1. Introduction

The organisation of minor symposia or workshops is a part of the Centre's research programme. The following publication contains the proceedings from a workshop on the parameterization of cumulus convection which was held at ECMWF 23 - 25 October 1978.

A realistic parameterization of the fluxes of heat, moisture and momentum due to convective processes is of primary importance for numerical weather prediction, in particular for periods beyond the first couple of days. Great attention has been devoted to this problem in recent years and the two major GARP experiments, GATE and AMTEX, have been more or less devoted to an improved understanding of this problem.

Present parameterization schemes used in numerical weather prediction and in climate simulation represent only in a crude way the convective processes and in particular the so-called deep cumulus convection, caused by the cumulonimbus clouds. Only a few attempts have been carried out to evaluate the impact of different convective schemes in weather forecasting.

An area which seems to need particular attention is the parameterization of convective processes when these are or organised in meso-scale systems smaller than a few hundred kilometers. Such convective systems are dominating features in the tropics, but as has been revealed by satellite cloud pictures recently, they are also common in certain areas at middle and high latitudes. These meso-scale eddies are mainly found in the winter time in the deep cold air masses over the oceans.

There is every reason to assume that the interaction between organised meso-scale systems and the large scale flow can be quite different than if the convective elements are randomly distributed.

In deep cumulus convection there is another feature, which needs considerable attention in the parameterization procedure. Careful observational studies as well as results from mathematical models of cumulonimbus clouds show that these deep and vigorous cloud systems can effectively transport substantial amounts of momentum, and it has been found that for certain values of the convective Richardson number an *enhancement* of the kinetic energy of the large scale flow is possible. This process is the equivalent, at least in principle, to the effect of large scale eddies on the zonal flow, and here we have obviously another example of what has been called *negative eddy viscosity*. This process is still insufficiently known and no attempt has been made to incorporate this particular effect in the parameterization of deep cumulus convection.

The present volume contains a discussion on the parameterization of cumulus convection as well as a review of our observational knowledge in this area and results from numerical experiments with cloud models. The scientific lectures presented during the workshop are included as well. The following scientists took part in the meeting:

Mr. M. Cunnington	United Kingdom
Prof. Dr. K. Fraedrich	Federal Republic of Germany
Dr. S. Lord	United States of America
Dr. M. Miller	United Kingdom
Dr. M.W. Moncrieff	United Kingdom
Dr. P. Rowntree	United Kingdom
Dr. E. Ruprecht	Federal Republic of Germany
Mrs. M. Slingo	United Kingdom

The following ECMWF staff members participated in the meeting :

Dr. L. Bengtsson
Dr. D. Burridge
Mr. J.-F. Geleyn
Dr. A. Hollingsworth
Dr. J.-F. Louis
Dr. A. Simmons
Dr. M. Tiedtke.

LIST OF ACRONYMS

AMTEX	AIR MASS TRANSFORMATION EXPERIMENT
ATEX	ATLANTIC TRADE WIND EXPERIMENT
BOMEX	BARBADOS OCEANOGRAPHIC AND METEOROLOGICAL EXPERIMENT
CISK	CONDITIONAL INSTABILITY OF THE SECOND KIND
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
FGGE	FIRST GARP GLOBAL EXPERIMENT
FSU	FLORIDA STATE UNIVERSITY (USA)
GARP	GLOBAL ATMOSPHERIC RESEARCH PROGRAM
GATE	GARP ATLANTIC TROPICAL EXPERIMENT
GFDL	GEOPHYSICAL FLUID DYNAMIC LABORATORY (NOAA)
GISS	GODDARD INSTITUTE FOR SPACE STUDIES (USA)
GCM	GENERAL CIRCULATION MODEL
ITCZ	INTER TROPICAL CONVERGENCE ZONE
NCAR	NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (USA)
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (USA)
MOUK	METEOROGICAL OFFICE OF THE UNITED KINGDOM (GB)
PBL	PLANETARY BOUNDARY LAYER
SESAME	SEVERE ENVIRONMENTAL STORMS AND MESO-SCALE EXPERIMENT
UCLA	UNIVERSITY OF CALIFORNIA AT LOS ANGELES (USA)
VIMHEX	VENEZUELAN INTERNATIONAL METEOROLOGICAL AND HYDROLOGICAL EXPERIMENT
WGNE	WORKING GROUP ON NUMERICAL EXPERIMENTATION

2. OBSERVATIONS ON CUMULUS CONVECTION

2.1. Introduction

In general, observations related to parameterization schemes can have two aims, to verify the parameterization, or to increase the understanding of the physical processes which should be parameterised, thereby improving the parameterization scheme. That means there is an interaction between the observations and the development of the parameterization methods.

Cumulus convection plays an important role in at least 3 different parameterization problems:

a) Interactions of cloud ensembles and the large-scale field.

b) Heating rates due to radiation.

c) Behaviour of the boundary layer.

2.2 Interaction of cloud ensembles and their environment

The interaction of the clouds and their large-scale environment can be described in mathematical form by the equation of the moist-static energy

$$Q_1 - Q_2 - Q_R = - \frac{(\overline{h'\omega'})}{\partial p} \qquad (1)$$

where Q_1 and Q_2 represent the sources for dry static energy and for moisture (latent heat), Q_R represents the radiative heating and $\overline{h'\omega'}$ is the sub-synoptic scale vertical flux of moist static energy. There are similar equations for the dry static energy and the specific humidity q. The right hand side of these equations gives the integral effect of all clouds of an ensemble on the heating and moistening of the large-scale environment which is the aim of the parameterization. The different parameterization schemes can be verified using these equations, since the left-hand side may be estimated from observations and the right-hand side is predicted by the cumulus parameterization.

a) large-scale parameters

The left hand side of eq.(1) describes the large-scale field. The observations from a rawinsonde ascent which provide the large-scale parameters, are often influenced by the clouds themselves. The following problems are encountered:

(1) Errors in the measurements which especially affects the divergence terms.

(2) No knowledge about the horizontal eddy transports, thus their divergence is mostly neglected.

(3) Smoothing or filtering procedure in order to exclude small-scale effects.

b) cloud-scale parameters

The right hand side of eq.(1) offers a wide range of cloud observations for verification:

(1) Cloud population

(2) Horizontal area of the clouds

(3) Vertical velocity within the updrafts

(4) Process of entrainment and detrainment

(5) Vertical profile of the cloud mass flux

(6) Cloud downdrafts (thermodynamic properties, originating level, strength, detrainment level)

2. 3. Over-view of previous results

GATE was an attempt to solve most of the above mentioned problems. A reasonable data set has been provided by this experiment from which can be derived the large-scale parameters. There are, however, some problems of the observations with the different rawinsondes. Now that the corrected data set is available, a comparison is needed to evaluate the different mathematical methods of filtering and of the computation of the divergences.

In general, however, the A/B-scale budgets which have been derived by different groups are in good agreement. The main difference is found in the derived cloud mass flux distribution. Depending on whether downdrafts are included or not, the contribution of the small cumuli changed drastically, very large mass flux occur without downdraft, small with downdrafts (Ogura and Cho, 1973; Nitta, 1977; Johnsson, 1976). Up to now it is still not clear what the effects of the downdrafts really are.

The above results are mostly based on composite studies. The GATE data set gave the opportunity to study actual cases and the time dependence of the interactions between the cloud ensemble and its large-scale environment. The cloud population for actual cases may be very different from the mean population which can be described by analytical functions (exponential or log-normal (Breuch and Ruprecht, 1977 and Lopez, 1976)).

The large-scale forcing of the development of a cloud ensemble must be studied by time-dependent parameter sets. Cho and Ogura (1974) and Johnson (1978) found a time lag between the large-scale vertical motion at 950 mb and the cloud base mass flux of deep cumulonimbus of several hours (5-18 hours). They interpret the boundary layer convergence as the large-scale forcing for the deep cumulonimbi, in agreement with CISK and also the Kuo-scheme. Lord (1978), using the Arakawa-Schubert scheme found that the thermal and moisture structure and the large-scale vertical velocity structure over the entire troposphere are the important components of the large-scale forcing for cumulus clouds.

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2.4 Thermo-dynamic interaction

Lord (1978) has shown the feasibility of using an array of rawinsonde data to verify a cumulus parameterization scheme. He applied the Arakawa-Schubert parameterization to an objectively analyzed (Thompson et al., 1978) time-series of the vertical distributions of temperature, relative humidity and horizontal winds from all ships of the B-scale and A/B-scale arrays during Phase III of GATE. The corresponding vertical velocity fields were diagnosed from the horizontal wind data using the mass continuity equation and O'Brien's (1970) scheme for adjusting the vertical p-velocity to zero at 100 mb. Lord's results show that the precipitation rates and the vertically averaged warming and drying due to cumulus clouds derived from the Arakawa-Schubert scheme are in good agreement with observed estimates derived from residuals in the large-scale budgets. However, experience has shown that the Arakawa-Schubert parameterization is quite sensitive to the large-scale vertical velocity distribution. Unsatisfactory results were obtained when the parameterization was applied to vertical velocity distributions calculated from only three of the A/B-scale ships. It appears that sufficient smoothing of the observed data, such as that performed by Thompson et al. (1978), is desirable when a sensitive cumulus parameterization scheme is being tested.

Lord's results have shown some discrepancies of the vertical distributions of cumulus warming and drying with those given by observations. It is possible that some physical effects which are not accounted for explicitly in the Arakawa-Schubert cloud ensemble model are responsible for these discrepancies. For the sake of this discussion, we mention three areas of weakness, although, of course, there are other possibilities.

First, the Arakawa-Schubert cloud ensemble model neglects the effects of downdrafts which may penetrate a large fraction of the cloud depth and may modify the subcloud layer over a substantial portion of the large-scale area. Although detrainment from the edges of clouds has been incorporated into the Arakawa-Schubert cloud ensemble model, this process does not parameterize the vertical transport effects of downdrafts nor does it take into account the possible feedback of downdrafts on the subcloud layer.

Second, the Arakawa-Schubert cloud ensemble model does not consider the effects of clouds averaged over an explicit life-cycle. It is difficult at this time to estimate the result of such considerations but they are potentially important for the cumulus parameterization problem.

Third, the Arakawa-Schubert scheme assumes that direct cloud-cloud interactions are small compared to the interactions between clouds through modification of the large-scale environment. This assumption is supported by the observational fact that the fractional area coverage of active cumulus convection is often small. However, there are instances in which shallow and deep cumuli are in close proximity and it may then be asked to what extent direct cloud-cloud interactions are important, particularly in the area of momentum transport by the convection.

It does not seem possible to answer all of these questions at the present state of observational knowledge. Some observational studies from GATE (e.g. Emmitt, 1978) have shown significant modification of the subcloud layer by downdrafts associated with cumulus convection. However, more similar studies are needed for documentation of both disturbed and undisturbed situations. In addition, direct observations of downdrafts associated with cumulus convection in the free atmosphere are needed. There are no direct observational studies on the life-cycle effects of clouds, although Cho (1977) has considered these effects in a diagnostic model.

Although considerable progress has been made, it appears very difficult to conduct direct observational studies in each of these unknown areas: downdrafts, life-cycle effects and cloud-cloud interactions. However, observational data may be used in an alternative manner for the improvement of cumulus ensemble models. The relatively standard rawinsonde data may be used as boundary conditions in a high resolution convection model which resolves the cumulus clouds explicitly. Some studies along these lines have already been performed for middle latitude cumulonimbi and for tropical squall lines - during GATE (e.g. Mansfield, 1977).

2.5 Cloud-radiation interaction

It seems likely that the interaction of cumulus convection with a cloud-modified radiation field is important in the development of tropical disturbances (Slingo, see this report), Krishnamurti et al (1978). The contrast in radiational cooling between a weather system and the surrounding cloud-free region has also been suggested as a possible explanation for the observed diurnal variation in oceanic tropical deep cumulus convection noted by Gray and Jacobson (1977).

We can separate the problem of radiative interaction with cumulus clouds into two questions: first, what effect does the presence of convective clouds have on the large-scale radiation field and, second, what is the effect of radiative processes on the development of cumulus clouds?

For the first point, the radiative schemes are now advanced enough to treat any possible input which could be provided by any of the existing parameterization schemes for the simulation of convective clouds in large-scale models. From the results of Slingo (presented at this Workshop) it appears that the area coverage ratio of high cirrus to cumulonimbus is an important parameter for the grid point radiation computations. Vertical distribution of cloud coverage within important convective systems is therefore needed (and should be sufficient to give accurate enough results) as an auxiliary output from the convective parameterization schemes. Some observational studies (to be included in more important programs) should be sufficient to verify the area coverages produced by cumulus parameterizations.

For the second point, the cooling rates at the top of convective clouds may be very large and therefore the upper part of the clouds may be destabilised by radiation. However, in the present state of the art, it appears extremely difficult and cumbersome to include this effect explicitly in models because this would mean a split of radiative effects between cloudy and non-cloudy areas; this could only be achieved with a high degree of sophistication in radiation computations if one did not want to over-simplify the geometry of the cloyd system. Therefore, one can only here think of case studies aimed at including implicitly this effect into existing parameterization schemes. Again, these studies should be supported by measurements, on a smaller scale this time, but including radiative flux observations near the individual clouds. Also, the effect of using a clear sky radiative heating profile in studies of the thermodynamic transports by convection (e.g. Yanai et al. 1973) should be considered critically.

Anyhow, because radiation will always be highly parameterized in models of any kind it is important to have strong coupling in these models between radiation and cumulus clouds, albeit only through modification of the temperature of the environment or through simplified cloud ensemble descriptions.

2.6 Boundary layer/cloudy layer interaction

The PBL provides bottom boundary conditions for the cumulus development. Three effects compete to determine the large-scale depth of the PBL: large-scale horizontal convergence, vertical eddy fluxes associated with dry convective plumes,and the effects of downdrafts and large-scale subsidence due to cumulus convection on the top of the PBL. Can they be separated?GATE data are good enough to give accurate large-scale horizontal convergence. Vertical eddy fluxes have been measured near the surface and there are some measurements of the structure of the fluxes within the PBL, but there is a lack of knowledge about what happens at the top of the PBL, especially as far as the down-drafts are concerned. The mutual interaction of large-scale, eddy flux and cumulus effects are important, however, since the height and thermo-dynamical structure of the PBL determines the onset and persistence of cumulus convection. It seems that the existing convection schemes can handle fairly well the flux of moisture and heat from the PBL into the clouds, but the flux of momentum is not well treated.

It is important to have observations of cumulus convective momentum transport across the PBL top. Vertical momentum transports affect the surface fluxes of heat and moisture since these fluxes are highly dependent on the surface wind. Certainly momentum transfer cannot be treated solely as a diffusive process, although it may often behave in that fashion. Part of the momentum transfer seems to result from energy transformations (potential or latent into kinetic) and could work in addition, and sometime in opposition to small scale diffusion.

In order to test completely a PBL parameterization scheme with respect to cumulus interactions, one would need measurements of the vertical eddy fluxes at the top of the PBL.

3. Parameterization of Cumulus Convection

3.1 General considerations

The importance of mesoscale organisation of cumulus activity for tropical dynamics has long been recognised. The distribution of systematic errors for some mid latitude forecast models (Fawcett (1969), Bengtsson, personal communication) has a large-scale structure which appears to be linked with the distribution of land and sea. Several factors contribute to these large-scale errors including, presumably, deficiencies in the treatment of air-sea interaction. This interaction in mid-latitudes is frequently mediated by cumulus convection with a marked mesoscale structure (Økland (1977)). Thus a sophisticated treatment of organised cumulus activity may be as essential for improvements in mid-latitude forecast models as for tropical models.

Most of the advances in our understanding of the interaction between convection and large scale flow has come from the study of tropical phenomena such as disturbances on the ITCZ and hurricanes. The work by many authors over the last 20 years led to great progress in understanding the complex ways in which the large-scale flow and the convection act in a mutually organising fashion. However, there remain a wide range of important problems from the scientific and from the forecasting points of view.

From the point of view of medium range forecasting for mid latitudes, it would seem that a correct treatment of convection in intense air-sea interactions is at least as important as the correct treatment of convection in equatorial disturbance, particularly as the errors in the former are likely to affect the forecasts sooner than errors in the latter.

Most studies of tropical convection have concentrated on air-flow over the oceans. This has been natural and proper as the problem is much simpler than the flow over the land. Over tropical land areas one must contend with the complex problems of monsoons, and of the strong diurnal variations in deep convective activity over Africa, the Amazon basin and Indonesia.

The significance of the diurnal variation of convection for the development of tropical disturbances has been shown in numerical experiments by Krishnamurti (1978).

3.2. Convection schemes used in large-scale models

Dry convection

Most models include a dry convective adjustment process which instantaneiously removes lapse rates exceeding the dry adiabatic. Some of the models include also vertical diffusion of heat for stable stratification as well as diffusion of momentum and moisture. A list of the schemes used in models is presented in Appendix A.

Moist convection

The schemes used in large-scale models are listed in Appendix A.

Parameterization schemes for moist convection may be defined by:

(i) The criteria for convection to occur

(ii) the nature of the grid-scale model used and

(iii) the closure conditions, or assumptions used to relate quantitatively the large-scale and subgrid-scale models.

While no attempt is being made here to discuss these differences in detail, it may be noted that only one of these schemes (Ceselski's) makes allowance for a deep downdraught as opposed to subsidence between adjacent layers and that none allow for the convective transfer of momentum.

However, a large vertical diffusion of momentum K_V 10^7 cm^2s^{-1}) is included in the NCAR model when convective precipitation is occurring, to simulate convective mixing of momentum; some versions of the MOUK schemes have been tested with convective momentum included.

Several of the schemes restrict the base of convection to the boundary layer whereas convection is observed with its roots at higher levels (e.g. during GATE as described by Simpson and Simpson (1975)). Several schemes include a low-level convergence or a similar parameter as an explicit criterion. It is not obvious that this is essential in a large-scale model because large-scale vertical motions can affect the convective process through modification of the temperature and moisture structure. However, Ceselski (1974) found that in prediction experiments, omission of such a criterion tended to produce a moisture-related disturbance.

3.3. Convection schemes used in meso-scale models

The incorporation of cumulus convection into meso-scale models causes a special problem as the resolvable scale (5 km - 50 km) overlaps with the scale of convection of deep convection and of meso-scale convection. Consequently only shallow convection (not being organized in meso-scale patterns) can be parameterized properly, whereas deep convection and meso-scale convection must be treated differently. The convection schemes used are described in Appendix B. ROSENTHAL (1978) considers cumulus convection explicitly in a model to simulate a hurricane development, neglecting subgrid scale convection, whereas ANTHES (1977) and KREITZBERG and PERKEY (1976) use parameterization schemes which compared to the schemes used in large-scale models are more sophisticated, as cloud-physical processes and lateral entrainment are included. However, none of the schemes considers the convective transfer of momentum except for ROSENTHAL's model which simulates explicitly meso-scale convection. The schemes do not consider cloud ensembles but only one type of convection (meso-scale convection or cumulonimbus).

The criteria for convection are formally the same as those for the large-scale models, either the existence of moist unstable stratification or the assumption that the rate of release of convective instability is given by the gridscale flow.

3.4. Convection Models and their use for parameterization

Some form of cloud model is central to all parameterization scheme of convective processes. These models range from simple lapse-rate adjustment to relatively complicated entraining jet models. This section of the report will attempt to summarize convection models and their applications with particular emphasis on their relevance to parameterization.

Almost all the discussion will refer to deep precipitating convection. This is deliberate and reflects the strongly held view that it is in the parametric models of cumulonimbus that existing schemes are so clearly lacking. Cumulonimbus are characterized by well-defined flows through the cloud system, both updraughts and precipitation-driven downdraughts. The convection is thus dominated by advective rather than turbulent processes with distinctive transports.

As a direct consequence of this, virtually all existing 1-D cloud models at present incorporated in parameterization schemes are unable to model the effects of large-scale vertical wind shear, pressure perturbations and downdraughts. The wind shear effectively controls the cumulonimbus dynamics and distinctly different transport laws arise. These convective regimes are characterized by a range of stabilities and wind shears. Consequently, different regimes prevail in different regions of the globe. Although more evidence is needed, it would seem that the organised cumulonimbus pertinent in this context are common in tropical latitudes, particularly over the land and in frontal and squall-line regions in higher latitudes. Observational studies to identify further the frequency of these regimes in various regions would be invaluable.

The usefulness or purpose of convection models is threefold. The first is to improve the understanding of the convection processes including dynamical mechanisms and microphysical interactions and to provide an experimental apparatus on which the sensitivity of the convection to various parameters can be tested. The second is the essentially practical use as a forecasting tool. The third is to use the model fields as a dynamically and thermodynamically consistent data set on which suitable budget analyses can be performed and interpreted parametrically. It is this latter that is most pertinent in the present context and has barely been exploited at all, either by modellers or by people with experience in observational data analysis.

The convective transports of heat, momentum and moisture in organised deep convection are dominated by cloud scale transports. The sub-cloud-scale turbulent diffusion and complex microphysics can be neglected by comparison. The transport processes are fundamentally different from those of shallow and disorganised convection. The thermodynamic transports are distinctive due to the substantial cloud scale mass transports wnich result in a cooling and drying of low level air and a warming of the upper level air. The organisation of the flow fields implicit in the models shows that deep convection can effect substantial transports of dynamical quantities such as momentum and vorticity; the work done by the pressure field is also large. Consideration of the energy budgets shows that deep convection effects a direct enhancement of the kinetic energy of the large scale flow; this is likely to be of particular significance in the tropics, where direct feedbacks are important. The main large-scale parameters which are of direct importance are the vertical shear and the convective available potential energy, in particular the relative magnitudes of these parameters expressed in convective Richardson number. Three main regimes of deep convection have been identified; for small shear a transient regime; for large shear a two-dimensional steady (mid latitude) regime is important, while in the tropics an alternative steady three-dimensional regime is predominant.

The basic transport processes have been formulated in terms of flux laws which depend on these parameters. These laws can be improved in two main ways. First, the analytic models can be refined to reproduce the effect of more realistic shallower downdraughts, while more effective use can be made of the budgets of heat, momentum, energy and moisture in fully three-dimensional simulations to give more general results.

These models have been tested against observations in the sense that general agreement has been obtained between the predicted and observed propagation speeds of the systems and also the modification effected on the large-scale momentum, heat and moisture fields. The data sets used were from experiments such as VIMHEX and GATE. It should be noted that an intensive observation network is beneficial. It is likely that data from SESAME will be very useful since this is an explicit mesoscale experiment. Detailed comparison of the internal structure of observed and simulated cloud circulations have not been made until very recently when three-dimensional data have been available.

The relationship to existing parameterization schemes is reasonably clear in the sense that the transport processes of the types considered here are excluded from the parameterization scheme of present models. In effect, existing schemes use models which bring about an environmental modification forcing adiabatic environmental descent mainly in mid levels. (The main compensation is on the large scale; this results in a warming of mid levels). The models considered here are distinctly different since the mass compensation is by cloud scale downdraughts resulting in a cooling of the lower troposphere and a warming of the upper troposphere.

Two main applications of these deep convection parameterizations are envisaged. First, the effect of convective transports on the large scale flow can be examined as a theoretical problem for idealised situations; this could take the form of a stability analysis with the nonlinear diffusion given by the analytic models included explicitly, extended to finite amplitude by a numerical model. Second, the direct inclusion in an existing large-scale or mesoscale model.

It is likely that the most useful application will be in mesoscale models where convective cells are organised into patterns. On a speculative note it will be interesting to identify if the point-by-point parameterisation is really valid in larger scale models or if the interaction between convective and large scale is through a mesoscale in the sense that the mesoscale patterns process mass, heat and moisture in a more organised manner than the point-by-point grid representations imply.

The cumulonimbus models developed by Miller and Moncrieff give cloud-scale fluxes of heat, momentum and moisture in terms of properties of the large-scale environment: wind-shear, stability and large-scale fluxes. An important feature of their models is the prediction of (predominantly counter-gradient) momentum fluxes. These may be of particular importance for large-scale models of the tropics for which modification of the mass field alone by a parameterization of convection is ineffective in modifying the wind field. Some assessment of the impact of these fluxes on the large-scale motion is thus desirable. To extend Moncrieff's analytic approach to produce a parameterization scheme for this dynamically-organised deep convection requires in the first place analytic forms for the flux of moisture and the associated rainfall. In principle no major difficulty is foreseen with regard to this. The other elements required are firstly conditions under which this scheme would be invoked, for example strong shear and marked instability, and secondly the area occupied by these storms. A scheme such as this must be regarded as only part of a complete parameterization scheme for convection and schemes for other types of convection would also be included.

Development and experimentation with this scheme could proceed along the following lines:

a) Limited-area tests over the tropics

Evaluation of the impact of the parameterization on the life cycle of an African easterly wave in which this type of convection is predominant should be a major test.

b) Limited-area studies of flow in the vicinity of cold fronts

c) Insertion in global models to assess the impact on medium-range weather forcasts and simulations of the general circulation of the atmosphere.

4. Development and testing of parameterization models

4.1. Sensitivity of forecast models to convective parameterisations

The commonly used parameterisation schemes (Appendix A) generally exclude convective mixing of momentum. Stephens et al. (1977) found, in a theoretical model, that this effect gave more realistic amplitudes for wave - CISK.. However, the MOUK tropical model has been tested with this included (Rowntree 1979). The flow fields were substantially modified by the transfer of momentum directly from low to high levels and more gradually downwards in the compensating environmental subsidence. The effects of convecting momentum at one grid point and not at the next on the vorticity fields appeared somewhat unrealistic and suggest that the more difficult approach of convecting vorticity might be more satisfactory. It was difficult to assess if the upper flow forecasts were better but the elimination of low-level westerlies due to downward transfer of easterly momentum was undesirable. However, the over-development of a wave in the west Atlantic was reduced. Rainfall patterns were considerably modified in the west Atlantic with generation of a rainfall area off the coast of South America by the third day in the run with convective mixing of momentum,which was almost absent both in the run without convective mixing of momentum and, judging by satellite pictures, in the real atmosphere.

The partial mixing between adjacent layers, when a parcel from the lower layer is buoyant when taken to the layer above, used in the MOUK during GATE, can produce a rather unstable and therefore cool atmosphere because the critical lapse rate will be less stable than the saturated adiabatic unless the lower layer is saturated. In a single column model where there is no ascent to generate saturation, a very cool atmosphere may be obtained (Rowntree 1979) . It is not clear how applicable these results are to general circulation models in which ascent will produce saturation at some points, but models in which the normal temperature structure generates convective rainfall only with a saturated atmosphere seem unlikely to give realistic predictions. The MOUK tropical model experience during GATE confirms this, the scheme giving small, slow-moving, intense convective storms, with excessive latent heating, vortical low-level inflow and upper-level outflow.

There have been several comparisons of convective schemes within models. Elsberry and Harrison (1972) compared convection schemes designed by Kuo, Rosenthal and Pearce and Riehl in a forecast of a Caribbean wave and found considerable differences in rainfall distribution; they noted that their single case was not sufficient to reach any firm conclusions.

Ohnishi and Asai (1972) compared convective adjustment and other schemes in a linearised model and noted the intermittent nature of convection with the convective adjustment schemes which tends to 'shock' the model atmosphere.

Ceselski (1973) compared several schemes in the FSU model, constructing composite profiles of temperature deviation and vertical motion relative to a Caribbean wave. Schemes due to Yamasaki with prescribed vertical heating profiles gave unrealistic temperatures. There was a wide divergence between the other schemes in the location of the maximum ascent relative to the wave's vorticity maximum, with ascent well behind the trough with convective adjustment and close to the trough with Arakawa and Kuo-type schemes. However, Ceselski did not compare the results to the observed distribution of ascent.

Miyakoda and Sirutis (1977) used a GFDL global model to compare the GFDL moist convective adjustment scheme with the Arakawa-Schubert (1974) ensemble penetrative convection scheme. They found that the latter gave less tropical rainfall than the adjustment schemes but not unrealistically so. The model's distributions of rainfall relative to Pacific waves near 7.5^{o}N were computed from 30 day forecasts with each scheme. The range of variability of rainfall through the waves was exaggerated, compared with Reed and Recker (1971)'s composite, with the convective adjustment schemes and underestimated with the Arakawa-Schubert scheme while the latter gave a more realistic location of the maximum.

The vertical profile of cumulus heating was calculated as an average for 5^{o}N over 13 days for the whole tropics; compared to the observations of (Q_1-Q_R) (apparent less radiative heat source) for the Central Pacific, shown by Yanai et al (1973), the convective adjustment gave heating at too low a level. The Arakawa-Schubert scheme was better in this respect but of less magnitude and much weaker than the observed (Q_1-Q_R). The observed apparent heat source estimates, shown by Johnson (1978) for the GATE area are generally similar in shape to, but smaller than, those shown by Yanai et al (1973); however, they still imply values of (Q_1-Q_R) substantially greater than those obtained with the Arakawa-Schubert scheme.

4.2. Diagnostic studies

One of the characteristic features of general circulation integrations from real data is that the long quasi-stationary waves tend to go through a period of adjustment in the first ten to twenty days of the integration period during which they weaken and then become re-established. The forcing for these waves is generally accepted to arise in about equal measure from the major mountain barriers and from the different thermal effects of land and ocean. It is essential that medium range forecast models be capable of maintaining the amplitude of these waves right through the forecast period. A good treatment of the convection process particularly in air sea interactions is therefore required. Much information on this area is forthcoming from the analysis of the AMTEX experiment. The AMTEX experiments covered periods of two weeks only. Efforts must be made to extract, from operational data, as much information as possible on diabatic effects over the ocean for longer periods. One possible means of doing this would be to subtract analysed fields separated by six hours in time; evaluate the tendency for each field; estimate the tendencies due to advection and so find the diabatic tendencies. Reliable estimates of total diabatic heating over large areas would enable considerable refinement in the accuracy of the cumulus parameterization.

We understand that research carried out at the University of Washington has shown success using such a technique on NMC analyses. Studies such as that just proposed would be of great value in improving convective parameterizations in mid latitudes where we have very little data on such questions as the variation of latent heat release with height in the different sections of a baroclinic wave.

As has been pointed out by many authors, the intense convection over the major monsoon areas of the tropics must have a direct interaction with the largest scales of motion in mid latitudes with time scales of a week or more. These interactions have been the object of much study for tropical forecasts. There has been relatively little study of the importance of large-scale tropical convectjon on the mid latitude flow. It would seem that some attention should be given to the analysis of the FGGE data and the Centre's forecast with this question in mind.

4.3 Comparison between observations, detailed cloud or meso-scale models, and parameterization schemes.

Parameterization of individual clouds or a cloud population (individual clouds interacting with each other within a larger meso-scale region) have been compared with the detailed numerical models and both of them with real data for a variety of conditions. Such tests seem appropriate before parameterization schemes are included into large scale models.

(i) deep convection (cumulonimbus)

One-dimensional models can hardly describe adequately the effects of pressure perturbations, vertical shear and the vertical transport of horizontal momentum, although simple formulations have been suggested (Ooyama, 1971; Fraedrich, 1974). Cloud models describing the detailed cloud evolution, dynamics and microphysics have the disadvantage that their complexity makes their incorporation into parameterization schemes difficult. Therefore, analytic models which relate the convection to the mean flow have been developed and tested (Moncrieff and Miller, 1976; Moncrieff, 1978). These idealized models retain, as far as possible, the basic dynamic processes and relate them directly to the large-scale parameters where the validity of idealized and comprehensive dynamical models have been tested against observed systems in the mid-latitudes and tropics (Betts, Grover and Moncrieff, 1976; Miller and Betts, 1977; Miller, 1978).

(ii) shallow convection (cumulus)

Sommeria (1976) has modelled a field of shallow cumulus clouds and compared it with observed turbulent fluxes (Sommeria and Lemone, 1977). Beniston (1977) used the detailed simulation of a field of shallow cumulus clouds (Sommeria and Deardorff, 1977) to verify some of the assumptions incorporated into the simpler parameterization schemes developed by Betts (1973, 1975) and Fraedrich (1977). Such a comparison can be extended to test the closure conditions and the turbulent fluxes of heat,moisture and momentum.

APPENDIX A: Convection schemes used in large-scale models

Dry convection

The dry convection schemes used in models are:

a) Smagorinsky et al (1965) - dry convective adjustment

b) Corby et al (1972) - diffusion scheme for temperature and moisture for unstable layers

c) ECMWF (1978) - convection considered by a generalised diffusion scheme for temperature, moisture and momentum

d) Miyakoda and Sirutis (1977) - Mellor-Yamada's '2½level' turbulent closure model

The schemes can be described in terms of criteria, model assumption and closure conditions as follows:

a) Smagorinsky et al (1965)

Criteria: Super adiabatic lapse rate

Model: redistribution of sensible heat with adjustment of the lapse rate to the critical lapse rate

Closure Conditions: Enthalpy conservation

b) Corby et al (1972)

Criteria: Super adiabatic lapse rate

Model: redistribution of temperature and moisture towards a less unstable state by use of a vertical diffusion scheme. The diffusion coefficients depend on lability (increasing with increasing lability) and a constant parameter is determined from single column experiments.

Closure Conditions: conservation of enthalpy and of moisture

c) ECMWF (1978, Techn. Rep. No 10)

Model: dry convective transports are considered by a generalized diffusion scheme, being applied under all possible situations. The diffusion coefficients depend on stability and vertical wind-shear. The equations applied within the free atmosphere are formally the same as those for the surface layer.

Closure
Conditions:

Conservation of enthalpy, of moisture and of momentum

d) Miyakoda and Sirutis (1977)- Mellor-Yamada's '2½ level' turbulent closure model

Model: dry convective transports are included by means of vertical diffusion of potential temperature, of moisture and of momentum.

The diffusion coefficient depend on stability, on vertical windshear and on the turbulent kinetic energy being predicted in the model.

Closure Conditions:

conservation of enthalpy, of moisture and momentum

Dry convective adjustment amounts to vertical heat diffusion with very large diffusion coefficients. The diffusion coefficient for neutral to slightly unstable situations are:

$$K \sim (10^3-10^4)\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$

in the ECMWF model. The effective valves of K obtained in the GFDL-GCM when the dry adiabatic adjustment scheme was replaced by the Mellor-Yamada scheme were

$$K \sim (10-10^4)\ \mathrm{cm}^2 \mathrm{s}^{-1}$$

Moist convection

The moist convection schemes are summarized as follows:

(a) Manabe et al. (1965)'s moist convective adjustment:- used in the GFDL model and some versions of the NCAR model. Convective adjustment is to the saturated adiabatic lapse rate, if saturated in the GFDL model, and if ascent is occurring in the NCAR model.

(b) Kuo (1974) (a development of Kuo (1965): used in the FSU model by Krishnamurti et al. (1976, 1978) and in the ECMWF - model)

(c) Arakawa (1969): used in the GISS model (Somerville et al.1974).

(d) Arakawa and Schubert (1974) (a development of Arakawa (1969) and Ooyama (1971): used in the UCLA model).

(e) Ceselski (1974) (combining features of Kuo (1965)and Arakawa (1969): used in tropical prediction experiments with the model of Krishnamurti et al. (1973)).

(f) Rowntree (1973) (version of Arakawa (1969) : used in the tropical version of the 11-layer general circulation model of the UlK. Meteorological Office (Lynne and Rowntree (1976)).

(g) Gilchrist: used in the 5-layer general circulation model of the UK Meteorological Office (Corby et al. (1976) (a development of the diffusive convection scheme of Corby et al. (1972)).

The schemes will be described below in terms of criteria, cloud model assumptions and closure conditions:

(a) Manabe et. al.(1965).

Criteria: Super-moist-adiabatic lapse rate. The definition of saturation is modified in some versions to, say, 80% relative humidity with corresponding modification of the critical lapse rate.

Model: Redistribution of heat and moisture with adjustment of the lapse rate to the appropriate critical lapse rate

Closure Conditions: Total energy conservation.

(b) Krishnamurti et al. (1976, 1978)(version of Kuo (1974)).

Criteria: Vertical structure conditionally unstable and positive, vertically integrated moisture convergence.

Model: Heating and moistening of the environment by mixing with a model cloud.

Closure Conditions: Cloud cover determined by area over which moisture convergence can generate cloud. An empirical assumption for the heat and moisture mixing coefficients, dependent on cloud cover.

(c) Arakawa (1969)

Criteria: Conditionally unstable as assessed by comparison of static energy of lower layer with saturation static energy of a higher layer.

Model: Mass-flux with entrainment and detrainment for a single cloud representing an ensemble of cumulus clouds in a statistically steady state.

Closure Conditions: Mass flux depending on a relaxation time in which convection restores stability.

(d) Arakawa and Schubert (1974)

Criteria: Conditionally unstable, solutions to closure exist (see below).

Model: Mass flux calculated assuming a spectrum of cloud sizes with entrainment rates depending on the cloud size. Cloud mass detrained when buoyancy reaches that of environment also with modification of environment by compensating mass fluxes.

Closure Conditions: The mass flux distribution over the cloud spectrum is determined by conservation of a cloud work function representing the cloud buoyancy.

(e) Ceselski (1974)

Criteria: Upward motion at 900 mb with parcel from the lowest layer buoyant at next layer up.

Model: Mass flux calculated with entrainment three possible cloud depths depending on parcel buoyancy. Environment modified by compensating mass fluxes and partial evaporation of cloud, depending on cloud cover as defined in Kuo's scheme, at detrainment level. For deep convection a direct downdraught from the middle to lower troposphere is modelled.

Closure Conditions: Initial mass flux equated to large-scale 900 mb ascent. Empirical assumptions for entrainment rates and for proportions of the deep convective downdraught assumed to be moist.

(f) Rowntree (1973)

Criteria: Parcel slightly buoyant in one layer is still buoyant in the layer above.

Model: Mass flux calculated for an ensemble of parcels with a vertical entrainment profile. The detrainment of smaller clouds at zero buoyancy is assumed to enhance the ensemble mean buoyancy;the convective depth is limited by that of an undilute parcel and by a minimum mass flux. Environment modified by compensating mass fluxes and evaporation.

Closure Conditions:	Empirical assumptions for the entrainment rate, the relation of the initial ensemble size to the vertical structure and the evaporation.

(g) Gilchrist (see Corby et al. (1977))

Criteria:	Parcel slightly buoyant in one layer is still buoyant in the layer above.
Model:	Initial mass flux with no entrainment and with detrainment determined by the parcel's buoyancy at next level. Environment modified by evaporation of precipitation and compensating mass fluxes.
Closure Conditions:	The dependence of initial mass flux on parcel bouyancy and boundary layer depth and detrainment rates determined from single column experiments.

APPENDIX B:

Convection schemes used in meso-scale models

(1) ROSENTHAL (1978)
Explicitly resolves meso-scale deep convection in a hurricane simulation experiment.
No parameterization of sub-grid scale convection.

(2) ANTHES (1977)
One dimensional cloud model used in simulation of hurricane development.

(3) KREITZBERG and PERKEY (1976)
A sequential plume model used in mid-latitude meso-scale forecast experiments.

(1) ROSENTHAL (1978)

Resolves explicitly deep meso-scale convection in a meso-scale model to simulate hurricane development.

Predicts grid-scale fields of water vapour, cloud water and rain water using Kessler's scheme for cloud physics.

(2) ANTHES (1977)

Criteria:
1. Conditionally unstable stratification.
2. Positive vertically integrated moisture convergence.

Model: Extension of the scheme by Kuo (1974); One-dimensional cloud model with entrainment to specify cloud temperature and cloud moisture.
Heating and moistening of environment by mixing with cumulus air and by convective fluxes of sensible heat and moisture.

Closure condition: Heat and moisture mixing coefficients depend on moisture distribution.
Fractional area of cloud cover is independent of height and diagnostically determined from moisture convergence rate and condensation rate.

(3) KREITZBERG and PERKEY (1976)

Criteria: Conditional unstable stratification over a minimum depth of 600m.

Model: One dimensional plume model (Lagrangian particle ascent) specifying the updraft (SIMPSON and WIGGERT model), temperature, moisture, cloud water and rain water.

Environment is changed by a sequence of plume-like clouds (rather than an ensemble). Each cloud effects the environment by subsidence and by final dissipation of the cloud and by evaporation of rain below the cloud.

Closure Condition:

Entrainment depends on cloud radius being diagnosed from mass conservation. Cloud base values of updraft and cloud radius are specified.