INTRODUCTION

The representation of convection and its associated cloud fields is recognized as a key process in numerical weather prediction at all time ranges. For seasonal prediction and climate simulation a good representation of convective processes is essential in order to model realistically the principal components of the general circulation especially in the tropics, and to enable the effective coupling of atmospheric and ocean circulation models.

As its title implies, this workshop was held to consider new insights and approaches to convective parametrization. It was jointly organized by ECMWF and the coordinators of GEWEX Cloud System Study (GCSS). GCSS is a continuing international programme which focuses on the use of very high resolution (large-eddy simulation or cloud-resolving) models to accurately simulate cloud systems thereby providing a framework for the improvement and future development of physical parametrizations for NWP and climate models. For this workshop the GCSS contribution was provided by the GCSS Working Group IV which concentrates on precipitating convective systems.

The workshop followed the usual format of invited lectures and discussions in working groups and concluded with a plenary session. Groups were set up on the topics of cloud resolving models, convection and its interaction with the boundary layer, and future ideas and directions in parametrization. The discussions and recommendations of these groups are summarized in the following three reports. The texts of the invited lecturers are also included. ECMWF thanks all the participants for their contributions to a successful workshop.

WORKING GROUP 1: CLOUD RESOLVING MODELS - THEIR VALIDATION AND USE FOR PARAMETRIZATION

1.1 INTRODUCTION

The working group reviewed the current state of the art in cloud resolving modelling and its use for the development of physical parametrizations for large-scale models with the aim of giving recommendations for future developments. In this context the group welcomes and strongly encourages the increasing collaboration between the observational, CRM, and GCM communities both at the individual level and in research programs such as GCSS and EUCREM. The recommendations are directed toward these wider communities, not just to ECMWF.

Studies carried out so far demonstrate the ability of CRMs to successfully simulate a variety of convective situations and provide useful synthetic data not available from observations that can be used in the development of parametrizations. A general strategy to link CRM and GCM development has been proposed by GCSS. It consists of

i. using CRMs to simulate convective cloud systems subjected to observed large-scale tendencies of temperature and water vapour mixing ratio,
ii. evaluating CRM predictions of the large-scale effects of convection against observational data sets, and
iii. evaluating SCMs by comparing them to observations and to domain-averaged CRM diagnostics.

This approach is strongly endorsed and ECMWF are encouraged to play an active role in its realization. The ability of the almost-explicit modelling offered by CRM's to test theoretical ideas on convection is a natural extension of this strategy which is beginning to occur and which should be similarly encouraged.

1.2 USE AND EVALUATION OF CRMs

A CRM approach that combines evolving large-scale observations with cloud scale models has shown great potential for producing realizations of tropical cloud systems and realistic cloud-scale data sets. A first and necessary step along the lines of the GCSS strategy is a thorough evaluation of the CRMs themselves.

Such evaluations have already been initiated, e.g., using independent data sources from tropical field experiments such as GATE, EMEX and TOGA COARE.

For TOGA COARE, the observational data sets include objectively-analyzed sounding data (i.e., temperature, water vapour, horizontal winds), budget-derived and radar rainfall estimates, surface turbulent and radiative fluxes from buoy measurements, and satellite measurements of cloud-top temperature, cloud amount, top-of-atmosphere radiative fluxes. For GATE, observations include gridded temperature, water vapour, and horizontal winds for an 18-day period and limited radar and satellite data, from which have been derived estimates of surface rainfall, OLR, cloud amount, and radiative heating profiles. For EMEX, comparisons have been made with radar, satellite, aircraft and sounding data. From the ARM (Atmospheric Radiation Measurement program) site in Oklahoma, USA, there are several 3-week periods for which preliminary gridded analyses are also available. Other ARM measurements include surface fluxes, precipitation, LWP and satellite measurements.

TOGA COARE has received major emphasis in CRM evaluation because of the large complement of coordinated observations (e.g., sounding, radar, satellite, aircraft) during the experiment. High quality observations are crucial to CRM evaluation; however, recent COARE workshops suggest that problems exist with some of the basic thermodynamic and wind fields that require further study. For example, boundary-layer humidities from the Vaisala sensors appear to be too dry. Work is underway to determine possible humidity corrections. Also, recent work has been completed to merge sounding and 915 MHZ profiler winds to fill gaps in omega sonde winds.

Preliminary results from a GCSS WG4 CRM intercomparison based on TOGA COARE IFA observations indicate that the bulk characteristics of the convective cloud systems are generally well represented by 2D CRM simulations. The results from various CRMs show similar temporal variations in the temperature, water vapour, cloud and mass flux profiles which are consistent with available observations. The ECMWF single column model was also run for this case. The results indicate that the CRMs are better at reproducing the observations than the limited number of SCM simulations. Additional intercomparisons are planned to investigate the effects of using corrected/improved sounding data that incorporate profiler winds and boundary-layer humidity corrections. Efforts are also underway to evaluate the effects of neglecting large-scale condensate advection.

Another GCSS WG4 intercomparison is based on aircraft data including radar and focuses on the detailed structure and evolution of an individual convective system. Simulations of this highly 3D cloud system will be used to investigate convective momentum transport. Additional GCSS cases are being considered that include more aircraft microphysical measurements and different convective regimes (e.g., shallow convection, continental convection).

Among the current and future research issues discussed were those of two-dimensional versus three-dimensional CRM simulations and the coupling of CRMs with ocean models (discussed below). Although not receiving much discussion, the representation of cloud microphysics and radiation continues to be an important issue for CRMs.

Because of the limitations of computer resources, a two-dimensional (2D) framework is usually applied in CRM studies. However, the natural situation is clearly three-dimensional (3D). The question arises to how the model results generated in 2D and 3D frameworks differ as far as the effects of cloud systems on the thermodynamic budgets, momentum transport, radiative fluxes and surface fluxes. More analyses and comparison between 2D and 3D model simulations and observations for cloud system structure are needed before drawing firm conclusions. Moreover, differences between cloud structures simulated with 3D horizontally homogeneous-initialized runs and objectively analyzed-inhomogeneous 3D runs should be made.

Current CRMs are interfaced to specified horizontally-homogeneous sea surface temperatures (SSTs). It is well known, however, that convective clouds can affect SSTs in various ways, e.g., through downdrafts, radiative/cloud-shading effects, precipitation-induced cooling and warm, fresh-water lenses. It is likely that such storm-induced anomalies in SST can alter the subsequent behaviour of cloud systems. It is urged therefore, that exploratory coupled ocean/CRM experiments be performed to evaluate the importance of such interactions for the ensemble statistics of the cloud systems.

Although measurements of area-averaged profiles of cloud- and ice-water content are not currently available, indirect evaluations of CRM-produced clouds can be made via satellite measurements of top-of-the-atmosphere radiative fluxes. Such evaluations suggest that more accurate microphysical schemes may be needed in CRMs to accurately represent the radiative effects of clouds.

1.3 CRMs AND PARAMETRIZATION DEVELOPMENT

Initial foci in the use of CRMs have been the development of new convective parametrization schemes and `narrowing uncertainties' in existing parametrizations. These are obvious uses of CRMs, which themselves are still subject to a level of uncertainty, and it appears particularly fruitful for convective parametrizations based on the mass flux approach, since the CRM's provide information, not available from observations, on the precise quantities involved in the parametrization. This methodology for testing of parametrization schemes is strongly encouraged.

Particular areas were identified where more use could be made of CRM data:

- cloud fraction, cloud water and cloud ice distributions
- updraught and downdraught properties
- convective and stratiform region characteristics
- cloud-radiation interactions
- cloud microphysics heating and cooling rates
- cloud and mesoscale momentum transports
- other effects of mesoscale processes.

These issues are particularly relevant at ECMWF, where the convective parametrization is strongly coupled to a prognostic cloud scheme and where the parametrizations are required to be valid over a wide range of resolutions, from "climate" resolutions used for ensemble and seasonal forecasting, to the operational resolution at which mesoscale systems begin to be resolved.

A second focus in the use of CRM's in the development of convective parametrizations is already beginning and offers the possibility both of major advances and the resolution of conflicting ideas on the nature and control of convection. This focus is the use of CRM's as experimental testbeds for theoretical ideas on convection and the use of CRM experiments to formulate new theories. It is a natural extension of existing collaboration between the CRM and GCM communities which also integrates the theoretical research community more fully into the process of parametrization development

Encouraging examples of this methodology were presented at the workshop and several important outstanding issues could be investigated this way:.

- the use of a mass flux formulation in the presence of falling precipitation and evaporatively driven downdraughts
- the roles of convective inhibition and other processes in the triggering of convection
- the role of mid-level relative humidity in the development of active deep convection
- conflicting closure assumptions in parametrization schemes.

A possible further use of CRM's is in sensitivity experiments designed to give information for adjoint modelling (e.g. to derive Jacobians). This was discussed and felt to be feasible: the next step is to define a strategy.

1.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Development of accurate, physically based parametrizations for GCMs will depend upon continued validation and evaluation of CRMs and establishing strong linkages between the theoretical, observational, CRM and GCM communities. CRM synthetic data need to be provided from CRM groups to those involved with the development and implementation of convective parametrizations, but the specific data requirements must be identified by GCM/theoretical groups and efficient means be set up for communication and interpretation of these data.

1. Continue cooperative programs and research activities like GCSS and EUCREM. Strongly encourage increasing involvement of observational and GCM community in these efforts.

2. Support and improve mechanisms whereby GCM/theoretical community can request and receive data from CRM groups in readable and understandable format. Examples are intercomparison fields, RMS error and other validation information, diagnosed properties of convection (e.g., cloud fraction, mass fluxes, properties of updrafts and downdrafts, etc.) and characteristics of CRM models.

3. Encourage continued evaluation of CRMs by comparison of CRM results with field data such as TOGA COARE. There is a unique opportunity to compare CRM momentum budgets with airborne Doppler radar results for specific case studies in COARE. When available, incorporate corrected and improved data sets.

4. Support further efforts to investigate data quality and determine corrections and improvements to TOGA COARE sounding data set. ECMWF re-analysis with much improved data would be welcome.

5. Extend the variety of cloud systems modelled by CRMs based on observations not used so far (e.g., shallow cloud fields, cirrus, cases over land etc). Consider using ECMWF analyses to provide the required initial and forcing fields.

6. Use idealized experimentation with CRMs both as a testbed for theoretical ideas on convection and its parametrization theories. Encourage collaboration between the theoretical, CRM and GCM communities in this process.

7. Investigate validity of cloud processes in 2D CRMs by running 3D models. Also, check the sensitivity of current CRMs to higher vertical and horizontal resolution and to the representation of microphysical and radiative processes.

WORKING GROUP 2: CONVECTION AND ITS INTERACTION WITH THE BOUNDARY LAYER

2.1 INTRODUCTION.

The working group reviewed the status of key problems in BL parametrization and the interaction with precipitating and non-precipitating convection, and made a few suggestions as to key problems where guidance from CRM's is needed. Although we would like to have a well integrated unified convection/BL scheme, which makes smooth transitions as convection evolves (dry through cumulus to stratocumulus or cumulonimbus to organised mesoscale systems), the reality is that GCM's have many separate parametrizations; one for each form or scale of convection, with consequently discontinuities and overlap problems.

2.2 MOIST BOUNDARY LAYER CONVECTION.

The fundamental difference between precipitating and non-precipitating convection is important (see Betts, these proceedings). As long as the cloud droplets are small, shallow convection can be treated as a mass-flux problem, or a convective adjustment problem. A cumulus scheme mixes conserved parameters through the cloud layer, and couples the entrainment process to the BL and surface. The biggest unsolved problems are connected to closure, and the transition between cumulus and stratocumulus.

2.2.1 **Shallow convection**

The ECMWF model has a shallow convection scheme with a rather arbitrary coupling to the boundary layer scheme and a closure that is based on moist static energy flux at the surface. The boundary layer scheme has dry entrainment at the top with no knowledge of the existence of clouds and moist convection, which leads to a potential overlap between schemes and possible double counting of transport mechanisms. However, the ECMWF convection and cloud schemes do treat liquid water/ice in a consistent way. Detrained condensate is used as a source term in the prognostic equation for cloud water.

The convection scheme closure is important because it has direct impact on the boundary layer ventilation, boundary layer equilibrium and surface evaporation. Some possible improvements are:

i Closure based on the characteristics of the whole cloud/subcloud layer. Such a closure might be based on CAPE for example.

ii. Closure based on separately considering cloud and subcloud layers. The closure must consider matching at the cloud/subcloud boundary and transports in the cloud layer.

The representation of clouds detraining in the inversion layer is important. The use of a diagnostic updraught kinetic energy to control part of this process (as it is currently done at ECMWF) is considered to be a good approach. An alternative might be to consider sub- ensembles with appropriately chosen cloud base properties.

2.2.2 **Stratocumulus**

In the ECMWF model, single layer stratocumulus clouds cannot be handled by the convection scheme, and are produced by different source terms (mixing is not represented, because we are dealing with a single layer only). Having a specific formulation for single layer clouds carries the risk, that switching from the one layer cloud formulation to the multilayer convection scheme leads to a strong dependency on vertical resolution. It is possible that a simple mass flux scheme could be constructed to represent stratocumulus in the presence of a single unstable saturated layer. The key aim here is to develop a model that makes a smooth transition from cumulus to stratocumulus.

2.2.3 A Unified Boundary Layer Scheme

The idea of constructing a Boundary Layer parametrization scheme that would somehow unify the different regimes of the dry and cloudy Boundary Layer is attractive. Three possibilities for parametrizing the sub-grid scale fluxes in a more unified scheme exist:

i. Develop a unified mass flux scheme to represent both dry boundary layer and cumulus convection. Ventilation of the boundary layer would then be performed by this scheme alone rather than by a combination of the convection scheme and boundary-layer top entrainment parametrization. At least in principle, cases of cumulus penetrating into stratocumulus (as observed during ASTEX) could also be accounted for. However, the sub-cloud layer is much less skewed than the cloud layer (e.g. Siebesma, these proceedings) and the difficulties of developing a mass flux scheme which could perform as well as a more traditional k-theory closure (across a range of conditions e.g. varying shear) was emphasized. The mass flux closure in such a scheme might use an equation (either diagnostic or even prognostic) to determine a subgrid scale updraft kinetic energy. Formulae are needed to estimate the updraught area and the entrainment/detrainment coefficients for the very different physical regimes.

ii. Shallow convection has also been parametrized using the k-diffusion approach associated with a prognostic TKE equation. However, this has been done mainly in high resolution 1D PBL models and CRM's. Also, some observational and LES studies indicate that mass-flux methods might be preferable and k-theory based shallow convection parametrization might be difficult to integrate with a mass-flux deep convection scheme.

iii. A third option would be to continue with separate schemes as at present, but with a more careful match between fluxes given by the main boundary layer scheme, the explicit boundary layer top entrainment scheme and the shallow convection scheme.

2.3 DEEP CONVECTION

The main interaction between precipitating convection and the boundary layer is through the cold unsaturated downdraughts. The following suggestions for improvements in the ECMWF model were made for the short term:

- The current parametrization of downdrafts in the ECMWF model (saturated downdrafts which are controlled by entrainment) is unrealistic, and should be replaced by unsaturated downdraughts. Observational studies on downdraught thermodynamics, and CRM diagnostics on the intensity of downdrafts as a function of shear are available, and could be used in an improved scheme (eg. *Xu and Arakawa*, 1992, JAS).
- The distinction between deep and shallow convection is based on moisture convergence in the current operational version. This should be replaced by a criterion that is more distinctive between precipitating and non-precipitating convection.
- As a first step, the effect of downdraft velocity perturbations on surface evaporation can be approximated by the introduction of subgrid velocity scale based on precipitation rate or downdraft intensities (*Jabouille and Redelsperger*, 1995).

In the longer term, it may be necessary to consider the footprint of the downdrafts in the boundary layer, because both downdraft (and updraft) air have properties that are different from the grid averaged properties. This can be done by carrying an additional variable describing the fraction of the surface layer that contains downdraft air. Such a parametrization could be developed on the basis of CRM data for a wide range of environmental conditions. This requires some recognition of convective organization.

The second interaction mechanism between boundary layer and deep convection relates to the issue of triggering. The current ECMWF scheme uses an excess temperature of 0.5 K for lifted parcels. This is seen as a random perturbation, and does not carry information about organization (e.g. downdraughts, gust fronts). In future with a better formulation of downdraughts, and perhaps information on the organization of convection, it may be possible to improve on the triggering. On the other hand, it was felt that capping inversion structures, created by the boundary layer scheme and differentially advected by the model were an important aspect of the triggering.

The diurnal cycle of convection has received little attention and could be studied with help of data from an ARM land site and with help of TOGA/COARE data which shows a pronounced diurnal cycle in the sea surface temperature during weak wind regimes.

Some study should be made of the impact of explicitly parametrizing the condensation/ evaporation couplet of mesoscale convective systems, which may not be adequately resolved in the model (Betts, these proceedings).

Anther aspect of interaction with the surface is the effect of surface heterogeneity on convection. Examples of such heterogeneity are orography, coast lines and lakes. CRM studies could shed more light on such complicated interactions.

2.4 LES/CRM STUDIES

It is important to continue doing intercomparison studies based on observations (EUCREM/GCSS) in order to test and improve the reliability of the CRMs. Additionally, CRMs should also be used to explore the behaviour GCM parametrizations across a wider range of environmental conditions.

Important parametrization issues that should be addressed by CRMs are:

i. The effect of shear and low equivalent potential temperature on the updraught/downdraught mass-fluxes
ii. The closure problem for deep convection.
iii. The trigger function for deep convection.
iv. The erosion rate of shallow clouds, which affects their lifetime and hence cloud fraction.
v. The effect of environmental conditions on the entrainment/detrainment rates.
vi. The closure problem for shallow convection.
vii. The diurnal cycle of convection over land.
viii. The cumulus/ stratocumulus transition.

It is more or less clear how to make these simulations simple enough to be able to run the CRM models for these type of cases. However, it is also clear that a good set of observations in order to perform all these simulations probably does not exist. Nonetheless CRM's could provide useful guidance.

5 RECOMMENDATIONS

Our key recommendations are in two areas.

1. There is a need to update the ECMWF BL and convection parametrizations.

   Consideration should be given to unifying the BL and shallow convection schemes. The closure and entrainment/ detrainment formulations for shallow convection should be reexamined. The closure and downdraught parametrizations for deep convection should be revised.

2. CRM studies should be formulated to address the important issues listed in (4) above, even though there may not be adequate experimental data for verification.

   Idealized simulations can provide guidance for parametrization on transports across a range of environmental conditions such as shear and equivalent potential temperature structure; as well as address closure formulation, cloud lifetime (admittedly a function of CRM microphysics), the diurnal cycle over land and the cumulus/stratocumulus transition problem.

WORKING GROUP 3: FUTURE IDEAS AND DIRECTIONS IN PARAMETRIZATION

3.1 DEFINING THE GOALS OF CUMULUS PARAMETRIZATION

From a strictly pragmatic viewpoint, parametrization seeks to represent the collective effect of sub-grid scale processes upon explicitly resolved flow in a numerical simulation. This is a well-defined exercise only when the statistics of the subgrid-scale process are well behaved as when they are uniquely related to resolved processes. This condition is seldom well satisfied in the case of moist convection and considerable care must be taken to form realistic expectations about what cumulus representations should be able to do in particular circumstances. One special problem that arises commonly is that while many forms of convection have horizontal scales considerably smaller than the horizontal resolution of forecast and climate models, their vertical extent may cover many model levels and their time scales are often longer than model time steps.

In models where horizontal grid sizes are on the order of 100 km or greater, one must represent not only individual convective cells, but a myriad of mesoscale circulations associated with convection as well. These include squall lines and other mesoscale convective systems together with their associated cold pools. For parametrization to be well-posed, we must be able to assert that the ensemble of sub-grid scale convective cloud is near some kind of statistical equilibrium with the resolved flow. The further away from equilibrium the actual systems are, the more we should expect the cumulus representation to provide us with a stochastic output, including probability distribution functions pertaining to convective heating, moistening and momentum flux. Even at this scale, it may be necessary to pass condensed water fluxes from a convection scheme to the calling model. One definite issue is how the forecaster, and the model itself, should handle stochastic output from sub-grid scale schemes.

When model horizontal grid sizes are on the order of tens of kilometres, we may be able to resolve certain mesoscale phenomena associated with convection, such as spreading cold pools and anvils. Here the goal of parametrization is to represent the fluxes by individual convective cells, while mesoscale processes should be explicitly resolved. We may reasonably ask the model to predict mesoscale phenomena such as squall lines on their intrinsic predictability time scale, provided they are properly initialized. A major issue here is coupling the convective scheme to the mesoscale dynamics. This will heavily involve, for example, the representation of condensed water flux from the convective scales to the mesoscale.

One final issue here is knowing when to quit. At what horizontal resolutions are we better off simulating convective cells explicitly, albeit crudely? This is one question that cloud-resolving models should attempt to address.

3.2 EXISTING PARAMETRIZATIONS

In recent years the value of the mass flux approach to the parametrization of the "cell scale" of convection has been recognised. However many differences exist between various schemes, in part reflecting the uncertainty in the specification of processes and parameters needed by this approach. Further work, using observations and cloud resolving model studies, should be carried out with a view to reducing such uncertainties.

Key to such schemes are the lateral mixing processes used to determine the vertical profile of cloud mass flux and other cloud properties. However interpretation of such processes is confused and understanding poor. Recent cloud resolving model studies have pointed out the inadequacy of current formulations and may hold the key for improved methods. Such studies also indicate that generally the representation of convective downdraughts is also poor, mass fluxes being weaker than in cloud resolving model simulations (although of similar magnitude to earlier observational diagnostic studies (e.g. Cheng and Yanai, 1989). Existing schemes take little account of sub-grid scale variability in generating convection (such as gust fronts), or the impact of convectively produced sub-grid scale features (e.g. cold pools produced by downdraughts) upon other processes. Consideration of such inhomogeneity may be important for determining the effects of convection, especially in cases when convective systems are well organised.

In recent years some clarification of the closure problem has been achieved, with a move away from methods relying on moisture convergence to those which determine the intensity of convection using some measure of the rate of change of instability. However, questions still remain as to the most appropriate techniques, with different methods being able to reproduce the observed "quasi-equilibrium" between various processes in a convecting atmosphere. One current question is whether it is important to include prognostic equations to provide a history of convective activity.

The use of cloud resolving models to study the bulk sensitivities of convective cloud ensembles to variations in humidity, temperature, shear and background vertical motion will provide useful insight into the ability of current convection schemes represent variations in convective activity observed in nature. One aspect in this area that requires further study is the sensitivity of convective intensity to low-level initiation as compared deep tropospheric forcing. Climatological enhancements of maritime deep convection near coastlines indicate that frequently low-level initiation is a significant factor. On the other hand, in strongly forced situations, convection invariably finds a way to begin organizing. Atmospheric variability as simulated by GCMs appears to be sensitive to the closure method; diagnostics relating to transient features are valuable in determining the suitability of a particular closure method. For example, some theoretical models of the tropical circulation, such as the Madden-Julian oscillation, are sensitive to the timescale at which convection responds to changes in its large-scale environment.

Mass transport by convection is not the whole of the cumulus parametrization problem. The formation, fallout and re-evaporation of precipitation are processes which play a large role in determining the impact of convection upon the atmosphere. Although in part these processes are coupled to convective mass transports (for example in downdraughts), they can be thought of as independent transport processes. Current representations of microphysical processes within existing convection schemes are crude and may contribute to uncertainties in the effects of convection upon the atmosphere, especially for moisture. Examples of specific areas which are affected by such processes are the magnitude of downdraught heat and moisture fluxes into the sub-cloud layer and the amount of condensate provided to the stratiform component of the system by cell scale processes, both of which affect the interaction of cloud scale convection with other key physical processes (e.g. surface fluxes, radiation and meso-scale processes). It is not clear as to what complexity of microphysical description is needed in order to capture these processes adequately.

3.3 REPRESENTATION OF THE MESOSCALE CONVECTIVE PROCESSES

It is recognised from observational and modelling studies that large extents of stratiform cloud are associated with deep convection. Recent prognostic cloud schemes (e.g. Tiedtke, 1993) with their link between the production of stratiform cloud and detrainemnt of saturated air from the cloud scale appear superfically to be able to represent such features. However upward and downward motion on meso-scales associated with such systems, driven by radiative destabilization, microphysical processes and pressure gradients (both in the vertical and horizontal), are not currently represented. It is unrealistic to expect coarse resolution GCMs (such as those used in seasonal forecasting and ensemble prediction systems) to have sufficient resolution to allow such processes to be represented adequately by the resolved dynamics and so parametrization of such motions must be included if the correct hydrological cycle of convective systems is to be represented, which take into account the balanced dynamics involved in the organisation process. Cloud resolving model studies will be valuable in determining the intensity of the mesoscale component in relation to the energy released at the cloud scale.

It is unclear what resolution large-scale models require to capture such mesoscale features. Comparison of high resolution "cloud resolving models" of idealised plumes and mesoscale forecast models would be useful in determining such a limiting resolution. This would provide insight into what is required to develop parametrizations which aim to adjust the model's flow to a current mesoscale balanced state.

If such parametrization is required, several methods might be considered. If one regards the convergence (divergence) of convective mass transfer as an effective mass source (sink), then it can be shown that this is equivalent to a sink of potential vorticity (dilution of potential vorticity substance by diabatic mass transfer in the terminology of Haynes and McIntyre, 1987). Introduction of apparent mass sources and sinks into the continuity equation of a forecast model could be used as a direct means of eliciting the dynamical response to convective updraughts/downdraughts - without introducing the notion of 'adiabatic convective warming'. Model air parcels would actually be forced downwards below a mesoscale anvil and upwards above. On top of this, the real diabatic cooling associated with evaporation of rain or snow (and melting of snow) could be treated explicitly.

Another idea would be to represent such activity in terms of a relatively low-order dynamical systems model, which would be coupled (over a range of scales) to the NWP model. A related idea would be to parametrise higher order moments of the effect of organised convective activity. However, it should be recognised that correlation functions associated with such higher order moments would extend over several adjacent grid boxes. From this point of view, any extension of current parametrization schemes (either using dynamical systems models, or high order moments) must account for horizontal non-locality, that is to say, parametrized tendencies at any gridbox G will depend on resolved tendencies at gridboxes within a neighbourhood of G.

In high resolution models (e.g . T213), such organised circulations are partially resolved. As such this may not necessarily be beneficial to the larger-scale circulation of the model. For example, if the model adjustment to convective heating occurs on too large a scale (a situation easy to envisage), then error fields associated with the misrepresentation of the organised circulation may cascade upscale to the synoptic scale flow, faster than if the organised circulation was not present at all in the model.

3.4 CONVECTIVE CONTROL OF ATMOSPHERIC WATER VAPOUR

Elementary considerations as well as single-column tests show that atmospheric water vapour content is sensitive to the representation of surface fluxes, cloud microphysical processes and cloud-radiation interaction. Single-column model studies also suggest that high vertical resolutions (at least 50 mb) are necessary to correctly predict atmospheric humidity. Coarser resolutions may result in artificial humidification of the upper troposphere, and mask the true sensitivity to cloud microphysics.

3.5 EVALUATION

3.5.1 Use of single-column models for evaluating convective parametrizations

Single-column models generally include only those processes that transfer heat, moisture and/or momentum in the vertical direction and can be useful for testing the effectiveness of model representations of such processes in isolation from other model processes such as horizontal advection. Single-column models are generally driven by actual data from atmospheric sounding networks but can also be driven (one-way) by model data.

The main processes represented in single-column models are convection, radiation and small-scale turbulent fluxes, including surface fluxes. In using single-column models to evaluate convective schemes, care must be taken to isolate problems with the convective scheme from problems with the other processes as well as problems with the data.

Data used to drive the single-column models are horizontal advections of heat and moisture and either vertical velocity or vertical advective tendencies, the former allowing the column model more opportunity to drift away from the observed state thus revealing flaws in parametrization although making comparison with observations of convection more difficult. Under some circumstances, it may be necessary to supply single-column models with horizontal advection of condensed-phase water as well. We emphasize that single-column tests will only be effective under circumstances in which the convective transports are the dominant process affecting the evolution of the column model fields. The evolution will be ineffective if, for example, the evolution is dominated by horizonal advection.

Short-range simulations (of a day or so) have been shown to be of use in evaluating convection scheme performance, although longer simulations, of at least 20 days, are probably required to investigate issues concerning the evolution of moisture in convective regimes due to the long radiative time-scales involved. We advocate using predictions of temperature, specific and relative humidity to assess the pertinence of convection schemes, as these quantities are sensitive to model parameters. Specification of "large-scale" vertical velocity is practically tantamount to specifying the net convective mass flux, Q_1 and Q_2 and therefore these quantities are less useful for evaluating the performance of the schemes, although the contribution to Q_1 and Q_2 from updraughts and downdraughts on both the cloud and meso-scale are useful for validating in detail the physical realism of schemes. Convection schemes can and should be optimized using single-column models, but evaluation of the schemes should then be performed by driving the single-column model with an independent data set, best derived under very different meteorological circumstances.

3.5.2 Process studies

In recent years, ECMWF has become involved with process studies in association with field experiments. This is clearly of mutual benefit since a range of cloud system categories has been spanned. We focus on two studies in particular.

a) *TOGA COARE*

TOGA COARE is moving into a modelling phase, although a considerable amount of field data analyses remain to be completed. The ECMWF models help set the process studies into a large-scale context and, conversely, the detailed field data improve the quality of the tropical analyses.

It is found that large (super) clusters in the tropical western Pacific (which also occur in the Indian Ocean) are being partly resolved at T213 and even T106 resolution. This relates to a fundamental issue in parametrization, namely, consequences of the grid scale being comparable to the dynamical scale of the parametrized process (i.e. mesoscales). This is unprecedented in global models.

ECMWF can contribute in several ways; for example, 1) Quantify the nature of the model errors associated with the surrogate cloud clusters; 2) investigate the impact of the assimilation of field data on the treatment of the cloud clusters; 3) quantify the impact of the resolution; 4) develop parametrizations for convectively-generated mesoscale circulations. Such studies are best conducted in unison with the cloud-resolving model approach of the GCSS.

b) *Cold air outbreaks*

There is no better example of transitions among cloud system types that occur in response to forcing (e.g. surface fluxes, radiative cloud forcing and large-scale vertical motion due to mid-latitude baroclinity) than cold air outbreaks. Parametrization schemes need to be tested, as do cloud-resolving models, over this wide range of conditions. To date there is a dearth of comprehensive data on cold air outbreaks and modelling of cloud-system transitions, and the behaviour of parametrization schemes in Lagrangian evolving situations. There is also conflicting evidence of the nature of, and reasons for, systematic errors in the presence of cold air advection. This issue encompasses basic research as well as parametrization. This is a good example of how CRMs can be used to help parametrization development, in conjunction with single-column models and observations.

3.5.3 Evaluation of convective parametrization in GCMs used for NWP and climate studies

An accurate simulation of the various time and space scales of organised tropical convection should be a fundamental requirement for forecast and climate models. Satellite observations, particularly from geostationary satellites, can provide a range of statistics on the organisation of convection and their scale interactions. These should be used routinely in the evaluation of the climate mean behaviour of forecast and climate models. These cloud statistics can be combined with dynamical quantities and fluxes from NWP analyses and reanalyses to assess the skill of the GCM in reproducing the resolved dynamical response to convection.

More detailed analysis of particular regimes should also be considered. Data from field experiments (e.g. TOGA-COARE) can be used to provide statistics on the variability of turbulent and radiative fluxes, SST response, precipitation and so on which could be used to assess whether GCM simulations (atmosphere-only and coupled) can reproduce these statistics. This approach is different, but complementary to the approach discussed above using single column and cloud resolving models, where the forcing is supplied from the observations.

It is recognised that assessment of convective activity in a 'free running' GCM cannot uniquely identify problems with the convective parametrization since it involves complex interactions between other aspects of the physical processes. However, experience suggests that convective parametrization is the dominant process which determines the tropical variability.

Closer links between CRMs, single-column models and the GCM are important. Despite considerable testing of a convective parametrization against observations using single-column models, the scheme may not perform well when implemented in the GCM. The possibility of using the large-scale forcing fields from the GCM as input to single-column and cloud resolving models should be considered.

A further possible method of evaluating the skill of cumulus parametrization now becoming viable is to test the scheme against equivalent cloud resolving simulations of the process on a two-way nested grid situated over the identical region parametrized on the outer grid. In this case, the parametrized tendencies in the inner nested area are calculated but not used. The statistically averaged tendencies of the nested cloud-resolving grid are then directly compared to estimates of the same tendencies by the parametrization. Such experiments must be followed by equivalent tests on a non-nested outer grid in order to evaluate the convective scheme's ability to drive the system evolution.

It is recognised that tropical cyclone simulation is sensitive to cumulus parametrizations. Testing of parametrizations within the tropical cyclone application should be encouraged, such systems providing a natural laboratory for simulating a variety of convective processes which are focused into a well-defined region amenable to grid nesting techniques.

3.5.4 Use of adjoint models for the evaluation of convective schemes

Convective parametrization should also be evaluated in terms of sensitivity of their response with respect to their input forcing parameters by computing their Jacobian sensitivity matrices or consideration of their adjoints. In order to better understand their behaviour and limitations, contrasted convective situations should be examined (cold air outbreaks, trade wind cumuli, deep tropical convection). CRMs and low order models (EOFs) fitted to observations could be used to represent the real sensitivity. Adjoints of convection schemes are efficient tools for optimizing tunable parameters against observed data sets, although the explicit Jacobian approach can be sufficient in research mode. In the context of numerical weather prediction, the ability of adjoint convection schemes to improve moisture analysis (particularly in the tropics) may be valuable.

3.6 RECOMMENDATIONS

1. More concerted effort should be made to rigorously evaluate representations of convection in large-scale models. This includes using single-column models and cloud-resolving models driven by observations, over periods of 10s of days, using the time-height evolution of temperature, and specific and relative humidity etc together with rainfall, Q_1, Q_2 etc. Efforts should be made to collect more data sets for driving these, with special efforts to measure upper tropospheric humidity, cloud fields and radiative fluxes. Use of techniques such as model adjoints and tangent linear models would likely prove useful in assessing the sensitivities to parameters and to the manner in which the schemes are forced.

2. We recommend that process studies be undertaken to evaluate in detail the performance of parametrization schemes. Use of 2-way grid nested techniques may be useful in this regard. We recognise that TOGA-COARE has a potential to play an important part in this and reanalysis at high resolution would be valuable. Extension to other cases (e.g. tropical cyclones, cold air outbreaks) would provide further 'laboratories' for such studies.

3. Implementation of convective parametrizations should include statistical tests of the time/space scales of organised tropical convection (as resolved by GCMs), and their associated fluxes and dynamical structures.

4. Parametrization schemes for climate model should be assessed in terms of whether they represent accurately the statistics of mesoscale organised convectively-driven circulations. Alternative methods for representing organised convectively driven scales should be explored. Nonlinear

dynamical systems theory and mass forcing techniques could play a significant role in formulating new methods. It is likely that any such method will involve horizontal non-locality.