Max-Planck-Institut für Meteorologie

Hans-Ertel-Zentrum für Wetterforschung
Deutscher Wetterdienst

DWD

Small scales do not forget!

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with Carmen Köhler (DWD), Claudia Frick (ETH Zürich),
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Overview

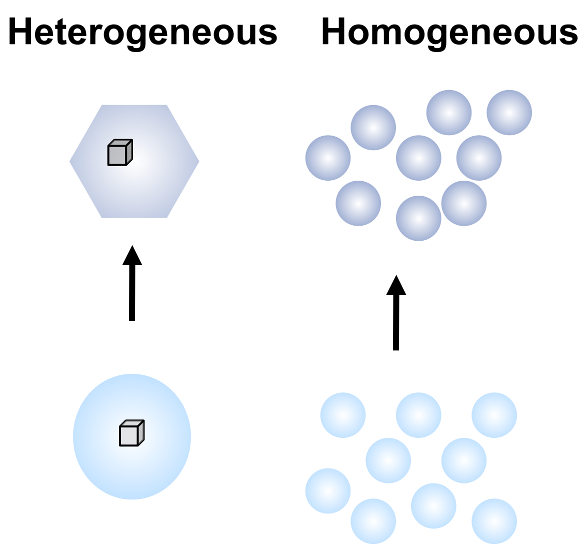
- Recent work on microphysics parameterizations
  - Prognostic cirrus microphysics
  - Prognostic melting scheme for snow
  - Two-moment microphysics for deep convection
- Some thougths on sub-grid precipitation
  - Autoconversion
  - Convective precipitation
- PDF-based vs stochastic schemes
- Conclusions

Parameterization of cirrus clouds: Multiple ice modes

- Heterogeneous and homogeneous nucleation produce very different number concentration, and compete with each other
- To properly describe this system we use a two-moment two-mode cloud ice scheme with a one-moment snow class

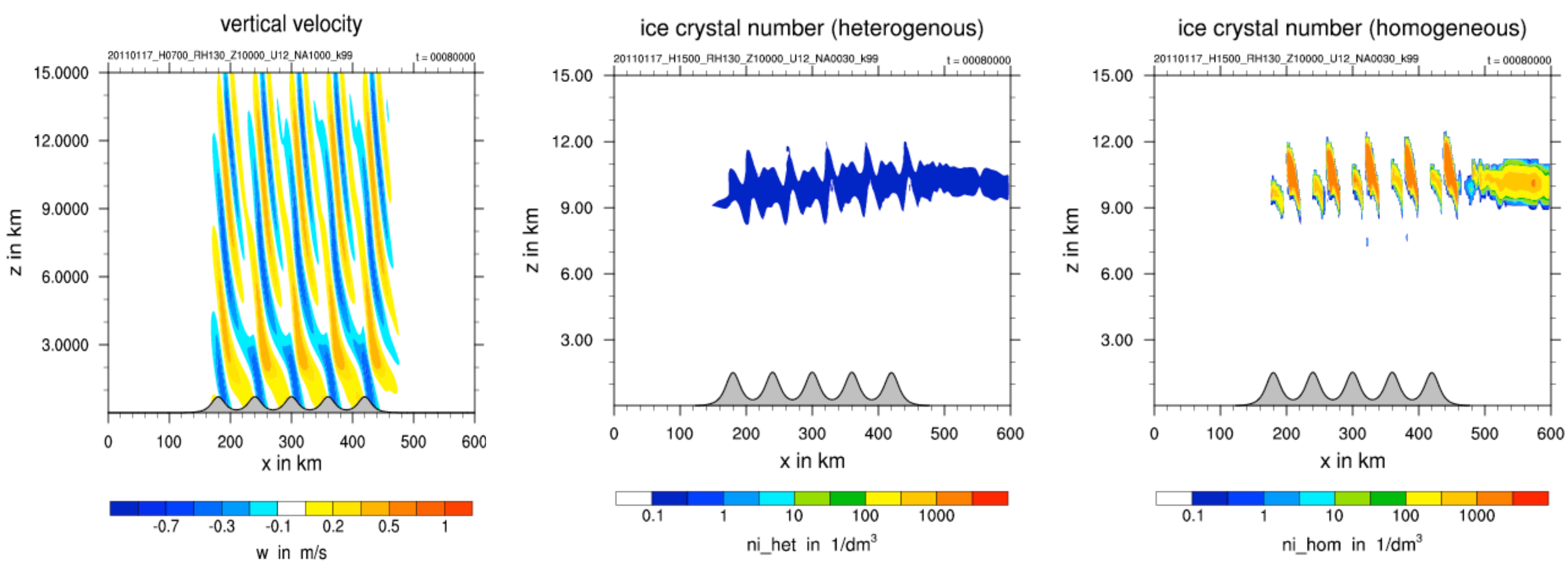
  Prognostic ice variables: $\mathbf{q_{hom}}$, $\mathbf{N_{hom}}$, $\mathbf{q_{het}}$, $\mathbf{N_{het}}$, $\mathbf{q_s}$

- Depositional growth can then be parameterized by a multi-timescale relaxation approach (e.g. Morrison et al. 2005)



Parameterization of cirrus clouds: Multiple ice modes

➔ Idealized simulations of orographic cirrus clouds



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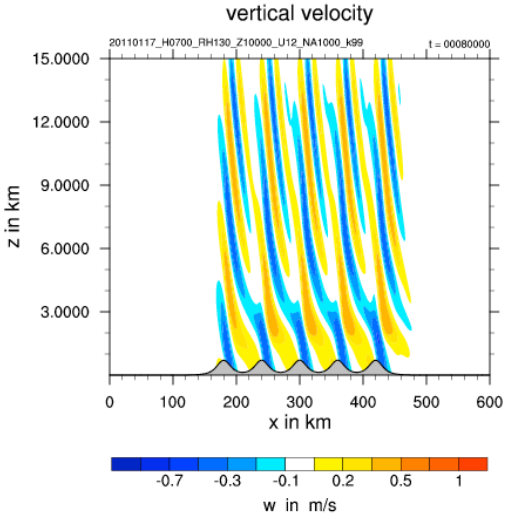
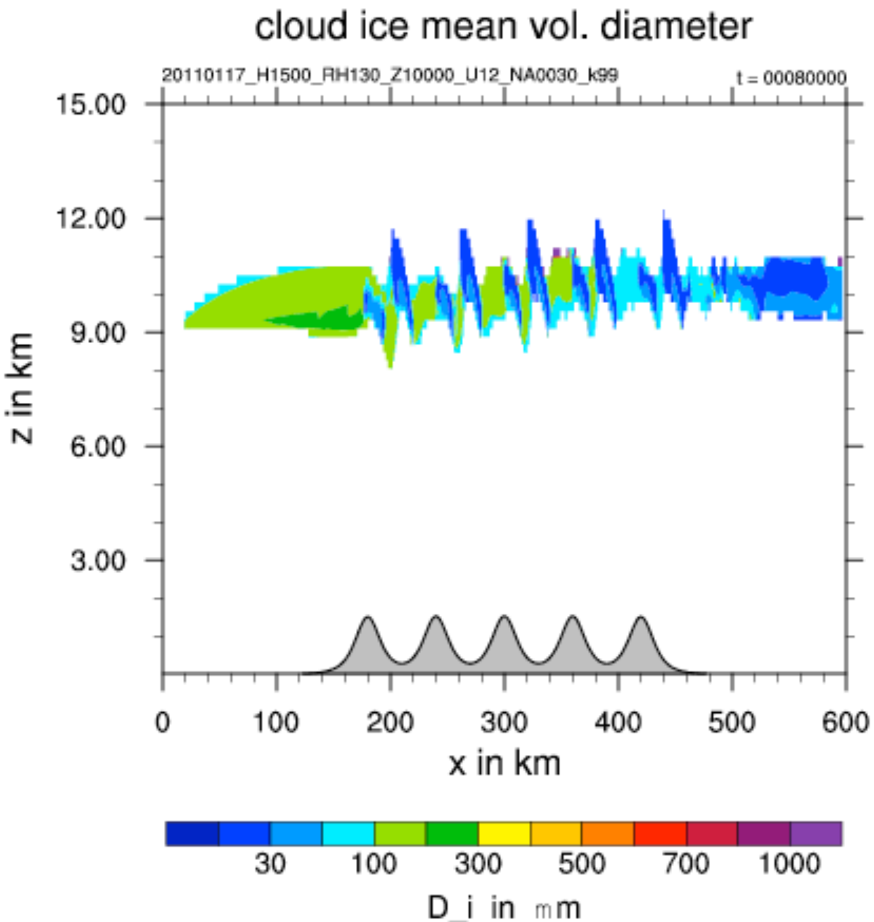
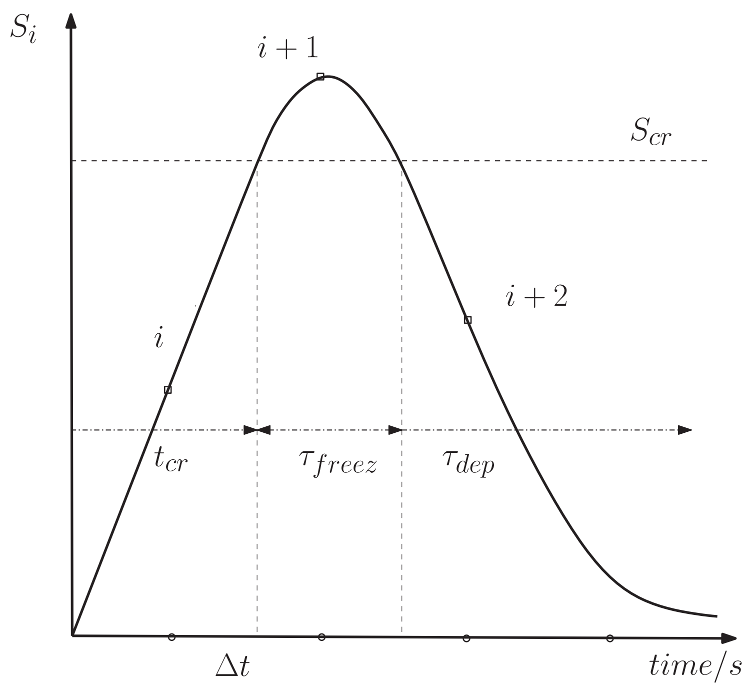


- Impact on radiation?



Homogeneous nucleation:

➔ Timescale of nucleation and depositional growth



Large-scale models:

$$\tau_{freez} < \tau_{dep} \ll \Delta t$$

Fully-resolved (large-eddy) model:

$$\Delta t \ll \tau_{freez} < \tau_{dep}$$

Current NWP models:

$$\Delta t \approx \tau_{freez} < \tau_{dep}$$

Explicit snow melting model: The problem

- In current microphysics schemes meltwater contributes to rain, i.e., external instead of internal mixture.
- This leads to unphysical behavior, e.g., rain/meltwater may have a much higher fall speed, but fall speed of snow is always assumed as ‚dry snow‘.
- In most NWP models snow melts too fast leading to problems in the forecasts of precipitation phase and wet snow.
- This can be a serious forecast problem!

A series of power line towers which snapped off during the wet snowfall event in November 2005 in Germany (picture by Sven Lüke, www.schneechaos-muensterland.de).

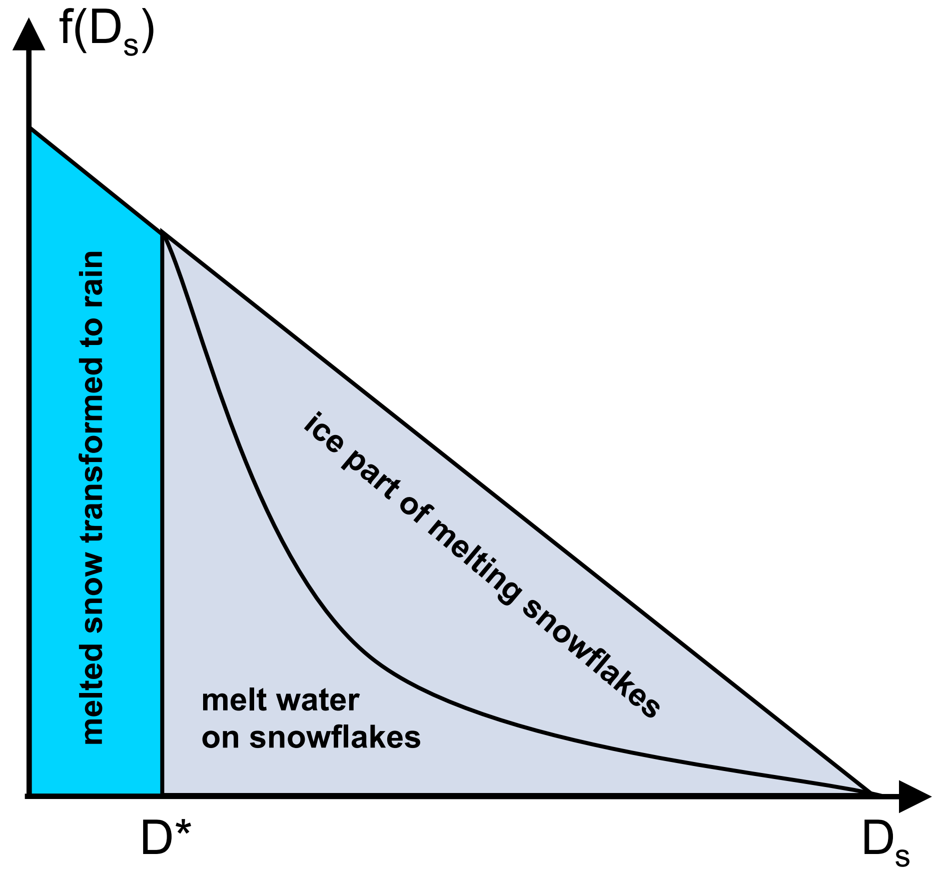
Explicit snow melting model: Prognostic melt water

- Parameterization concept follows Szyrmer and Zawadzki (1999, JAS)
- Snowflakes below a critical size D* have melted completely
- Larger snowflakes are partially melted with LWF ~ $1/D_s$
- Instead of predicting q_s and D* we use mixing ratios of ice and liquid part

$$\mathcal{L}_{s,i} = \int_{D_*}^{\infty} m_i(D_s) f_m(D_s,\ell) dD_s$$

$$\mathcal{L}_{s,w} = \int_{D_*}^{\infty} m_w(D_s) f_m(D_s,\ell) dD_s.$$

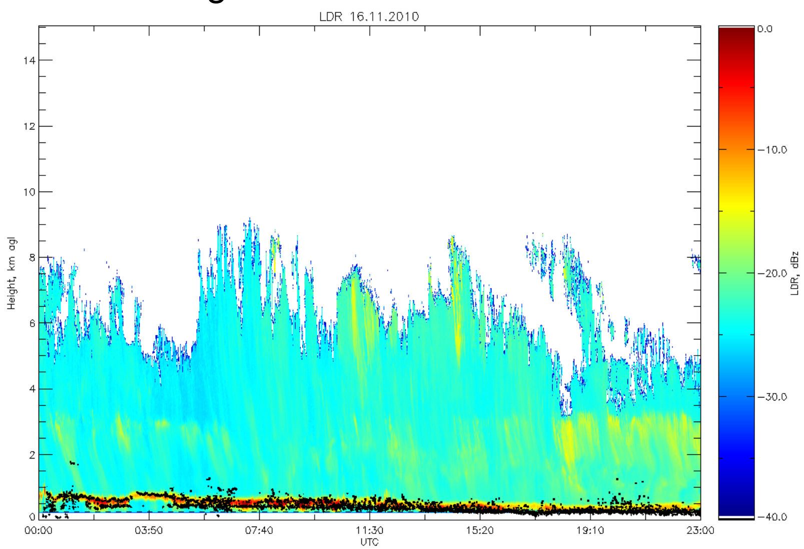
and diagnose D* each time step.

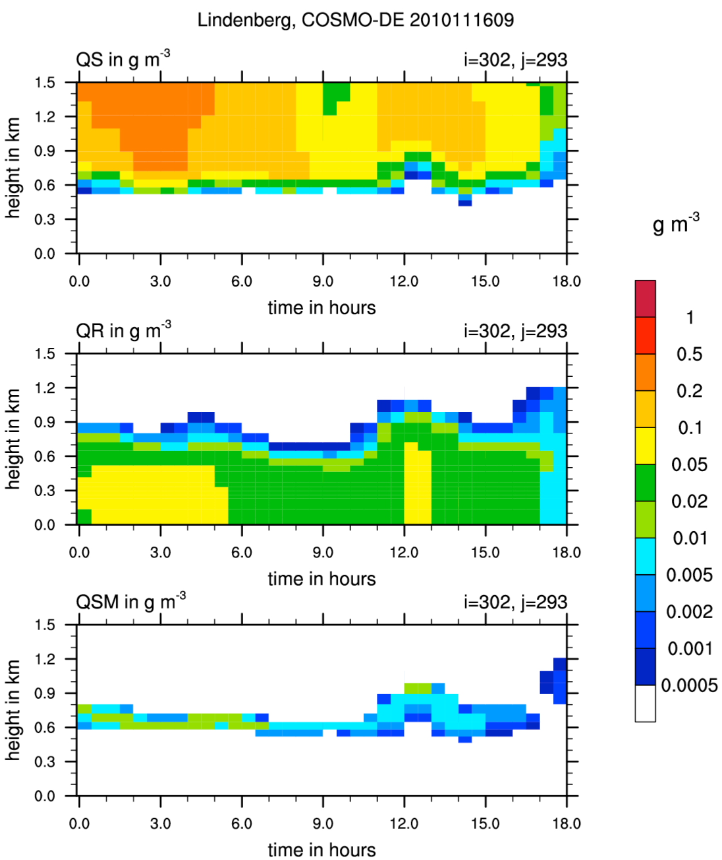


Explicit snow melting model: a case study

➔ Stratiform precipitation over Germany on 16 Nov 2010

Lindenberg cloud radar LDR





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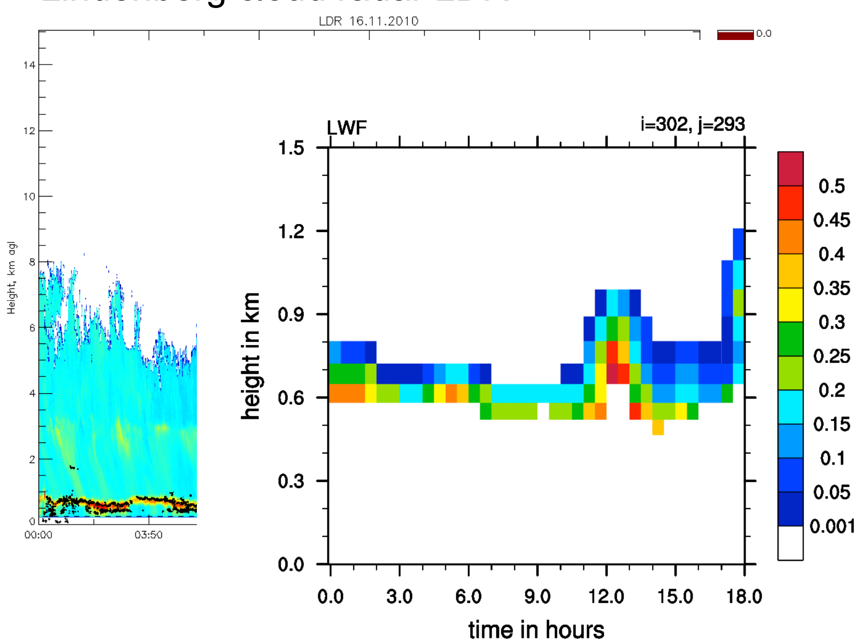

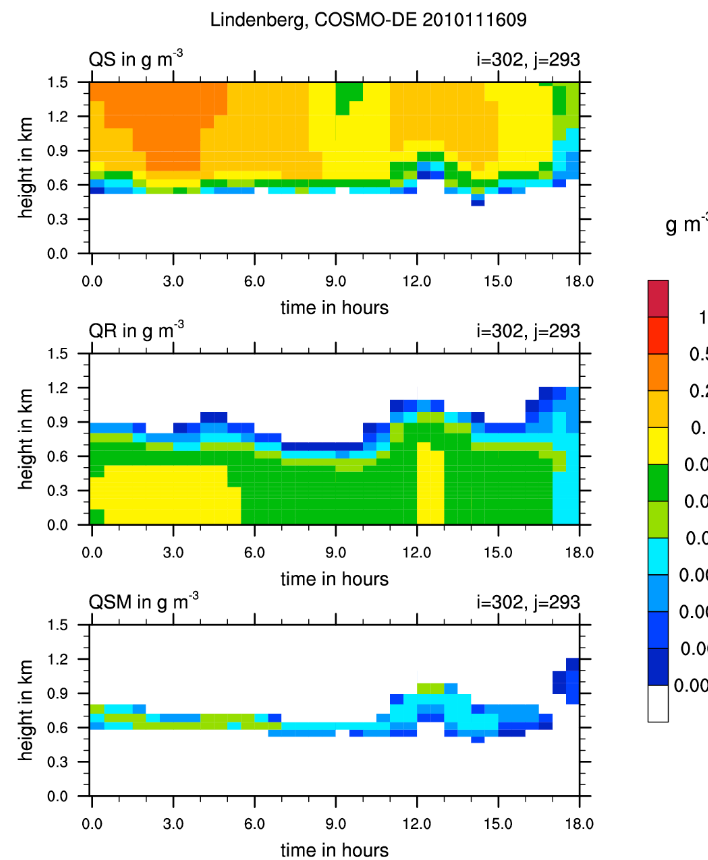

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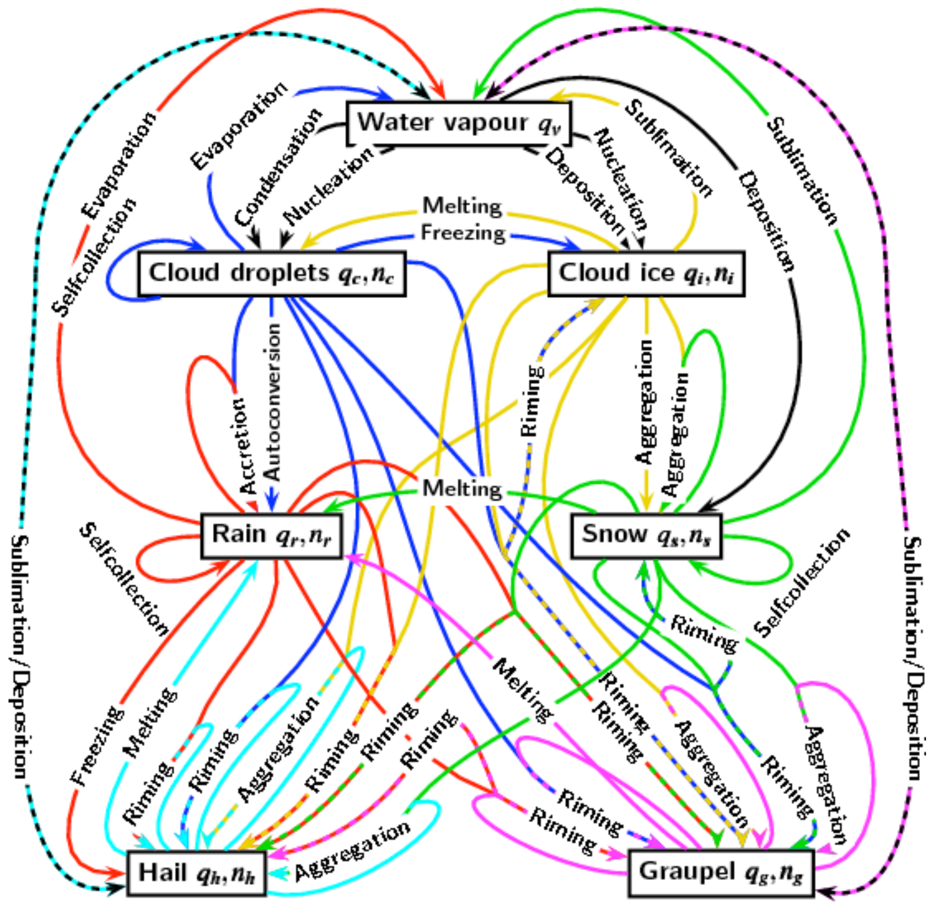
The Seifert and Beheng two-moment scheme:

Extended version by Blahak, Noppel, Beheng and Seifert



Number and mass concentrations of six different species

- cloud droplets
- rain drops
- cloud ice
- snow
- graupel
- hail (including wet growth)

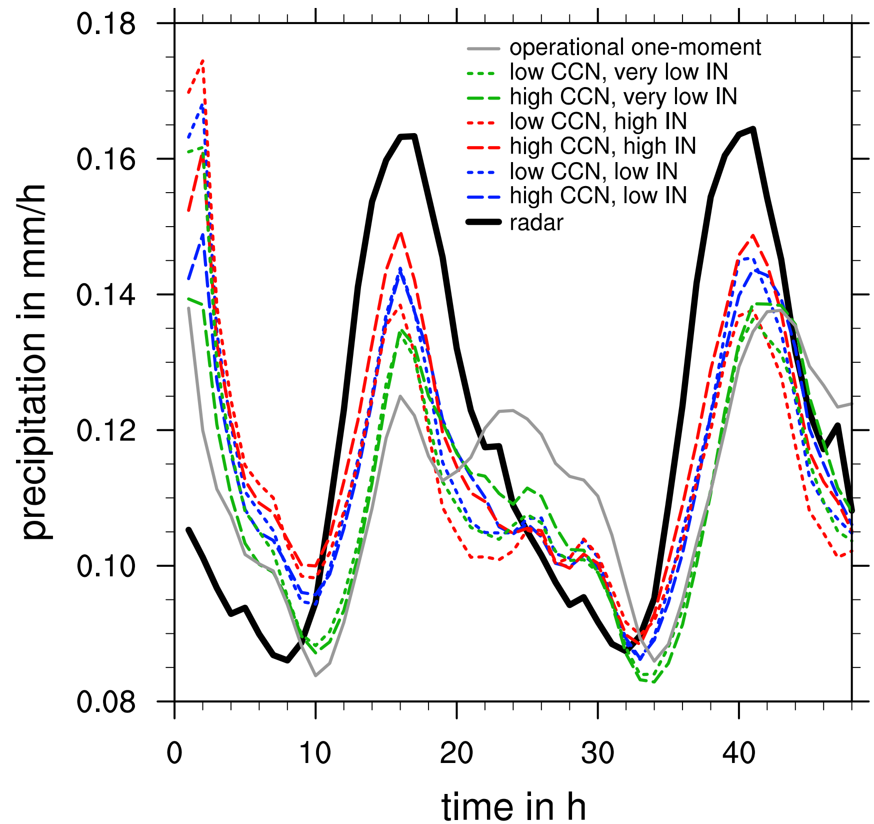
Process parameterizations:

- Drop activation/nucleation scheme using Segal&Khain (2006).
- Homogeneous ice nucleation based on Kärcher et al. (2008).
- Heterogeneous ice nucleation using the empirical scheme of Phillips et al. (2008).

12 prognostic variables compared to five of the operational one-moment microphysics.

Diurnal cycle of precipitation (space-time averaged)

- Diurnal cycle of hourly precipitation averaged over the evaluation domain.
- Two-moment scheme (colored lines) gives a better representation of the diurnal cycles compare to the operational one-moment scheme
- Currently the two-moment scheme is too expensive for operations, and the actual skill scores are only marginally improved.



Advanced microphysics needs memory

- For a better representation of microphysical processes we tend to add more prognostic variables, e.g.,
  - More moments of the particle size distribution, e.g., number and mass density or even a ‚radar reflectivity' (2nd moment w.r.t. mass)
  - Additional particle types like graupel, hail, drizzle or various ice modes
  - Variable for meltwater on particles or rimed mass on snowflakes etc.
  - Some variables to track available CCN and IN, i.e., a simple aerosol model.
- Additional prognostic variables become necessary when we start to resolve the spatial and temporal scales of the individual processes.
- Prognostic variables provide memory only for resolved processes.
- **Do we need memory for sub-grid parameterizations?**

Does autoconversion need memory?

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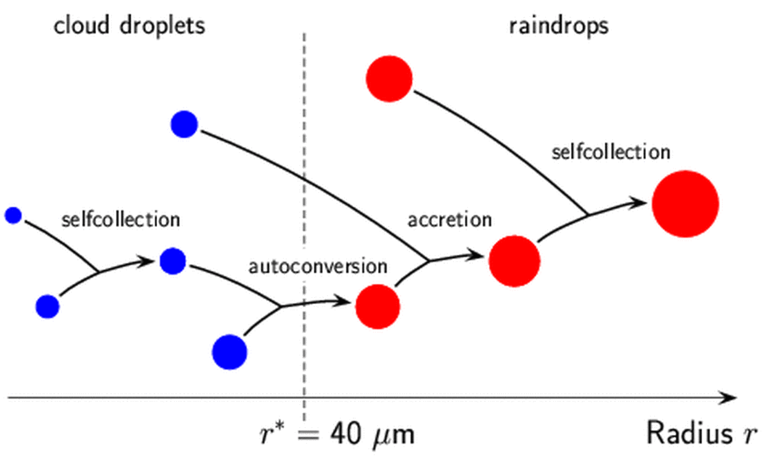
Collision-coalescence of droplets is a key process for rain formation. Bulk schemes usually rely on autoconversion schemes.

The time evolution of the cloud droplet size distribution (CSD) leads to a memory effect:

Within the lifetime of a cloud parcels the CSD broadens (becomes positively skewed) which is crucial for autoconversion.



Schemes with no explicit assumptions about the evolution of the CSD:

- All Kessler- and Sundquist-type schemes including Liu and Daum (2004)
- Berry and Reinhardt (1974)
- Khairoutdinov and Kogan (2000)

Schemes with explicit parameterization of the evolution of the CSD:

- Lüpckes et al. (1989): Three drop classes including two cloud categories with explicit size distributions.
- Seifert and Beheng (2001): Dynamics similarity using rain water as a proxy for large cloud droplets.
- Sant et al. (2012, submitted): Similar to Lüpckes et al. approach, but drizzle class instead of 2nd cloud mode.

➔ More advanced schemes include memory to represent the broading of the cloud size distribution.

Does convection need memory?

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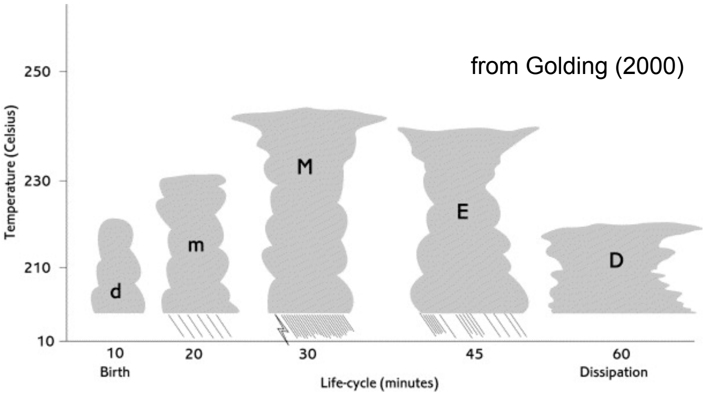
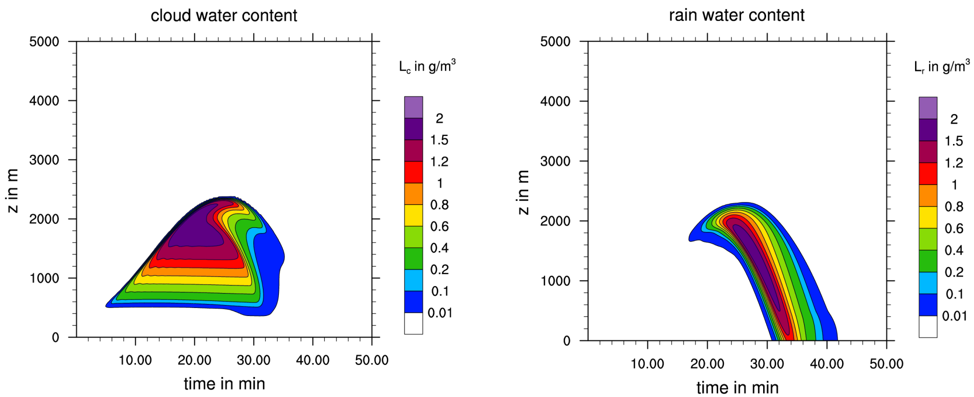
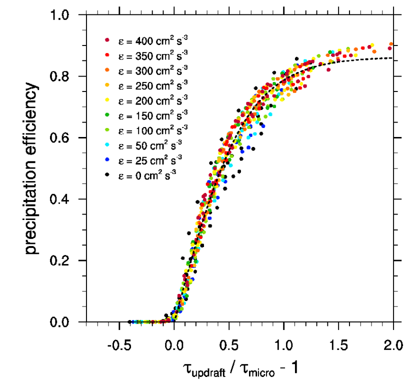
- ➔ **Convective clouds have a pronounced lifecycle**
- ➔ **Usually they need at least 15 min to develop precipitation.**
- ➔ **The precipitation efficiency of warm shallow clouds shows a dependency on cloud lifetime (Seifert and Stevens 2010, JAS).**



A simple kinematic 1D cloud model:





- ➔ **The lack of a representation of the cloud lifecycle, i.e., the lack of memory in current convection schemes makes a physically-based parameterization of convective precipitation very difficult.**

Statistical physics point of view...

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Recently **Wouters and Lucarini (2012, J. Stat. Mech., P03003)** have shown that a systematic coarse-graining (using Ruelle response theory) of two weakly coupled nonlinear dynamical systems with slow variables X and fast variables Y leads to the following parameterized dynamics of X

$$\dot{X}(s) = F_X(X(s)) + M_1 + \sigma(s) + \int_0^\infty \mathrm{d}\tau\, h(s-\tau, X'(t-\tau)).$$

which are the original dynamics of X and three parameterization of the dynamics of Y: a constant drift term, an additive noise term, and a **memory term**. Due to the memory term the system does in general show non-markovian behavior:

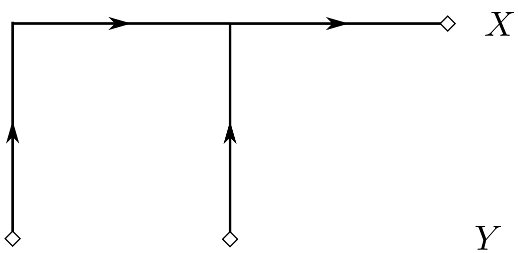

Fig. 2 of WL12: Fluctuation of Y affecting the slow variables X (‚stochastic term‘).

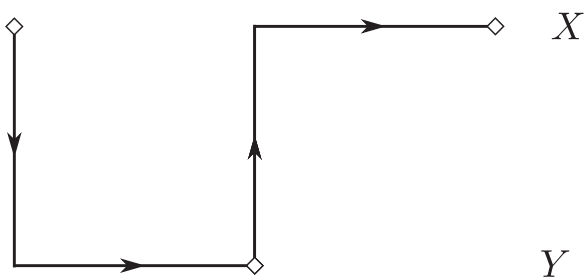

Fig. 3 of WL12: Memory effect describing how X affects itself through the lagged-response of Y.

➔ **Large-scale forcing leads to the formation of clouds at the small scales, but their response back to the large scale is delayed, i.e., the small scales have memory and depend not only on the current large-scale state but also on previous large-scale states.**

PDF-based vs stochastic schemes

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PDF-based subgrid scheme:

- can represent spatial heterogeneity
- can be used to achieve consistency between different parameterizations
- well established in the parameterization community
- prognostic schemes can provide large-scale memory
- scale adaptivity can be included, but is challenging.
- Small scale spatial or temporal correlations cannot easily be included, i.e., lack of small-scale memory.

Stochastic parameterization:

- can represent spatial and temporal variability.
- can maybe be used to achieve consistency between different parameterizations.
- not well established in the parameterization community, but well established in theoretical physics and ensemble forecasting.
- scale adaptivity is, to some extent, intrinsic in the scheme.
- Small scale temporal correlations and memory can be represented.

(A stochastic scheme is actually sampling a much more complicated PDF than the ones assumed in current explicit PDF schemes.)

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Mixed scheme with PDF-based large-scale state and a stochastic scheme sampling the small-scale variability including lifecycle and memory effects.

Summary and conclusions

- High resolution NWP needs a more detailed representation of cloud microphysics.
- This can be achieved be more sophisticated parameterizations which have additional prognostic variables.
- This allows us to choose the appropriate microphysics scheme for a certain scale, but unstructured grids with varying grid-spacing would still be challenging.

- In sub-grid parameterizations, e.g., convection schemes, the microphysics is often treated quite poorly.
- PDF-based schemes are attractive for parameterizations, but lack the small-scale correlations or memory.
- Therefore stochastic schemes with an explicit representation of cloud lifecycles might be an interesting extension of currently available parameterizations.

In large-scale models parameterization are built upon

$$\tau_{process} \ll \Delta t$$

but now we have to deal with

$$\Delta t \approx \tau_{process}$$

and this maybe even for spatially sub-grid processes with

$$\ell_{process} \ll \Delta x$$

i.e., even sub-grid processes can have memory.