1. INTRODUCTION

The organisation of symposia and workshops is a part of the Centre's research activity. The following publication contains the proceedings of a workshop on "Diagnostics of Diabatic Processes", which was held at the ECMWF, Shinfield Park, Reading, from 23 to 25 April, 1980. Diabatic processes play a dominant role in forcing atmospheric motions and the response of the large-scale atmospheric flow to diabatic forcing may be found after a rather short time, i.e. a couple of days. Whereas, therefore, short range weather prediction can be successfully made on the basis of adiabatic models, diabatic processes must be considered in medium range forecast models, as omission or misrepresentation of diabatic processes may effectively reduce the forecast quality. Indeed, we have indications that the systematic errors found in the operational forecast at the Centre are largely caused by erroneous diabatic forcing. There is therefore a great need to diagnose the diabatic forcing in the atmosphere as well as in numerical models. The purpose of this workshop was to exchange information in the area of diagnostics of diabatic processes and to recommend further research activities in this field at the Centre. The workshop was organised in the usual way: in the first section invited scientists and scientists from the Centre presented papers on special subjects (their contributions are included in this report as appendices). In the second part, the following more general subjects were discussed in working groups:

1. Geographical distribution of diabatic processes (Arpe, Hantel, Holopainen, Julian, Kanamitsu, Louis).

2. Diabatic forcing of large-scale atmospheric flow (Hoskins, Lau, Simmons, Tibaldi, Webster).

3. Diagnostics of diabatic processes (Derome, Geleyn, Girard, Savijärvi, Talagrand, Tiedtke).

The results of these discussions are summarised in the following chapters.

2. OBSERVED GLOBAL DISTRIBUTION OF DIABATIC PROCESSES

Diabatic heating in the strict physical sense is the right-hand side of the first law of thermodynamics in non-averaged form:

$$c_p \frac{T}{\Theta} \frac{d\Theta}{dt} = Q \tag{1}$$

Q consists of all irreversible processes present in the atmosphere; contributions due to the following physically different processes can be distinguished: condensation and evaporation (Q_L), radiation (Q_R), and molecular effects (conduction, friction and diffusion). Averaging Eqn. (1) over space and time generates eddy-like sensible heat flux terms which we shall include as Q_S. This transforms (1) into:

$$c_p \frac{T}{\Theta} \left(\overline{\frac{d\Theta}{dt}}\right) = \bar{Q}_L + \bar{Q}_R + \bar{Q}_S = \bar{Q} \tag{2}$$

In (2) we have neglected the molecular terms and have assumed that the averaging is on pressure surfaces (i.e., $T/\Theta = (p/p_o)^\kappa$).

2.1 Observed diabatic heating

We shall now discuss the existing knowledge about $\bar{Q}$, presumably on a monthly and hemispheric scale.

Zonal mean $\bar{Q}$

The most often quoted zonal mean pattern of $\bar{Q}$ for the globe is that of Newell et al. (1969, 1974). These authors determined the three terms in Eqn. (2) separately; we may call this the *direct method*. The results of the two papers differ considerably, both in magnitude and pattern. These differences are largely due to the different radiation heating rates used in the two papers.

A more recent account of zonal mean $\bar{Q}$ for the seasons of the northern hemisphere based on estimating the left of Eqn. (2), which may be called the *indirect method*, will be described in the contribution by Hantel. Hantel's estimate indicates that the overall error of $\bar{Q}$ is about 10^{-6}K/s.

Most recent estimates of zonal mean $\bar{Q}$, also based upon the indirect method, are becoming available at ECMWF and are described in the contribution by Savijärvi.

Vertical mean $\bar{Q}$

For a geographical distribution of $\bar{Q}$ the only complete source seems to be the vertically averaged annual pattern of Budyko (1963, p. 69), based upon parameterization. Vertically averaged $\bar{Q}$ is also becoming available at ECMWF.

Level estimates of $\bar{Q}$

By level estimates we mean geographical distributions of $\bar{Q}$ at a specific atmospheric level. There are not very many available. The best known example seems to be Lau's account of $\bar{Q}$ at the 700 mb level for a climatological average of 11 winters for the northern hemisphere; this estimate is based upon NMC analyses. This pattern is included in the contribution by Lau. Similar evaluations for the northern summer will become available soon.

We shall now briefly discuss the components of Q in vertical mean form.

Precipitation

Climatological global data of observed precipitation for the winters have been published by Jaeger (1976). Their accuracy is unknown. Monthly patterns of observed precipitation on a routine basis are available in Monthly Climatic Data for the World (NOAA-publication, sponsored by WMO) and should be used.

One further promising avenue of research seems to be the micro-wave measurements from satellite, yielding surface precipitation over the oceans (e.g., Rao et al., 1976). Recent experience is, however, not too promising. According to Lovejoy and Austin (1980) errors of the order ± 50% are unavoidable due to the inherent limitations of the method.

Radiation

Satellite data at the top of the atmosphere are available on a routine daily basis (e.g. Stephens, Campbell and Vonder Haar, 1980). Things are more difficult at the earth's surface. The only presently known source seems to be the radiation centre at Leningrad which collects measured surface radiation fluxes on a routine basis. These should be made accessible with more ease.

Sensible heat flux

The most complete source appears still to be Budyko's (1963) estimates. Independent estimates over the North Atlantic Ocean have been published by Bunker (1976). Direct measurements of $\overline{\omega'\Theta'}$ at the earth's surface have been carried out with correlation techniques by many groups but only on a local scale which is not representative for the resolvable scale of the model.

Accuracy

Contemporary accuracy of $\bar{Q}$ is difficult to estimate. One objective method would be to compare independently gained estimates and take the difference as a measure of the error (a method used by Clapp, 1961); for example, consider the difference between Newell's estimates of 1969 and 1974 which is of the same order as $\bar{Q}$ itself. Comparisons of this sort should be further encouraged and could be undertaken at ECMWF, especially from FGGE data.

Another objective method is to over-specify the budget of $\bar{Q}$ in integrated form and take the resulting imbalance as a measure of the error. This is discussed in the Appendix by Hantel. For example, Hacker (1980) compiled the dry static energy budget for the northern hemisphere by over-specification and came up with an rms-error of 26 W m^{-2}. This is the error of each single flux entering the budget; however, it may still be an underestimate.

Comparison of the "observed" and "parameterized" processes

The diagnostic studies of budgets of moisture, thermal energy and kinetic energy being done by ECMWF provides interesting material for getting deeper understanding of the working of the atmosphere. The residual terms in these budgets (evaporation minus precipitation, net diabatic heating and frictional dissipation, respectively) give, in principle, values, against which the corresponding quantities, parameterized in the model, can be checked.

2.2 Recommendations

The diagnostic studies made so far at ECMWF are very valuable and should be continued. Great care has, however, to be taken of possible systematic errors arising in the determination of "observed" quantities by the residual technique. In particular,

a) The budget calculations should be done (at least for some shorter period) both from uninitialized and initialized data. Also, for some areas such studies can be done using the primary FGGE IIb aerological data. (An investigation of this kind is planned to be undertaken at ECMWF in cooperation with the University of Helsinki).

b) In the comparison of the "parameterized" and "observed" (residual) processes special emphasis should be given to areas with good data where the uncertainties associated with the "observed" quantities are in minimum.

c) The time-space resolution for $\bar{Q}$ and its components should be sufficiently high as to identify single synoptic systems. This means specifically that systems of a time scale of about 5 days and a horizontal scale of about 1000 km should be resolvable in the data. This requirement is consistent with the contemporary data sampling density.

3. THE DIABATIC FORCING OF LARGE-SCALE ATMOSPHERIC FLOW

The diabatic processes of latent and radiative heating and of turbulent transfers, particularly in the boundary layers, are major determiners of the character of large-scale atmospheric flow. Quite apart from their fundamental role in driving the mean zonal circulation of the atmosphere, diabatic processes force a significant part of the large-scale standing-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. An accurate representation of diabatic processes is thus a prerequisite for accurate medium-range weather forecasts.

The following discussion is divided into two parts. In the first we outline some of the outstanding modelling problems which have become evident during the first months of operational forecasting at ECMWF, and set down some of the questions which arise when we consider these problems. In the second we propose some research studies aimed at answering these questions. In doing so we do not restrict ourselves to a narrow interpretation of the word "diagnostics" such that we consider only the study of analysed or forecast data. Rather, in addition to suggesting diagnostic studies of this type, we also discuss sensitivity and idealized-model studies which may shed light both on the specific modelling problems which face ECMWF and, more generally, on our understanding of the diabatic forcing of large-scale atmospheric flow.

3.1 Outstanding problems

From the examination of a series of ECMWF forecasts for middle latitudes it soon becomes evident that there is a tendency to predict too large amplitudes for low pressure systems. This becomes most marked beyond day 4, but nevertheless can sometimes be evident at earlier stages of the forecasts. Over-development is often accompanied by an increase in spatial scale, too large an eastward movement of the systems into continental areas to the east of the major ocean basins of the northern hemisphere, and an inadequate rate of decay. New developments of baroclinic waves appear to be lacking during the second half of the forecast period. In the time-mean, the Aleutian and Icelandic lows are too deep, and displaced eastward. Error fields are largely independent of height.

In considering the causes of these deficiencies a number of questions arise. To what extent is the overdevelopment of waves a 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 standing-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 or mechanical forcing? Does the 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?

Anomaly correlation coefficients computed for zonal wavenumbers up to 20 for the extratropical troposphere of the northern hemisphere decrease substantially more slowly during the first two or three days of the forecasts than they do beyond this time. Does this behaviour represent primarily the spread of error from shorter tropospheric scales, from the stratosphere, or from the tropics? Diagnostic studies and a limited synoptic evaluation indicate major deficiencies in the model tropics, in particular in the large scale structure. Simple model studies suggest that there may be strong influences on mid-latitude flow within a one week period.

A misrepresentation of the horizontal scale of tropical systems raises questions regarding the model's convective parameterization. A tendency for intense small-scale systems when using the Kuo scheme has been found not only at ECMWF but also elsewhere. Should we be considering the state of the atmosphere at several neighbouring grid-points as input for a convective parameterization?

The fact that the model can maintain too warm an 850 mb temperature and too cold a 500 mb temperature in the extended integrations is a serious problem. Why were cold pools inadequately warmed during the autumn forecasts? Are these products of the Kuo scheme? Indeed, is the scheme really appropriate for extra-tropical convection? To what extent will implementation of a diurnal cycle influence heating deficiencies in the tropics and middle latitudes?

3.2 Recommendations

Extra-tropical baroclinic waves - Case studies

Detailed case studies of baroclinic wave behaviour are necessary. Diagnosis of the wave structure and diabatic heating in height/longitude sections should be performed for both analyses and forecasts in which wave development is evident. Sensitivity studies should follow in conjunction with idealised experiments.

In connection with the diagnostic studies some expansion of the model facility for grid-point diagnostic prints of diabatic tendencies is desirable, as is the archiving of 6-hourly σ-coordinate analysis files for either an extended (one year) operational period or the FGGE year.

Idealized experiments

Linear baroclinic instability calculations should be performed to evaluate the influence of the changed model static stability and zonal flow on subsequent wave growth. In view of the lack of quantitative theoretical results concerning diabatic influences on baroclinic wave motion, idealized life cycle experiments extending those already performed at Reading University should be carried out using differing parameterization schemes. Scope exists for collaborative projects in these areas.

Transient-wave diagnostics

It is desirable to extend the type of diagnostic study described by Lau in these proceedings to ECMWF analyses. The data sets for this project will not be of sufficient length for some years. Using ECMWF analyses shorter-term diagnostics concentrating on transient stationary wave interactions on the one week time scale are being undertaken in a joint University of Reading - UK Met Office project. When some preliminary results are available such statistics should be evaluated also for the forecast model to provide an insight into relationships between transient and standing waves in the model.

Tropical/extra-tropical interactions

A major effort should be made to identify whether or not the spread of error from the tropics to middle latitudes is primarily responsible for the observed degradation of the forecast product after 4 days. The use of streamfunction and velocity potential in detailed diagnostic studies would appear most appropriate.

Forecast experiments in which the tropical atmosphere is prescribed from 6-hourly analyses may indicate some of the improvement in mid-latitude forecasts to be expected from the correction of major errors in the tropical initialization and parameterization schemes. Since both simple and general circulation model studies indicate a significant high-latitude response to tropical forcing, further experiments should examine the sensitivity of 10-day forecasts to prescribed, localized tropical and mid-latitude heating. The vertical and horizontal scale of the heating should be varied systematically. Subsequent experiments should introduce the heat indirectly through sea-surface temperature anomalies.

A further potentially informative experiment would be to use an adiabatic model to calculate the tendencies from the observed monthly-mean fields and the corresponding mean forecast fields, for example the monthly-mean day 1 forecast. The difference in the geographical location of tendencies should indicate areas of erroneous diabatic forcing, mechanical forcing, or transient/standing wave interaction.

The diagnosis of convection

A synoptically-oriented diagnostic study of the occurrence of convection should be implemented. The level of convective activity in different mid-latitude and tropical situations should be monitored. The vertical distribution of latent heating is reasonably well known for tropical convection and should be compared with model representations for different regions. Further use of single-column experiments should be made for this work.

Depending on the results of these studies the use of various parameterizations of convection should be investigated. This investigation should include (i) the use of neighbouring points in determining the onset of convection, that is the development of a disturbance-scale convective parameterization, and (ii) the use of more appropriate convection schemes for mid-latitudes.

Incorporation of the diurnal cycle is viewed as important; an initial indication of the effect may be achieved by using the current scheme but with a reduced threshold for vertical fluxes.

Tropical disturbances

Our knowledge of the treatment by the forecast model of important types of tropical disturbances, for example the African easterly wave, is extremely limited. Thus a detailed synoptic assessment of the tropical simulations is needed. In the longer term, scope exists for tropical wave case studies and idealized model investigations along the lines proposed for extra-tropical waves. Such work may also yield further critical information on the performance of convection schemes.

Other studies

Additional studies should be performed to evaluate the choice of moisture variable, large-scale precipitation criteria, and the sensitivity of forecasts to the humidity analysis.

4. DIAGNOSTICS OF DIABATIC PROCESSES

4.1 Diagnostics of diabatic processes in the atmosphere

It is generally agreed that diabatic heat sources and sinks play an important role in medium-range forecast models. Unfortunately, our knowledge of the time distribution of heat sources in the atmosphere is far from perfect and hence it is difficult to ascertain the quality of any model's parameterization of the true heating field.

Traditionally, the two methods which have been used to estimate the true atmospheric heating field have been: (i) to calculate each of the components entering the heating, e.g. the radiative and sub-grid scale sensible heat flux components and condensational heating, independently of a forecast model, although some form of modelling is normally involved; (ii) the second method is to obtain the net diabatic heating as a residual of the thermodynamic equation when all other known terms have been computed. The latter method was used by Wiin-Nielsen and Brown (1960), Brown (1964) and Geller and Avery (1978). All these authors used simplified forms of the thermodynamic equation. It would seem highly desirable to repeat their approach in a somewhat modified form at the Centre.

Recommendations

The vehicle for this study would either by the quasigeostrophic equations or one of the Centre's forecast models and the data would be the FGGE analyses at 6 hour intervals. We recommend the use of the Centre's operational model. The procedure would then be to produce 6-hour forecasts and to compare forecast versus verifying temperatures. The residuals (observation minus forecast) arise in part from errors in the initial flow and in part from errors in the final flow used for verification. In single cases the latter kind of error may be predominating but for a large ensemble, say, all the 6-hour forecasts within the data assimilation during one month, the largest proportion of the residuals are presumable due to errors in the diabatic forcing and in adiabatic processes. The diabatic heating calculated in the model plus the correction should then be close to the true heating especially in the absence of feedback between the additional diabatic heating and the flow. As a more refined method we recommend using the 6-hour forecast temperature error to compute an average heating rate over the forecast period, which would have been required to produce a perfect temperature forecast in the absence of intersections between this part of the heating and the flow. This heating field would then be added to the thermodynamic equation and the 6-hour forecast repeated. This time the temperature forecast should agree better with observations and the cycle can be repeated as many times as necessary to bring the forecast temperature error down to a prescribed level. The true diabatic heating field would then be taken as that which is computed by the model's parameterization scheme plus the correction added as described above. Similar corrections would have to be made in the momentum and moisture equations. The convergence criteria for this procedure would have to be investigated. It must be recognized that this procedure is equivalent to requiring the heat, moisture and momentum sources to account for all forecast errors. For example, any part of the forecast error due to the numerical scheme would be compensated for, or incorporated into the residuals. While this is a drawback it is likely that the above procedure provides the best estimates that can be obtained at the moment. Naturally, the results will be most reliable over data dense regions and least reliable over data sparse areas, as is usually the case in a study based on observations. All we can do is hope that the FGGE data will minimize these problems.

In addition to the question of determining a best possible estimate of the true atmospheric heating field, there is the problem of diagnosing the model's diabatic forcing.

4.2 Diagnostics of diabatic processes in numerical models

1) A method of residuals for budget calculations applied on both analysed (whether initialized or not) and forecast fields is used to diagnose total forcing by diabatic processes on pre-specified regions of the earth (see contribution by Savijärvi).

2) Directly from the operational model, individual forcing terms can be obtained as zonal averages or as vertical integral. Thus, gross model deficiencies can be found. Their causes are very hard to diagnose.

Due to the highly non-linear feedback mechanisms in both atmosphere and model, budget calculations of as many quantities as possible are needed and their geographical distribution as well as vertical profiles must be studied.

Ideally, budgets of individual diabatic as well as adiabatic terms should be obtained from models with as much local detail as possible throughout the forecast period. Average contributions as well as meteorologically significant contributions in special cases are needed to understand the role and importance of diabatic processes in models. In view of the practical problems in obtaining comparisons, results from observations of parameters such as precipitation, cloud amount, etc., should also be used as much as possible.

Recommendations

We need to acquire a data base more appropriate to the detailed diagnoses of diabatic and other processes in the model. This is felt to be the mode history (σ-coordinate) files (plus the uninitialized and initialized analysis files) from which individual forecasts can be diagnosed locally.

We need to develop a procedure that consists essentially in performing the equivalent of a single model timestep, the contributions from the separate components of the diabatic and adiabatic processes being calculated, stored and displayed immediately: u- and v- momentum changes, vertical and horizontal dissipation, large-scale and convective moisture changes, turbulent vertical transfers of latent and sensible heat, large-scale and convective latent heat release and radiative heating.

For comparison purposes we need to run the residual method on the analysis without spatial averaging to get an equivalent data base for the observed state. However, this would not contain any information about the separate processes and would need to be time-averaged. The problem of time-averaging could perhaps be overcome by using the iterative method mentioned in the recommendations of Section 4.1. However, this could only be done as a special project.

With this procedure, large local discrepancies between observed and forecast diabatic effects can be linked to geographical areas and/or meteorological situations. Knowledge of the contributions by specific processes to the total forecast effect is more likely to give clues about the cause of erroneous tendencies, the circumstances of local imbalances and compensations between processes.

One should also try to find statistical correlations between the observed residuals minus the model's computed forcing and its individual components in an attempt to partition the local forcing into its basic components.

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