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Cloud Parameterization for Climate Modeling: Status and Prospects

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ABSTRACT

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The current status of cloud parameterization research is reviewed. It is emphasized that the upper tropospheric stratiform clouds associated with deep convection are both physically important and poorly parameterized in current models. Emerging parameterizations are described in general terms, with emphasis on prognostic cloud water and fractional cloudiness, and how these relate to the problem just mentioned.

RESUME

L'état actuel de la recherche en paramétrisation des nuages est passé en revue. On souligne que les nuages stratiformes de la haute troposphère associés avec la convection profonde sont à la fois physiquement importants et mal paramétrisés dans les modèles actuels. Les paramétrisations que émergent sont décrites en termes généraux, en insistant sur l'eau du nuage prognostiquée et la nébulosité fractionnelle, et comment ces quantités sont reliées au problème mentionné.

INTRODUCTION

As we approach the end of the 1980s, several important developments have pushed cloud parameterization to the forefront of climate research. Recent observational and theoretical studies have pointed to the radiative effects of clouds as an important forcing function for both large-scale atmospheric circulations and deep cumulus convection (e.g., Cox, 1969; Albrecht and Cox, 1975; Cox and Griffith, 1979; Stephens and Webster 1979; Webster and Stephens, 1980; Ackerman et al., 1988). ISCCP, ERBE, FIRE, and other observational programs are strengthening the empirical basis for cloud-climate studies. Climate simulations have demonstrated some success in simulating the effects of clouds on the earth's radiation budget (Charlock and Ramanathan, 1985; Randall et al., 1985; Slingo, 1985; Ramanathan, 1987a,b; Charlock et al., 1988; Harshvardhan et al., 1989). Numerical experiments have revealed strong, direct effects of the clouds on the large-scale atmospheric circulation (Herman et al., 1980; Ramanathan et al., 1983; Slingo and Slingo, 1988; Randall et al., 1989). At the same time, uncertainties concerning cloud feedback have emerged as the most serious obstacle preventing reliable prediction of climate change due to increasing greenhouse gas concentrations (Hansen et al., 1984; Cess and Potter, 1987; Schlesinger and Mitchell, 1987; Wetherald and Manabe, 1988).

One approach to cloud parameterization, and to parameterization in general, is to identify intuitively plausible relationships between the unknowns, such as cloud amount, and the known variables of the problem, such as relative humidity, static stability, and vertical velocity. This approach was pioneered by Smagorinsky (1960), and has recently been pursued by Slingo (1980, 1987). The resulting parameterizations are often called "empirical", but that term seems inappropriate, since in many cases no scatter diagrams or other systematic observational basis are presented. A more accurate descriptor might be "inductive", since general rules are formulated on the basis of a finite number of particular cases. An advantage of the inductive approach is that it can quickly yield parameterizations that are undeniably useful, e.g., for numerical weather prediction. A disadvantage is that inductive parameterizations lack theoretical underpinnings that could indicate their limits of applicability.

The alternative, "deductive" approach is based on the philosophical view that parameterization development should proceed, as far as possible, from general physical principles. A deductive parameterization provides a condensed representation of the important physical processes of interest, and so can give physical insight into the phenomenon being parameterized. The limits of applicability of such a parameterization can be inferred, a priori, from its physical basis. Its assumptions must, of course, be observationally testable. This review article emphasizes deductive parameterizations.

We can pose the following questions concerning the role of clouds in climate.

(1) *What is the distribution of cloudiness?*. The International Satellite Cloud Climatology Project (ISCCP; Schiffer and Rossow, 1983) is intended to provide an observational answer to this question. Alternative cloud climatologies are also being produced, using a variety of satellite retrieval algorithms (e.g., Susskind et al., 1987; Stowe et al., 1988) and surface data (Warren et al., 1986). Simulated cloudiness distributions produced by general circulation models (GCMs) must be critically compared with such observations.

(2) *What determines the distribution of cloudiness?* This is one of the two key problems of cloud parameterization. Large-scale motions, surface fluxes, moist convention, and radiative cooling can all influence the distribution of cloudiness over the globe. Observational studies designed to address this question include FIRE (Cox et al., 1987).

(3) *What are the direct effects of the clouds on the atmosphere?* This is the second key problem of cloud parameterization. Clouds assert their influence through three distinct but interrelated and more or less equally important "cloud forcing" mechanisms, none of which are adequately included in any existing climate models:

(a) Clouds modulate the solar and terrestrial radiation fields. Ramanathan (1987a,b) has termed these effects the "cloud radiative forcing" (CRF). The CRF can be defined as the difference between the radiative flux (at the top of the atmosphere, say) which actually occurs in the presence of clouds, and that which would occur if the clouds were removed but the atmospheric state were otherwise unchanged. The term CRF can also be used to denote warming or cooling tendencies due to cloud–radiation interactions. Measurements of the CRF at the top of the atmosphere are being provided through the Earth Radiation Budget Experiment (ERBE; Ramanathan et al., 1989), as well as several other satellite-based observational studies. Parameterizations of the CRF require information about the amount and type of cloud particles in a GCM grid volume, as well as the distribution of the particles inside the volume. The former problem is usually discussed in terms of the "cloud water content", and the latter in terms of the "fractional cloudiness". As pointed out by Harshvardhan and Randall (1985), both the cloud water content and the fractional cloudiness must be known in order to determine the CRF. A parameterization of radiative transfer in a partly cloudy grid volume should take into account finite cloud effects, which result from photons that enter or escape through the sides of clouds.

(b) Clouds are associated with latent heat release and precipitation. This can be termed the cloud latent forcing (CLF). It has been addressed through a number of major observational studies, notably including GATE (Houze and Betts, 1981). Climate models typically divide the CLF into two somewhat arbitrarily distinguished components, namely cumulus effects and large-scale saturation effects. Considerable effort has been expended on the development of CLF parameterizations.

(c) Clouds are associated with strong small-scale convective circulations that carry out important vertical transfers of energy, moisture, momentum, and various chemical species. These motions are closely associated with the release of latent heat, but they are logically distinct from it. This third type of cloud forcing can be called the cloud convective forcing (CCF).

(4) *What role does the cloud forcing play in regulating or maintaining the present climate?* The climate system's response to cloud forcing is realized in part through highly nonlinear interactions among radiation, convection, and the large-scale atmospheric circulation. GCMs are ideal tools for investigating these interactions, through controlled numerical experiments.

(5) *How do the clouds feed back to influence climate change?* This problem

can only be addressed with confidence after satisfactory answers to the preceding four questions have been established.

The earliest GCMs included the CLF, since this was already known to be a key energy source for the large-scale circulation of the atmosphere, and they also included simple parameterizations of the CCF. In contrast, many of these same models used prescribed zonally averaged cloudiness distributions as inputs to their solar and terrestrial radiation parameterizations. In those days it was not universally recognized that the CRF has strong direct effects on the atmospheric general circulation.

Beginning in the mid-1960s, several GCMs incorporated simple parameterizations of radiatively interactive cloudiness, typically parameterized in terms of water vapor mixing ratio, temperature, and vertical motion. The CRF associated with these interactive clouds fed back through the radiation parameterization to modify the temperature, and so influenced the development of the large-scale circulation. Up until the late 1970s, however, very few published studies addressed the simulated cloudiness or its effects on the models' climate. This may have been partially due to a lack of observations suitable for comparison with model results.

The next step, inspired by the work of Lilly (1968), was to allow the radiative effects of the clouds to influence the turbulence parameterization of the GCM. Since all GCMs contain a parameterization of boundary layer turbulence, the most natural place to introduce a coupling between cloudiness and turbulence is in the parameterization of boundary-layer clouds. Lilly's idea was implemented in the UCLA GCM during the mid-seventies, under the direction of A. Arakawa, and the results of this effort were published by Suarez et al. (1983) and Randall et al. (1985). In this approach, the coupling between the turbulence and the clouds is a direct, "fast", parametric coupling, as opposed to an indirect coupling through the prognostic fields; the latter occurs only on the time and space scales that are explicitly resolved by the GCM. In this class of models, however, the cloud–turbulence coupling is "one-way"; the clouds directly influence the turbulence, but the turbulence does not directly influence the clouds. This allows a straightforward computational algorithm: the cloud properties are determined first; they are provided as input to the radiation parameterization; and finally the radiative fluxes are used (together with other parameters) to determine the turbulence statistics.

The emerging parameterizations described later in this paper feature new prognostic variables for cloud particle species such as cloud water or ice, following the pioneering work of Sundqvist (1978, 1981). In addition, the variability of cloud optical properties with temperature and other atmospheric state variables is now being recognized as a potentially important aspect of cloud–climate feedback (e.g., Somerville and Remer, 1984; Platt and Harshvardhan, 1988). New, physically based fractional cloudiness schemes (e.g., Randall, 1987) are linking cloud amount with turbulence variables. It appears likely that in the next generation of parameterizations, the cloudiness, the radiative tendencies, and the turbulence statistics will have to be solved for simultaneously, greatly increasing the algorithmic complexity of the models.

The purpose of this paper is to review the cloud parameterization problem, with emphasis on what current parameterizations tell us about the role of cloud radiative forcing in maintaining the present climate, and also on the status and prospects for further improvements of cloud generation parameterizations.

KEY DEFICIENCIES OF CURRENT CLOUD PARAMETERIZATIONS

Although water vapor is not a cloud variable per se, there are or should be strong physical links between a model's simulations of water vapor and cloudiness. Obviously, high absolute humidities are favorable for cloud formation. Less obviously, the distribution of water vapor simulated by a GCM is strongly influenced by its cloud parameterizations. This can be seen from the following equation:

$$\frac{\partial \bar{q}}{\partial t} + \nabla\cdot(\bar{V}\bar{q} + \overline{V'q'}) + \bar{E} - \bar{C} = 0 \qquad (1)$$

Here q is the water vapor mixing ratio, E is evaporation, C is condensation, and $\boldsymbol{V}$ is the three-dimensional velocity vector. An overbar denotes a grid-box average, and a prime denotes a fluctuation from the average. The condensation term of eq. 1 is obviously associated with cloud formation, and the evaporation term can represent the effects of evaporating precipitation falling from clouds, or of evaporating cloud droplets. The small-scale transport term is dominated, above the boundary layer, by convective transports due to clouds. For example, by far the most important mechanism for transporting moisture from the boundary layer to the upper troposphere is deep penetrative cumulus convection. Even within the boundary layer, stratocumulus clouds and shallow cumulus clouds can strongly affect the turbulent moisture flux. The point is that parameterized cloud processes dominate three of the four terms contributing to the time-rate of change of the mean water vapor mixing ratio. For these reasons, prediction of the water vapor distribution itself is an important aspect of the cloud parameterization problem. Current GCMs can simulate some important features of the observed distribution of atmospheric water vapor, but there are still many problems with the results (e.g., Randall et al., 1989).

As mentioned above, deep cumulus convection is the primary mechanism for transport of moisture from the planetary boundary layer to the upper troposphere, especially in the tropics and summer midlatitudes. Each day, tens of thousands of cumulonimbus clouds inject enormous quantities of boundary-layer air into the upper troposphere and lower stratosphere (e.g., Riehl and Malkus, 1958). The detrained air forms horizontally extensive and deep "anvil" clouds that contribute as much as 40% of the total precipitation that falls from the convective systems. The anvil clouds contain mesoscale circulations (e.g., Houze, 1982) and probably also small-scale moist convective circulations, which influence the evolution of the convective systems and the large-scale circulations in which they develop. They also exert very powerful effects on both solar and terrestrial radiation. Some of the cumulus-injected ice crystals form cirrus clouds, which can remain in the upper troposphere for several days, during which the upper-troposphere winds can carry them thousands of kilometers from the convective events that generated them. Along their trajectory, they block infrared emission from lower levels, and scatter sunlight back to space.

Unfortunately, existing general circulation models do not include adequate parameterizations of upper-tropospheric stratiform clouds or the convective processes that often give rise to them. Stratiform clouds are incorporated through "large-scale saturation" parameterizations, which are not directly coupled with the convective parameterization. Stratiform precipitation is typically assumed to fall out instantaneously, despite observational evidence that ice crystals, in particular, can have long lifetimes. No existing GCM includes a direct, physically consistent coupling between the convection parameterization and the large-scale saturation parameterization, despite the overwhelming observational evidence that such coupling exists. *This may be the most serious deficiency of the cloud parameterizations in current GCMs.* Research designed to remedy this deficiency must address the following key questions.

(1) What are the physical couplings between upper-troposphere stratiform anvil and cirrus clouds and deep cumulus convection, and how do the clouds and convection interact with the large-scale circulation?

(2) How can we parameterize the radiative effects of these convective cloud systems when the cloudiness fluctuates significantly on unresolved scales?

(3) How do convective cloudiness, and the resulting radiative and latent heating, influence the large-scale circulation?

Results obtained from current GCMs clearly demonstrate that current parameterizations of the upper-tropospheric stratiform clouds associated with deep convection are both deficient and potent. This is a dangerous combination.

Although current GCMs do produce upper-tropospheric tropical cloudiness maxima (e.g., Hansen et al., 1983; Charlock and Ramanathan, 1985; Randall et al., 1989; Harshvardhan et al., 1989), they are often weaker than observed, in spite of the abundant tropical precipitation produced by the models. In addition, the simulated tropical clouds tend to fluctuate unrealistically on sub-synoptic time scales (Charlock et al., 1988; L.D. Smith, 1989).

These deficiencies stem from the model's inadequate parameterizations of both cumulus cloudiness and the cirrus debris associated with cumulus activity. In the models, the radiative effects of convective cloud systems "shut off" as soon as the convection stops. In reality, of course, the upper-level cloud sheets produced by cumulus detrainment persist for hours or even days after

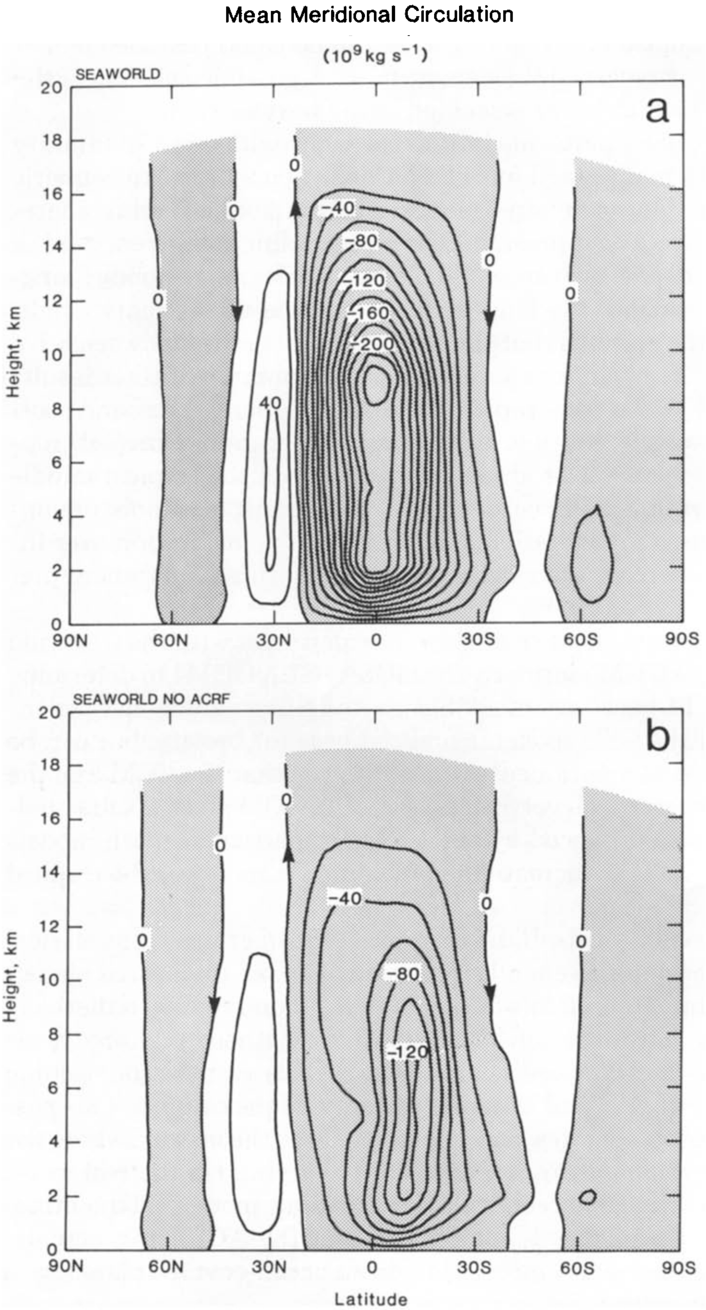

Fig. 1. Mean meridional circulations for a cloudy run (a) and a cloud-free run (b), in simulations of an ocean-covered planet, as reported by Randall et al. (1989).

the convection has died out. In order to improve the models, we need to give up the unrealistic assumption that all of the detrained cloud particles immediately precipitate out or revert to the vapor phase. A possible solution is the use of prognostic cloud variables, as discussed in the next section.

Slingo and Slingo (1988) performed an experiment with the Community Climate Model (CCM) maintained by the National Center for Atmospheric Research, in which the longwave atmospheric cloud radiative forcing (hereafter, ACRF) was artificially suppressed. Clear-sky cooling rates were used to predict the atmospheric temperature, while the usual (clear and cloudy) longwave flux was used to predict the land-surface temperature. January conditions were chosen on the grounds that the land-surface is minimally sensitive to longwave ACRF in the northern winter. A partial summary of their results is as follows: the ACRF warms the tropical upper troposphere by 4 K and cools the tropical lower stratosphere by 6 K, causing an acceleration of the subtropical jets in both hemispheres. It produces a moistening of the tropical middle troposphere by invigorating moist convection, which transports moisture upwards. It causes increased precipitation and large-scale rising motion over Indonesia, and tends to increase the rate of precipitation in regions where precipitation is likely to occur anyway.

Randall et al. (1989) performed an analogous experiment with the Colorado State University (CSU) GCM (formerly the UCLA/GLA GCM) to determine to what extent the CCM-based results of Slingo and Slingo are model-dependent. A description of the CSU model is omitted here for brevity, but can be found in the reference just mentioned. Suffice it to say that the CCM and the CSU GCM are very different. Nevertheless, the CSU GCM gives results qualitatively similar to those produced by the CCM. In particular, both models suggest that the ACRF acts to increase the precipitation rate over the tropical oceans.

To explore the reasons for this, Randall et al. (1989) performed numerical simulations of the atmospheric general circulation of an ocean-covered planet, with and without the radiative effects of clouds. They found that by radiatively warming convectively active columns, the ACRF strengthens the large-scale rising motion, the low-level convergence, and the surface evaporation, leading to more convective cloudiness and a further warming of the column. This positive feedback mechanism operates very effectively over the oceans, where the simulated sea surface temperature is either slowly varying (in the real world and in coupled ocean–atmosphere models) or fixed (in models of the atmosphere alone). As shown in Fig. 1, they found that the ACRF can actually double the strength of the Hadley circulation on an ocean-covered planet with fixed sea surface temperatures.

EMERGING CLOUD PARAMETERIZATIONS

Prognostic cloud variables

Following the lead of Sundqvist (1978, 1981), several modeling groups (e.g., R.N.B. Smith, 1989) are currently developing parameterizations that employ prognostic variables for cloud species such as cloud liquid water, cloud ice, and cloud rain water. The utility of condensed water variables is obvious; condensates are the physical link between the latent heat effects and the radiative effects of clouds, so the consistent use of condensate variables helps to ensure physical consistency among the latent heating, radiation, and precipitating parameterizations. Although it is not so obvious that the condensate variables must be *prognostic* (one could envision neglecting the time-rate-of-change term, and solving a diagnostic or balance equation for the condensates), there are at least two possible motivations for determining the condensate distribution prognostically.

The first possible motivation is that a PCV is demanded by the physics, in the sense that the current distribution of the condensate is influenced by its past history over the space and time scales of interest. If this is the case, accurate determination of the distribution of the condensate necessarily involves the use of a prognostic equation. It is not at all clear, however, that the physics actually does demand a PCV for all types of clouds. Consider a subtropical boundary-layer stratocumulus cloud, consisting entirely of liquid water droplets. These droplets are formed by condensation that occurs primarily in microscale (i.e. turbulence-scale) convective updrafts a few hundred meters across, with life times of a few minutes. Many of these droplets are subjected to evaporation in nearby microscale downdrafts. The lifetime of an average cloud droplet in the stratocumulus layer is, therefore, very brief. This means that the conservation equation for the *large-scale average* liquid water concentration is dominated by strong condensation and evaporation terms, which very nearly balance each other. For the space and time scales resolved by a climate model, the local time rate of change and advection terms are quite negligible, compared to these source and sink terms. A similar line of reasoning applies for some other cloud types, such as fair-weather cumulus clouds or frontal stratus clouds. It should be noted, however, that these arguments do not apply to the mesoscale and microscale models that are used to simulate individual cloud elements. This is why such small-scale models have been using PCVs for many years.

The local time rate of change and advection terms are important for cirrus clouds, even on the relatively large space and time scales resolved by a climate model. Typical cirrus clouds contain many small crystals with terminal velocities less than or on the order of 0.1 m s^{-1}, and also larger crystals with terminal velocities on the order of 0.5 m s^{-1} (e.g., Heymsfield, 1975; Starr and Cox, 1985a), and so take several hours to fall through the depth of the troposphere. Of course, the smaller crystals, which are radiatively important, fall even more slowly. The effective fall speed can be further reduced by mesoscale rising motion and/or convective lofting associated with the cirrus clouds themselves. Crystals are capable of surviving for extended periods as they fall through subsaturated air (e.g., Hall and Pruppacher, 1976).

Observations (e.g., Webster and Stephens, 1980) show that cirrus outflows from tropical convection can extend for many hundreds or even thousands of kilometers downstream from the convective disturbance that generates them. In such cases, the local time rate of change and advections terms of the conservation equation for the large-scale average cirrus ice water concentration must be comparable to the source and sink terms, so that a prognostic approach including advective effects is necessary for accurate predictions of the cloudiness. In short, PVCs are necessary for accurate simulations of the effects of cirrus clouds on climate.

A second, very practical reason for the use of a PVC is that a prognostic scheme can actually simplify the computational algorithms of the cloudiness parameterization. This should not come as a surprise. There are many problems for which quasi-equilibrium assumptions complicate the mathematics, even though they can be justified by scaling arguments. Examples include quasigeostrophic models, in which the vertical velocity is determined through the notorious ω-equation; turbulence models based on higher-order closure, in which balance assumptions can lead to poorly behaved algebraic systems, and anelastic models, in which filtering of sound waves is achieved at the expense of a troublesome elliptic equation for the pressure. A PCV potentially provides a relatively convenient algorithm to determine the cloud water content of GCM grid volumes.

The difficulties of implementing a PCV should not be underestimated, however. In particular, advection of a lumpy, non-negative scalar is a difficult numerical problem (e.g., Rood, 1987). A GCM may need vertical resolution on the order of 500 m to adequately resolve the precipitation physics. The small equilibration times and high terminal velocities of some precipitating particles will require careful design of unconditionally stable time-differencing schemes, in view of the relatively long time steps used in GCMs (not less than several minutes). On these multi-minute time scales, the microphysical processes will never stray significantly from equilibrium, but under some conditions the large-scale advective processes mentioned above can produce significant nonequilibrium behavior.

For climate modeling, precipitation processes and the radiative effects of the clouds are of roughly equal importance. This suggests that it may be useful to distinguish between precipitating and nonprecipitating drops. The same line of reasoning is more compelling for ice particles. Small ice particles are radiatively very important (Prabhakjara et al., 1988), but in many cases represent only a tiny fraction of the ice mass in a grid volume. The total ice mass is, therefore, not necessarily a good measure of the radiative properties of the cloud. On the other hand, the larger ice particles are important because they precipitate and are involved in latent heat exchanges. These considerations suggest that is may be useful to separately prognose precipitating and nonprecipitating liquid water drops and ice particles.

The use of PCVs to determine the large-scale average distribution of precipitating and nonprecipitating cloud particles obviously amounts to an alternative parameterization of "large-scale saturation", which can directly replace the large-scale saturation parameterizations that are typically used in current GCMs to determine the rate of precipitation from stratiform clouds. For consistency, the same PCVs should also be incorporated into the cumulus parameterization. The parameterized convective clouds can then act as generators of cloud particles for the parameterized stratiform clouds. In this way, a true coupling of the convective and stratiform cloud parameterizations can be achieved.

Fractional cloudiness

Methods exist to determine the optical properties of a grid volume containing a known concentration of cloud water (e.g., Stephens, 1978). This does not imply, however, that a PCV solves the problem of determining the cloud radiative forcing. As discussed by Harshvardhan and Randall (1985), the distribution of cloud water inside a grid volume strongly determines its optical properties. For example, if all of the liquid water is in one lump, its optical effects will be negligible. On the other hand, if the same mass of water is distributed over the grid volume as a uniform aerosol, its optical effects will be formidable. There is as yet no proven method, based on physical principles, to determine the subgrid-scale distribution of cloud water in a GCM grid volume. This subgrid-scale cloud water distribution is related to but more complex than what is usually called the "fractional cloudiness".

It is useful to distinguish between two types of fractional cloudiness. The first, which was discussed by Sundqvist (1978, 1981) occurs because a cloud sheet of arbitrary shape must be imperfectly resolved on a finite grid (Fig. 2 left). Such *extrinsic fractional cloudiness* depends in an essential way on the grid used. The cloud fraction can change dramatically as the grid spacing is altered by a factor of two (say), so that a moderate increase in the resolution of the grid can lead to a significant improvement in the representation of the cloud field. For this reason, extrinsic fractional cloudiness is essentially a problem of resolution, comparable to the many other problems of resolution faced by numerical modelers.

In contrast, *intrinsic fractional cloudiness* is associated with the mesoscale and microscale dynamics of a cloud field. Examples are the cloudiness associated with cumulus convection, and with thin stratocumulus and cumulus humilis layers (Fig. 2 right). Explicit resolution of intrinsic fractional cloudiness requires a grid-spacing at least two to three orders of magnitude finer than that of existing GCMs. Within the range of typical current resolutions, the intrinsic fractional cloudiness is not sensitive to the grid size.

Through the use of a PCV, we can predict the *large-scale average* condensate mixing ratio for each GCM grid volume. The *cloud-scale average* condensate mixing ratio within individual cloud elements has been shown, in both observational and theoretical studies (e.g., Feigelson, 1978; Somerville and Remer, 1984; Betts and Harshvardhan, 1987; Platt and Harshvardhan, 1988), to vary systematically with temperature; these cloud-scale average mixing ratios are controlled by microphysical and small-scale cloud-dynamical processes, and so should be amenable to semi-empirical parameterization.

The ratio of the large-scale average mixing ratio to the cloud-scale average mixing ratio is a measure of the fraction of the grid volume that is occupied by cloud. Let this ratio be denoted by w, i.e.

$$w=\frac{\text{large-scale average condensate mixing ratio}}{\text{cloud-scale average condensate mixing ratio}} \tag{2}$$

A possible approach is to determine the numerator of eq. 2 from the PCV, and the denominator by an empirical assumption in the spirit of those mentioned above. In case the cloud-scale mean mixing ratio is uniform within the cloud elements, w is exactly equal to the fractional cloudiness (in a volume sense). Even when the cloud-scale mean mixing ratio varies within the cloud elements, w should be useful measure of the small-scale variability of the cloud field. Evidence for this was presented by Stephens (1988), who found that the satellite observations of the meridional distribution of *large-scale* average cloud water reported by Prabakhara et al. (1986) do not show the systematic poleward decrease to be expected from the observed dependence of the *local* average

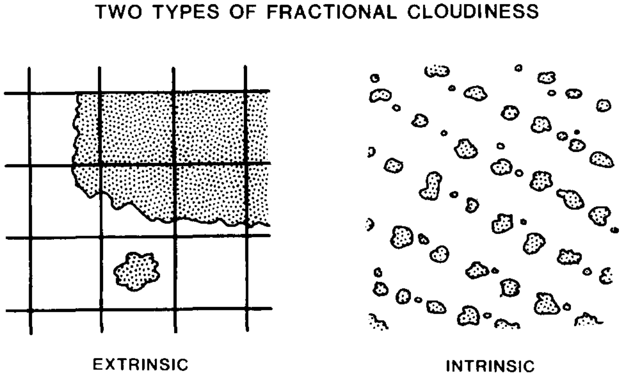

Fig. 2. Diagrams illustrating extrinsic and intrinsic fractional cloudiness. See text for details.

cloud water mixing ratio on temperature. This suggests that the observed variations in the large-scale average cloud water are dominated by variations in "cloud amount" rather than local cloud water concentration. It may be possible to develop a parameterization of the radiative, dynamical and cloud-physical effects of the small-scale variability of cloudiness, based, in part, on this approach.

It may also be necessary, however, to take into account the role of small-scale convective motions in determining the fractional cloudiness. These motions are known to play an important role even in stratiform cloud systems (e.g., Lilly, 1968, 1988; Starr and Cox, 1985a,b). Randall (1987) has proposed elements of a parameterization for convectively driven small-scale cloudiness fluctuations. Perhaps the most natural cloud types to parameterize in this way are stratocumulus and shallow cumulus clouds that reside in the planetary boundary layer (PBL), since existing climate models already include boundary-layer turbulence parameterizations. Although stratocumulus cloud sheets are sometimes completely unbroken over tens of thousands of square kilometers, both common experience and satellite photos show that they are often riddled with small holes that appear to be associated with the turbulent character of the cloud. Even when the cloud sheet is unbroken, there are significant undulations of cloud top and cloud base, so that at a given level the fractional cloudiness can be between zero and one. The commonly observed break-up of a stratocumulus sheet into shallow cumuli (Randall, 1980) necessarily entails a reduction in the fractional cloudiness; a satisfactory theory of the break-up must allow arbitrary cloudiness.

Betts (1973, 1983), Hanson (1981), Penc and Albrecht (1986), and Wang and Albrecht (1986) have discussed models of partly cloudy PBLs containing a single family of convective circulations. The circulations have both ascending and descending branches, and cloudiness can occur (or not) in either branch. Similar ideas have been used in observational studies (based on conditional sampling and/or joint distribution functions) by Lenschow and Stephens (1980, 1982), Greenhut and Khalsa (1982), and Wilczak and Businger (1983), Mahrt and Paumier (1984), Grossman (1984), Khalsa and Greenhut (1985), and Penc and Albrecht (1986).

These models show that the fractional cloudiness is closely related to the fractional area covered by rising motion, and also to the convective fluctuations of temperature and mixing ratio. To date, no method to determine these quantities has been demonstrated. Even if one can be found, the resulting fractional cloudiness parameterization will be rather complicated, since the fractional cloudiness will be determined, in part, by the turbulence, but at the same time the intensity and character of the turbulence will be determined in part by the presence of the clouds and their effects on the radiation field. The cloud, turbulence, and radiation parameterizations will give rise, therefore, to a coupled system of equations that must be solved simultaneously. It will be a challenge to devise an algorithm that is accurate yet computationally fast enough for use in a GCM.

CONCLUSIONS

Interactive cloud parameterizations are now accepted as necessary components of any climate model, but their development is still at an early stage. We lack adequate understanding of what the distribution of global cloudiness actually is, what determines it, what effects the clouds have on the large-scale circulation of the atmosphere and on the climate system generally, and how the clouds feed back to influence climate change. The clouds most urgently in need of better parameterization, in view of their importance for climate and the inadequacies of current parameterizations, are the upper-tropospheric stratiform clouds associated with deep convention. Two key modeling issues currently facing us are how to use prognostic cloud water variables, and how to parameterize fractional cloudiness. These are critical problems, since reliable cloud parameterizations are a necessary prerequisite for reliable predictions of anthropogenic climate change.

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