INTRODUCTION

A good representation of clouds and cloud/radiation interaction in numerical weather prediction models is essential for accurate direct local prediction of weather elements and for accurate prediction of the general circulation of the atmosphere in the medium range. For seasonal prediction and climate simulation the representation of clouds is important also because of its influence on the prediction and simulation of, for example, the global water cycle and the ocean circulation.

This Workshop was held to consider recent developments in the modelling of clouds, the validation of cloud models, the assimilation of observed information on clouds into models, and the observation of clouds. The aims were to identify strategies for addressing problems in each of these areas and to seek ways of improving interactions between these areas of activity.

The Workshop was jointly organized by ECMWF and the coordinators of the GEWEX Cloud System Study (GCSS). It considered cloud studies of relevance either for numerical weather prediction or for the climate interests of GCSS. GCSS is a long-term programme which focuses on the use of very high resolution (large-eddy simulation or cloud-resolving) models to simulate accurately cloud systems and hence provide a framework for the improvement and future development of physical parametrizations for forecast and climate models. For this workshop the GCSS contribution emphasized extra-tropical layer clouds and cirrus.

The Workshop followed the usual format of invited lectures and discussions in working groups. Groups were set up on the topics of large-scale modelling, validation and assimilation, cloud-resolving models and observational studies. The discussions of these groups are summarized in the following four reports.

1. WORKING GROUP 1: LARGE-SCALE MODELLING

1.1 GOALS

The working group on large-scale modelling gave consideration to the following research goals:

1. Determination of the four-dimensional distribution of clouds and water vapour;

2. Determination of the effects of these clouds on the general circulation of the atmosphere and on energy fluxes through radiative, thermodynamic and hydrological processes.

Current large-scale models fail to produce surface fluxes including surface radiation with sufficient accuracy to allow either successful coupling with ocean models or accurate forecasts of the thermal and hydrological state of the land surface. These failures are a severe impediment to seasonal forecasting, climate studies and data assimilation systems with a surface hydrology that is not controlled by data. The surface-flux errors of current models are on the order of 20 W/m^2 or more in the zonal means. This should be compared with the 4 W/m^2 radiative forcing estimated to result from a doubling of CO_2. Errors in simulated top of the atmosphere fluxes in some GCMs are smaller but this is due to substantial tuning.

Weaknesses of current cloud parametrizations also contribute to errors in the simulated hydrological cycle and to uncertain upper tropospheric water vapour.

In numerical weather forecasts, clouds, besides being an important forecast product themselves, strongly influence the prediction of many near surface and upper air parameters (e.g., near surface temperature, upper air moisture) and thereby the quality of the forecast.

Recently on the order of ten global modelling centres have moved toward adoption of prognostic cloud water variables. This represents significant progress towards more realistic cloud parametrizations, but much more remains to be done. These developments have been motivated by a recognition of the need for a more realistic coupling between cloud formation processes (e.g. convection) and the radiative effects of clouds, and also by the strategy of some centres to use a single "unified" model that can be used in both large-scale and mesoscale applications. The importance of the quality of water vapour analyses for accurate treatment of clouds is now increasingly recognized.

1.2 STATE OF THE ART

Recently several new approaches have emerged for the parametrization of cloud amount in large-scale models. These include both prognostic and diagnostic methods, as well as statistical schemes based on second order closure. Further tests are needed to establish the relative strengths and weaknesses of these various approaches.

Following the pioneering work of Sundqvist, an increasing number of general circulation models include a prognostic equation for the mass of cloud water and/or cloud ice to parametrize cloud processes. The main cloud microphysical processes are highly parametrized following the equations proposed by Kessler or developed for mesoscale models. Such processes include condensation/evaporation, deposition/sublimation, autoconversion and accretion. Some micro-scale processes (e.g., evolution of droplet-size spectra and crystal shapes) are more often neglected. Precipitation of rain and snow is in most cases treated diagnostically. The coupling between large-scale processes and convection is parametrized through detrainment of cloud liquid water and cloud ice from cumulus towers. Radiation then interacts with the hydrological cycle through cloud optical properties.

GCMs do not take into account the sub-grid scale variability within clouds as opposed to cloud fraction. This prevents turbulent processes from influencing sufficiently the thermodynamics of clouds. Efforts to take into account several cloud types in a GCM gridbox are very limited.

There is an increased need for process-driven cloud-formation parametrizations.

The determination of cloud optical properties from the prognostic cloud variables is generally limited to the use of cloud water and/or ice path and an assumed drop/crystal effective size and shape. Some groups are now including the effect of aerosol on the effective radius and simple temperature-dependent crystal characteristics.

Over the last decade or so great efforts have been put into studies of boundary layer clouds. These clouds are vitally dependent on the turbulent fluxes in the planetary boundary layer, but these fluxes are in turn also dependent on the cloud-induced circulation and entrainment at the cloud top. Similar considerations apply to cirrus clouds which also may be considered an inversion type of cloud, although with other characteristics. Stratocumulus, Arctic stratus and cirrus stand out as particularly important for the atmospheric radiation budget. Present-day parametrizations of stratocumulus in large-scale models show a wide variety of accuracy in simulations between both different models and different circulation situations.

Concerning parametrization schemes for cirrus and Arctic stratus, only limited work has been performed. Some studies essentially comparing effects of black and prescribed opaque cirrus have been done. Recently developed diagnostic and prognostic parametrizations for atmospheric ice are expected to advance knowledge of this problem.

Parametrization schemes applied in large-scale models distinguish between convective and stratiform clouds, and they have traditionally been treated separately. With regard to the important role of convective clouds as a source for cirrus via anvil formation, it is noted that improvements in the representation of anvil cirrus have resulted from changes in the treatment of convective-stratiform coupling. There has been limited research on mixed-phase clouds e.g. mid-level altocumulus.

1.3 STRATEGIES FOR FUTURE DEVELOPMENT

Research is required on several important issues related to GCM development and initialization of cloud-related fields. Among these are

- treatment of fractional cloudiness

- determination of realistic initial conditions (e.g. humidity, distribution of cloud variables)

- treatment of ice formation and sedimentation

- sensitivity to time step and resolution

- treatment of fast processes when long model time-steps are used

- saturation humidity used for cloud formation

- representation of mixed-phase clouds

- parametrization of presently unrepresented sub-grid clouds (e.g. clouds due to unresolved orography, mesoscale rain bands, multiple cirrus layers)

- complexity of cloud representations required for adequate simulations on global scales

- effects of in-cloud inhomogeneities and multiple cloud types within a grid box on radiation and precipitation

Sensitivity experiments with GCMs can provide valuable insights on the model response to imposed modifications in internal or external forcings. They are thus an important contribution for identifying the cloud parameters or processes that can have the largest impact on the model climate, especially for microphysical properties or parameters that are poorly determined or constrained from observations. Sensitivity experiments should be encouraged to estimate in a systematic fashion

- the response of individual weather systems, which are the building blocks of climate;
- the response of the mean climate to changes in selected parameters or processes;
- the possible modification of the climate sensitivity (e.g., in experiments of the FANGIO type with ± 2K SST) as a result of changes in the cloud treatments.

By comparisons of simulations using 3D and single column versions of the models, the degree of complexity required in the microphysics of the GCMs should be assessed. Although the more complex and detailed prognostic schemes with elaborate cloud microphysics will be needed to obtain the most accurate results, it may be useful to try to develop from them, by means of suitable approximations, simplified parametrizations that may prove useful in situations (such as multi-decadal or multi-century simulations) where the computational cost must be reduced. A hierarchy of cloud parametrizations may be needed to assess the degree of complexity of the cloud parametrization suitable for use in different applications (NWP, short-term climate simulations, or climate change scenarios). Also note the need for inverse/adjoint schemes for use in variational analysis. This requires simplified schemes to ensure sufficient continuity and to reduce computational cost.

Observational information is required on the 3D structure of clouds. There is a need for both global statistical data and more detailed local field studies to elaborate the structure of particular cloud systems.

Information is required on the global distributions of the ice- and liquid-water paths, the size, shape and phase distributions important in defining the radiative properties of cloud (e.g. effective radius), the spatial and temporal distribution of cloud (e.g. cloud cover, variations in concentration within clouds, layering) and associated environmental parameters such as temperature and vertical velocity on all scales. Information is also required on precipitation amount and phase both at the surface and in the atmosphere.

It is felt that data from some existing programmes are probably under-utilised and need to be processed into a form more accessible to those developing parametrization schemes. Also, the limitations of the data need to be evaluated and clearly stated. Examples are SSM/I and programmes such as ARM, CERES, EUCREX, FIRE, GEWEX, SHEBA, TRMM, WCRP/SRB.

In particular there is a critical need for observations of the ice-water path globally, the liquid-water path over land and the occurrence of mixed phase cloud, which are not provided by current programmes. This will allow the climatologies of the models to be validated.

Field data are also required on a case study basis. This will allow the important processes involved in the formation and evolution of the clouds, their representation in models and the ability of models to simulate particular cloud types (e.g. deep convection, boundary layer clouds and frontal cloud bands) to be investigated.

Cloud resolving models (CRMs) can be used as surrogate observations once they have been validated. Information required would be the same as from the observations listed above. Indications of the accuracy of the CRM simulations are required: information on the interaction of turbulence and clouds, radiation and clouds, the amount of gridscale cloud produced from convective processes, e.g. anvil production, and the criteria for their production. Averaged CRM phase changes and eddy fluxes can be compared with corresponding quantities yielded by GCM parametrizations (e.g. apparent sources/sinks of heat, moisture, momentum etc.). Also CRMs may be used to assess physical assumptions employed in GCM parametrizations (e.g. water budgets, distributions of mass fluxes and vertical velocities). Another application is to evaluate possible simplifications of complex physical processes used in GCMs (e.g. microphysics).

There is a need to carry out three-way comparisons of field observations, cloud resolving models and GCMs.

2. WORKING GROUP 2: VALIDATION AND ASSIMILATION

2.1 CURRENT ACTIVITIES

Current research activities on cloud modelling include the diagnostic and prognostic approaches. Much progress was evident at the workshop on the treatment of the formation, maintenance and decay processes for the explicit (prognostic) treatment of clouds. However, the need for validation was stressed.

Basic to any attempt to compare model cloud fields with observed cloud should be validation of the model's moisture field. Traditionally, this validation has emphasised precipitation verification. However, a method of routinely assessing a model's three-dimensional moisture field is essential.

The two possible ways to validate clouds in a model are the "satellite-to-model" and the "model-to-satellite" approaches. Both are currently being exploited. The first aims at comparing model variables directly with products retrieved from radiance measurements. This method requires a thorough knowledge of the retrieval process and of the associated errors, and an appreciation of the differences between model variables and retrieved quantities.

The second approach aims at simulating the measured quantity, e.g. global radiance measurements, and the comparison is carried out in terms of radiance differences. In this case the discrepancies are immediately evident, and the error analysis is simpler since the error of the measured variable is typically much smaller than that of the simulated one. However, a detailed interpretation is required to understand the causes of discrepancies.

Both approaches were presented at this Workshop, including use of brightness temperatures (Rizzi, Rikus), of multi-spectral processed AVHRR data (Karlsson), of USAF real-time nephanalyses in three cloud layers (Campana) and of radiative fluxes and cloud liquid water (Ricard). Conventional surface data is used by Karlsson to indicate error characteristics of AVHRR-derived cloud information.

Current progress in assimilation at ECMWF, using 4D-variational analysis, is impressive and well conceived as a long-term programme. This effort will continue, but it is clear that the assimilation of cloud observations is still premature at the present time. Operational centres are awaiting further advances in the development of adjoints of the physical processes within their assimilating models prior to this effort.

Another approach, called physical initialization, provides a means to assimilate precipitation estimates or related information from satellite-based (SSM/I, OLR) and surface-based data, as discussed by Krishnamurti at this Workshop. This approach can be interpreted as using an approximate adjoint of the convective and planetary boundary layer parametrizations. It has been shown to give highly skilful nowcasts and one-day forecasts of precipitation over the tropics. Related cloud prediction (using the diagnostic approach) also appears to be improved in the short range. These results are impressive given the known uncertainties in the algorithms used to estimate latent heat release from satellite data, and provide strong motivation to develop 4D-variational analysis systems to include diabatic effects.

2.2 VALIDATION DATA SETS

2.2.1 Validation of cloud and radiation parameters from "historic" data sets

The main datasets currently available for such validation (usually carried in satellite-to-model mode) include:

- the ISCCP datasets (C1 and C2) and the Surface Cloud Climatology (Warren and Hahn) for cloud parameters;
- the Nimbus-7 ERB and ERBE datasets for the SW and LW radiative fluxes at the top of the atmosphere
- the Surface Radiation Budget derived from ISCCP data and the surface SW radiation derived from ERBE data (Li et al.)
- SSM/I for the precipitable water and vertically integrated cloud water
- the precipitation climatologies (Jaeger, Legates and Wilmot)
- cloud microphysical parameters from aircraft measurements from TOGA-COARE
- global cirrus climatology (Menzel and Wylie).

The main advantages of these datasets are their long time-spans and the easy access (CD-Rom, or few tapes) to the data. However, the processing required in the satellite-to-model approach involves the use of assumptions which introduce uncertainties into the data making it more difficult to assign the source of discrepancies. This can be exacerbated if the actual processing is not done locally. Where only processed data are available, it is very important that efforts are made to get an assessment of the inherent errors in the datasets, for example significant variations exist in published cloud amount climatologies, where global values of total cloud amount range from approximately 50% for Nimbus-7 data to over 60% for ISCCP data (Mohkov and Schlesinger). In some cases, the biases in these datasets are well known (e.g. in ISCCP for polar regions, or over the Southern Ocean for SCC).

2.2.2 The use of real-time datasets for validation

There is a large volume of satellite data of global coverage which is available in real or near real-time at a temporal frequency suitable for validation of NWP models. It is desirable to have both raw radiance and processed data (e.g. USAF RT.NEPH) available at the highest available resolution to meet the requirements of the current NWP models. The advantage of raw data is that any discrepancy between model and satellite is generally a model error (i.e. there is no introduction of errors by an intermediate processing of the data).

Instantaneous data provides a means for stringent validation of an NWP model. However, the large volume of data may present problems in dissemination and storage, requiring some spatial sampling or preprocessing to be done with the accompanying possibility of introducing errors.

2.2.3 Future systems

The next generation of polar orbiters will fly Advanced TOVS (ATOVS) with improved sounding capability in cloudy areas. Towards the end of the decade instruments of high spectral resolution in the infrared will offer significant improvements in vertical resolution. The contemporaneous availability of advanced microwave and infrared instrumentation will provide the basis for more stringent model validation, but extensive work will be required to make full use of the available data.

Future geostationary platforms (e.g. GOES8, METEOSAT Second Generation) will contain imaging instruments with multispectral measurement capabilities, with the potential of producing higher quality products than presently possible. Some work will be needed in the adaptation of the multispectral retrieval methods that are currently applied to polar-orbiter data.

2.3 RECOMMENDATIONS

2.3.1 Routine comparison of model-simulated radiances with observed data at several forecast times should be actively pursued, the objective being to characterize errors in the thermodynamic and hydrological structure of the troposphere. There will be a continuing and increasing need for exchange and processing of raw data.

2.3.2 Use of retrieved geophysical parameters should be actively pursued so that they can be used to facilitate the interpretation of the results from comparisons with raw data.

2.3.3 Scientific and technical work needed to provide a full capability for four-dimensional variational assimilation of cloud-sensitive observations is strongly supported.

2.3.4 Pending such development, the alternative approach of physical initialization should be considered.

2.3.4 The use of GRIB and BUFR encoding should become standard for the exchange of data.

3. WORKING GROUP 3: CLOUD RESOLVING MODELS

3.1 STATE-OF-THE-ART PERFORMANCE OF CRMs

Since the GCSS participants at this workshop principally had expertise in extra-tropical layer clouds and cirrus, the attention of this working group focused on these cloud systems. Several presentations on the ability of CRMs to capture aspects of these clouds systems were made at the workshop.

There are several different issues related to the use of CRMs in support of GCSS: horizontal and vertical resolution, physical parametrizations, initialization and validation of simulations. These issues are addressed here.

3.1.1 **Horizontal and vertical resolution**

The choice of resolution depends on the particular system being considered.

- For non-convective regions of extra-tropical cyclones, horizontal resolution up to 20-30 km can be sufficient to address some GCSS problems. Other problems associated with embedded features may require 100 m resolution. The vertical resolution also appears to be important, though this was generally not considered in the past. This choice is particularly important to simulate layer clouds and interactions with the PBL. Vertical resolution around 100 m is recommended in regions of interest.

- For the convective regions of extra-tropical cyclones, CRMs should be used with horizontal resolution under or equal to 5 km. There can still be problems linked with embedded convection however.

- For cirrus forming or decaying in situ, turbulent eddies may need to be resolved. For this reason, Large Eddy Simulations (LES) with horizontal resolution of 5-10 m may have to be performed.

- For cirrus forming in anvils, CRMs could be used to simulate the convective system and the anvil in the same framework.

- In order to have fine horizontal resolution in some parts of the simulation domain, 1-way or 2-way grid nesting techniques are necessary, with computers currently available.

3.1.2 **Initialization**

For frontal cloud simulations, the knowledge of the geostrophic forcing seems sufficient to get realistic simulations at cloud-scale, although a comprehensive comparison against a full complement of observations has not been accomplished. This is also the case for clouds forced by topographic inhomogeneities. For these cases, current operational analyses can be sufficient to initialize CRMs. In other cases, specific initialization/assimilation may be required on the cloud scale. In all cases, moisture initialization is considered as a key point.

3.1.3 **Physical parametrizations**

3.1.3.1 *Radiative scheme*

Radiative effects should be considered in CRMs for the purpose of testing radiative codes developed for GCMs. A key point is to make sure that the radiative scheme is coupled to the microphysical scheme.

3.1.3.2 *Cirrus*

Previous attempts to model the radiative properties of cirrus clouds have reduced the ice particle size distribution to equivalent area (or volume) spheres, and then applied Mie theory to calculate the radiative properties. However, both observational programmes and modelling work on the single scattering properties of ice crystals have shown that spheres do not adequately represent the radiative properties of ice crystals.

More recently, parametrizations have been developed for treating the radiative properties of hexagonal ice crystals (plates and columns). However, ice particles in cirrus are often more complex in shape than pristine hexagonal columns and plates. Other common shapes are bullet rosettes and planar polycrystals, which are 3-dimensional. These crystal types are readily treated using anomalous diffraction theory. They can produce reflectances approximately twice those produced by simple hexagonal crystals. Cloud emissivities also depend strongly on ice particle shape.

Cirrus cloud radiation schemes which address the complexities of ice particle shapes have been shown to agree favourably with observations. For instance, radiative properties predicted from observed microphysical properties in cirrus agree reasonably with corresponding measured radiative properties. However, such comparisons are limited, and no radiation scheme has been validated for use in the remote retrieval of cloud properties. Developments in this area are sorely needed.

3.1.3.3 *Turbulence scheme or PBL representation*

For Large Eddy Simulations of cirrus and simulations of cloud systems involving important interactions with the PBL, improvement/validation of turbulence schemes or PBL representation should be made.

3.1.3.4 *Microphysical schemes*

a) Bulk water parametrizations of microphysical processes

A number of climate-sensitive processes such as cloud evaporation and ice-water formation are parametrized in CRMs using bulk water techniques. The accuracy of these techniques, however, depends on the sophistication of the parametrization, such as one or two moment techniques, and the values of the constants specified in the parametrization. Some examples for critical constants are the auto-conversion thresholds for cloud to rain and ice to snow, the collection efficiencies for various hydrometeor species and the constants in the specifications of mean terminal velocity. Such schemes need to be well tested.

b) Cirrus cloud microphysics

Cirrus clouds are currently simulated using a variety of models with various degrees of sophistication. Two basic models have been developed: 1) models predicting ice crystal concentration via homogeneous and heterogeneous nucleation, and 2) models predicting the evolution of the size distribution slope parameter using calculated ice water profiles. Both methods use a double-moment parametrization to calculate ice particle size distributions at various levels in cloud. The second method has been shown to predict the evolution with height of ice particle size spectra for several case studies.

3.2 REQUIREMENTS FOR CRMs

3.2.1 **Data for Initialization**

The fields for initiating CRMs need in general to take advantage of the latest developments in four-dimensional data assimilation. Since the appropriate data sets for validating these models generally occur within specialized field experiments, this data assimilation needs to incorporate enhanced observations with particular attention paid to humidity.

3.2.2 **Data for Validation**

3.2.2.1 *Precipitation and dynamics*

A key component of the CRM model validation is the determination of dynamic and cloud fields. This requirement can be accomplished through the use of currently-available technology including Doppler polarization radar, surface measurements of standard parameters, satellite measurements, and in-situ aircraft observations. A key additional source of information will be the deployment of cloud profiling radar to document the presence of non-precipitating layers.

3.2.2.2 *Radiation*

Radiation information for validating the CRMs must take advantage of the satellite information that is available. However, this must be supplemented by surface arrays to examine near-surface fluxes, and aircraft to examine inter-layering radiational perturbations.

3.2.2.3 *Microphysical requirements*

a) Ice initiation

The initiation of ice in clouds is key to determining the number concentration of ice crystals and the ice/water fraction. Currently, the initiation of ice at temperatures warmer than -38° C is poorly understood, with most cloud model parametrizations still using an ice nuclei curve developed by Fletcher over 30 years ago. More field and laboratory studies are needed to understand the key processes causing the observed variability of ice in the atmosphere. We suggest that experiments, such as the WISP94 experiment in Colorado, be performed that focus on basic mechanisms for ice formation. CRMs should be run for various geographic locations in order to determine the sensitivity of ice to the various ice formation processes proposed. The importance of the boundary layer to ice formation should also be investigated.

b) Complexity of microphysical schemes

Current cloud resolving models use a variety of microphysical schemes with varying degrees of complexity. Recent studies have suggested that single-moment schemes (those predicting only mixing ratio of condensed water and ice) may not adequately capture the key cloud-precipitation and radiative transfer processes in CRMs.

Double-moment schemes (predicting mixing ratios and concentrations of hydrometeors) however, have shown improved skill in the prediction of these quantities. It is recommended that double moment schemes be tested in order to evaluate whether their added complexity and cost are justified.

c) Evaluation of GCM evaporation parametrizations

About half of the condensed water in GCMs returns to the atmosphere through evaporation and sublimation and some current GCMs furthermore have difficulties in accounting for the global water budget. To evaluate the potential impact of parametrization schemes on moisture uncertainties, CRM simulations should be conducted on relevant cases with good ground truth. These CRM simulations can be used to improve current parametrizations of cloud evaporation in GCMs.

3.3 CRM/GCM INTERACTION PLAN

To utilise the capabilities of CRMs effectively in the development of improved parametrizations of cloud systems, it is critical that well-validated case studies be simulated. The use of several CRMs will furthermore lead to a better assessment of the capabilities of CRMs.

The output products of these CRMs must not only include those needed for direct validation. The products must include GCM-grid scale information of derived products, to be specified by the large scale community itself. This will probably include statistics on vertical velocities, turbulence and cloud parameters, and it also includes ice water content as well as radiation parameters.

Such an analysis will be conducted on a few extra-tropical layer-cloud case studies to be selected. With experience from the chosen case studies, it is expected that similar studies will be carried out over other geographic areas of the same cloud system type, so as better to assess natural variabilities and the transferability of results.

3.4 SPECIFIC RECOMMENDATIONS

3.4.1 **Short term CRM/GCM interactions**

The detailed large-scale requirements from CRMs need to be clearly identified. The initial case studies should be chosen from a sample that includes a weak upslope snow case (from WISP), a weak extra-tropical cyclone (from CASP II), a well-documented cold front (from Fronts'87), and perhaps a weak high latitude warm front (from BASE). Other cases will be suggested and the final decision will be made with a view towards steady state systems with acceptable data for initialization and validation.

3.4.2 **Moisture assessment**

In view of the uncertainty of moisture budgets linked with large-scale models, it is suggested that a specific effort be placed on better understanding the key parameters controlling the budgets in different weather systems.

3.4.3 **Multi-layering of clouds**

Another issue to consider is the use of CRM models to address the question of the impact of non-precipitating layers within extra-tropical cyclones. A significant amount of cloud-profiling radar information on these layers is available, and should be collated into a partial climatology. An assessment of the consequences of these layers is needed.

3.4.4 Embedded convection

A special modelling effort needs to be developed in order to address properly the question of embedded convection and its consequences. This problem is distinct from that of coupling well-defined convective regions of convective systems with their stratiform components.

3.4.5 Ice-phase parametrization

The explicit amount of ice in the simulated GCM clouds has an important influence on the results of large-scale numerical integrations. However, the current treatment of cloud microphysics in GCMs does not allow a satisfactory representation of glaciated and supercooled clouds in particular. To improve this important aspect, numerical experiments with CRMs including sophisticated cloud microphysics have to be performed over a wide range of meteorological situations. The results of these numerical experiments should be analyzed in detail to create simple parametrization schemes for use in large-scale models.

3.4.6 Improved process parametrizations

A number of key aspects of processes occurring within extra-tropical layer clouds are not properly parametrized and some of these are not adequately understood such as ice nucleation, mixed phase precipitation, evaporation, sublimation and aggregation. In addition, processes occurring at cloud top or at the melting layer may have substantial large-scale impacts. These issues need to be addressed with high resolution models applied to existing data sets.

4. WORKING GROUP 4: OBSERVATIONAL STUDIES

4.1 REQUIREMENTS FOR MODEL VALIDATION

4.1.1 Introduction

The aim of GCSS is to develop a plan for the interaction between cloud-resolving models (CRMs) and large-scale models, making use of the state-of-the-art performance of CRMs. The strategy is to use models to develop a physical understanding of the coupled processes within cloud systems. The recommendations of this Working Group (WG) focus primarily on the cloud processes associated with extra-tropical stratiform cloud systems and with cirrus clouds (GCSS's groups 2 and 3). The Data Blueprint document produced by GCSS group 3 provides a more complete review of these issues for extra-tropical stratiform cloud systems.

Validation of large-scale models is considered in more detail in the report of Working Group 2 (WG2). Here, WG4 has made the following assumptions concerning the observational goals to support validation activities at the larger scale:

- that they should include 4-dimensional fields of water vapour, cloud water and ice, and precipitating water and ice;
- in addition, an accurate description of the environment variables (temperature and wind) is needed.

Such activities will mainly use routinely available observations with a widespread (and preferably global) distribution. These include: conventional surface observations of cloud cover and type, satellite imagery and sounding data over a wide range of wavelengths, operational rain radar, and data from commercial aircraft. Observations from special observational programmes are also very valuable, but their utility is limited by their restricted spatial and temporal coverage.

4.1.2 Requirements for process validation for extra-tropical stratiform cloud systems

The role of observations in these systems is discussed in the Data Blueprint document of GCSS group 3. It gives an account of the structure and processes of cloud associated with extra-tropical cyclones and related systems. These systems are highly structured in terms of the dynamics of the large-scale baroclinic flow within which cyclone wave perturbations develop clouds associated with a set of mesoscale flows (conveyor belts). They possess moisture and cloud configurations characteristic of the inflow regions of the wave, changing through the wave's evolution but modified according to the underlying surface and the cloud and precipitation transfers of moisture, heat and momentum. The main microphysical processes are the nucleation and condensation growth of droplets, nucleation and growth of precipitating ice crystals by vapour deposition, riming and aggregation, sublimation and melting to form rain, and its subsequent evaporation.

The following issues are highlighted:

a) Theoretical studies predict substantial dynamical structure on the 5-100 km scale from a range of dynamical mechanisms such as frontogenesis driven by ageostrophic motion or latent heat transfers, but also gravity wave ducting and instabilities such as CSI (Conditional Symmetric Instability). These have been little validated by observations, and as yet there is no consensus as to the relative importance of these mechanisms in specific systems, so that 3-dimensional mesoscale models with resolution of order 10-20 km or better are an essential intermediary between cloud-scale observations and general circulation models. The circulations within these models in turn need to be diagnosed and parametrized.

b) The overall moisture budgets of these systems have not been adequately validated against appropriate data sets.

c) There is very little knowledge of the occurrence of intermediate cloud layering within these systems.

d) Some of the transfer processes, eg. deposition growth, sublimation and melting appear in principle to be reasonably well defined by bulk parametrizations, though there is a need for sharply focused process studies to confirm or refine this situation, ideally under steady state conditions.

e) Progress is being made in the understanding of ice nucleation in cirrus. There remains a need for further understanding of the origins and distribution of the ice nucleating fraction of the atmospheric aerosol in order that this understanding can be extended to ice formation at intermediate temperatures. This understanding is necessary before the full role of secondary ice formation can be fully understood.

f) There is a need for modellers and observers to agree a proper functional definition of "cloud ice" and "snow" (which is likely to be grid-length dependent) in order to model adequately the likely limits of cirrus cover and radiative interaction. The factors determining the parameter N_0 for ice are not well understood but are highly important in the context of liquid water distributions in storms.

g) The physics of the ice-phase generation has not been comprehensively described by an explicit scheme, being extremely computer-intensive.

h) There is no adequate explanation of the spectral transition from small ice crystals to the exponential large particle spectrum; whilst auto-conversion is physically justified for water, this is not known to be so for ice.

i) Methods of calculating the radiative properties of complex (as opposed to idealised hexagonal) ice crystals show promise for the parametrization of cloud-radiation interactions.

j) Almost no observations of microphysical data such as particle characteristics or spectra exist over the oceans or level topography.

4.2 REVIEW OF EXISTING OBSERVATIONAL FACILITIES AND DATA SETS

4.2.1 **Facilities**

Long-endurance research aircraft are an essential requirement, and there is concern at pressure to reduce facilities. It is necessary to ensure a continuing programme of appropriate aircraft resources, particularly of aircraft with long-range and high-altitude capabilities.

Of previously-identified weaknesses in instrumentation on research aircraft, a number of significant ones are now, or are about to be, addressed, in particular:

- liquid water, with measurement of low values at cold temperatures or embedded in ice cloud (advanced hot-wire and optical probes),
- small ice crystals, $5<D<100$ μm (replicators, holographic imaging),
- humidity in upper troposphere (cryogenic, Ly-alpha fluorescence),
- integrated ice-water content (evaporative methods),
- non-wetting temperature sensors.

A key gap related to the understanding of ice-phase microphysics remains the observation of ice-forming nuclei (IN) and the relationship of IN to the overall aerosol loading. Some initiatives to address this are under way, and methods suitable for aircraft use have been proposed, although these still require extensive development.

Aircraft-borne active remote-sensors (lidar and/or radar) can provide a valuable context to detailed in-situ measurements, especially in respect of layering and vertical profiles of bulk microphysical properties. Also, airborne Doppler radars can, given appropriate flight patterns, be used to retrieve precipitation terminal velocities. Such patterns will be incorporated in FASTEX (using the ELDORA/ASTRAIA radar).

Ground-based dual-wavelength and dual-polarization radar holds promise for the measurement of vertical profiles of size spectrum parameters (N_0, λ). This may assist the understanding of aggregation processes.

4.2.2 **Existing data sets suitable for testing CRMs**

A recent WMO Workshop (on Cloud Microphysics and Applications to Global Change, Aug 1992, Toronto, WMO WMP Report No. 19) considered a number of existing field programme data sets of cloud microphysical measurements. This emphasised a number of problems which affect the usefulness and comparability of different data sets:

- differences in observing methods, data processing methods, and sampling strategies,
- lack of comparison of sensors during field programmes,

- geographical biases,

- the documentation of data from field experiments should be as comprehensive as possible, even fo parameters or features which appear peripheral to the original aims of the experiment.

The design of future field experiments should attempt to address these issues wherever possible.

Of data sets currently in existence, the following were identified as being of particular relevance for th purposes of development and validation of CRMs. Omission of data sets from this list is not taken to impl adverse criticism.

- STORM-FEST, 1992, central USA. Continental frontal clouds (data available on CD-ROM).

- CASP-II, 1992, NW Atlantic. Maritime frontal clouds.

- ASTEX, 1992, E Atlantic/Azores. Maritime stratocumulus/cumulus transition properties and processes.

- ICE/EUCREX, 1989/1993, NW Europe. Multi-aircraft observations of cirrus microphysical properties and associated radiation fields (top-of-the-atmosphere and aircraft), synoptic-scale fields.

- FIRE-II, cirrus, 1991, central USA. As above.

- BASE, 1994, Canadian Arctic. Precipitating frontal clouds in Arctic environment, remote location, different "balances" of microphysical processes.

- FRONTS-87, FRONTS-92, 1987/1992. Mesoscale measurements of dynamical environment of cold-frontal clouds in eastern N Atlantic.

Effective exploitation of such field data usually requires in addition an accurate specification of the larger scale environment. Useful information can be provided by NWP analyses/forecasts and by satellite imagery (including microwave imagery such as SSM/I), but in some situations there is a need to enhance this with special observations (e.g. dropsondes).

4.2.3 Exchange of data sets

Although there is a general good will on the principles of making existing data sets available to the community, it is in practice a time-consuming job. In the above-listed fields experiments, different organisations and formats have been used for the data sets. For example, FRONTS87 data tapes containing microphysical measurements are available to interested users. However, the formatting is somewhat specific. TOGA-COARE data sets, on the other hand, are organised in data bases soon to be available through electronic networks.

It is recommended that data sets from future field experiments be organised as data bases. The use of WMO standard codes such as GRIB and BUFR is encouraged, especially for environmental variables such as temperature and wind.

4.3 FUTURE FIELD EXPERIMENTS AND OBSERVATIONAL PROGRAMMES

4.3.1 Future observing systems

There are many planned observing systems directly relevant to the goals of GCSS and to improving data sources for validating large-scale models. They include:

- The GEWEX sub-programme BALTEX. This will, among other things, create a data base on precipitation over the Baltic catchment area, measure surface fluxes, set up a radar network covering the area, as well as performing high-resolution (~10 km) atmospheric modelling with the goal of coupling to an oceanographic model.

- The Large-scale Atmospheric Moisture Balance of Amazonia using Data Assimilation, LAMBADA, scheduled to start in 1998. Doppler radars will provide precipitation and cloud data for the Amazon River basin. These data, in conjunction with meteorological fields from mesoscale data assimilation schemes, are expected to quantify energy and water budgets for the Amazon and their impact on large-scale atmospheric circulations.

Ground-based lidars are capable of depicting water vapour and layered clouds. Lidar development has matured and networks of these instruments will provide data of use to GCSS.

The CASH (Commercial Aviation Sensing of Humidity) programme exploits the opportunity to acquire routine measurements of relative humidity profiles in the vertical and along commercial air routes. The planned high-accuracy relative humidity measurements will improve the vertical structure information.

The plans of the space agencies promise substantial advances over the next decade; they offer numerous instruments which will contribute to the improved observation of cloud, including: improved visible/infra-red imagery (e.g. MODIS), infra-red sounders (instruments of the AIRS or IASI type) and microwave imagers (e.g. MIMR). Active instruments such as lidar and radars are also under consideration. The latter are particular interesting as they offer height-resolved profiles through clouds and quantification of cloud ice contents. A proposed satellite mission of great importance to GCSS is one that combines a lidar with a cloud-profiling radar (CPR). This is expected to provide critical information on the vertical structure of non-precipitating layers. Other proposed satellite systems include the Lightning Imaging Sensor (LIS) and Doppler Wind Lidar (DWL). In addition, the Global Positioning System (GPS) offers improved information on water vapour, both total column (from satellite-to-ground measurements) and limb-sounding profiles (from satellite-to-satellite occultation measurements).

The TRMM (Tropical Rainfall Measurement Mission) is scheduled to be launched in 1997. This will carry a radar at 3 cm wavelength in an orbit between +/- 30 deg latitude. The satellite will also be equipped with a microwave imager, visible/IR scanner, short- and long-wave radiation sensor, and a lightning imaging sensor. A TRMM follow-on mission is being planned, to carry two radars, the second being at 1 cm in order better to delineate snow. The orbital configuration of this mission will cover latitudes up to 55 or 60 degrees.

4.3.2 Field experiments

Projects planned for the future will exploit opportunities to gain further understanding of energy budgets including radiative fluxes. Special care should be taken in planning these programmes to promote multi-scale measurements so that GCM grid-scale properties are easily recovered. This can be achieved by suitable combinations of in situ measurements, and above- and below-cloud remote sensing.

Projects that have been planned with direct relevance to GCSS and that involve such strategies include:

- FASTEX (the Fronts and Atlantic Storm-Track EXperiment), planned for early 1997. This is oriented towards weather forecasting and dynamical objectives directly relevant to large-scale modelling activities. The focus of FASTEX is the life-cycle of cyclones developing over the Northern Atlantic ocean, and measurements within and upstream of cyclones will be made at several stages of development. There is a need to supplement planned observations with airborne and remote-sensing measurements of clouds and radiation.

- MCTEX (the Maritime Continental Tropical EXperiment). This joint US-Australian programme examines the dynamic forcing involved in the initiation and evolution of intense thunderstorms produced over Mannis Island (north of Darwin). An ARM (Department of Energy / Atmospheric Radiation Measurement programme) component of this study is under consideration. Here there is a need for supplementary air-borne in-situ microphysical measurements in the anvil cloud.

Other projects planned for the future and related to GCSS objectives include:

- A joint low-level Arctic cloud field programme scheduled for 1997 which will examine the surface heat and energy budgets of the Arctic (SHEBA). The field programme will be located near the ARM Arctic site to be installed in the next few years.

- The Southern Alps Experiment (SALPEX), October 1996/7, to be conducted in the New Zealand Alps. This is primarily an orographic precipitation experiment, and environmental and microphysical parameters will be measured up-wind over the ocean.

- A new decade-long programme, JACCS (JApan Cloud-Climate Study), designed to develop better parametrizations of cloud and radiation processes used in climate models.

- The GAME (GEWEX Asian Monsoon Experiment), with objectives which include understanding the role of the Asian Monsoon in the global energy and water cycles, and improving the simulation and seasonal prediction of the Asian monsoon.

4.4 CONCLUSIONS AND RECOMMENDATIONS

4.4.1 GCSS should continue to refine and develop the data requirements for extra-tropical and cirrus cloud systems (GCSS Data Blueprint documents).

4.4.2 GCSS working groups should identify case studies suitable for "intercomparison" workshops (e.g. COMPARE).

4.4.3 Research aircraft can now measure in a fairly comprehensive manner, though with limited spatial sampling, the variables needed for validating cloud models, but a greater geographical distribution of measurements is required.

4.4.4 Measurements are required to allow the characterization of microphysical and dynamical properties over scales commensurate with GCM grids (~100 x 100 km).

4.4.5 Data sets from future field experiments should be organised as data bases. The use of WMO standard codes such as GRIB and BUFR is encouraged, especially for environmental variables such as temperature and wind.

4.4.6 There is a great diversity in the literature in reporting standards for experimental cloud observations. The existence of a set of recommended reported quantities, e.g. definition of "rainband width", inclusion of melting level information, could lead to substantial improvements.

4.4.7 Encouragement should be given to cloud physics studies that generalize the climatology of ice crystal numbers and develop a theoretical basis for the ice spectrum transition in the sub-millimetre range.

4.4.8 Observations should be used to test theoretical representations of ice crystal shapes and their importance for radiative and microphysical parametrization.

4.4.9 Cloud microphysical measurements should be used to validate estimates of particle size and cloud liquid path retrieved from satellite radiance measurements.

4.4.10 Datasets giving the 3-D distribution of water vapour and cloud layering need to be obtained regionally and globally.