# INTRODUCTION

Cumulus convection in the atmosphere is one of the main energy producing mechanisms which occur at scales unresolvable by forecast models and which strongly interact with large-scale processes. The accuracy of its parameterisation becomes more crucial due to the rapid development and sophistication of numerical weather forecasting and climate modelling. Moreover, it is now evident that the large-scale circulation in the tropical areas have a strong influence on mid-latitude systems and on the general circulation as a whole. The fact that large-scale tropical systems are largely driven by convective processes emphasises the importance of the quality of convective parameterisation schemes.

The requirements of convective schemes are now much more subtle than those which existed when general circulation models were in their infancy, where the main purpose of the convection was to maintain a stable vertical profile. Modern ideas lead to refinements in formulations in order to produce a realistic cloud cover and to take into account radiation interaction and the influence of convection on boundary layer processes. However, the question of how much sophistication is necessary for convective parameterisation in medium range weather forecasting is still open. Furthermore, the relative importance of dynamic transports compared to thermodynamic transports is a very debatable point, to which no answer exists at present.

The workshop was intended to give an overview of the state of the art in the field of convection parameterisation in large-scale numerical models. This includes the various steps which lead from the design of schemes to their actual use and validation within models.

The Centre has already dedicated a major effort to the development and testing of convection schemes, as well as to theoretical approaches to the impact convection may have on the large-scale dynamics of the atmosphere. The present operational convection scheme, adapted from the "Kuo" scheme has definite shortcomings which may be overcome by present research developments and the main goal of this workshop was to evaluate and compare the various possible alternatives. Special attention was also given to the dynamical impact of diabatic processes which needs a more global approach to understanding the relationship between dynamical and thermodynamical processes.

Apart from the oral presentations, discussions were held in four sub-groups on the following topics:

1. Design of the optimal parameterisation scheme and its interaction with other physical processes.

2. Verification methods for convection schemes.

3. Impact of convection schemes on large-scale forecasts and on the climatology of GCM's.

4. Large-scale response to diabatic heating.

The following sections summarise the discussions and recommendations of these four groups. The remainder of these proceedings contain the text of the seminars presented at the workshop.

**DESIGN OF THE OPTIMAL PARAMETERISATION SCHEME AND ITS INTERACTION WITH OTHER PHYSICAL PROCESSES**

DISCUSSION

1. Current convective parameterization schemes

There are now a number of different parameterization schemes in existence and these are either presented in the literature or in the proceedings of this workshop. It is convenient to summarise the broad differences between individual schemes. Convection schemes can be classified into two types, namely those including explicit cloud models and those without explicit cloud models. This is not a unique classification, but it is a useful concept.

(a) Schemes having no explicit cloud model

(i) **Moist adiabatic adjustment method**

This is simple to implement but in its standard version it does not adjust the atmosphere to a realistic state.

(ii) **Saturation point method**

The atmosphere is adjusted to a specified profile determined from observations [Betts].

(iii) **Kuo scheme**

A basic problem which has not been overcome with this scheme is the partitioning of the heating and moistening effects. Its performance in single column and global models is not generally good, particularly with regard to the vertical structure and the very high values of convective available potential energy (CAPE) in tropical regions. The moisture convergence closure is, however, a useful physical concept, at least over tropical oceans.

(b) Schemes having explicit cloud models

These schemes use a convective mass flux concept and in principle are capable of treating dynamical transports which make the schemes more comprehensive and flexible.

(i) **Arakawa-Schubert**

Although the cloud model is simple, the ensemble concept and the closure are sources of major complication, which also lead to a computationally inefficient scheme. The dynamical transports can be included, as can downdraughts. Partitioning between overall heating and drying is reasonable, but the vertical structure of the drying is not particularly good.

(ii) **Miller-Moncrieff**

Different analytic cloud models can be incorporated depending on grid-scale properties such as CAPE and vertical shear. Both thermodynamic and dynamic processes are consistently represented, and the cloud mass flux can be directly determined from cloud models. A novelty of the scheme is that different types of momentum transport can be implemented depending on the cloud model used. Thermodynamic transports in single column models are at least as good as existing schemes but momentum transports and the impact on global integration have yet to be properly assessed [Miller and Moncrieff].

(iii) **Other schemes**

Various other methods of specifying convective mass flux, have been implemented [Rowntree, Beniston, Bougeault, Golding].

No scheme predicts cloud cover adequately and this causes major difficulties regarding cloud-radiation interaction. Also the initiation of convection in all schemes is an important problem which is poorly understood.

## 2. Interaction between convection and other processes

Convection schemes cannot be considered in isolation and their formulation must be cconsistently related to the parameterization of surface fluxes, boundary layer processes and radiative fluxes. Surface fluxes and boundary layer properties serve as input to the cloud convection which in turn feeds back on the boundary layer through downdraughts and precipitation. The radiative field plays a significant role in the development of convection, and its modification by the cloud cover may, in turn, affect the whole atmospheric dynamics.

### a) Surface forcing

The problem is to formulate surface fluxes over land and sea as input to the planetary boundary layer scheme; they form as well an important part of the input to convection schemes. At the moment almost all models use the Monin-Obukhov similarity theory which is adapted to a local description of the surface layer. Miller and Moncrieff's recent work on the simulation of GATE suggests that the present type of scheme underestimates surface heat fluxes over the ocean in the case of deep convection because it does not include the statistical effect of subgrid scale downdraughts. As fluxes averaged over a grid square of a few hundred kms side are required, account should be taken of spatial inhomogeneities of the surface and/or of the atmospheric properties.

b) Planetary boundary layer (PBL)

**(i) Undisturbed (shallow) convection**

This includes a statistically homogeneous boundary layer in equilibrium with the large-scale field such as clear air PBL, cases of small cumuli and strato-cumuli.

The problem is to formulate accurately the properties which will serve as input for the initiation of deep convection; that is mainly the height of the PBL, the moisture and heat content of the mixed layer, and the statistical properties of the possible cloud layer (fluxes at cloud base, fractional cloud cover). The estimate of the cross-isobaric flow at cloud base is another important input parameter which is linked to the vertical momentum transport within the PBL and thus to the surface stress. The formulation of all the above PBL properties is very sensitive to the vertical resolution of the model.

At the moment the PBL formulations associated with the convection schemes are valid for dry turbulent exchanges but do not allow a realistic evolution of the PBL in cases of shallow convection. They are not adapted to the initiation of convection - the PBL remains too shallow and moist before the onset of convection. New developments in this direction have been proposed in order to include turbulent exchanges within shallow cloud layers and to formulate a fractional cloud cover [Tiedtke and Manton]. A statistical treatment of subgrid clouds associated with a 1½ order closure scheme as suggested in Sommeria and Deardorff (1977) is another possible approach.

(ii) **Disturbed (deep) convection**

The PBL scheme should provide fluxes at cloud base which are compatible with the convection scheme and should take into account the feedback effect of the convection on the PBL (evaporation of precipitation, and the thermal and dynamical effect of downdraughts - all occurring at subgrid scales).

Presently, PBL parameterization schemes are used throughout the atmosphere independently from the convection scheme, although subgrid turbulent exchanges computed by the two schemes should be compatible.

A method based on the saturation point adjustment [Betts] seems promising. Another approach based on a statistical treatment of subgrid clouds similar to that used in shallow convection cases seems more problematic for deep convection.

c) Cloud-radiation interaction

At present the interactions between cumulus convection and radiation are modelled in only a minority of forecast models. Current methods, which relate cloud cover to a parameter of the convection scheme, ignore the persistence of dissipating clouds and the generation of stratiform cloud by convective areas. Use of cloud liquid water as a prognostic variable may simplify the inclusion of such effects. There are two main classes of radiative effects. The dominant one over land is the reduction of short wave radiation to the surface resulting in suppression of surface fluxes, but there is also the contrast in long-wave cooling between clear and cloudy areas which may be an important feedback over the sea. This may have an important influence on the diurnal cycle. There are, however, a number of mechanisms by which the radiation balance in the clouds themselves can feedback into the grid scale circulation.

## 3. Parameterization of mesoscale systems

Observed mesoscale systems have a length scale comparable to the model gridlength (200 km) and schemes are not at present available which specifically consider this type of problem. Representation of mesoscale organisation is likely to become more difficult as large-scale model gridlengths are reduced.

Relevant examples include:

a) Tropical cloud clusters: the convective scale updraughts and downdraughts on a scale of 10 km have completely different transport properties from the (forced) mesoscale updraughts and downdraughts on a scale of 100 km.

b) Mid-latitude fronts: the development of slantwise convection of horizontal scale 100 km can destabilise the atmosphere to smaller scale upright convection elements, so cloud-scale instability may not develop without the existence of mesoscale circulations. This may distort the development of depressions.

c) Mesoscale convective complexes: these systems, particularly over the continental US, are associated with organised convection and severe weather. The organising processes may be similar to those in tropical and cloud clusters.

d) Orographic effects: mesoscale circulations forced by sub-grid-scale orography may generate convective instability in mountainous regions.

RECOMMENDATIONS

1. Convective momentum transports should be implemented in global models and their impact on the tropical circulations investigated. There are two fundamental considerations of importance, the specification of momentum transports and the representation of vertical vorticity forcing. It is important to make the dynamic and thermodynamic transports consistent.

2. The saturation point adjustment method of Betts should be tested and compared to other schemes in global integrations.

3. Shallow convection should be included in PBL schemes by relating the turbulent fluxes to conditional instability and deriving a fractional cloud cover. Another approach worth exploring is a bulk PBL formulation which provides an estimate of the cloud base height and of sub-cloud fluxes independent of the model levels. This computation would be done in parallel with flux computations at model level.

4. The PBL scheme should be made compatible with the deep convection scheme by providing turbulent fluxes in agreement with the convective activity and by including evaporation of rain and downdraughts. Two approaches are possible, one related to a profile adjustment and the other using a statistical description of cloud properties in association with a turbulence closure scheme.

5. Cloud cover should be recognized as a necessary output of a parameterization scheme, including cumulus clouds and the extent of cirrus outflow; a prognosis of cloud liquid water may be necessary.

The nature of the interaction between clouds and radiation fields needs further study. The inclusion of cloud-top cooling directly into the representation of cloud processes rather than averaged throughout the grid-box should be considered. This is particularly relevant to the representation of stratocumulus.

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# VERIFICATION METHODS FOR CONVECTION SCHEMES

## DISCUSSION

In evaluating the quality of convection schemes it is necessary to consider model output specific to convection in addition to the standard skill scores. These are rainfall amount and distribution, thermodynamic structure produced by convection, cloud base and cloud top, cloud amount and distribution, budgets of heat, moisture and momentum, and time evolution of convective systems. Verification will have to be done locally, regionally and for specific weather systems. A thorough verification is no easy task, but several approaches were considered and problems raised.

## 1. Data base for validation

The present analysis procedure pays insufficient attention to the generated initial thermodynamic structure, and in particular the low level moisture and convective available potential energy are physically unrealistic. This causes problems in the early stages of the tropical forecasts. An important test of a convective (and boundary layer) scheme is whether it produces a realistic initial thermodynamic data set. Adjustment to observationally determined structures using saturation point techniques might be advantageous in this respect.

The analysis fields are unsuitable for verification of the thermodynamic aspects of the forecasts, partly because of the deficiencies mentioned above and partly because of the dependence of the analyses on the model generated first guess field and on the model parameterizations.

The need for a climate data base derived purely from observations (rather than an initial data set derived interactively using the model and its physics) was apparent. A regional climatology of atmospheric structure (T, q, $\underline{V}$) is not readily available at ECMWF.

The most sensitive model output which can be used to verify a convection scheme is the precipitation rate. However, one problem in verifying against observed precipitation distributions is that in extra-tropical latitudes there is a significant contribution from sloping convection. While in forecast experiments it may be possible to select only those cases where precipation is convective in origin, this is not possible in interpreting climatological data. The representation of sloping convection should be considered as a problem in its own right.

## 2. One-dimensional testing of convection schemes

All new schemes should be subject to one-dimensional testing which can reveal problems with the vertical distribution of heat and moisture. Problems with the interactions of cumulus, boundary layer and radiation schemes have been found with these tests.

The understanding and validation of cloud-scale momentum transport remains an unsolved problem. The possibility of extracting subgrid scale residuals (for mechanical forcing) from global budgets should be considered.

There is a need for additional deep and shallow convection data sets for parametric testing.

## 3. Diurnal cycle

An important test of a convection (and boundary layer) scheme is how well it reproduces the diurnal cycle. This is essential for the correct forecasting of convection in summer and over land in the tropics. The absence of a diurnal cycle in the ECMWF model presents problems in data assimilation and the verification of the temperature field.

## 4. Short-term forecasts

The evaluation of the impact of convection schemes on the short to medium range forecasts can be considered as a method of verification; two approaches are possible. The first involves comparisons of routine precipitation forecasts (or reruns of selected events) with precipitation distributions over Europe (as determined by the radar network) or over the MONEX region (as given in Krishnamurti's rainfall atlas). In the second, case-study forecasts are performed using specialised FGGE or SESAME data sets. It might be possible to improve the dynamical tendencies from analyses, leaving the model to only transport moisture. This could isolate the specific effect of convection and boundary layer schemes. If this technique is possible, it would be analogous to the way the GATE data have been used in one-dimensional models.

One striking result of the model simulations is that the differences of convection over the tropical continents and oceans are much larger than are observed in reality [Tiedtke] and the model seems to increase these differences with forecast time. This deficiency may be the result of an incorrect analysis or of a weakness in the model's physics. Convection over land is strongly forced by the diurnal cycle. Over the oceans convection is in general more organised and associated with easterly waves. It seems that the ECMWF model treats the easterly waves incorrectly; it may even ignore them.

In order to verify the analysis and the model output, various tests can and should be performed with independent data sets. The observations from space are very helpful in this sense. The parameters which can be derived from satellite observations and used for such verifications are: outgoing longwave radiation, cloud parameters (cloud cover, cloud top height, optical thickness), rainfall, and humidity fields.

5. Long-term climate studies

It is difficult to determine the usefulness of long time period model simulations (e.g. 50 days) as tests of parameterization schemes, although they do show the sensitivity of some aspects of the climatic structure to the parameterization changes. Comparisons of the long-term equilibrium thermodynamic structure with observation should be made and the model cloud and radiation fields compared with satellite data.

6. Mesoscale models

Small-scale or mesoscale models may help improve the understanding of deep convection. Certain very high resolution models have proved useful for shallow cumulus studies; in particular tests of convective flux parameterizations, cloud morphology and distribution assumptions inherent in some shallow convection schemes have already been carried out with the Sommeria/Deardorff model. Extension of these types of study to deep convection in coarser resolution models is not straightforward. However, model/atmospheric data inter-comparisons may well be easier to undertake with a mesoscale model. Hence it is probably worth trying to find ways of using mesoscale models in this context.

## RECOMMENDATIONS

1. ECMWF should produce or acquire an observational climate data set of rawinsonde data (using the full vertical resolution available) for comparison with simulated data. It might also acquire NOAA climate data sets (as used for global budget studies). It should obtain the cloud cover and radiation budget information from the ISCCP and ERBE.

2. One-dimensional testing of convection schemes should continue, including tests with interaction of cumulus, boundary layer and radiation schemes.

Additional deep and shallow convection data sets should be acquired, such as SESAME and KONTUR, as well as those from future experiments.

3. Initialization and analysis procedures should be modified to produce more realistic initial thermodynamic fields, particularly moisture, which is a crucial variable for any comparison of model features with satellite data.

4. Further comparison with observations of the long-term equilibrium thermodynamic structure and cloud fields in climate simulations should be carried out.

5. Work should continue on testing the impact of the diurnal cycle on the convection and boundary layer schemes.

6. Forecast experiments should be made to investigate the impact of convection schemes on the distribution and intensity of precipitation in short to medium-range forecasts, either over Europe or using specialised data sets, such as from MONEX, or those which may become available from experiments within ISCCP.

## IMPACT OF CONVECTION SCHEMES ON LARGE-SCALE FORECASTS AND ON THE CLIMATOLOGY OF GCM'S

### DISCUSSION

In this report we consider the impact of parameterization of cumulus convection on the behaviour of large-scale numerical models. Convection schemes interact with other processes, such as radiative transfer, boundary layer transfers of heat, moisture and momentum and surface energy exchanges. We consider the nature and extent of impacts that have been detected, and the desirable objectives for future impact studies.

The discussion is limited to time scales covering the medium- (2 to 10 days) to long-range (months to several seasons) and space scales from the macro- to planetary scales.

The impact of convection schemes on forecasts and the quasi-equilibrium state of large-scale models is considered.

### 1. Impact on medium-range forecasts

A systematic study to investigate the impact of cumulus convection on medium-range forecast has not been undertaken till now. Preliminary results are available from case studies performed at ECMWF and the UKMO (UK Met. Office). They indicate that cumulus parameterisation can have a significant impact on the forecasts in some synoptic situations. Large differences were obtained in the ECMWF forecast of the monsoon onset (June 1979) using different convection schemes; the onset was accurately predicted with the A-S (Arakawa-Schubert) scheme but not with the Kuo scheme. Also the onset of the monsoon was found to be sensitive to modifications within a scheme - for example the inclusion of the evaporation of condensates held back the monsoon onset [Rowntree]. Experiments performed at the UKMO (Rowntree and Cattle, 1983) indicate that the westward progression of African Easterly waves can be sensitive to cumulus parameterisation; they are too slow with a MCA (moist convective adjustment) scheme but improved with a PC (penetrative convection) scheme.

## 2. Impact on long-range forecasts

An impact experiment has been conducted for the monthly time-scale [Miyakoda] which appears to indicate that the two types of cumulus parameterisation (the MCA and the PC) produce substantial differences in the forecast skill score for the geopotential height at the extra-tropics, with the PC giving the best results. Also significant impacts are found in the predicted temperature in the tropics, and the precipitation distribution is better predicted by the PC scheme than the MCA scheme.

However, there are some drawbacks. The temperatures in the tropics tend to be excessively low in the forecast with the PC schemes and the amplitude of westerly waves in the summer mid-latitudes is smaller than observed (this is manifested by an appreciably reduced amount of transient eddy kinetic energy).

## 3. Sensitivity to GCM simulations

The replacement of fractional MCA by PC in the UKMO 11-layer model reduced negative temperature errors in the tropics and generated smoother rainfall distributions even in monthly means. However, the rainfall became excessive over the tropical western Pacific, though more realistic over adjacent land areas. Changes in middle latitude pressure patterns mostly appeared to be below the model's noise level.

Considerable changes have been obtained in simulations with the UKMO 11-layer model by eliminating the evaporation of convective condensates [Rowntree].

Though most of the atmosphere became much too dry, there was a warming and moistening of the boundary layer associated with decreased convective mass fluxes. Consequently, the middle and upper troposphere became generally relatively warmer with lower surface pressures, increased low level convergence and increased rainfall over the land compared to the ocean. The upper tropospheric flow, especially in the tropics and the middle latitude pressure distribution, were substantially changed.

Donner, Kuo and Pitcher have carried out an experiment to study the role of deep convection in the maintenance of the mean circulation by adding a Kuo-scheme to a model using a MCA scheme. The main result was a warming of the upper troposphere with a weakening of the Hadley cell due to an increase in stability.

The role of cumulus friction in the large-scale dynamics has been investigated by Helfand (1979). The angular momentum budget was significantly changed, and in response the meridional flow was also modified with a strengthening of the winter Hadley circulation.

Experiments at ECMWF [Tiedtke] with the MCA, A-S and Kuo convection schemes, show a strong sensitivity of the zonal mean and zonally asymmetric flow to cumulus parameterization. The PC schemes produced a colder tropical and subtropical atmosphere, weaker Hadley and Walker circulations, reduced precipitation over the tropical continents and western Pacific, but more rain along the east Pacific and Atlantic ITCZ. Introduction of shallow convection increased the depth of the moist boundary layer in the trade wind regions, and this in turn had a significant effect on the hydrological cycle in the tropics and on the extra-tropical flow.

The effect of cumulus convection through cloud-radiation interactions has a major effect on the zonal asymmetry of heat sources and the associated forced circulations and the hydrological cycle over land [Le Treut, Tiedtke].

## 4. Impact on the initial condition

The cumulus parameterisation appears to affect appreciably the vertical velocity in the tropics and therefore both the velocity potential and moisture fields in the 4-dimensional data assimilation. Although it is undesirable, at present the initial condition for forecasts are influenced by the cumulus convection schemes used in the GCM , especially in the tropics where there is a sparse network of wind observations.

Convective processes depend strongly on the temperature and humidity structures so it is important that these be adequately analysed. This is particularly difficult to achieve for the humidity field which can have a major impact, as found in the UKMO tropical model when 70% relative humidity was imposed everywhere (Rowntree, 1979). Other experiments with the same model have shown large impacts of the temperature and surface pressure analyses on the large-scale divergent flow, and hence on the predicted convective precipitation (Rowntree and Cattle, 1983).

## 5. Summary

The evaluation of the major deficiencies of the convection parameterization schemes seems to be related to the performance of the different GCMs and the interaction between various physical parameterizations.

Many aspects of the impact of these schemes are not yet fully understood and need further investigations. However, some conclusions about the major outstanding deficiencies seem to be possible from the results obtained so far.

a) The use of PC schemes generally produces a zonal mean thermal state which is colder than the observed values. Some of the experiments have also shown that some schemes (Kuo, A-S) decrease the intensity of the Hadley and Walker circulations.

b) A misrepresentation of the moisture supply in the subtropics is a common feature of various schemes.

c) A major problem occurs due to the fact that the schemes in use have been designed to represent deep cumulus convection and thereby misrepresent the impact of shallow convection.

d) Since sensitivity studies indicate that the interaction between radiation and cumulus clouds plays a role of similar importance to the convection scheme itself, there is a need for a better assessment of convective cloud cover.

RECOMMENDATIONS

1. Convection schemes are currently implemented to represent sub-grid-scale processes. As the grid-scale of forecast models approaches the size of mesoscale convection, it is clear that the decoupling of resolved and parameterized effects becomes ambiguous. Future impact studies should consider the interaction between grid resolution (both horizontal and vertical) and convection schemes. An ideal convection scheme should adjust to differing grid resolutions.

2. Some studies suggest that the large-scale momentum balance in both tropical and extra-tropical regions is approximately in a local steady state. Convection schemes generally do not attempt to maintain such a balance. Other studies imply that cumulus friction significantly affects the tropical circulation. Impact studies should therefore seek to determine the effects of convection schemes on the momentum and kinetic energy budgets in large-scale models; in particular, the partition of the large-scale response between gravity and planetary waves should be studied.

3. Although the greatest impact of convection schemes is found to be in the tropics, extra-tropical effects have been detected in some large-scale studies. Future studies should determine whether extra-tropical effects of convection are caused directly, or by the propagation of disturbances from the tropics.

4. Because the short-term behaviour of numerical models is sensitive to the initial moisture field, and because convection schemes are largely controlled by the moisture field, it is important to ensure that the humidity structure of the atmosphere (particularly in the tropics) is accurately analysed and initialized.

5. A systematic study should be undertaken to study the sensitivity of medium-range forecasts to convection parameterizations in a variety of synoptic and seasonal situations. It should compare the impacts of convection schemes based on different physical assumptions, with particular attention to the large-scale dynamical response.

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## LARGE SCALE DYNAMICAL RESPONSE TO DIABATIC HEATING

### DISCUSSION

### 1. Diabatic heating and model systematic biases

The diabatic processes of latent and radiative heating, and of turbulent transfers play a major role in determining the character of large-scale atmospheric flow. Quite apart from their fundamental driving of the mean zonal circulation of the atmosphere, diabatic processes force a significant part of the large-scale stationary wave motion in the troposphere. They may modify, sometimes substantially, the baroclinic wave motion of extra-tropical latitudes, and are of profound importance in the life cycles of tropical disturbances. As such, deficiencies in diabatic heating may be responsible for a wide range of systematic errors seen in the performance of the ECMWF forecast models, and indeed of prediction and climate models in general.

Understanding of the large-scale response to steady tropical forcing has advanced significantly in recent years, and provides a basis for the diagnosis of a number of model errors. In particular, the idealized models presented by Gill at this workshop provide a description of the tropical response to localized forcing in good agreement with the observed relationship between cloud and flow patterns, and they also may be used to suggest the source of a number of deficiencies in tropical flow simulations of the ECMWF model. Studies of the extratropical response to tropical forcing have been reported by Simmons in previous workshops on tropical meteorology (1981) and the intercomparisons of large-scale models (1982). It is difficult to draw quantitative conclusions from these studies, but results have proved useful in the interpretation of some prediction experiments.

Examination of mean day-10 forecast errors in stream function and velocity potential shows the largest errors to occur in the tropics. A major deficiency which has previously been discussed, and which is still very evident in results for the most recent (northern hemisphere) winter, is a tendency for the model not to maintain the two distinct centres at 200 mb in velocity potential over Africa and South America, but rather to develop a pronounced wavenumber one pattern, with predominant divergence over Indonesia. This and other features point to substantial errors in the model's diabatic forcing of the largest scale tropical circulations. The closure assumptions which ignore some important dynamical effects may contribute to this problem [Cho, Miller and Moncrieff].

Errors of a more local nature can also be found. Some marked deficiencies in the simulation of the Asian summer monsoon have been traced to erroneous diabatic heating associated with unrealistic surface or initial conditions; this is exacerbated by a tendency for convective heating to generate a balancing vertical motion and circulation anomaly, rather than rapid stabilization of the atmosphere [Wergen].

Sensitivity of the extratropical stationary waves to the model orography has been discussed by Wallace et al. (1983). However, it was not clear from this study if diabatic forcing, particularly from the tropics and subtropics, could be ruled out as a source of error- therefore there is a danger of tuning the orography to compensate for such errors. Also it has been demonstrated that the mean circulation is sensitive to the treatment of diabatic processes [Miyakoda, Tiedtke].

A number of changes are planned for the Centre's operational model which are expected to affect some of the above deficiencies. Notable are the introduction of a diurnal cycle, a representation of shallow convection, and a modified radiation scheme. It is thus important to reassess the performance of the model once all relevant changes have become established.

Examination of a series of ECMWF forecasts for middle latitudes reveals some characteristic deficiencies in the treatment of transient extratropical waves. The over-development which characterised early forecasts appears to have been controlled by changes already introduced into the parameterization schemes, and other improvements in phase speed and track are likely to have resulted from the change to a spectral model with envelope orography in April, 1983. Despite this, a number of questions raised during preceding workshops are worth repeating:

> To what extent is the erroneous treatment of transient waves a direct consequence of an inaccurate representation of latent heat release, surface fluxes and cloud/radiation interaction? How sensitive is the baroclinic wave development to the erroneous distribution of static stability which arises during the course of the forecasts? Does the misrepresentation of baroclinic-wave activity contribute significantly to the zonal-flow and stationary-wave error in the model, for example through a lack of decay by diabatic processes and consequent anomalous increase of barotropic decay? Conversely, do features such as the spurious eastward penetration of systems reflect a deficient zonal-mean flow and standing-wave pattern which has arisen because of deficient diabatic forcing? Does a lack of new developments result from an inaccurate representation of pre-existing mature systems or from an inadequate diabatic trigger, for instance, convection on trailing cold fronts? How important are tropical influences, either through an effect on the equatorward limits of deep mid-latitude troughs, or through a direct movement of tropical disturbances into middle latitudes?

Although partial answers to some of these questions have been given by recent work, much remains to be done. A particular need is for detailed case studies of baroclinic wave behaviour, with diagnosis of the wave structure and diabatic heating performed for both analyses and forecasts for cases in which erroneous wave development or decay is evident. Sensitivity studies should follow in conjunction with idealised experiments on the life cycle of baroclinic waves when parameterized processes are included.

## 2. Synoptic features in the tropics

One of the most striking deficiencies of the long-term simulations of the tropical atmosphere in the ECMWF model is the near absence of an ITCZ over the Atlantic and East Pacific Oceans. The convection occurs mainly over the tropical continents and predominantly over Indonesia. These features of the model's atmosphere are probably closely connected with the deficiencies in the forecasts discussed above.

It is known from observational studies and theoretical studies that the propagating cloud clusters are essential contributors to the time mean convection field over the oceans. These features are not found in the long-term integrations, and their absence may well be an important reason for the weakness of the convection over part of the ocean (i.e. tropical east Atlantic). It seems important to investigate the treatment of these propagating oceanic disturbances in the model. A sensible starting point would be a synoptic survey of the behaviour of these disturbances in the early stages of the forecasts. Such a survey would seek to identify systematic deficiencies in the structure, propagation characteristics, and dynamical environment of the disturbances.

Assuming that systematic deficiencies can be identified in this way, it would be illuminating to do case studies of the forecasts of individual disturbances. These could be done with a limited area model to test the effect of resolution; one would also like to study the sensitivity to alternative physical parameterizations, and indeed to errors in the initial data. Such studies would give a much clearer appreciation than is currently available on the sensitivity of these systems to the different components of the forecast system. In this respect, it is important that the parameterization schemes for the limited area model be compatible with those of the Centre's global operational model.

If resources permit, the synoptic survey should also consider some of the other important synoptic systems of the tropics such as cold surges in the winter monsoon, and the tropical depressions of the summer monsoon. Case studies and idealised studies of these phenomena would probably be very valuable in identifying model deficiencies.

## 3. Momentum transports by convective systems

The efficiency of diabatic forcing increases with increasing horizontal scale, decreasing vertical scale, increasing latitude and decreasing static stability [Wergen]. On small vertical scales, horizontally large scale diabatic forcing is the dominant factor. This result agrees well with experiments described by Tiedtke, who showed that the incorporation of shallow convection is an important factor in atmospheric simulations. On the other hand, barotropic synoptic scale structures are most influenced by mechanical forcing, especially in the tropics. There is, however, an intermediate domain, where mechanical and thermal forcing are roughly equivalent. Therefore, besides reviewing the different parameterizations for mechanical and thermal forcing with respect to their spectral efficiency, it seems important to develop cumulus parameterization schemes which include the thermodynamic and dynamic sources in a consistent manner. Observational studies show that the heat sources tend to spin up the rotational flow associated with a cloud cluster while the vorticity sources tend to spin it down.

The effect of cumulus on the large scale vorticity field has been diagnosed using data from the Marshall Islands (Yanai and Nitta, 1967; Reed and Johnson, 1974; Reprecht and Gray, 1976; Chu et al, 1981) and GATE (Shapiro and Stevens, 1980; Cho et al, 1981). In these studies, the cloud effect, called the apparent vorticity source, is determined from the observed synoptic scale wind field and its time tendencies as a residual in the large-scale vorticity equation. Despite the natural problems of data accuracy, results from these studies are quite consistent with one another. The magnitude of cloud forcing on the vorticity field was found to be the order of $10^{-10}$ $s^{-2}$ which is comparable to that due to horizontal advection by the mean flow. It should be noted that all of these studies were made for synoptic scale disturbances.

Theoretical studies to derive parameterization schemes for the cloud effect on the momentum field have already been made. There are some differences in the basic assumptions being made. In Reed and Johnson's (1974) formulation only eddy vertical advection of vorticity was assumed to be important in the mean vorticity equation. At the cloud scale, vertical advection of cloud vorticity was assumed to be balanced by horizontal convergence. No tilting effect was considered. In the formulation proposed by Shapiro and Stevens (1980) and Yanai et al (1982), both the eddy tilting of vorticity and the eddy vertical advection were included. In the formulation proposed by Cho et al (1979) and Cho and Cheng (1980), the horizontal eddy flux of vorticity was considered in addition to the vertical eddy advection and tilting.

RECOMMENDATIONS

1. To re-assess the performance and climatology of the model after all the imminent changes in the analysis and model (new structure function, diurnal cycle, shallow convection, revised Kuo scheme, etc.) have been introduced.

2. To pursue more detailed study of the transient disturbances on the ITCZ and in the monsoons. These studies should cover:

   a. synoptic survey of model performance by an experienced tropical synoptician;

   b. case studies of forecasts;

   c. verification of analyses, implied diabatic forcing fields, and forecasts against satellite data.

3. To study the relative effectiveness of thermal and mechanical forcing by convective systems on the large-scale flow, especially once momentum and vorticity transports have been included in the convection scheme. This should also make use of estimates of apparent vorticity sources derived by residual techniques from observational data.

4. To encourage simplified model studies - for example, two dimensional studies (zonally symmetric) of the Hadley cell with various convection schemes, or three-dimensional idealized studies of the Hadley cell and superimposed easterly wave.

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