CRITICAL ASPECTS OF CLOUD-PARAMETRIZATION IN LARGE-SCALE MODELS

M Tiedtke
European Centre for Medium-Range Weather Forecasts

Summary

Accurate representation of cloud processes has been recognized as a major problem in climate modelling and numerical weather forecasting. However, progress in this field has been slow and there are still many unsolved problems. In this paper we discuss three critical aspects of cloud parametrization:

1. There is still uncertainty about the basic modelling approach. Although it is generally agreed that parametrization should be process oriented, i.e. formation and dissipation of clouds be based on cloud processes, cloud variables are defined empirically in almost all models (diagnostic and semi-prognostic schemes). A fully prognostic scheme being developed at ECMWF is described and compared with conventional schemes.

2. Success of cloud modelling with fully prognostic schemes depends critically on the ability of large-scale models to accurately represent adiabatic and diabatic processes associated with clouds. The question of accuracy of the relevant processes is discussed in the context of the ECMWF prognostic cloud scheme.

3. An area of great uncertainty and likely cause for systematic model errors is the simplifying assumption concerning the representation of cloud fields. Present cloud schemes predict only grid averages of cloud properties for the radiative transfer calculations and therefore spatial variabilities of liquid water content due to the inhomogeneous and heterogeneous character of clouds are ignored. The neglect of cloud variabilities may introduce large errors in shortwave radiative fluxes. A parametrization which accounts for subgrid scale variations of liquid water content has been developed for the ECMWF global model.

1. INTRODUCTION

In this paper we focus on critical aspects of cloud modelling in large-scale models. First of all there is the question of the basic approach to cloud parametrization. Cloud parametrization is still rather empirical despite considerable efforts during the last two decades to improve cloud schemes. Cloud cover is diagnosed from model variables (i.e. relative humidity, vertical velocity, static stability etc) and cloud water content is either diagnosed (e.g. *Slingo*, 1987) or treated semi-prognostically (e.g. *Smith*, 1990). Little progress has been made towards the aim of a physically based approach, where cloud formation is determined from adiabatic and diabatic processes. This is because cloud formation depends critically on the realistic treatment of cloud related processes such as advective transports, subgrid scale processes, cloud microphysics and cloud optical properties. All of these processes may contain large uncertainties. The uncertainties are particularly large for parametrized processes, most noticeable cumulus convection and boundary layer turbulence. There is the further difficulty in interfacing the cloud scheme and these parametrizations. Some progress has been made recently regarding the interface with convection as shown for the ECMWF prognostic scheme (*Tiedtke*, 1991 and 1993).

One of the unsolved problems of cloud parametrization is how to account for spatial variabilities in cloud optical properties in the calculation of grid-mean radiances. At present radiative transfer is calculated with a two-stream method under the assumption of horizontally homogeneous conditions. Thus, clouds are represented simply by cloud amount and grid mean cloud water content ignoring subgrid scale variations. Errors arising from this simplification can be large (e.g. *Harshvardhan and Randall*, 1985) and current general circulation models have to use unrealistically small cloud water amounts to produce realistic albedos. The effect of inhomogeneity on albedo appears to be quite large already for marine stratocumulus clouds which are probably the closest of all cloud types to homogeneous conditions. *Cahalan et al* (1994) have estimated from observational data of liquid water amounts that mean albedo values are reduced by about 15% due to horizontal variations in the vertically integrated liquid water path. In order to reproduce the same reduction in a GCM with plane parallel assumption the mean liquid water content would have to be reduced effectively by 30% of its value. In the simple parametrization described in section 4 we shall account for the effect of inhomogeneity by rescaling the model cloud water content by 30% (*Calahan et al*, 1984). We shall do so for all cloud types realizing that inhomogeneities may be much larger in convective clouds.

Cloud water variations within a grid box of a GCM can be even larger in cases where clouds of different liquid water content occur simultaneously within the same grid box. This is a common situation in tropical and subtropical regions where cloud fields contain active convective clouds of relatively small area coverage but high water content and at the same time stratiform clouds of small liquid water content. Plane uniform radiative calculation based on average liquid water contents would in these situations produce large albedo errors. In order to reduce model biases in radiances a parametrization is being developed at ECMWF to represent convective and stratiform clouds.

2. BASIC APPROACH OF CLOUD PARAMETRIZATION

Cloud parametrization in present GCMs and numerical weather forecast models is still rather empirical. Cloud cover is determined diagnostically in all schemes and cloud liquid water content has only recently been treated as a prognostic variable in some schemes.

In diagnostic cloud schemes (e.g. *Slingo*, 1987) cloud cover and cloud liquid water content are determined from the model's large-scale parameters such as relative humidity RH, vertical velocity ω and static stability S. Diagnostic schemes are attractive because they are simple and yet quite successful in reproducing some of the gross features of the global cloudiness. However, they lack a sound physical basis and therefore have several shortcomings:

a) Incomplete hydrological cycle as storage and reevaporation of cloud liquid water is not considered.

b) Uncertainty of the diagnostic relationships in synoptic conditions for which they had not been tested (e.g. relevant in the context of climate change).

c) Necessary retuning of the diagnostic relationships in cases of model changes affecting the input parameter (e.g. RH) for the cloud scheme.

d) No realistic representation of cloud formation due to cumulus convection.

Present prognostic schemes are more realistic as the hydrological cycle becomes more complete. However, deficiencies b) to d) remain as cloud cover is still determined diagnostically and cloud liquid water content follows statistical distributions (s. for example *Smith*, 1990).

In view of the inadequacies in present cloud modelling a more realistic parametrization has been developed at ECMWF. The new scheme is fully prognostic, i.e. cloud formation and dissipation are determined directly from model processes. In the following section we present a brief description of the scheme (s. *Tiedtke*, 1993 for details) and discuss uncertainties in the parametrization.

2.1 ECMWF prognostic cloud scheme

In the scheme, cloud water/ice content and cloud cover are determined from prognostic equations which follow from the mass balance equations for cloud water/ice content

$$\frac{d}{dt}\int \rho_w dV = S_w - D_w \tag{1}$$

and cloud air

$$\frac{d}{dt}\int \rho dV = S_\rho - D_\rho \tag{2}$$

where ρ_w and ρ are density of cloud water/ice and cloud air, respectively. Equations (1) and (2) are transformed into prognostic equations for the grid mean values of cloud water content l and cloud cover a respectively. The equation for the time change of the grid averaged cloud water/ice content is

$$\frac{\partial l}{\partial t} = A(l)+S_{cv}+S_{BL}+C-E-G_p-\frac{1}{\rho}\frac{\partial}{\partial z}(\rho w'l')_{Entr}. \tag{3}$$

$A(l)$ represents transports of l through the boundaries of the grid volume, C is the condensation/sublimation rate, E is the rate of evaporation of cloud water/ice, G_p is the rate of generation of precipitation by conversion of cloud droplets into raindrops and deposition of cloud ice, S_{cv} and S_{BL} are the sources of cloud water/ice from convection and boundary layer turbulence respectively, and the last term is the flux divergence due to entrainment processes at the top of stratocumulus clouds.

The prognostic equation for cloud cover a is

$$\frac{\partial a}{\partial t} = A(a)+S(a)_{cv}+S(a)_{BL}+S(a)_C-D(a). \tag{4}$$

$S(a)_{cv}$, $S(a)_{BL}$ and $S(a)_c$ represent the formation of cloud area by convection, boundary layer turbulence and condensation processes respectively and $D(a)$ is the rate of decrease of cloud area due to evaporation.

It should be noted that the scheme has two prognostic equations and, in contrast to other prognostic schemes, predicts cloud water content l as well as cloud cover a. The time evolution of the cloud variables is determined entirely from forcing terms and therefore the quality of cloud prediction depends on the accuracy of these terms. Cloud formation/dissipation processes which depend on processes that are resolved (e.g. large-scale vertical velocity) are presumably more accurate than those due to parametrized subgrid scale processes (e.g. cumulus convection, radiative heating). Cloud dissipation by precipitation processes and turbulent mixing have to be specified from additional closure assumptions whereby uncertainties are introduced. In the following sections we shall briefly describe the parametrization of the various processes of cloud formation and cloud dissipation and discuss the uncertainties involved.

2.2 Cloud formation by cumulus convection

Cumulus convection can produce clouds of various types such as precipitating and non-precipitating cumuli, cumulonimbus clouds and anvil- and cirrus-clouds. These clouds are difficult to represent in large-scale models and present parametrizations are often unrealistic. In conventional schemes convective clouds are treated either as stratiform clouds (e.g. *Smith*, 1990) or are linked to the convective precipitation rate (e.g. *Slingo*, 1987) which is inadequate for non-precipitating cumuli and anvil/cirrus clouds originating from cumulus convection.

The new scheme provides a more realistic treatment of convective clouds as the evolution of clouds is linked to the formation of condensates produced in cumulus updraughts and detrained into the environmental air. The representation of cloud formation by convection is rather straightforward if cumulus convection is parametrized by means of a massflux scheme (e.g. *Tiedtke*, 1989) because the detrainment terms are readily available:

$$S_{cv}=\frac{D_u}{\rho}l_u \tag{5}$$

$$S(a)_{cv}=(1-a)\frac{D_u}{\rho}. \tag{6}$$

Uncertainties: Accurate cloud formation by cumulus convection is of primary importance for cloud modelling in large-scale models, since a) a large part of global cloudiness is of convective nature and b) more cloud liquid water is produced through cumulus convection than by all other processes together (s. Fig 1). Accuracy of the scheme is difficult to assess, but tests performed so far seem to indicate its

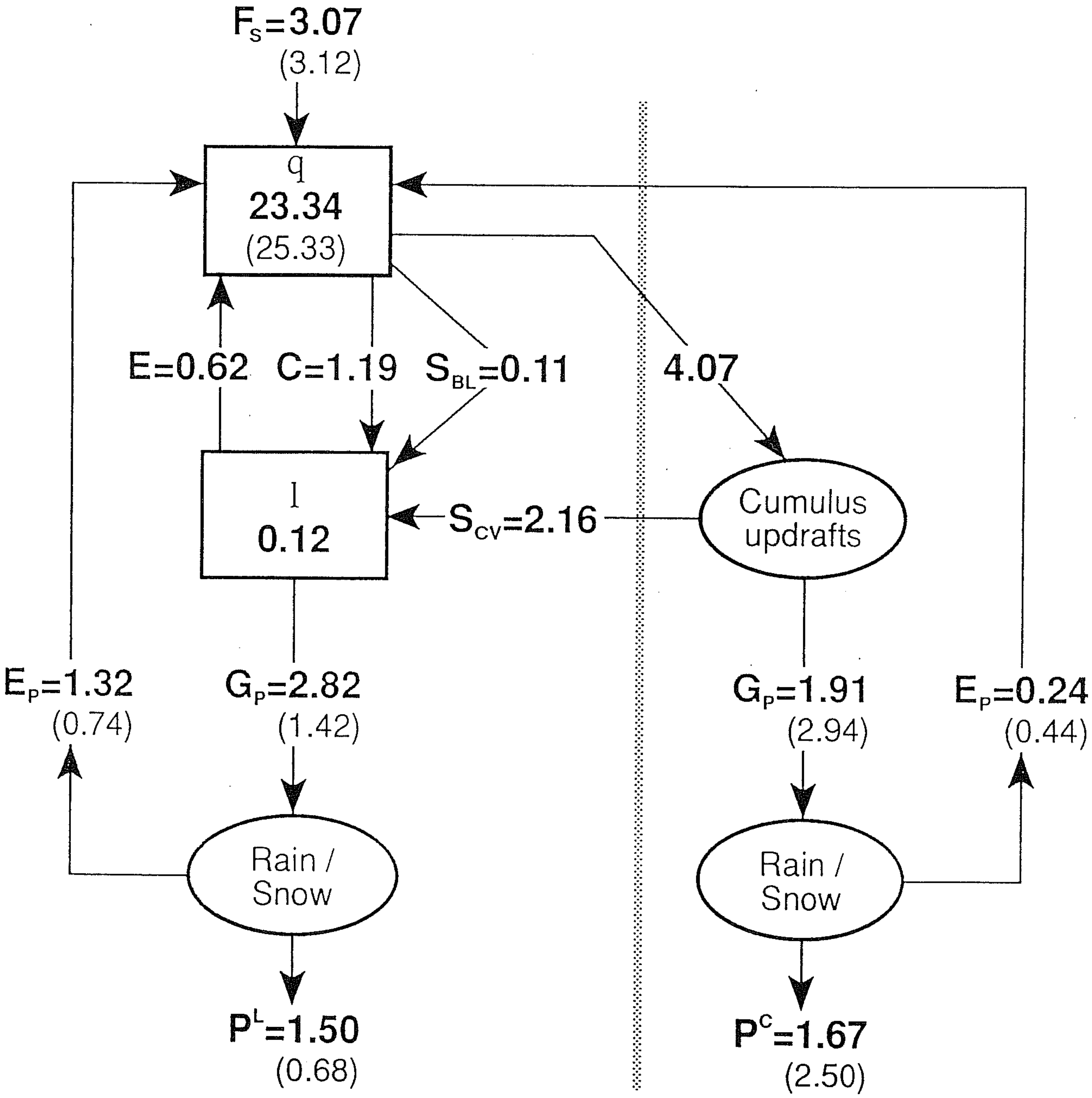

Fig 1 Hydrological cycle: globally averaged values of atmospheric water vapour q(mm), cloud liquid water content 1(mm) and conversion (mm/d) between water vapour, cloud water and rain/snow in stratiform clouds (left) and in cumulus updrafts (right) for integration with prognostic cloud scheme (forecast from 1.7.87, 12Z, T63L31). Values in brackets are for ECMWF operational cloud scheme (s *Tiedtke*, 1993).

superiority over the ECMWF operational diagnostic cloud scheme in several aspects:

a) It provides a more realistic time evolution of anvils and cirrus clouds originating from penetrative convection (Fig 2).

b) The hydrological cycle is more complete (Fig 1), with significant benefits to the precipitation characteristics and vertical humidity profiles in tropical regions (s. *Tiedtke*, 1993).

Improvements a) and b) can be attributed to the more realistic formation of anvil/cirrus clouds from penetrative convection. Thus coupling the formation of stratiform clouds to the model's convection scheme is an important extension of the model's cumulus parametrization. However, apart from the apparent advantages over the diagnostic approach, cloud formation by cumulus convection is likely to contain large uncertainties because cumulus parametrization itself is uncertain. In the context of the cloud scheme we have to remember that vertical profiles of updraught massflux and liquid water content required in (5) and (6) are determined empirically.

2.3 **Formation of boundary layer clouds**

The parametrization is based on the observation that the occurrence of boundary layer clouds is closely connected both to the turbulent moisture flux from the sea and to the cloud circulation which are the principal transport mechanisms for heat and moisture. Cloud transports are represented in the framework of the massflux approach similar to trade cumulus regimes; for example for moisture we have

$$F_q = \rho w_*(q_u - q_d) \tag{7}$$

where q_u and q_d are updraught and downdraught specific humidity respectively and $\rho w_*(=\rho\sigma w_u)$ is the cloud massflux. Updraught and downdraught values are calculated from dry/moist adiabatic ascends and descends respectively (s. *Tiedtke*, 1993) and the cloud base massflux is calculated from the turbulent moisture transport at cloud base produced by the boundary layer parametrization (e.g. ECMWF vertical diffusion scheme) as

$$\rho w_* = \frac{(F_q)_{Base}}{q_0 - q_d}. \tag{8}$$

The net generation of cloud water due to condensation in updraughts and evaporation of cloud water in downdraughts is

$$S_{BL} = -\frac{1}{\rho}\frac{\partial(\rho w_*)}{\partial z}(l_u - a l_d) \tag{9}$$

and the source of cloud air in terms of cloud cover is

$$S(a)_{BL} = -\frac{1}{\rho}\frac{\partial(\rho w_*)}{\partial z}(1-a). \tag{10}$$

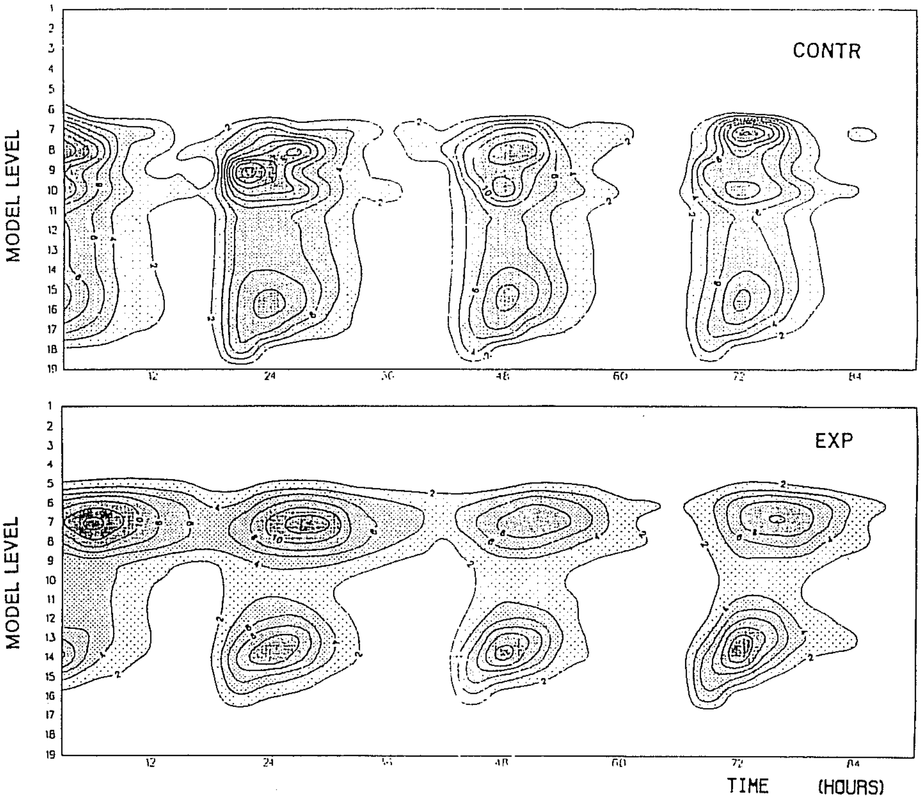

Fig 2 Time evolution of area mean convective cloud fields processed in 3 hr intervals for Central Africa (15E-45E, 10N-20S) for T42 integrations from 16.4.85, Z.
Top: ECMWF operational scheme
Bottom: Prognostic cloud scheme (*Tiedtke*, 1991).

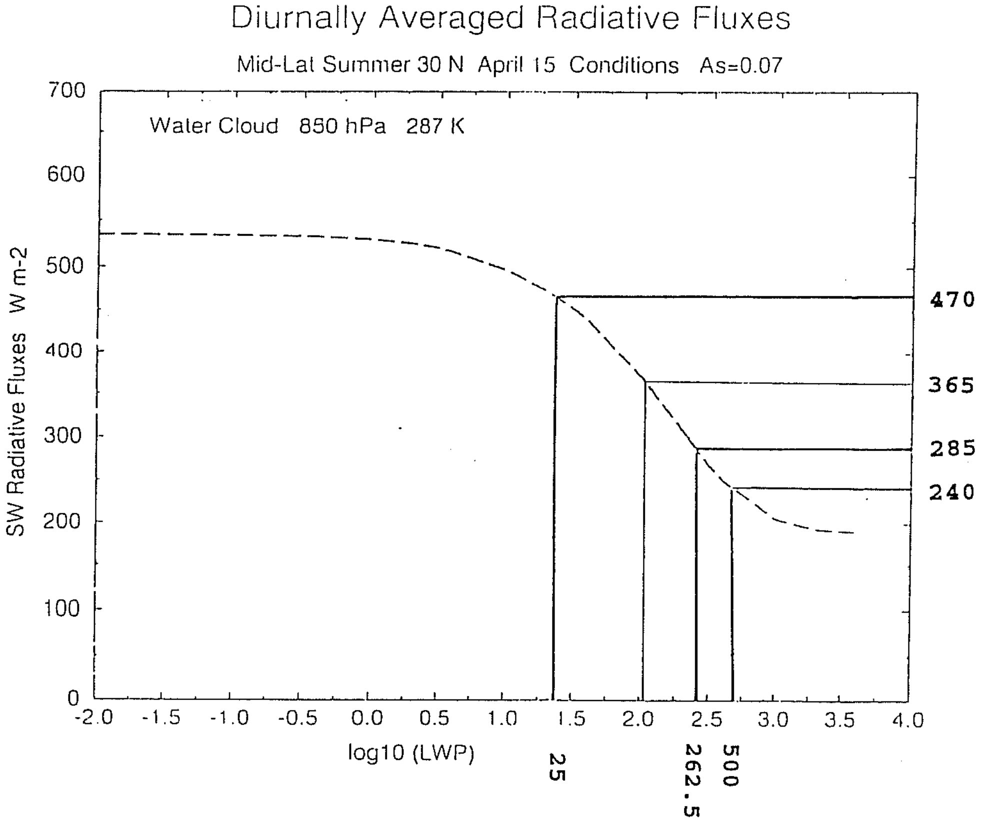

Fig 3 Diurnally averaged net short wave radiative flux at top of atmosphere as a function of liquid water path for low-level cloud; for 15 April at 30N over sea. Radiative fluxes have been derived from ECMWF operational radiation scheme. Extra values added on x-coordinate are in units of g/m^2.

It is worth noting that the generation of cloud water (9) and cloud air (10) depends on the detrainment of updraught air in the same way as for cumulus convection in (5) and (6).

Stratocumulus cloud decks are strongly affected by large-scale subsidence, radiative transfer and the turbulent entrainment of warm and dry air from above the inversion. Large-scale subsidence and radiative processes are described in section 2.5. Entrainment fluxes are represented, say for q, as

$$(w'q')_H = -w_e \Delta q \tag{11}$$

where the entrainment velocity includes contributions from boundary layer turbulence (*Deardorff*, 1976) and longwave radiative cooling at cloud top (*Stull*, 1988).

Uncertainties: The representation of boundary layer clouds is still a major problem area in large-scale modelling. The new scheme appears to reproduce the major stratocumulus cloud fields observed over the oceans (*Tiedtke*, 1993). This is presumably because cloud processes identified as important for boundary layer clouds have been represented in the scheme and seem to be in proper balance. Model aspects determining the accuracy of cloud parametrization are:

Cloud base massflux: is critical to the scheme as it determines, through (8), the formation of boundary layer clouds. It is derived from the turbulent moisture transports at cloud base and therefore reflects errors in boundary layer parametrization.

Cloud top entrainment: is still very uncertain, in particular the part due to longwave radiative cooling at cloud tops (e.g. *Kahn and Businger*, 1979). The inclusion of the radiative effect on entrainment has been beneficial to the model's precipitation characteristics as spurious drizzle was removed, but was detrimental to cloudiness which decreased too much.

Vertical resolution: The assumption in the present scheme is that model clouds cannot be thinner than a model layer depth. This assumption is presumably too restrictive for clouds developing near coastlines where the turbulent moisture transport through cloud base might be sufficient to maintain thin clouds but not clouds as deep as a model layer (~ 40 mb).

2.4 Formation of stratiform clouds

Here we consider the formation of clouds by non-convective processes, large-scale lifting of moist air and diabatic processes such as radiative cooling. The parametrization is based on the principle that formation of cloud water is determined by the rate at which the saturation specific humidity q_s decreases. Thus the effects of large-scale lifting and diabatic cooling can be represented as

$$\frac{dq_s}{dt} = \left(\frac{dq_s}{dp}\right)_{ma}(\omega + gM_c) + \frac{dq_s}{dT}\left(\frac{dT}{dt}\right)_{diab} \tag{12}$$

where ω is the area mean generalized vertical velocity, M_c the cumulus induced subsidence between the updraughts, $(dT/dt)_{diab}$ the net temperature tendency due to radiative and turbulent processes including entrainment processes (s. Section 2.3) and $(dq_s/dp)_{ma}$ is the change of q_s along the moist adiabat through point (p, T). In the scheme we distinguish two cases: 1) condensation in already existing clouds and 2) the formation of new clouds

$$C = C_1 + C_2. \tag{13}$$

Condensation in existing clouds increases cloud water content as

$$C_1 = -a\frac{dq_s}{dt}, \quad \frac{dq_s}{dt} < 0. \tag{14}$$

New clouds are assumed to form when the grid averaged relative humidity exceeds a threshold value, which is prescribed to be 80% at 650 mb increasing towards 100% as boundary layer and stratosphere are approached. The increase in cloud cover is determined by how much of the cloud free area exceeds saturation within a time step, which in turn depends on the moisture deficit in the cloud free area and how fast saturation is approached (s. *Tiedtke*, 1993):

$$S(a)_c = -(1-a)\,\frac{\dfrac{dq_s}{dt}}{(q_s-q)}\,, \quad \frac{dq_s}{dt}<0. \tag{15}$$

We note that the humidity threshold applies only to the formation of clouds but not their occurrence. In fact, in the scheme clouds can occur at lower values of relative humidity, for example in situations of cumulus convective activity or when clouds dissipate rather slowly while relative humidity decreases. The generation of cloud water is accordingly

$$C_2 = -\Delta a_c\,\frac{dq_s}{dt}\,, \quad \frac{dq_s}{dt}<0 \tag{16}$$

where $\Delta a_c = S(a)_c\Delta t$ is the fractional cloud cover produced per time step.

<u>Uncertainties:</u> When discussing uncertainties we must realize that parametrization (12) to (16) applies to a wide range of clouds and therefore eventual uncertainties will affect clouds in various synoptic situations; for example formation of cloud water by (14) applies equally to stratiform clouds and to clouds of convective origin (e.g. condensation in anvil and cirrus clouds through large-scale ascent). According to (12) various processes can contribute to cloud formation, with varying degrees of accuracy.

Cloud formation by large-scale lifting: is the most reliable cloud forming process in models, which might explain why large-scale models are best in reproducing frontal cloud systems. Errors in extratropical cloudiness along stormtracks are presumably more an indication of deficiencies in the large-scale flow than in the parametrization.

Cloud formation by diabatic processes: have larger uncertainties since they depend on subgrid scale processes which are often based on uncertain parametrization assumptions. Errors associated with these processes are most significant for clouds in conditions where subgrid scale processes are dominant (i.e. undisturbed conditions with weak ascent).

Criteria for the formation of new clouds: The simple relative humidity criterium in (15) has been chosen because reliable relationships which apply to all synoptic regimes are not available. It is worth noting that the humidity threshold value is the only disposable parameter introduced for cloud formation processes. Again, uncertainties through this parameter will mostly affect cloud prediction in undisturbed flow situations.

2.5 Evaporation of clouds

In the scheme clouds can evaporate through two processes: 1) in connection with large-scale descent and cumulus induced subsidence and diabatic heating and 2) by turbulent mixing of cloud air and unsaturated environmental air

$$E = E_1 + E_2 . \tag{17}$$

The first process is represented in the same way as cloud formation by condensation except that now $dq_s/dt > 0$:

$$E_1 = a\frac{dq_s}{dt} , \quad \frac{dq_s}{dt}>0. \tag{18}$$

For cloud dissipation by turbulent mixing of cloud air with environmental air we assume, as has been done in the earlier study (*Tiedtke*, 1991), that it is proportional to the saturation deficit of the environmental air

$$E_2 = a\ K(q_s-q) , \quad K=10^{-6}\ s^{-1}. \tag{19}$$

The decrease in cloud cover is parametrized as

$$D(a) = \frac{E_2}{l_c} \tag{20}$$

where l_c is the specific cloud water content per cloud area.

Uncertainties: Cloud evaporation is the main process through which non-precipitating clouds (e.g. trade wind cumulus, stratocumulus) dissipate.

Evaporation due to large-scale subsidence: Its parametrization is reliable and produces relatively small errors as long as the large-scale flow is realistic (e.g. early in the forecast), but errors increase as the large-scale circulation becomes unrealistic (later forecast stages and climate models).

Evaporation due to cumulus induced subsidence: This process is a major component in the balance of trade wind cumulus clouds. Its accuracy is affected by the uncertainties of cumulus parametrization. The new cloud scheme appears to overpredict cloud liquid water contents in trade wind regions (when compared to SSM/I observations) suggesting insufficient cloud dissipation by subsidence or turbulent mixing.

Cloud dissipation due to turbulent mixing of cloud air and dry environmental air: This is the most uncertain process, but its contribution to cloud dissipation is much smaller in magnitude than from other processes. We are uncertain in particular about the correct magnitude of the diffusion coefficient K in (19). Increasing its value by a factor of 10 (~ order of uncertainty) reduces global cloudiness by ca 0.10.

Finally we add that clouds dissipate when warm and dry air is entrained at cloud tops (s. Section 2.3). Parametrization of this process is again uncertain which would affect stratocumulus clouds.

2.6 Precipitation processes

For warm clouds and mixed water/ice clouds we apply the parametrization proposed by *Sundqvist* (1988). Precipitation processes are represented in the context of a bulk water parametrization technique where the liquid phase is subdivided into cloud water and rain water. The conversion of cloud water into rain is parametrized as

$$G_p = a c_0 l_c \left(1 - e^{-\left(\frac{l_c}{l_{crit}}\right)^2}\right) \tag{21}$$

where c_0^{-1} represents a characteristic time scale for the conversion of cloud droplets into drops and l_{crit} is a typical cloud water content at which the release of precipitation begins to be efficient. The disposable parameters are adjusted, by means of coefficients, to take into account the effect of collection of cloud droplets by raindrops falling through the cloud and the Bergeron-Findeisen process.

In the original version of the cloud scheme (*Tiedtke*, 1993) precipitation in ice clouds at low temperatures ($T<250$ K) was also parametrized following Sundqvist, but the parametrization produced excessive ice sedimentation rates and consequently ice contents were too low and OLR too high (Rizzi, ECMWF, personal communication). Larger contents of cloud ice, producing more realistic OLR (*Rizzi*, 1994), are obtained when sedimentation of ice is parametrized following (*Heymsfield and Donner*, 1990)

$$G_p = -\frac{1}{\rho}\frac{\partial(\rho V_i l)}{\partial z}\,, \quad V_i = 3.29(\rho l_c)^{0.16}. \tag{22}$$

Uncertainties: Since precipitation processes are discussed at length in other papers of this workshop only a few general comments are added here without referring specifically to the parametrization (21) and (22). Firstly we emphasise that accurate parametrization is of crucial importance since precipitation processes are very efficient in depleting cloud water and in fact are often the only dissipative process. This is the case, for example, in anvil and cirrus clouds in tropical regions, as they are affected little by adiabatic and diabatic heating. Here, cloud ice contents are very sensitive to parametrization assumptions on ice sedimentation. We are also concerned with the question of the level of sophistication of parametrization necessary in large-scale models. Detailed parametrizations developed for cloud resolving and mesoscale models can in principle be adopted in large-scale models as has been done, for example, by *Randall and Fowler* (this workshop), but this approach seems questionable in view of the heterogeneous character of cloud ensembles encountered in large areas such as a GCM grid box. We argue that, in order to improve cloud forecasts, it might be more important to develop simple and economic parametrizations for the various cloud types encountered in a grid box (e.g. precipitating/non-precipitating, convective/non-convective clouds) than to adopt complex parametrizations for homogeneous conditions.

3. SPATIAL VARIABILITIES OF CLOUD FIELDS

3.1 The problem

The state-of-the-art of cloud modelling in climate and forecast models is to predict cloud liquid water/ice content l and cloud cover a and provide them as input to the radiative transfer calculation. Radiative transfer in cloudy conditions is simplified, through the plane-parallel assumption, to the idealized case of a homogeneous cloud of specific water content $l_c = l/a$ and cloud cover a. This oversimplification seems hardly justified in view of observational evidence that broken cloudiness and cloud inhomogeneities are the predominant forms of cloud fields, but a realistic treatment, in particular of broken cloudiness, is not feasible for various reasons, such as lack of model information on subgrid scale cloudiness, increased complexity and computational costs for non plane-parallel computations. Unfortunately little is known about the errors introduced through this simplification but *Harshvardhan and Randall* (1985), among others, have stressed that climate models would produce unrealistic high albedo values if realistic liquid water contents were used and that some correction for spatial variabilities of liquid water is necessary in order to produce realistic radiances. To demonstrate potential model errors, which arise if subgrid scale variabilities are ignored, we refer to the simple example shown in Fig 4, i.e. a composition of two clouds of equal size but different optical thickness of a) 500 g/m^2 and b) 25 g/m^2. In this case climate models would produce radiative fluxes too small by 70 W/m^2, since the radiative transfer would be that for a homogeneous cloud of the average liquid water path 262.5 g/m^2, whereas the correct flux is the average of the fluxes obtained separately for

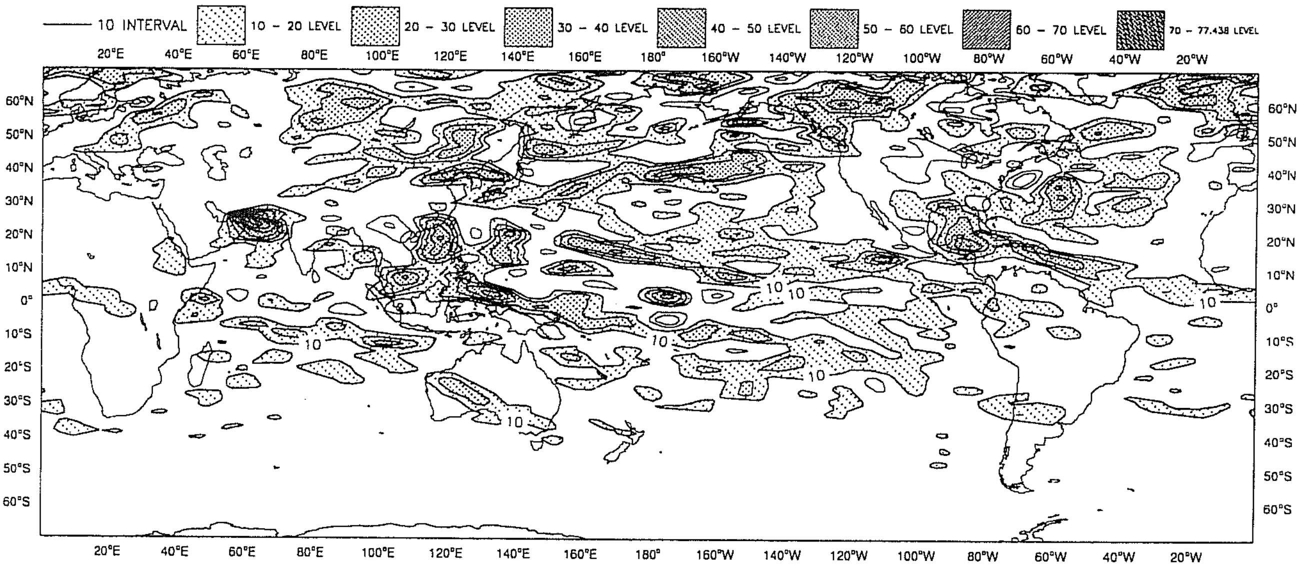

Fig 4 30-day mean differences of model generated net short wave radiation at top of the atmosphere between forecast experiments with and without inhomogeneous cloud effects. Forecasts are with ECMWF model at resolution T63L31 and with prognostic scheme; initial date is 1200 UTC, 1 July 1987.

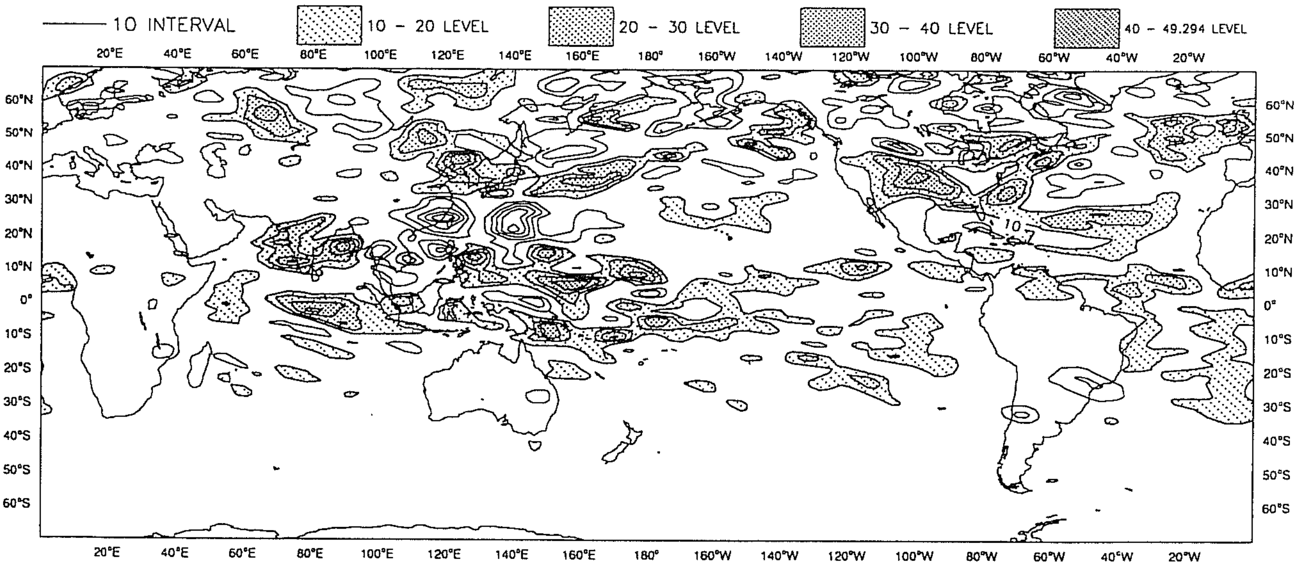

Fig 5 As Fig 4 but differences refer to heterogeneous cloud effects due to different mean liquid water contents in convective and stratiform clouds.

the two clouds (s. Fig 4). However the error can be reduced to 10 W/m^2 if the radiative transfer calculation is based on an 'effective' liquid water path by averaging water contents logarithmically. The spread of liquid water path is typical for many cloud fields (e.g. cumuli vs. stratus clouds, inhomogeneities in clouds) and therefore may give a rough estimate of model errors associated with the plane-parallel assumption. Yet, radiative fluxes produced by climate models are often quite realistic having smaller errors than expected which seems to indicate that model liquid water contents are being adjusted to account for spatial cloud variabilities, most likely through intentional or unintentional tuning of the cloud scheme. While tuning of cloud water content and cloud cover is possible in present climate models since cloud parametrization is empirical to a large extent, there is little room for tuning with a fully prognostic cloud scheme such as the ECMWF scheme, as it contains only a few disposable parameters. With a fully prognostic scheme spatial variabilities have to be represented through a separate parametrization. Such a parametrization should ideally represent broken cloudiness, cloud inhomogeneities and variances due to the various cloud types encountered in a grid box. The parametrization developed for the ECMWF model does not represent broken cloudiness, as the model does not provide any information of this kind, but it does account for cloud inhomogeneities and heterogeneities by distinguishing convective and stratiform cloudiness. The proposed parametrization is simple. Radiative transfer is still based on the plane-parallel assumption, but for the radiative transfer we adjust the cloud optical properties for the radiative transfer.

3.2 Parametrization of short wave radiative transfer in inhomogeneous clouds

The parametrization is based on the above-mentioned observational study by *Cahalan et al* (1994) on marine stratocumulus cloud fields during FIRE. They calculated area average albedo values using detailed measurements of liquid water content and found that the albedo is smaller than that of a uniform cloud having the same microphysical structure and the same total water content, on average by 15%. Most of the differences are associated with scales of a few hundred metres. They further showed that the albedo can be reproduced with the plane-parallel calculation, if an "effective" liquid water content is used

$$l_{eff} = \beta l \tag{23}$$

where the reduction factor during FIRE is typically

$$\beta = 0.7. \tag{24}$$

We shall use the same parametrization and the same value for β, although we realize that β changes with cloud type. The value is presumably too large for convective clouds having larger variabilities than stratocumuli (e.g. *Kogan et al*, 1995; *Raga and Jonas*, 1993) and too small for stratiform clouds when turbulence is weak.

The parametrization has been tested in global forecasts with the ECMWF model. They show that mean radiative reflectivities are reduced substantially when cloud inhomogeneities are introduced (Fig 4). Net radiative fluxes over the tropical and subtropical oceans increase by 9 W/m^2 on average.

3.3 Parametrization of cloud ensembles composed of convective and stratiform clouds

Cloud ensembles encountered in large areas such as a GCM grid area may contain clouds of different optical properties depending on cloud type, size, age etc. Large-scale models do not provide detailed information on cloud ensembles. However, a separation of convective clouds (optically thick) and stratiform clouds (optically thin) in terms of cloud cover and average liquid water content is possible in the framework of the ECMWF prognostic cloud scheme. Based on this input we propose two alternative parametrizations for calculating mean radiances.

Parametrization 1 is based on Fig 4 which shows that the dependency of short wave reflectivity on liquid water path is almost linear in logarithmic scale over a wide range of liquid water input values. Therefore, instead of averaging liquid water content linearly we average logarithmically which provides an "effective" liquid water content for the short-wave radiative transfer calculation. For a cloud ensemble of convective and stratiform clouds the "effective" liquid water content is

$$l_{eff} = 10^{\frac{a_{cu}}{a}\log(l_{cu})_{eff}+\frac{a_{st}}{a}\log(l_{st})_{eff}} . \tag{25}$$

In (25) we have already accounted for inhomogeneities within convective and stratiform clouds, by means of (23), and convective and stratiform liquid water contents are weighted according to fractional cloud cover.

Implementation of heterogeneities in the ECMWF model again lead to substantial reduced reflectivities (Fig 5) over the tropical and subtropical oceans, on average by 7 W/m^2.

Representation of cloud inhomogeneities and heterogeneities in the ECMWF model brings simulated radiative fluxes to more realistic values, as is evident from Fig 6 which shows errors in simulated fluxes when verified against ERBE data. Model errors are largely reduced over the tropical and subtropical oceans, in some regions by more than 40 W/m^2.

In Parametrization 2 we determine cloud optical properties for absorption and scattering separately for both convective and stratiform clouds and then use their averages for the plane-parallel radiative transfer calculation

$$\alpha_i = \frac{a_{cu}}{a}(\alpha_i)_{cu} + \frac{a_{st}}{a}(\alpha_i)_{st} . \tag{26}$$

Note that the optical properties for convective and stratiform clouds contain already inhomogeneous effects. Parametrization 2, which essentially follows a proposal of *Stephens* (1988), is presumably more accurate than parametrization 1 and has the advantage that it can be extended to the Infrared.

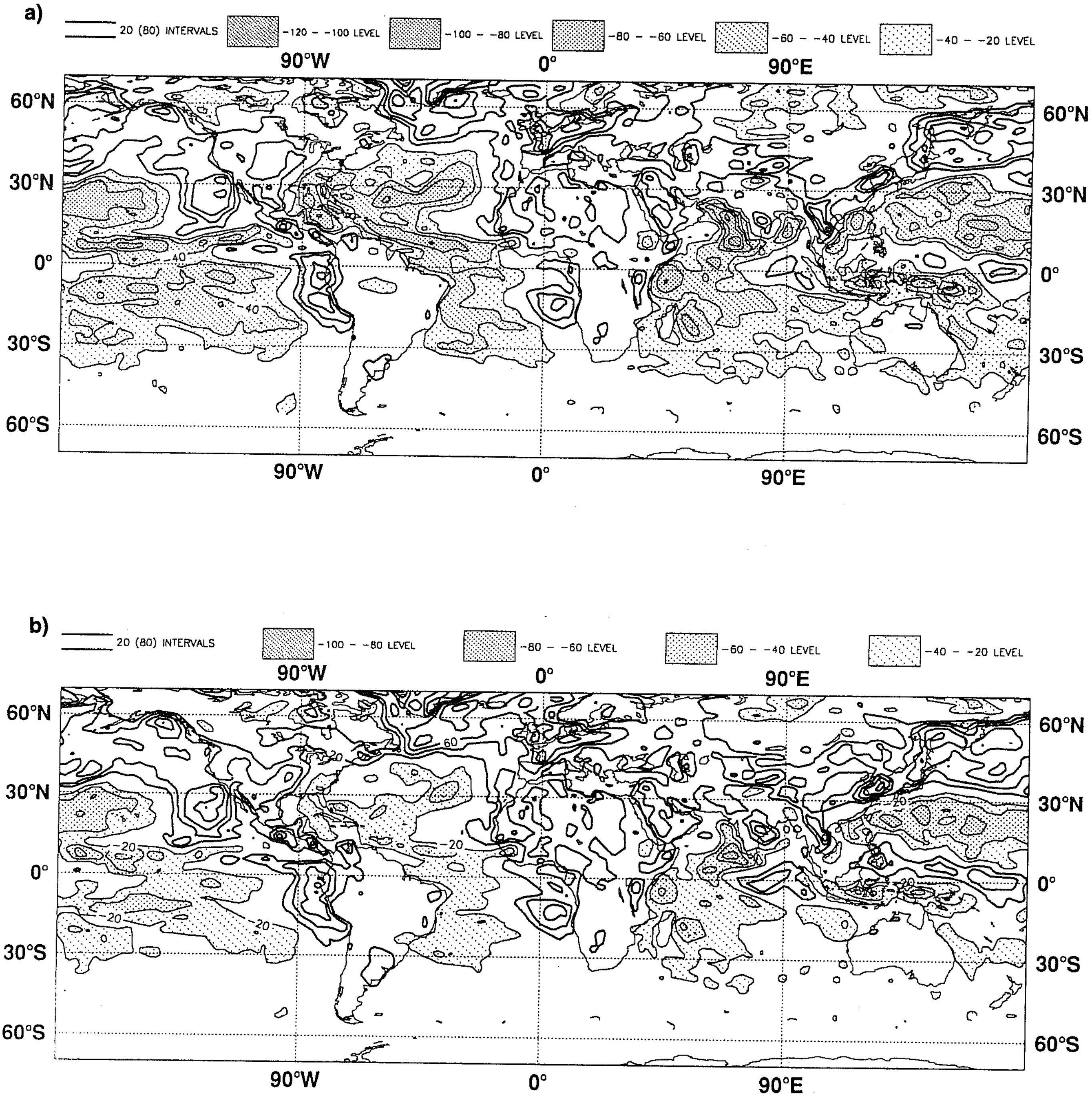

Fig 6 Differences with ERBE observations (July 1987) of the net short wave radiation at the top of the atmosphere: a) for control experiment, b) for experiment with parametrization of cloud inhomogeneities and heterogeneities.

Diagnosis of convective cloudiness

Convective cloudcover required in (25) and (26) is diagnosed from the assumption that the ensemble of convective clouds is in a steady state containing growing and decaying clouds. Clouds grow as condensate is formed in cumulus updraughts and clouds decay as the result of evaporation and precipitation processes. Applying the same parametrization as for total cloudiness in (3) and (4) we obtain

$$a_{cu} = \frac{1}{1+\frac{\left(\frac{dq_s}{dt}+K(q_s-q)+l_{cu}g_p\right)/l_u}{D_u/\rho}} . \tag{27}$$

Thus convective cloudiness is determined entirely by the relative magnitude of the processes for cloud dissipation and cloud formation. The cloud ensemble shall represent growing and decaying clouds and therefore the average cloud water content is assumed to be half the cumulus updraught value

$$l_{cu} = 0.5 l_u . \tag{28}$$

The values a_{st} and l_{st} for stratiform clouds are inferred from those of convective and total cloudiness. Parametrization (27)-(28) represents only steady state conditions and therefore might, in some cases, produce values larger than predicted total cloudiness. In order to avoid inconsistencies we impose limits for convective cloud cover, $a_{cu} < a$, and liquid water content, $l_{cu} < 10 l_{st}$.

The parametrization has been tested in extended integrations with the ECMWF model. Verification of model-produced 30-day mean convective cloud amounts (Fig 7) appear realistic when compared to climate estimates from surface observations (*Warren et al*, 1986 and 1988): simulated cumulus cloud amount (Fig 7a) exceeds 20% over the subtropical oceans, along the ITCZ and in midlatitudes in the Southern Hemisphere, and penetrative clouds (Fig 7b) are predominant in the tropics along the ITCZ as observed. However, the large cumulus cloud amount over China is not present in the climate estimate and penetrative cloud amount appears to be too large over the eastern Pacific and too small over the western Pacific. Model-produced globally averaged total convective cloud amount of 16.8 agrees well with the climate estimate of 16.5.

4. CONCLUDING REMARKS

Cloud parametrization in large-scale models is still highly uncertain. Experience at ECMWF indicates that a fully prognostic approach can have several advantages over diagnostic and semi-prognostic schemes, mainly through a more complete hydrological cycle and by coupling the cloud scheme to the model's convection scheme. Model simulations have improved in tropical as well as extratropical regions, e.g. precipitation characteristics and moisture profiles in the tropics, the time evolution of anvil and cirrus clouds and cloudiness along stormtracks. Still, uncertainties in cloud parametrization remain large as cloud

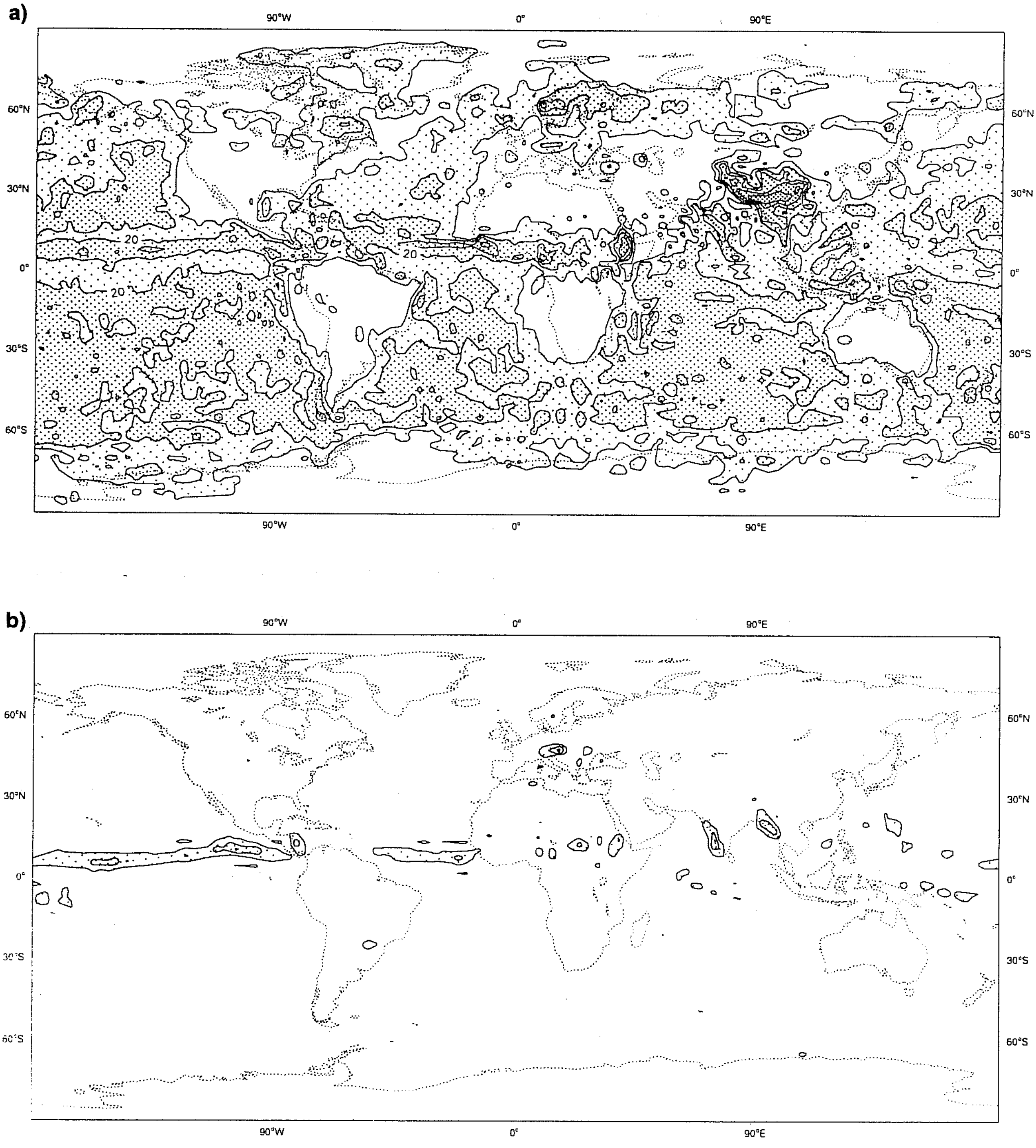

Fig 7 30-day mean diagnosed convective cloud cover for forecasts with ECMWF model (T63L31) and prognostic cloud scheme (*Tiedtke*, 1993): a) cumulus clouds, b) for penetrative clouds with tops above 450 hPa level.

formation depends on uncertain model processes (e.g. cumulus convection, boundary layer turbulence) and cloud microphysical processes are poorly represented.

We have presented a new parametrization to account for the effects of subgrid scale variabilities of cloud water contents in radiative transfer. So far we have included cloud inhomogeneities and heterogeneities associated with convective and stratiform clouds but have ignored broken cloudiness which can also modify radiative transfer (e.g. *Schmetz*, 1984).

Refinements of the scheme are required in several aspects:

The coefficient β for rescaling liquid water cloud water should not be fixed but vary with cloud type. The introduction of heterogeneities associated with optically thick convective clouds and thin stratiform clouds depends critically on a realistic treatment of convective cloudiness. The parametrization for convective cloudiness appears to produce realistic cloud amounts compared to climate estimates. Further verification requires additional observational data on cloud amount and liquid water content.

Acknowledgements: I would like to thank Bodo Ritter (DWD) for his correspondence on model validation over subtropical oceans. Dr J-J Morcrette provided Fig 3 and modified the radiation code to include heterogeneous cloud effects.

REFERENCES

Cahalan, R F, W Ridgway, W J Wiscombe and T L Bell, 1994: The albedo of stratocumulus clouds. J Atm Sci, 51, 2434-2455.

Deardorff, J W, 1976: On the entrainment rate of a stratocumulus-topped mixed layer. Q J R Meteor Soc, 102, 563-582.

Harshvardhan and D A Randall, 1985: Comments on "The Parametrization of Radiation for Numerical Weather Prediction and Climate Models". Mon Wea Rev, 113, 1832-1835.

Heymsfield, A J and L J Donner, 1990: A scheme for parametrizing Ice-cloud water content in general circulation models. J Atmos Sci, 47, 1865-1877.

Kahn, P H and J A Businger, 1979: The effect of radiative flux divergence on entrainment of a saturated boundary layer. Q J R Meteor Soc, 105, 303-306.

Kogan, Z N, D K Lilly, Y l Kogan and V Filyushkin, 1995: Evaluation of radiative parametrizations using an explicit cloud microphysical model. Atmos Res, 35, 157-172.

Raga, G B and P R Jonas, 1993: Microphysical and radiative properties of small cumulus clouds over the sea. Q J R Meteor Soc, 119, 1399-1417.

Rizzi, R: 1994: Raw HIRS/2 radiances and model simulations in the presence of clouds. ECMWF Res Dept Tech Rep No 73, 29 pp.

Schmetz, J, 1984: On the parametrization of the radiative properties in broken clouds. Tellus, 36A, 417-432.

Slingo, J M, 1987: The development and verification of a cloud prediction scheme for the ECMWF model. Q J R Meteor Soc, 113, 899-927.

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

Stephens, G L, 1978: Radiative properties in extended water clouds. II: Parametrization schemes. J Atmos Sci, 49, 805-822.

Stephens, G L, 1988: Radiative transfer through arbitrarily shaped optical media. Part II: Group theory and simple closures. J Atmos Sci, 45, 1837-1848.

Stull, R B, 1988: An introduction to planetary boundary layer meteorology. Kluwer, p 576.

Sundqvist, H, 1988: Parametrization of condensation and associated clouds in models for weather prediction and general circulation simulation. In M E Schlesinger (ed), Physically-Based Modelling Simulation of Climate and Climate Change. Kluwer, 433-461.

Tiedtke, M, 1989: A comprehensive massflux scheme for cumulus parametrization in large-scale models. Mon Wea Rev, 117, 1779-1800.

Tiedtke, M, 1991: Aspects of cumulus parametrization. ECMWF Seminar on tropical extra-tropical interactions, Reading, UK, 10-14 Sept 1990, 441-466. (Available from ECMWF, Shinfield Park, Reading, Berkshire, UK).

Tiedtke, M, 1993: Representation of clouds in large-scale models. Mon Wea Rev, 121, 3040-3061.

Warren, S G, C J Hahn, J London, R M Chervin and R L Jenne, 1986: Global distribution of total cloud cover and cloud type amounts over land. NCAR Tech Note NCAR/TN-273 + STR, 29 pp.

Warren, S G, C J Hahn, J London, R M Chervin and R L Jenne, 1988: Global distribution of total cloud cover and cloud type amounts over the oceans. NCAR Tech Note NCAR/TN-317 + STR, 42 pp.

Wentz, F J, 1992: User's Manual SSM/I Monthly Ocean Tape. 1987-1991 Monthly Averages of Wind Speed, Water Vapour and Liquid Water. RSS Tech Rep 050192, Remote Sensing Systems, Santa Rosa, Ca 95404.