Joint Centre for Mesoscale Meteorology, Reading, UK

GEWEX Cloud System Study Science Plan

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GEWEX CLOUD SYSTEM STUDY: SCIENCE PLAN

1. Introduction

1.1 Importance of cloud-related processes in large-scale models

Cloud processes have an important effect on the large-scale behaviour of the atmosphere and indeed on the whole climate system. Many of these processes occur mostly on scales smaller than the grid spacing of the global numerical models used for climate and weather prediction. Therefore a major preoccupation of the modelling community is to determine how the large-scale effects of ensembles of clouds may be parameterised in numerical weather prediction (NWP) models, general circulation models (GCMs), and climate models in terms of the basic variables defined on the models' coarse grid (of order 100km).

The large-scale modellers are concerned not just with the proper representation in the models of, for example cloud cover, liquid water content and cloud microphysical structure; they are also concerned with the effects of the clouds, via radiative and dynamical processes.

The effect of clouds in large-scale models is felt in several ways:

- Cloud-induced vertical profiles of apparent sources of heat, water vapour and momentum (Q_1, Q_2, Q_3).
- Cloud-induced increments in surface fluxes of heat, water vapour and momentum.
- Cloud-induced flux across the tropopause of heat, water and momentum.
- Probability density function for surface precipitation intensity.
- Cloud transports of trace gases and pollutants.

These effects are important in many different ways and different effects dominate in different circumstances; for example

- The vertical heating profile is thought to have a big impact on the large-scale dynamics; in the tropics, for example, realistic variations in the altitude of cloud-induced heating can alter the period of intra-seasonal oscillations from 20 to 50 days.

- The vertical distribution of water vapour sources and sinks is crucial to climate prediction because any cloud-induced increase (due to detrained ice) or decrease (due to compensating subsidence) in the amount of water vapour in the large-scale environment, especially in the upper troposphere, could lead to a positive/negative climate feedback.

- The vertical redistribution of momentum due to fields of motion associated with clouds is probably important but too little is known about it to be sure; what makes it so problematical is that momentum transfer can be downgradient or upgradient depending on the type of cloud, ie the cloud dynamics.

- Where vertical transport of water vapour (and other trace gases) through the tropopause is concerned, it may be that tall cumulonimbus clouds are the predominant mechanism in the tropics.

- Surface fluxes are indirectly affected by clouds, because of their effects on longwave and shortwave radiation and also the production via downdraughts of cool gusty surface winds.

- Precipitation plays a vital role in surface hydrology which is strongly dependent on whether a given amount falls, for example, as drizzle over a grid square or as a heavy shower over a small part of it.

- A key issue in the global hydrological cycle is precipitation minus evaporation, P-E; this determines soil moisture and agricultural viability and it also strongly influences climate via the ocean's thermohaline circulation.

At present the parameterisation of clouds is not performed very effectively. Existing parameterisations do not address the wide range and interactions of the processes involved; nor do they adequately represent the different types of cloud. The results of a survey of the views of the GCM community are given in Appendix 1. It is generally recognized that the inadequate parameterisation of clouds is one of the greatest sources of uncertainty in the prediction of weather and climate. This has led the World Climate Research Programme to establish a Cloud System Study as part of its Global Energy and Water Cycle Experiment (GEWEX).

1.2 The purpose of GCSS

The aim of GCSS in a nutshell is to develop better parameterisations of cloud systems within climate and NWP models via an improved understanding of the coupled physical processes within different types of cloud system.

The two over-arching issues confronted by GCSS are coupling and scales. The first has to do with the fact that, at the system level, it is often impossible to study the central processes separately; rather they must be studied in a coupled system. This is why we refer to GCSS as a Cloud System Study. It is also why we use cloud-resolving models in GCSS (see later). The second issue is that of scales: the coupled processes within cloud systems produce phenomena that span a larger range of space and time scales than may be encompassed by the individual processes. The most obvious example is that it is the atmospheric dynamics that set the scale of cloud systems, not the small-scale microphysics, but it is the action of the microphysical processes occurring on dynamically-induced scales that produces a cloud system. Hence GCSS is novel because it concentrates on the scale relationships and how they arise out of the processes (which is really a coupling issue).

Although many cloud-related processes can be considered sub-gridscale, some important processes occur on scales comparable with GCM grid scales. The problem of representing these is far greater than that of deriving parameterisations for individual small-scale processes. And since the small-scale processes may interact strongly with these intermediate scales (mesoscales) the latter often cannot be ignored in deriving overall parameterisation schemes. This is a key issue underlying the formulation of the GCSS programme.

2. Approach of GCSS

2.1 Emphasis on physical understanding

The usual approach for developing cloud parameterisations in large-scale models involves empirical tuning to minimise model errors. However, a model tuned to the present climate is an unreliable tool for prediction of climate change. In general the subtlety of clouds is such that the tuning adopted to make a large-scale model perform well in one circumstance may be inappropriate to other circumstances. Moreover it is difficult to diagnose model errors in terms of errors in specific cloud processes because the model performance is affected by many (often interacting) facets of the representation of clouds and other processes. It will, therefore, be necessary to achieve a better physical understanding of the cloud processes and the way they interact in order to be able to develop parameterisations that are transferable over a wide range of circumstances and suitable for global application. This is the approach adopted in GCSS.

2.2 Emphasis on cloud-resolving models (CRMs)

As described in the Report by the GEWEX Cloud System Science Team (Bulletin, American Meteorological Society, 1993) the primary focus within GCSS is the use of cloud-resolving (and mesoscale) models, along with observational data, as the means towards the end of deriving parameterisations for large-scale climate and NWP models. This approach is summarized in Figs 1 and 2. An example of the output from a CRM is shown in Fig 3. The CRMs, with resolutions of order 1 km, are used both as a test bed for developing understanding and ideas for parameterisation schemes, and also for providing cloud system realizations (synthetic data sets) to be used for developing parameterisation schemes for the larger-scale models.

It is of course necessary to develop parameterisations for the CRMs themselves before they can be used as tools to develop the parameterisations in the large-scale models (Fig 2(a)). It is, however, much easier to do this for CRMs because of the greater homogeneity of cloud processes on the 1km scale compared with the 100km of the large-scale models. The parameterisations required for CRMs relate mainly to cloud microphysical processes and turbulence: the other processes can be represented explicitly. The resulting cloud system realizations, by incorporating the proper dynamics and non-linear interactions explicitly, represent the combined effects of a wide range of physical processes in a realistic way. They can therefore be used to derive useful estimates of the large-scale transports and apparent sources of heat, moisture and momentum that are required to be parameterised in the large-scale models.

This approach is illustrated by the example in Fig 4 which shows components of the heat budget from a CRM as a function of height averaged over a 50 x 50 km domain and over one hour of integration. Fig 4(a) shows the latent heating profile due to formation and evaporation of precipitation. Fig 4(b) shows the flux divergence of liquid water static energy,

T_L (a temperature variable that is conserved in the presence of phase changes and vertical displacement). The net heating rate, $\Delta T_L / \Delta t$ (Fig 4(c)), as required for a large-scale model, is the sum of these components (this is only an approximation since the contribution from radiation is not included). Each of these components depends in a complicated way on the cloud-scale processes and it is the purpose of GCSS and its CRMs to determine their effect.

The CRM can be used to validate and improve a parameterisation scheme in a larger-scale model by running a single-column version of the large-scale model and then comparing the heating rates with those derived from the CRM. Once this has been done for a range of cloud systems, the parameters in the parameterisation scheme - entrainment and detrainment rates, for example - can be set so that the two models give similar heating rates. Of course, both heat and moisture budgets must be set at the same time. It may also be possible to calculate the entrainment rates, and other quantities internal to parameterisation (such as mass fluxes in updraughts and downdraughts) directly from the CRM, and so validate the cloud model parameterisation scheme internally as well as the model's output.

2.3 Emphasis on different types of cloud system

We have already explained that the GCSS is concerned with cloud systems consisting of coupled processes rather than with the individual clouds themselves. There are a variety of types of cloud systems. Their variability, and how to take it into account in developing parameterisations, is a complex issue. There are two levels of complexity. At the lowest level of complexity it is possible to think in terms of a number of major cloud system types for which different physical processes are dominant (but not exclusively so). Although our ideas may evolve in the light of further research, an initial categorization is:

- boundary layer clouds, dominated by turbulent boundary layer processes.
- high-level layer clouds, dominated by advection of cloud debris or water vapour from regions of active convection or slantwise ascent,
- extratropical layer-cloud systems, dominated by slantwise (stratiform) ascent,
- precipitating convectively-driven clouds, dominated by vertical convection and its consequences,

To the extent that these types are driven by physical processes that can be represented individually within large-scale models, they can be incorporated within the framework of a fully prognostic cloud scheme where cloud-related processes are treated in a unified way. An appropriate vehicle for applying such understanding will be a large-scale model with explicit cloud water content.

There is, however, a further level of complexity that needs to be addressed within GCSS. There is evidence that there exists, through different coupling of physical and dynamical processes, a range of cloud system types whose organization and large-scale effects differ not just in degree but also in kind. If the distinction were solely one of cloud extent or intensity (in some sense) then it would be inappropriate to complicate matters by introducing further categorizations. However, there are different categories of mesoscale convective system that are characterized by qualitatively different dynamical organizations and differently coupled physical processes, and which lead to fundamentally different large-scale effects (Sec 8). For example, some mesoscale convective systems are organized so as to transport momentum in a downgradient sense while others do so in an upgradient sense. Mesoscale convective systems also differ considerably from ordinary cumulonimbus clouds in terms of heating profiles, cloud radiative effects and rainfall production.

It is not obvious whether equally important distinctions exist for other cloud types. In the case of boundary layer cloud, consider, for example, the distinction between a homogeneous cloud sheet, cumulus cloud streets, and cumulus clouds organized in open or closed cells. It needs to be determined whether the associated differences in eddy fluxes and radiative heating are sufficiently great to need to be represented within large-scale models.

A detailed cloud system categorization will evolve as part of the GCSS research programme. For the time being the four cloud types listed above will be adopted as the primary categories but these will be refined in the light of the detailed GCSS studies. Such a categorization is certainly an important component of developing understanding; what is not yet clear is the extent to which the categorization will actually have to be applied to future parameterisation schemes in large-scale models. The latter will be difficult because it implies the need to be able to identify the occurrence of each category of cloud system from the large-scale forcing. It will be necessary to resolve the large-scale changes that cause one kind of system to evolve into another, often via some kind of instability mechanism. Activation algorithms may also be needed to identify the time of development of particular types of cloud systems. Such algorithms are obviously important for limited-area models applied to very-short-range forecasting for which good timing (eg of thunderstorm outbreaks) is essential. Timing errors would not be a critical issue for large-scale climate models if the errors were random; however, clouds of different types have different diurnal variability and, since the radiative effects of clouds depends on time of day, it is necessary to represent correctly the diurnal variability of cloud activation.

2.4 Emphasis on global generalization

The occurrence of the different cloud types, and their importance, varies seasonally and also regionally. GCSS therefore has to be a multi-regional/global programme. This means not only that intensive observational field programmes need to be undertaken in different key regions but also that global observations are required to put the detailed studies in perspective and to generalize the findings from them. This calls for studies of satellite measurements that discriminate between different types of cloud system. In the short and medium term progress can be made by subtle use of existing global data sets (eg ISCCP). Further progress will require improved global observations from space, for example, of the vertical structure of clouds using radar and lidar to complement multifrequency infrared and microwave radiometry.

Satellites, because of their extensive coverage, are able to observe a wide range of regional variations as well as different stages in the life cycle of cloud systems and they are well suited to discerning systematic variations in their structure and optical properties. Satellite observations can play a key role in stratifying large quantities of conventional meteorological observations by the characteristics of the clouds so as to provide statistical relationship of cloud properties to atmospheric conditions. One such study has been able to separate the influences of surface conditions and atmospheric vertical structure to explain the observed spatial distribution and seasonal variations of tropical deep convection. The key step was the sorting of sparse rawinsonde and surface meteorological observations using the satellite to classify different locations and time periods as convectively active or inactive. Another study surveyed the variations of the size distribution of tropical convective cloud clusters over the whole tropics for two years and examined the similarities and differences of different sized systems. The key to recognizing systematic variations in the structure of these systems is the large number of cases that can be studied using satellite observations. This study also illustrated a key contribution of satellite data to diagnostic studies of mesoscale dynamical systems: namely, the satellite measurements can more readily be used to determine some of the radiative feedbacks of clouds on such systems because the variation of the optical properties of the clouds can be determined over the whole system and over its complete life cycle.

Similar uses can be made of satellite measurements to study the factors controlling the spatial structures of marine stratocumulus clouds and cirrus clouds. Significant features that are explainable using conventional surface and aircraft data sources can be identified in satellite observations. Models of the structure and evolution of particular clouds obtained from a combination of satellite, surface and aircraft measurements can be generalised using satellite surveys of cloud system structures and life cycles.

3. The use of cloud-resolving models and observations for studying different types of cloud system

3.1 Use of cloud-resolving models (CRMs)

It has long been suggested that CRMs would prove useful for the development of improved cloud parameterisations. What now makes this approach within GCSS timely is the increasing availability of the computer capacity needed to make the approach viable. As explained above, once validated against observational data, CRMs have the potential for providing a proxy dataset against which parameterisation schemes can be compared in a wide variety of meteorological situations, assuming that sub-grid processes in the CRMs themselves (ie turbulence, radiation, microphysics) are accurately parameterised.

Since parameterisation schemes aim to represent the impact of a variety of clouds upon the large-scale atmosphere, the models used in such studies must be capable of simulating an ensemble of convective elements and also the interactions between the various scales found within cloud systems. Domains are required larger than the grid boxes of large-scale models (ie significantly greater than 100km square), with sufficient horizontal and vertical resolution (1km and 500 m at least) to allow accurate simulation of the impact of small-scale processes upon cloud-scale motions.

Tests of, for example, convection schemes in single-column models against CRM results will be valuable in determining the validity of the schemes in a variety of different conditions around the globe. They will also be valuable in determining their internal parameters, for example entrainment rates for updraughts and downdraughts and the dependence of such parameters upon the environment in which the cloud exists. Examples of key questions that could be addressed by the calculation of statistics from simulations of cloud ensembles are factors determining fractional cloud cover, the impact of convective motions upon surface fluxes and the importance of mesoscale features.

Convection is known to transport momentum in the vertical. Although included in some parameterisation schemes, the methodology used is, as already mentioned, clearly inadequate for organised convective systems. This is an important problem which CRM studies can address. However, the adjustment of the atmosphere to such transports is not local but occurs on the scale of the Rossby radius, implying that the adjustment of a models' dynamics and thermodynamic fields to convection may need to be carried out over a wider area than a single grid point, with the mesoscale cloud organisation being accounted for. CRMs with large domains need to be developed to study the approach to a balanced state more fully, especially in the tropics. Resolution would have to be such that cloud-scale momentum transports are adequately represented; this implies a resolution probably better than 1km. Increases in computer power over the next few years will make such models possible.

Study of CRM simulations with clouds growing in a variety of different initial conditions and under different large-scale forcing allows the closure problem for convection to be investigated more fully than has so far been possible using observational data. The impact of shear and cloud organisation can also be quantified. Observations suggest that vertical temperature profiles of deep convective atmospheres are characterised by well defined equilibrium structures. It is not clear whether similar equilibrium structures exist for moisture. Provided that cloud microphysics schemes are realistic, CRM studies will allow the interaction of cloud systems and moisture to be studied in detail.

Boundary layer clouds are also important for determining the general circulation of the atmosphere. In large-scale models the tropical circulation is extremely sensitive to the treatment of shallow convection in the trade-wind boundary layer. Comparison of the performance of current boundary layer and convection schemes in single-column models against detailed CRMs applied to boundary layer clouds (Sec 5) will bring further understanding of this crucial area. Simulation of low cloud in the sub-tropics and polar regions will contribute to the improvement of climate models because the failure to represent such clouds correctly can lead, as noted earlier, to large errors in the surface radiation budget, leading to the necessity of applying large flux corrections in coupled atmosphere ocean models. The heterogeneity of boundary layer fluxes caused by both surface heterogeneity and variations induced in the surface layer by cloud motions can be quantified from simulations of the cloudy boundary layer and new parameterisations can be derived allowing for these impacts.

In the mid-latitudes, layer-cloud systems rather than convective clouds are dominant (Sec 7). They have a large impact on the radiation budget of the atmosphere. The quality of the radiative simulation in climate models is very dependent upon the microphysical treatment, the cloud optical properties depending upon the number of particles, their phase and shape. Large-scale models are now beginning to employ layer-cloud schemes which predict cloud water content with reasonable agreement against in-situ and satellite observations. However, the variability of water contents within cloud is not considered in the calculation of precipitation which may be a factor in the over-estimation of the humidity content of the mid-latitudes by large-scale models. Studies of detailed microphysical models within CRMs will provide an opportunity for improved bulk microphysical schemes to be developed and for the rescaling of such schemes to scales appropriate to NWP and climate models.

Mesoscale variability is also important in mid-latitude layer-cloud systems. Current mesoscale models with grid lengths of a few tens of kilometres, together with further observations of mid-latitude systems, will assist the quantification of this variability, but such models still rely on the parameterisation of cloud-scale motions. If progress is to be made in the parameterisation of mesoscale cloud features, such as slantwise convection, embedded within frontal systems, then the use of models with increased horizontal and vertical resolution will be required.

3.2 Use of observations

Almost all previous and most current studies of cloud processes have used measurements made from the surface or aircraft; only rarely, as part of large expensive projects, have co-ordinated observations been made from more than one surface site and/or aircraft. The occasional use of scanning radars and lidars has improved coverage of scales up to 100km in some experiments. Otherwise these datasets provide very poor sampling of even a single cloud element, much less the larger-scale circulation systems they occur in. Thus, although we have gained good understanding of the basic cloud micro-processes and their interaction with atmospheric motions up to scales of a few kilometres, this body of knowledge falls short of what is needed for improving climate models in three key ways. Firstly, even collection of all available observations about a particular cloud type does not produce a general understanding because there is no way to determine the statistical significance of the samples we have. Selection criteria used by investigators are not usually described or quantifiable nor can we determine whether the sample is "typical" for that cloud type. In other words, we do not know which features of the observed clouds are key and which are unimportant details. Secondly, very few datasets provide a Lagrangian sample of a cloud system's development, evolution and decay, so that the interpretation of the sparse collection of observations provides ambiguous information about the factors controlling the cloud system life cycle. Thirdly, while recent observations have begun to cover space/time scales of 10-100km and 1-10h, cloud processes are involved in a set of feedbacks that couple these small scales to larger scales of atmospheric motion. The coupling of small and large scales is especially crucial for climate model design, because the central problem is to produce practical predictions of small changes (a few percent) with high accuracy by representing some processes explicitly and other implicitly. This scale coupling of cloud processes cannot be studied with available datasets.

Since the key to scale interaction is cloud dynamics, we must emphasise datasets with a proper match of space and time resolutions. Smaller scale (< 10km) clouds need to be observed with a time resolution less than 1h; larger scale (100-1000km) cloud systems require time resolutions of 1-10h. Satellite cloud observations provide global coverage with space/time resolutions of about 10km and 3h, in principle. (Although much higher spatial resolutions can be obtained, these measurements are made from low-flying satellites with poor time sampling at about 12 hr intervals). The most completely analysed dataset from the International Satellite Cloud Climatology Project (ISCCP) is summarized at 280km and 3h resolution. Measured cloud properties are cloud cover, cloud top temperature/pressure, cloud optical thickness and some information on the distribution of cloud-top locations. A higher spatial resolution (about 30km) version of these results provides a spatially sampled measure of cloud horizontal structure over the mesoscale range and can be used to track larger cloud systems throughout their life cycle. Additional analyses are being done to retrieve cloud particle size estimates from the ISCCP datasets that, together with optical thickness values, can be used to estimate cloud liquid water path. Techniques that combine passive microwave and infra-red sounder measurements are being developed that can provide some discrimination of liquid and ice phases and ice water path.

Satellite measurements do not provide all the key properties of clouds; in particular, more complete information about vertical structure is lacking. Also notably missing are measurements of the dynamics. Thus there is a need for data from major field experiments with multiple aircraft and ground-based observations to provide multi-faceted measurements to represent the various interacting cloud processes. Those properties that can be mapped by satellite will provide a useful context for the interpretation of these detailed measurements.

The basic satellite observations, plus intensive surface and aircraft datasets, exist for some cloud systems; however, a lot of work is still required to assemble a set of matched observations for particular cloud types. GCSS will combine its plans for model studies with concerted efforts to find out what datasets are available and to pull together matched case study datasets to perform the joint analyses. In fact the data analysis proceeds much better in parallel with development of interpretative models. This is a lot of work and so the most practical procedure is to convene working groups focused on a specific key cloud system types.. These groups, composed of modellers and data analysers, will be charged with collecting case study datasets, together with some routinely available model products (eg weather forecast model analyses to initialise mesoscale models), that set the stage for focused investigation of particular cloud systems by means of CRMs and mesoscale models. These activities will highlight deficiencies in the existing datasets and will point the way toward additional judiciously-selected field programmes.

4. Deliverables and organisation of GCSS

4.1 GCSS deliverables

To ensure that the GCSS research is well targeted it is necessary to identify clearly what outputs are required. The term 'deliverable' can be used to identify those outputs. The terminology is adopted despite some unease on the part of those researchers who consider that it obscures the fact that the main obstacle to improved parameterisations is lack of understanding. Although this is a term used by engineers, its use is not at variance with the stated aim of GCSS which is to make progress via increased understanding of the processes and categories of cloud systems. Such understanding is one of the intended deliverables.

It is convenient to identify two levels of deliverables. The ultimate deliverables will be a set of algorithms, expressed in terms of the variables in the large-scale model, which represent the net effects of the unresolved cloud processes (vertical transports Q_1, Q_2, and Q_3 etc). Their generation will require a cooperative effort between the cloud-resolving modellers and the large-scale modellers. But, first, there will also have to be another set of deliverables, as listed in Table 1, which represent the tools for deriving the wanted algorithms for the large-scale models.

Table 1: List of intermediate products required for the generation of the wanted parameterisations

- A set of cloud-resolving (and mesoscale) models suitable for studying different types of cloud systems and which have been verified against observations for at least a few case studies.

- Publication (eg CD ROM) of several case study observational data sets for each type of cloud system for comparison with models.

- Publication of 4-D synthetic data sets of model-derived cloud-system realizations, in terms of dynamic and thermodynamic variables plus bulk water/ice properties and limited microphysics, for each type of cloud system.

- Improved understanding of processes in each type of cloud system.

- Global cloud measurements (from satellite) to generalise the results from the regional studies and to compare with the statistics of the synthetic datasets.

A question that has been raised is whether it is indeed the function of GCSS to become involved in developing, for each cloud system category, general algorithms for calculating the net effects such as vertical transport, Q_1, Q_2, and Q_3 etc., or whether the scope of GCSS should be limited to predicting the individual cloud properties (3-D distribution of microphysics) that affect radiation, latent heating etc, leaving it to the sub-routines in the large-scale models to derive the net large-scale effects. The Science Panel believes that GCSS must pursue both sets of goals. It is precisely because of the complex non-linear interactions within cloud systems, and the fact that different modes of interaction exist within different categories of cloud system, that it is necessary to represent explicitly the combined effect of different processes within CRMs. The CRMs can then be used to calculate the net large-scale effects and the appropriate algorithms. The emphasis in GCSS is on cloud systems and their effects, not on individual processes per se.

Many specific GCSS activities are described in later parts of this plan but two generic activities that will be most conspicuous in the early stages of GCSS are:

(1) Preparation and publication (eg CD ROM) of carefully crafted case-study datasets. The objective will be to collect some standard model outputs from different models (as in the Atmospheric Model Intercomparison Project), together with observational datasets, and to make them available to other investigators who are in a position to explore particular issues but who may not have either their own model or comprehensive observational datasets. By leaving behind a legacy of documented datasets it will thus be possible to enlarge the working community in this field.

(2) Sponsorship of model comparisons. The objective here is to stimulate progress by encouraging the modelling community to explain in detail the differences in the behaviour of their models.

4.2 Organization of the research activity within GCSS

The GCSS Panel has identified a set of four broad cloud types and has established corresponding Working Groups as given in Table 2. See Appendix 2 for membership of the Panel and Working Groups. Much of the research undertaken under the auspices of GCSS will be based upon modelling and observing cloud systems over flat uniform terrain. However, the effects of inhomogeneities due to variable physiography will also be treated within the working groups. Orographic precipitation may be treated separately by another WCRP group because the research approach that needs to be adopted is rather distinct. Studies of orographic precipitation are location-specific and not easy to generalise. The precise way forward has yet to be finalised but in any case it will be important for a specific person on the GCSS Panel to have responsibility for physiographic and orographic effects and cross-membership on any other WCRP group that takes a special interest in this aspect.

Table 2: Working Groups within GCSS

GCSS Group	Cloud Type	Comments
1	Boundary layer clouds	Includes stratus, stratocumulus and cumulus; non-precipitating and drizzle-producing. Also includes marine cold air convection with and without precipitation.
2	Cirrus cloud fields	Includes middle- and high-level stratiform clouds that are all ice or mixed phase.
3	Extratropical layer cloud systems	Cyclonic and frontal cloud systems, mainly stratiform but with embedded convection. Also includes polar lows and comma cloud systems.
4	Precipitating convectively-driven cloud systems	Mesoscale convective systems and tropical cyclones; these systems contain slantwise as well as upright convection.

Each of the Working Groups will focus the activities of the relevant segment of the international research community on defined areas of work. They will exploit a hierarchy of models. Groups 1 and 2 will mainly exploit CRMs with resolution better than 1 km. Groups 3 and 4 will need to exploit both CRMs and mesoscale models with resolution of order 10 km. All of the groups will require access to observations from special field programmes to develop and validate the cloud models. Where possible data will be used from past or planned field experiments organized under other auspices.

Specific activities for each Working Group are to:

- Identify and develop the CRMs and mesoscale models appropriate for each cloud type.

- Assemble, for particular cloud types, case-study datasets accessible to the community, of (a) matched observations from satellites, surface and aircraft, and (b) model-derived synthetic datasets.

- Conduct workshops, including model intercomparisons using the above case study datasets.

- Specify blueprints of minimum observational data requirements for the development and validation of CRMs.

In situations where inadequate observational datasets exist Working Groups will

- Promote the requirements for observational data and encourage other planned experiments to be enhanced accordingly.

Each group will develop its own plans but the Group Chairs will maintain a common modus operandi through their membership of the overall GCSS Panel for Cloud Systems. Activities will be planned jointly where, for example, a common observational programme may be able to address different categories of clouds, as in the case of extratropical layer cloud systems (Working Group 3) and cirrus (Working Group 2).

5. Boundary layer clouds: Plan prepared by Working Group 1

5.1 Introduction

The focus of Working Group 1 is to develop parameterisation schemes of clouds that reside in the atmospheric boundary layer, or that are mainly residing in it, for use in large-scale models for medium-range weather prediction and climate research, especially GCMs. The approach is to use CRMs of boundary layer clouds to assist in the formulation, calibration, and testing of parameterisation schemes of those clouds. We begin by examining the priority issues in the field of parameterisation development for the cloudy boundary layer as perceived by the global modelling community. We then examine strategies for parameterising clouds in the marine and continental boundary layer. We end by outlining GCSS activities in this area; in particular intercomparison studies for CRMs, including Large Eddy Simulation (LES) models and mesoscale models of the cloudy boundary layer.

5.2 Key issues

Both atmospheric and oceanic GCMs need realistic parameterisations of boundary layer cloudiness. The atmospheric GCMs need it to simulate the large-scale circulation; in addition, they should predict clouds as part of their output. Low clouds strongly influence the surface energy budget, which ocean GCMs need in order to produce realistic thermohaline circulations and sea-surface temperature patterns. Low clouds also affect surface temperatures over land. Coupled ocean-atmosphere models, which are essential for climate change studies, depend even more critically on a realistic surface energy budget. The formation and breakup of stratocumulus drastically affects the surface energy budget, and so must be parameterised in order to achieve satisfactory weather forecasts and/or climate simulations with GCMs.

5.2.1. Specific problem areas

Although processes tend to be coupled and should be studied as part of a total system, for ease of presentation we shall consider them individually:

- *Entrainment.* Entrainment is a key process in boundary-layer cloud dynamics, which brings upper-level air into the boundary layer, and which under most conditions favours drying and a thinning of the clouds. Under typical stratocumulus conditions the addition of only a few per cent of upper-level air to a cloud-top cloudy parcel is sufficient to evaporate all of its liquid water. Even with relatively modest entrainment rates, drying and warming by entrainment of the upper-level air can produce large changes in cloud liquid water contents. Entrainment can also be of importance to the overall budget of cloud condensation nuclei. These processes are complicated by the dynamical and radiative feedbacks resulting from the altered cloud properties in the upper levels. Entrainment is difficult to parameterise in GCMs partly because the physics of the entrainment interface occurs in a region less than 100 m thick, across which the mean state changes drastically. Special vertical coordinates have been proposed to deal with this, but this approach has not been widely adopted.

- *Stratocumulus breakup.* Under certain conditions, evaporative cooling accompanying entrainment can produce mixed parcels that are negatively buoyant with respect to the unmixed cloud. It has been suggested that this situation would be unstable since the downward acceleration of such parcels could generate turbulent kinetic energy in the mixed layer and thus bring about further entrainment, possibly leading to cloud breakup or cloud top entrainment instability (CTEI). The analysis of observations of Pacific stratocumulus decks, however, has shown that there is little correlation between observed cloud breakup and the existence of conditions that could give rise to negatively buoyant mixed parcels. Sometimes breakup occurred when those conditions were not obtained, suggesting that there are other mechanisms for cloud breakup. Sometimes breakup did not occur even though it was predicted on the basis of the hypothetical entrainment instability mechanism. Recently a new threshold for runaway CTEI has been defined and it has been shown that trade cumulus soundings usually meet that criterion while most of the stratocumulus soundings during the FIRE project did not. Historically, discussions of the breakup of stratus clouds have focused on the cloud top entrainment instability mechanism. Although the exact formulation of the instability criterion has evolved over the years, the instability is still formulated in terms of the mean thermodynamic properties of the atmospheric boundary layer relative to the overlying free troposphere. Mesoscale and larger scale dynamical processes, as well as radiation and precipitation, are left out of this theory. High-resolution, CRMs provide invaluable complements to field observations for studying the transition processes. Even though precise three-dimensional, numerical simulation of the stratocumulus transition may not currently be possible, models can nevertheless play a key role in testing hypotheses and in sensitivity investigations. Any model that can satisfactorily simulate well-documented test cases, such as those recently observed during ASTEX (Atlantic Stratocumulus Experiment), can then be used to test the sensitivity to different physical and modelling assumptions.

- *Decoupling between stratocumulus layer and the atmospheric boundary layer.* Maintenance of layer clouds requires a flux of moisture from the surface to counteract the drying effect of entrainment. A modified mixed layer model has been used to show that diurnal solar heating in the cloud layer and/or evaporation of precipitation below the cloud can damp convection in the layer and weaken the turbulent fluxes to the cloud. Observations from GATE (GARP Atlantic Tropical Experiment) show signs of this decoupling in the form of a sharp change in the water content at about half the layer depth. The level at which the layers decouple may or may not coincide with cloud base, and the decoupling need not always produce a distinct, sharp step. Because the mixed layer model included no provision for partial cloud coverage, the decoupling resulted in diurnal thinning, but not breakup, of the cloud layer; it is not known whether this process acting alone may be able to produce breakup.

- *Importance of cloud microphysics.* Cloud microphysical processes, including the nucleation of droplets on cloud condensation nuclei (CCN), the evolution of the cloud droplet size distribution by condensation and evaporation, and the evolution of drizzle/raindrop spectra by coalescence and drop breakup, are being increasingly recognized as important for the bulk radiative properties of boundary-layer clouds. Not only do these cloud life-cycle processes influence the cloud's radiative properties, but radiative properties themselves affect cloud life-cycle processes. In other words these aspects are coupled and cannot be considered in isolation. Some workers have studied the effects of entrainment on droplet spectra, focusing on production of the large drops that are important for both radiative interactions and drizzle formation. Also observational studies of ship tracks suggest that the addition of CCN in the marine boundary layer can cause changes in cloud properties that are visible from satellite, indicating that the radiative characteristics of clouds may, in part, depend on CCN spectra. In FIRE, in situ airborne measurements have been obtained in ship tracks. Some researchers have examined droplet spectral evolution in radiative fields, and in one study the equilibrium raindrop spectra have been computed from vertical profiles of in-cloud turbulence statistics. We do not understand this problem well enough to begin immediately implementing CCN prediction in GCMs, but we should begin background studies aimed at that goal.

- *Mesoscale organization.* Some theoretical studies have linked entrainment dynamics with closed mesoscale cellular convection. It has been suggested that CTEI prefers narrow downdraughts, similar to those observed around the edges of closed cells. In addition, the large liquid water concentrations required for CTEI to operate may be favoured in regions of cloud-top convergence. For these reasons mesoscale cellular convection is of particular interest in connection with CTEI. Shear-driven mesoscale circulations can also regulate the cloud fraction, and so influence the surface energy budget. Until now, almost all studies with detailed cloud physics have failed to cover a sufficiently large domain to study the mesoscale organisation. Thus it is not surprising that there is not yet any adequate explanation of why mesoscale organisation occurs at all within stratocumulus.

- *Trade cumulus layer.* The trade-wind cumulus layer is arguably a type of boundary-layer cloud, and is important for the global climate, for the following reasons:

— A large fraction of the Earth's surface is covered by the trade-wind cloud regime, which is, therefore, an important climatic regime in itself.

— Strong and persistent surface evaporation occurs in the trade-wind regimes, far in excess of the precipitation; the trade-wind cumulus are thus a source of moisture for the general circulation of the atmosphere. Convective mixing transports moisture upward, drying the near-surface air and so permitting further moisture to be evaporated from the ocean. The rate of surface evaporation is thus regulated by the depth and vigour of the convection that is trapped below the trade inversion.

— The depth of the moist layer feeding into the ITCZ is controlled by the trade-wind cumulus processes acting upstream. Together with the sea surface temperature, the depth of the moist layer essentially determines the mass of moisture converging into the deep convection zones of the tropics.

— Trade-wind cumulus clouds often produce a saturated layer just below the trade-wind inversion, creating a shield of clouds. These stratiform clouds have potentially important effects on the Earth's radiation budget.

Most current GCMs were not designed with simulation of the trade-wind boundary layer in mind, and are not particularly successful in such simulations. GCMs do produce trade-winds with strong surface evaporation, of course, but the depth of the moist layer, the shallow cumulus clouds, and the stratiform clouds that sometimes form just below the trade inversion are typically not well simulated. Perhaps for this reason, only a few detailed studies of GCM-based simulations of the trade-wind boundary layer have been reported. This is unfortunate, since the trade-wind boundary layer is energetically just as crucial as deep convective zones for maintaining the structure and dynamics of the general circulation of the atmosphere, and also for the ocean surface energy budget.

5.2.2 Summary

The above problem areas may be summarized in the form of a number of recommendations to the GCSS community:

- Better parameterisations of cloud-top entrainment, suitable for use in GCMs with traditional Eulerian vertical structures, need to be obtained to improve boundary-layer cloud simulations in GCMs.

- Improved routines for diagnosis or prediction of boundary layer clouds are needed in GCMs. Evidence is not yet conclusive that cloud top entrainment instability affects the large-scale distribution of boundary-layer clouds. CRMs can be used to examine processes affecting cloud cover.

- GCMs should include parameterisations capable of representing the decoupling between the stratus layer and the sub-cloud boundary layer.

- Studies are needed that are designed to allow parameterisation of microphysical and chemical processes including explicit CCN prediction in future climate models.

- Studies are needed to determine why mesoscale cellular convection exists and to derive parameterisations of its effects in GCMs.

- Parameterisations are needed that enable climate models to simulate the geographical extent, depth, convective transports, and radiative properties of the trade wind boundary layer. This is a major challenge, given the coarse vertical resolution and computational constraints of GCMs.

- Boundary-layer clouds affect the interaction between the ocean and atmosphere and so the parameterisation of boundary-layer clouds needs to be tested in coupled ocean-atmosphere GCMs, rather than dealing only with atmospheric GCMs.

5.3 Priorities, tools and strategies

5.3.1 Parameterisation of the cloudy marine boundary layer

The boundary layer cloud regimes that are considered in the marine category include:

- Sub-tropical marine fogs and stratus-topped boundary layer

- Trade cumulus

- Middle- and high-latitude marine fog and stratus-topped boundary layer

- Middle- and high-latitude marine cumulus and stratocumulus associated with cold air outbreaks.

The processes that should be given high priority to meet the goals of GCSS include:

1. Decoupling of the boundary layer

2. Broadening of the droplet spectrum and drizzle formation, including the role of CCN.

3. Mesoscale organization in the marine atmospheric boundary layer

4. The transition of the cloud-topped boundary layer from stratus to cumulus.

Each of these processes is a result of complicated interactions among large-scale circulations, radiation, cloud microphysics and chemistry, and boundary layer circulations on scales from metres to tens of kilometres. Because of this complexity, the research approach should consist of the application of CRMs, together with field studies, to study the total coupled cloud system. Such studies should be undertaken for a variety of atmospheric boundary layer regimes.

The first two regimes listed above have been studied more extensively than the other two regimes. The climatic importance of middle- and high-latitude marine stratus has been noted in some recent climatological studies. Only the Southern Ocean Experiment (SOCEX) has focused on this regime, but it mainly focused on the microphysical/radiative properties of those clouds.

Cumulus and stratocumulus clouds are often associated with cold air outbreaks over the Sea of Japan, the northwestern Pacific, and the northwestern Atlantic, as well as other ocean areas. They cover areas as large as 10^6 km^2 and last for several days. Ice phase cloud microphysical processes often complicate the physics of these clouds. A few field experiments have encountered these clouds but more comprehensive data sets are needed.

LES models represent the most fundamental type of CRMs that are useful for assisting in the development, refinement, calibration, and testing of boundary layer cloud parameterisation schemes for large-scale models. LES models can currently be applied to

- Non-precipitating stratocumulus and cumulus topped atmospheric boundary layer
- Ordinary marine or trade-wind cumuli
- The transition from stratus to cumulus.

Recently LES models have been applied to the simulation of drizzling stratocumulus with explicit bin-type microphysics but these complicated models need further evaluation against field data. LES models can also be used to examine the transitions from solid stratus to cumulus regimes by moving the model domain in a Lagrangian sense over varying surface and upper-level boundary conditions (eg sea surface temperatures, subsidence). These studies are very computationally intensive, however. Other CRMs that can be used to investigate clouds in cold air outbreaks, mesoscale organization, and cloud regime transitions, include two-dimensional cloud ensemble models (CEMs) and three-dimensional mesoscale models in which detailed boundary layer circulations are parameterised. Because these models have coarser grid spacing than LES models and/or are limited to two dimensions, they are not quite as fundamental as LES models. Nonetheless, they are a class of CRMs and can yield valuable insight into the behaviour of the cloudy boundary layer.

Regardless of whether we are talking about LES, CEM, or mesoscale models, they are just models, which means they should not be treated as absolute. Verification and testing of these models is essential to determining their credibility and their usefulness in cloud parameterisation development. Therefore GCSS will take a lead in defining data requirements for field studies on middle- and high-latitude marine stratocumulus clouds. There is also a need for further climatological studies of marine boundary layer cloud regimes. GCSS will serve as a focal organization for compiling and organizing integrated case study data sets for testing models and parameterisation schemes. This will be done for existing datasets to show the organisers of the new field experiments what is really required from them. Candidate integrated data sets include BOMEX, FIRE, ASTEX, and SOCEX.

5.3.2 Parameterisation of the cloudy continental boundary layer

The boundary layer cloud regimes considered here include:

- Boundary layer clouds over relatively flat terrain, including cumulus, fogs, and stratocumulus

- Boundary layer clouds over hills and mountains
- Cold season versus warm-season boundary layer clouds over land
- Boundary layer clouds over continental interiors versus coastal regions.

The processes that should be given high priority to meet the goals of GCSS include:

- Cloud entrainment, turbulence, cloud structure, cloud coverage, and transitions for heterogeneous versus homogeneous surface boundaries
- Cloud radiative fluxes for scattered and broken cumuli; how anisotropic and three-dimensional are they?
- Warm cloud and ice-phase cloud microphysical processes and the effect of CCN
- Mesoscale and synoptic-scale forcing including differential advection, subsidence, and physiographically-driven mesoscale circulations.

The large-scale air masses affecting boundary layer clouds over the continental interiors are quite different from those affecting open oceanic regions. Truly continental air masses have colder cloud-base temperatures and higher concentrations of CCN. Moreover, continental boundary layer clouds are strongly influenced by anthropogenic effects including aerosols and surface land-use.

The other major distinguishing feature between boundary layer clouds over the sea and over land, is that over land the underlying surface can be quite irregular. Variations in soil type, vegetation cover and stress, and surface physiography (e. g ., hills, mountains, lakes, coastal waters, and swamps) all can have a large influence on the behaviour of the boundary layer which can regulate the type and intensity of boundary layer clouds. Moreover, clouds alter the surface energy budget on short and long time scales by reducing solar insolation which effects subsequent cloud behaviour. Thus bulk formulations of cloud entrainment rates, turbulence, cloud fractional coverage and precipitation that may be a useful first approximation for maritime clouds may not work over continental interiors.

What this means to GCSS is that it is much more difficult to assess the credibility of a CRM or a boundary layer cloud parameterisation scheme over land. Few, if any, field campaigns have documented the nature of the underlying surface in adequate detail along with mesoscale forcing and the details of boundary layer clouds. Satellite observations can play an important role here. Ground-based and airborne measurements are also needed. GCSS will participate in cooperative field campaigns that identify the diurnal cycle of the cloudy boundary layer over land. Experiments such as BLX83, HAPEX, and FIFE provide some opportunity to examine this. BOREAS will provide some data on this problem over the Boreal forest in Canada during 1994. GCSS will encourage a more comprehensive cloud observational component to that programme.

As for the marine boundary layer clouds, LES models provide the greatest opportunity for credible cloud-resolving simulations of the cloudy boundary layer. The LES models should be coupled to full surface energy/hydrological models so that cloud feedbacks onto the surface energy budget can be realistically modelled. Likewise, two-dimensional CEMs and three-dimensional cloud-resolving and mesoscale models are useful for examining the mesoscale organization of clouds and the effects of mesoscale physiographically-driven circulations on boundary layer cloud properties. Finally, middle- and high-latitude boundary layer clouds during the cold season have a vigorous ice-phase precipitation process. It is therefore important that the CRMs contain both warm-rain and ice-phase precipitation physics.

5.4 Plans for GCSS Activities

5.4.1. Intercomparison of CRMs and boundary layer cloud parameterisation schemes.

An important step in establishing the credibility of CRMs is to intercompare simulations using those models, with each other and with definitive field datasets. GCSS will initiate this process by designing and running an intercomparison of LES models for a marine stratus case that has a horizontally uniform environment, with no drizzle and no solar radiation. An intercomparison of model output statistics (eg cloud top height, mean liquid water content, variances, fluxes and cloud fractional coverage) will be made among a number of CRMs. In addition, developers of boundary layer cloud parameterisation schemes will be encouraged to run their models for the same test case.

This idealised case represents a modest start on an evolutionary path. By the end of the first year GCSS will organize a workshop to discuss the results of this first case and plan for the next case which will contain more complicated physical processes such as drizzle and solar heating.

The action items will be:

- Announce a call for participants in the First Boundary-Layer CRM Intercomparison Study.
- Request that participants provide a brief summary of their CRMs including descriptions of dependent variables, conservation equations, numerical schemes, and physical parameterisations (eg radiation).
- Prepare a description of the idealized uniform stratus boundary layer case.
- Try to ensure that each model contains at least one passive scalar to examine top-down fluxes and entrainment fluxes.
- Emphasize intercomparisons of 3D models. Two-dimensional model and parameterisation model results are welcome, but the 3D CRM results will be considered the standard.

Before the first CRM intercomparison workshop, a description of an observed case from FIRE or ASTEX, suitable for CRM simulation, will be prepared. This second case will be presented at the first workshop as the second intercomparison case.

5.4.2 Schedule of activities

The following is a schedule of activities for Working Group 1:

Year 1

- Organize a cloudy boundary layer CRM/cloud parameterisation intercomparison workshop for a simple, idealized case. Participants should include LES modellers as well as other cloud-resolving modellers, especially those developing boundary layer cloud parameterisation schemes.
- Identify, describe, and compile a more complex case (eg a drizzle or post-frontal case) for the second workshop.
- Discuss procedures for producing CRM datasets, data formats (eg CD ROM), critiques of model output and model formulations, that would be useful for cloudy boundary layer parameterisation development.

Year 2

- Organize a CRM/cloud parameterisation intercomparison workshop based on FIRE 1 or ASTEX cases.
- Further define CRM data formats useful for cloud parameterisation development, testing, and calibration.
- Identify a tradewind cumulus or a continental cloudy boundary case for the next CRM intercomparison workshop.
- Prepare a blueprint of minimum observational requirements and use it to assess the need for future field studies.

Year 3

- Organize CRM/parameterisation intercomparison workshop for a tradewind cumulus or continental cumulus case.
- Investigate need for datasets on intercomparison between interactive ocean boundary layer and atmospheric boundary layers.
- Identify data sets for a case on high-latitude marine stratus and/or baroclinic boundary layer.

5.5 Summary

The following are some required features of CRMs to meet the goals and requirements of GCSS:

- They should contain warm-cloud and ice-phase microphysics, especially in explicit, bin-resolving models.

- They should have aerosol physics and chemistry modules.

- They should have cloud radiative parameterisations that respond to hydrometeor and aerosol spectra.

- They should be able to simulate cloud coverage including the transition from stratus to cumulus and decoupling from the atmospheric boundary layer.

- Cloud top entrainment should be represented in detail.

- They should be able to simulate mesoscale organization.

- Surface boundary conditions should include variable sea surface temperatures, sea-ice/lead coverage, and soil/vegetation coverage.

GCSS will take the lead in compiling and publishing datasets of observations and CRM results and in organizing intercomparison workshops among cloud-resolving modellers of the boundary layer and boundary layer cloud parameterisation modellers. The intercomparison workshops will be conducted for well-documented observational cases that include drizzling and non-drizzling clouds, ice-phase precipitation, trade-wind cumulus, transition from stratus to cumulus, mesoscale organization, and cases with variable surface conditions. Since well-documented observations do not exist for all these regimes, GCSS will promote and participate in cooperative field programs to fill the voids.

6. Cirrus cloud fields: Plan prepared by Working Group 2

6.1 Introduction

Cirrus, like most other cloud fields, are the visible product of a broad range of scales of motion in the atmosphere: They occur at temperatures well below -20°C when saturation is reached due to convection from below (anvils), gentle slantwise lifting of air-masses, as associated with frontal areas, or in the ascending branches of jet streams. There are also cirrus fields of orographic origin, occurring downstream of mountain barriers. Aircraft water contrails also lead to enhancements of all of these cirrus fields, especially during their formative phase. In the tropics large and long-lived ice-cloud fields are often observed near the cold tropopause, possibly as remnants of earlier convective systems (cloud clusters and hurricanes) or due to larger-scale lifting of air masses in the Inter Tropical Convergence Zone.

It is clear from the nature and origin of these cirrus fields that even perfect parameterisation schemes for cirrus and its properties would fail if the model's dynamical representation is not correct. Ideally, therefore, CRMs with horizontal resolutions high enough to reproduce very fine-scale (~ 100m) structures in cirrus fields must be nested within larger-scale models capable of providing the historical developments (life cycles) and further distortions of the air-mass under consideration. Of course, the cloud radiative effects alter the air mass too, sometimes on the large scale.

Although they contain only small concentrations of water, cirrus cloud fields are effective at enhancing the atmospheric Greenhouse effect. When optically thin they are almost transparent to incident solar radiation. However, ice crystals are very effective at absorbing the infrared radiation. Optically thick cirrus can substantially reduce the incoming solar flux. If it occurs more frequently with increasing surface temperatures over oceans, it might cause some thermostat effect.

Ongoing observational studies of cirrus include FIRE and EUCREX/ICE. The GCSS should provide the impetus for establishing more modelling activities in support of these studies. It is of course vital that there should be close interplay between the modelling and observational communities.

6.2 Key science issues and priorities

Previous experimental and numerical studies of cirrus fields have concentrated primarily on describing the radiative transfer properties of cirrus in terms of its optical thicknesses. These relationships depend on total ice content and possibly also crystal sizes, shapes, orientations and concentrations. The many measurements made during the FIRE and EUCREX/ICE field phases provided data on some of these microphysical properties and related them to environmental parameters, such as air temperature, humidity and mean large-scale vertical velocity. Relatively little quantitative attention has yet been paid to the structure of cirrus fields and its dependence on large-scale forcing. The structure of cirrus fields affects the interpretation of airborne measurements of up- and downward radiative fluxes. No unique strategy has yet been developed, apart from simple arithmetic averaging along flight paths, to relate the measured up- and downward flux densities to the measured cloud structure, in order to derive representative quantities for inhomogeneous cloud fields.

Several research issues should be addressed within the context of GCSS

- *Careful intercomparisons of model results and observations* (possibly in both the climate and the weather forecast modes). Provided the observations are correctly analyzed, these intercomparisons should identify for each geographical region the inadequacies in the model. Such intercomparisons should identify the error sources: either in the cloud parameterisation, or in the atmospheric dynamics, or both. But since we are dealing with highly nonlinear systems, the intercomparisons must be done with great care. The GEWEX regional experiments (GCIP, MAGS, BALTEX, GAME and others) might provide useful data sets over limited regions, where numerical simulations will also be carried out with spatial resolutions of 20 km and higher. Such intercomparisons should be given priority. Their results could guide the planning for further experiments. A further problem is that we do not know enough about the occurrence of cirrus over all portions of the globe.

- *Occurrence of cirrus in relatively narrow streaks embedded between much drier layers.* This is a common phenomenon. It must be clarified how important radiatively such structures are, where and when such horizontally and vertically layered structures occur, and how they could be identified and predicted operationally. The GVaP research may help in addressing this problem. Satellite data do not always resolve such fine structures. They can qualitatively be seen in radiosondings and in water-vapour profiles obtained from ground-based lidar: however, the way in which lidars are currently used makes it difficult to use their data statistically. Radiosondes are quantitatively unreliable for the upper-tropospheric layers. Such observational data are available over only about 15-20% of the globe, whereas cirrus occurs everywhere. Means should be sought to relate the occurrence of fine cirrus structures to the wind field and turbulence. In this connection the parameterisation of turbulence in the upper atmosphere must be checked carefully in the models.

- *Factors determining the microphysical properties of cirrus.* Cirrus microphysical properties depend on ambient temperature and water vapour. With increasing temperatures the particles not only become larger, but also more complicated in structure (clusters). The particles can also be affected by wind shear since the associated turbulence can break large crystals into smaller pieces. Further the availability and nature of ice-nuclei, and of haze/CCN particles, has an affect on cirrus occurrence and properties. There may even be relationships to the sun's particle fluxes to the earth. Field measurements of microphysical properties need to be made in higher cirrus layers. We may have to observe the mean orientation of dominant crystal species.

- *Transport of atmospheric water from higher into lower layers by cirrus.* Cirrus may have a large-scale affect not only by its radiative transfer properties, but also by its seeding of lower-level clouds. It is necessary to investigate the extent to which this sedimentation affects the properties of lower clouds and even their precipitation. Such effects would modify water cycles in the climate system but it is necessary to determine whether this effect is important globally.

- *Maintenance of anvil clouds.* We do not know enough about the life-cycle or dynamics of cirrus anvils, which may stay in the atmosphere for several days before they dissipate.

- *Tenuous cirrus.* It needs to be determined whether tenuous cirrus is sufficiently abundant to play a significant radiative role and whether it might, perhaps, be enhanced by air traffic along major flight routes.

6.3 Tools

There are, in principle, five categories of numerical models available for cirrus research. Only models (b) and (c) can be considered as CRMs.

(a) Detailed microphysics of individual crystals is investigated in laboratories, often in connection with its dependence on available ice nuclei. Detailed models are used to interpret such observations, eg particles alone in electrostatic fields. Analogous models have been developed to study the clustering of the interplanetary dust.

(b) One-dimensional models using slightly parameterised microphysics are often used to study the growth and decay of crystal ensembles as a function of ambient air temperature, moisture and also radiation fields. Such models allow crystals to sediment and can be used as a tool for sensitivity studies ***without*** interactions with atmospheric turbulence.

(c) Two-dimensional and even most advanced non-hydrostatic three-dimensional models use parameterised microphysical processes and radiative transfer schemes. The 3-D models allow spatial resolutions of any desired scale, provided the computational power is available, and have been embedded in larger-scale models.

(d) Limited-area mesoscale models with spatial resolutions of about 10-20 km are used operationally for weather forecasting. Some are also now nested into climate models for detailed regional studies of climate variations and their impacts. Such models are well suited for use in future experiments such as BALTEX.

(e) There are many global weather forecast and climate models. Their performance with respect to cirrus should be checked over each geographical area. The AMIP may play a leading role by intercomparing various models.

6.4 Plans for GCSS activities

(a) The cirrus community will join the communities of other cirrus-producing cloud-systems: namely extratropical layer cloud system (Working Group 3) and precipitating convective cloud systems (Working Group 4). In particular we shall collaborate with Working Group 3 in organizing a Workshop on Extratropical Layer Clouds and their Large-Scale Parameterisations at ECMWF (see Sec 7.4.4 for details). Other cirrus will be studied separately, as appropriate.

(b) The members of this Working Group (see Appendix 2) will meet as opportunities arise in 1994 (Nashville, Grenoble, London, Beijing, Bergen) and discuss the various scientific issues mentioned above Towards the end of 1994 the time will be ripe to plan more definitely for future actions in this area.

(c) The EUCREX and FIRE communities will be encouraged to work together in future activities, together with CRM inputs from GCSS.

7. Extratropical layer cloud systems: Plan prepared by Working Group 3

7.1 Introduction

Extratropical layer clouds are common features of the Earth's atmosphere. Such clouds are typically associated with frontal systems in middle and high latitudes, or with tropical-extratropical cloud bands, or with orographic lifting. A related phenomenon at high latitudes is polar lows. These, as well as comma clouds, are also within the remit of this working group.

Extratropical cyclones are responsible for a major portion of the atmosphere's transport of heat and moisture. Much of this redistribution is done through layer clouds and their associated precipitation; these clouds are widely but inhomogeneously distributed throughout the systems. The formation and properties of these clouds are closely linked to the dynamics and evolution of the weather systems in ways that are not yet fully understood. These clouds also contribute substantially to the Earth's global radiation budget, the relative importance of long wave and short wave cloud forcing differing between summer and winter. Furthermore they account for a major fraction of the precipitation in many regions of the world and so are critically important to hydrology. Both the distribution of the snow and rain in surface precipitation and the influence of orographic barriers upon weather systems present major challenges from a hydrological point of view.

Because of the important consequences of extratropical cyclones and realizing the complex nature of these features, a programme to better incorporate their impacts on climate is being developed. The overall approach envisaged in the study will be to use CRMs and mesoscale models with detailed observations to aid the development and validation of parameterisations for GCMs. A major challenge is to cover a sufficiently large domain to contain the entire cloud system, especially in the case of a cyclone. Coupling of many processes operating at several scales is the central issue. What we need to answer are questions about how clouds alter the energetics of these circulation systems and how the characteristics of the cyclone affect the nature of the cloud properties.

7.2 Key science issues and priorities

7.2.1 Issues

Extratropical cyclones have been extensively studied for many years, yet there are still a number of areas with potential impact on climate that have not adequately been addressed. Such issues will be briefly introduced here.

- *What is the vertical structure of these cloud systems?* Satellites currently provide little information on vertical cloud structure, and there are few other observations over the oceans. There is a need to provide measurements of cloud layering and thicknesses, liquid/water contents and partitioning between water phases, along with the associated temperature, moisture and wind profiles (including vertical velocity) for a reference set of weather systems. There is also a need to determine the optical properties that influence the radiation budget and the amount of precipitation produced by these systems, particularly over the sea.

- *How do the 3-dimensional dynamical and cloud fields evolve?* Since most of the diabatic (latent and radiative) heating in extratropical cyclones is associated with layered cloud and precipitation processes, the study of the cloud is inseparable from the dynamics of the systems. Because of this interlinking it is essential that cloud and precipitation measurements be viewed in terms of measured system dynamical parameters where possible. The overall cloud fields are produced by broad slantwise ascent within conveyor belts that redistribute heat, momentum and moisture over great distances. These conveyor belts are synoptic scale in origin but mesoscale ascent may significantly influence their character. Such mesoscale motions alter the local properties of the layered clouds and precipitation through modification of the profile of moisture and temperature. The measurement of the pattern of mesoscale vertical motion is important to quantitative studies of this issue.

- *What are the roles of frontogenesis, conditional symmetric instability and diabatically forced circulations within these cloud systems?* The forcing of mesoscale circulations is largely associated with dynamically-imposed frontogenetic processes driven from larger scales, but two main types of secondary mechanisms result in mesoscale circulations. These mechanisms are conditional symmetric instability and diabatically-forced circulations. In the case of conditional symmetric instability, latent heat is released during ascent. The second mechanism can be triggered through this and other processes such as radiative effects or the evaporation, sublimation and melting of precipitation. The relative roles of these mechanisms in weather systems is not yet clear. Numerous individual case studies and modelling studies are being carried out for particular processes, but the emergence of a consensus view depends upon an integration of the diverse approaches used and a much wider study than has yet been possible. This is not simple, however: both types of mechanism are complex to measure and model, and are influenced by many mesoscale environmental factors not amenable to routine measurements. There is a need to investigate whether there is sufficient scale separation between these circulations and those represented explicitly in GCMs for them to be parameterised within the coarser-resolution models.

- *What features of these systems are responsible for large-scale radiational impacts of these clouds?* The vertical radiative heating profiles within these layer clouds, and indeed the partition between surface effects and atmospheric effects, need to be better related to the actual nature of the systems. The common presence of multiple layers and highly variable microphysical attributes means that these profiles are difficult to determine. Over the North Atlantic, for example, the cloud fields in the mid-latitude cyclonic storm tracks are responsible for net heating aloft and cooling in the lower troposphere.

- *How well are precipitation and its consequences aloft accounted for?* Precipitation represents a major transport mechanism for water. Present NWP models often appear to have reasonable accuracy in the prediction of the broad patterns of surface rainfall over land but snowfall and orographically-affected situations may be less well simulated even though they have major hydrological implications. Model resolution in the vertical as well as horizontal is an important factor to consider in regard to precipitation because these layer clouds may be only a few hundreds of metres deep and because precipitation can sublimate, evaporate, melt or freeze within a few hundred metres. The accurate representation of these processes may well be important to describing the atmospheric water content in middle- and high latitudes. The microscale processes that lead to precipitation also need to be understood because of their direct impact on vertical profiles of diabatic heating. The latent heat transfers that occur within and below cloud can lead to either cooling or warming of the atmosphere, These effects can substantially alter airmass properties such as static stability.

- *How much do mesoscale features and microphysical processes influence overall moisture budgets and precipitation efficiency?* There is a need to quantify the overall moisture and other budgets of these systems and reconcile them with the CRMs and observations. Since mesoscale vertical velocities can greatly exceed those on the synoptic scale, the transport properties of weather systems may be substantially influenced by these embedded circulations. Although these circulations are mesoscale in extent across a frontal discontinuity, they may extend for hundreds of kilometres along the front. Such processes, as well as microphysical effects, can significantly influence the precipitation efficiency of extratropical cyclone. This topic has been little studied since the introduction of detailed microphysical schemes into models.

- *The microphysics has a strong control over the conversion of moisture into condensate and on the radiational properties of the clouds, but how well does this have to be parameterised?* The ice/water/water vapour system is complex, and uncertainties exist in a number of the processes. There are also variations in the morphology of the ice particles, because of the complex temperature/humidity dependence of ice growth. These processes and microphysical properties are likely to influence the observed onset and dissipation of some of the clouds, and hence the extent and influence of these clouds through both precipitation and radiation. There is a clear need to evaluate the sensitivity of model results to the rates of processes such as sublimation and melting and the dependence of those rates upon both uncertainties in laboratory measurements and atmospheric variability in microphysical properties such as particle size or density.

- *How sensitive are the locations of these cloud systems to surface features?* The locations of storm tracks are thought to depend principally upon large-scale dynamical factors outside the scope of this study. However, a number of smaller-scale factors at the surface, such as sea surface temperature gradients, sea ice cover, land-sea contrasts and other topographic features, have been shown to modify sometimes the locations of either the entire cloud systems or some of their layered cloud regions. Such effects need to be well simulated in climate models.

- *What are the global features of these layer clouds?* Extratropical layer clouds and other closely related systems occur in many regions of the world, including over land and ocean. The characteristics and climatic impacts of the clouds varies substantially. Cloud base and cloud top characteristics, sub-cloud dryness, degree of embedded features and multi-layering are just a few of the features that vary widely, but for which there does not appear to be any definitive study at present.

- *Although important for weather prediction, do polar lows and comma clouds also have a significant climate impact?* Polar lows and comma clouds may not have significant climatic impact, because of their small scale and relatively infrequent occurrence. Although this perspective is believed to be valid, it has also been argued that they may be able to initiate convective overturning in the ocean as a consequence of intensified cooling of the upper ocean that results from the strong localized winds.

- *How do these systems interact with orographic barriers and what level of sophistication in models is required for climate issues?* Layer cloud systems can be extensively modified through interaction with orography. This modification affects many attributes of these clouds, their precipitation and cloud layering characteristics.

7.2.2 Summary and Priorities

There are many issues linked with the impact of extratropical layer clouds. As described above, some of these often interrelated issues are:

- vertical as well as horizontal distribution of key parameters
- 3-dimensional dynamic and moisture fields
- frontogenesis, symmetric instability and diabatic forcing
- radiative attributes
- precipitation production and direct thermal impacts

- moisture budgets and precipitation efficiency
- microphysical properties and processes
- layer cloud locations as affected by surface conditions
- global and also seasonal variations
- polar low consequences
- orographic interactions.

The adequate incorporation of the effects of extratropical layer clouds within large-scale models will require a long period of study. Some of the priority items are:

- slantwise ascent processes
- precipitation aloft and at the surface
- radiation/microphysical effects
- multiple layering including cirrus
- global variations.

A substantial amount of work is presently underway on the first three of these aspects and considerable expertise can be brought to bear on the problems. The fourth issue, layering, is felt to be so critical that a substantial initiative should be developed; this could take advantage initially of a few studies already conducted in different regions. The last issue, global variations, is also important.

It is unlikely that Working Group 3 will be able for some time to address in detail some of the other issues, such as orographic influences, layer cloud location, and polar lows. It is hoped that another group will investigate orographic precipitation. The importance of features such as surface conditions to layer cloud locations is considered to be potentially an issue for climate but it is not as critical as those issues mentioned above. And, finally, any actions on polar lows will require that a more definitive physical basis for large-scale impact be established

7.3 Tools

Observations are essential to give definitive information on the physical processes and nature of extratropical layer cloud systems. There is a need to use satellite observations as well as detailed in-situ measurements from multiple sources. The satellites can measure a number of important cloud and atmospheric properties synoptically and so help to tie together the more detailed observations. For example, the satellites can be used to identify the part of a cyclone sampled by a detailed dataset from surface or aircraft and the whole collection of such datasets can then be sorted by location within a composite cyclone. Individual intensive case studies are also required. However, even with such special observational data sets, the incompleteness of observations, and the complexity and interdependence of physical processes within the clouds, are such that the whole system can be studied only by recourse to numerical models.

Because of the range of scales spanned by these processes, it will be necessary to employ a range of models, from CRMs to mesoscale models: Nonhydrostatic CRMs are required, with grid lengths of the order of 1 km or less, fine-scale vertical resolution and detailed microphysical schemes, to develop and validate these aspects of the large-scale models. The simulations of such CRMs can be directly compared with in-situ observations to aid understanding of the physical processes involved and to develop less complex bulk microphysical schemes for the larger-scale models in the manner described in earlier sections. To simulate the life cycle of extratropical cyclones, however, it is necessary to use slightly coarser-resolution mesoscale models with 10-50 km resolution and 20-60 levels and larger domains. Model sensitivity studies and cross-comparison between the observations and models at different scales will be a valuable approach. This approach will be used to assign priorities to the study of particular processes and to examine issues such as the required degree of microphysical sophistication in cloud parameterisations and the representation of mesoscale processes within GCMs.

7.4 Plans for GCSS activities

A number of initiatives relating to extratropical layer cloud systems are being pursued as part of the GCSS. These are described below.

7.4.1 Background studies

Two review articles are being prepared on extratropical layer clouds. One article deals with the processes discussed in Section 7.2, stressing their large-scale impact, The second article documents the nature of these systems in different regions of the world. This study is utilizing information from the large number of field projects in different regions. The emphasis is on using satellite information to define the large-scale characteristics of the cloud system and using detailed in-situ measurements to characterize the nature of the systems such as layering, cloud depth, and microphysical characteristics.

7.4.2 Data blueprint

A preliminary version of the data requirements for GCSS has been prepared. Such a blueprint identifies the key parameters that need to be measured, the required spatial and temporal scales, and the necessary accuracy of the measurements. This blueprint will be refined by presenting it at planning meetings and inviting feedback from the community. Statements on critical needs are required from the CRM and radiation communities. To be meaningful, it is critical that such a list carefully balances the requirements to solve perceived problems against the available resources.

7.4.3 Plan of attack

Within the working group, a draft plan of attack is being refined. This plan will serve as the basis for discussions with the community at large. Key components of this plan will be the course of action for generating datasets, for relating CRM results to large-scale models and for establishing whether particular features have a significant large-scale impact. Meetings with the broader community will be held on an opportunity basis. For example, in the summer of 1994 the following meetings will be held:

- June 20-24, 1994 at the Polar Lows Workshop in Paris. The purpose of this meeting is to establish the significance of the potential climate impact of polar lows.

- July 2, 1994 in Bergen, Norway, after the conference on the Lifecycles of Extratropical Cyclones. Here, the draft modelling plan and the data blueprint will be presented. Particular augmentations to the Fronts and Atlantic Storm Tracks Experiment (FASTEX), see Section 7.5 below, will be discussed as well.

- July 18-22, 1994 at the European Conference on the Global and Water Cycle Experiment in London. These discussions will further update the draft plans.

7.4.4 Workshop

A workshop will be held on November 14-18, 1994 at the European Centre for Medium-range Weather Forecasting in Reading. This Workshop on Extratropical Layer Clouds and their Large-Scale Parameterisation will be organized with GCSS Working Group 2. It has several objectives:

- assess the state-of-the-art performance of CRM models
- finalize the CRM and large-scale model interaction plan
- define the data requirements for this modelling effort
- identify existing data sets that may be suitable
- recommend very specific and achievable modelling efforts
- recommend appropriate augmentations to future field experiments.

Members of the GCSS community will complement the large-scale modellers invited to attend the previously planned ECMWF Workshop on Modelling, Validation, and Assimilation of Cloud in Numerical Weather Prediction. The invited GCSS scientists will be CRM modellers and observationalists.

7.4.5 Enhancement of future field projects

It is likely that no dataset exists that is adequate to satisfy the data requirements of this aspect of GCSS. If this situation is confirmed, then we shall consider whether an augmentation to proposed activities can be made. The activity that appears most acceptable for augmentation is the Fronts and Atlantic Storm Tracks Experiment (FASTEX) to be conducted over the north Atlantic. This experiment is being promoted initially by groups in France and Britain and it aims to tackle the dual issues of weather prediction and climate. Until now in the preparation for this experiment, the weather prediction aspects have been foremost in mind and the radiational aspects have not yet been fully examined. The experiment involves a requirement for aircraft dropping sondes from high levels as well as for observations of cloud properties. The large-scale dynamic fields will be well specified, with the extra soundings (dropsondes) made available in real time for assimilation into operational NWP models.

A focus of Working Group 3 will be to develop specific augmentations to this experiment that will satisfy the perceived needs. Actions for doing this are already in hand although the November 1994 workshop will formalize these activities. It is expected that the augmentation will call for special observations that can be provided by only a few well-instrumented aircraft. High-flying long-duration aircraft will also be needed. Attention needs to be paid to the possibility of using drone aircraft presently under development.

7.4.6 Further activities

A programme of actions in following years will evolve through the activities already discussed. However, some possible activities for this working group over the 1995-1997 time period can already be foreseen; they include workshops on the following:

- incorporation of slantwise ascent into large-scale models.
- layering within extratropical cloud systems. This could be conducted jointly with Working Group 2 which is concerned with cirrus clouds.
- radiation within extratropical cyclones. This could also be conducted jointly with Working Group 2.
- hydrological impacts and cold- region precipitation.

7.5 Summary

The primary focus of Working Group 3 over the next several years is to establish:

- a detailed strategy for developing CRMs and applying their results to large-scale models
- detailed evaluations of critical aspects of cloud systems with emphasis on slantwise ascent, radiation, layering and precipitation
- potential augmentation to a field experiment.

These tasks will be accomplished through various means including meetings of opportunity and specific workshops.

8. Precipitating convective cloud systems: Plan prepared by Working Group 4

8.1 Introduction

Precipitating convective cloud systems interact strongly with all the other sub-gridscale processes (microphysics, surface layer, boundary layer, radiation, and turbulence) and are highly nonlinear and physically diverse. This makes analytic theories of evolution, structure, and scale interaction of these systems difficult to develop; requires observations on many space- and time scales; and places great demands on numerical simulation. Moreover, precipitating convection is manifested not only sometimes as quasi-random cloud elements (as represented in present parameterisations) but also as organized mesoscale cloud systems spanning dynamical scales from less than a kilometre to many hundreds of kilometres (not represented in present schemes).

There is a need to introduce as much physical basis as practicable into parameterisation and the issue of whether or not a process *can* be parameterised also needs to be raised, in effect helping to establish the limits of parameterisation. An example is mesoscale processes associated with convectively-generated stratiform anvil clouds that make substantial contributions to the large-scale heat and moisture budgets. The 'parameterisability' of such motions is a fundamental matter since there is some question about whether the processes exhibit sufficient scale separation from the resolved motion in terms of the relationship of their respective statistical equilibrium states. As atmospheric GCMs attain higher resolution, these issues can be expected to become more acute.

Present parameterisations are fairly simple in their conceptual formulation, often ignoring processes that *appear* to be required for an accurate description of the collective influence of sub-gridscale clouds. The representation of these processes in terms of large-scale variables is a formidable scientific problem that has confounded the community for decades.

8.2 Key science issues and priorities

8.2.1 Issues

In order to make significant advances in the parameterisation of precipitating convection, we must obtain better answers than are presently available to the following set of questions:

- *How do individual precipitating clouds interact with their environments?* It is extremely difficult to obtain detailed measurements in and around active convection and to determine their interaction with the environment. The presumption of separation of cloud and environment, as is usually made in cumulus parameterisation approaches, is to some degree artificial and made primarily to make the parameterisation of cumulus convection more tractable. Important problems involving scale interaction include 'closure' assumptions for a grid size less than 50 km and to determine if scale-separation is indeed a fundamental problem.

- *How does precipitating convection interact with the boundary layer?* The interaction of moist convection with the atmospheric boundary layer remains poorly understood. Despite cumulus convection and boundary layer processes being coupled in reality they are parameterised in large-scale models using separate packages that are often based on quite different physical assumptions. Quantification of this coupling could yield better closures of parameterisation schemes without resorting to questionable assumptions of equilibrium. Equally important is to understand how convective downdraughts affect the boundary layer, modify surface heat, moisture, and momentum fluxes, and thus affect the large-scale circulation.

- *How do convection clouds, stratiform clouds, and radiative processes interact?* One of the principal cloud climate interaction issues in recent years is manifested in the effect of convectively-produced cirrus/stratus anvils on the radiative budget of the atmosphere. This is widely recognised as one of the fundamental issues facing climate modelling. Its solution will require an innovative approach spanning theory, numerical modelling and observational studies and is one issue that the mesoscale community is well-positioned to address.

- *How can mesoscale convection be included as a sub-gridscale process in atmospheric GCMs?* The concept of mesoscale organization is at the root of the cloud system concept and is another fundamental problem faced in the sub-gridscale treatment of convection. The processes involved are sometimes in part explicitly resolved and in part sub-gridscale. This raises doubts as to whether there is any effective scale separation. If there is a scale separation the question arises as to what GCM resolution is best for treating such processes. The stratiform component of convective systems is poorly represented in global models, even though it is recognized to play a major role in the large-scale thermodynamic (radiative and convective components) and the momentum budget. The effects of slantwise convection in the stratiform region, mesoscale processes, and even balanced flows may have to be parameterised in GCMs: a consistent treatment of both upright and slantwise convection must then be sought. Sub-gridscale organization of convection is not featured in any parameterisation, yet it is important for the way in which convective-scale motions transport horizontal momentum and generate stratiform cloud decks.

- *How does the mode of organization of convection affect the large-scale impact of cloud systems?* We must discover what features of the large-scale circulation differentiate between convection manifested as ordinary convection, weakly-organized populations of cumulus, highly-organized mesoscale convective systems (MCSs), and vast tropical cloud clusters. As far as parameterisation is concerned, it is vital to determine those environmental factors (such as those that exist on GCM grid scales) that distinguish MCSs from ordinary convective clouds; their interactions with the boundary layer; their interactions with the local vertical wind shear; and how they are coupled to large-scale circulations. The variability of convective heating and moistening during the convective life cycle is not well known. For a given environment, should convection and large-scale interaction be described as neutral, slantwise-stable, or balanced in the mature or 'final' state?

- *How should microphysical processes be parameterised in numerical models?* As a consequence of the importance of the radiative process in GCMs, and the strong effect of microphysics on radiative transfer, it is necessary to have much better representations of microphysical processes in these models. Since strong nonlinearities are involved in microphysics, convection, and radiation coupling, a 'scaling -up' or 'tuning' of microphysics schemes that are quite reasonable for CRMs cannot be expected to be appropriate for prognostic water substance representation in GCMs. In particular, vertical velocities that determine peak supersaturations, hydrometeor sedimentation speeds and, thereby, water contents are all sub-gridscale in GCMs. MCSs are especially challenging in this regard because vertical velocities range from approximately $10 ms^{-1}$ in the cores of convective drafts to $1 ms^{-1}$ or less in slantwise mesoscale branches.

- *How do the vertical profiles of mass fluxes vary temporally and among cloud systems?* Parameterisation schemes often use the 'mass flux' approach largely because it has considerable flexibility and scope for systematic improvement. It is necessary, however, to have a representation of the effects of vertical shear, the height of cloud base, cloud depth, available potential energy, cloud microphysics and subcloud-layer properties on mass flux profiles. Likewise, the vertical structure of cloud entrainment and detrainment profiles (pertinent to the production of upper-tropospheric water substance and stratiform clouds) needs to be better quantified.

- *What procedures should be used to 'trigger' different types of parameterised convection?* This question involves the initiation of convection which, like most issues itemised here, are fundamental problems in their own right. Moreover, mesoscale convection is at the margins of dynamical predictability and is complicated by interaction with orography and boundary layer phenomena (such as gravity currents) that are themselves sub-gridscale and thus need to be represented in mean-flow terms. Present schemes use pragmatic approaches to determining the onset of convection. The most commonly used methods are: a threshold value of moisture convergence, the ratio between negative and positive area for pseudo-adiabatic ascent, a hydrothermal perturbation proportional to upward motion, a specified depth of lifting, or the magnitude of the 'work function' to trigger convection: these ideas need to be critiqued.

- *How does convective momentum transport affect the atmospheric general circulation?* The role of convective momentum transport in the general circulation of the atmosphere is poorly understood. Several facets are involved: First, the redistribution of horizontal momentum by cloud system circulations are generally not included in convective parameterisations, and then only as downgradient transports. Modification of in-cloud momentum by local pressure gradients, and the organizing effects of environmental shear may need to be included in the sub-gridscale process models. Second, surface stress perturbations by precipitating convection affects surface-atmosphere interaction and the ocean boundary layer circulation. Third, gravity waves that are an intimate part of convection can propagate into the middle atmosphere and, through the process of wave-breaking and critical layer effects, modify the mean flow. Orographically-generated gravity waves are widely recognised as a major contributor to the dissipation of kinetic energy in atmospheric GCMs but convectively-generated gravity waves have been largely ignored. This is not to say they are unimportant, especially over the tropical oceans where deep convection is common and orographic-wave stress is zero. Note that the effect of convection can extend into the middle atmosphere through gravity wave propagation, and because of the many density scale-heights spanned, large-amplitude waves and wave-breaking can occur.

- *How important is the convective transport of chemical species?* This is a poorly understood issue but one that has both climate and microphysical relevance. Through precipitating convection, species that originate near the earth's surface (eg carbon monoxide, carbon dioxide, nitrogen oxide, nitrogen dioxide, sulphur dioxide, methane and several hydrocarbons) can be efficiently transported to the upper troposphere, and occasionally even into the lower stratosphere, where their residence times are greatly extended and the faster windspeeds can transport them great distances. Convective and mesoscale downdraughts often originate in mid-troposphere and cause rapid downward transport of species (eg ozone).

8.2.2 Summary and priorities

Following is an unprioritised list of processes currently ignored in GCMs, most of which involve mesoscale processes either directly or indirectly:

- relationship between convective and stratiform components in mesoscale cloud systems
- interaction of precipitating convection with the atmospheric boundary layer.
- cloud-radiative feedback, eg role of microphysics

- sub-gridscale organization of convective cloud systems (eg effect of shear on transports)
- mesoscale precipitating cloud systems (eg role of mesoscale fluxes)
- convective transport of horizontal momentum
- parameterisation of slantwise convection and rotational effects
- convective transport of chemical species.

In the short term we shall focus on issues for which the scientific basis has been laid and which can be started immediately, even while only quite modest new resources are available. We would on a longer-term basis progress to other issues at a rate dictated by the availability of scientific expertise, computational facilities, and funding. Our short-term priority centres on the many facets of cirrus-producing mesoscale cloud systems over the tropical oceans and over the Maritime Continent. This prioritisation was made in view of the abundance and recognised climatic importance of these cloud systems. Specific objectives are to:

- Establish the large-scale effect of mesoscale convection (including its transport properties expressed in mean-flow terms and a suitable closure) and parameterise them in GCMs.

- Model and observationally verify the life-cycle of cirrus-producing convection with emphasis on its effect on environmental interaction and microphysical/radiative interaction.

8.3 Tools

8.3.1 Models

Regional-scale mesoscale research models or limited-area weather-prediction models incorporate parameterised convection and have grid lengths of about 10-25 km. These have often been used to study weather phenomena on a regional scale. Some of the problems encountered, such as lack of a well-defined scale separation, are shared with operational atmospheric GCMs having a mesh of about 50 km. These common factors need to be examined and are specially relevant to operational NWP models.

Recent advances in computer modelling and hardware now make it possible to resolve explicitly an entire convective system within a large domain by using convection resolving models or cumulus ensemble models. These were essentially developed from cloud models and, through modern computer power, can now span the individual cloud scale and larger-scale motions. Several have two-way (interactive) nesting capability. The CRM approach can also provide insight into the higher-order statistical behaviour of such systems (eg address questions related to the average response of convective phenomena exhibiting temporal fluctuations on scales typical of what an atmospheric GCM can resolve). We outline some of the needs in the CRM approach:

- Existing CRMs are, by and large, similar in their overall computational setup but there is a diversity in their capability of representing sub-gridscale effects (boundary layer and surface processes, turbulence, microphysics, and radiation). Such issues need to be assessed.

- The effects of microphysics on the structure of precipitating cloud systems, their transports, and the interaction between deep convection and the stratiform region need to be formulated in terms of macroscale parameters. These include CAPE, wind shear, and cloud base temperature; there may be other useful parameters. The validity of bulk microphysical schemes compared to more sophisticated treatments needs to be critiqued.

- Long CRM integrations presently use cyclic lateral boundary conditions, but should progress towards specified time-dependent boundary conditions from field experiment data or from operational GCMs. Likewise, CRMs could be embedded within limited-area models capable of simulating scale interactions over areas of many thousands of kilometres.

- Future, more physically advanced and computationally-demanding, CRMs are required to tackle the coupled physics modelling of cloud systems, namely interactions among dynamics, radiation, water-cycle, boundary and surface layer, and cloud microphysics. This requires model integrations extending for weeks or more in both two and three dimensions. An example is a tropical ocean basin-scale CRM that fully utilizes massively parallel computing technology; extensive development is required.

8.3.2 Observations

In terms of the observational verification of the climatic effects of cloud systems, a mix of in-situ and remote sensing measurements is clearly necessary. This puts great demands on observational strategies, noting that traditional mesoscale measurements follow a case study (localised) approach, while global or climatic effects of cloud systems traditionally require a statistically-based treatment. In terms of assessing the large-scale effect of convection, some of the critical data needs are: Global distribution of precipitation; three-dimensional water vapour distribution; three-dimensional condensed water distribution (particle size distribution, habit, phase, density); regional budgets of heat, moisture, and momentum; global estimates of surface energy exchange; and top-of-atmosphere radiative fluxes.

Existing datasets relevant to cloud system studies should be assembled and fully exploited. In particular, there is a wealth of multi-scale data from the recently completed TOGA COARE experiment, as well as from several other tropical experiments. These data are appropriate for diagnostic studies of convective systems per se, or in conjunction with modelling approaches. However, in many instances, data sets are inadequate for those studies that address cloud-environment interaction. This means that special field campaigns may be necessary from time to time. We distinguish studies of tropical and mid-latitude systems, principally due to logistical reasons:

- *Tropical Cloud Systems.* As far as tropical convection and its climatic effects are concerned, there are three principal geographic regions of interest. 1) The Tropical Pacific has been recently studied in the TOGA COARE and CEPEX programmes and these datasets will be a major feature for many years to come. Convection over the Indian Ocean has not been observed at a comparable level of detail, but has many features in common with the western Pacific. 2) The Maritime Continent has been addressed in EMEX and WMONEX, and the proposed Maritime Continent

Thunderstorm Experiment (MCTEX) will help address some aspects in greater detail. 3) Convection over the tropical continents (Africa and Amazonia) remains virtually unexplored despite its importance established by cloud radiative forcing and GCM diagnostics.

- *Mid-latitude Cloud Systems*: The most comprehensive data sets presently available (or in the foreseeable future) are those over the continental U.S. Despite the amount of data, environmental interaction and parameterisation remain poorly understood. The US Weather Research Program (USWRP) may alleviate this situation later in the decade. However, since USWRP goals relate to short-term weather prediction rather than climate, collaboration also with the ARM programme and the GEWEX Continental-scale International Project (GCIP) in the central US is vital to address the transport properties of convection over continental areas. It is noted that similar GCIP - type programmes (but of more limited scope) are being contemplated for other parts of the globe.

8.4 Plans for GCSS activities

We plan to study and approximate the physical processes in a fundamental way and then build parameterisations from this improved knowledge base. Two objectives have been prioritised by Working Group 4 that, together, address several of the science issues raised in section 8.2:

- *Role of mesoscale convection in GCMs*: In terms of our overall objectives, this is a research area expected to enjoy substantial progress. There is reason to be optimistic for the following reasons. CRMs are capable of addressing mesoscale convection at a sophisticated physics level; mesoscale theory is well advanced; and more or less adequate data sets are available (TOGA COARE is most relevant here). Note that NMC and ECMWF operational models could not incorporate all the special observations during COARE, so it is important that these be re-run at the highest practicable resolution with the full data set (ie conventional sounding and profilers). This is a major computational undertaking.

- *Life-cycle of cirrus-producing, multi-cellular cloud systems over the Maritime Continent*: Since a quality dataset does not exist for this CRM study, it can progress only in conjunction with a field campaign. A suitable experiment (MCTEX) is planned. An objective is to obtain high temporal and spatial resolution measurements of convection initiation in a coastal locale, interactions between tropical deep convection and its environment, interaction among the boundary layer, microphysical, and radiative processes. The MCTEX, scheduled for Nov-Dec 1995 near Darwin, Australia, is an opportunity for GCSS to collaborate, together with the ARM and TRMM programs. A mix of CRM modelling, theoretical and observational studies will be used to study a highly-predictable, multi- cellular, cirrus-producing cloud system over a mesoscale island. We plan to: 1) conduct numerical experiments with CRMs prior to the MCTEX to assist experimental design; 2) establish the level of sophistication necessary for sub-gridscale physics in CRMs. Model intercomparisons may be established later (3) but this is not an early priority. Two planning activities will take place, the first during the AMS Annual meeting in Nashville on Jan 25, 1994, and the second at a proposed Workshop at the BMRC, Melbourne, Australia in early 1994. A principal consideration will be the incorporation of the GCSS-related aspects into the experimental design.

8.5 Summary

Precipitating convective cloud systems are highly nonlinear and physically diverse. They interact strongly with all other sub-gridscale processes - microphysics, surface layer, boundary layer, radiation, and turbulence. The CRM approach spans the range of scales involved. It can approximate, to varying degrees of accuracy, the processes involved. However, this approach must progress in concert with theoretical studies and with observational analysis to formulate transport laws, determine new closures, and to test hypotheses against the quality datasets. It is important that sufficient observational data be available to establish the credibility of the CRMs.

The priority will be to study cirrus-producing, deep, precipitating cloud systems over the western Pacific and the Maritime Continent. This choice was made in view of the recognized importance of the effect of these cloud systems on the tropical atmosphere and in global climate. Focus will be on cloud-mean flow interactions that are relevant to the formulation of new ideas on the parameterisation of precipitating convection in GCMs.

Two principal activities have been identified:

- *The effect of mesoscale convection in atmospheric GCMs.* This will be developed in collaboration with other programs in the tropical western Pacific (eg ARM Tropical Western Pacific and TOGA COARE) assuming a co-operative agreement is reached. This activity has started in a small way but requires augmented support to be effective. Emphasis will be on the use of TOGA COARE data sets for initialisation and verification of CRM results and the parameterisation of mesoscale convection in GCMs.

- *The life-cycle of cirrus-producing, multicellular cloud systems over the Maritime Continent.* The GCSS Working Group 4 has accepted an invitation by the MCTEX Science Team to participate in the experiment scheduled for a six-week period in November-December, 1995. The emphasis will be on the life-cycle of the convection and the radiative effects of the attendant cirrus decks.

The working group will establish a procedure whereby CRM and observational datasets can be made readily available to the community.

9. The sensitivity of cloud-resolving models (CRMs) to parameterisation schemes: collaboration with International Commissions

The whole point of using CRMs is to resolve explicitly the processes associated with cloud systems. Although CRMs are able to resolve the important dynamical scales within clouds, it is usually necessary to parameterise the microphysical and radiative processes. Some CRMs are being developed in which the microphysical processes are treated explicitly, but it seems unlikely, in view of the computational requirements, that such models will be used to study the full range of processes that need to be investigated as part of GCSS. It is therefore necessary to ensure that the parameterisations used in the CRMs are sufficiently accurate that they do not affect the conclusions drawn using the CRMs or the ability of such models to provide cloud parameterisations for large-scale models.

CRMs used by all of the above Working Groups (Secs 5-8) must include a representation of the processes governing the formation, growth and movement of hydrometeors as well as the processes governing the transmission of solar and long-wave radiation through an inhomogeneous medium.

9.1 Microphysical parameterisations in CRMs

A few CRMs are being developed in which the evolution of the droplet spectrum is treated explicitly, by considering a large number of size classes of droplets whose growth is determined from the condensation and stochastic collection equations. However, most CRMs use simplified schemes based on that outlined by Kessler. In such schemes, the model cloud variables are water vapour, liquid water and precipitation mixing ratio; the rate of conversion between these variables is determined using equations whose development is based on a number of assumptions concerning the cloud and precipitation spectra. In the case of clouds containing ice particles, additional bulk parameters are introduced, including, for example, the mixing ratios of hail and small ice crystals, together with the necessary conversion equations.

The success of such schemes depends on the purpose to which the CRM is being put and the applicability of the conversion equations to the situation being modelled. For example, the parameterisation schemes often use a critical liquid water threshold, below which no water is converted into precipitation. A constant value is normally assumed for the threshold whereas it is observed that different types of clouds have distinctly different thresholds. For example, stratocumulus clouds often produce drizzle when the water content is much less than that in non-precipitating cumulus. It is also necessary that such parameterisations take into account, in more detail than is used at present, the effect of aerosol which acts as a source of cloud condensation nuclei. In the case of clouds containing ice particles, the physics of the processes leading to the glaciation of clouds are poorly represented. In particular, a simple temperature-dependent conversion rate is often used although observations suggest that cloud top temperature, rather than local temperature, may be more appropriate.

9.2 Radiative transfer

The effect of clouds on the transfer of infra-red or solar radiation is often approximated by the use of simplified two-stream models in which the important parameters are the liquid water content and cloud particle effective radius. While such approximations have been verified for transfer through plane-parallel, homogeneous, water clouds their applicability to optically thin ice clouds, in which the scattering particles are non-spherical, or to clouds with irregular surfaces and exhibiting internal inhomogeneity, has not been demonstrated. Indeed, the shape, as well as the size of ice crystals has been shown to have a significant effect on the optical properties of ice clouds.

Recent studies using accurate, but computationally demanding, Monte Carlo models have demonstrated the importance of inhomogeneities and attempts are currently being made to develop six-stream parameterisations to take these into account. Verification of the parameterisations against observations is difficult because of the lack of sufficiently comprehensive data sets.

9.3 Planned activities

In order to have confidence in the microphysical parameterisations used within CRMs, it is proposed to initiate a project under the auspices of the International Commission for Cloud and Precipitation (ICCP) and the International Radiation Commission (IRC) to test microphysical and radiative transfer parameterisations against the results of more detailed calculations and observations. The project will be undertaken in parallel with the GCSS, and the results made available to the GCSS community. As part of this project, sensitivity studies will be made in order to assess which are the more critical parameterisations in terms of their effects on CRM simulations. It is anticipated that, in simulations of cloud systems in which radiative processes have little effect on cloud development, only parameterisations of processes which result in latent heating and cooling will have a significant effect. On the other hand, where radiative processes are important, it may be necessary to correctly parameterise the effects of cloud particle concentration.

The following specific actions are planned. They underpin all of the GCSS modelling activities described in Secs 5-8.

- Compile list of currently used parameterisations.

- Invite sensitivity studies using CRMs and collate the results.

- Organize a Workshop to identify critical areas and plan studies (a) to improve parameterisations using detailed microphysical and radiative transfer models, and (b) to identify suitable data sets for parameterisation verification. The Workshop is likely to be held late in 1994.

- Organize a second Workshop in 1996 to compare improved parameterisations and to assess their accuracy and suitability for particular purposes. The schemes will be tested in CRMs applied to a limited number of dynamically simple situations, in order that the effects of differences in model dynamical formulations might be minimised.

Cloud-resolving models: a) Derivation, b) Use

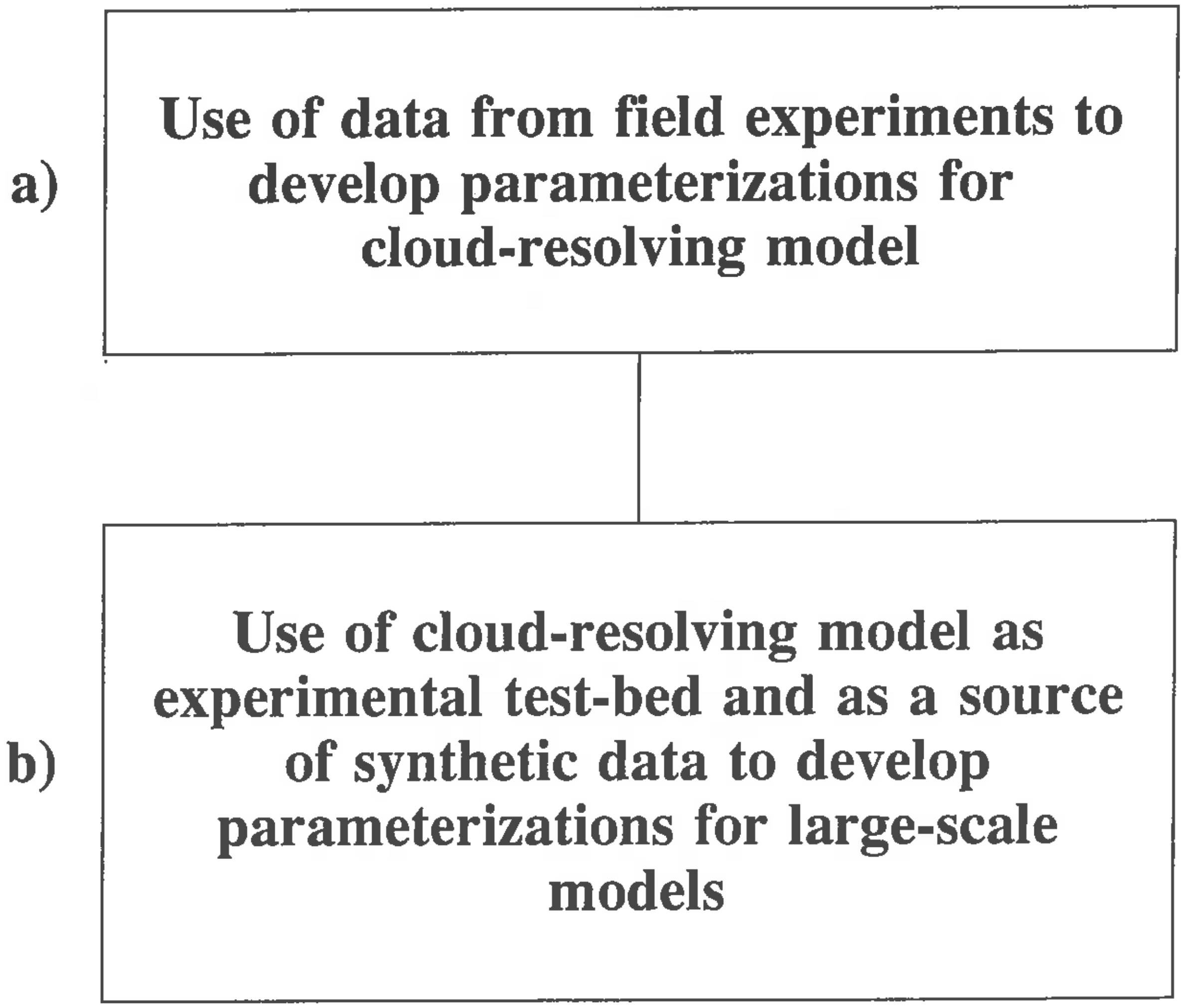

Fig 1: The two-stage process of deriving and using CRMs.

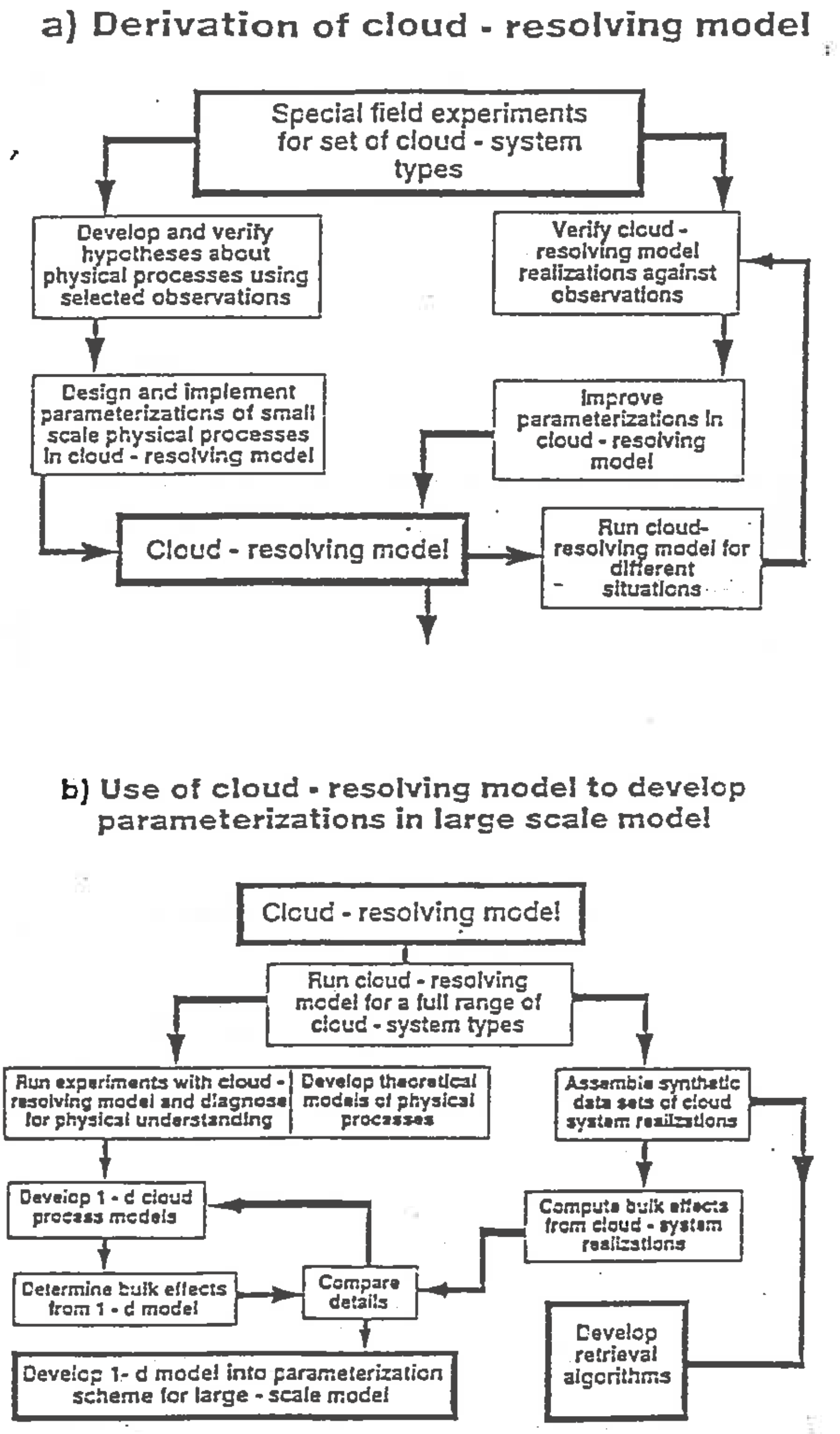

Fig 2: Flow charts showing how field observations and simulations using cloud resolving models may be combined for the purpose of improving parameterizations in large-scale models.

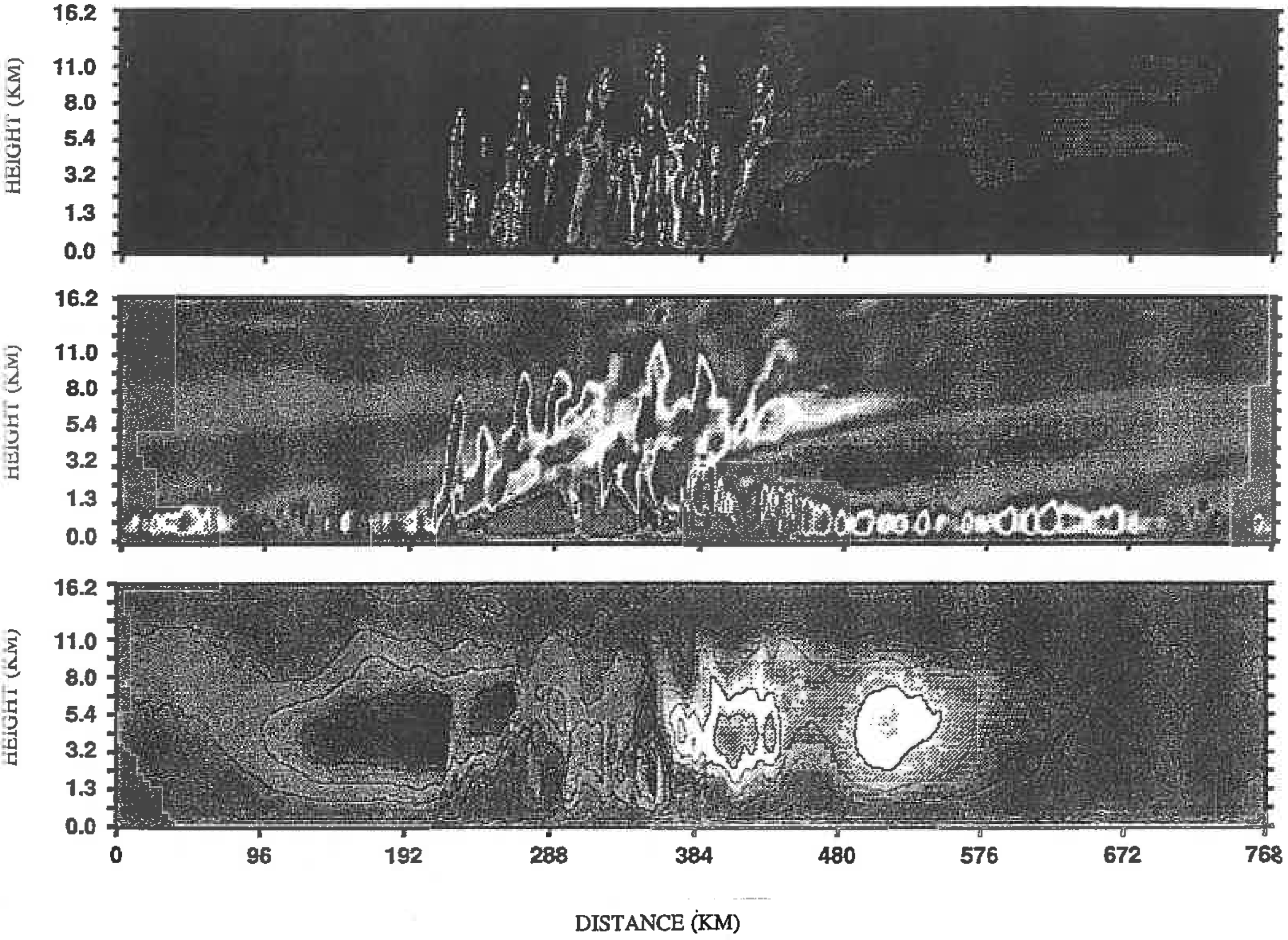

Fig 3: A snapshot of model-simulated cloud fields in x-z cross-sections for (a) total cloud water content, q_c, (g kg^{-1}), (b) equivalent potential temperature deviation, θ_e (°C) and (c) mass stream function (g cm^{-1}s^{-1}). Units in horizontal and vertical axes are kilometres. (Courtesy of W-K Tao, NASA GSFC).

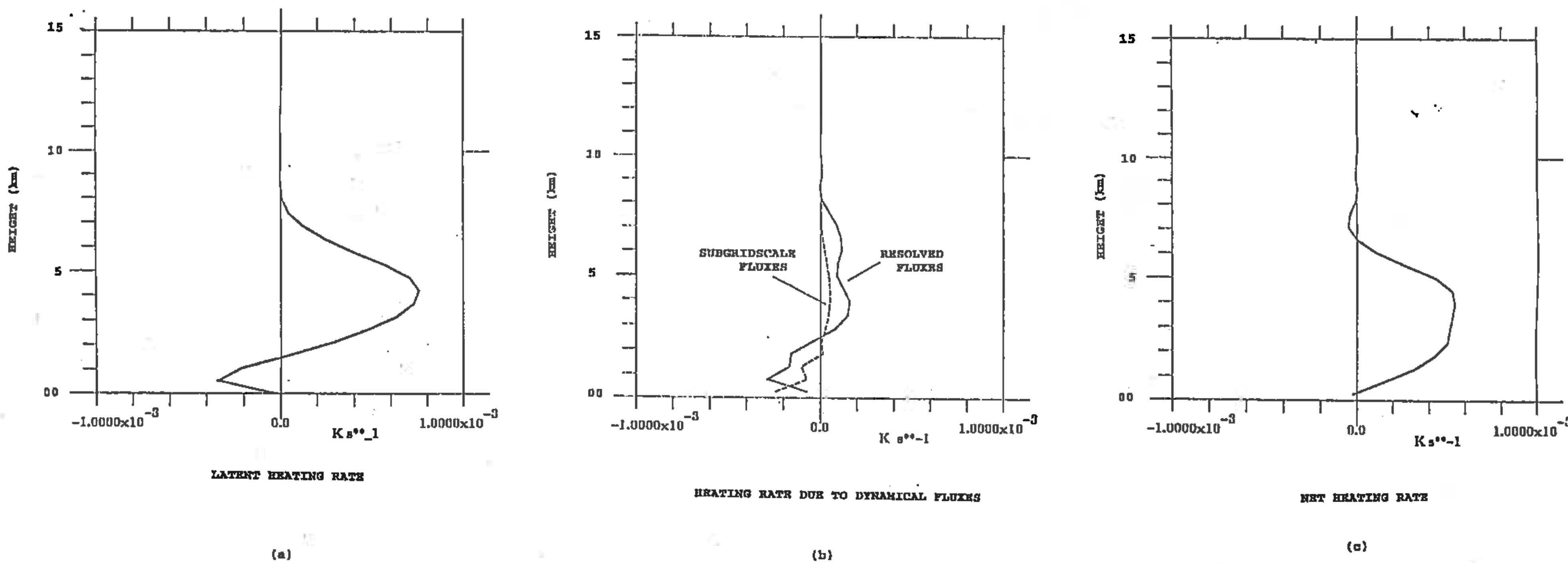

Fig 4: Heat budget graphs from a 3-D cloud resolving model (courtesy R Kershaw, Joint Centre for Mesoscale Meteorology, Met Office/Univ. of Reading). The graphs show the following components of the heat budget, plotted against height:

(a) latent heating rate,
(b) divergence of resolved (full line) and sub-gridscale (dashed line) dynamical fluxes,
(c) net heating rate. (c=a-b; calculations use T^L, liquid water temperature).

The values are averaged over the second hour of a 2-h integration and over a 50 km x 50 km horizontal domain. Resolution 1 km (horizontally) and ½ km (vertically). Cyclic lateral boundary conditions. No shear. Kessler warm rain parameterisation. Surface fluxes: 100 W m^{-2} (sensible) and 1200 W m^{-2} (latent).

Survey of perceived priority issues in the parameterisations 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 parameterising 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 five 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, 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

*This survey was published in QJR Meteorol. Soc. (1994), 120, pp. 483-487 and is reproduced by permission of the Royal Meteorological Society.

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 parametrisations of sub-gridscale 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 prioritisation 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 parametrisations 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 parametrisations 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 parametrisations 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 parameterisations 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 parameterisations 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 parameterisations, momentum transport is ignored. It seems likely that even a zero-order parametrisation 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 sub-gridscale 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 parameterisations because so many of the processes are coupled. Some went further by stressing that cloud parameterisations 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 parameterisations must be coupled to the radiative parameterisations 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 parametrisation 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 parametrisation 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 parametrisation 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 parametrisation, 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 parametrisation schemes and of the cloud models they use, and thereby reduce our present dependence on empirical tuning of parametrisation schemes. However, realism must not be bought at the expense of too much complexity in the parametrisation schemes.

A further principle is the importance of unifying parametrisation 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 generalise 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 parametrisation 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 parameterisations 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
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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
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