Uncertainty and complexity in cloud microphysics

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1 Introduction

The parameterization of cloud microphysical processes is essential for numerical weather prediction (NWP) and climate models. Over the last decades much progress has been made in the understanding and parameterization of cloud microphysical processes. Nevertheless, large uncertainties remain even today. The reasons for the uncertainties are manifold, but the main problems are:

- There are still gaps in the empirical and theoretical description of cloud 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.

The literature on the subject is vast and many topics are still controversial. Here only some of the more relevant and recent results are reviewed.

Klein and Jakob (1999) showed that high clouds in frontal systems of ECMWF forecasts are more sensitive to the parameterization of ice microphysical processes than to other processes and parameters. Especially the gravitational settling controls the amount of high clouds and their ice water content. A decade later Waliser et al. (2009) highlight that different climate and NWP models show a large range of simulated ice water paths which shows that the uncertainties regarding ice clouds are still unresolved. This problem is also a major motivation for the Cloudsat mission (Stephens et al., 2002).

Over the last decades many microphysical schemes for use in NWP and climate models have been developed. Many such studies have shown that more sophisticated microphysics parameterizations, e.g. including an explicit ice phase and several particle species, can reduce model errors and outperform simpler parameterizations (McCumber et al., 1991; Reisner et al., 1998; Liu and Moncrieff, 2007), but other studies showed examples where increased complexity did not necessarily lead to improved forecast skill (Colle and Mass, 2000; Grubisic et al., 2005). Nevertheless many operational NWP center have introduced schemes with several prognostic variables, e.g. for an explicit prognostic treatment of cloud water, rain, cloud ice and snow.

Recently Wu and Petty (2010) evaluated several bulk microphysical parameterizations for the simulation of polar lows and found large differences in the resulting cloud-top temperatures and the predicted hydrometeor types. Nevertheless, independent of the scheme used all the model experiments successfully reproduced the main precipitation patterns. Another interesting example that assumptions and model errors in cloud microphysics can indeed affect large-scale systems is the sensitivity of hurricane tracks to upper level cloud ice as shown by Fovell et al. (2010).

Deep convective clouds exhibit the richest and most complicated microphysical behavior, including the formation of graupel and hail. The explicit simulation of severe deep convection has therefore been a special target of microphysical modeling. Maybe the most advanced treatment of microphysical processes is by spectral bin models which explicitly resolve the particle size distributions (Khain et al., 2004; Lynn et al., 2005). Such a detailed treatment of microphysics may help to reduce model errors, but is computationally very demanding as it involves several hundred prognostic variables. As an alternative two- and three-moment bulk microphysics schemes have been developed (Cotton et al., 1986; Murakami, 1990; Ferrier, 1994; Morrison et al., 2005; Milbrandt and Yau, 2005; Seifert and Beheng, 2006). Most of these studies argue that their newly developed and more sophisticated schemes lead to forecast improvements, but most often this is only shown for individual case studies. Morrison et al. (2009) show that a two-moment scheme can give, in general, superior results for the representation of stratiform regions of convective systems. They argue that the primary reason for this difference are reduced rain evaporation rates in the two-moment compared to one-moment scheme. Similarly, Baldauf et al. (2011) show an example that two-moment vs one-moment microphysics can make a pronounced difference for the simulation of organized convection systems in a convective-scale NWP model. For a simpler standard one-moment scheme Gilmore et al. (2004) presented a systematic investigation of the sensitivity of isolated convective cells to microphysics assumptions. They found that precipitation amounts from simulated multicell and supercell storms vary by a factor of 3 to 4 due to changes in intercept parameters defining the hail/graupel distribution. In a similar study, Van Weverberg et al. (2011) emphasized how the assumptions about the particle size distribution of graupel and hail can significantly affect the precipitation amounts from simulated supercells. They conclude that separate graupel and hail categories may be necessary for the simulation of severe convective storms. The use of the simpler one-moment schemes can also lead to larger model errors in observed quantitities like radar reflectivity (Gilmore et al., 2004; Dowell et al., 2011). To reduce such problems the use of two-moment schemes might be attractive in convective-scale or storm-scale data assimilation (Xue et al., 2010; Dowell et al., 2011).

In the following sections an attempt will be made for a more systematic evaluation of uncertainty and model errors in cloud microphysics.

2 Uncertainty of particle properties

A source of uncertainty is the large variety of possible shapes or habits of ice particles in clouds. For example, the Magono and Lee snowflake classification distinguishes between 80 different ice particle habits (Pruppacher and Klett, 1997). There has been some controversy in recent years whether such classifications are in fact very helpful given that the structure of observed particles is often 'irregular', but, for example, Stoelinga et al. (2007) argue that a classification is, when properly done, indeed possible and useful.

The assumptions about particle habits enter the parameterization schemes through empirical mass-size and mass-area relations (Locatelli and Hobbs, 1974; Heymsfield and Kajikawa, 1987; Mitchell, 1996). These relations are needed to calculate the terminal fall velocity of the particles, e.g. using aerodynamic scaling laws, and either directly or through the fall velocity those assumptions affect all microphysical process rates like depositional growth, aggregation etc.

In principle, the particle habit depends on the growth regime and for pure depositional growth the habit diagram is relatively well known and depends on temperature and the amount of available water vapor (Pruppacher and Klett, 1997, p. 41-44). There have in fact been some first attempts for habit prediction

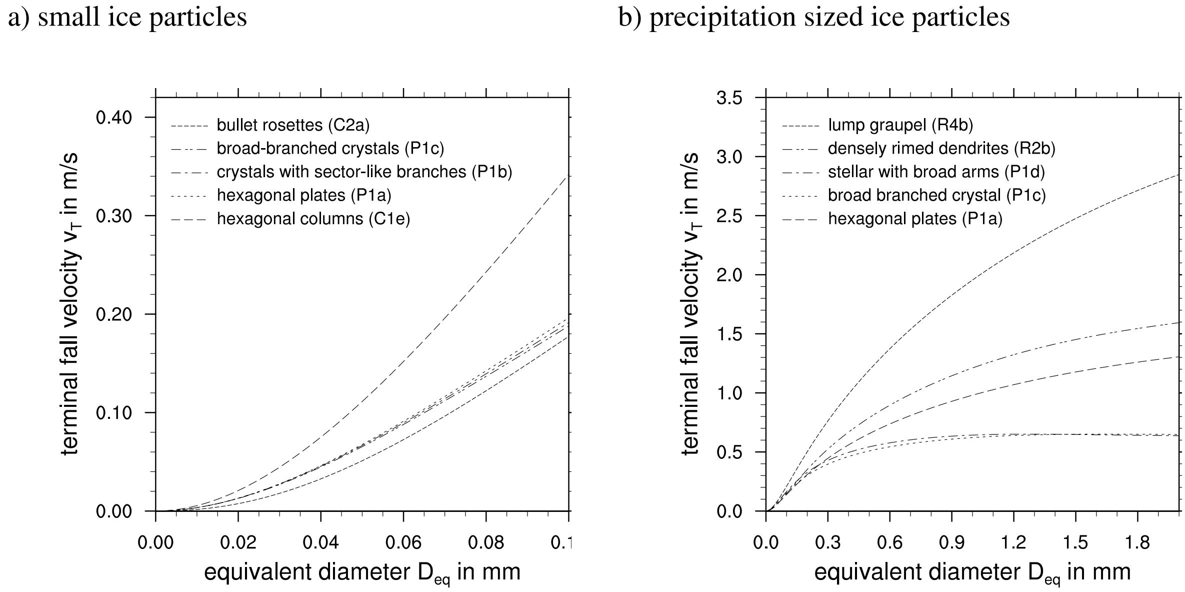

Figure 1: Terminal fall velocity of ice particles as a function of equivalent (melted) diameter for small particles (left) and larger precipitation sized particles (right) of different habit. Mass-size and area-size relation have been taken from Mitchell (1996). The terminal fall speeds have been calculated following Khvorostyanov and Curry (2005).

models in either bulk (Woods et al., 2007) or spectral microphysics schemes (Hashino and Tripoli, 2007), but usually a few habits are chosen for 'cloud ice', snow and graupel.

A wrong choice of particle habit can lead to errors in the fall speeds (see Fig. 1), particle sizes and microphysical growth rates of a factor 2 or more which then affects the radiative properties, precipitation formation and the evolution of the cloud as a whole. For the radiative properties the choices for the small crystals are of greatest importance while for precipitation formation the largest uncertainty is maybe between unrimed snow, rimed snow and graupel. To overcome the problem of the specification of certain particle shapes and the conversion between those categories, e.g. for snow, rimed snow and graupel, some studies suggest to use a prognostic variable for the degree of riming instead (Morrison and Grabowski, 2010; Lin and Colle, 2011).

3 Uncertainty of size distribution assumptions

All microphysical parameterizations in operational NWP and climate models are bulk schemes, i.e. the shape of the particle size distributions is prescribed and only a few moments of the distributions are predicted. In most schemes only a single moment, the mass (content or mixing ratio), is chosen as prognostic variable and the particle size distribution is often assumed to be a simple inverse exponential (Marshall and Palmer, 1948)

$$f(D) = N_0 e^{-\lambda D} \tag{1}$$

Here $f(D)$ is the number density distribution in m^{-4}, D is the drop diameter in m, N_0 the intercept parameter with units m^{-4}, λ the slope in m^{-1}. In most models the slope λ is directly related to the prognostic variable, e.g. the mass mixing ratio, and N_0 is assumed to be constant. For stratiform precipitation the assumption of a constant N_0 agrees, in many cases, reasonably well with observations, but sometimes N_0 changes by an order of magnitude within a rainfall event. Such sudden changes are called N_0-jumps

(Waldvogel, 1974) and may be attributed to convective activity (embedded convection) or changes in microphysical processes aloft. Observations, e.g. Joss and Gori (1978), and detailed modeling (Seifert, 2005) also show that especially gravitational sorting can lead to 'instantaeneous' spectra ($\sim$1 min time resolution) which are very much different from size distributions obtained from averaging over larger times intervals. Such 'instantaeneous' spectra tend to be more monodisperse and deviate significantly from the usual assumptions in bulk microphysics schemes. This poses additional challenges for the parameterizations, e.g., of raindrop evaporation during convective events. Nevertheless, two-moment schemes are able to describe such small-scale variability and their effects, e.g. on evaporation below cloud base, quite successfully (Seifert, 2008), which may explain the improvements gained from those schemes in the simulation of organized deep convection (Morrison et al., 2009; Knippertz et al., 2009; Baldauf et al., 2011).

Observational data of ice clouds in frontal systems of Field et al. (2005) shows that N_0 of snow variies over 3 orders of magnitude (see their Fig. 10a). Even when taking account the temperature dependency of N_0, the remaining uncertainty of N_0 is at least one order in magnitude. This is especially important for the ice water path and the spatial precipitation patterns, e.g. of orographic precipitation.

4 Aerosols as a source of uncertainty

The effect of aerosol particles on clouds and precipitation is seen as a major scientific challenge in climate modeling (Solomon et al., 2007), but has not yet received that much attention in numerical weather prediction. One reason might be the fact that aerosol indirect effects lead to subtle changes in the radiation budget, which are, of course, relevant for climate modeling, but less so for NWP. This might be different for the aerosol effects on precipitation which, as some studies have shown, can lead to pronounced differences in the precipitation efficiency of clouds (Khain, 2009). Aerosol particles can change the precipitation processes in many ways: They can act as cloud condensation nuclei (CCN), and, for example, higher CCN concentrations can lead to a slower and less efficient rain formation in warm clouds. In cold clouds, in which ice nuclei (IN) become important, the effects are much more complicated. A higher concentration of IN can, similar to CCN, slow down the precipitation formation as particles become smaller, but more IN do also lead to a more rapid, more efficient glaciation of the clouds, and the additional latent heat release and the increase in available condensate may lead to an increase in surface precipitation. In mixed-phase clouds the effects of CCN and IN depend on each other which further complicates the analysis.

Some recent studies argue that the aerosol effects are maybe smaller that previously thought. For example, Posselt and Lohmann (2009) point out that large-scale climate models with diagnostic precipitation schemes overestimate the importance of autoconversion compared to accretion for the precipitation amounts. This affects the CCN sensitivity of the model, because autonconversion does depend much more strongly on cloud droplet number concentration than accretion. Grabowski and Morrison (2011) investigated the impact of different microphysics schemes on the indirect aerosol effect in radiative-convective equilibrium simulations. The most significant difference between the simpler microphysics scheme and a more sophisticated two-moment scheme was a large reduction of the difference between the pristine and polluted aerosol assumptions when using the more complex scheme.

To contribute to this discussion Seifert et al. (2011) have performed CCN/IN sensitivity studies over three summer seasons with a convective-scale NWP model at 2.8 km grid spacing using a two-moment microphysics scheme. Figure 2 shows the results for the relative differences in daily 12h-precipitation amounts averaged over a regional scale of roughly 400x300 km^2. The potential variability of surface precipitation due to different aerosol load is mostly below 10 %, and only in a few cases larger differences up to 20 % occur. This suggests that the regional-scale variability due to aerosol is much smaller

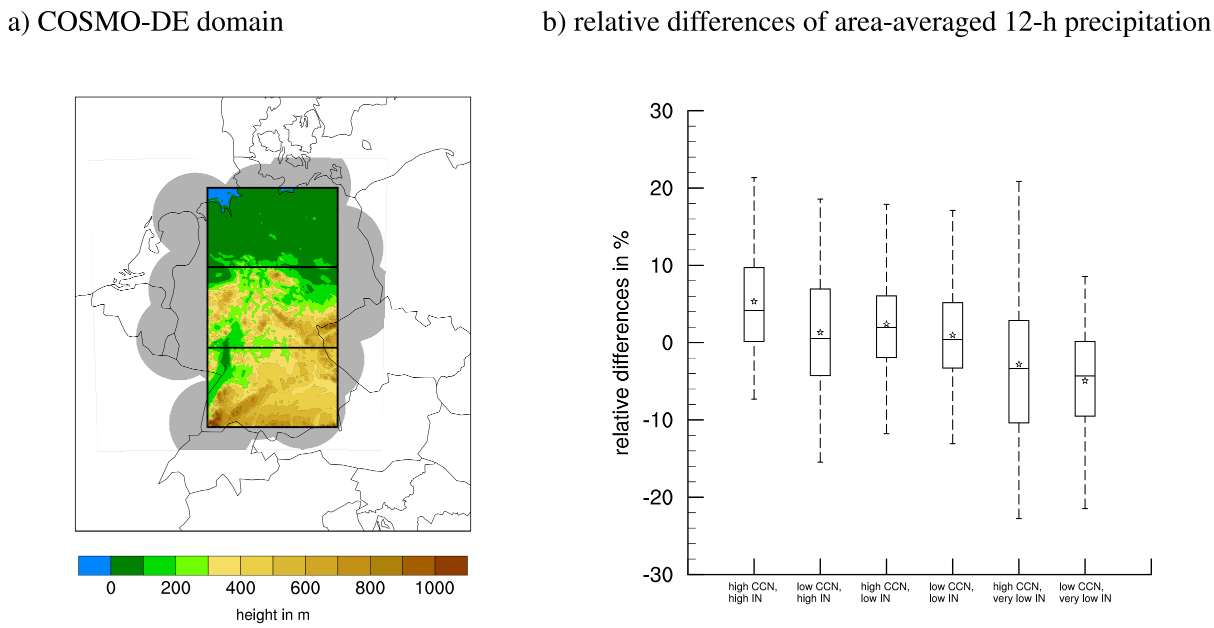

Figure 2: (a) COSMO-DE model domain with insertions of coverage of the German radar composite (grey), and the three evaluation sub-domains with the model orography. (b) Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008-2010 for various CCN/IN experiments. 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.

than current forecast errors of global or limited-area NWP models. The reasons for this robustness of the simulations are discussed in the next section.

5 Non-linearity, complexity and buffered systems

Cloud microphysical processes are highly nonlinear, e.g. autoconversion, which describes the process of droplet growth by collision-coalescence, is sometimes parameterized proportional to L_c^4 where L_c is the cloud water content. This strong nonlinearity corresponds to the colloidal instability, and the difficulties in precipitation forecast are, to some extent, caused by the attempt to explicitly predict the time evolution of an intrinsically unstable system. Precipitation forecast are further complicated by the fact that cloud particles and their interactions are numerous. Figure 3 depicts the processes and interactions which are included in the latest version of the Seifert and Beheng (2006) two-moment microphysics scheme. Some processes, like riming splintering (Hallett-Mossop ice multiplication) are included in the scheme, but not shown in the diagram. Most of these interactions are nonlinear.

Given the uncertainties (discussed in the previous sections), the nonlinearity of the processes, and the complexity of the system, how can we hope to be able to predict the evolution of clouds at all? And why are NWP models, to some extent, successful in predicting precipitation? First of all, the precipitation formation is usually rather fast, i.e. for most clouds the associated time scales are of order 10-30 min. If we are not interested in the detailed temporal evolution, e.g. because the model time step is larger than the time scales of precipitation formation, then a simple adjustment scheme will give a useful forecast. To some extent the well-known Kessler scheme can be interpreted as such an adjustment

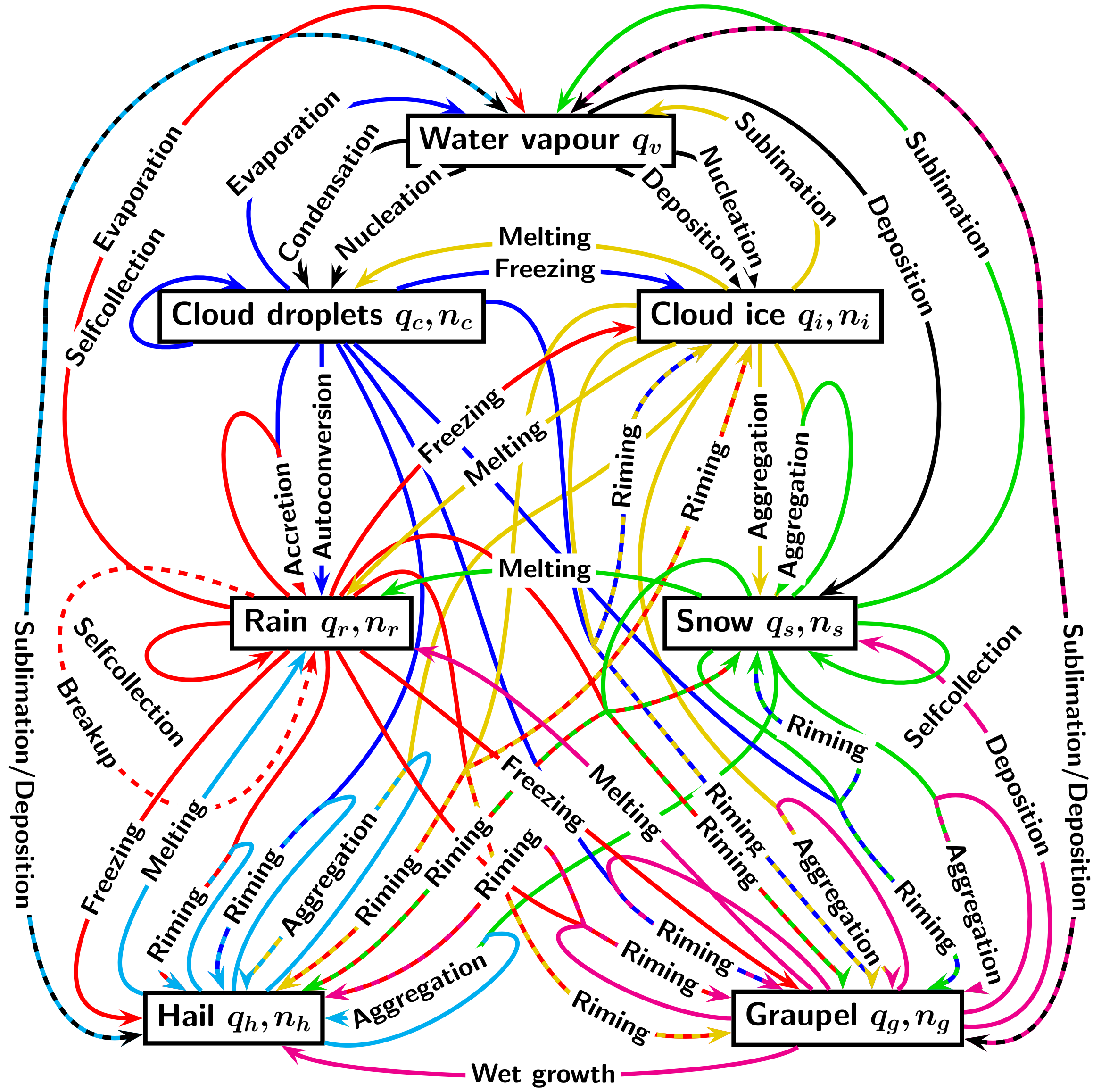

Figure 3: Microphysical processes implemented in the Seifert and Beheng two-moment microphysics scheme including hail formation (Seifert and Beheng, 2006; Blahak, 2008; Noppel et al., 2010).

approach that ignores the microphysical details. And even for high-resolution models the differences in surface precipitation between various microphysical parameterizations are often small, because most of the cloud processes act as negative feedbacks, i.e. they make the system more robust. Some examples for such negative feedbacks or cloud buffers, mostly studied in the context of aerosol-cloud effects (Stevens and Feingold, 2009; Seifert et al., 2011), are

- In a high CCN environment the decrease in rain formation (autoconversion) due to an increased cloud droplet number concentration is often compensated by an increase in liquid water content (LWC), i.e. the LWC increases until it yields a similar precipitation efficiency as in the low CCN case. Due to the strong nonlinearity in L_c a small increase in cloud water content can buffer a larger variation in number concentration. In terms of model error this means that an error in number concentrations will probably lead to a compensating error in cloud water content, and not necessarily to an error in surface precipitation amounts.
- If a precipitation forming process is suppressed (or suffers from model errors) then other microphysical pathways can compensate this and the precipitation efficiency does not change as strongly as in simpler, less complex systems. For example, mixed-phase processes can become dominant when warm rain is suppressed in a polluted CCN regime. As a consequence, spurious sensitivities, which are too strong, can occur when the complexity is not sufficiently represented, i.e. when the scheme is incomplete. It has, for example, been found in many studies that not having separate graupel and hail categories can introduce significant model errors in simulating deep convection.
- If the microphysical growth processes are suppressed, then dynamical feedbacks, e.g. an invigoration of convective dynamics, can compensate a slowed-down microphysical precipitation formation.

The last point goes beyond purely microphysical processes, but is in practice often observed in NWP models, e.g., errors in the grid-scale precipitation are often compensated by the cumulus parameterization and vice versa. On one hand, such negative feedbacks make the system much more robust (or buffered), which can help to make useful forecasts even if some parts of the model have significant errors. On the other hand, the numerous negative feedbacks make it often cumbersome if not impossible to attribute errors to individual processes.

6 Conclusions and outlook

The uncertainties and model errors in the cloud microphysical parameterizations of NWP and climate models are large and numerous. Further improvements are necessary, especially since the cloud microphysical parameterization can, in contrast to the cumulus parameterization, not be eliminated by an increase in model resolution. On the other hand, errors in parameterizations of individual microphysical processes do often not directly lead to large forecast errors in large-scale surface precipitation, because of the buffered behavior of the system.

Some of the uncertainties in cloud microphysics can maybe be tackled be stochastic parameterization approaches, e.g.,

- A stochastic Markov jump model could be used to model the various ice particle habits, i.e. depending on the environmental conditions (temperature, moisture) the model would transition to the most likely habit according to the thermodynamics habit diagram. In a deterministic model there is little hope that such a scheme would give an improvement, but as a stochastic jump model it might be able to capture some of the variability of the system.

- A stochastic sampling of an assumed size distribution would be possible to represent the small-scale variability but this might only become relevant for large-eddy simulations with grid spacings below 10 m.
- 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.

During the next years we will probably see more detailed, more sophisticated microphysical schemes in operational NWP models, e.g. two- and three-moment bulk approaches, but also simplified stochastic schemes which would be attractive for use in high-resolution ensemble prediction systems.

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