



# **Uncertainty and complexity in cloud microphysics**

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## Overview

- Introduction
- Some examples of microphysical sensitivities and model errors
- Uncertainty of particle properties
- Uncertainty of particle size distribution assumptions
- Aerosols as a source of uncertainty
- Nonlinearity, complexity and buffered systems
- Conclusions and Outlook





## Uncertainty in cloud microphysics?

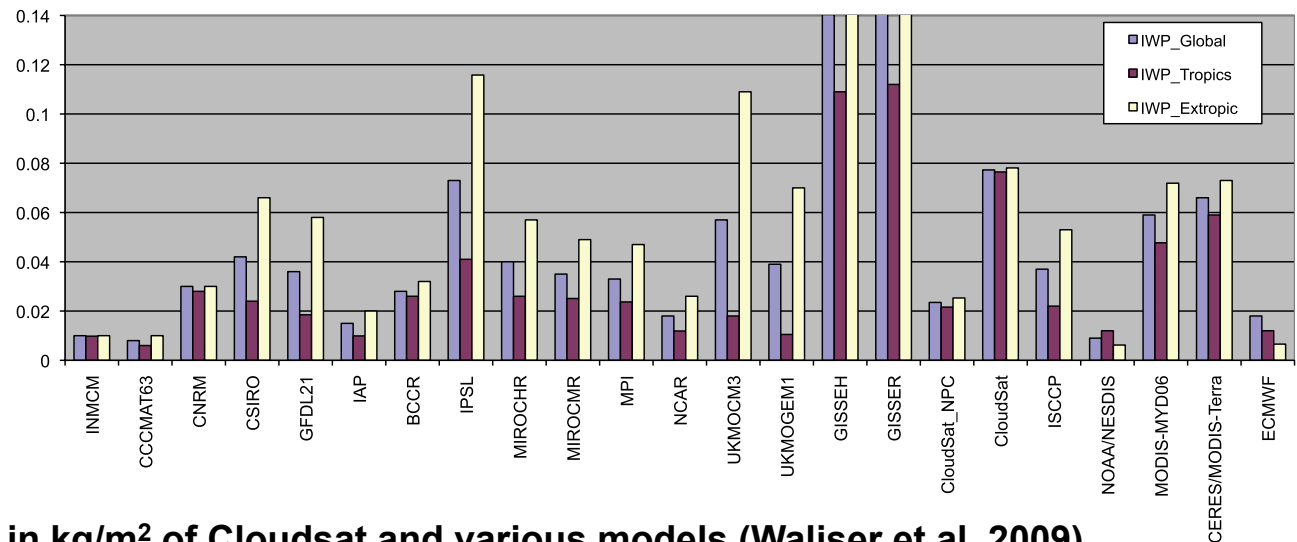
Cloud microphysics is often mentioned as a primary source of model error and uncertainty. Reasons are:

- There are still **gaps in the empirical and theoretical description** of microphysical processes like ice nucleation, aggregation and splintering of ice particles, collision rates in turbulent flows, breakup of drops etc.
- The **natural variability of clouds**, cloud particles and aerosol is overwhelmingly large, e.g., the different particle habits (including degrees of riming), the time-spatial structures in clouds, as well as the particle size distributions etc.
- The **strong nonlinearity and high complexity** of cloud processes hinders any rigorous analytic and theoretical approaches.
- Although measurements have been improved over the last decades, e.g. Cloudsat, there is still a **lack of detailed observations**.



## Ice water content - a major uncertainty

- Klein and Jakob (1999) showed the importance of microphysical assumptions for the upper level cloud ice content in frontal clouds in the ECMWF model.
- A decade later, Waliser et al. (2009), show that there are still very large differences between climate models in ice water content (IWC).
- Although Cloudsat provides valuable information, the problems are still unsolved.

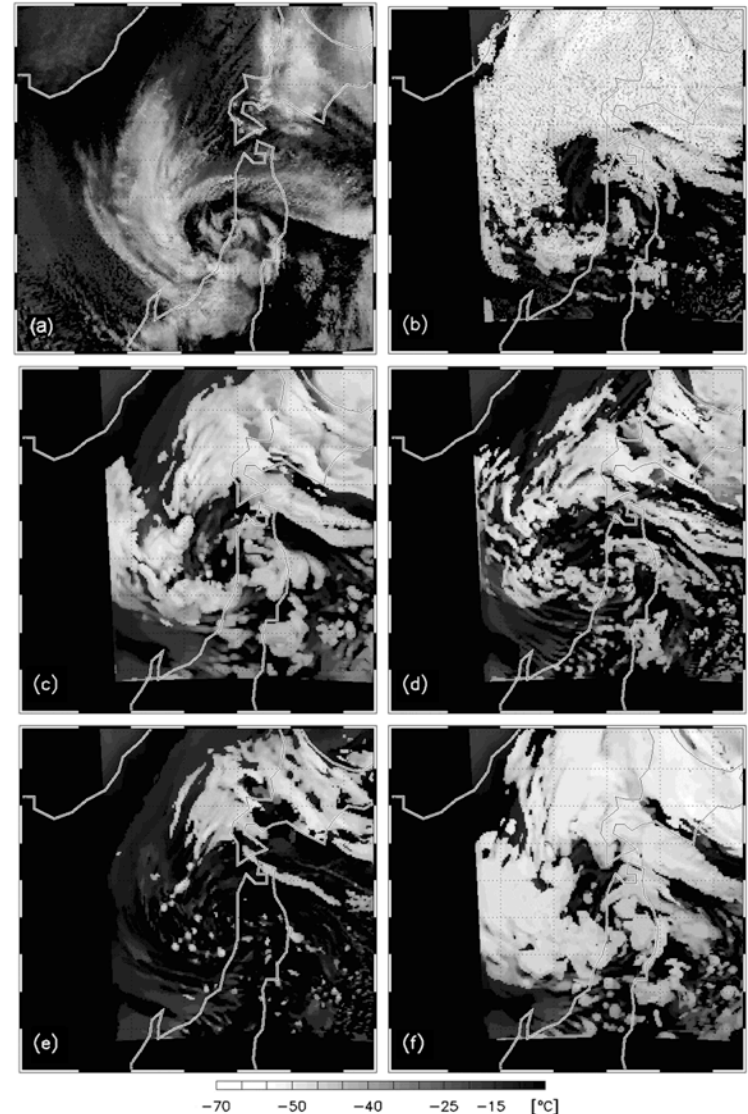


Mean ice water path in kg/m<sup>2</sup> of Cloudsat and various models (Waliser et al. 2009)

## Different microphysics schemes can give very different results

- For example, Wu and Petty (2011)  
„Intercomparison of Bulk Microphysics Schemes in Model Simulations of Polar Lows“, Mon. Wea. Rev.

Cloud top temperature in K, (a) observations, and (b-f) different microphysics schemes in WRF (Wu and Petty 2011, MWR)

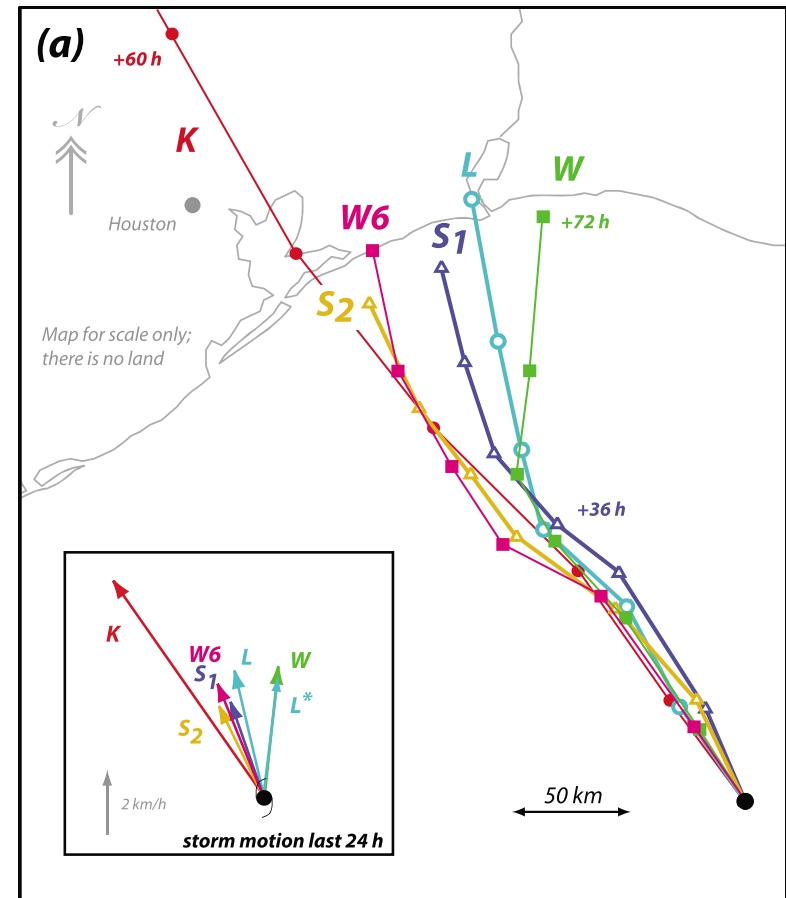


-70 -50 -40 -25 -15 [°C]

# Different microphysics schemes can give very different results

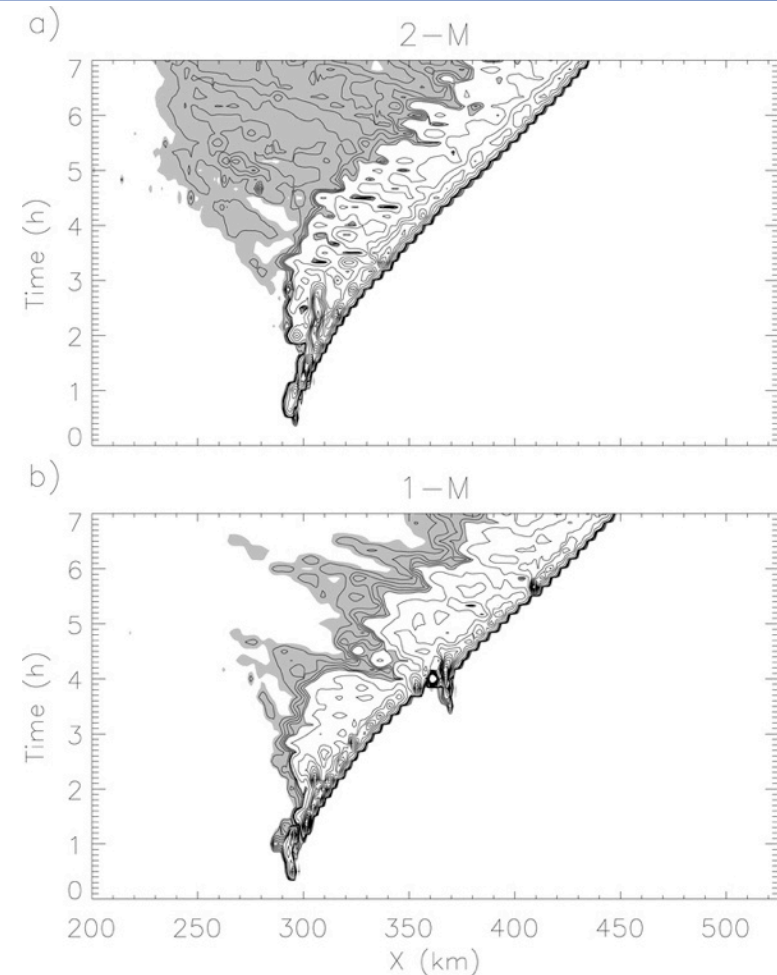
→ Another example, Fovell et al. (2010) found a pronounced effect of ice microphysical assumptions on hurricane tracks.

Twelve hourly cyclone positions over 72 h for different microphysics schemes in WRF (Fovell et al. 2010)



## And better microphysics schemes can sometimes lead to better results

- Better representation of stratiform regions of convective systems with two-moment schemes (Morrison et al. 2009, Baldauf et al. 2011)
- Many more studies show a positive impact of advanced schemes
- ... but there are also many studies showing no or only marginal improvement.



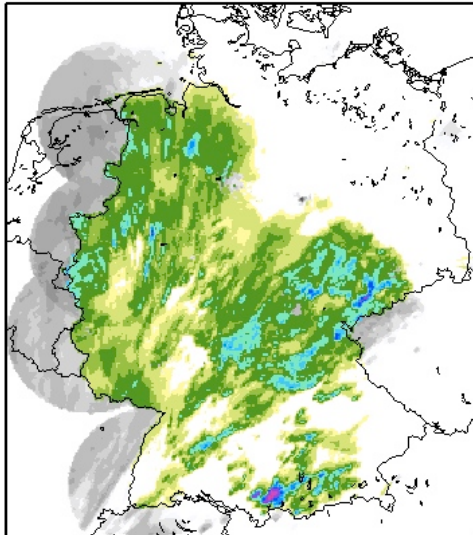
Hovmöller plot of the surface rainfall rate for the (a) two-moment and (b) one-moment simulations. To highlight the stratiform rain precipitation region, moderate precipitation rates between 0.5 and 5 mm h<sup>-1</sup> are shaded gray. (Morrison et al. 2009, MWR)

# Better microphysics schemes can sometimes give better results ...

→ Result of sensitivity studies with DWD's COSMO-DE (Baldauf et al. 2011)

observations

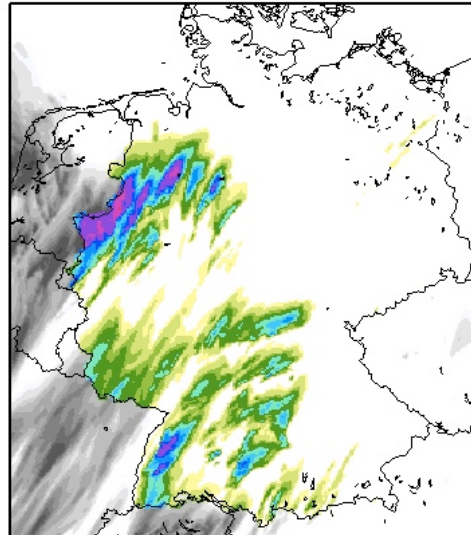
Precipitation 20.07.2007 06 UTC + 12h (RY)



Mean: 3.4448 Min: 0.0 Max: 89.427 Var: 19.443

one-moment micro

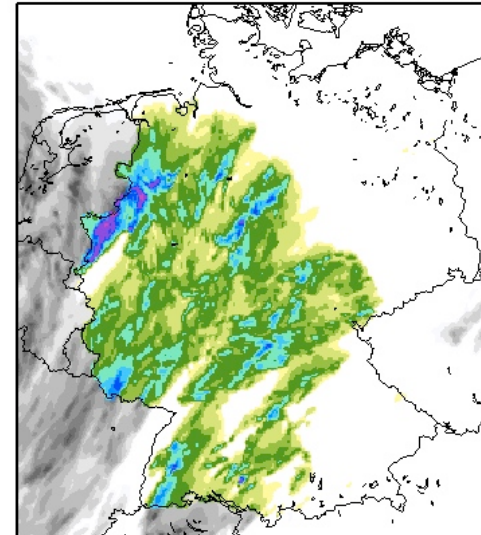
Precipitation 20.07.2007 06 UTC + 12h (LMK)



Mean: 2.6705 Min: 0.0 Max: 89.649 Var: 46.311

two-moment micro

Precipitation 20.07.2007 06 UTC + 12h (LMK)



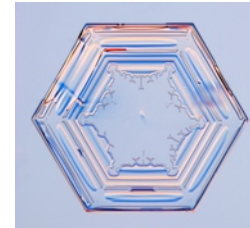
Mean: 3.4792 Min: 0.0 Max: 67.406 Var: 28.647

12-h accumulated precipitation for a 00 UTC forecast using the COSMO model with 2.8 km grid spacing. Simulation of squall line event of 20 July 2007.



# Uncertainty of particle properties

- Ice particles have many different shapes or habits.
- Preferred growth regimes depend on temperature and supersaturation.
- But due to sedimentation and advection there is no unique diagnostic relation between state variables and particle habits.
- Only very few attempts have been made for prognostic habit prediction in cloud-resolving models, usually a few habits are prescribed.



Hexagonal plate

Pictures from  
SnowCrystals.com



Needles



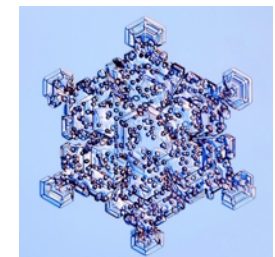
Bullet rosettes



Stellar dendrites



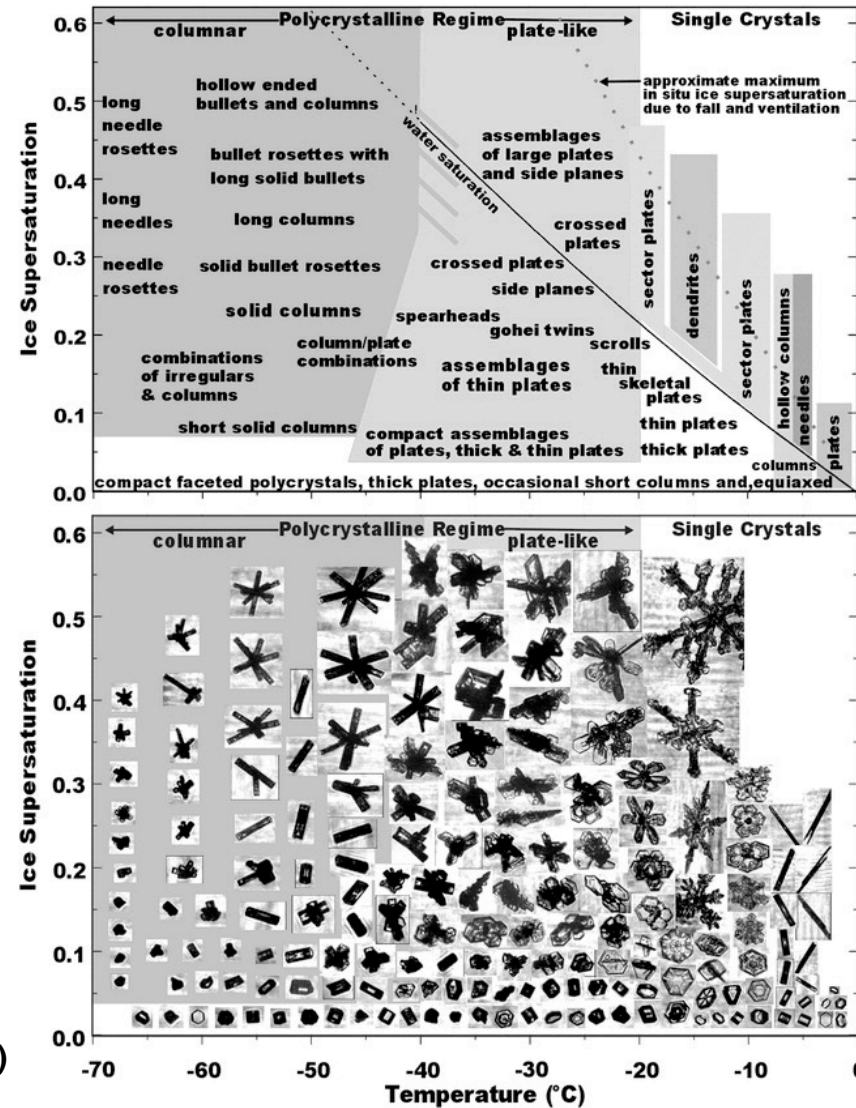
Rimed crystals



# Uncertainty of particle properties

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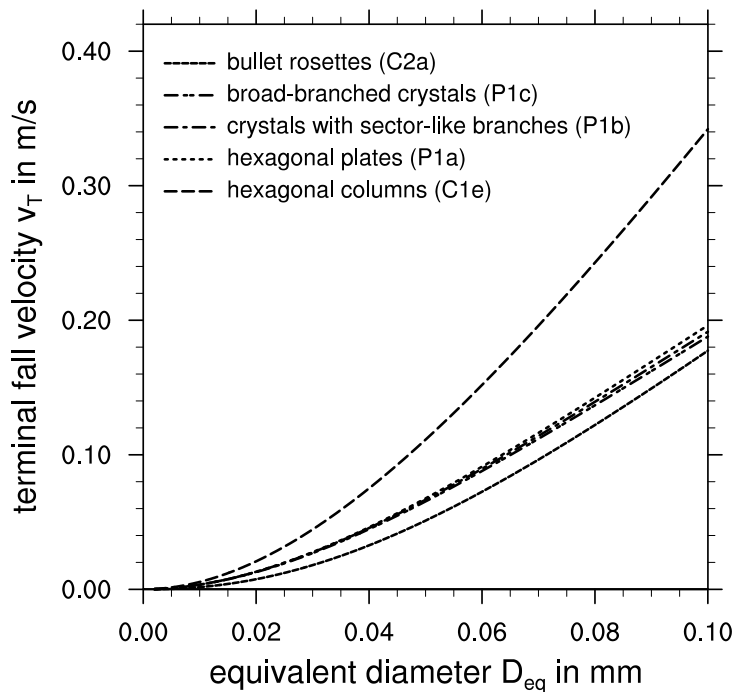
Habit diagram of Bailey and Hallet (2009)



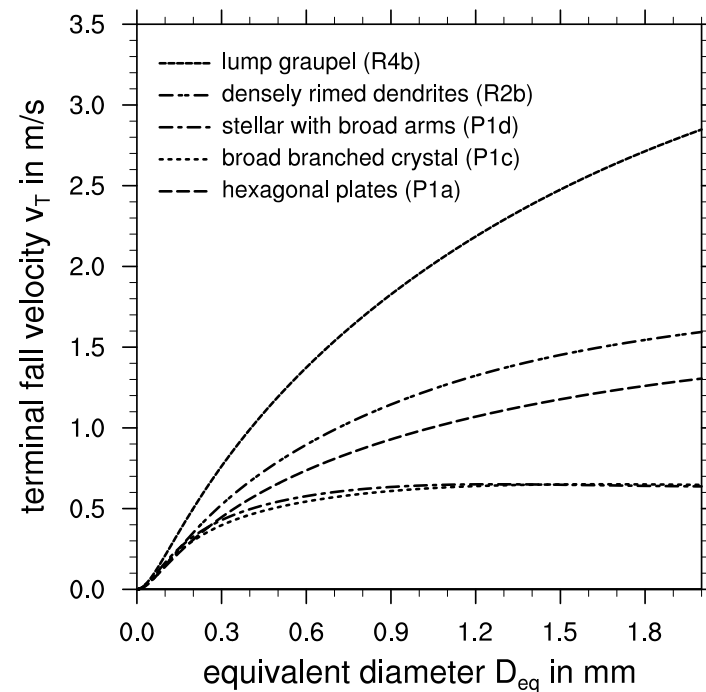
## Uncertainty of particle properties - fall speeds

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

small ice crystals



precipitation-sized crystals





## Uncertainty of size distribution assumptions

- What we usually call particle size distribution is more precisely the spectral number density function, and following Gillespie (1972,1975) we may apply the following two models:

**quasi stochastic:**  $N(m,t)$  is the number of particles of mass  $m$  at time  $t$ .

**pure stochastic:**  $P(n,m,t)$  is the probability that exactly  $n$  drops have mass  $m$  at time  $t$ , and  $N(m,t)$  is the average number of particles of mass  $m$  at time  $t$ .

- Usually we follow the quasi-stochastic interpretation and neglect stochastic fluctuations of  $N(m,t)$ . Gillespie (1975) gives an estimate for the amplitude of such fluctuations.

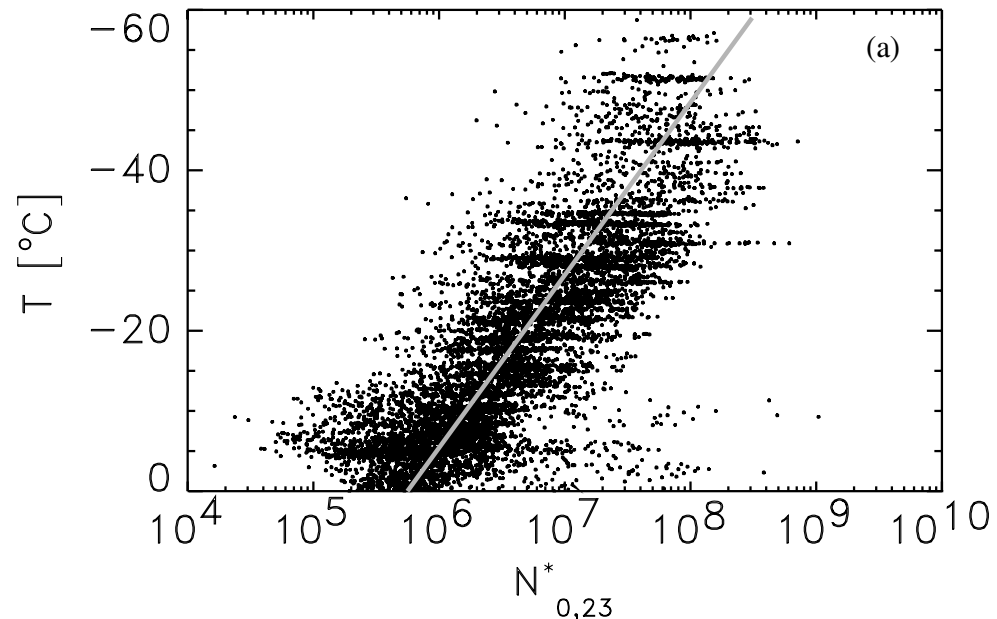


## Uncertainty of size distribution assumptions

- In-situ measurements of snow particle size distribution in frontal clouds show a strong variation of the intercept parameter in the exponential distribution:

$$N(D) = N_0 e^{-\lambda D}$$

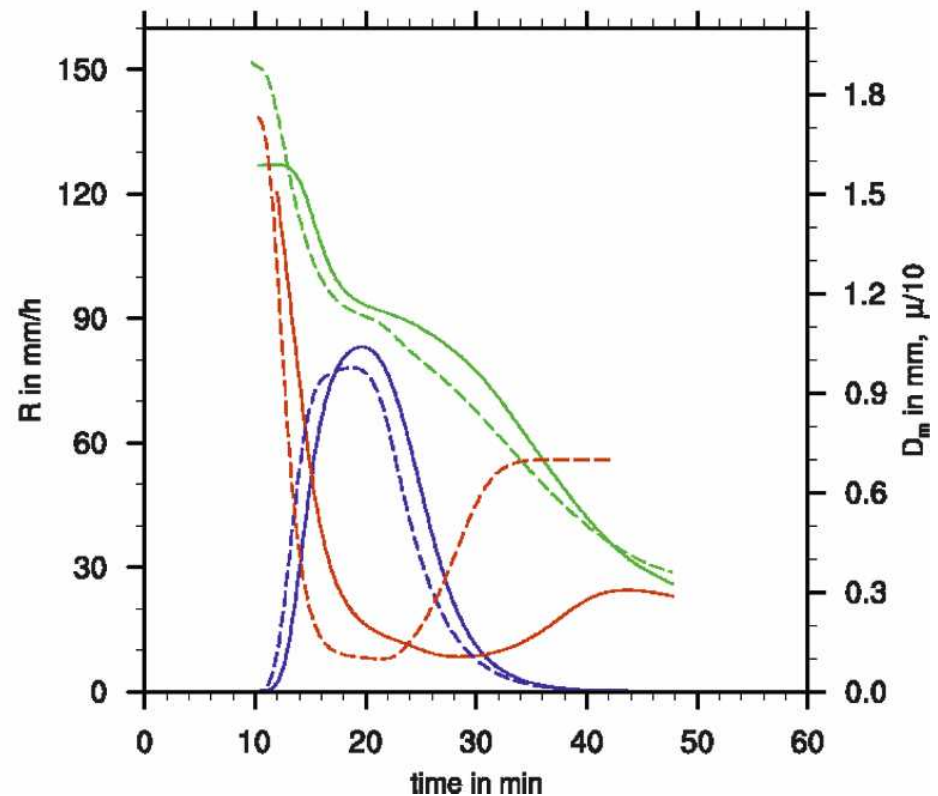
- This leads to an uncertainty, or model error, in the sedimentation velocity of snow and all microphysical process rates like depositional growth, aggregation etc.
- This variability has many sources, e.g., dynamical forcing, different particle habits, stochastic aggregation etc.
- One-moment approach insufficient?



**$N_0$  calculated from measured snow size distributions in frontal clouds (Field et al. 2005). Scatter can be further reduce by applying double-moment scaling.**

## Uncertainty of size distribution assumptions

- Time evolution of raindrop size distribution during a convective event (Seifert 2008)
- Gamma distribution parameters:
 
$$N(D) = N_0 D^\mu e^{-\lambda D}$$
- Observations show similar time evolution, e.g. Zhang et al (2001).
- Important for evaporation of rain below cloud base.
- One-moment schemes are insufficient to represent such details (Morrison et al. 2009)



Time evolution of the rain rate  $R$  (blue), the shape parameter  $\mu$  (red), and the mean vol. diameter (green), bin (solid) and two-moment bulk (dashed) scheme.



## Aerosols as a source of uncertainty

- Aerosol indirect effects are a major scientific challenge in climate research
- Sensitivities to aerosol assumption have received less attention in NWP, maybe because the radiative indirect effects are less important on short timescales, and aerosol-cloud-precipitation effects are difficult to quantify.
- Recent studies suggest that aerosol indirect effects are maybe smaller than previously thought:

**Posselt and Lohmann (2009)** point out that climate models with diagnostic precipitation overestimate the importance of autoconversion compared to accretion. This affects the CCN sensitivity, because accretion has a weaker dependency on cloud droplet number.

**Grabowski and Morrison (2011)** show that the CCN sensitivity of radiative-convective equilibrium simulations is reduced when using a more sophisticated two-moment scheme.

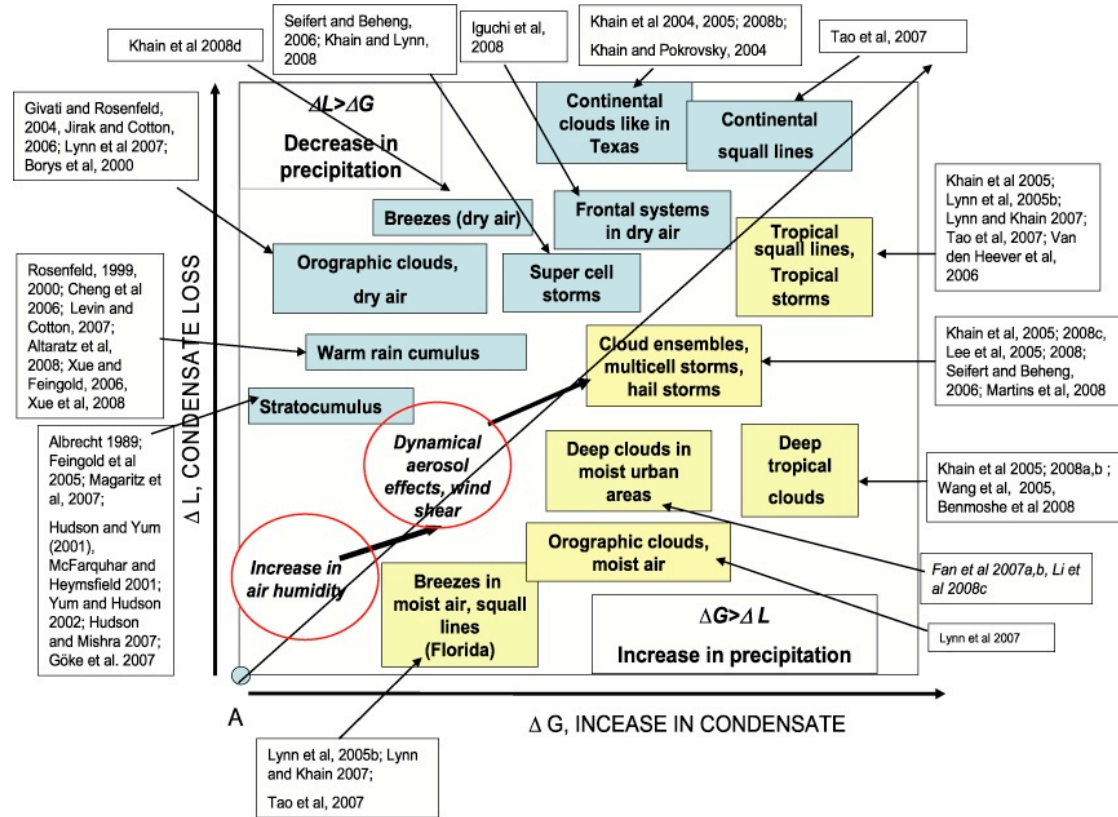
**Stevens and Feingold (2009)** emphasize the importance of negative dynamical and microphysical feedbacks which buffer the system and lead to much weaker sensitivities.





# Aerosol-cloud-precipitation effects

→ Different cloud regimes can show very different sensitivities to cloud condensation nuclei (CCN), e.g. Khain (2009)



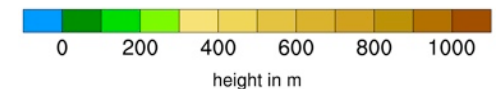
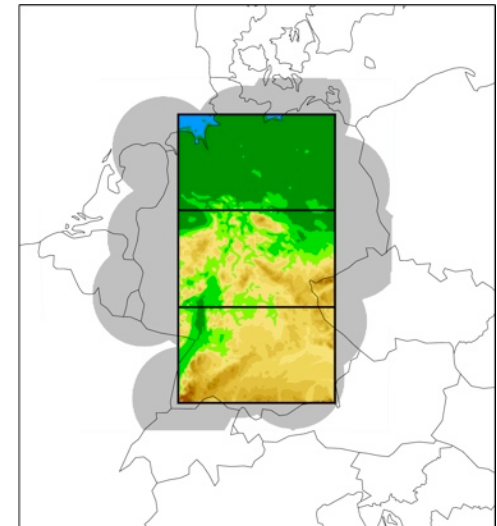
Classification scheme of aerosol effects on precipitation of Khain (2009).





## Re-forecasting experiments with COSMO-DE

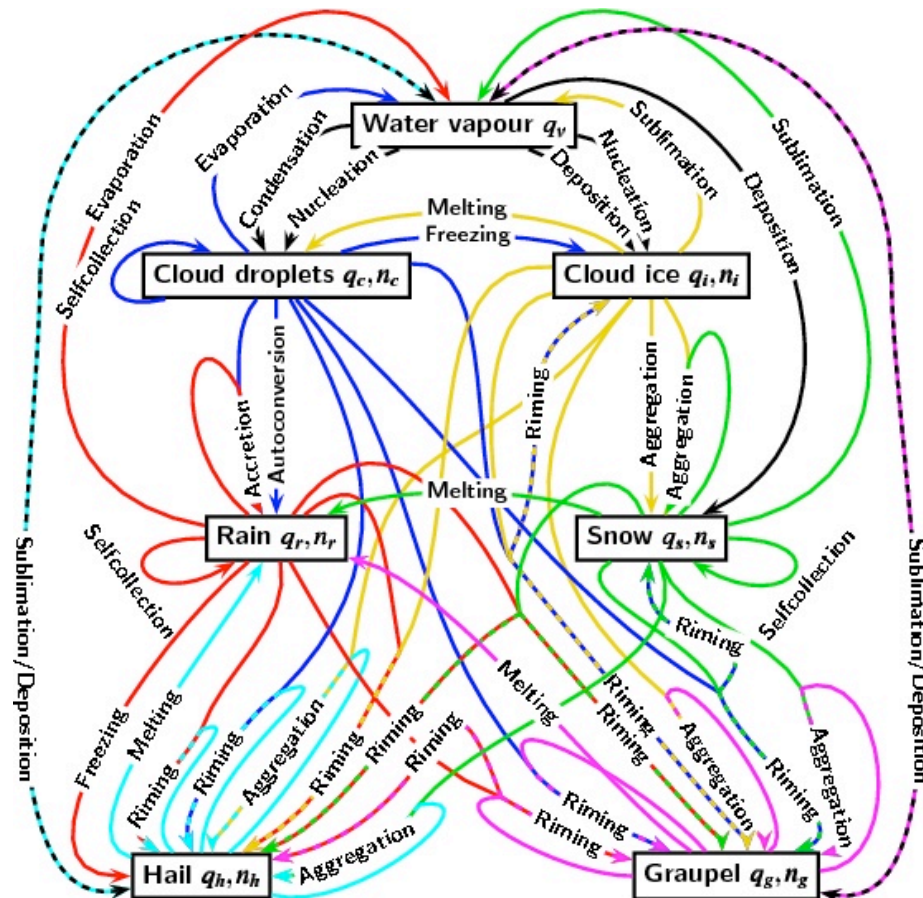
- Use the operational convective-scale NWP model COSMO-DE as a framework to investigate aerosol-cloud-precip effects
- We replace the simple one-moment microphysics with the two-moment scheme of SB2006 including an explicit cloud-radiation coupling (Zubler et al. 2011)
- But no data assimilation, all simulations start from the same operational COSMO-DE analysis. This will lead to a model spin-up (or spin-down).
- Instead of the operational 21 h forecasts, we have performed 48 h simulations to have a better control of spin-up and trends in our evaluation.
- Simulate JJA of 2008, 2009 and 2010 to assemble a large enough dataset covering many cloud regimes for statistical evaluation.
- **Main research question: Many idealized simulations show quite strong CCN sensitivities. Will this convective-scale NWP model show a more robust behavior?**



*COSMO-DE model domain, and the evaluation region with the orography shown. Grey region show the coverage of the German radar network.*

# The Seifert and Beheng two-moment scheme:

Extended version by Blahak, Noppel, Beheng and Seifert



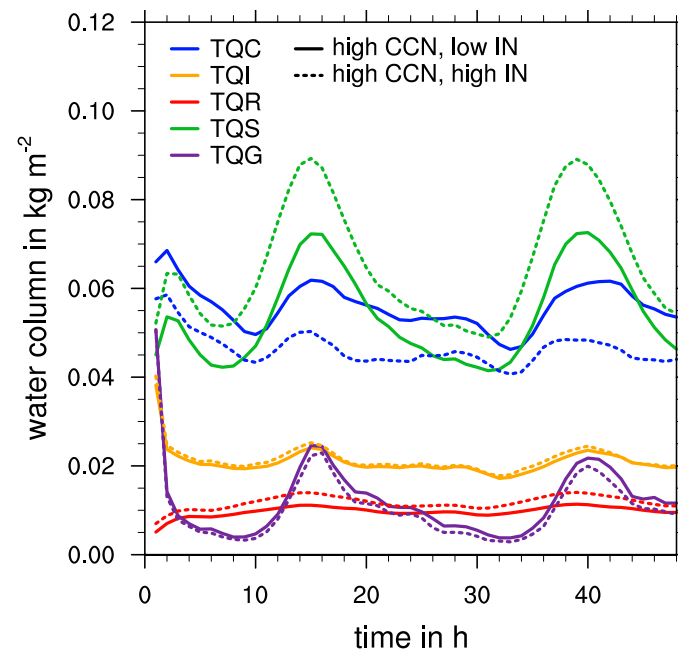
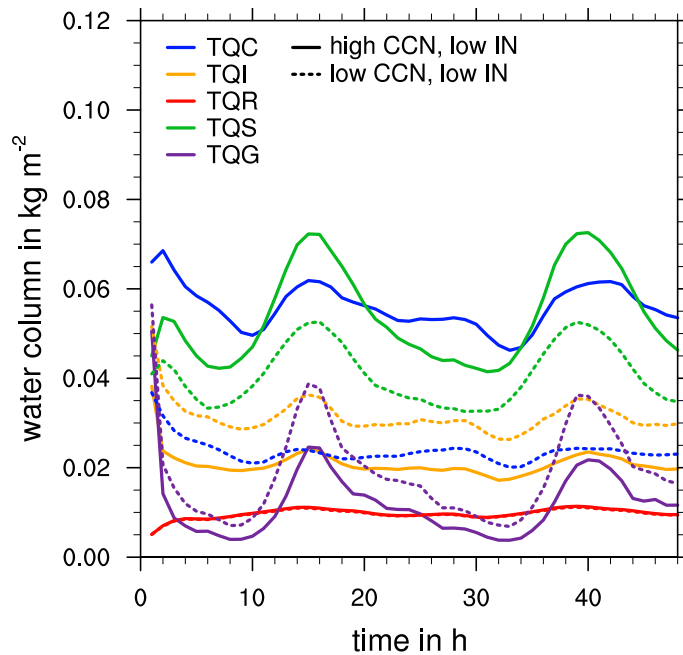
Number and mass concentrations of 6 different species

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

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).

➔ **Factor 10 modifications of CCN/IN assumptions as sensitivity studies.**

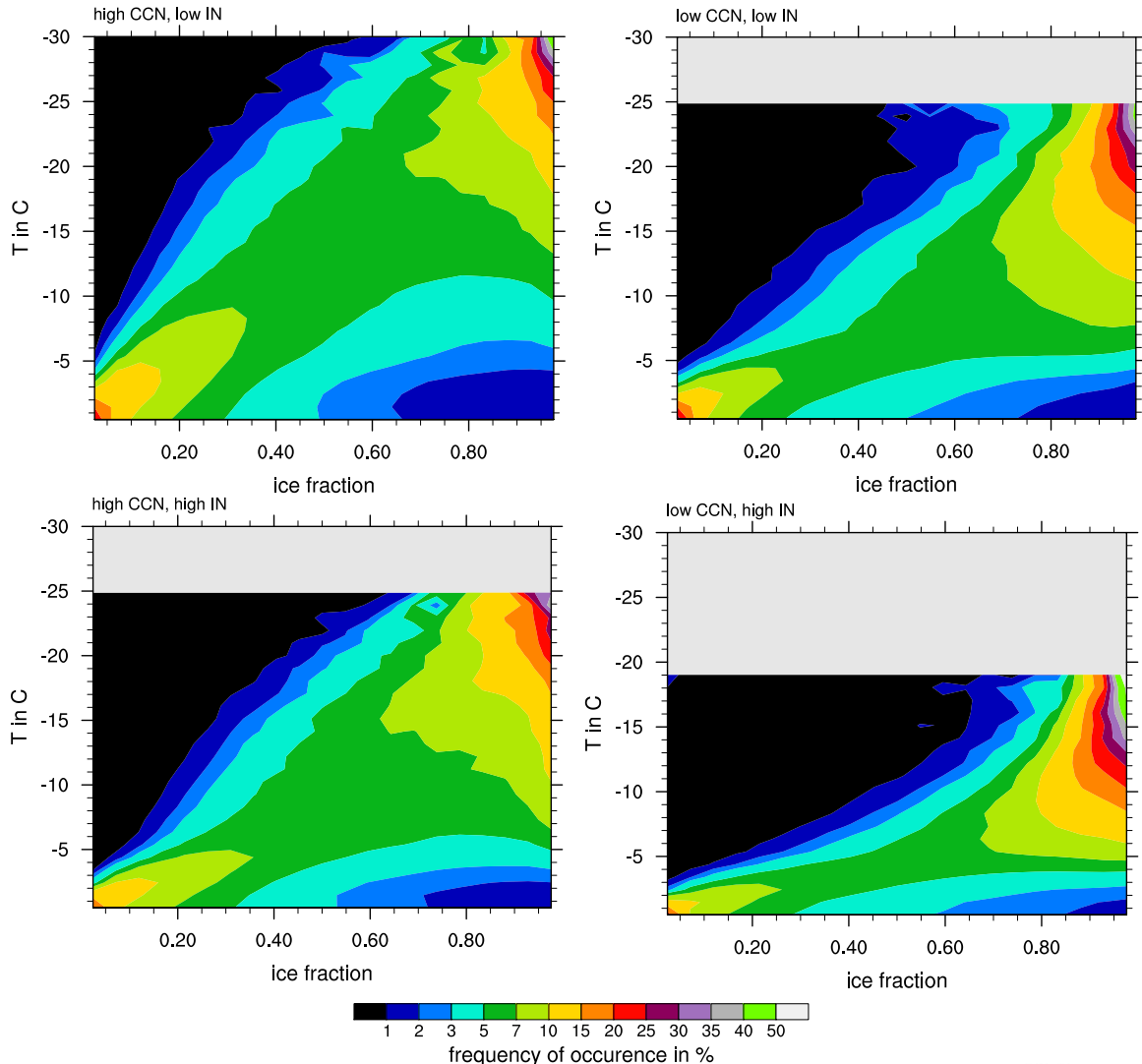
## Sensitivity of average cloud properties to CCN / IN



- ➔ higher CCN concentration leads to an increase in cloud water and snow, but cloud ice decreases.
- ➔ increasing the IN concentration leads to more snow, and reduced cloud water, i.e. the cloud glaciates more rapidly.

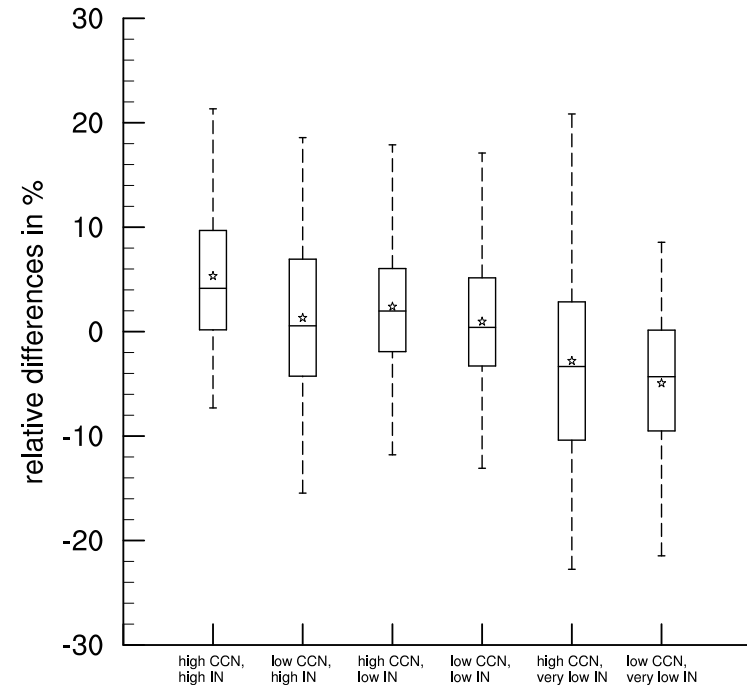
# Cloud glaciation for different CCN / IN

- more IN lead to a more efficient glaciation
- less CCN lead to a more efficient glaciation, because large drizzle drops or rain have a higher freezing probability



## Variability of 12-h accumulated precipitation

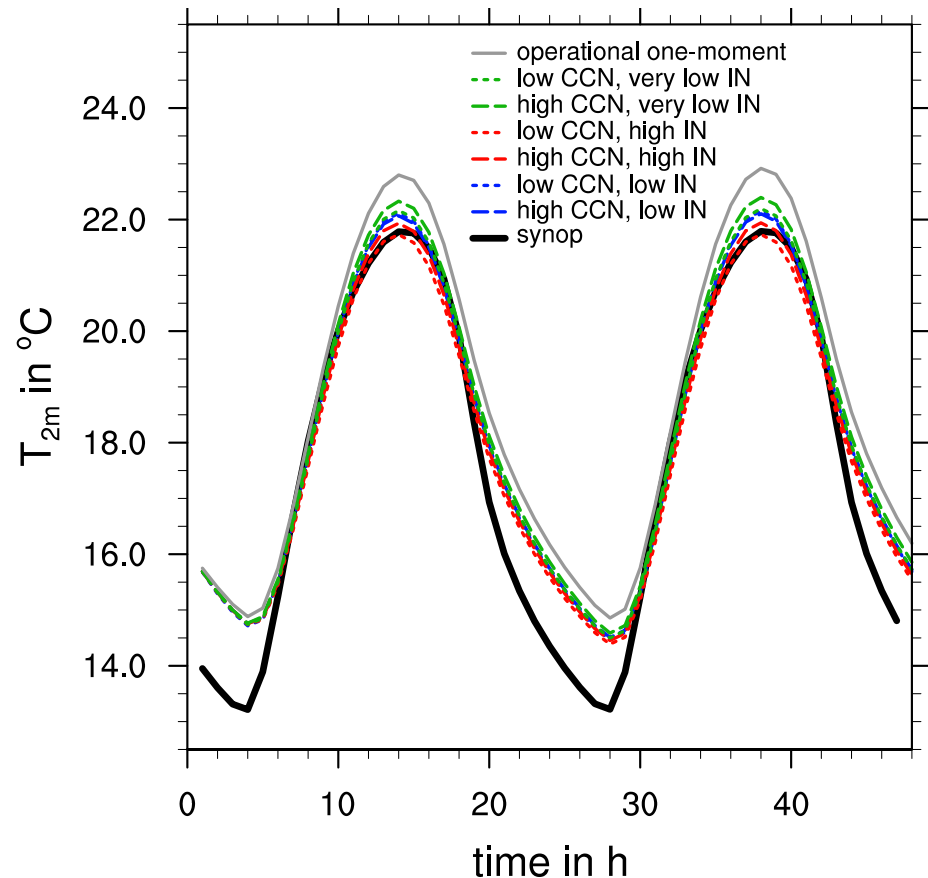
- In most cases the sensitivity of area-averaged precipitation to CCN / IN perturbations is smaller than 10 %.
- The mean and the median are below 5 %.
- Sensitivities of 20 % in both directions are possible.
- higher IN (and CCN) concentrations lead to more precipitation, i.e. dynamics dominates of microphysics effects.



**Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008-2010. Shown are changes relative to mean of all experiments and the precipitation data has been averaged over either one of the three sub-domains. The bottom and top of the boxes are the lower and upper quartiles, the line near the middle of the boxes is the median, whiskers are the 5th and 95th percentiles and the stars represent the mean value.**

## Aerosol indirect effect on 2m-temperature

- CCN/IN assumption lead to about 0.5 K difference in mean maximum temperature. Much larger for individual cases!
- Preliminary result, because cloud structures and radiative fluxes need to be carefully validated.



# Nonlinearity, complexity and buffered systems

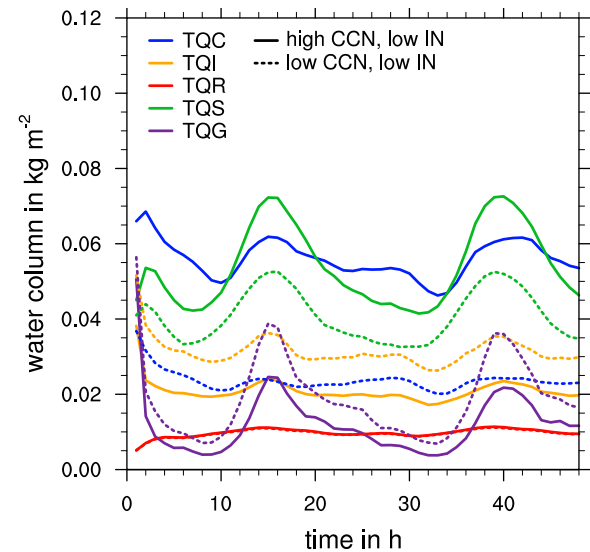
→ Clouds are highly nonlinear, complex multiscale phenomena. Thus strong negative feedbacks can lead to a buffered behaviour of the system.

## 1. Nonlinearity:

$$AU \sim L_c^4 / N_c^2$$

Buffered response to polluted aerosol conditions:

- higher CCN
- higher  $N_c$
- $L_c$  increases
- precipitation decrease much weaker than expected from  $N_c^2$



# Nonlinearity, complexity and buffered systems

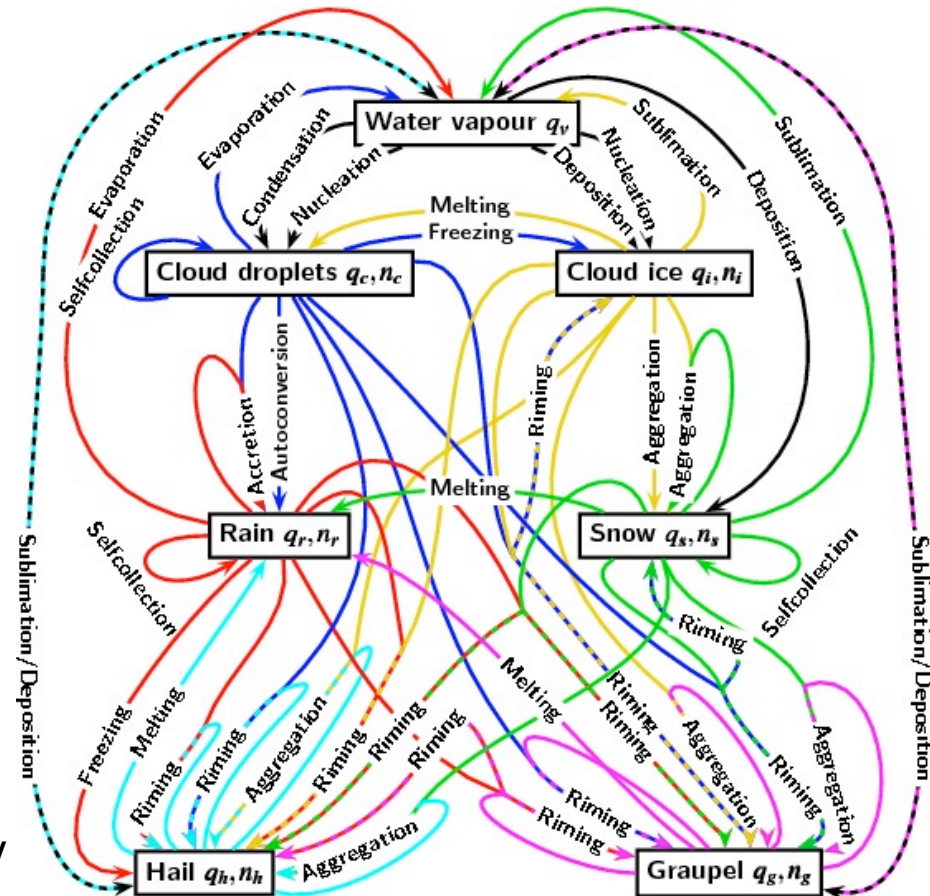
## 2. Complexity

Multiple precipitation pathways do also lead to a buffered system.

Buffered response to polluted aerosol conditions:

- higher CCN
- higher  $N_c$
- autoconversion decreases
- more ice particles
- more precipitation from snow, graupel and hail

Potential model error: Lack of complexity leads to spurious sensitivities





# Nonlinearity, complexity and buffered systems

## 2. Multiscale response

Multiscale phenomena and cloud dynamics do also provide strong negative feedbacks.

Buffered response to polluted aerosol conditions:

- higher CCN
- higher  $N_c$
- autoconversion decreases
- more ice, stronger latent heat release
- increase updraft velocity
- increase in precipitation

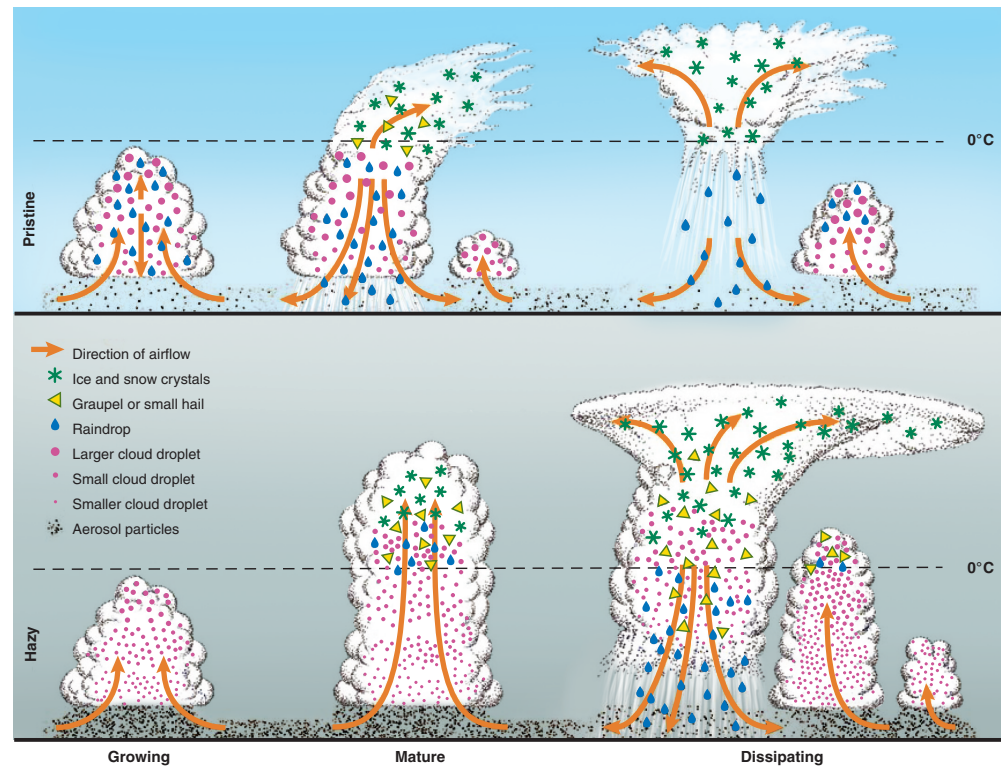


Figure from Rosenfeld et al. (2008). See also Seifert and Beheng (2006) for a numerical simulation of this aerosol-dynamics feedback.



## Conclusions and Outlook

- Uncertainties, approximations and even model errors are numerous in parameterizations of cloud microphysics. Examples are
  1. Particle habits
  2. Particle size distributions
  3. Aerosol effects on cloud microphysics
- More advanced (two-moment) schemes may improve some aspects and help to explain more variability, but large uncertainties will remain.
- Strong negative feedbacks make the system very robust (or buffered), which can, on one hand, help to make useful forecasts even if some parts of the model have significant errors. On the other hand, the numerous negative feedbacks lead to compensating errors and make it very cumbersome to attribute errors to individual processes.





## Conclusions and Outlook

→ Some ideas for stochastic parameterization approaches:

- A) **Particles habits:** A stochastic Markov jump model which follows the thermodynamics habit diagram, but can mimic effects of advection and sedimentation by delaying the transition between habits.
- B) **Particle size distribution:** Sampling the PSD sounds attractive due to its probabilistic interpretation, but is maybe only appropriate on LES scales.
- C) **Aerosol effects:** The time-spatial variability of the aerosol distribution could be represented by a very simple aerosol model, or alternatively a cellular automaton, that might have little deterministic forecast skill itself, but is able to represent the natural variability in a statistical sense.

