PARAMETERIZATION OF PHYSICAL PROCESSES

Contents

Clouds

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Introduction

At any given time clouds cover between 60% and 70% of the globe and for most of mankind they are an everyday experience. Clouds exert various influences on the Earth–atmosphere system, of which the most important are:

- modification of the radiative fluxes in the atmosphere and at the Earth's surface;
- release and consumption of latent heat related to phase changes of water either directly inside the clouds or in precipitation generated in them;
- transport of heat, moisture, momentum and atmospheric trace constituents over large distances in the vertical in convectively generated clouds;
- modification of the surface hydrology through precipitation generated in clouds.

For a more detailed discussion of these cloud effects the reader is referred to other articles in the Encyclopedia (*see* **Clouds:** Classification; Climatology; Measurement Techniques *In Situ*, **Convection:** Laboratory Models of) and to the textbooks of Cotton and Anthes (1989), Liou (1992), and Houze (1993).

Given the importance of the various influences clouds have in the evolution of both the atmosphere and the surface, it is immediately obvious that those effects need to be included in the atmospheric models that are used for the simulation of climate and the prediction of weather. As described in the articles dealing with general circulation models and numerical weather prediction (*see* **General Circulation:** Models. **Weather Prediction:** Regional Prediction Models), these models seek numerical solutions to the hydrodynamic equations that govern atmospheric motions.

Various numerical techniques can be applied to achieve this goal, but all of them ultimately involve splitting the area over which the model is applied into 'boxes' of finite size in both the horizontal and the vertical. While the continuous differential equations describe atmospheric motions on all spatial and temporal scales, their discrete form can only describe processes on spatial scales of the order of twice the grid length. Processes that occur in clouds cover a wide range of spatial scales, from micrometers in the condensation and evaporation of individual cloud droplets, through a few hundred meters in the case of fair weather cumulus clouds, up to several hundred kilometers for the cloud systems associated with extratropical baroclinic systems. Hence, describing the detailed dynamics of individual clouds requires model gridbox sizes on the order of meters or less. Current computing power as well as difficulties in finding the necessary initial conditions at those spatial scales prohibit the use of such grid-box sizes in global atmospheric models. In reality, typical horizontal grid lengths in contemporary global models range from around 50 km in numerical weather prediction applications to more than 250 km in climate modelling. Processes that act on scales smaller than these grid sizes are normally referred to a subgrid-scale processes and are, *per se*, not represented in the solution of the finite difference equations. Many of these processes do, however, affect the dynamic and thermodynamic state of the atmosphere on larger spatial scales. Obvious examples are the large amounts of water vapor, heat and momentum that are transported by turbulent and convective motions. Since an explicit description of the subgrid-scale processes is prohibited, only their statistical effects on the grid box-mean state can be taken into account. Since the numerical solution of the model equations allows the atmospheric state to be known only on scales on the order of the grid box size, the description of these statistical effects has to be expressed in terms of those scales. The technique involved is generally referred to as parameterization.

To describe the main effects clouds have on the atmosphere as outlined above, the following cloud-related quantities need to be known:

- horizontal coverage of cloud, normally referred to as cloud fraction;
- vertical extent of the clouds;
- sources and sinks of cloud condensate including condensation, evaporation/sublimation, and conversion into precipitation and fallout;
- phase of the condensate;
- particle size and shape;
- in-cloud distribution of condensate;
- amounts of heat, water vapor, and momentum that are transported in convective clouds.

This list implies scales much smaller than the typical resolution of most atmospheric models. The problem of representing clouds in large-scale atmospheric models is therefore one of parameterizing their overall effects on the resolved scales.

There are a number of problems to be overcome in the parameterization of clouds. First, there exists a variety of cloud types, such as stratocumulus clouds at the top of convective boundary layers, vast cloud systems associated with extratropical disturbances, deep convective systems that may or may not be organized, and upper-tropospheric cirrus clouds. These different cloud types are formed, maintained and dissipated by different physical processes, such as convection, small-scale turbulence, large-scale ascent or descent, and cloud microphysical processes that lead to the generation of precipitation. Many of these processes are poorly understood and act on scales smaller than those resolved in a large-scale model, which makes them the subject of physical parameterization themselves. Furthermore, the radiative effects of clouds depend on a large number of different cloud parameters that all need to be described accurately to ensure their correct treatment in the radiation parameterization.

It is worthwhile pointing out that, because of their distinctive properties, cumulus and cumulonimbus clouds have been recognized as being of particular importance. This has led to (an artificial) separation of the description of the vertical transport and condensation effects from the radiative effects of convective clouds in what is now known as cumulus convection parameterizations. As will be briefly discussed below, current efforts in improving cloud parameterizations involve attempts to overcome this artificial process splitting. Furthermore, the details of the radiative transfer in clouds are normally dealt with in radiation parameterizations. Thus, typical cloud parameterizations need to

1. describe the generation and dissipation of clouds and the precipitation formed in them; and
2. provide the radiation parameterization with the necessary information to evaluate the cloud effects on the radiative fluxes, most prominently the area coverage and cloud condensate content.

Before a brief overview of how the problem of cloud parameterization can be addressed, some general concepts for any type of cloud parameterization will be outlined.

General Concepts in Cloud Parameterization

The sizes of many of the observed clouds are often significantly smaller than the sizes of the model grid boxes quoted above. Even on integration over all individual clouds in an area comparable to those grid sizes, one finds from observations that often the area is only partially covered with cloud. Since this has important consequences, especially for the radiative cloud effects, almost all cloud parameterizations describe the fractional coverage of a model grid box with cloud as one of their key parameters. Since cloud fraction is such a fundamental concept that is used in many different ways across a whole variety of cloud parameterizations, it seems worthwhile to highlight the general implications of the concept of fractional cloud cover.

Assuming that clouds form whenever the specific humidity locally exceeds its saturation value, which occurs if sufficient cloud condensation nuclei are available (see below), fractional cloud cover implies that certain parts of a model grid box become supersaturated before others. This has several implications. One of them is that clouds exist in the model grid box before the grid-mean relative humidity reaches the saturation value of 100%. This has been used in many cloud parameterizations to determine the cloud fraction by defining a critical relative humidity, RH_{crit}, above which clouds exist in a grid box and a functional relationship that increases cloud cover from zero below RH_{crit} to one when the entire grid box is saturated. It should be obvious that the definitions of both RH_{crit} and the functional relationship are far from unique and for many years cloud parameterization was nothing more than attempting to find and refine such definitions.

Another consequence of considering cloud fraction is that there must exist a distribution of the distance from the local saturation point within the model grid box. This implies some variation of humidity and temperature around their mean value. The knowledge of these variations would in fact be sufficient to describe the cloud field within a grid box. **Figure 1** provides an illustration of this idea. In a one-dimensional model 'grid box', both specific humidity, q, and its saturation value, q_s, are assumed to be nonuniform. In those areas where $q > q_s$, clouds are assumed to exist and the sum of the cloud areas divided by the size of the grid box is the total cloud fraction, a, where $a = c/x$. The mathematical technique used to describe these variations describes joint probability distribution functions for a temperature variable and a humidity variable. Unfortunately, the distribution functions are neither known nor expected to be unique and will depend on many different physical processes. Nevertheless, the introduction of the idea of distributions provides a conceptual framework for the development of cloud parameterizations.

One of the microphysical processes to be described in any cloud parameterization is the condensation process. This theoretically involves the description of two distinct processes: the nucleation of cloud particles and their initial growth by diffusion of water vapor toward the nucleated particles. It is well known that the main nucleation process in the atmosphere is that of heterogeneous nucleation of cloud particles on small aerosol particles, usually referred to as cloud condensation nuclei (CCN) (*see* **Cloud Microphysics**). In the presence of CCN condensation occurs whenever the relative humidity exceeds its saturation value of 100%, while in the absence of CCN large values of supersaturation need to exist to allow the nucleation of sufficiently large droplets. In order to avoid the complex treatment of nucleation processes, most cloud parameterizations to date assume that CCN are always available in sufficient numbers and the condensation problem reduces to removing any supersaturation. The nucleation of ice particles in the atmosphere can occur via heterogeneous or homogenous nucleation. Supersaturations with respect to ice are frequently observed in the upper troposphere, complicating the parameterization of ice clouds.

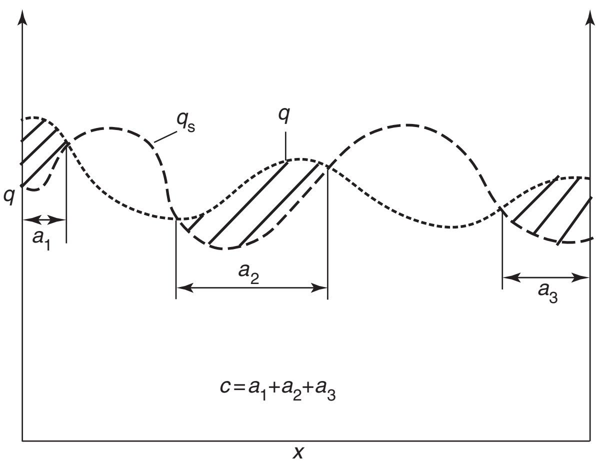

Figure 1 Schematic of the existence of clouds in the supersaturated areas of a one-dimensional model grid box. The x-axis represents space. The short-dashed line (q) shows the value of specific humidity as a function of location within the grid box. The long-dashed line (q_s) shows the saturation value of specific humidity. Areas in which $q > q_s$ represent clouds, indicated by the hatched areas.

Common Approaches to Cloud Parameterization

The previous section has established the reasons why cloud processes need to be parameterized in atmospheric models. The main effects of clouds were found to be their influence on the radiative fluxes, their latent heat effects, and the ability to transport heat, moisture, and momentum in case of convective clouds. It was also established that all but the radiative effects of convective clouds are treated in a separate convection parameterization, which is not the subject of this article. The role of clouds for atmospheric models was recognized early on, although in the first models it was mainly the latent heat effects that were considered to be important. This section gives a brief overview of the major steps in the history of cloud parameterization. The various approaches will be considered in the context of the major effects that need to be described in models. Each of the periods of development in cloud parameterization can be assessed using the following four questions.

1. How are nonconvective condensation processes on subgrid scales described?
2. How are the radiation effects of the clouds derived after answering (1)?
3. How are the convection and cloud parameterizations linked?
4. How are the microphysical processes that lead to precipitation generation described?

Table 1 provides an overview over the timeline of key aspects of the treatment of cloud-related processes in atmospheric models.

Early Condensation Schemes

In the development of early general circulation models (GCMs) in the 1960s, the latent heat effects of both convective and nonconvective condensation processes were considered. Furthermore, since the model included an evolution equation for a humidity variable, unphysical states of supersaturation needed to be avoided in the evolution of the model variables.

Table 1 An overview of the historic evolution of key aspects of cloud parameterization. The symbols are defined as follows: q is the grid-mean specific humidity; q_s is the grid mean of its saturation value; a represents cloud fraction with a_{cu} describing the contribution from convectively generated clouds to that value; l represents the condensate content, with l_{cu} again describing that in convective clouds; RH is the grid-mean relative humidity and CP is the rate of convective precipitation

	Modeling period			
	1960/70s	*1970/80s*	*1980/90s*	*Now and beyond*
Condensation (nonconvective)	$\bar{q} > \bar{q}_s$	$\bar{q} > \bar{q}_s$	l prognostic function of outcome of processes	l prognostic function of the processes themselves
Radiation effects	Prescribed zonal mean albedo and emissivity of clouds	$a = f(\mathrm{RH})/l$ prescribed	$a = f(\mathrm{RH})/l$ prognostic	a prognostic/l prognostic
Convection	No cloud interaction	$a_{cu} = f(\mathrm{CP})$ l_{cu} prescribed	$a_{cu} = f(\mathrm{CP})$ l_{cu} prescribed	Condensate and mass as sources for a and l
Microphysics	None	None	Simple bulk microphysics	Complex bulk microphysics

Therefore, a simple but effective condensation scheme was introduced into the models. Its basic idea was to readjust back to saturation any possible supersaturated states occurring on the grid scale at the end of a model time-step. The condensate thus formed was removed instantaneously as precipitation. Hence, although condensation processes and therefore their latent heat effects were described, it was not clouds but precipitation that was formed during the condensation. A similarly simple description of convection was used in which the temperature lapse rate for saturated grid columns was not allowed to exceed that of a moist adiabat. Any condensate formed in this 'moist convective adjustment' process was also removed as precipitation. The role that radiation effects of clouds play in the general circulation was considered small, so that most early GCMs used prescribed zonally averaged cloud albedos and emissivities as input for their radiation calculations. Since all condensate was removed as precipitation, no description of microphysical processes was necessary; hence, early GCMs described only condensation processes with no cloud interaction whatsoever. In fact one could argue from today's point of view that early GCMs did not parameterize clouds but precipitation. The first column in **Table 1** represents this period in the evolution of cloud parametrization.

Diagnostic Cloud Schemes

It was soon recognized that the radiative effects of clouds might play a crucial role in the general circulation of the atmosphere. The next generation of cloud parameterizations was therefore aimed at providing some interaction of cloudiness and the other model variables. This was usually achieved by parameterizing the cloud fraction as a function of relative humidity. This type of parameterization had already been proposed for early models but it was not used in GCMs until the 1980s. The reasons for this are not entirely obvious, but the difficulties of validating the model predictions of cloud fraction and the rather limited computing power available at the time were factors.

Relative humidity schemes rely on the concept that if the grid-mean relative humidity exceeds a threshold value, usually on the order of 80%, it is likely that some part of the grid volume has already reached saturation and therefore clouds start to form. If the grid-mean relative humidity reaches 100%, the entire grid box is assumed to be covered with clouds. Since all models using this approach still used the description of condensation as before, the radiative and latent heat effects of clouds were entirely decoupled. Furthermore, since condensation occurred only for grid-mean values of relative humidity above 100% but clouds existed before that, the amount of condensate needed for the description of the radiative effects of the model clouds was simply prescribed.

The development of more complex convection parameterizations allowed convectively generated clouds to be described as a function of the results of the convection parameterization. This was often achieved by linking the cloud fraction to the precipitation produced in the convection scheme and again prescribing the condensate content. The simple removal as precipitation of any moisture in excess of the saturation humidity makes the description of microphysical processes unnecessary.

This type of cloud parameterization is usually referred to as the 'diagnostic' approach, since the main cloud parameters (cloud fraction and condensate amount) are diagnosed using the grid-averaged quantities, and is represented by the second column in **Table 1**. Over the years, the basic relative humidity approach was developed, by introducing additional predictors such as vertical motion and inversion strength at the top of convective boundary layers, into the cloud fraction description. It is noteworthy that this approach provides reasonable estimates of many of the main observed cloud patterns and can be made to work well by adjusting the many free parameters in the parameterization. This, together with a low computational cost, made it a widely used parameterization approach right up to the mid-1990s.

Prognostic Condensate

One of the major drawbacks of the diagnostic approach described above is the obvious disconnection of the cloud latent heat effects from the radiative effects. Sundqvist, who introduced an additional prognostic model equation for cloud condensate, previously only applied in cloud-scale modeling, established this link in models in a parameterization. By explicitly predicting the amount of condensate formed, a link to the radiative impact of the clouds could be established through the direct use of the predicted condensate in the radiation calculations. A consistent diagnostic treatment of cloud fraction was also introduced in which the cloud fraction remains a function of the grid-mean relative humidity, which is now directly influenced by the condensation processes that are allowed to occur before grid-mean saturation is reached.

The description of convective clouds remained unaltered by Sundqvist's approach. One immediate consequence that should play a major role in the further development of cloud parameterizations is that the conversion of some of the cloud condensate to precipitation needs to be described. Very simple descriptions of the autoconversion process together with some intuitive parameterization of the precipitation-enhancing collection and Bergeron–Findeisen mechanism were used. Although simple, the use of a parameterization scheme of this kind for the first time acknowledged the need to describe microphysical processes as part of the cloud parameterization problem.

Statistical Schemes

In parallel to the introduction of what is now usually known as 'the Sundqvist parameterization', another approach emerged, based on ideas originally applied in much higher-resolution cloud models. Here, the parameterization of clouds is based on the idea outlined above that the existence of clouds on a subgrid scale requires that the humidity and its saturation value be somehow distributed around their grid-mean values. The knowledge of their probability distribution functions (PDFs) is therefore sufficient to describe both cloud fraction and condensate content within a grid box. The most common use of this idea is by means of a joint PDF for a temperature variable and a humidity variable. Since it was originally developed for the description of nonprecipitating boundary layer clouds, conservative thermodynamic variables such as liquid water potential temperature and total mixing ratio are often preferred.

Figure 2 illustrates the general idea of this approach. Liquid water potential temperature and total mixing ratio are assumed to be distributed with a joint PDF. A saturation curve for a given grid-mean temperature and pressure is then drawn. All the values of the PDF that lie above this saturation curve represent clouds and the cloud fraction and condensate content can be calculated by integrating over this part of the distribution. The crucial question for a successful application in GCMs is the definition of the distribution function itself. Different approaches were taken here using either fully prescribed and fixed PDFs or simple links of some of the distribution parameters to the turbulence parameterization. A critical issue for the use of the PDF of variables, as for those above in a GCM, is that their conservation breaks down in the presence of precipitation. Although it is of obvious importance, little discussion of this issue has taken place so far.

Since it is obvious that cloud fraction and cloud condensate content within a grid box do depend on PDFs as used in the parameterization, this approach for parameterization appears promising if the evolution of the PDF can be predicted from the evolution of

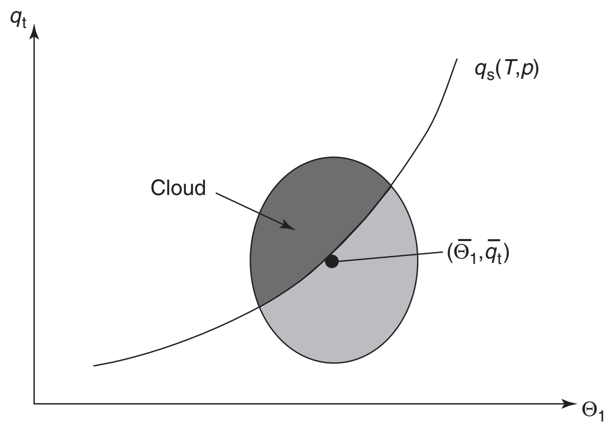

Figure 2 Schematic diagram of a possible distribution of Θ_l and q_t in a model grid box and its implication for clouds.

the resolved scales. Note that since the result of a PDF-based parameterization is a condensate content and a cloud fraction, there is a similar requirement as for the Sundqvist scheme to describe the conversion to precipitation.

Fully Prognostic Schemes

In the early 1990s a new approach to cloud parameterization emerged, in which both the time evolution of the cloud condensate and that of cloud fraction are described using prognostic equations (eqns [1a,b]).

$$\frac{\partial l}{\partial t} = A(l) + S(l) - D(l) \qquad [1a]$$

$$\frac{\partial a}{\partial t} = A(a) + S(a) - D(a) \qquad [1b]$$

In eqns [1a] and [1b], l is the grid-mean condensate content and a is the cloud fraction. $A(l,a)$ represents the advection of the two variables, $S(l,a)$ represents any sources of condensate or cloud fraction, and $D(l,a)$ represents their dissipation. This approach was pioneered by Tiedtke and has been introduced into a number of GCMs.

More recently, research has been focusing on combining the fully prognostic approach with that used in statistical schemes. Here, instead of predicting grid-mean condensate and cloud fraction, the moments of a probability density function are used as prognostic model variables and the relevant cloud parameters are deduced from the PDF as in the traditional statistical cloud parameterizations.

Contemporary Issues

Convectively Generated Clouds

Both the introduction of a prognostic variable for the description of cloud condensate and the use of a PDF-condensation scheme solve the problem of linking the latent heat effects of clouds with the macroscopic parameters entering the radiation calculations. A major remaining problem in both approaches is that they do not include clouds produced by convective processes as an integral part of their formulation. In models using either of these two cloud parameterization approaches, convective clouds are usually still treated as they were in diagnostic cloud parameterizations. Randall in 1989 identified this problem as 'the most serious deficiency of the cloud parameterizations in current GCMs'.

A variety of approaches for tackling this problem have been devised since then. The most common approach used in the schemes solving a prognostic equation for the condensate is to treat water substance detrained from convective updraughts as a source of liquid water for the 'stratiform' clouds. The exact nature of the link depends on the definition of 'detrainment' and can vary for different schemes. Although using 'detrained' condensate from convection as a source for cloud condensate has become a standard way of linking convection and radiation through cloud formation, the variety of different *ad hoc* techniques used points to a lack of understanding of how exactly this link should be represented. A further major problem is how to represent the cloud fraction resulting from the detrainment process. Recent parameterizations have attempted to derive consistent treatments of both condensate and cloud fraction from convection. Despite the progress made in this area, the inclusion of clouds generated by convective processes remains an uncertain area of active research.

Process-Oriented Approaches

More and more contemporary cloud parameterizations have moved from what can be described as an integrating approach to a process-oriented treatment of clouds. The difference between the two approaches is illustrated in **Figure 3**. **Figure 3A** summarizes the concept of integrating cloud parameterizations. Various physical processes, such as resolved scale ascent, convection, turbulence, etc. modify one or several resolved variables and/or their tendency. Those resolved quantities (e.g., relative humidity or its tendency) are then used to evaluate the evolution of the model clouds. A major drawback of this approach is that the effects of parameterized processes, such as convection, that contribute directly to cloud formation and dissipation are first 'integrated' onto the grid scale only to be reinterpreted for subgrid-scale cloud processes.

In contrast, in a process-oriented approach (**Figure 3B**) each potentially cloud-modifying process, resolved (e.g., large-scale ascent) or parameterized (e.g., convection) directly alters the model's cloud variables as well as other resolved-scale model variables. In this way information available at the level of other physical parameterizations can be directly used in the cloud scheme and the clouds become a more integral part of the parameterization package. The physically more appealing process-oriented approach to cloud parameterization significantly raises the level of complexity of the parameterization, since the influence that each physical process exerts on the model clouds needs to be explicitly described.

Cloud Microphysics

Most recently, the attention in cloud parameterization has shifted significantly toward the treatment of cloud

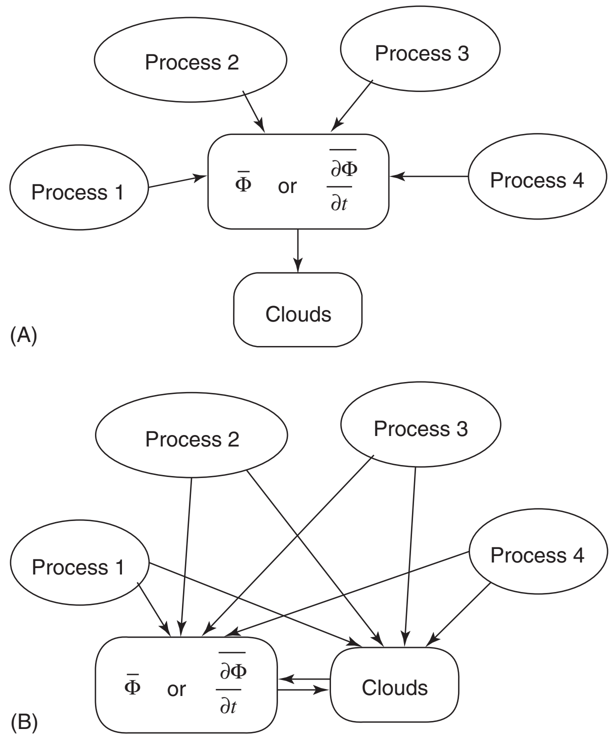

Figure 3 Schematic of the different approaches to cloud parametrization: (A) the principles of 'integrating' cloud schemes; (B) the process-oriented approach. Note that arrows indicating the obvious direct interactions between individual processes other than cloud processes have been omitted for clarity.

microphysics. This has been facilitated by increased computing power and the availability of sophisticated microphysics parameterizations from cloud-resolving and meso-scale numerical models. Although increased sophistication in describing precipitation processes in GCMs is certainly justified, the transplantation of a microphysics scheme from a cloud-resolving model to a GCM is not without problems. This is mainly due to the scales at which the input variables of the microphysical scheme are available and to the difference in time steps used by the different models. Microphysical processes are highly nonlinear and their parameterization has to rely on the knowledge of the local amount of condensate. In GCMs only the grid-mean value (or cloud-mean value if cloud fraction is a model variable) for condensate is known. This has led to the need for significant modifications to microphysical constants in the parameterizations in order to achieve reasonable cloud condensate and precipitation amounts. The detailed treatment of microphysical process would also require the use of very short model time steps. Since GCMs are used either at high resolution in numerical weather prediction or for long integrations in climate research, the use of such short time steps might be prohibitive and alternative solutions need to be found.

With increasing horizontal and vertical resolution, the concept of cloud fraction becomes less important and grid-point values of cloud condensate are more representative for local conditions. Hence, in numerical models with horizontal resolutions of less than a few kilometers it is common to apply more complex and physically more realistic parameterizations of cloud microphysics. This is usually achieved by introducing additional condensate species (e.g., graupel, hail) and a more realistic description of the microphysical processes themselves (e.g., a separate description of nucleation and deposition; a description of riming). For more details on cloud microphysical processes (*see* **Cloud Microphysics**).

See also

Cloud Microphysics. **Clouds:** Classification; Climatology; Measurement Techniques *In Situ*. **Convection:** Laboratory Models of. **Convective Cloud Systems:** Modelling. **General Circulation:** Models. **Weather Prediction:** Regional Prediction Models.

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