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Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs

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Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs

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1. Introduction

The World Climate Research Programme, through its Global Energy and Water Cycle Experiment (GEWEX), has set up the GEWEX Cloud System Study (GCSS) to improve the representation of cloud processes in climate and numerical weather prediction models - see GEWEX Cloud System Science Team (1993). As part of the process of developing an implementation plan I have written to the directors of centres concerned with global modelling to ascertain what they regard as the priority issues needing to be addressed in parametrizing the large-scale effects of clouds and cloud-related processes. I have to admit that the question as posed was rather broad: the kind and level of parametrization tasks and problems, in fact, depend on the physical and numerical structure of the model, on the task it is designed for and even on the specific model aspect that one would like particularly to address. Nevertheless, in the replies some clear themes emerged which are summarized in this short note. Twenty four centres (Table 1) expressed an interest in the survey and 20 of these provided a detailed response. I have tried to retain the forms of words used by the respondents and have ascertained that this summary accommodates their views in a reasonably balanced way.

2. The major issues

2.1 Factors affecting cloud cover

Cloud cover is a key parameter in general circulation models (GCMs) and any errors in cloud cover will affect both the long and short wave radiative transfer calculations and the distribution of heating at the surface and vertically throughout the atmosphere. Many respondents referred to inadequacies in the present schemes for representing cloud cover,

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mainly but not entirely in the context of boundary layer cloud. In some models there is a systematic underestimate of boundary layer clouds. This is thought to be due to insufficiently detailed microphysics. A major problem is also the inadequate specification of the mixing processes across the inversion. The poor representation of boundary layer cloud cover limits our ability to treat cloud-radiation interactions in several important regions, eg over upwelling regions of oceans and over the Arctic in summer. The warming of the ocean in coupled models, in the areas west of Namibia, Chile and California, may be caused by excessively high insolation due to the underestimation of the boundary layer cloud cover. The turbulent fluxes driven by cloud-topped boundary layers also affect the energy balance at the ocean-atmosphere interface and the present failure to represent them properly in GCMs is likely to impair a models' coupling between the ocean and atmosphere.

The problem facing us is that we still do not have an adequate physical basis for predicting cloud cover in GCMs. In the case of boundary layer clouds we need to understand better the role and interactions of microphysical processes including drizzle formation and the exchange of heat and moisture between surface, boundary layer and free atmosphere. In addition we need to examine aspects of the large-scale cloud environment such as vertical velocity that might influence their formation and decay.

The respondents also highlighted the importance of understanding the factors controlling the extent and persistence of tropical anvils. Some of these factors are mentioned later under the headings of cloud optical properties (Sec 2.2) and redistribution of moisture (Sec 2.3). Another factor that might affect the persistence of anvils and needs to be understood better, is the possibility of small-scale circulations associated with radiative and microphysical processes. The role of anvil clouds is poorly represented in GCMs.

It is not only the horizontal extent of cloud that is important; it is also its vertical distribution. Far too little is known about either the actual distribution of multilayered clouds or of the factors that control their vertical distribution. The use of explicit cloud water schemes in GCMs will open the way for the development of more realistic predictions of cloud layering. Experiments are needed with GCMs using higher vertical resolution in the boundary layer. In the case of shallow cloud layers there may be a need to devise parametrizations of subgridscale cloud thickness.

A problem in the area of cloud-radiation interaction is the need to decide where a cloud sits within a GCM grid box, in other words the morphology of the cloud field. This problem applies both to empirical cloud prediction schemes and to explicit cloud water schemes. Similarly, for multiple cloud layers, the use of different overlap assumptions relating to the cloud cover at different levels gives rise to different large-scale effects. Even though top-of-atmosphere radiative fluxes can be tuned to fit observations, the different overlap assumptions still lead to unacceptably large differences in the vertical profile of radiative heating.

The concept of cloud cover is essentially limited to binary information (cloudy or clear) and so it is poorly suited to accommodating aspects of variable cloud type, overlap, optical depth, vertical velocity, etc, within a model grid box. One respondent suggested that a possible approach would be to explore the concept of 'effective cloud cover' in which ensemble cloud effects from a radiative and water mass cycling viewpoint would be treated stochastically. Probability density functions of cloud properties, as opposed to just means, could then be diagnosed or represented.

2.2 Factors affecting the optical properties of clouds

Optical properties (albedo, absorptivity, emissivity) were high on lists of priorities, at least in the cases where the respondents felt that prioritization was appropriate (cf. Sec.2.5). One respondent, for example, gave top priority to the problem of determining the optical thickness of boundary layer clouds as influenced by drizzle formation and cloud top entrainment. Another specifically cited the need to study factors affecting the absorption of short wave radiation especially by boundary layer clouds. High priority was also given to determining the optical properties of other clouds. An example given was the distinction between anvils and thin cirrus.

Mentioned specifically, but at a lower priority, was the need to improve the parametrization of the ice/water fraction. With respect to stratiform cloudiness, the formulation of a physically based explicit cloud water/ice scheme will be important for a more accurate prediction of precipitation patterns and intensities and also for calculating cloud feedback in studies of climate change. Also, lacking altogether in GCMs are parametrizations of effective drop size in liquid clouds and the effective particle size and shape in ice clouds, including the ways in which they are influenced by aerosols. The absence of such parametrizations prevents an adequate treatment of the interactions between clouds and radiation, especially in the case of cirrus whose optical properties vary strongly over the observed ranges of ice water paths, and crystal sizes and shapes.

The 3-D geometry of clouds, mentioned above, is clearly important for determining the radiative effects of clouds. What is not yet clear is the extent to which the generally-used assumption of plane-parallel cloud layers is adequate, or whether it will be necessary to incorporate explicitly the radiative effects of broken cloud fields.

2.3 Factors affecting the redistribution of heat, moisture and momentum by clouds

Recent research has shown that different cumulus parametrizations produce very different large-scale organization of convection. There is a lack of understanding of the processes that organize convection on the large scales and thus of an appropriate closure assumption to use within the convection scheme. The ability of a convective parametrization to represent the correct spatial and temporal organization is relevant to a wide range of important issues, such as prediction of local tropical weather phenomena, coupling with the extratropics, ocean-atmosphere interaction and middle atmosphere dynamics. A systematic study of the ability of existing convection schemes to organize tropical convection is needed.

Convection parametrizations have until now been developed for only a limited set of observed cases and there is a need to develop schemes for a much wider range of situations. The range of situations should embrace a variety of different dynamical types of convective clouds in different regions to determine the extent to which the different dynamical organizations impact the profiles of apparent sources of heat, moisture and momentum (Q_1, Q_2, and Q_3). Slantwise convection and mid-level convection, common in mid-latitude storm systems, need to be studied too. Storm tracks may be sensitive to the representation of these processes especially in regions of cyclone development, over western ocean basins. Their proper parametrization might also help reduce the overestimate in mid-latitude relative humidity found in some models. It will of course be a major challenge to predict the occurrence of different cloud (dynamical) types from the gridscale mean thermodynamic variables in GCMs.

Although observational studies indicate that the occurrence of different types of coupled disturbances (waves, vortices) and their associated cloud systems is greatly influenced by large scale factors such as wind shear, sea surface temperature and latitude, the full reasons for the selection of the type and time-scale of disturbances are not understood. For example, selection due to wind shear appears to act via its effect on the mesoscale cloud structure but such effects and the resultant large-scale feedback are not directly considered in current cumulus parametrization schemes. This complex issue can be studied using a combination of field measurements and cloud-resolving models. A comparison of the statistical behaviour of disturbances generated within climate models with those observed in the real atmosphere may also shed light on the selection mechanisms.

Convection determines the thermodynamic structure of the tropical atmosphere directly and that of the sub-tropical atmosphere indirectly through the strength of the descending branch of the Hadley circulation. Errors in the thermodynamic structure can influence the clear sky radiative fluxes and hence the greenhouse effect. The verification of humidity structures, particularly in the upper troposphere, is especially problematic. Highest priority was assigned by some respondents to improving our understanding of the vertical heating profile due to convection and also the upward transport of condensate by convection. The latter affects the amount of ice detrained into mesoscale anvils and, therefore, the tropical components of cloud and water vapour feedback. A key question that arises in connection with the vertical profile of Q_2 is whether the convectively induced drying at most levels is replaced by moistening near the tropopause and, if so, at what level.

The above discussion has concentrated on the parametrization of deep, precipitating convection. Shallow convection is of comparable importance as a means of transporting moisture from the boundary layer into the free atmosphere, and in determining the structure of the boundary layer, such as in the trade winds and in cold air outbreaks. In most GCMs there is an artificial distinction between precipitating and non-precipitating convection, with only one type allowed in a grid box at any time. This has possibly led to problems in the simulation of the trade wind boundary layer and the maintenance of the trade wind inversion. There is a clear need to develop parametrizations that will represent the relative co-existence of these two types of convection.

Improving the parametrization of momentum transport and Q_3 is potentially important because different types of cloud system behave in opposite ways: unorganized convection transports momentum downgradient whereas some organized convection transports it upgradient. Gravity waves generated by convection exert a drag on the large-scale flow whose overall importance also remains to be assessed. While heat and moisture transport are now represented to some extent in all parametrizations, momentum transport is ignored. It seems likely that even a zero-order parametrization of momentum should have an impact.

2.4 Factors affecting the distribution of precipitation

The parametrization of precipitation, both stratiforms and convective, and including that from water, ice and mixed ice/water clouds, is another problem area. The common practice in GCMs that do not include explicit treatment of cloud liquid water is to release stratiform or large-scale precipitation only when the grid box reaches saturation. This assumption is not realistic and some degree of sub-saturation would be more appropriate, depending on the probability of some part of the grid box being saturated. GCMs that include liquid water schemes are still sensitive to assumptions within those schemes, such as autoconversion rates, phase changes from water to ice, and fall speeds for clouds droplets. This has produced highly diverse results for the role of cloud feedback in climate change. It was also noted that the poor representation of precipitation mechanisms in stratocumulus can lead to overprediction of precipitation from such clouds. The poor representation of mixing in clouds may be an even greater problem. Finally, the ability to assess the subgridscale distribution of precipitation was recognized as important for the calculation of surface evaporation rate.

2.5 Coupling between physical processes

Several respondents expressed reservations about attempting to prioritize the importance of specific cloud-related parametrizations because so many of the processes are coupled. Some went further by stressing that cloud parametrizations have to be considered as a whole in order to take proper account of the feedbacks between them. They argued, in particular, that the thermodynamic and hydrological elements of cloud parametrizations must be coupled to the radiative parametrizations in a physically consistent manner. One source of inconsistency in many models is that the time interval for radiative calculations is much longer than that for cloud. Some cloud parametrization schemes, based on relative humidity for example, are tuned to give the right radiative heating but give the wrong latent heating.

The coupling between convective clouds and stratiform clouds was a recurring theme. Most clouds, even stratocumulus, are convective to some degree. And all moist convection leads to some stratiform cloud debris, of which mesoscale anvils in the tropics are an extreme example. Mesoscale anvils are radiatively very important and the absence of proper coupling to enable their parametrization in GCMs, is believed to limit greatly the ability of the models to simulate cloud-radiation interactions, especially in key areas such as the western Pacific.

Coupling exists, too, between convective processes and boundary layer processes and it is thought to be necessary to unify these schemes. This applies, for instance, to convective systems that generate downdraughts with dry gusty outflows, leading to enhanced evaporation and sensible heat flux. There is no adequate parametrization of these sub-gridscale effects in current GCMs. Surface moisture and energy fluxes are also modified by the radiative effects of the clouds, for example their shadows. Over the oceans these effects combine to influence the large-scale dynamics which maintains the west Pacific warm pool.

At present the radiative effects of anvil clouds are put directly into the large-scale temperature field of a GCM rather than being involved directly in determining the lifecycle of the cloud. The overall impact of the cloud-radiation interaction may be quite different in the two approaches. Other examples exist where the coupling between physical processes should take place within a unified approach to parametrization, rather than applying a sequential adjustment to changes in the large-scale environment. Such a unified approach can be developed only by a systematic study of all the interacting processes using a range of models beginning with ones at the smallest scales.

3. Concluding remarks

The responses from the GCM modellers indicate a wide variety of issues that need to be addressed. But, as noted above, certain priorities emerged, and also some guiding principles. One principle that emerged is the need to give priority to gaining physical understanding. We must improve the physical realism of the parametrization schemes and of the cloud models they use, and thereby reduce our present dependence on empirical tuning of parametrization schemes. However, realism must not be bought at the expense of too much complexity in the parametrization schemes.

A further principle is the importance of unifying parametrization schemes to take into account the coupling between physical processes. It was widely felt that the use of cloud resolving models, as advocated by GCSS (1993), provided the key to developing an understanding of these complex interactions. The cloud resolving models will also shed light on the often strong dependence of parametrization schemes on model resolution. This is important because the typical resolution of GCMs will be substantially higher than 100 km when GCSS comes to full maturity, say in 10 years time.

In regard to the development of the cloud resolving models, concern was expressed about the lack of good observations, especially of water vapour, cloud water (including droplet size distributions), and ice. Better in situ field measurements are needed on the scale of individual cloud systems, and better remote sensing measurements, with the capability to resolve vertical cloud structure, are needed to generalize the local results to the global scales. The view was also expressed that the GCSS, in promoting the development, intercomparison and use of cloud-resolving models, should encourage the production of modules or subroutines that could be used interchangeably within the cloud-resolving models being developed by different groups. Along with the increasing use of cloud-resolving models, it will remain important for global scale diagnostic studies with GCMs to be continued as a means of identifying systematic errors.

Finally, several of the global modelling centres indicated that they either had developed or were planning to develop the use of prognostic cloud water variables within their GCMs. This approach can be expected to provide an important vehicle for implementing improved parametrization schemes.

Reference

GEWEX Cloud System Science Team 1993. The GEWEX Cloud System Study (GCSS). Bull.Amer.Meteorol.Soc., **74**, 387-399.

Table 1. Centres running atmospheric GCMs who replied to this survey

(those marked by an asterisk responded in detail regarding aspects of cloud-related parametrizations that require priority attention)

Modelling Centre	Point of Contact
Bureau of Meteorology Research Centre* (Melbourne, Australia)	Mike Manton
Centre for Climate System Research (Univ. of Tokyo, Japan) in collaboration with National Institute for Environmental Studies* (Tsukuba, Japan)	Atusi Numaguti
Centre for Global Atmospheric Modelling* (Univ of Reading, UK)	Julia Slingo
Centre National de Recherches Meteorologiques* (Toulouse, France)	Jean-Luc Redelsperger
Chinese Academy of Meteorological Sciences* (Beijing, PR China)	Liu Yubao
Colorado State University* (Fort Collins, Colo., USA)	David Randall
CSIRO, Div of Atmospheric Research (Aspendale, Vic. Australia)	Brian Ryan
Danmarks Meteorologiske Institut (Copenhagen, Denmark)	Leif Laursen
Deutscher Wetterdienst Research Dept* (Offenbach, Germany)	G Doms
European Centre for Medium-range Weather Forecasts (Reading,UK)	Tony Hollingsworth
Fleet Numerical Oceanography Center (Monterey, California, USA)	-
Geophysical Fluid Dynamics Laboratory* (Princeton, New Jersey, USA)	Leo Donner
Goddard Space Flight Center* (New York, N.Y., USA)	Anthony Del Genio

Modelling Centre	Point of Contact
Hadley Centre, Meteorological Office* (Bracknell, UK)	David Gregory
Japan Meteorological Agency, Numerical Prediction Division* (Tokyo, Japan)	Toshiki Iwasaki
Laboratoire de Meteorologie Dynamique* (Paris, France)	Hervé le Treut
Los Alamos National Laboratory* (Los Alamos, New Mexico, USA)	Sumner Barr
Marshall Space Flight Center* (Alabama, USA)	Franklin Robertson
Max Planck Institute for Meteorology* (Hamburg, Germany)	Erich Roeckner
Meteorological Research Insitute* (Tsukuba-city, Japan)	Shoji Asano
National Center for Atmospheric Research* (Boulder, Colo., USA)	Mitchell Moncrieff Jeff Kiehl
National Meteorological Centre* (Washington, DC, USA)	Hua Lu Pan
Phillips Laboratory* (Hanscom AFB, Mass., USA)	Donald Norquist
The Florida State University (Tallahassee, Florida, USA)	T N Krishnamurti
University of Illinois* (Urbana, Illinois, USA)	Mankin Mak

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