# Cloud parametrization - Progress, Problems and Prospects

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## 1 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:

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

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.

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. In order to describe the main effects clouds have on the atmosphere as they were outlined above, the following cloud-related quantities need to be known in a GCM

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

It is obvious from this list that many of these imply 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 parametrizing their overall effects on the resolved scales. There are a number of problems to overcome in the parametrization of clouds. First of all there exists a variety of cloud types,

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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 a large number of 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 only poorly understood and act on scales smaller than those resolved in a large-scale model, which makes them the subject of physical parametrization themselves. Furthermore, the radiative effects of clouds, one of the main purposes for their parametrization, depend on a large number of different cloud parameters that all need to be described accurately to ensure their correct treatment in the radiation parametrization.

It is worthwhile pointing out, that the atmospheric impact of transport processes in convective clouds has been recognized as being of particular importance. This has led to an (artificial) separation of the description of those effects from the radiative effects of convective clouds in what is now known as cumulus convection parametrizations. As will be briefly discussed below current efforts in improving cloud parametrizations involve attempts to overcome this artificial process splitting. However, since most existing cloud parametrizations do not deal with the description of convective transport processes, the remainder of this paper will also not discuss issues related to them. Furthermore the details of the radiative transfer in clouds are normally dealt with in radiation parametrizations. Thus typical cloud parametrizations need to

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

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

## 2 The general problem

The size of many of the observed clouds is significantly smaller than the sizes of GCM grid-boxes. Even when integrated 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 (e.g., Warren et al., 1986; Warren et al. 1988; Rossow and Schiffer, 1999). Since this has important consequences especially for the radiative cloud effects, almost all cloud parametrizations 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 parametrizations, it seems worthwhile to highlight its general implications.

Assuming that clouds form whenever the specific humidity locally exceeds its saturation value, a common assumption in all cloud parametrizations today but only true if sufficient Cloud Condensation Nuclei (CCN) are available, 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 parametrizations 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 definition of both $RH_{crit}$ and the functional relationship are far from unique and for many years cloud parametrization was nothing more than attempting to find and refine such definitions.

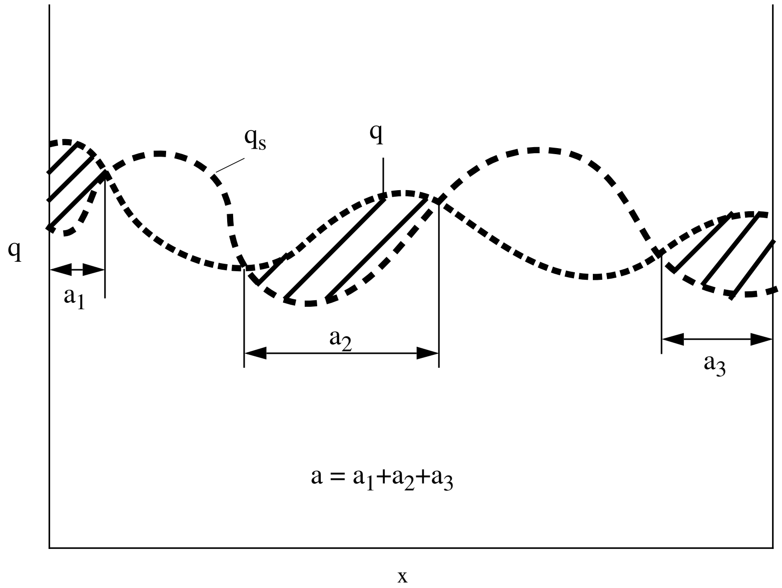

Figure 1: Schematic of the existence of clouds in the supersaturated areas of a one-dimensional model grid box. The x-axis represents space. The short-dashed line ($q$) shows the value of specific humidity as a function of location with in the grid-box. The long-dashed line ($q_s$) shows the saturation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

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. 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 non-uniform. 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. It is obvious from Figure 1 that the knowledge of the temperature and humidity variations within a grid box is not only useful to describe the cloud fraction, but would be sufficient to describe the cloud field within a grid box, when combined with a description of cloud microphysical processes. This is so since the distance from the saturation point at each point within the grid box yields the potential cloud water/ice content, which will subsequently be modified through the generation and fallout of precipitation. The mathematical technique to describe these variations is to describe joint probability distribution functions for a temperature and a humidity variable. Unfortunately these 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 parametrizations (see next section).

## 3 APPROACHES TO CLOUD PARAMETRIZATION

The general design of cloud parametrizations can be distinguished in four classes characterized by two attributes. One attribute is whether the the parametrization scheme is *diagnostic* or *prognostic*, the other is whether the scheme is *integrating* or *process-oriented* as defined in Jakob (2001). The following paragraphs will first identify the general meaning of these attributes and then provide examples for each of the four classes. Another criterion used frequently in the literature to distinguish classes of cloud parametrizations is *statistical* versus *non-statistical*. Given the discussion in the previous section it should be obvious that all cloud parametrizations are statistical in nature and therefore a distinction as above appears not useful. As will be highlighted below reference to a statistical cloud parametrization is usually made for schemes that *explicitly* describe the moments of probability distribution functions compared to those that do not. It will be shown that these parametrizations can be grouped within the classification scheme proposed here. Note however, that as with any classification scheme there are parametrization schemes who will lie on the boundary between the classes used here.

For simplicity it will be assumed that the cloud parametrization provides two variables as its result, the cloud fraction ($a$), and the cloud condensate content ($l$). Modern cloud parametrizations can and do provide more information, such as a separate cloud water and ice content and/or several species of precipitation (e.g., Lohmann and Roeckner, 1996; Fowler et al., 1996). Although important for the individual parametrization schemes, these details are omitted for the more general discussion here.

### 3.1 Diagnostic vs prognostic

In a diagnostic cloud parametrizations the vector of the cloud variables is deduced as a diagnostic function of other model variables, i.e.,

$$a = f_1\left(\Phi_1, \ldots, \Phi_n, \frac{\partial \Phi_1}{\partial t}, \ldots, \frac{\partial \Phi_n}{\partial t}\right); \quad l = f_2\left(\Phi_1, \ldots, \Phi_n, \frac{\partial \Phi_1}{\partial t}, \ldots, \frac{\partial \Phi_n}{\partial t}\right). \tag{1}$$

This approach makes the strong assumption that the state of the cloud field is uniquely determined by other variables (known in the model) and does not depend on the state of the cloud field at some earlier time. The parametrization task for such schemes is to find functional relationships between the cloud and other variables so that the state of the cloud field is fully determined.

In prognostic cloud parametrizations the assumption of a instantaneous functional relationship between the cloud field and other variables is not made. Instead the time evolution of the cloud field is calculated using evolution equations of the form

$$\frac{\partial a}{\partial t} = A(a) + S(a) + D(a); \quad \frac{\partial l}{\partial t} = A(l) + S(l) + D(l), \tag{2}$$

where $A(*)$ describes the advection of the cloud variable, $S(*)$ represents the sources and $D(*)$ the sinks of the cloud variable (e.g., precipitation is a sink for cloud condensate). It is trivial to write equations of the form in (2). The difficult and main part of the parametrization problem in this approach is to find parametric descriptions of the source and sink terms in the equations. Note that although in this example $a$ and $l$ refer to cloud fraction and cloud condensate, those are not necessarily the only possible prognostic variables used in cloud parametrization (see below).

### 3.2 Integrating vs process-oriented

An important distinguishing feature of cloud parametrizations is how much direct use is made of the sub-grid scale information provided by the other parametrization schemes, such as those for convection and the boundary layer. A simplified view of process-orientation of cloud parametrizations is given in Figure 2.

Many early cloud parametrizations can be described as "integrating" parametrizations represented by the top panel of Figure 2. Various physical processes, such as resolved scale ascent, convection, turbulence etc., modify one or several resolved variables and/or their tendency. Those resolved quantities

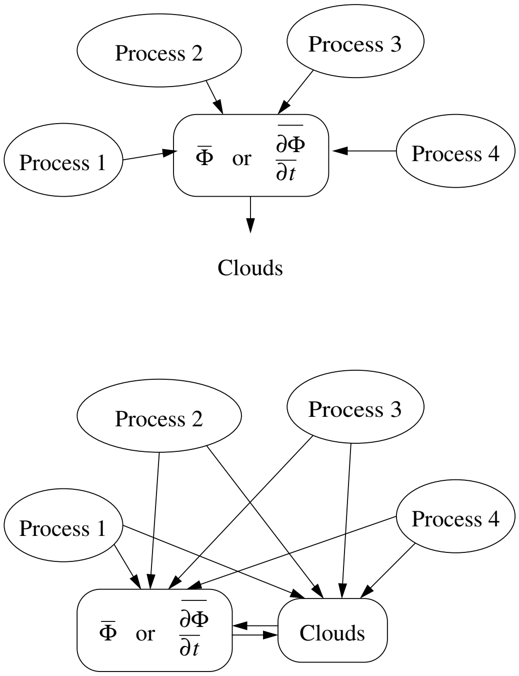

Figure 2: Schematic of the different approaches to cloud parametrization. The top panel shows the principles of "integrating" cloud schemes, while the bottom panel illustrates the process-oriented approach.

(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 parametrized processes, such as convection, which 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 the process-oriented approach, each potentially cloud-modifying process, resolved (e.g., large-scale ascent) or parametrized (e.g., convection), directly alters the model's cloud variables as well as other resolved-scale model variables. This way information available at the level of other physical parametrizations can be directly used in the cloud scheme and the clouds become a more integral part of the parametrization package. This approach is illustrated in the bottom panel of Figure 2.

### 3.3 Some examples

The classic example for a *diagnostic integrating* scheme is the relative humidity scheme (e.g., Geleyn, 1980). Here cloud fraction is derived solely from the grid-mean relative humidity. Realising that relative humidity alone was not a good predictor of clouds, Slingo (1987) was the first to design a *diagnostic process-oriented* cloud parametrization. This parametrization still used relative humidity as a major predictor, but added additional information, most notably on the large-scale vertical velocity and convective activity, to the diagnosis of cloud properties.

The first *prognostic* cloud parametrization was designed by Sundqvist (1978) and was essentially *integrating* in nature. With the introduction of cloud condensate as a prognostic variable cloud parametrizations for the first time had to include simple descriptions of cloud microphysical processes describing the conversion of cloud size particles into precipitation. The description of these processes has been a major challenge since. Another example for a prognostic integrating scheme is the parametrization of Smith (1990) and derivatives of it (e.g., Ricard and Royer, 1993; Rotstayn, 1997). Here the grid-mean values of variables that are conserved in some thermodynamic processes, such as liquid water temperature and total water content (the sum of water vapour and cloud condensate), are predicted. Then an assumption about their sub-grid scale distribution is made to derive which parts of the grid box are cloudy and how much condensate is contained in them.

Most of the more recent cloud parametrization schemes fall into the *prognostic process-oriented* category. Examples for such schemes can be found in Tiedtke (1993), Fowler et al. (1996), DelGenio et al (1996), Bony and Emanuel (2001), and Tompkins (2002). The early schemes of this category use the parametrized cloud parameters (e.g., cloud fraction and condensate content) directly as the prognostic variables. In more recent schemes (e.g., Tompkins, 2002) it is the moments of the distribution function of total water that are the prognostic variables, which can then be used to derive various cloud parameters.

The most notable contribution of all process-oriented approaches is the attempt to closely link the parametrization of clouds to that of convection, one of the major cloud generating processes in the atmosphere. Marked as one of the major difficulties in cloud parametrization in the late 1980's (Randall, 1989), the more explicit link of these two related parametrizations is probably the biggest achievement of this type of parametrization.

## 4 Current key issues

There are many facets of the cloud parametrization problem that remain unsolved or "solved" in unsatisfactory ways. It is difficult at best to pick and prioritize these issues mainly because of gaps in our understanding of some of the crucial cloud processes and because of insufficient understanding of which of the many problems encountered will, when addressed, provide the most benefit to simulations of weather and climate. The short list of issues provided here is far from comprehensive and the choice of its content is largely subjective.

### *Cloud inhomogeneity*

The by far most discussed current issue in cloud parametrization is the representation of what has been loosely termed "cloud inhomogeneity". The issue arises from the fact that many processes, such as the radiative transfer in clouds and microphysical processes, depend nonlinearly on cloud parameters, such as the condensate content. Hence, if these parameters are non-uniformly distributed within a model grid box, representing them by only their mean value will invariably result in errors in the simulation of cloud effects. Barker et al. (1996), amongst others, have shown that the cloud albedo calculated using grid-average cloud properties can overestimate the true albedo of an inhomogeneous cloud field by more than 30%. Pincus and Klein (2000) have shown that errors in the process rate when using assumed homogeneous clouds depends strongly on the non-linearity of the relationship in question and can reach up to 100% in relations typically used for the parametrization of microphysical processes.

Cloud inhomogeneity is mainly discussed as horizontal variability. However, cloud fields do also show large variations in the vertical. Some of this vertical variation is resolved by GCMs, since many of them predict cloud fraction as a function of height, but other obvious vertical variations (e.g., the increase of the adiabatic condensate content with height) are currently neglected. Jakob and Klein (1999) showed that although available, the information on the vertical cloud fraction variations were usually not used correctly in microphysical calculations, leading to large errors in precipitation rates. They proposed a parametrization to remedy the problem in the ECMWF model (Jakob and Klein, 2000).

Tiedtke (1996) was the first to attempt to address some of the inhomogeneity issues for radiative transfer in a GCM by introducing a simple parametrization of their effect. Large efforts have since been made to address cloud inhomogeneity in radiative transfer (e.g., Kato et al., 2001, Fu et al. 2000, Oreopoulos and Barker, 1999) and more importantly, to introduce a consistent description of the horizontal variability of cloud parameters in the parametrizations (e.g., Bony and Emanuel, 2001; Tompkins, 2002)

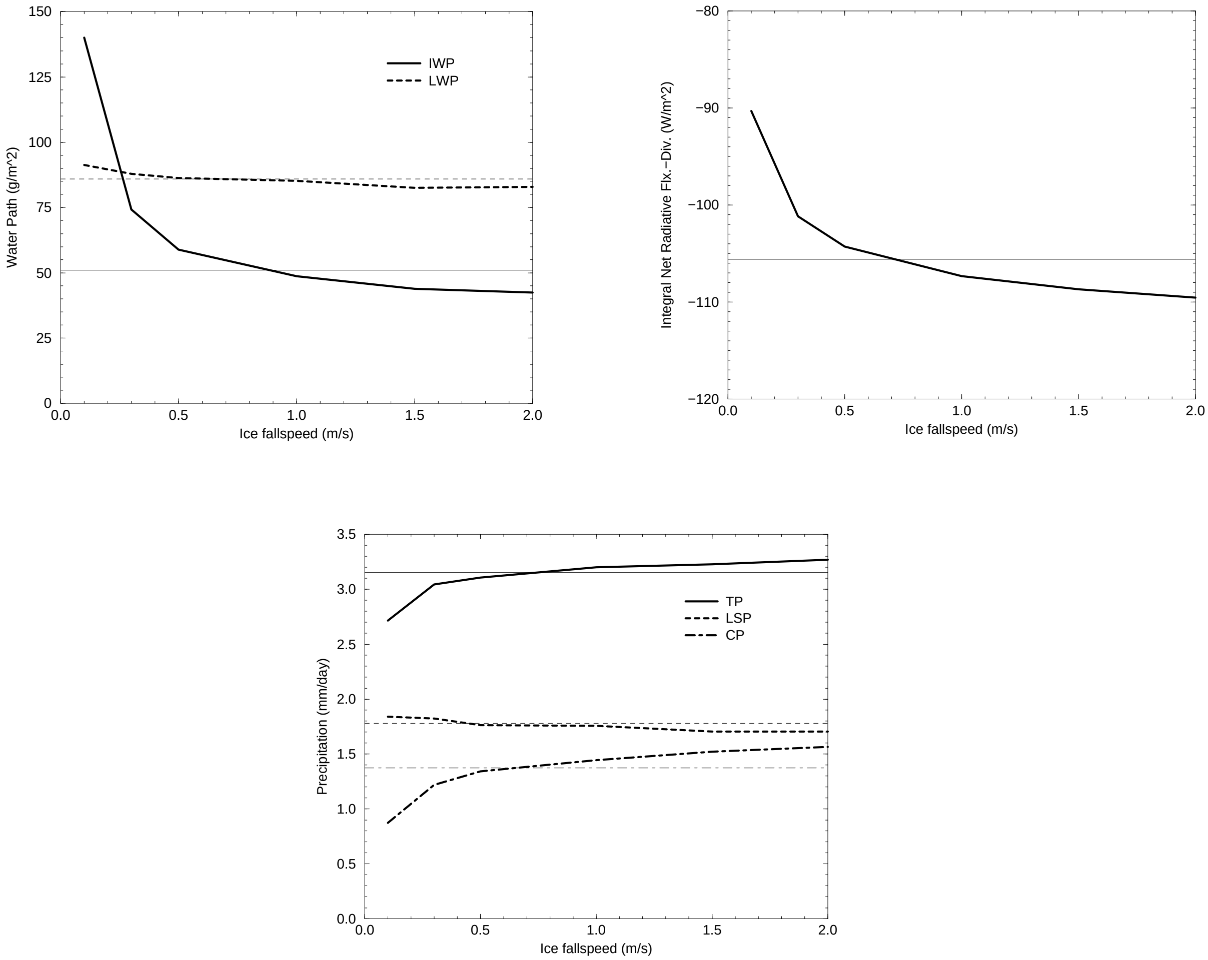

Figure 3: Three-months averages (JJA87) of the global means of ice water/liquid water path (top left), integral radiative flux divergence (top right) and precipitation (bottom) in a T63L31 version of the ECMWF model as a function of the assumed fallspeed for ice. Control model results are shown as horizontal lines. Precipitation is shown as total (TP), convective (CP) and large-scale (LSP) precipitation. From Jakob (2002).

*Ice clouds*

One of the most important and yet least understood group of clouds are those composed of ice crystals (Note that often the term cirrus is used to describe this class of clouds, but there are many more ice clouds than just cirrus). Their importance results from their large effects on the radiative fluxes in the atmosphere, in particular in the longwave part of the spectrum. Since they reside high in the atmosphere they move the effective radiative surface to colder temperatures, thereby giving rise to an additional greenhouse effect. It is this effect that potentially makes them important regulators of climate and various regulation mechanisms involving tropical cirrus, such as the thermostat (Ramanathan and Collins, 1991) and iris effect (Lindzen et al, 2001) have been proposed.

Figure 3 (adapted from Jakob, 2002) illustrates the importance of ice clouds for climate using idealized experiments with the ECMWF model (4-months integrations using a T63L31 version of the model; results are for June/July/August (JJA) 1987). In these experiments the sedimentation velocity of ice particles was varied from 0.1 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$. The response of several global mean parameters to the change in fallspeed are shown in the figure. Note that most of the influence on these parameters results from changes in tropical latitudes (not shown). The top left panel indicates that by reducing the fallspeed of ice, the ice water path is increasing, while the liquid water path is hardly affected. A direct consequence of the increased ice water path is a decrease in the net radiative flux divergence (or radiative cooling of the atmosphere) shown in the top right panel of Figure 3. With the decrease of radiative cooling a marked decrease in precipitation, resulting entirely from a decrease in the convective component, is observed. This is indicative of a strong feedback process induced by increasing the residence time of ice in the upper troposphere, through a change in the radiative forcing onto the convection in the model.

Showing that a model is very sensitive to processes in ice clouds does not necessarily make them a major issue for cloud parametrization. If their occurrence and microphysical and radiative effects were well understood, a parametrization could be designed. However, ice clouds are probably the poorest observed in the entire spectrum of clouds. This is mainly due to the inaccessibility to both in-situ measurements and passive remote sensing from space (Stephens et al, 1998a). This is the reason that to date there is only very indirect information on the global distribution of cloud ice (Lin and Rossow, 1996). More recently the use of active ground-based remote sensing (e.g., Sassen and Mace, 2002 and references therein) has improved our knowledge, but it will be until space-borne remote sensing instruments are available on satellites such as the planned CloudSat satellite (Stephens et al, 1998b) before better knowledge of the global distribution of cloud ice will emerge.

### *Convective clouds*

Figure 4 shows the error in net solar radiation at the top of the atmosphere for a T63L31 simulation for JJA 1987 with a recent version of the ECMWF global model (CY23R3). Areas shaded in green and blue indicate an overestimation of the reflected solar radiation, orange and red colours indicate an underestimation. A striking feature of this figure is that by far the largest errors occur in regions in which predominantly convective clouds are observed, such as the Intertropical Convergence Zone (ITCZ; strong overestimation of reflection), the trade-cumulus areas (overestimation) and in the stratocumulus (a convective cloud in the broader sense) regions (strong underestimation).

It has been highlighted above that modern cloud parametrizations aim to include the effects of convection on cloud generation and dissipation directly in their formulation. Convective transports of mass, heat, total water (water vapour + condensate) and momentum are classically simulated with a cumulus parametrization scheme. Including cloud effects in those schemes requires them to not only describe these transport terms, but additionally that of cloud mass and condensate separately. The latter requires reliable parametrizations of microphysical processes within the models of convective draughts, a problem that is probably even more complex than describing them in the relatively quiescent regions of stratiform clouds. Some efforts in improving the description of microphysical processes have been made (e.g., Donner et al., 2001). Apart from microphysical processes, the description of the generation, transport and evaporation of cloud condensate poses new challenges to cumulus parametrization. It is probably fair to assume that a substantial part of the progress in simulating clouds in GCMs will depend on improvements in the cumulus parametrizations themselves and their coupling to cloud processes.

### *Cloud overlap*

As mentioned above, today's cloud parametrizations tend to predict cloud properties, including cloud fraction, at all of their model levels. In the calculation of both radiative transfer and precipitation,

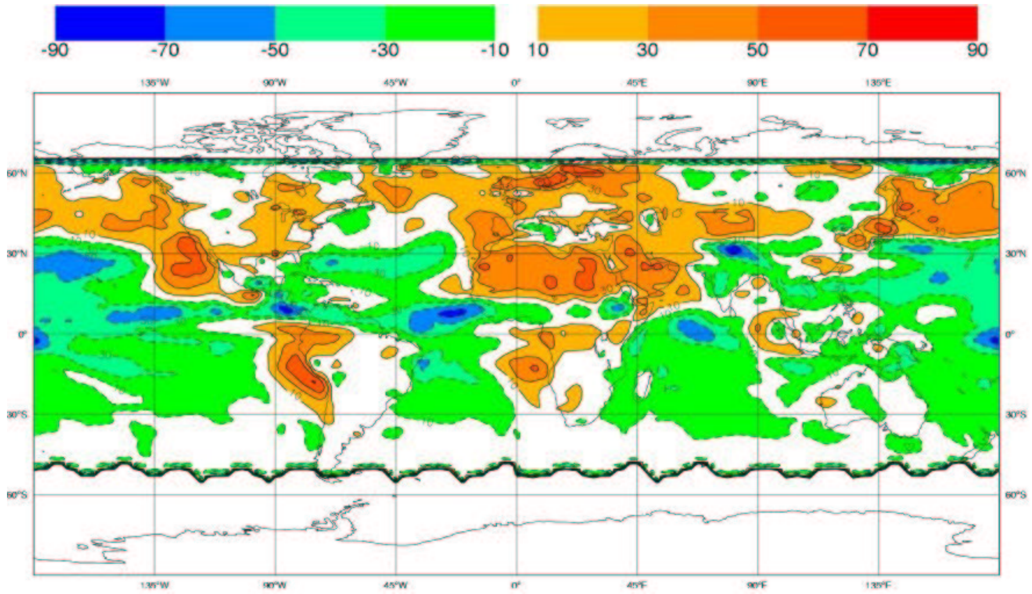

Figure 4: Solar radiation error (model long integration minus ERBE climatology) of ECMWF model cycle 23R3 for JJA 1987.

the individual cloud layers need to be aligned and this alignment will affect the outcome of those calculations. The method of aligning individual cloud layers is usually referred to as the cloud overlap. The three most common rules for cloud overlap used in GCMs are illustrated in Figure 5.

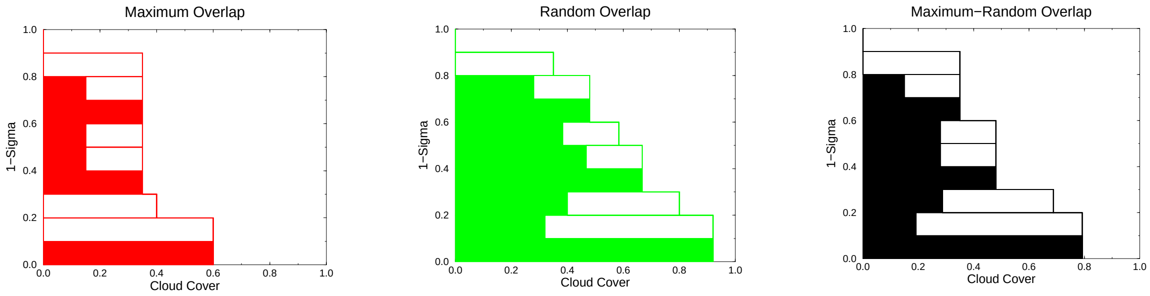

Figure 5: Illustration of the maximum (left), random (middle) and maximum-random (right) overlap assumption. White blocks indicate clouds at individual layers. Right from the white blocks there is clear sky above. The shaded areas indicate cloud free layers that are affected by clouds at other layers in the radiation computations.

Research has recently refocussed on the cloud overlap problem (e.g., Morcrette and Jakob, 2000) for a number of reasons. Firstly, the increase in vertical resolution in GCMs may require a rethinking of the cloud overlap descriptions from their original application to the very few cloud layers early cloud parametrizations predicted. Secondly, cloud overlap has been shown not only to affect the radiative calculations but also those of precipitation processes (Jakob and Klein, 1999, 2000). Most importantly though, attention has resulted from the availability of information on the vertical structure of cloud fields from observations made with ground-based cloud radars (e.g., Mace and Benson-Troth, 2002; Hogan and Illingworth, 2000, Hogan et al., 2000, Mace et al., 1998), which allow the evaluation of the overlap parametrizations currently in use in GCMs.

*Other issues*

As indicated at the beginning of this section, there is a large number of issues not discussed above, many of them probably equally important as those discussed. These include the *evaluation* of cloud parametrizations, the parametrization of *microphysical processes*, and the *numerical treatment* of the cloud processes in model, to name but a few. For discussions on these issues the reader is referred to the references provided here and in Jakob (2001).

## 5 SUMMARY

The main purpose of this brief and necessarily incomplete overview of the cloud parametrization problem was to provide the reader with some background on the history and current active research areas. It has been shown that considerable **progress** has been made moving from the early *diagnostic integrating* cloud schemes to the more recent *prognostic process-oriented* approaches. Nevertheless a large number of **problems** remain to be solved, as a quick look at Figure 4 reveals. The consistent treatment of cloud inhomogeneity for both radiative transfer and cloud microphysics, the integration of cloud and convection parametrization into one coherent description of transport and cloud processes, the representation of cloud microphysics and the validation of both assumptions and results of cloud parametrizations using observations will remain challenges for years to come. Recent progress in combining prognostic cloud schemes with the explicit description of the distribution of water vapour and/or temperature (e.g., Tompkins, 2002) could provide a solution for a consistent inhomogeneity treatment highlighting one of the many **prospects** for new ideas to address some of the key issues discussed here.

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