud ice, snow and graupel.
- Graupel has much higher fall speeds compared to snow
- Used for convective-scale NWP, e.g. ICON-D2.

ICON two-moment microphysics scheme



subroutine: two_moment_mcrph
namelist setting: inwp_gscp=4

- Prognostic number concentration for all particle classes, i.e. explicit size information.
- Prognostic hail category.
- Aerosol-cloud-precipitation effects can be simulated
- Using 12 prognostic variables the scheme is computationally expensive.
- This scheme should **not** be used on coarse grids with a deep convection parameterization.

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ICON spectral bin microphysics (SBM)

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Warm-phase spectral-bin microphysics in ICON: reasons of sensitivity to aerosols

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[b] Pacific Northwest National Laboratory, Richland, WA, United States of America
[c] The Hebrew University of Jerusalem, Jerusalem, Israel

Contributed and implemented by Israeli Meteorological Service (IMS) and Hebrew University Jerusalem.

subroutine: sbm in mo_sbm_main.f90
namelist setting: inwp_gscp=8

- Explicit condensation, no saturation adjustment.
- Currently only liquid clouds. Ice microphysics will be implemented later.
- Aerosol-cloud-precipitation effects can be simulated.
- **Computationally very expensive.**
- Code does not vectorize, cannot be used at DWD.
- Full mixed-phase SBM is in preparation and should be part of the next ICON release.

Some namelist parameters of gscp=1

tune_zvz0i	pre-factor of the terminal fall velocity of cloud ice default is 1.25 m/s, but original empirical value 3.29 m/s
tune_v0snow	pre-factor of the terminal fall velocity of cloud ice default is 25 m/s, possible range is 10 to 30 m/s
rain_n0_factor	scaling factor of intercept parameter of size distribution of rain, default = 1.0, <1 → more small raindrops, slower sedimentation, more evap. >1 → more large raindrops, faster sedimentation, less evap.

In general, faster sedimentation leads to thinner clouds and smaller mixing ratio. Modifying the bulk sedimentation velocity by changing either the fall speed or the particle size distribution can be an efficient way to improve the precipitation patterns, e.g., for orographic precipitation.
The fall speed of cloud ice has a pronounced impact on outgoing longwave radiation, esp. in the tropics.

Clouds

The cloud fraction parameterization in ICON

Why do we need a cloud scheme?

- The radiative parameterization needs a cloud-fraction that needs to be provided by a different scheme. You always need a cloud scheme.

- Microphysics is an all or nothing scheme. It considers that the grid box is full with liquid water/ice if some is present.

- Sub-grid variations inside the grid box can can create clouds with an important radiative effect.

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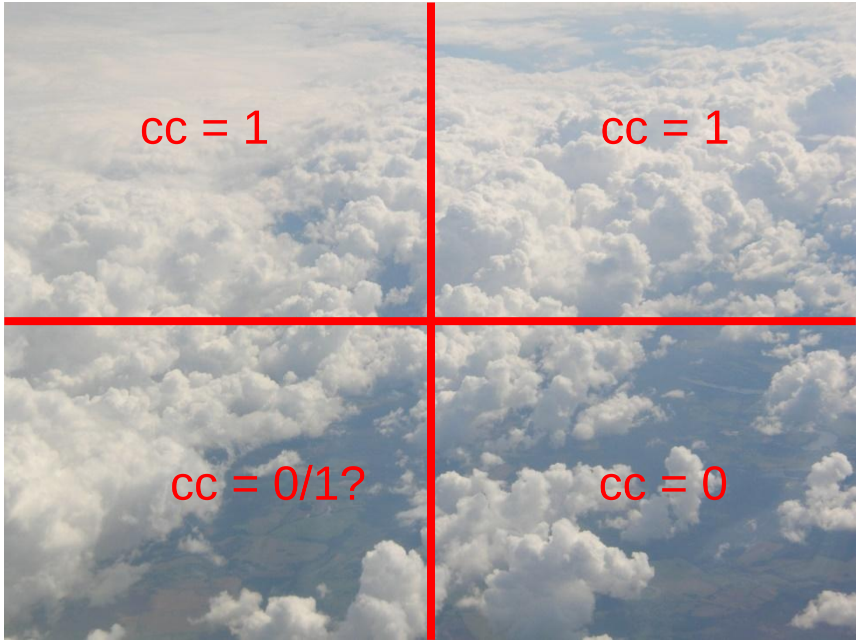

Basics

- The cloud scheme provides a cloud fraction for the radiation scheme: it provides liquid and ice clouds.

- It considers the turbulent fluctuations inside the grid box. The cloud fraction can be above zero with no cloud water from the microphysics.

- It consistently increases the cloud water/ ice seen by radiation (q_{dia}). This information is not transferred into the prognostic variables.

Basics

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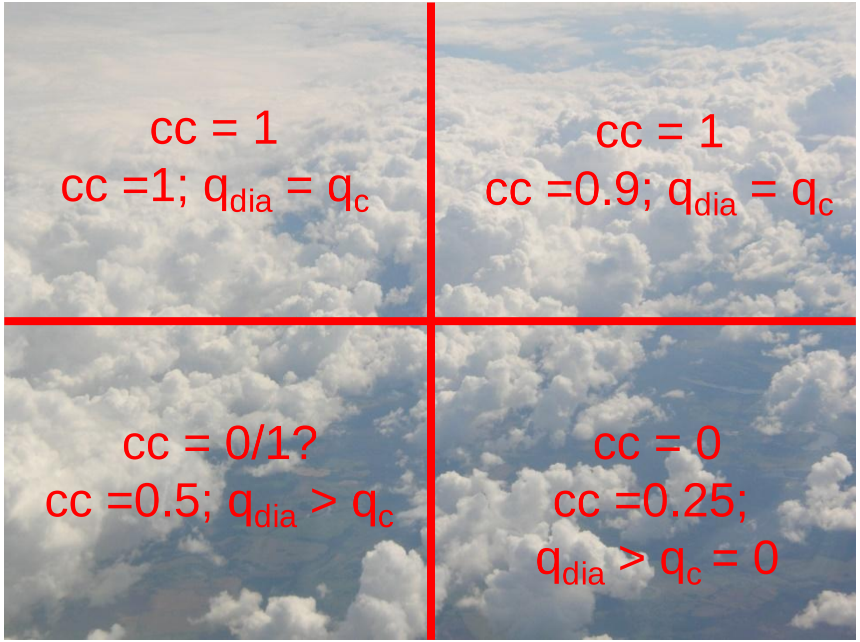

Useful Namelists

inwp_clouds = 0, 1, 5

0: no clouds seen by radiation.

1: ICON cloud scheme (see next slides)

5: All or nothing scheme consistent with the microphysics (recommended for LES)

Some notation

- Prognostic variables in ICON: q_c, q_i, q_v.
  - Microphysics works on these variables assuming that are equally distributed in each grid box.

- Total water: $q_t = q_v + q_c$. The saturation adjustment enforces:
  - T below saturation: $q_t = q_v$ (RH <1)
  - T above saturation: $q_t = q_{sat}(T) + q_c$ (RH >1)

- Diagnostic variables: $q_{c,dia}$, $q_{i,dia}$, $q_{v,dia}$.
  - These are the mixed ratio as seen by radiation.
  - These are pure diagnostic; they are calculated before each radiation step.
  - They have a turbulent (turb) and convective (conv) contributions.

Two different kind of clouds

It is useful to think of subgrid clouds of two different types:

- Convective clouds. They are generated by updrafts that mostly originate in the boundary layer.

- Clouds generated by turbulent fluctuations inside the grid box.

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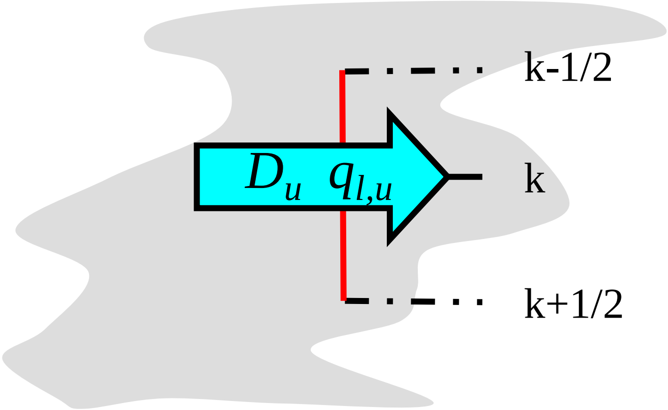
Convective cloud cover

- The cloud scheme only consider the anvils from the convective cloud.
- The anvil cloud cover and water content is provided by the equilibrium between detrainment and dissipation.
- In ICON-D2 the contribution of convective clouds to the total cloud cover is relatively small.



$$\cancel{\frac{\partial CC}{\partial t}} = (1 - CC)\frac{D_u}{\rho} - \frac{CC}{\tau_{decay}}$$

anvil decay time-scale

ICON: τ_{decay} = 1500s

Two different kind of clouds

It is useful to think of subgrid clouds of two different types:

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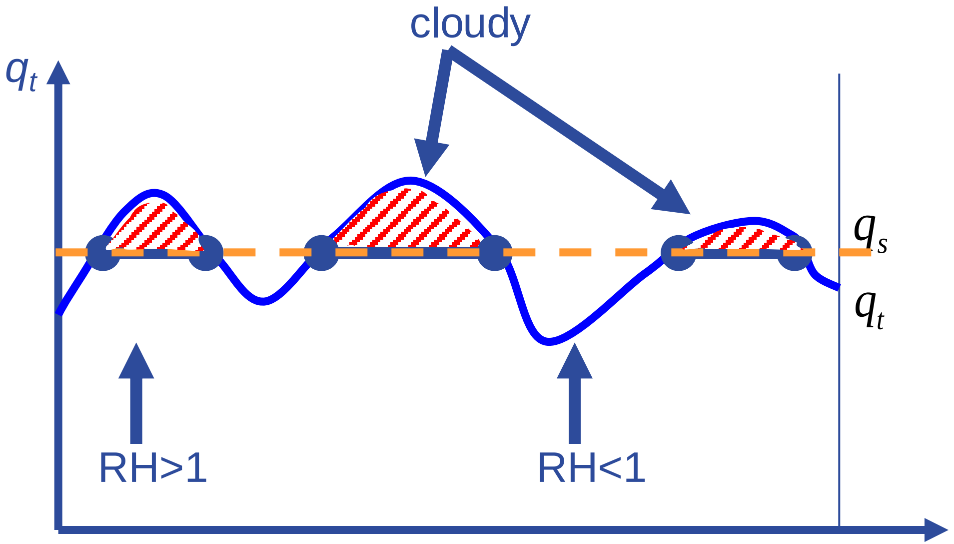
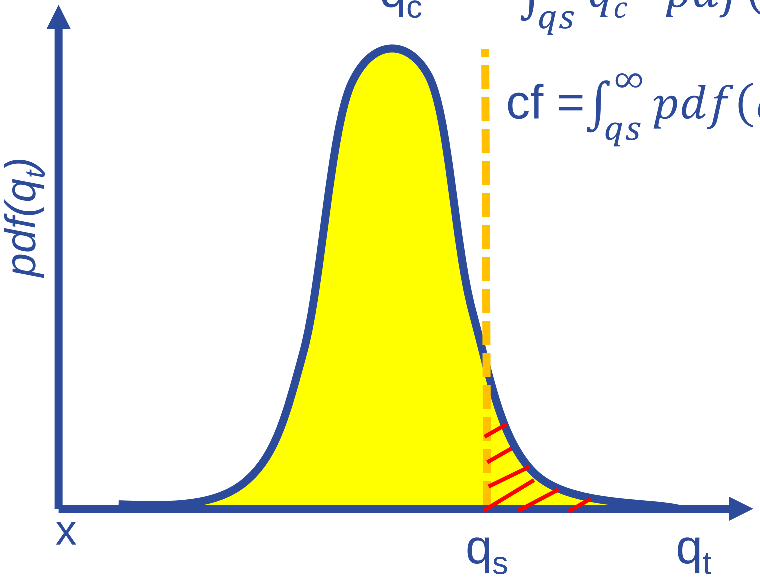
- **Clouds generated by turbulent fluctuations inside the grid box.**

Clouds due to fluctuations



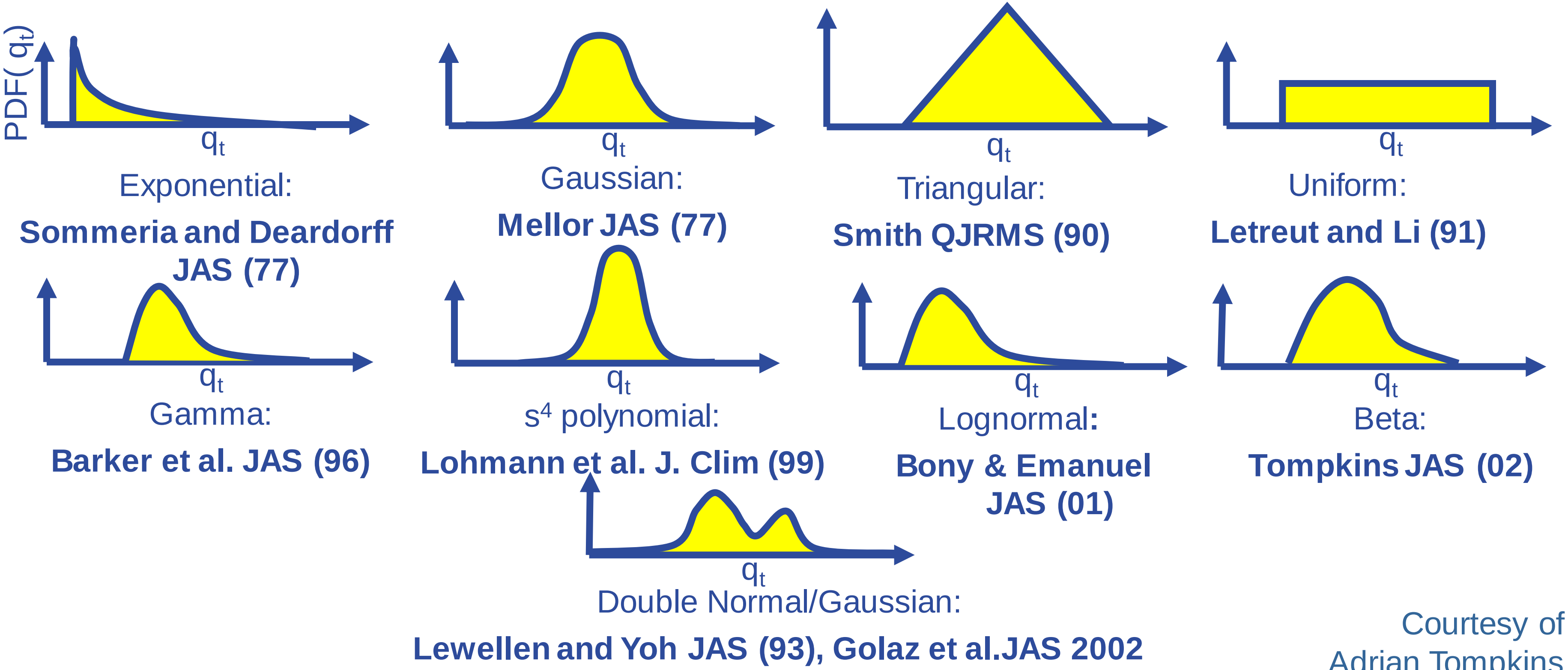
$$q_c^{turb} = \int_{qs}^{\infty} q_c \cdot pdf(q_t)\, dq_t$$

$$cf = \int_{qs}^{\infty} pdf(q_t)\, dq_t$$



- Fluctuations of total water can produce clouds even when the mean value is below saturation.
- If we assume saturation and neglect fluctuations of temperature, we can calculate cloud fraction and liquid water from the total water pdf.

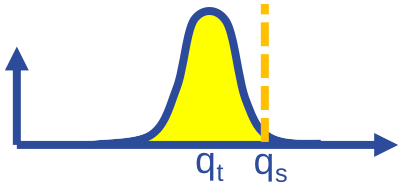
Many different choices



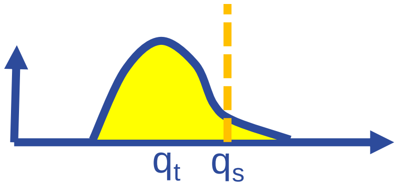
Courtesy of
Adrian Tompkins

Parameters that describe a pdf

- Asymmetric pdfs predict clouds at a lower vapor pressure than symmetric ones. They tend to predict larger cloud cover.

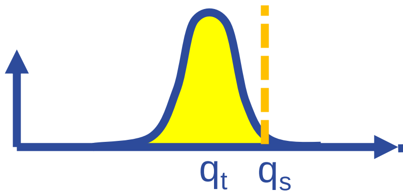


s^4 polynomial

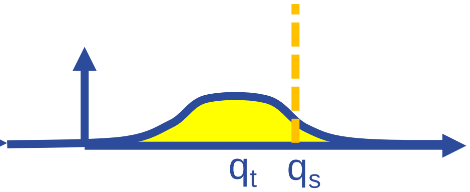


Beta

- Broader pdfs also predict clouds at lower vapor pressure than narrower ones. However the effect here is different. For example, for a very narrow distribution we recover the all or nothing behavior.



s^4 polynomial



s^4 polynomial

q_s

ICON turbulent clouds

- ICON scheme is starts from a pdf formulation with an asymmetric quadratic function. However, the scheme is further tuned so that it cannot be considered a pure pdf formulation.

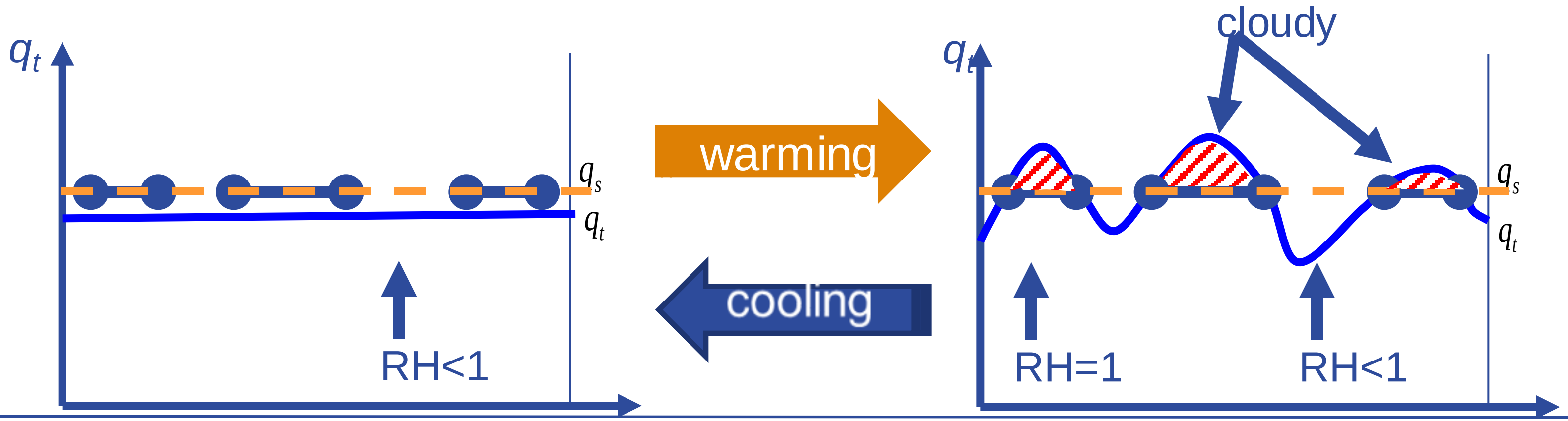
- The properties of the initial pdf has a similar impact as in a pure pdf formulation. In particular the pdf is characterized by:
  - An asymmetric factor A, which is a tunable parameter.
  - A broadening factor that depends on the variance of total water provided by the turbulent scheme: $\Delta q \propto \sqrt{\overline{q_t^2}}$

- Ice clouds follow a similar formulation. The scheme treats some snow as ice when little ice is present.

Sub-grid scale condensation

- The latent-heat released by the formation of turbulent clouds is small, but it can serve as a trigger for convection in unstable weather conditions.

- There is an option in ICON to consider this latent-heat (only liquid clouds): it produces a small temperature tendency in the slow physics according to the change in sub-grid clouds.



Some suggestions

- The cloud scheme has a direct impact on radiation while not changing the prognostic variables. It is therefore quite suitable for tuning: ICON global and ICON-D2 use a slightly different set of parameters, while IMS uses a set that they found more adequate for Mediterranean clouds.

- For example, you can change to a more symmetric/narrow distribution if you have too many clouds or to a more asymmetric/broad distribution if you have too few clouds.

- Indirect effects can however have broader consequences. For example, a model with more liquid clouds is expected to be colder and to produce less summer precipitation.

- Ice and water clouds can be tuned independently.

Useful Namelists

Liquid clouds:

tune_box_liq_asy	= 3.0	Asymmetry factor. (1.0 for symmetric pdf)
allow_overcast	= 1.0	It changes the CC for RH=100%.
tune_box_liq	= 0.05	It scales the pdf broadening: $\Delta q \sim tbl\ q_{sat}$
icpl_turb_clc	= 1/2	1: broadening mostly determined by turbulence 2: broadening mostly determined by tune_box_liq
lsgs_cond	= .true./.false.	Applies temperature changes according to variations in the turbulent sub-grid clouds.

Ice clouds:

tune_sgsclifac	= 1.0	Scaling factor for subgrid-scale ice.

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Questions?

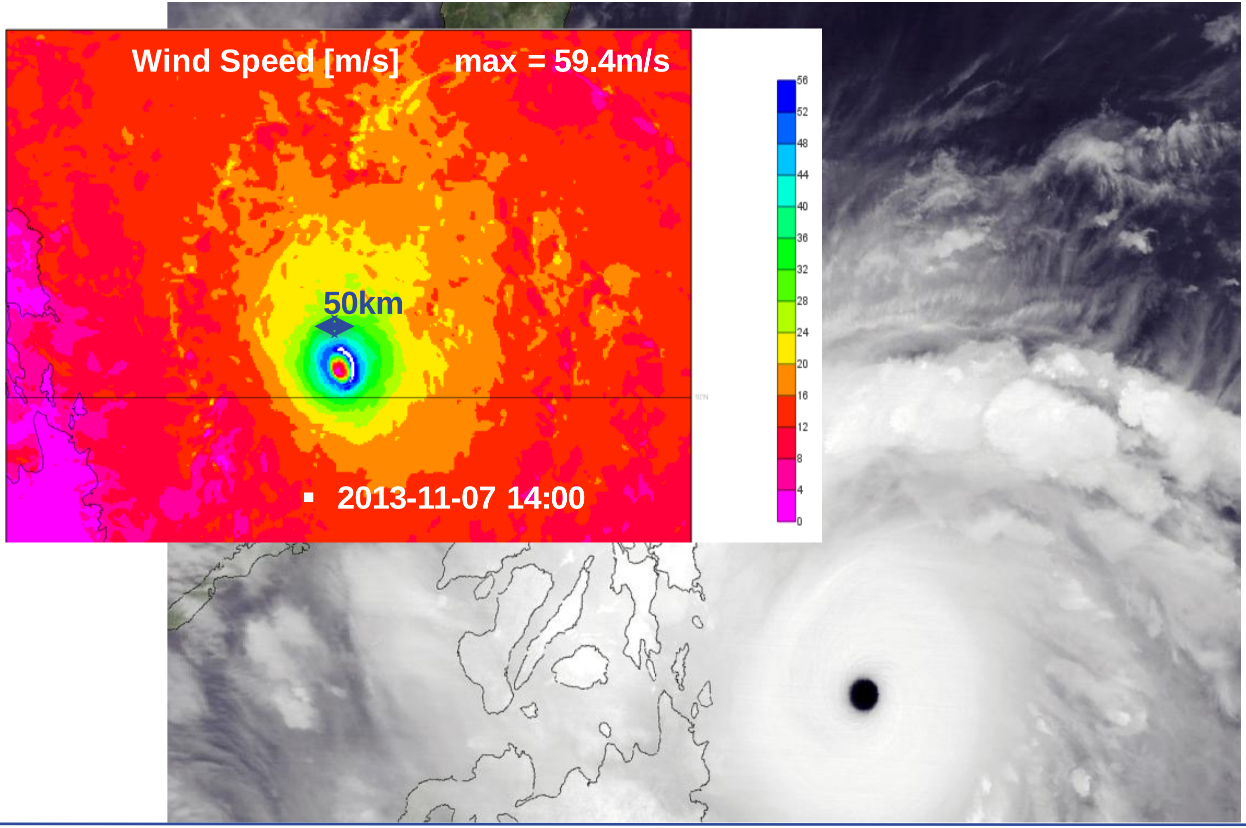
Recap

- The cloud microphysics in ICON is an all or nothing scheme:
  - It allows for clouds only when the air is fully saturated.

- Sub-grid clouds are an important component of ICON.
  - Their importance depends on the model resolution.

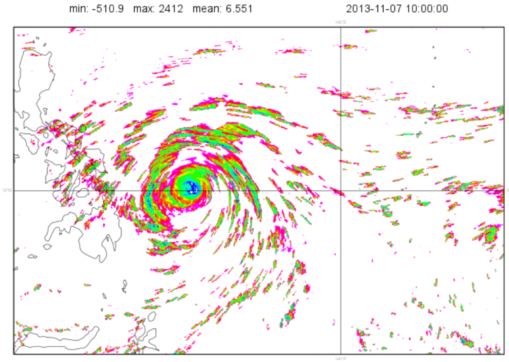
- Sub-grid clouds influence precipitation, radiation, heat, momentum and moist transport and on precipitation.
  - Physical parameterizations must take care of these clouds.
  - In this lecture we will focus on the convective and cloud parameterization.

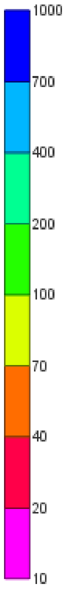
Typhoon Haiyan



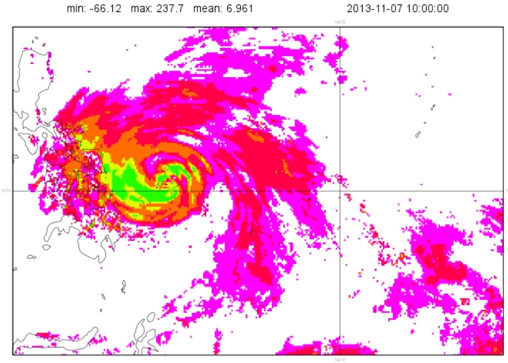
Typhoon Haiyan: 10km vs 2.5km

total precipitation
2.5km nested grid

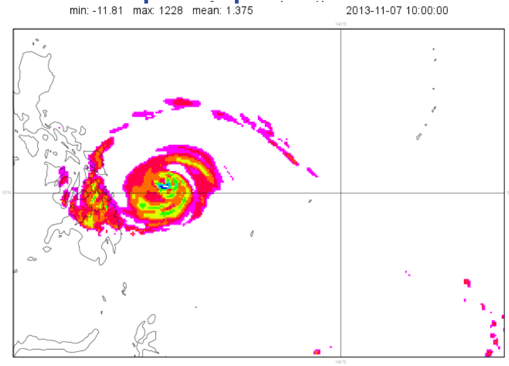




convective precipitation 10km run



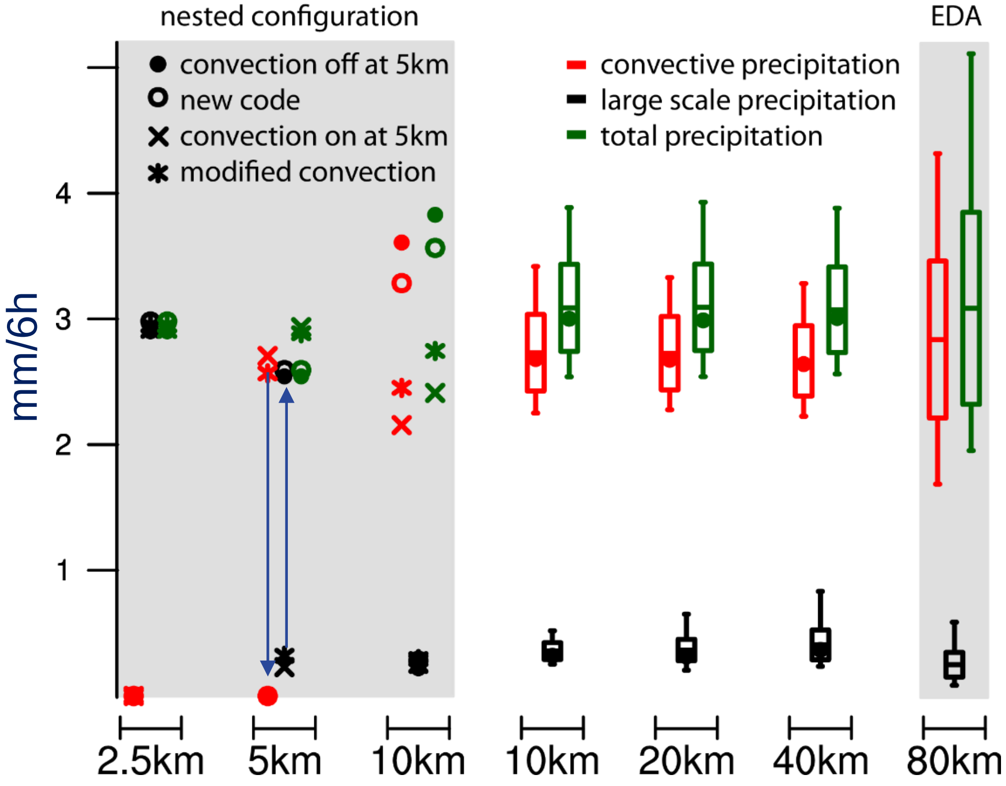
large-scale precipitation 10km run



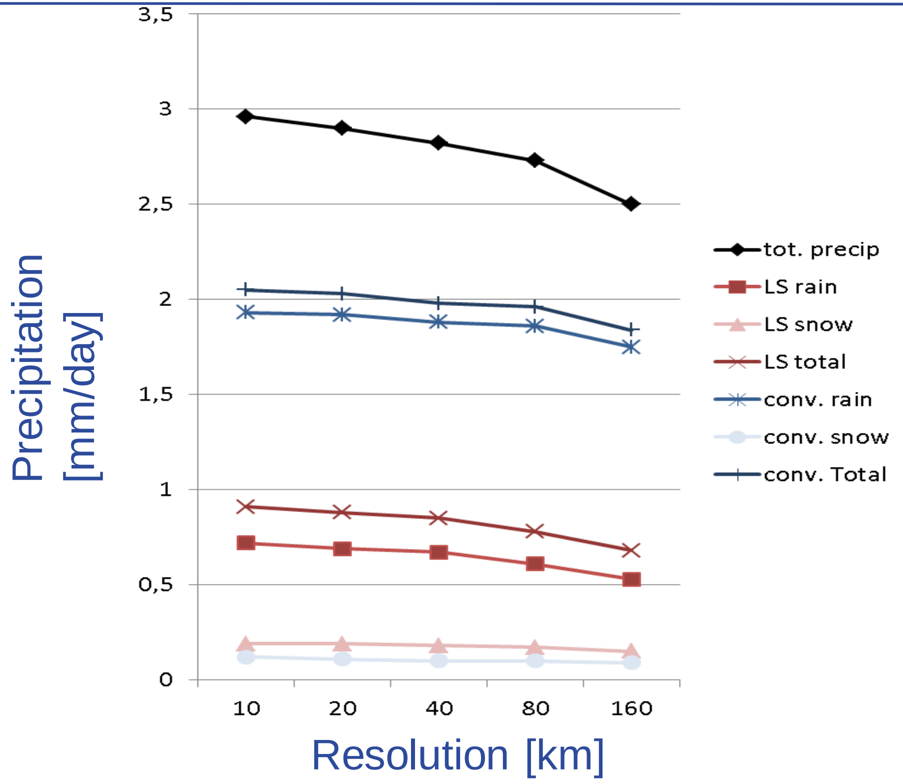
Typhoon Haiyan: precipitation

- Most precipitation arise from the convective parameterization (in red) when this is allowed to run.

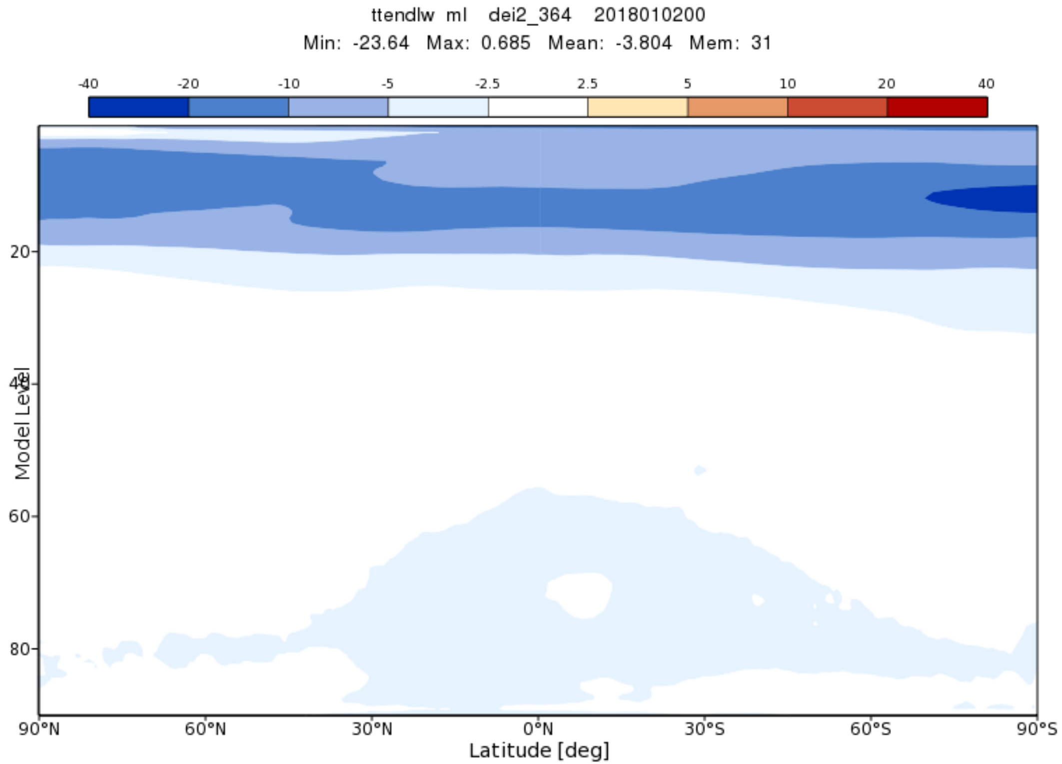
- If we switch the convective parametrization off (blue arrows), the resolved clouds (large-scale flow) will take over and produce a similar amount of precipitation.



Parameterized vs resolved rain

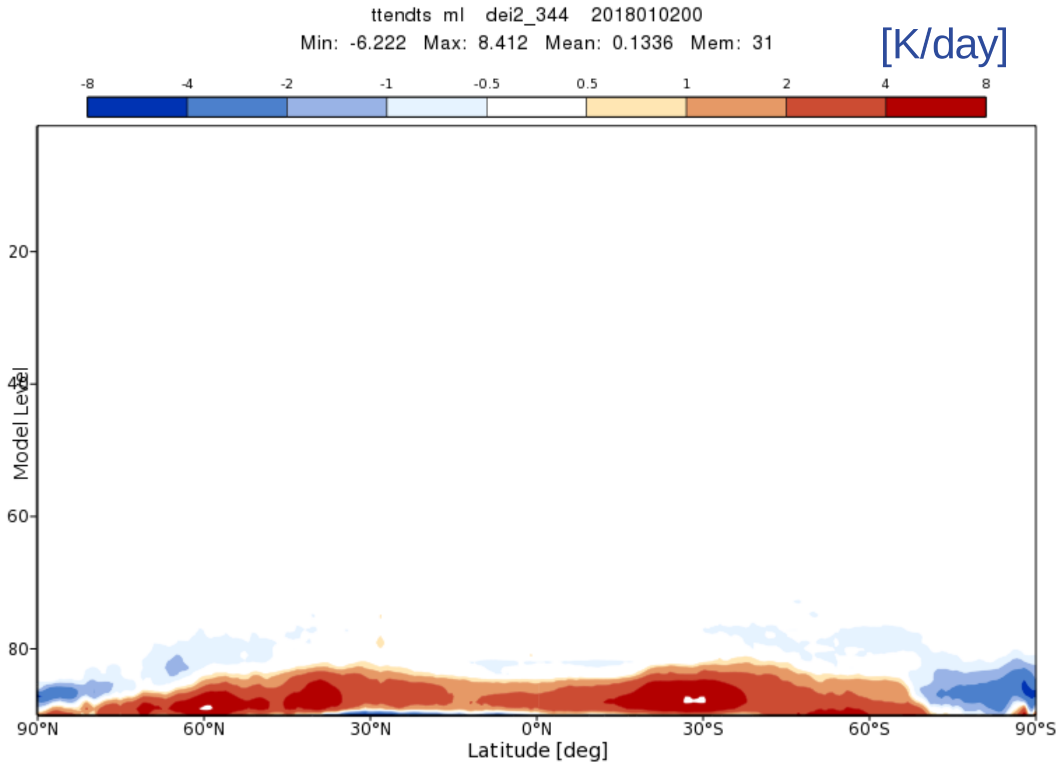


Temperature change due to LW radiation



January 2018

Temperature change due to turbulence

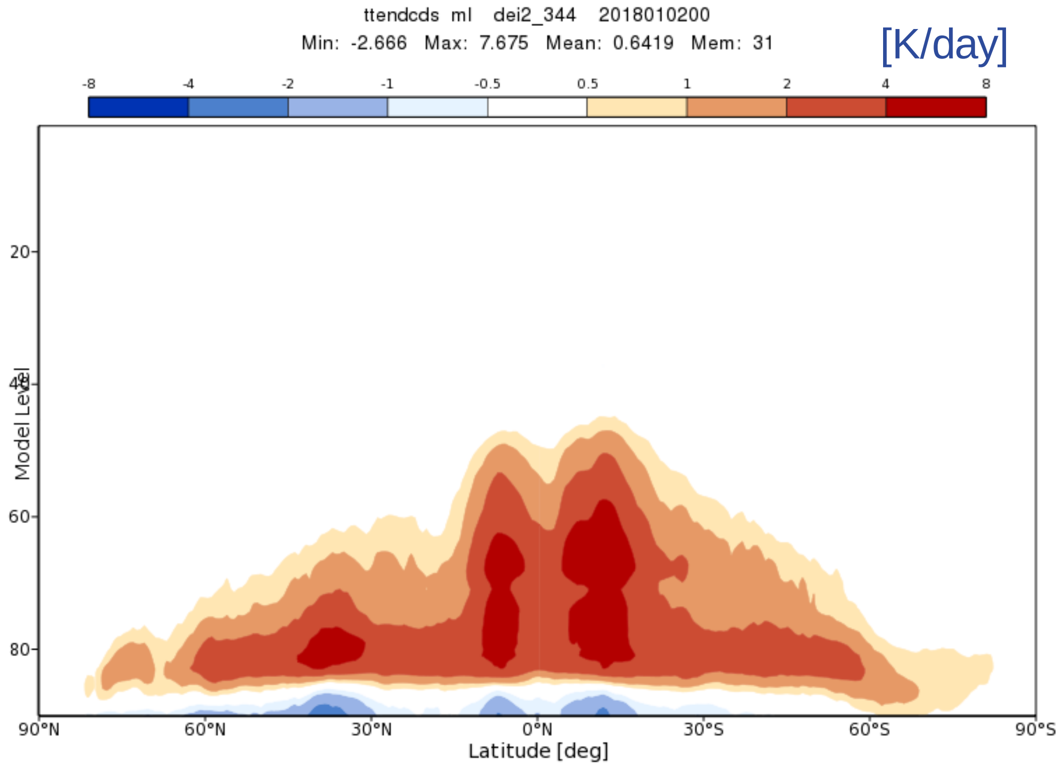


[K/day]

January 2018

Temperature change due to convection

[K/day]



January 2018

Spectral formulation of cloud microphysics

To derive microphysical schemes, 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

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

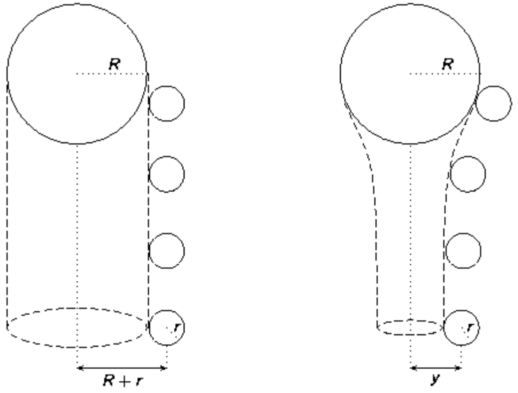
with

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

Spectral formulation of cloud microphysics

The gravitational collision kernel ***K(x,y)*** is given by

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



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

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 density of particles:

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

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

Increasing complexity of microphysics schemes

	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).

🡐 Similar to Cotton et al. (1986) the two-moment cloud ice scheme (gscp=3) has a prognostic number density for ice, but gscp=3 has no graupel.

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

Increasing complexity of microphysics schemes

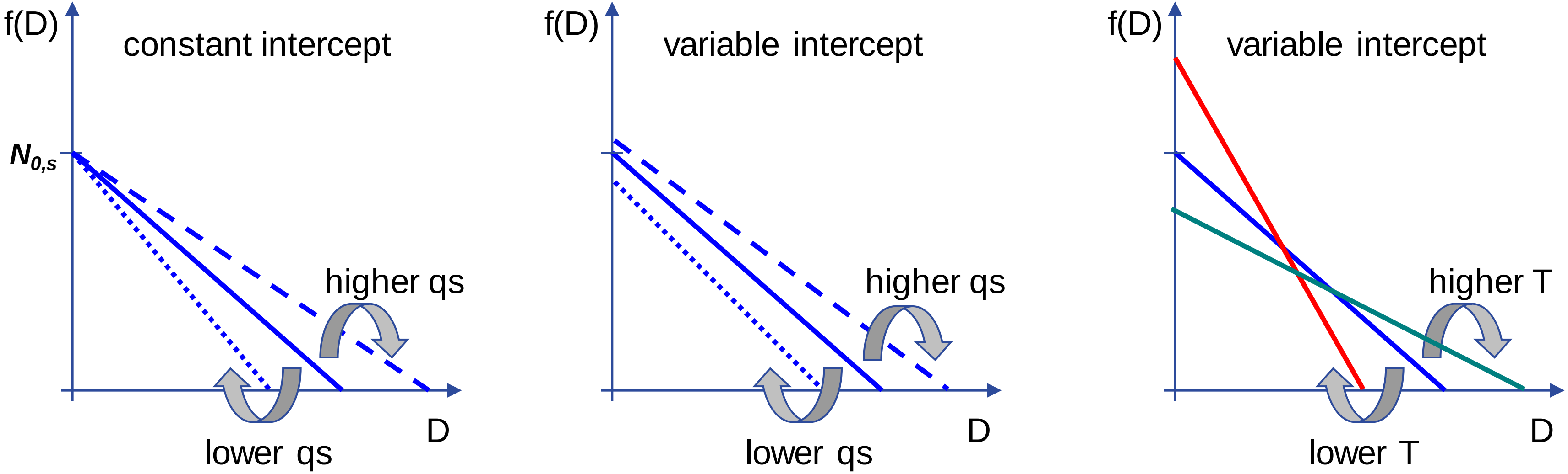
	cloud		rain		ice		snow		graupel		hail	
	N	L	N	L	N	L	N	L	N	L	N	L
Kessler, 1969; Berry, 1968		□		□								
Wisner et al., 1972		□		□								□
Lin et al., 1983		□		□		□		□				□
Rutledge & Hobbs, 1984		□		□		□		□		□		
Cotton et al., 1986		□		□	■	□		□		□		
Mölders et al., 1995		□		□		□						
Kong & Yau, 1997		□		□		□						
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

The development did not stop in 2002:

For example, the P3 microphysics scheme of Morrison and Milbrandt (2015) predicts additional variables like rime mass, rime volume, or liquid mass.
P3 will become available as a ComIn plugin for ICON, hopefully soon.

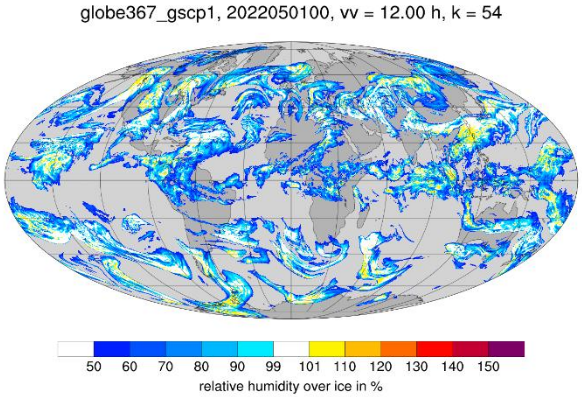
Aggregation of snow in a one-moment scheme

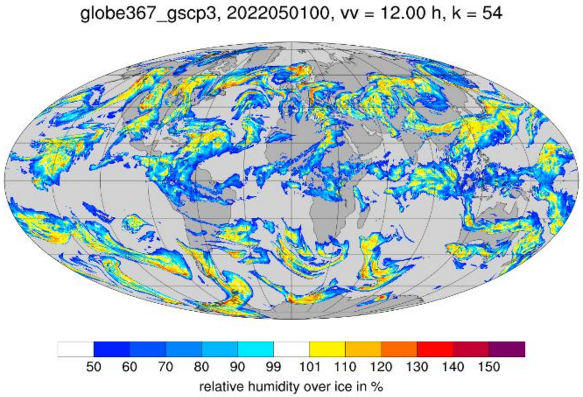


➔ One-moment schemes rely on an empirical parameterization for the intercept parameter because they predict only the slope of the exponential distribution.

ICON one-moment vs two-moment cloud ice scheme

Relative humidity over ice for an arbitrary day in May 2022.





➔ Operational one-moment (gscp1) has very little ice supersaturation, two-moment cloud ice scheme (gscp3) has much higher supersaturation and is more realistic.

➔ Spatial patterns are nevertheless similar. Not much impact on actual forecasts.

Aerosol effects on clouds

Most clouds form through activation of **cloud condensation nuclei (CCN)** or by heterogeneous nucleation on **ice nucleating particles (INPs)**. Hence, the availability of aerosol particles can affect or even determine cloud properties.

A lower number of CCN leads to fewer cloud droplets, which reflect radiation less efficiently. A high number of CCN leads to a large number of cloud droplets and brighter clouds. This is called the **Twomey effect**.

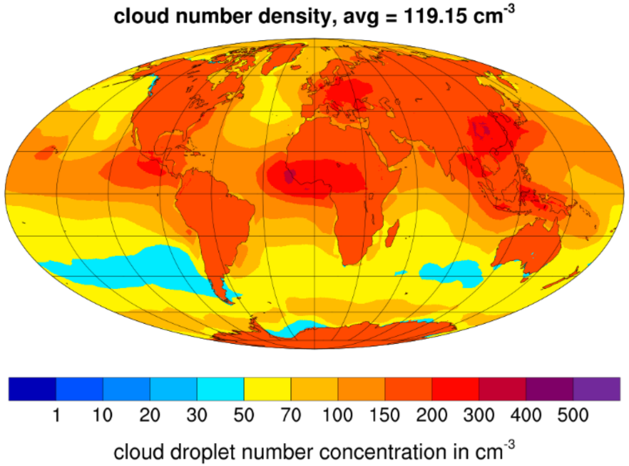
A larger number of cloud droplets and, hence, smaller droplets makes collision processes less efficient. As a consequence rain formation is delayed and the liquid water path increases. These are called indirect effects or **cloud adjustments**.

Aerosol effects on clouds – cloud droplet number concentration

In the operational ICON the number of cloud droplets is estimated from the Tegen aerosol climatology (left). This differs from the MODIS climatology that is derived from satellite measurements. Significant differences occur in the tropics. Amazonia becomes a „Green Ocean“ with MODIS CDNC.

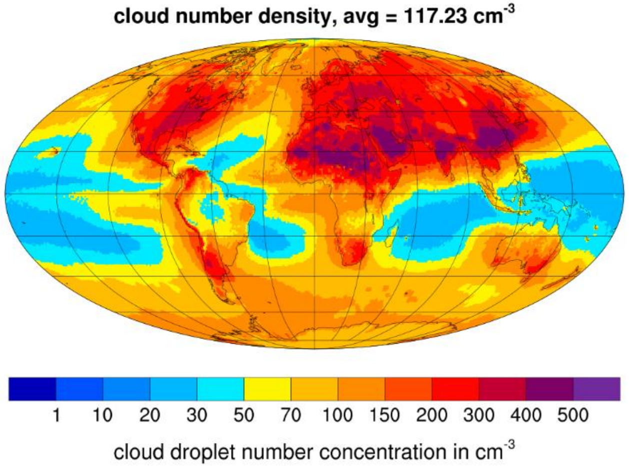
Tegen-based CDNC climatology

icpl_aero_gscp=1



MODIS CDNC climatology

icpl_aero_gscp=3

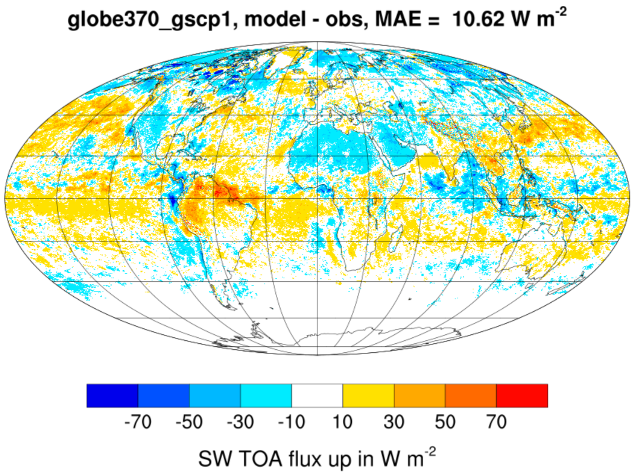


➔ This choice primarily affects the properties of liquid clouds and reflected shortwave radiation.

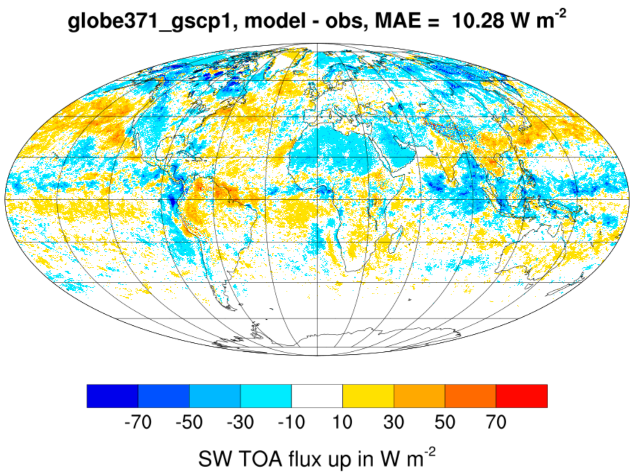
Aerosol effects on clouds – cloud droplet number concentration

Comparison of CERES reflected shortwave at TOA with ICON forecasts on R03B07. Operational model shows significant positive bias in tropics.
This bias can be reduced by switching to the MODIS CDNC climatology.

with Tegen-based CDNC



with MODIS CDNC

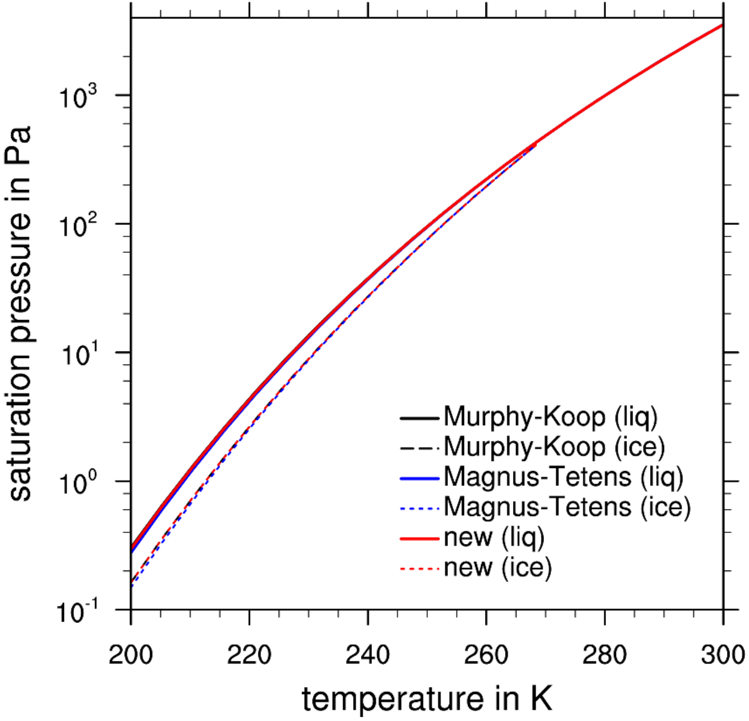


Saturation vapor pressure

The saturation vapor pressure is important because deviations from saturation pressure determine condensation and evaporation, and the Wegener-Bergeron-Findeisen process in mixed-phase clouds. The WBF described the growth of ice particles at the expens of liquid drops.

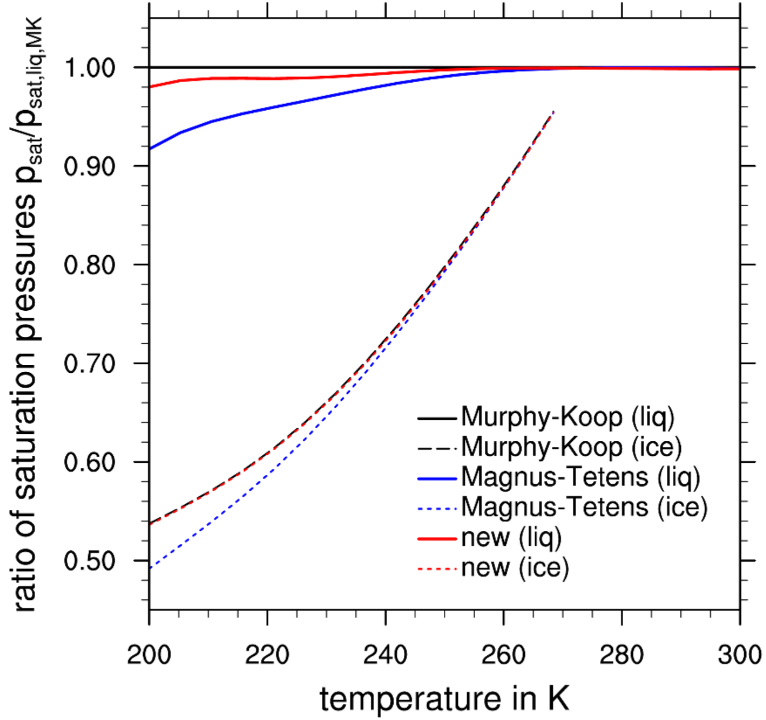
➔ Errors in saturation pressure should be avoided!

➔ But the formulas in ICON were from the 1930. Are they any good?



Saturation vapor pressure

- Compared to the modern empirical reference of Murphy and Koop (2005), the old Magnus-Tetens formula has large errors below -30 C.
- Even the errors below -40 C where no liquid water exists are relevant, because often we use RH_liquid as moisture variable.
- Therefore we have recently introduced better approximation that reduce this error to 0.5 % at -40 C.
- itype_satpres_coeffs = 2 in nwp_phy_nml



Quasi-equilibrium saturation adjustment:

The bulk schemes in ICON use saturation adjustment for condensation of water. Usually this done for thermodynamic equilibrium with RH=100 % or zero supersatuturation. In convective updrafts, significant supersaturation can exist, though. Unfortunately, there are very few measurements in convective updrafts with w > 20 m/s.

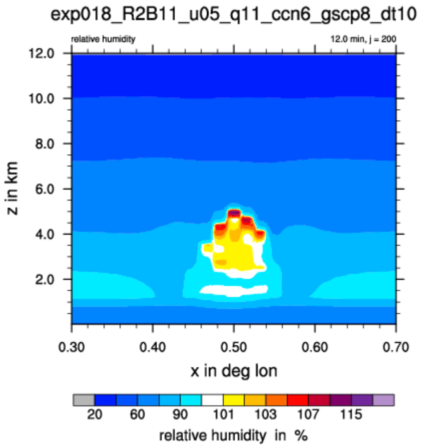
Recently we have generalized the saturation adjustment to quasi-equilibrium in which supersaturation depends linearly on vertical velocity w.

- ➔ tune_supsat_limfac = 0: standard adjustment to thermodynamic equilibrium with S = 0
- ➔ tune_supsat_limfac > 0: allow supersaturation with S = MIN(1 + 0.005*w, k*qc/qv)
- ➔ Non-zero supersaturation leads to weaker updraft and reduced rain intensity
  (only relevant for grid-scale convective precipitation).
- ➔ Note that tune_supsat_limfac sets the parameter k, not the slope of the w-relation.

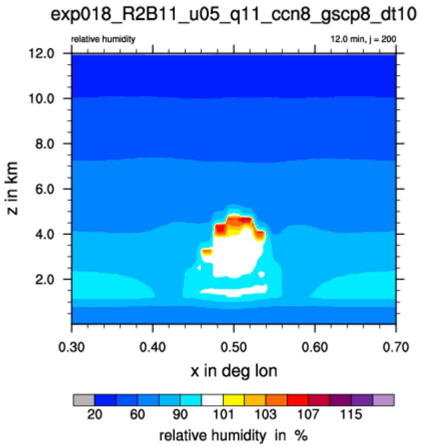
Quasi-equilibrium saturation adjustment:

spectral bin microphysics

low CCN

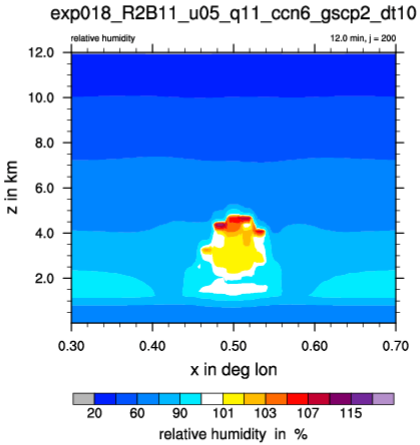


high CCN

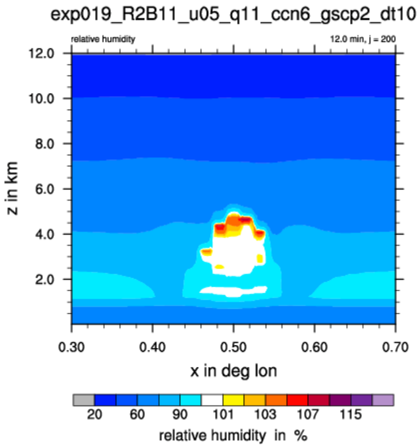


one-moment bulk microphysics

quasi-equilibrium



thermodynamic eq.

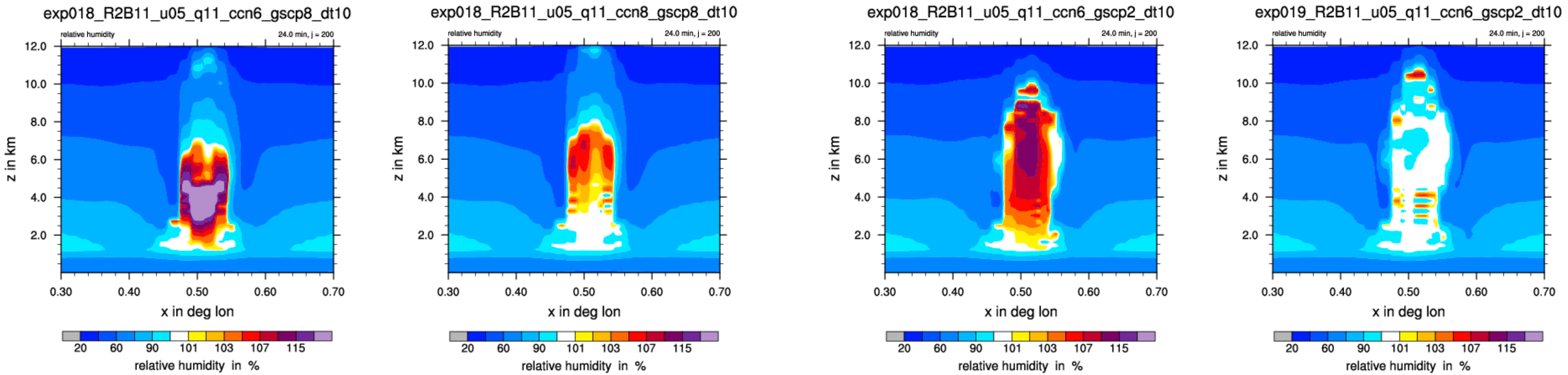


➔ Thermodyn. equil. is consistent with high CCN, quasi-equilibrium better in low CCN regime.

Quasi-equilibrium saturation adjustment:

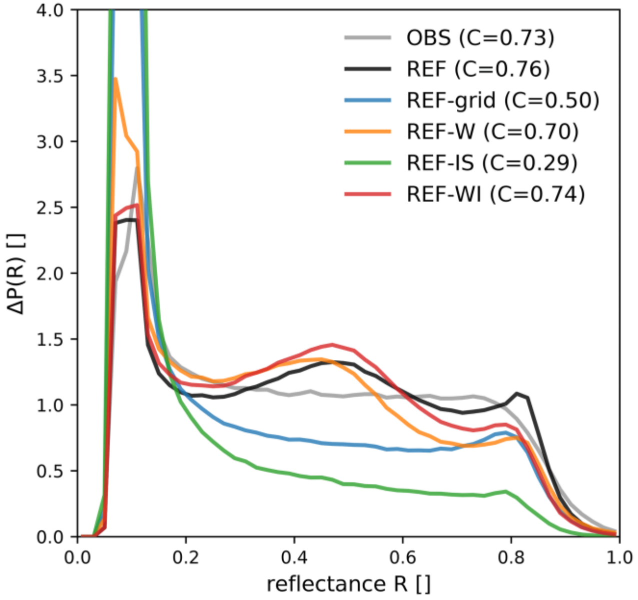
spectral bin microphysics | one-moment bulk microphysics

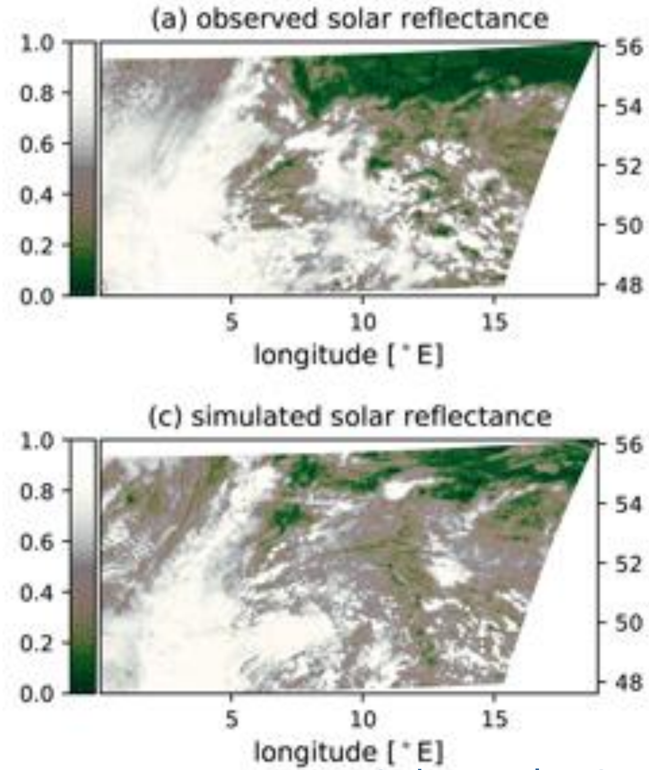
low CCN | high CCN | quasi-equilibrium | thermodynamic eq.



➔ Now quasi-equilibrium matches SBM better, but the bulk scheme has to much liquid aloft.

Histogram from visible channel (ID2)





- The cloud parameterization change the 30 days histogram from the <u>blue</u> (only grid clouds) to the <u>black</u> line. Around one third from the signal can be attributed to the clouds parameterization.

Geiss et al. ACP 2021