Issues concerning the representation of clouds in GCMs

A.M. Tompkins

ECMWF
Reading, United Kingdom

1 Introduction

The ECMWF 2006 workshop was called to target the research required to improve the representation of clouds in large-scale global models. The representation of clouds is an complex task, since it involves so many components of the atmospheric model.

In addition to the fidelity of the cloud scheme microphysics, the cloud ice and liquid water droplet radiative properties and the interaction with cloud generating processes such as shallow and deep convection needs to be accurately described. Moreover, cloud processes are highly nonlinear and may occur on small spatial scales compared to the model horizontal and vertical grid-scale, demanding a description of the grid box partial cloudy volume and possibly also the sub-cloud structure. The mix of fast and slow timescale processes in clouds also places demands on the numerical framework required for global models using long timesteps. Finally, a good representation of clouds can only be achieved and verified if high quality and comprehensive observations are available, and the workshop therefore aimed to assess the current and potential future methods of model cloud evaluation and validation.

This presentation aims to briefly outline some of the above issues that arise when attempting to represent clouds in large-scale models.

2 Subgrid issues

Many of the difficulties that arise when attempting to represent clouds in large-scale models are explicitly linked to the large size of the grid box. While vertical resolution can be inadequate to represent some cloud processes such as the melting layer (Tompkins and Emanuel, 2000), here the discussion will be restricted to horizontal subgrid-scale variability.

Fractional cloud cover can *only* occur if there is horizontal subgrid-scale variability in humidity and/or temperature (controlling the saturation mixing ratio, q_s). If temperature and humidity are homogeneous, then either the whole grid box is subsaturated and clear, or saturated and cloudy. This assumes that supersaturation can not exist; a poor assumption for the ice phase.

This is illustrated schematically in Fig. 1. Fluctuations in temperature and humidity may cause the humidity to exceed the saturated value on the subgrid scale. If it assumed that all this excess humidity is immediately converted to cloud water (and likewise that any cloud drops evaporate instantly in subsaturated conditions), then it is clear that the grid-mean relative humidity ($\overline{RH}$, where the overline represents the gridbox average) must be less unity if the cloud cover is also less than unity, since within the cloudy parts of the gridbox $RH = 1$ and in the clear sky $RH < 1$. Generally speaking, since clouds are unlikely when the atmosphere is dry, and since RH is identically 1 when $C = 1$, there is likely to be positive correlation between RH and C.

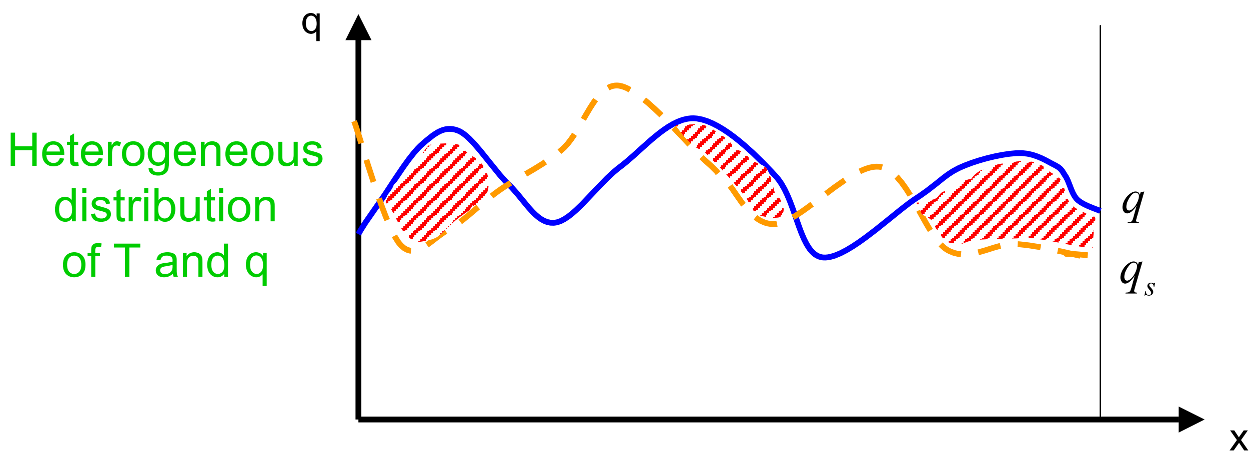

Figure 1: Schematic showing that partial cloud cover in a gridbox in only possible if temperature or humidity fluctuations exist. The blue line shoes humidity and the yellow line saturation mixing ratio across an arbitrary line representing a gridbox. If all supersaturation condenses as cloud then the shaded regions will be cloudy.

The main point to emphasize is that, *all* cloud schemes that are able to diagnose non-zero cloud cover for $\overline{RH} < 1$ (i.e. any scheme other than an "all-or-nothing" scheme) must make an assumption concerning the fluctuations of humidity and/or temperature on the subgrid-scale, as in Fig. 1. Either (i) they will *explicitly* give the nature of these fluctuations, most usually by specifying the probability density function (PDF) for the total water at each gridcell, or (ii) they will *implicitly* assume knowledge about the time-mean statistics of the fluctuations (i.e. the actual PDF at each grid point is maybe not known). It is important to recall, when trying to categorize the seemingly diverse approaches to cloud cover parametrization, that *this central fact ties all approaches together.*

2.1 Relative humidity schemes

Relative humidity schemes are called such because they specify a diagnostic relationship between the cloud cover and the relative humidity. RH schemes formulise this by setting a critical RH (denoted RH_{crit}) at which cloud is assumed to form, and then increase C according to a monotonically increasing function of RH, with C=1 identically when RH=1. One commonly used function was given by Sundqvist et al. (1989):

$$C = 1 - \sqrt{\frac{1-RH}{1-RH_{crit}}} \tag{1}$$

Thus it is apparent that RH_{crit} defines the magnitude of the fluctuations of humidity (the humidity variance). If RH_{crit} is small, then the subgrid humidity fluctuations must be large, since cloud can form in dry conditions. It is clear that one of the drawbacks of this type of scheme is that the link between cloud cover and local dynamical conditions is vague. Convection will indeed produce cloud if its local moistening effect is sufficient to increase RH past the critical threshold, but it is apparent that a grid cell with 80% RH undergoing deep convection is likely to have different cloud characteristics than a gridcell with 80% RH in a frontal stratus cloud. RH schemes simply state that, averaged across all conditions across the globe, a gridcell with X% RH will have Y% cloud cover. The use of further predictors such as the mean cloud liquid water (e.g. Xu and Randall, 1996) can refine these relationships.

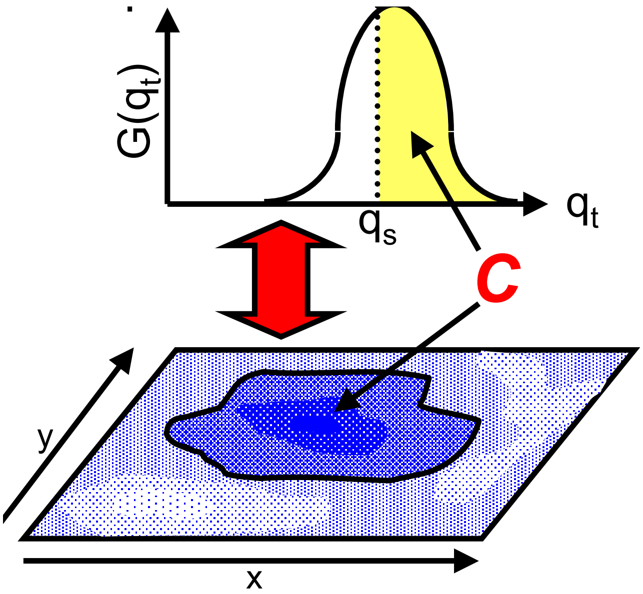

Figure 2: Schematic showing the statistical scheme approach. Upper panel shows an idealized PDF of total water (q_t). The vertical line represents the saturation mixing ratio $q_t = q_s$, thus all the points under the PDF to the right of this line are cloudy. The integral of this area translates to the cloudy portion of the gridbox, marked on the lower part of the figure, with darker shading schematically representing high total water values.

2.2 Statistical schemes

Instead of describing the spatial and temporal mean statistics of the humidity fluctuations such as the *RH* schemes, another group of schemes take a different approach, *by specifying the underlying distribution of humidity (and/or temperature) variability at each grid box*. This is shown schematically in Fig. 2. If the PDF form for total water q_t is known, then the cloud cover is simply the integral over the part of the PDF for which q_t exceeds q_s:

$$C = \int_{q_s}^{\infty} G(q_t)dq_t, \tag{2}$$

Likewise, the cloud condensate is given by

$$\bar{q_c} = \int_{q_s}^{\infty} (q_t - q_s)G(q_t)dq_t. \tag{3}$$

As always we are assuming that all supersaturation is immediately condensed as cloud. Here we are also ignoring temperature fluctuations for simplicity, but these can be included.

The main tasks of the statistic scheme is therefore to give a suitable form for the PDF of total water fluctuations, and to derive its defining moments.

Defining the PDF requires a compromise between having the flexibility to model subgrid total water fluctuation for diverse cloud conditions and having the necessary simplicity to permit mathematical tractability and the ability to set the PDF defining moments. Mostly unimodal and often symmetrical PDFs have been used in existing scheme, although Lewellen and Yoh (1993) and Golaz et al. (2002) outline bimodal PDF schemes for shallow convection schemes.

The second task of statistical schemes is to define the higher order moments of the distribution. If the distribution is simple then it can be defined by a small number of parameters. In the case of the uniform distribution, just two parameters are required. These could be the lower or upper bounds of the distribution or, equivalently, the first two distribution moments: the mean and the variance. Likewise, more complicated PDFs that require 3 parameters can be uniquely defined using the first three moments: mean, variance and skewness; four-parameter distributions need the fourth moment of kurtosis (describing the PDF 'flatness'), and so on.

Some schemes diagnostically fix the higher order moments of the distribution, such as the variance. However, it is clear that this is not an ideal approach, since by having a fixed distribution width (for example), the PDF (and thus cloud properties) are not able to respond to local dynamical conditions. The fixed width (and higher order moments) are then equivalent to the specification of the critical relative humidity at which cloud is assumed to form in the *RH* schemes. Indeed Smith (1990) actually sets the width of the triangular distribution in that scheme in terms of a RH_{crit} parameter.

The question is therefore how to set the moments of the distribution. A prognostic statistical scheme is likely to predict the evolution of the total water moment distribution, such as the variance and the skewness. The approach would be to introduce sources and sinks of each moment due to the other processes. The problem is that the way to do this is not always clear. The sources and sinks of variance due to turbulence and convective subgrid-scale transport can been derived (Golaz et al., 2002; Klein et al., 2005, e.g.), however, the contribution of various microphysical processes is less clear. The sources and sinks of skewness due to, say, ice crystal sedimentation are difficult to derive and will depend not only on the local assessment of sub-cloud ice mass fluctuations, but also on how these are assumed to overlap in the vertical.

In summary, although the statistical scheme approach appears to be a promising avenue to develop in terms of cloud parameterization, and allows a far greater consistency between various model components, difficulties remain concerning the representation of microphysical processes in a statistical framework.

3 Microphysical issues

The above discussion of ice sedimentation leads on the second major issue - the representation of microphysical processes. The microphysics of clouds is complex, involving a plethora of warm rain and ice-phase processes, not to mention the complications of the mixed phase. The representation of these processes is hindered by the difficulty to observe them with aircraft or cloud chamber measurements. This presentation will not discuss individual microphysical mechanisms in detail, but will rather focus on the complications specific to representing microphysics in large-scale models.

Some bulk microphysical schemes in use in cloud resolving models prognose many different cloud and precipitation categories, with multiple pathways linking these, often exceeding 40 or so in number. However, the task of representing cloud microphysics in cloud resolving models is facilitated by the short timesteps of a few seconds these models generally use, and the small spatial scale of the grid-box, which by definition resolves the cloud scale motions and requires no representation of partial cloud cover.

The short timesteps allow the microphysical equations to be solved by simple explicit techniques, with simple clipping applied to prevent negative values. A GCM with timesteps of O(1 hour) must employ an alternative approach. This may be an implicit solver, a robust solution which is conserving if advection terms such as ice sedimentation are written in flux form. However, if the Courante-Friedrich-Lewy (CFL) limit is significantly exceeded the method is highly diffusive.

The diffusivity of the advection terms can be tackled by using a separate solution for these such as MPDATA (Smolarkiewicz and Margolin, 1998), semi-Lagrangian methods (Lopez, 2002) or time-splitting techniques. Semi-Lagrangian methods are efficient and can be non-diffusive, are commonly used to achieve numerical accuracy for long timesteps (Leonard, 1991; Wallis and Manson, 1996) and were implemented into the scheme of Lopez (2002) recently. The disadvantage of these methods are the complexity of considering the interaction with other fast processes during the descent, such as the melting of ice or collection and aggregation processes. With time splitting techniques the same process interaction concern applies; simply handling the ice sedimentation process itself using shorter sub-timesteps for example, would lead to inaccurate solutions. However, including the consideration of melting, autoconversion and evaporative processes would imply a considerable portion of the cloud physics being run at short timesteps, making schemes costly.

Another difficulty of tackling microphysics in a large-scale models again relates to the subgrid issue, namely that the microphysical processes are occurring only in one part of the grid-cell. The process of ice nucleation is taken as an example. Outside the cloudy area in the clear-sky environment highly supersaturated states may be maintained, while deposition can rapidly (i.e. fast compared to a typical GCM model timestep) deplete available supersaturation within the cloudy region. To model this accurately in a GCM from time-step to time-step a memory of the humidity both inside and outside the cloudy region is necessary. With only one prognostic equation usually used in GCMs for the grid-mean humidity, this means that either an additional prognostic equation is required (the environmental humidity for example) or simplifying diagnostic assumptions (a diagnostic parametrisation) need to be applied to divide the grid mean humidity between the cloudy and clear sky portions. Tompkins et al. (2007) discuss this in more detail. Another similar example is the case of mixed-phased clouds, which is illustrated in fig. 3, a theme also discussed in Rotstayn et al. (2000).

4 Observational issues

Observations are required to validate any cloud scheme. These can be from a variety of sources, such as in situ aircraft or balloon measurements, or remotely sensed observations from the ground or space. While the variety of observation type has grown recently, there has typically been a dearth of information relating to cloud ice microphysics. It is only recently that this has started to be addressed with remotely sensed observations from platforms such as MLS (Li et al., 2005) or Cloudsat (Stephens et al., 2002). As well as climate means, and individual case studies, other methods of cloud validation have included separation of statistics by regime (Bony et al., 1997) and use of long-term timeseries from ground-based observations.

This presentation will not go into details of observational techniques, but it should be pointed out that the NWP environment of ECMWF and similar centres poses a particular challenge for cloud validation. This is due to the fact that the forecast system is continually updated, with maybe 3 or 4 model revisions occurring per year, which often impact the model climate. This rapid model cycling means that any validation technique must render results over a short timescale. A complex case study that takes a long while to organise may give feedback that refers to a model version that is already out of date and therefore limited in relevance. For example, studies that evaluate the clouds of the ERA-40 reanalysis are useful for other users of this important dataset, but are not helpful for future development of the IFS operational cloud scheme which has diverged so greatly from the ERA-cycle. It is suggested that further development of centralised and easy accessible databases of remotely sensed observations would facilitate this validation effort. Projects such as Cloudnet (Illingworth et al., 2006), which aim to validate models using a large number of long-term ground-based observations processed using identical retrievals algorithms are also encouraged.

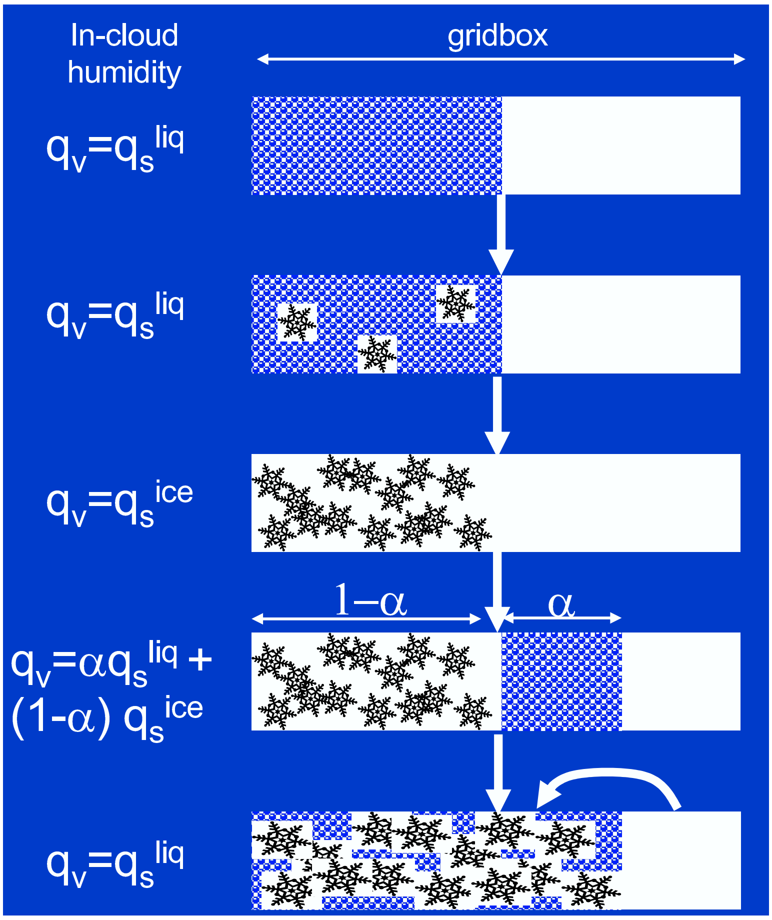

Figure 3: Schematic illustrating the problems representing mixed phase clouds in large-scale models. The panels show the temporal evolution of an idealized grid-box from top to bottom. The top panel shows a partially cloudy cell, with only liquid drops present. The in-cloud humidity is thus equal to the liquid water saturation mixing ratio, q_s^{liq}. *The second panel shows that ice nucleation has occurred, as the temperature is below the freezing point. In-cloud humidity remains at* q_s^{liq} *since the ice crystals grow at the expense of the surrounding liquid droplets by the Bergeron process. This can be modelled in a GCM, since the prognostic equation for cloud liquid water provides a memory for the water reservoir available for ice crystal growth. In panel 3, the cloud becomes completely glaciated, and then the ice crystals continue to grow by deposition of water vapour, and the in-cloud humidity decreases from* q_s^{liq} *to* q_s^{ice}. *As discussed in the main text, this involves a distinct evolution of the water vapour within and without the cloud and thus it is not possible to model accurately without an additional prognostic equation, for example for the in-cloud humidity.*

In the fourth panel further cooling of the grid-box leads to an additional portion of the clear sky becoming cloudy, forming liquid drops. In reality the mean in-cloud water vapour would be a linear mix of the q_s^{liq} *and* q_s^{ice} *according the relative cloud fractions of the glaciated and liquid clouds. However, once again a GCM that does not prognose these variables must make a diagnostic assumption. For example, if only cloud fraction and ice and liquid cloud mass mixing ratios are known, the model may assume that the ice and liquid are well mixed. Thus the in-cloud humidity would be assumed to equal* q_s^{liq} *as in panel 2. Note, that as this is higher than the value assumed in panel 4, this would result in an artificial flux of vapour from the cloud environment to the cloud, depicted by the curved white arrow; detrimentally affecting the calculation of ice deposition growth rates as a result.*

5 Summary

In summary, clouds are a complex phenomenom resulting from many interacting processes. Their representation in large-scale models is complicated by the large gridboxes and long timesteps. This presentation has attempted to summarise some of these difficulties and issues. They were summarised by posing the following questions to the ECMWF cloud workshop working groups:

Microphysics:

- Which microphysical processes are key for NWP/climate?
- How much complexity is required?
- What additional numerical requirements are needed to represent the mix of fast and slow microphysical processes in large-scale models with long timesteps?

Macrophysics

- Are statistical cloud schemes the way forward?
- If yes, what complexity of PDF is required?
- How will process influences on the PDF moments be parametrized, especially microphysics?

Observations

- Where should our priorities lie with cloud observations?
- What timeliness is required for NWP?
- What is the future potential for data assimilation of cloud-related observations?
- Should models be validated in both a NWP and climate mode?
- How can we best use the observations we already have?

To see the answers that the working groups provided for some of these dilemmas, the reader is referred to the working group summaries available online at www.ecmwf.int.

References

Bony, S., K.-M. Lau, and Y. C. Sud, 1997: Sea surface temperature and large-scale circulation influences on tropical greenhouse effect and cloud radiative forcing, *J. Climate*, **10**, 2055–2076.

Golaz, J., V. E. Larson, and W. R. Cotton, 2002: A PDF-based parameterization for boundary layer clouds. Part I: Method and model description, *J. Atmos. Sci.*, **59**, 3540–3551.

Illingworth, A. J., R. J. Hogan, and coauthors, 2006: Cloudnet - Continuous evaluation of cloud profiles in seven operational models using groundbased observations, *Bull. Amer. Meteor. Soc.*, **87**, submitted.

Klein, S. A., R. Pincus, C. Hannay, and K.-M. Xu, 2005: Coupling a statistical scheme to a mass flux scheme, *J. Geophys. Res.*, **110**, 10.1029/2004JD005017.

Leonard, B. P., 1991: The ULTIMATE conservative difference scheme applied to unsteady one-dimensional advection, *Comput. Methods Appl. Mech. Eng.*, **19**, 17–74.

Lewellen, W. S. and S. Yoh, 1993: Binormal model of ensemble partial cloudiness, *J. Atmos. Sci.*, **50**, 1228–1237.

Li, J.-L., D. E. Waliser, J. H. Jiang, D. L. Wu, W. Read, J. W. Waters, A. M. Tompkins, L. J. Donner, J. D. Chern, W. K. Tao, R. Atlas, Y. Gu, K. N. Liou, A. Del Genio, M. Khairoutdinov, and A. Gettelman, 2005: Comparisons of EOS MLS cloud ice measurements with ECMWF analyses and GCM simulations: Initial results, *Geophys. Res. Lett.*, **32**, L18710, doi:10.1029/2005GL023788.

Lopez, P., 2002: Implementation and validation of a new prognostic large-scale cloud and precipitation scheme for climate and data-assimilation purposes, *Q. J. R. Meteorol. Soc.*, **128**, 229–257.

Rotstayn, L., B. Ryan, and J. Katzfey, 2000: A scheme for calculation of the liquid fraction in mixed-phase stratiform clouds in large-scale models, *Mon. Wea. Rev.*, **128**(4), 1070–1088.

Smith, R. N. B., 1990: A scheme for predicting layer clouds and their water-content in a general-circulation model, *Q. J. R. Meteorol. Soc.*, **116**, 435–460.

Smolarkiewicz, P. and L. Margolin, 1998: MPDATA: A Finite-Difference Solver for Geophysical Flows, *Journal of Computational Physics*, **140**(2), 459–480.

Stephens, G. L., D. G. Vane, and coauthors, 2002: The CloudSat mission and the A-Train, *Bull. Amer. Meteor. Soc.*, **83**, 1771–1790.

Sundqvist, H., E. Berge, and J. E. Kristjansson, 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model, *Mon. Wea. Rev.*, **117**, 1641–1657.

Tompkins, A. M. and K. A. Emanuel, 2000: The vertical resolution sensitivity of simulated equilibrium temperature and water vapour profiles, *Q. J. R. Meteorol. Soc.*, **126**, 1219–1238.

Tompkins, A. M., K. Gierens, and G. Rädel, 2007: Ice supersaturation in the ECMWF integrated forcast system, *Q. J. R. Meteorol. Soc.*,**133**, 53–63.

Wallis, S. G. and J. R. Manson, 1996: Accurate numerical simulation of advection using large time steps, *Int. J. Num. Meth. Fluids*, **24**, 127–139.

Xu, K.-M. and D. A. Randall, 1996: A semiempirical cloudiness parameterization for use in climate models, *J. Atmos. Sci.*, **53**, 3084–3102.