Future Directions for the Parametrization of Cloud and Precipitation Microphysics

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1. Introduction

The parametrization of clouds and precipitation in numerical weather prediction (NWP) models has evolved significantly over the years, yet it remains a challenge to represent the complex system of microphysical interactions whose influence spans the range of scales from microns to hundreds of kilometres. Significant approximations must be made and there is always a balance between the complexity of the parametrization, the limitations of our knowledge of the real world and the computational constraints of an operational NWP system. The model is an integral part of modern data assimilation systems and for the assimilation of cloud and precipitation data, it is imperative that there is a good understanding of the representation of cloud and precipitation in the model. The purpose of this paper is to discuss some future directions for the parametrization of cloud and precipitation, which are relevant for the future development of data assimilation schemes for assimilating satellite observations of cloud and precipitation into NWP models. It is by no means a comprehensive survey, but is intended to be more of a discussion to highlight just some of the challenges that may be faced in the future.

2. A Brief Overview of Cloud Parametrization: Microphysics and Macrophysics

It is convenient to split the problem of the parametrization of cloud and precipitation into "microphysics" and "macrophysics", where the former describes the representation of micro-scale physical processes and the properties of collections of particles, and the latter describes the sub-gridscale variability of humidity and condensate and to some extent the geometry of the cloud and vertical overlap.

2.1. Microphysics

Figure 1 is an example of a vertically pointing ground-based cloud radar reflectivity field, which illustrates the complexity of the microphysical parametrization problem, in terms of different phases (vapour, liquid, ice), different hydrometeor characteristics, (e.g. ice at high altitudes with low fallspeed advected horizontally whereas rain below the melting layer falls much faster), different microphysical processes (ice nucleation, diffusion growth and aggregation, warm phase microphysics, evaporation and melting), and the significant spatial variability across a range of scales. Microphysical processes are complex micro-scale phenomena and the collective effect must be greatly simplified and approximated in atmospheric numerical models used for NWP, climate prediction and other applications. The complexity of the parametrization depends on the available computing power, the particular application of the numerical model, and the degree of our understanding! The parametrization in a model designed for studying small-scale convective processes may be very different to a parametrization designed for a global climate model.

It is convenient to place cloud and precipitation particles into a number of discrete categories. As well as water molecules in the vapour phase, liquid and solid particle types in the atmosphere can be described in terms of cloud water droplets, raindrops, pristine ice crystals of varying shape (habit), aggregates of pristine crystals (snow), rimed ice crystals, graupel (heavily rimed ice particles) and hail. A typical operational NWP parametrization scheme will represent cloud liquid water, cloud ice, snow and rain, with graupel and hail as additional variables for convective-scale models. Particle size distributions are implicitly assumed within simplified microphysical formula or are explicitly parametrized. Phase changes, particle collection processes and sedimentation are described by microphysical process equations with varying degrees of approximation.

2.2. Macrophysics

The problem of representing the macrophysics in a model is illustrated in Figure 2 in which a representative grid highlights the issues of partial cloudiness, and variability of cloud, precipitation (and humidity) within each model grid box. In practice, the complexity of the problem is significantly simplified. In most models, clouds are assumed to fill the layer in the vertical so that cloud fraction is equivalent to cloud cover, although sub-grid vertical parametrizations have been attempted (e.g. Brooks et al. 2005). However, many models include a representation of partially cloudy grid-boxes through a diagnostic (e.g. Smith, 1990; Rotstayn, 1997) or prognostic (Tiedtke, 1993; Wilson et al., 2008) cloud fraction. For some processes such as condensation, there is an assumption of sub-grid variability of humidity, which allows cloud to form before the whole grid-box reaches saturation (and hence allows partial cloud fraction). For other processes, such as precipitation formation and collection processes, in-cloud condensate and precipitation are usually assumed to be homogeneous. In addition there are assumptions about cloud overlap in the vertical for the radiation (Geleyn and Hollingsworth, 1979; Hogan and Illingworth, 2000) and sometimes precipitation (Jakob and Klein, 2000).

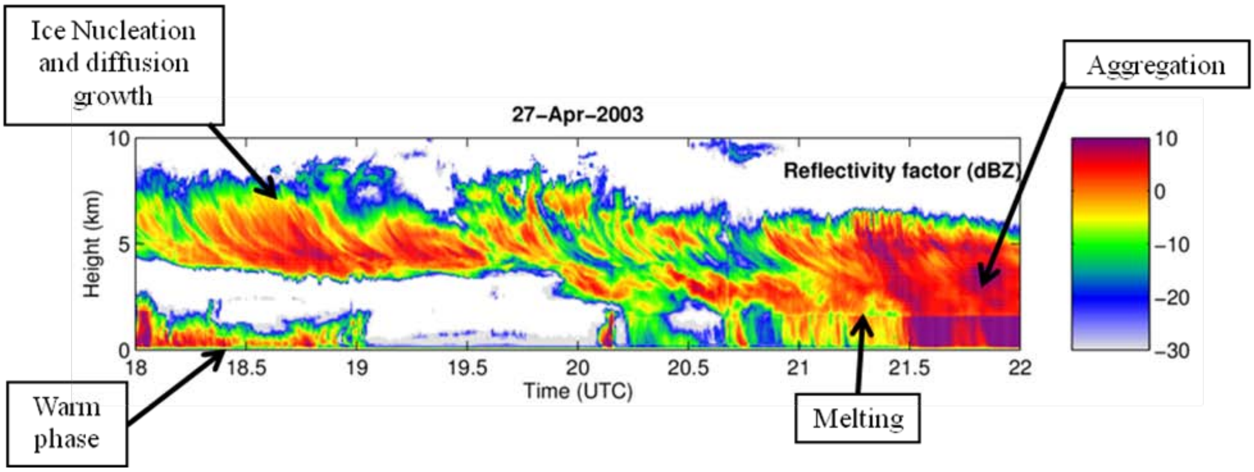

Figure 1*:Time-height cross-section of radar reflectivity factor (dBZ) from a vertically pointing 94GHz radar at Chilbolton, UK, for a period of 4 hours on 27 April 2003. The image shows the passing of a frontal system to illustrate the complexity and variability of cloud and precipitation processes in the atmosphere. Image courtesy of Robin Hogan. Data courtesy of RCRU/RAL.*

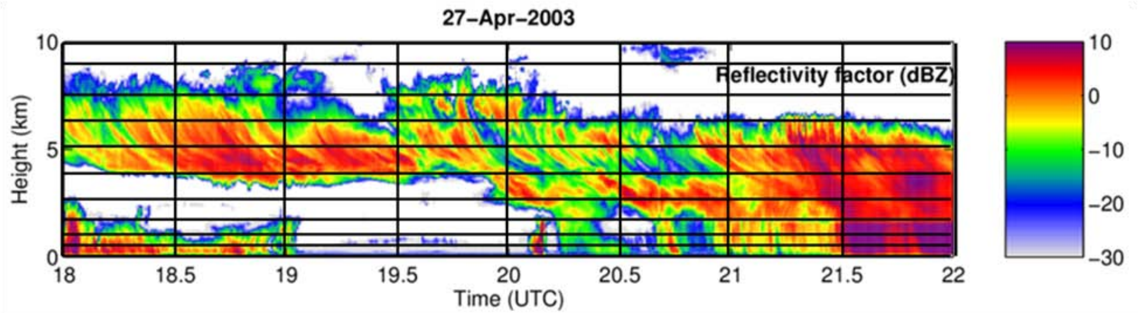

***Figure 2**: As Fig. 1 but with a (rather coarse) illustrative grid to highlight the potential problems of macrophysical representation of cloud variability at the sub-grid scale.*

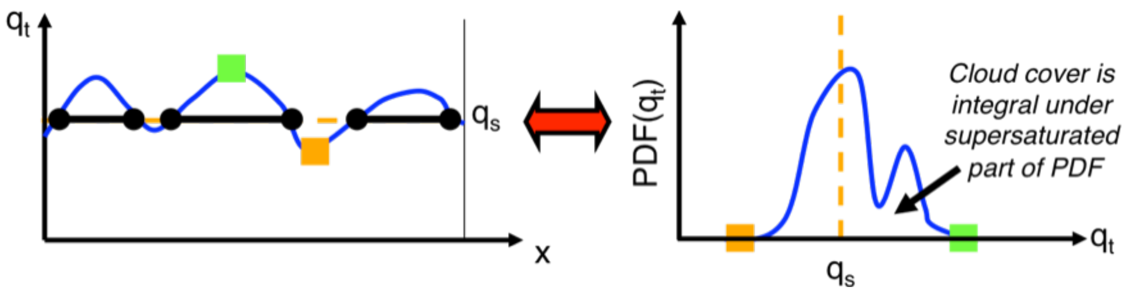

***Figure 3**: Representation of the heterogeneity of total water (water vapour + condensate) within a grid-box with horizontal dimension x, (a) variation of total water, q_t, across the grid box with saturated cloudy air above the saturation line, q_s, and clear air below, (b) the equivalent representation of the heterogeneity as a PDF of total water which may be approximated with simplified functions in a parametrization scheme. The orange/green squares are equivalent points on the two distributions.*

A more physically based approach is to represent the heterogeneity in the form of a probability density function (PDF) for humidity, condensate, or the combined "total water" (Fig. 3) in a so-called statistical cloud scheme. Most sub-grid cloud schemes can be formulated in terms of an assumed PDF of total water. There is then a choice of different variables to represent the moments of the PDF, either through prognostic or diagnostic variables, such as water vapour, cloud condensate and cloud fraction (Tiedtke, 1993) or the mean, variance and skewness of total water (Tompkins, 2002). There need to be sufficient degrees of freedom to represent the observed wide variations in humidity and cloud distributions, but also sufficient information to constrain the sources and sinks of the variability.

3. Driving Factors for Cloud and Precipitation Parametrization Development

There are many factors that are driving changes and developments to the moist parametrization schemes in NWP models as computational resources continue to increase:

- *Improving the large-scale dynamics*

  Cloud and precipitation can affect the atmospheric dynamics directly through latent heating and cooling due to condensation and evaporative processes, and through radiative heating/cooling due to cloud-radiative interactions in the short-wave and long-wave. The three-dimensional distribution of water and ice cloud, rain and snow and their particle characteristics affect the distribution of heating/cooling, and thus a better representation will lead to improvements in the dynamics of the atmosphere and improved skill for NWP.

- *Improving forecasts of weather parameters*

  Accurate prediction of the timing, distribution and characteristics of cloud and various forms of precipitation at the surface are a crucial part of any NWP forecast. There is an ongoing requirement to improve the "weather" parameters (cloud cover, rain, snow, fog, etc.), which certainly depends on the parametrization of moist processes and microphysics in the models.

- *A desire to improve the physical basis of the parametrization*

  For confidence in the model and a path towards long-term improvement, there must be a requirement for improving the physical basis of the parametrization scheme, making the most of new observations, theory and understanding to get the right answer for the right reasons. In addition, there is a drive towards consistency of assumptions across the model parametrization schemes to reduce the number of independent tunable parameters.

- *Increasing model resolution*

  There is a continuing trend towards higher model resolution in order to solve the atmospheric equations of motion more accurately and remove the need to parametrize convection. Many NWP centres now have operational models at convective-scale resolution (of order 1 km to 4 km), which require additional complexity in the microphysical parametrization to respond to the small-scale high vertical velocities of deep convective clouds (graupel, hail).

- *Representing aerosol-cloud-radiative interactions*

  Increasing research effort is being directed towards improving the understanding of aerosol-cloud-radiative interactions, particularly to represent cloud feedbacks for climate prediction, but also for improving aspects of cloud prediction for NWP. This is leading to prognostic equations for aerosol, double-moment representation of hydrometeors and more complex microphysical parametrizations.

- *Assimilation of cloud/precipitation affected data.*

  There is a desire to get more information out of satellite data (e.g. radiances) within a NWP data assimilation system, including data that is affected by cloud and precipitation. This is a challenging task, but certainly benefits from an improved representation and prediction of cloud and precipitation in the NWP model.

4. Future Development of Cloud and Precipitation Parametrization

There are a wide range of NWP models in use with different resolutions, different applications, different degrees of parametrization complexity and different priorities for future development. The purpose here is to identify and discuss some general directions of development for cloud and precipitation parametrization that are applicable to all models and some of the challenges for data assimilation. Three general areas of development are highlighted and discussed; (i) an improved physical basis for the parametrization, (ii) an improved use of observations, and (iii) increasingly unified assumptions across the model.

4.1. Improved physical basis

The complexity of microphysical schemes will continue to increase as our understanding of microphysics improves through continuing fundamental research, more comprehensive observations and the availability of greater computational capacity. This will manifest itself in terms of the number of prognostic variables representing the different hydrometeor categories and particle size spectra (e.g. a change from mass [single moment] to mass and number concentration [double moment]), increasing complexity of the representation of microphysical processes, improved representation of the ice phase and ice supersaturation, representation of aerosol and cloud-aerosol interactions. Again, it should be emphasised that there should always be a balance between the complexity of the parametrization and how well we can constrain and validate the scheme based on the available observations and the state of our knowledge. It is possible to show that increasing the complexity of some aspect of the parametrization can have a positive impact in a particular case study, particular regime or certain region of the world, but for global NWP we need a parametrization that is applicable across the full range of meteorological regimes and phenomena.

The sub-grid aspect of cloud schemes (the "macrophysics") will also evolve in order to provide an improved physical representation of the spatial heterogeneity of water vapour, cloud and precipitation in a grid column. There is likely to be a move away from diagnostic schemes and *ad hoc* assumptions relating to sub-grid variability towards increasingly prognostic schemes with greater degrees of freedom and a form of parametrization that contains explicit information on spatial variability. Whether this is in the form of total water PDFs (as mentioned in section 2) with prognostic sources and sinks of humidity, condensate and precipitation, or alternative approaches, is still an open question.

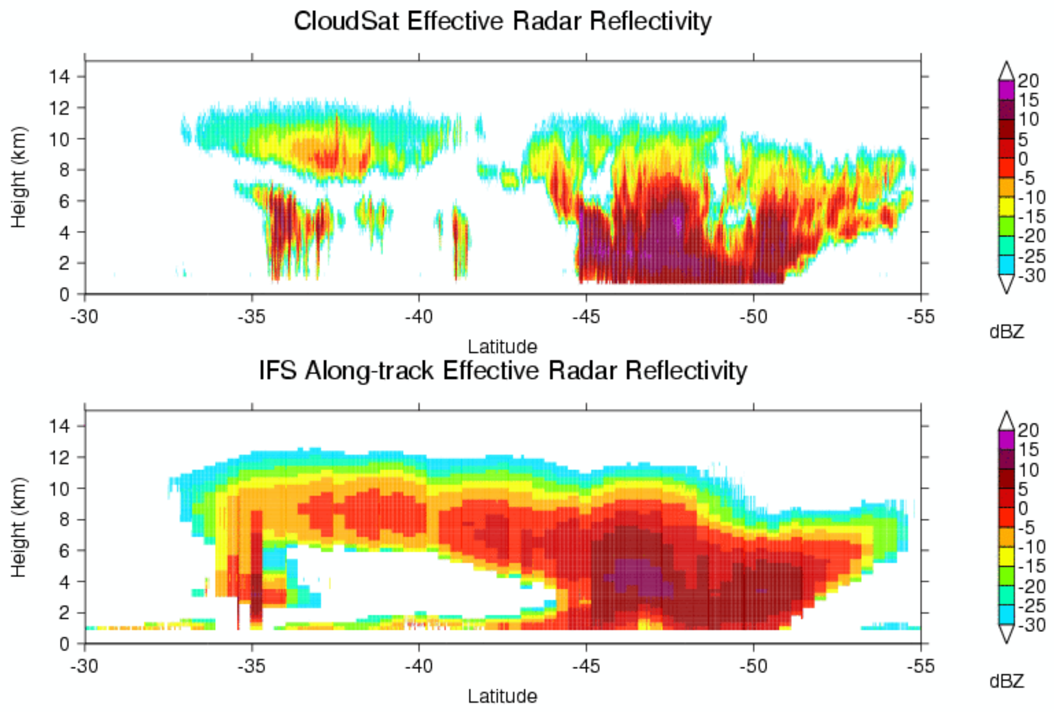

***Figure 4**: CloudSat effective radar reflectivity cross-section (upper panel) for a mid-latitude frontal cyclone and the equivalent cross-section for radar reflectivity derived from the ECMWF IFS model (lower panel).*

There are a number of challenges for data assimilation development, one of which is how to gain the most benefit from any additional information on hydrometeor categories and particle size spectra and sub-grid variability that is provided by the cloud scheme (see section 4.3 for a further discussion of consistent assumptions across the model). There is the possibility of increasing non-linearities in microphysical schemes as they become more complex. Non-linearities can be a particular problem for the formation of an appropriate tangent linear model and adjoint for 4D variational assimilation. There will of course continue to be many uncertainties in the parametrization due to the hugely complex nature of the problem, particularly for the ice phase and for interactions with aerosols, but the aim is to include as much realism as possible with traceability of the approximations and assumptions to observations, theory and more detailed microphysical modelling.

4.2. Improved use of observations

In recent years there has been a significant increase in the amount of remote-sensing observations for cloud and precipitation from both satellite (A-Train - Stephens et al., 2002) and ground (ARM sites – Ackerman and Stokes, 2003; European sites – Illingworth et al. 2007). In particular, the CloudSat radar and CALIPSO lidar are for the first time providing vertical profiles of cloud and precipitation hydrometeors around the globe over a multi-year time period. There is much information to extract to inform model parametrization development and new ways of using observations to improve evaluation of models. However, it is vital to compare "like-with-like" and have a good understanding of observational errors to ensure that differences are due to real deficiencies in the model and not artefacts of the comparison or biases in the observations. This process has benefit for both model evaluation and data assimilation. The challenge of accounting for different spatial scales in the model and observations could be addressed by utilising sub-grid information from the model where the observations have a higher resolution than the model (e.g. model O[50 km] versus CloudSat O[1 km]). Further, using CloudSat as an example, there is a sampling mismatch, essentially a narrow one-dimensional track for the radar versus a two-dimensional grid-box. The other issue to deal with is the difference in the observed parameters compared to the quantities predicted by the model. There are two approaches; to retrieve the model variable from the observational data (including synergistic use of multiple observations, e.g. Delanoë and Hogan, 2010) or to use a forward operator to derive the observed parameter from model variables (e.g. radiances or radar reflectivity, Haynes et al. 2007). The former (retrieval of model parameters) has often been used for model evaluation whereas the latter (forward model the observations) is usually the choice for data assimilation systems, although the latter is increasingly being used for model evaluation as well (Bodas-Salcedo et al, 2008). Figure 4 shows an example cross-section of CloudSat radar reflectivity compared to the forward modelled equivalent field from the ECMWF NWP model taking account of sub-grid variability from the model cloud fraction. There is clearly a need for accurate forward models for both model evaluation and data assimilation systems.

4.3. Increasingly unified underlying assumptions

In most cases, different parts of an NWP modelling system have been developed separately and have evolved gradually over time resulting in various inconsistencies in microphysical and macrophysical assumptions. For example, there is some component of microphysics (e.g. particle size distributions, effective radius, ice particle characteristics) in the parametrizations of stratiform cloud, convection and radiation as well as in forward models for data assimilation of cloud-affected observations. In a similar way, there are macrophysical assumptions (e.g. PDFs of humidity/condensate, vertical overlap of cloud and precipitation), which can potentially differ in different parts of the model. Inevitably, as the uncertainties in these assumptions decreases with new observational datasets and ongoing research, there will be increased confidence in applying consistent assumptions across the different parts of the model (Fig. 5). One example is the development of the Monte Carlo Independent Column Approximation (MCICA) for radiation parametrization (Pincus et al., 2003; Räisänen et al., 2004), implemented in the ECMWF model (Morcrette et al., 2008). The scheme splits each grid-box into a number of sub-columns and stochastically distributes the cloud in each sub-column according to the cloud fraction in each layer and the vertical overlap assumptions. For the purpose of the radiation, the radiative calculations for different spectral bands are also distributed randomly across the sub-columns. Within this framework, sub-grid information from the cloud scheme is used by the radiation parametrization in a consistent way. In principle, other components could also be used such as information on the PDFs of water vapour and condensate, or even microphysical properties of ice clouds. A similar approach could be applied to account for the vertical overlap of cloud and precipitation for the purpose of the microphysical process calculations (precipitation evaporation, accretion) in each column, although the computational cost increases linearly with the number of sub-columns.

There are some challenges in terms of making consistent microphysical assumptions across the model. Different processes and radiative wavelengths are sensitive to different parts of the particle size spectrum describing the PDF of particles of diameter D; for example, many microphysical processes depend primarily on the mass-weighted part of the size spectrum (D^3), the radiation parametrization is more sensitive to the small end of the size spectrum (D) and the radar reflectivity depends on higher moments (D^6). Representing the particle size spectrum in a consistent manner, that adequately represents the wide range of needs, requires careful attention. Another example is the consistency of the full microphysical parametrization and the tangent linear approximation in a 4-dimensional variational data assimilation system.

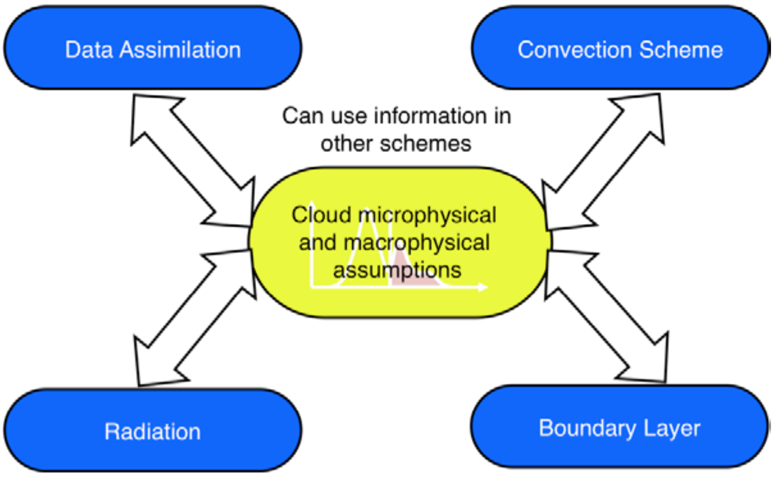

Figure 5*: Illustration of the potential for consistent use of cloud microphysical and macrophysical information across different parts of an NWP modelling system.*

5. Some Concluding Remarks

This paper has attempted to highlight a few of the general trends for the representation of cloud and precipitation in NWP models. It is by no means comprehensive but gives a flavour of some of the problems and issues that may affect the development of assimilation systems for satellite observations of clouds and precipitation. In summary, developments were discussed within three general themes; (i) an improved physical basis for parametrization leading to a more realistic three-dimensional distribution of cloud and precipitation and better information for data assimilation; (ii) an improved use of observations depending on appropriate forward models/retrievals, and allowing a more comprehensive validation/verification of models with obvious benefit for cloud parametrization development; (iii) increasingly consistent assumptions across the model reducing disparate assumptions and the number of free parameters, and using the best information we have for all parts of the model physics and data assimilation schemes. However, there are many challenges ahead and we must recognise the limitations of our knowledge and not over-extend the degrees of freedom of our cloud parametrizations beyond what can be reasonably constrained by observations.

In terms of accelerating progress in the future for assimilation development for satellite observations of clouds and precipitation into NWP models, an obvious but vital requirement is to keep physical parametrization, data assimilation and observation research scientists communicating and working together. There needs to be further work on improving forward models and retrievals in order to have as close a match as possible between model and observations, benefitting both evaluation of the model and assimilation of the data. Finally, successful assimilation will depend to some extent on the accuracy of the cloud and precipitation predictions from the model and we must ensure that the wealth of information from data assimilation in an operational NWP system (first guess errors, assimilation increments) is used to maximum benefit for the continued improvement of cloud parametrization.

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