INTRODUCTION

As the forecast length increases, the importance of the diabatic processes in numerical weather prediction models is such as to eventually dominate the forecast quality and 'climate' of a model. The parametrization of these subgridscale processes (such as radiation, turbulent transports, convection and gravity wave drag) in terms of parameters derived from the resolved scale fields of wind, temperature, etc. is a very difficult task, and progress in this, perhaps more than in most fields, can only be achieved by concerted studies based on observations, models and theory.

For this workshop held on 30 November - 2 December 1987, scientists with expertise in different disciplines came together to discuss aspects of parametrization and to make recommendations for future research at ECMWF. The workshop was arranged in the usual way, starting with presentations on recent research, followed by discussions in three groups and finally a plenary discussion.

Since data are extremely important for the design and verification of parametrization schemes, considerable time was spent on the discussion of data aspects, and the use of observational data sets was encouraged. Moreover, the Centre was strongly advised to pursue methods for diagnosing deficiencies in diabatic forcing using the Centre's data base including the new technique recently developed at the Centre. The existence of typical equilibrium/ neutrality states should also be verified.

Diabatic processes were discussed individually. In view of the importance of tropical forcing for the general circulation, the parametrization of the tropical boundary layer under convective situations was particularly stressed. The Centre was further encouraged to base parametrizations on physically sound concepts. The current treatment of clouds was cited as an example of an ad hoc approach.

During the discussions of systematic model errors it was reaffirmed that the errors encountered in our forecasts are common to other models as well. However, connections to defects in parametrization can still not be made conclusively.

A common model deficiency is to underestimate low frequency variability such as the transition to blocked states over the Pacific and North Atlantic. In this regard, it was recommended that the rôle of diabatic heating be studied by budget calculations for anomalous circulation regimes. In addition, "relaxation" experiments, in which, for example, the tropics are prescribed, should be carried out.

Overall, the workshop was very stimulating and will certainly have an impact on the Centre's future research.

ECMWF WORKSHOP ON DIABATIC FORCING
30 November - 2 December 1987

Report of Working Group 1

1. DIABATIC FORCING IN LARGE SCALE MODELS: DESCRIPTION OF DEFICIENCIES, AND RECOMMENDATIONS

1.1 Introduction

Among the most problematic aspects of large scale numerical models are the numerous parametrizations of sub-grid scale processes that are required both to represent actual small scale physical processes and, in some instances, to provide for numerical stability. Some of these parametrizations (e.g. radiation) rest on fairly solid physical arguments while others (e.g. horizontal diffusion) are almost entirely ad hoc. These representations invariably contain adjustable parameters which are often poorly known either because observational evidence of their proper value is lacking or because they are not directly comparable with data. The immediate problem is the engineering problem of tuning the parameters to produce the best forecasts. However in the longer range we are interested in the more scientific problem of determining the parameters on physical grounds, where that is possible, and replacing ad hoc representations with physically based ones as our understanding matures. In either case we wish to apply diagnostic tests of models that unambiguously show the dependence of model calculations on the various parameters and for this purpose it is crucial that the output of the schemes be in a form that can be compared directly to observations.

The purpose of this report is to outline what we feel are the most serious deficiencies of physical parametrizations of diabatic processes in present models and to suggest which physical processes that are currently neglected altogether might be profitably represented. In the course of doing so we desire to bring to the attention of theoreticians and experimentalists those physical processes of which a better understanding would most likely improve numerical forecasts, and to suggest diagnostic tests of the model that would help us to further understand the nature of the model deficiencies.

In this section we shall deliberately avoid discussing those physical parametrizations which we feel are relatively well handled, such as large scale rain.

We begin by describing the diagnosed deficiencies of several contemporary operational numerical models. We then turn to a description of the most problematic sub-grid scale representations and discuss means by which they might be improved.

1.2 SYSTEMATIC ERRORS IN MODELS

The following table provides a summary of systematic errors, which parametrizations they are sensitive to and in which models they have been found. The errors may also be sensitive to formulation of dynamics but this is not mentioned in this table.

Systematic model error	Known to be directly sensitive to parametrization of	Error is found in model of
Poleward and upward shift of subtropical jets	Convection, momentum fluxes**	most centres*
Excessive easterlies in upper tropical troposphere	Convection, momentum fluxes	most centres
Upper branch of Hadley circulation too weak and spread over too many layers	Convection (knowledge of truth)	most centres
Cooling of mid-troposphere	Convection radiation cloud levels	UK 15L NMC at 700
Too cold and too moist tropical and subtropical boundary layer	Shallow convection	French EC before May 1985
Zonalization of mean mid-latitude circulation, i.e. too weak diffluent flow over Europe and Northern Pacific and dipole pattern of 500 mb height error.	Momentum fluxes radiation in stratosp.	Most centres
Weakening of trade winds	Convection	EC, NMC
Weakening of divergent mean flow over main tropical convection areas in connection with reduced precipitation	Convection radiation	EC, NMC not UK11L in winter
Overestimation of ITCZ in eastern Pacific	?	EC, NMC, UK
Increase of eddy momentum flux together with increased tilting of troughs and ridges	?	Most centres, except low resolution models
Siberian anti-cyclone not developed enough	?	UK 11L
Weakening of transients in mid-latitudes	Momentum fluxes (envelope orography)	EC, GFDL NMC
Weakening of transients in tropics	Convection momentum fluxes	EC
Lack of variability of standing waves from month to month (too small low frequency variability)	?	EC, NMC
Western Europe too cold after a blocking	?	UK
Inability of forecasting blockings more than 5 days ahead	?	EC, UK
Insensitivity of model to tropical SST anomalies	?	EC, others less severe, not UK 11L
To many low clouds over winter continents and over the poles, it makes snow linger	Boundary layer explicit representation of cloud water/ice	UK 11L
Too much precipitation over tropical oceans and too little over tropical continents in northern hemisphere summer	Cloud/radiation	UK 11L
Too great contrasts between wet and dry areas	?	UK 11L
Too few clouds over subtropical anticyclones	Boundary layer explicit representation of cloud water	UK 11L

*most means all known except those where the error is not applicable i.e. tropical errors in hemispheric models

**momentum fluxes including gravity waves, vertical+horizontal diffusion, and mountain blocking

1.3 Convective parametrizations

Virtually everything in large scale models is sensitive to convection and it is therefore crucial to represent it properly.

Many poorly understood aspects of the cumulus parametrization problem remain thorns in the side of numerical modellers. Perhaps the only aspect on which there is general agreement is that in the tropics deep convection tends to adjust the atmospheric virtual temperature to a virtual moist adiabat on relatively short time scales. Which adiabat depends crucially on the partitioning between moistening and heating and virtually all parametrization schemes contain fairly ad hoc treatments of this partitioning. Since the relevant virtual moist adiabat represents the moist entropy content of the sub-cloud layer, the partitioning also has a strong effect on this quantity. Herein lies an opportunity: by comparing the model's lowest level moist entropy to observations, one can hope to assess the performance of the convective scheme, provided one is confident that surface fluxes are being handled well (see Section 5). Better ways of representing the partitioning between moistening and heating are badly needed, as models are quite sensitive to this parameter.

Evaporation of rain and the production of low entropy downdrafts that penetrate the sub-cloud layer are effects which are poorly understood and which, where attempts have been made to represent them, noticeably affect the model fields. Carefully thought-out experiments with detailed cloud models might suggest avenues by which these effects could be usefully represented in large scale models.

We should like to point out that certain kinds of comparisons may be misleading in diagnosing the effectiveness of cumulus parametrization schemes. In the tropics, the observed close link between the boundary layer moist entropy and the free atmosphere virtual moist adiabat puts strong constraints on the heating profile. If this is properly built into a cumulus parametrization scheme then the vertical profile of heating is strictly determined by the environmental vertical velocity and radiational cooling, so that diagnosis of heating profiles is more informative about the large scale dynamics than about the effectiveness of the cumulus representation. Once again, however, the observed partitioning between heating and moistening is a useful measure of the all important precipitation efficiency parameter in this representation.

Dynamical transports by convection remain a difficult and poorly understood component of diabatic forcing on atmospheric motions of all scales.

While there is clear evidence that individual convective circulations can transport momentum both up and down the vertical shear and also through horizontal fluxes, the evidence for the importance of this process on larger scales i.e. in the context of NWP on general circulation modelling is much less clear. Indeed, there is no clear agreement on this from data studies. More disturbing is the cavalier way in which this process is parametrized by some convection schemes. While great care is taken to verify the thermodynamic transports of each scheme using single-column data sets etc., no attempt is generally made to do this for the momentum transports, clearly highly unsatisfactory and at odds with good scientific method. This 'suck it and see' approach is potentially dangerous and at worst disastrous in introducing compensating errors into the models physics.

The efficiency of vorticity or potential vorticity transports is even more dubious and a source of controversy in the literature.

Progress in representing these dynamical convective transports clearly hinges on better diagnostics of observational data, not 'ad hoc' model experiments.

1.4 Sub-grid scale transport in the free atmosphere

This is a rather controversial and possibly critical area. Sub-grid scale transports of heat, moisture and especially momentum cannot be neglected in the models if they occur in nature to a significant extent. However we are not sure about that point. Nevertheless, the dynamical "truncation" problem of itself requires the existence of a certain amount of dissipation essentially in the horizontal, but perhaps also in the vertical. Furthermore, although the problem is a three dimensional one, technical constraints force us to treat it as two separate processes. Over- (or under-) estimation in either area will have consequences on both horizontal and vertical gradients in the model. It might even be that one could get the right amount of dissipation through the wrong process.

The only two points that can be made with confidence are the following:

- In the case of dry static instability vigorous vertical exchange should be modelled to avoid numerical instability and to mimic the so-called dry convective adjustment; this can usefully be done as an extension of a PBL scheme like that used by ECMWF.

- In the case of dry static stability the dissipation given by the actual ECMWF scheme is almost certainly overestimated. This should probably be reduced to the lowest level compatible with a reasonable control of noise.

Theoretical work should address the best way to split the 3-D problem into vertical and horizontal parts and how to eliminate the arbitrariness of present assumptions. Comparison with higher order closure models with special attention devoted not only to the PBL but to the free atmosphere is certainly a potential tool for that. However implementation of such schemes require that vertical resolution is adequate to allow for correct estimates of various source and sink terms, particularly the counter gradient fluxes.

Further diagnostic budget studies of the overall dissipation rate are required in order to provide modellers with a clearly defined goal.

The sub-grid scale transport parametrization may have to distinguish between horizontal diffusion necessary to avoid spurious waves, and the effect of sub-grid scale transports inside the grid box on the mean flow at the resolved scale. Part of the horizontal diffusion possibly should be treated in physical space to account for the fluid deformation rather than entirely in spectral space as in the current ECMWF model. Diabatic processes may occasionally lead to regions of inertial instability in real and in model atmospheres. As inertial instability is of very small scale, it might be worth developing simple schemes of 'inertial adjustment' which prevent the formation of regimes of negative absolute vorticity. Similarly, dry 'slantwise' adjustment may occasionally be called for in regions where potential vorticity is tending to become negative.

1.5 Surface fluxes

Surface fluxes are a primary source of heat and moisture for the atmosphere, and are important factors in the development and life-time of baroclinic disturbances and in generating non-homogeneous boundary layers. The surface fluxes interact strongly with convection. Momentum fluxes at the surface can be considered as the first source and the ultimate sink of momentum for the atmosphere. They interact with gravity wave motions in stratified rotating flows and should adjust to the total diabatic heating globally. Restricting our attention to models with physically based surface flux parametrizations (e.g. Monin-Obukhov similarity theory, explicit diurnal cycle and stability dependent drag), the disposable parameters are the roughness lengths for momentum, heat and moisture. Their specification is still largely empirical, but NWPMs and GCMs are sensitive to them, though marginally in the sense that modest variations in the PBL flow are sufficient to reestablish the surface fluxes corresponding to the model "needs".

Certainly, field experiments to study the momentum, heat and moisture budgets of the PBL in perturbed situations (e.g., over warm seas cyclones tracks, polar seas, in the trades and in deep convection areas) are required, especially over the oceans (HAPEX-MOBILY looks promising in studying some aspects of the PBL over land).

Specific attention should be paid to the surface fluxes when building relevant PBL diagnostics in order to yield a further in-depth understanding of the interaction between the PBL and baroclinic disturbances or convection. This will be of crucial importance for those phenomena which are almost entirely driven by surface fluxes, like tropical hurricanes.

Another important aspect in which surface fluxes have to play a rôle is the apparent lack of momentum extraction in the lower part of the atmosphere over mountainous areas. This significant defect can be related to problems in pressure gradient term estimates and horizontal diffusion of vorticity and divergence for the dynamical, surface frictional stress and low level drag and influence of envelope orography for the physical part of the model.

An effort should be made to rationalize, if not unify, the description and the parametrization of the various aspects of the interaction between the PBL flow and the orography. Specific emphasis should be placed on the coupling between frictional stress and low-level drag.

1.6 Radiation

Despite the fact that radiation has longer large scale time constants than other diabatic processes, it should be stressed that its importance in diabatic forcing lies in the difference between radiative and radiative-convective equilibrium profiles. The speed at which the model tends to go from one to the other seems to be a robust and important controlling parameter for the large scale flow. Indeed, several medium range studies of interactive vs. non-interactive radiative forcing substantiate this point.

One can obviously split the radiative problem into two: computation of clear sky fluxes and extension of the techniques to cloudy atmospheres. The clear sky computation is in principle a tractable problem. The use of line-by-line reference computations should make it possible to tune the necessarily-simplified schemes used in NWP to an optimum accuracy (optimum with respect to their computer cost). However, the tuning problem is not entirely simple. Line-by-line codes are too expensive to provide a sufficiently diversified test bed and the ICRCCM study (Inter Comparison of Radiation Code for Climate Modelling) has shown that the so-called "narrow-band" models aimed at bridging the gap between line-by-line and climate or NWP codes are not exactly fulfilling this role. Nevertheless, progress is quite rapid in this area and time and computer resources should help to solve the problem rather soon.

We shall assume, although it is a bit more risky, that rapid progress will also be made in the area of calculating the radiative transfer in the presence of clouds (we shall come back to these two "technical" problems later).

Far more complicated is the task of determining exactly what kind of partial cloud cover and optical properties should enter the calculation. It is now widely accepted that cloud cover should be a model interactive quantity (and as such a potential diagnostic tool) and that liquid (or ice) water content should probably become so in the future. The problems associated with these two steps are unfortunately totally different:

- In the cloud cover case we lack an effective feedback mechanism because of inconsistencies (in today's models) between the different cloud descriptions inside the same model (diagnostic and highly tuned for radiation, implicit and rather unrealistic - basically only 0 or 1 - for all moist thermodynamical processes: large scale rain, deep convection, shallow convection). At present the problem is mainly in the hands of those responsible for modelling of the atmospheric hydrological cycle. The task of providing a unique and consistent cloud description should be given high priority for all sorts of reasons. Tools of verification for that "interdisciplinary" step should probably be sufficient with the arrival of ISCCP data as well as those of other field special programmes.

- The liquid water content will create far more problems; the model cloud's vertical extension will always be related to the model's layer depth. Hence the parameter controlling the cloud optical properties is a combination of numerically and physically specified parameters which at best can be tuned. Unless vertical resolution increases dramatically we shall have to verify three model parameters: cloud cover, cloud liquid water content, rainfall efficiency with <u>two</u> "observations": rainfall rate and radiation at the top of the atmosphere (for which the ERBE measurements offer a good observational basis). It would seem logical to be flexible on the definition of cloud cover and to accept that it is a rather abstract quantity in the model. However this is in total contradiction with the strategy of verification adopted up to this point (i.e. as long as LWC is diagnostic). A theoretical investigation of these problems in the framework of idealised cases with a LAM version of an NWP system would surely be an important first step for which no real verification data are necessary.

Tests of a new cloud liquid water scheme at the UKMO improve the model's radiation budget although, at present, cloud optical properties are still prescribed.

If we can solve all the above mentioned problems satisfactorily there remains a last but unavoidable hurdle. What is the optimal trade-off between the absolute accuracy of radiative calculations and what the frequency at which they are evaluated in the model? It has been customary to perform sophisticated calculations at long intervals, but the strategy of more simplified schemes every time step can also be envisaged (it was chosen in the French models to represent the meso-scales more accurately but had surprisingly acceptable results even for climatic cases). An intermediate solution for which clear sky and cloudy processes are not interactive at the same frequency is an attractive alternative. ECMWF is clearly in the position to investigate this question (and its dependency on the above mentioned interactivity problem) in its research program.

1.7 Slantwise convection and saturated baroclinic circulations

There is theoretical evidence that saturated updrafts in baroclinic circulations operating at or near slantwise neutrality may collapse to very small vertical scales. Diagnoses might be made of models operating in these circumstances to determine whether this is happening and whether the vertical resolution of the model imposes a significant limitation on the mass flux of the sloping updrafts.

1.8 Recommendations

1. A more unified documentation of deficiencies in various forecast models would greatly assist in the identification of common problems in treatments of physical processes.

2. More attention needs to be paid to the model boundary layer which, among other things, strongly controls the dynamics of the tropical atmosphere. Diagnostics of the boundary layer moist entropy budget would greatly assist in the validation of convective parametrizations and surface flux representations.

3. In view of the major uncertainties concerning the importance of convective momentum transports and methods to parametrize and verify them, the inclusion of these in models should be treated with considerable caution, or better still, delayed until better diagnostics are available.

4. In view of the uncertainty regarding the intensity of sub-grid scale transport of momentum, heat and moisture and their importance for the large scale flow, further work incorporating higher order turbulence closure approximations for comparison purposes needs to be carried out. We must explore the possibility of allowing for a down-gradient potential vorticity flux rather than a down-gradient momentum flux in large scale models, since it is the former quantity and not the latter that is conserved.

5. Concerning radiation, emphasis in research should be on ensuring maximum consistency between radiative and thermodynamical properties of modelled "clouds" both in the case of diagnosed liquid water contents and in the forthcoming case of interactive predicted ones.

6. Parameters used in representations of various physical processes should be physically based and should be directly comparable to observational data.

Report of Working Group 2

2. VERIFICATION OF DIABATIC PROCESSES: DATA AND METHODS

2.1 Data

For the verification of the diabatic processes in a forecast model independent observational data are required. Estimated global fields of diabatic forcing are generally derived from the same data which are used to produce the fields of temperature, wind and other circulation variables in the data assimilation system. Direct and proxy observations of precipitation, and satellite data on the radiation balance at the top of the atmosphere are examples of data which are not yet used by the data assimilation system, and which can initially be used in the validation of the diabatic forcing estimates and later to improve these estimates. An extended use of data from some field experiments will probably also lead to progress in this area. In this section various data sets which can be used for verification will be discussed.

2.1.1 Precipitation data

(i) GATE precipitation data

Precipitation data for model verification are generally unavailable over tropical oceans. At present, the only comprehensive precipitation data set is that obtained in GATE, when a network of calibrated, intercompared quantitative radars and ship rain gauges gave detailed rain amounts and patterns over the GATE B-scale array (Hudlow, 1979). The precipitation data are embedded in a multi-scale, nested sounding array. The GATE radar data can be used to distinguish between stratiform and convective rain (Cheng and Houze, 1979; Leary, 1984).

(ii) Current satellite precipitation data

Currently available passive microwave satellite data sets (SMMR, ESMR) can be used to identify precipitation areas over oceans (absorption channels) and deep convection over land (scattering channels). If used in conjunction with Outgoing Longwave Radiation (OLR), which is a useful proxy for precipitation patterns in the tropics, the microwave channels could possibly improve rain estimates over tropical oceans. The microwave data might prove particularly useful over middle latitude oceans (MacMurdie and Katsaros, 1985) where the OLR patterns are ambiguous because of the presence of large areas of non-precipitating cirrus.

(iii) Western European radar data network

In the UK and France precipitation is measured in a comprehensive quantitative operational radar network.

(iv) Future satellite precipitation data

The only foreseeable replacement for the GATE precipitation data set is the proposed Tropical Rainfall Measuring Mission (TRMM), which is a satellite program proposed for the 1990's as a joint endeavour of NASA and the Japan Space Agency (NASA 1987). In TRMM, a low-inclination, low-altitude (high-spatial resolution) satellite will carry a precipitation-measuring radar, multi-channel passive microwave radiometers, and visible and IR sensors. The objective of the TRMM satellite is to produce a multi-year data set from which 30-day, 500 km x 500 km area precipitation amounts can be determined. The satellite sampling will cover the diurnal cycle and will provide sufficient vertical structure to distinguish convective and stratiform precipitation areas associated with mesoscale convective systems.

TRMM is motivated by the need to provide comprehensive tropical precipitation data to validate climate models and by the need to understand the role of tropical precipitation in the global hydrological cycle (NASA, 1987). In this latter respect, TRMM objectives overlap with those of GEWEX, and GEWEX leaders have embraced the TRMM concept (WMO, 1987).

2.1.2 Radiation data from satellites

Satellite data on the net radiation at the top of the atmospheric provide important constraints for the energy budgets. Over continental regions, where the heat storage in the underlying surface is small, this net radiation should be the same as the vertically-integrated flux divergence of dry static energy plus latent heat, which can be estimated from the circulation data. Over the oceans the situation is not so good because the heat storage in the oceans is large and cannot be estimated with sufficient accuracy.

Since November 1984, the Earth Radiation Budget Experiment ERBE has been providing radiometric measurements of high quality of the shortwave and longwave components of the radiation budget. Together with the data of the

International Satellite Cloud Climatology Project (Schiffer and Rossow, 1985), they provide a reference for the cloud radiation parametrizations in the large-scale numerical models.

Data from ERB and ERBE instruments can, in principle, be used in the validation of the energy source estimates, inferred from circulation data.

2.1.3 Field experimental data sets

The only comprehensive multi-scale field project ever held in the tropics is GATE. This data set is characterized by a nested, multi-scale sounding network. Embedded in the small-scale part of the network are extensive boundary layer measurements (tethered balloons, buoys, etc.).

Since GATE, several high quality field experiments have been carried out. These experiments, generally, consist of higher quality but much more specialized data sets than GATE. These experimental data sets should be considered supplementary to the more comprehensive GATE data set. Each of these more recent field projects can contribute more detail in some specific aspect of diabatic processes, as indicated in the table.

Experiment 1		Main Focus
WMONEX	-	Tropical-Island, diurnally generated tropical cloud clusters.
AMEX/EMEX	-	Sounding network and radar in Australian monsoon.
	-	Airborne Doppler radar in Australian monsoon cloud clusters.
PRE-STORM	-	Dual-Doppler radar, surface measurements, mesoscale soundings for mid-latitude mesoscale convective systems.
NOAA-HURRICANE FLIGHTS	-	Hurricane data sets.
GALE	-	Extratropical cyclone data sets.
JASIN	-	Boundary layer, air-sea interaction.
TRMM GROUND TRUTH PROJECT	-	Detailed rain data sets in Florida, N. Australia, and West Pacific.

TAMEX - Cloud systems over Taiwan.

MONSOON-77 - RS/RW over fixed polygons, surface radiation balance, radiation
S MONEX fluxes vertical profiles, upper ocean sounding, and boundary layer measurements.

FIRE - Cloud-radiation interactions.
2 Intensive Field Observations Programs devoted to maritime stratocumulus and cirrus clouds.

COPT 81 - Tropical convective systems in West Africa (Ivory Coast).

ALPEX - Comprehensive data set related to a mountain area.

FRONTS 84 and 87 - Field experiment for the study of frontal systems in Western Europe.

2.1.4 Profiler derived wind and vertical motion data in the tropics

Vertical air motions are closely related to diabatic heating. An effort is underway to set up 4-5 UHF/VHF radars (profilers) in a chain across the Pacific. These profilers provide a continuous record of the vertical profile of vertical and horizontal wind. One profiler has already been operating two to three years on Ponape in the tropical West Pacific. (Balsley et al., 1987). Another is being installed by Japan on Borneo. Preliminary results indicate that these data, when averaged over long times, give a reasonable vertical distribution of vertical velocity. In the next 2-3 years these data may become more extensively available (through NOAA/ERL and Japanese agencies).

2.2 Verification methods

At present the global distribution of diabatic heating (temperature forcing) can be inferred best from analysis data. Indirect calculations of the diabatic forcing as a budget residual have been very useful in estimating model errors. The most consistent way to derive budget residuals from the analysis is to employ the equations of the model used for the data assimilation. At comparatively little computer cost diabatic and adiabatic tendencies for all the model's degrees of freedom can be calculated at once by running the model for one time step.

Uncertainties in the continental scale averages of the vertically-integrated monthly-mean diabatic heating are at present at least of the order of 10 W m^{-2} in the northern extratropics but larger than this in the tropics, where the uncertainty in the divergent wind is the crucial factor. Despite these large uncertainties, the situation is encouraging. Compared with, say, ten years ago, meteorologists are much better able to describe the planetary-scale driving force of the general circulation much more accurately, at least on time scales of one month or longer. Time averages over adiabatic timestep residuals give heating rates which agree in their pattern very well with the monthly mean OLR data. It remains to be seen whether useful estimates can be derived for shorter time scales. Future work should explore to what extent 6-hour tendencies could be applied to calculate diabatic forcing on time scales shorter than a month.

In contrast to the energy budget, which is heavily dependent on the poorly-known divergent wind, the major features of the potential enstrophy budget are (at least in the extratropics) determined by the more accurately known fields of temperature and rotational wind. Accordingly, potential enstrophy might turn out to be a useful tool in diagnosing the net effect of diabatic and frictional processes in the atmosphere, and in the verification of large-scale models (see the paper by Holopainen).

2.3 Recommendations

1. The use of rain gauge precipitation observations over land should be further pursued on the basis of both SYNOP and CLIMAT data. The Western European radar precipitation network should also be explored for validating the mid-latitude precipitation estimates by the model.

2. SMMR and ESMR passive microwave data should be exploited to enhance OLR analyses, e.g., over mid-latitude oceans where OLR is more ambiguous.

3. The possibility of using ERB and ERBE net radiation data in the validation of the diabatic heating estimates over continental areas should be explored. Satellite measurements of the radiances (ISCCP)

should be used for validating the cloudiness produced by the model and the associated radiation fields and for verifying the response of the model's physical processes parametrizations to the diurnal forcing.

4. The possibility of using the extensive GATE data set is encouraged. High priority should be given to the re-analysis of the GATE data, because of its comprehensive multiscale character. Field experiments conducted since GATE should be referred to as necessary to provide more detailed and specific information not adequately provided by the GATE data set.

5. The applicability of the diagnostic technique developed at the centre for diagnosing the diabatic forcing terms appears very promising. Some aspects of the derived residual need, however, further research. The most obvious use of this technique is in the estimation of temperature forcing (diabatic heating). If it can be successfully applied in the case of moisture the temperature and moisture forcing together provide an improved "(Q_1, Q_2)" approach for determining, from large-scale variables, the vertical profile of the subgrid-scale energy flux. The question whether the net surface flux determined in this way is superior to the model flux (which now is given by the centre to the TOGA community) also needs to be investigated.

Report of Working Group 3

3. INTERACTIONS BETWEEN THE LARGE SCALE FLOW AND THE DIABATIC FORCING

3.1 Large Scale Control of the Diabatic Forcing

There was a consensus that diabatic processes are organised by the large scale flow in the tropics and also in mid-latitudes. Examples of self-organisation in the tropics include the organisation of the regions of large-scale ascent and descent and the approximate equilibrium between convection and the large scale flow. In mid-latitudes a blocking anticyclone can control the track and so the latent heat release in transient eddies while being maintained by the transient eddies. Thus, on short timescales in mid-latitudes, diabatic processes are controlled by the large-scale flow, while the example just cited suggests that this is not entirely the case on longer time scales.

The mechanisms by which scale-interactions operate are poorly understood. Simple models have an important role to play in elucidating the mechanisms by which the processes of self-organisation operate.

An important aspect of every parametrization package is the partitioning between the forcing of the balanced and the unbalanced part of the flow, i.e. the forcing of Rossby and gravity modes. According to geostrophic adjustment theory, the forcing of the divergent wind component will have little impact on the balanced flow. Likewise, vertically deep heating on small horizontal scales will mainly force gravity waves. In this context, physical processes cannot be treated in isolation, as the partitioning in the Rossby and gravity wave forcing depends on the three-dimensional structure of both the thermal and mechanical forcing. Furthermore, the response of the balanced flow will also depend on the timescale of the forcing. The Rossby mode response is generally larger for slowly varying forcing.

In a wider context, there is also a problem in the interaction between the assimilated data and the parametrizations manifesting itself in the so-called spin-up problem. Generally the dynamical and thermal structure implied by the data and/or the analysis need not be consistent with the structure implied by the parametrizations. It is not clear to what extent the resulting adjustment process depends on the scales involved. Ultimately one should aim for an initialization where the dynamics and the physical processes are in balance. Current efforts in this direction should be continued.

A possible way to test the parametrization behaviour as resolution increases would be to infer balance of wind, temperature and moisture from field experiments such as GATE and AMEX, reanalysed at the proper scale.

3.2 Neutrality of the atmosphere

One area in which the problem of parametrization is particularly severe is that of convection. The factors that are important for the existence of and the impact of a single cumulonimbus cloud are probably not relevant to the average in space and time that is parametrized in a large-scale numerical model. It has been argued that, when viewed in the "correct" thermodynamic manner, the tropical atmosphere in convective regions is approximately neutral to convection. If this neutrality is exact, the only way to get warming (as opposed to diabatic heating balanced by adiabatic cooling) is by raising the boundary layer θ_e. This would imply a change in our priorities for the modelling of the tropical atmosphere. The analysis of temperature and moisture in the boundary layer, and the modelling of the surface fluxes of these quantities would be absolutely crucial.

An alternative view, supported by observation system simulation experiments, is that in the tropics it is the evolving wind field that dominates and the thermal perturbation structure is that demanded by "thermal wind" balance. The very small residuals in the thermodynamic equation between diabatic heating and adiabatic cooling would be crucial in providing the necessary very small temperature perturbations ($\sim$1K), which are anyway within the observational error. In this view neutrality is only approximate and the thermodynamic equation is not the best way to diagnose the reasons for thermal perturbations. Diagnosis of the potential vorticity would enable a comparison of the dynamic and thermodynamic effects.

In middle latitudes, observational studies are beginning to suggest that in poleward moving warm moist air in a cyclone there may be approximate neutrality to slantwise ascent. The difference in time-scales and spatial structure between the synoptic system and the adjusting process is not nearly so apparent here as in the tropics. Frontogenesis has a time-scale not much longer than f^{-1} and the cross-frontal circulation is similar to a symmetric instability roll. The inclusion of a parametrization based on assumed slantwise neutrality in the warm air in simple frontogenesis and baroclinic instability calculations has shown the possible importance of this neutrality. The frontal scale is one which is partially represented in the ECMWF model and parametrization here may be very difficult.

3.3 Low frequency variability

One of the serious shortcomings of the ECMWF model is its underestimation of low frequency atmospheric variability. This is manifest, for example, in the model's difficulty to forecast the transition to blocked states over the Pacific and North Atlantic. In order to study this problem in an objective manner, it is necessary to quantify the modes of low frequency variability that exist in the atmosphere, and assess whether there are well defined flow regimes in which the atmosphere is resident for significant periods of time. This is currently being assessed through cluster analysis procedures. It is not clear whether local or hemispheric scale cluster anaysis will give the most meaningful results.

Given that such flow regimes can be meaningfully defined, the mechanisms that give rise to maintenance within regimes, and transitions between regimes, can be investigated. The role of diabatic heating, both locally and remotely, within the regimes would be a major ingredient of such investigations, though cause and effect cannot be readily identified.

The importance of such investigations is already becoming apparent through studies of one of the dominant modes of atmospheric low-frequency variability, the Pacific North American mode. It is known that the skill of NWP models in the medium and extended range is dependent of the signed amplitude of this mode. It is thought that this mode can be forced by anomalous diabatic heating in the tropical Pacific, though recent calculations suggest that more local midlatitude thermal forcing mechanisms may also play an important role. The role of diabatic heating in transitions between positive and negative PNA states is not well understood.

In general tropical diabatic heating may have a significant effect on the mid-latitude air flow. A clear Rossby-wave type signal is however difficult to detect unambiguously in observations since it is known that internal mid-latitude variability is large. A small energy source (for instance over Indonesia or over the Caribbean) could nevertheless modify the mid-latitude flow quite significantly by shifting the sub-tropical jet and could thus act as a catalyst. This modification could occur on time scales varying from a few days up to a season.

Within the tropics, the Madden and Julian mode (30-60 day oscillation) has been identified as an important contribution to tropical low frequency variability and may also influence significantly the extratropical jets. Within a ten-day forecast period the oscillation could have progressed through a significant fraction of its period. At present, the ability of the forecast model to represent this oscillation is poor at least in forecast mode. The impact of parametrization schemes (e.g. convection) on simulations of the oscillation would be a valuable diagnostic for their assessment.

3.4 The formulation of parametrizations for large scale modelling

3.4.1 Parametrization and simulation

Whatever the resolution of a GCM or forecast model, there will be processes it can resolve, processes it cannot resolve, and processes that it can partially resolve. One tries to simulate the resolved motions, one tries to parametrize the effect of unresolved motions on the resolved scales, and one undoubtedly ill-treats the effect of the partially resolved scales.

There is a case for explicitly parametrizing the physical effects of all scales beyond a truncation limit different from the truncation limit of the numerics. One could do this either by using a coarser grid for the physics or by filtering the (input to and) output from the physical parametrizations. Such an explicit approach has not been tried, despite many suggestions along these lines. The apparent reluctance to experiment in this area indicates a tension between the desire to simulate as much as possible, and the need to be rigorous in approach; it may also be because quasi-stationary (orographic) features at the limit of resolution add verisimilitude to forecast model output.

Since most of these local features are related to the direct dynamical effects of orography, orography should be retained at full model resolution. For numerical reasons dissipation should also act on the shortest retained scales. The situation for other parametrizations is less clear. Tropical convection, for example, involves no clear scale separation between the cumulus scale and the cloud cluster scale (~500 km); moreover the geographical location is not precise. The fine scale detail produced by the convective scheme is largely illusory and may not interact adequately with the dynamics; a lower resolution representation may be more appropriate here. These considerations are especially relevant if global models with a stretched horizontal coordinate are developed.

3.4.2 Identification of processes needing to be represented

Many processes are not represented, or are poorly represented, in forecast models. How does one identify the physical processes that ought to be represented in a model at a given resolution? A simple-minded approach would be to determine the residuals in the dynamic and thermodynamic budgets empirically, and then use these as corrections to the physical forcing in the model. Such an approach in research would be helpful in designing sensitivity experiments.

The dynamic and thermodynamic budget residuals are an extremely interesting and important first step in determining the processes to be represented in a forecast model. If the budget residuals cannot be explained as errors in explicitly described processes, then one must appeal to existing field experiment data, or design a new field experiment, to identify the processes leading to the imbalance. It is important to make the residual caculations for particular weather regimes where the findings could be especially helpful in designing parametrization schemes.

One recognises of course that the calculations of residuals will always have errors, because of errors in the analyses. Equally, the interpretation of field experiments is difficult, because of the necessarily limited sampling. Nevertheless, a systematic exploitation of both offers a rational way forward.

Examples of processes which may be important, but whose role is not yet adequately quantified, include drag due to ocean waves, lower troposphere drag near mountains, momemtum transport by cumulus clouds, and a unified explicit treatment of cloud liquid water. For some of these processes we have measurements in extreme events, but know little about the normal level of activity. Aircraft can only measure wave drag in extreme events; profilers in mountain regions might help in estimating the 'normal' level of stress due to gravity waves.

3.4.3 Accuracy in the treatment of feedbacks

The accuracy requirements for the representation of a process need to be specified. Budget residuals can give an indication of zero-order magnitudes for a given process. However, there are many feed-back loops in the atmosphere, some of which are circuitous but nonetheless important. Examples include radiative- convective interactions, or the feedback between surface drag and baroclinic conversion rates.

The determination of the magnitudes of the feedbacks is an important problem. The problem is equivalent, in the linear approximation, to the determination of the Jacobian matrix of the problem. At least one new approximate approach to the problem was presented at the workshop. As proposed the method could identify feedbacks acting within a day. Some important feedback loops are thought to have much longer time scales. The validity of the method for such loops is unclear. For the moment, we should exploit available methodology to identify and quantify fast-acting feedbacks, and hope that improved methods can be developed when the models are more accurate.

There is no unique solution to the parametrization problem and it may be necessary to account for some of the uncertainties in a stochastic manner.

3.5 Recommendations

Concept of neutrality in the Tropics

1. A careful study of boundary layer θ_e and its changes, the neutrality of the free atmosphere, the diabatic heating and changes in θ_e in the model atmosphere in various regions and situations (e.g. El Nino and non-El Nino).

At the same time the vorticity budget should be analysed to see if the small changes in θ in the free atmosphere can alternatively be viewed as being demanded by balance requirements. This study should be performed with a number of available schemes. Comparison should be made with the real atmosphere wherever possible.

2. We should use the concept of neutrality in convection regions in the determination of the statistical models underlying the analysis scheme.

Concept of neutrality in middle latitudes

3. Continuation of work on monitoring the stability to slantwise ascent in the current model and on parametrizing the effects of neutral slantwise stability on a sub-grid scale.

4. Use of the limited area model at very high resolution to monitor the neutrality and help design the parametrization. Cases observed in the Mesoscale Frontal Dynamics Project/Fronts 87 and in GALE as well as in the forthcoming ERICA experiment would provide a good observational basis.

Low frequency variability

5. Budget (residual) calculations be carried out using initialized fields to compute the diabatic heating during anomalous circulation regimes, for example at different phases of the PNA. In the tropics where use of initialized data for such purposes may be inadvisable it is suggested that the OLR data be used as a simple measure. In addition the amplitude, phase and vertical structure of the planetary waves during these anomalous periods should be documented.

6. The transition between flow regimes and the possible role of tropical influences in remotely triggering them be studied by seeking teleconnections between OLR and height field anomalies.

7. Further "relaxation" experiments be carried out in different flow regimes in which the tropics is relaxed back to the observed analysis, to assess the impact of tropical forecast error on the extratropics, as a function of flow regime.

8. Studies of the Madden and Julian mode (30-60 day oscillation) within the current operational model should be undertaken. The impact of any changes in tropical parametrizations (convection, surface fluxes, radiation etc) on this oscillation should be carefully assessed.

9. Forecast errors which occur very early may be best investigated by case studies.

Formulation of parametrizations

10. Coordination of the views of modellers on what field experiments will be most useful to them would be invaluable to the funding agencies.

References

Balsley, B.B., W.L. Ecklund, D.A. Carter, A.C. Riddle, and K.S. Gage, 1987: Average vertical motions in the tropical atmosphere observed by a radar wind profiler on Pohnpei (7°N latitude, 157°E longitude). Accepted, J.Atmos.Sci.

Cheng, C.-P., and R.A. Houze, Jr., 1979: The distribution of convective and mesoscale precipitation in GATE radar echo patterns. Mon.Wea.Rev., 107, 1370-1381.

Hudlow, M.D., 1979: Mean rainfall patterns for the three phases of GATE, J.Appl.Meteor., 18, 1656-1669.

McMurdie, L.A., and K.B. Katsaros, 1985: Atmospheric water distribution in a midlatitude cyclone observed by the Seasat scanning multichannel microwave radiometer. Mon.Wea.Rev., 113, 584-598.

Leary, C.A., 1984: Precipitation structure of the cloud clusters in an tropical easterly wave. Mon.Wea.Rev., 112, 313-325.

NASA, 1987: On Requirements for a Satellite Mission to Measure Tropical Rainfall, NASA Ref. Publ. 1183, Goddard Space Flight Center, Greenbelt, Maryland. NASA Sci. and Tech. Info. Branch, 49 pp.

Schiffer, R.A., and W.B. Rossow, 1985: ISCCP Global Radiance Data Set: A new resource for climate research. Bull.Ameri.Meteor.Soc., 66, 1498-1505.

WMO, 1987: Report of the workshop on space system possibilities for a Global Energy and Water Cycle Experiment (Columbia, MD., USA., 4-23 January 1987). WCP-137 (WMO/TD-NO. 180).