1. INTRODUCTION

The organisation of workshops is a part of ECMWF's research activities. The following publication contains the Proceedings of a workshop on Radiation and Cloud-Radiation Interaction in Numerical Modelling which was held at ECMWF, Shinfield Park, Reading from 15 to 17 October 1980. The first part gives a summary of the discussions held at the workshop while the second part contains the lectures which were given prior to the discussions.

Radiation is the only way in which the earth-atmosphere system can exchange energy with space. Clouds are the most important regulating mechanism on small and long time scales for this exchange. The accurate modelling of radiation and cloud-radiation interaction is therefore of paramount importance for climate simulation. This fact led the GARP JOC to organise a study conference on "Parameterization of extended cloudiness and radiation for climate models" (Oxford 27 Sept - 4 Oct 1979) and as a consequence GARP WGNE has undertaken a programme of comparison of results on the subject. However the relevance of radiation and cloud-radiation problems to medium range weather forecasting is less obvious. In fact preliminary results obtained at ECMWF were ambiguous; despite a somewhat crude parameterization of the cloud-radiation interaction some influence would be noticed in the model's energetics, but these differences were not reflected in the skill of the forecasts before the predictability limit was reached.

The aims of this workshop were therefore: to assess the importance of radiation and cloud-radiation treatment in numerical modelling and especially in the ECMWF forecasting system; to critically review the parameterizations of radiation-interacting clouds and of radiative transfer at ECMWF and elsewhere, and to suggest means of improvement; to consider possible cooperation of ECMWF with other groups involved in the problem especially in the fields of numerical comparison of models and of acquisition of verification data.

The discussions were conducted among four subgroups formed by the workshop participants on the following subjects:

a) Impact of radiation on numerical forecasts
(Burridge, Cubasch, Mitchell, Paltridge, Simmons, Slingo J.)

b) Cloud parameterization for radiation schemes
(Geleyn, Hense, Herman, Letreut, Roach, Tiedtke, Wilderspin)

c) Design of radiation schemes
(Fouquart, Haigh, Hollingsworth, Panhans, Rodgers)

d) Verification data requirements
(Arpe, Barton, Louis, Morcrette, Raschke, Slingo A.)

The following sections contain the summaries of these group discussions in the form of comments and recommendations. The four summaries are presented in what we considered to be the most logical order; the same is true for the order of each group's recommendations. A summary of the main recommendations can also be found in Section 6.

2. IMPACT OF RADIATION ON NUMERICAL FORECASTS

2.1 Discussion

A year of operational forecasts and many hundreds of research forecasts have confirmed the early conclusions and expectations expressed by Hollingsworth et al (1979). These were that extratropical northern hemisphere forecasts with the N48 15-level grid-point model are generally good up to three days and have useful predictability for five to six days, but that they also consistently exhibit a number of systematic errors.

Recent experiments reported by Cubasch (1981) show that the five-day forecasts of the extra-tropical height field are insensitive to major changes in the parameterization of radiation and clouds, although there are large synoptic differences evident before day 10. In these experiments the ECMWF radiation scheme gives forecasts with higher (and more realistic) levels of eddy energy. This raises the question of whether or not there are other, more meaningful, measures of forecast skill such as wind or precipitation which would reveal sensitivity to differences between radiation schemes, particularly in the tropics. This is in fact one of the points raised by GARP WGNE for their study.

The principal systematic errors revealed by extended as well as medium range integrations of the ECMWF model are

1) A substantial cooling of the lower stratosphere by up to $12^{\circ}C$ over 50 days, with a corresponding upward displacement of the tropopause by about 100 mb over this period.

2) A general cooling of the middle troposphere by about $1^{\circ}C$ per 10 days.

3) A substantial warming of the boundary layer especially over land which spreads equatorward from the North Pole.

4) An overintensification and a lack of decay of individual cyclones, and an eastward shift of the Aleutian and Icelandic low pressure areas.

5) An underestimate of the strength of the Hadley circulation and rainfall in the tropics.

6) A poleward shift of the subtropical jet in both hemispheres.

7) A "spin-up" time of one to three days for precipitation and boundary layer fluxes. Large-scale tropical divergences are particularly slow to develop.

The immediate question which arises in the context of this workshop is to what extent these errors, which might be interrelated, are due to errors in the radiation calculation, and in particular the cloud parameterization. For the design of the Centre's second generation of forecasting models we need to answer a more general question, namely what is the accuracy required in the calculation of the radiative heating or cooling for a large-scale model with a particular vertical resolution. This cannot be answered in isolation, since the question of computational efficiency of the radiation calculation compared with that of other components of the forecasting system will need to be considered.

To answer these overall questions it is necessary first to answer some more detailed ones. The following list, by no means exhaustive, is a first approach to this problem.

a) What is the impact of radiation on specific atmospheric phenomena, for example developing baroclinic waves?

b) What errors are introduced by computing the radiation every twelve hours? Is the resulting phase lag between the field of radiative heating and a developing synoptic situation important?

c) How important is the diurnal cycle? This question can be subdivided into two: how important is the effect of non-linearities in surface exchanges during the diurnal cycle; how important is the diurnal change in the interaction between clouds and radiation especially in the tropics?

d) Are errors in the parameterization of radiation more important in the summer hemisphere?

e) Are there systematic errors in the model's humidity structure, particularly in the tropics and if so, how do they affect the validation process for the radiation field?

f) Should we initialize moisture?

2.2 Recommendations

i) In view of the insensitivity of the extratropical height field to changes in radiative parameterizations, the question arises as to whether there are more sensitive measures of forecast skill which would lead us to choose one particular parameterization rather than another. Thus, there should first be a more thorough diagnosis of the large experiments that have already been carried out. If in the future the diurnal cycle is to be implemented a complete review of these diagnostics with and without it must be done with high priority and new diagnostics developed accordingly to the new situation.

ii) A second question is how good is the cloud parameterization scheme presently used by ECMWF, especially as regards the geographical correlation of the cloud field with the individual synoptic systems. The horizontal and vertical distribution of cloud as used by the radiation scheme should therefore be verified against satellite and surface data. Here a distinction should be necessary between the "intrinsic" and "tunable" features of the cloud field; the work could also include comparison with other schemes. This verification is evidently of intrinsic importance, but also is required for a number of the investigations and experiments listed below. Special attention should be given to the tropics in view of the fact that the Centre's scheme does not include any output from the convection scheme in the cloud cover calculation.

iii) The temperature of the lower stratosphere is largely determined by the effective radiating temperature of the troposphere and the radiative properties of carbon dioxide, ozone and water vapour present in the lower stratosphere. The ECMWF scheme has more cooling than the other schemes we have examined and the dependence of the calculation on the tropospheric cloud distribution and small stratospheric humidity mixing ratios should be investigated.

iv) At first sight the other systematic errors (see Sect. 2.1) may arise from the parameterization of convection, large-scale precipitation and the planetary boundary layer, but the possible contribution from the radiation scheme should be investigated.

v) In order to find out the degree to which clouds are important in our models it is necessary first to know the likely magnitude of the radiative heating or cooling of the atmosphere for clouds of different height and type. A "table" should be drawn up showing the vertical profile of the heating rate computed by the Centre's scheme for various cloud distributions. Special attention should be paid to the roles of surface parameters such as emissivity and albedo in these calculations. These will be single column experiments. The input parameters can be extracted from idealised profiles, radiosonde data, or the Centre's analyses and forecasts with an eye on representing various temperature and humidity conditions. No such coherent table has, to our knowledge, been drawn up. In addition, equilibrium calculations must be carried out with a one dimensional version of ECMWF's physical package. More details about this problem can be found in Sect. 4.1.3.

vi) Having obtained this information one can then ask the question as to what effect heatings and coolings of this magnitude may have when inserted in specific positions relative to given synoptic situations. A number of regional studies, using both limited area forecast models and limited-area diagnosis of global forecasts, should thus be performed for various synoptic situations, for example developing and decaying baroclinic systems. Results could be compared with theoretical computations of simple models with simple radiative forcing.

vii) Following the above two experiments, the importance of the clouds for global integrations should be investigated. Four types of calculations should be performed on a small number of cases, preferably including some with high predictability. These are:

- No clouds
- Zonally-averaged clouds
- Model-generated clouds (i.e. the standard model)
- "Observed" clouds.

The fourth type is obviously difficult to perform. Should the model-generated clouds in the early stages of the global forecasts verify well, these can be used instead. (See recommendation 2(ii)).

viii) In addition to these experiments, the series of experiments using different radiation schemes that has already begun should be continued, and diagnosed carefully (see recommendation 2(i)). These experiments should include integrations with simple schemes and perhaps one with a substantially more accurate, if more expensive, scheme. The seasonal dependence of results should be determined and documented.

3. CLOUD PARAMETERIZATION FOR RADIATION SCHEMES

3.1 Discussion

It appears that the problems facing modellers in their attempts to develop or improve parameterization schemes for radiation-interacting clouds are fourfold.

1. The global distribution of cloudiness is controlled by widely different processes and leads to different types of cloud formation (for example, cirriform, stratiform and cumuliform). It might be necessary for these distinctions to be reflected in parameterization schemes but there may be difficulties in combining more than one cloud parameterization scheme without introducing obvious contradictions. Nevertheless, if sufficient care is taken to focus only on those clouds having an impact on medium range forecasting, the strategy of separating clouds according to their mechanism of formation may lead to some progress because:

a) Boundary layer clouds are well understood and successful idealized models are available, (for example, Deardorff (1976), Randall (1976), Slingo (1978) etc.). The problem of the incorporation into a global model and of the applicability to all types of stratus situations has yet however to be solved; for instance a correct treatment of fog is important also for direct weather forecasting.

b) Following a lack of understanding of the physical processes that govern mid level cloud formation, simple relative humidity methods have been used up to now and verification is still needed; hopefully improvements will follow from the more physical approach to the cloud problem discussed in the next paragraph (cloud liquid/ice water content).

c) The same comments could be made about cirrus cloud, and here also the situation might improve if some progress were made in the parameterization of vertical transport of moisture. The problem of possible radiative maintenance of thin clouds, and the question of the different optical properties of water and ice clouds must be considered.

(d) Convective clouds parameterization for radiative purposes could rely upon results of the convective scheme of the model (see Slingo, J. (1978)). Although it is a very general problem the adequacy of applying radiative heating or cooling uniformly inside a grid box should be questioned here because of potential interactions between the subgrid scale convection and radiation.

2. The last two remarks emphasize a second problem area: there is a potential need for more direct interaction in the model between the radiative aspect of clouds and their latent heat release aspect. The failure of a first attempt in this direction at ECMWF (relating cloud cover with condensation rate) may be attributed to the lack of sufficient moisture prognostic variables in the actual version of the model. The introduction of a supplementary prognostic variable (related to liqud/ice water content) would create dynamical problems but could improve substantially the cloud treatment. Another possibility is given if sub grid scale fluctuations of primary thermodynamic quantities are considered. Both approaches could also be combined.

3. All these relatively ambitious considerations must be put into perspective by our third series of difficulties (of a more practical type). Simple and not too dramatic modifications of the present scheme can be envisaged without much difficulty, but more radical changes have first to be studied extensively with a one-dimensional version of the model. There is however no observational evidence that physical-dynamical feedback is not important for cloud maintenance or dissipation on a relatively short time scale. Thus part of the experimentation must be conducted with the global model and many difficulties are associated with this type of work. The "technical interface" with the radiation transfer computation scheme can also bring some difficulties (for example, overlapping versus random positioning of cloud layers).

4. Finally, another essential part of the experimentation programme envisaged here will be the verifications. These should be considered at two levels

- Firstly, direct comparison with field experiments taking due account of the sampling problems which will arise;

- secondly, diagnostics in the global model (comparison with satellite measurements, energetics, forecasting impact, etc.); here the existence of complicated self-regulating mechanisms during the integrations may potentially amplify the problem of extracting errors due to the radiation scheme from all other errors.

These four groups of considerations lead to the following recommendations:

3.2 Recommendations

i) Results following from recommendation 2(v), (vi) and (vii) (one dimensional, local and global studies of cloud's influence on forecast models' behaviour) should be used to determine the types of clouds on which the main parameterization effort should be concentrated.

ii) ECMWF should select some of the existing parameterization schemes for planetary boundary layer clouds and try to test them within the framework of the one-dimensional version of the operational model with adequate data, taken from different seasons and locations.

iii) ECMWF should undertake sensitivity studies to test the impact of introducing model prediction of cloud liquid/ice water content.

iv) Verifications of potential new parameterizations of clouds and their radiative transfer properties for the ECMWF model should be conducted at two levels:

(a) Special comparisons with earlier, current and planned field studies'results; see recommendation 5(ii).

(b) Test of the incorporation of the scheme in the model by global diagnostic verifications.

4. DESIGN OF RADIATION SCHEMES

4.1 Discussion

The design of radiation schemes is a topic that has been discussed at length in many places, (see for example, Lenoble (1980)) and it seems unnecessary to repeat these discussions. In this report we do not offer any new ideas or make detailed proposals as to which approach the ECMWF should use. Instead we make some general comments on the testing and validation of individual schemes, on the determination of an appropriate level of complexity, and on the identification of problem areas. We also offer some suggestions about the solution of some specific problems, namely the known systematic error in the stratospheric cooling rate, and the treatment of diurnal variations in radiation. This latter question is of course of more general applicability.

4.1.1 Validation of radiation schemes

In comparing the results from different radiation computation schemes, it should be borne in mind that there are several different sources of error that will need different techniques to identify them. It is important to examine only one source of error at a time. The sources are the

- numerical and mathematical approximations used
- spectral data for the gases and aerosols involved
- errors in physical input from the model
- errors in physical input not from the model (e.g. 0_3 climatology)
- programming errors
- treatment of inadequately specified input (e.g. overlapping of cloud layers).

Real validation of radiation schemes involves comparison with the real atmosphere. Unfortunately, this is still very difficult to do properly with present technology mainly due to the high spatial density of simultaneous measurements that are necessary to define the field of radiation and other parameters involved. However, the satellite measurements of the earth radiation budget gives the possibility of testing radiation codes at least for the systematic errors by using monthly means over specific areas. This simple test can be used to avoid unwanted large consequences on the radiation field resulting from any parameterization modification (radiative or not).

It could also be possible to test a radiation code for random errors in the clear atmosphere when the atmospheric parameters are well defined, and for erroneous treatment of the radiative influence of aerosols (in Western Africa one can observe some extensive quasi permanent and homogeneous aerosol layers). In cloudy conditions, a case study is much more complicated since the radiation experiment implies determination of cloud optical properties, large scale cloud cover overlapping, etc.

Finally, we may mention that it is clearly worthwhile to identify those aspects of cloud specification (and other specifications) to which a radiation scheme is sensitive or insensitive. Such information is invaluable in further development work on the scheme as a whole.

4.1.2 Complexity of radiation schemes required for medium range weather forecasts

There is not a great deal that can be said with assurance on this matter at the moment. Some of the proposals contained in this section of the report are aimed at addressing this question. Cubasch's (1981) results presented at the workshop were a beginning on this question.

A characteristic feature of the Centre's forecast model is the high level of eddy activity which it maintains. This is rather different from the behaviour of other forecast models which tend to lose eddy activity after a few days. If there is to be an improvement in forecast skill beyond the current average of 5 days or so then it is clearly essential to maintain the level of eddy activity. This characteristic of the model probably depends on many things such as the other parameterizations, the finite difference scheme, the analysis, etc.

Cubasch (1981) showed that in the context of the model the current ECMWF scheme (Geleyn and Hollingsworth (1970)) had more realistic zonal to eddy kinetic energy ratios than the Köln scheme (Hense, Kerschgens and Raschke (1980)) or the GFDL 1965 scheme (Manabe and Strickler (1964)). Geleyn (1981) showed some calculations which suggest that the correlation of heating and temperature is quite different between the ECMWF scheme and the Köln scheme. These differences were consistent with the ECMWF scheme having a higher level of eddy energy in the lower troposphere. What is not clear at the moment is whether the differences between these schemes is due to the treatment of the cloud case or the treatment of the clear case. If it is the treatment of the clouds which is significant then the question arises as to whether or not a similar result could be achieved with a much simpler radiation scheme together with the same treatment of clouds. This question is particularly relevant when we consider the question of the diurnal cycle (see below).

In general there should be compatability between the level of accuracy of the treatment of the different physical parameterizations in the forecast model. For the radiation calculation this implies that the feedback loops with other processes would be in the right sense and of the right order of magnitude. High accuracy of the cooling rate calculation in the face of the difficulty of cloud parameterization, is probably impossible. It is therefore important to establish the crucial factors in maintaining the feedback loops so that the calculation may be simplified in those areas, if any, which are expensive but do not contribute a lot to the overall value of the computation. This investigation should be concentrated on the clear sky computation. However a higher level of accuracy should be sought for time and/or space averaged results (see Sect. 4.1.1).

4.1.3 Single column comparisons of the EC model with other radiative models of similar complexity

The ECMWF radiation model tries to combine the advantages of a number of methods used for the approximate solution of the equation of radiative transfer, (two-stream procedure, mean-pathlength determination when treating multiple scattering and Curtis-Godson approximation). The aims were to keep the accuracy of the model good enough, the programming simple, and the computing time and the computer storage as low as possible. The effects of the following processes are treated: absorption by atmospheric gases, Rayleigh scattering, scattering and absorption by aerosols and cloud elements. Moreover partial cloudiness is introduced in a very advantageous manner combining random distribution of isolated cloud layers and maximum overlap of consecutive cloud layers.

In order to get more information about the efficiency of the present model and possible propositions for improvement, it would be desirable to perform comparisons with other radiative models of similar complexity. It is also desirable to make comparative computations with models which try to use the possibly most efficient method for certain spectral regions instead of combining all advantages of the methods for the whole, spectrum, e.g. emissivity methods in the long wave spectrum or a sum-of-exponential schemes combined with the two-stream approximation in the short-wave spectrum. The models must obviously be also able to treat partial cloudiness.

The procedure to perform these comparisons should be to make a sufficiently great number of runs with selected and fixed distributions of the atmospheric quantities: temperature, absorbing amounts of water vapour, carbon dioxide, ozone, liquid water content, aerosols.

The selected atmospheres must be chosen carefully in order to avoid unrealistic and contradictory distributions of, e.g. cloud cover, relative humidity and temperature. An homogeneous substract of the full global field used as input to the ECMWF radiation scheme after a short range forecast (long enough to eliminate spin-up problems) could be a first step towards this goal. This proposal would give an estimate of the scatter between different radiation calculations and is therefore interesting in itself. The next step would be to study in isolation the effect of each of the approximations such as multiple scattering, number of spectral levels, method of vertical integration, numerical techniques, etc. Such a project would probably best be organised under the auspices of the relevant international body such as the RC of IAMAP.

4.1.4 Diurnal cycle

The radiation code of the ECMWF model in its present form is run at twelve hourly intervals, with the consequence that the diurnal cycle of solar heating cannot be modelled and has been eliminated through the use of a daily mean of the solar zenith angle's cosine.

The most important variable quantities on this time scale are probably solar zenith angle, cloudiness and temperature (both atmospheric and surface), although water vapour, and surface albedo (through snow depth changes) will also vary.

The use of 12 hour means or spot values for all these quantities is likely to introduce systematic biases in the calculated radiative heating because all enter the equation of transfer non linearly.

The omission of a proper diurnal cycle in radiation can cause problems in other areas. For example, surface heating by solar radiation is related to latent and sensible heat transfer and convection which, via convective cloudiness, can react back on the radiation field.

The present radiation scheme is too expensive to run at every time step. One possible improvement might be to run a much simpler scheme more frequently, perhaps once per hour, and adjust its results by reference to the present scheme run once or twice per day. The details of the simpler model must be chosen to suit the computational time available, but it must be capable of dealing reasonably with diurnal variations of solar zenith angle and cloudiness in the case of solar radiation, and the diurnal variation in cloudiness and temperature in the simple long wave scheme. The simpler model must be tuned in order to provide results which are not too different from those of the standard model for the same situation. The principles behind the development of the Köln scheme (Hense et al (1980)) could be used here with profit: research of linear operators which would give the same results as the complicated scheme in a given situation. This "time interpolation" solution can also be replaced by a similar space (or space and time) interpolation.

4.1.5 Path length distribution in the stratosphere

Contrary to other radiation schemes using the same data (GFDL, Köln) the ECMWF radiation scheme shows a strong bias towards stratospheric cooling (see Cubasch (1981)). The difference with the GFDL scheme could be explained by the latter's use of climatological moisture distributions. But both the ECMWF and Köln schemes use the same moisture input and the original data on which gaseous transmission functions were parameterized are also the same for both. So we must obviously search for design weaknesses in the ECMWF scheme which would explain this stratospheric cooling.

In the ECMWF radiation code the basic hypothesis for the treatment of interactions between scattering and molecular band absorption is that the photon path lengths for gaseous absorption can be evaluated by a perturbation treatment of the grey case (Geleyn and Hollingsworth (1979)). That supposes that the photon path lengths distribution is monomodal. In the lower troposphere the distribution function is generally monomodal because of the multiple reflection between clouds and surface, however if we consider the upper layers the distribution tends to be bimodal for two reasons:

(i) the upper clouds are optically thin

(ii) the water vapour concentration rapidly decreases with the altitude.

Above the upper cloud layer the radiation is composed of one part (I_1) which is reflected (or emitted) by the upper cloud and another part (I_2) which comes from the lower level. The amount of water vapour encountered by the photons which contribute to I_1 is weak whereas it is much larger for I_2.

The way the mean path length is calculated introduces a bias to the second mode. That bias could be a reason for an anomalous cooling in the stratosphere.

As a complement to the remarks in Sect. 4.1.3 about comparisons of schemes, when these schemes use path length methods it is important, in order to obtain a physical analysis, that the mean path lengths be calculated explicitly and compared at each atmospheric level, but more specifically in the upper levels. This could be done for instance in cooperation with the group of the Laboratoire d'Optique Atmospherique (University of Lille). It is also important that the absorption parameterization be made as close as possible in order to isolate the influence of the basic simplifying hypothesis.

4.2 Recommendations

We summarize the discussion in this section with the following recommendations to ECMWF and to the relevant international scientific associations.

i) A new generation of radiation schemes is now in existence, all of them involving many different approximations. Efforts should be made to cross-validate these models on the same data, whether observational or model produced. Moreover, efforts should be made to identify the individual effects of the many approximations used in the various schemes, with special attention being paid to the influence of soil emissivities and albedos.

ii) In support of the recommendations 2(v), (vi), (vii) and 3(i) (studies of cloud impact on forecasts and subsequent classification of cloud parameterization requirements) and given the inevitable errors of the calculation one should try to use, in the radiation transfer parameterization, only that level of complexity necessary to describe the essential features.

iii) A specific proposal is made to study the influence of the non-unimodel character of the path length distributions in the stratosphere as calculated in the ECMWF model in order to investigate the excessive stratospheric cooling in the calculation. The fact that the Köln scheme did not have this defect when computing on the same data should also be used to understand the ECMWF problem.

iv) In order to introduce the diurnal cycle in the ECMWF model it is proposed that a simpler model be developed which can handle the essential quantities in a reasonable way. The results produced could then be revised by reference to a less frequent but more complete calculation before being introduced in the model.

5. VERIFICATION DATA REQUIREMENTS

5.1 Discussion

5.1.1 Generalities

The radiation-cloud parameterization scheme of the forecast model of the ECMWF and schemes of similar complexity are based on model variables (i.e. fields of temperature and moisture) and some prescribed boundary conditions (e.g. surface albedo, ocean temperature, seasonal - and diurnal - changes of solar zenith angle). These data provide the input for computations of radiation fields and heating/cooling rates in each layer, where parameterized cloud variables (in each layer fractional cover with prescribed optical thickness and overlap) are also taken into account. The data required to verify this type of parameterization scheme and the computational results, only as far as clouds and radiation parameters are concerned, should be considered here from two points of view:

- cloudiness and radiation data for parameterization development and test cases (comparison with field experiments)

- cloudiness and radiation data for global verification and climate diagnostics (for integrations with the global model)

These are of different scales in time and also in space.

5.1.2 Cloudiness data for parameterization and test cases

These may serve two purposes:

- verification of the computations

- special studies of the effect of radiation on dynamics to verify the level of complexity of radiative transfer calculations necessary in medium range numerical forecasts (e.g. behaviour of baroclinic waves . . .)

Over several areas and possibly in relation with special field experiments of other goals, such as Alpex and KonTur, the following data should be collected.

- radiation budget components - at least above and below the cloud fields

- fractional cover, areal distribution and overlap in several layers. (Cirrus occurrence should be treated separately since they represent a more difficult problem to be tackled probably at a later stage)

- liquid/ice water content; precipitation

- variations of these parameters with time (e.g. diurnal cycle)

Due to the different natures of data sets from different sources (e.g. ground routine network, radar, satellites) methods must be developed to merge data into one unique data set. It is also important that experiments be conducted over a significant period of time to ensure representative samples and to attempt to relate the cloud cover and radiation to the large-scale fields (e.g. as in Nephos II).

5.1.3 Global verification and climate diagnostics

The intensive observing periods of FGGE provide the most reliable data sets for a global model verification. Processing existing satellite data will be necessary in order to obtain cloud information to be used in connection with knowledge of the atmospheric state deduced from other measurements. Possibly cloud cover in at least three conventional levels (low, medium, high) is needed with special identification of cirrus, and cloud top height. Furthermore a distinction between diurnal variation of cloudiness and associated radiative transfer properties and "random" variations (i.e. travelling disturbances) is needed. The surface radiation data collected around the world for the same period would be a very useful complement to this dataset.

5.1.4 Possible data sources

Data on the radiation budget and cloudiness may be obtained from NOAA, NASA, ETAC, NSSDC, WDC, ESA if not transmitted routinely in the GTS. The data from the ETAC project may be especially useful for limited area studies. ECMWF has no role as a data handling Centre and therefore all previous remarks are addressed to specialized groups. However, the following specific recommendations to ECMWF can be made.

5.2 Recommendations

i) ECMWF should keep FGGE radiation budget archives (as later to be released from the Nimbus ERBE-teams). Also the compressed "climate data set", which will be derived from original satellite data over a five year period during the ISCCP, should be kept to allow the application of various algorithms (developed elsewhere) for extraction of cloudiness data. It should also store a selected set of test data, which may be available from individual field experiments.

ii) Close cooperation should be sought between ECMWF and individual research groups, particularly those involved in large field experiments (Alpex, KonTur, Nephos) for which an extra saving of detailed results of operational analysis and forecasts could be performed.

iii) One of the goals of such cooperative efforts should be to demonstrate the level of interactive radiative transfer calculations required within the numerical forecast model.

iv) In view of the sensitivity of ECMWF models to different conditions of cloud overlap, extreme care should be taken in the combination of various data sets and subsequent parameterization for use in the global models.

v) A limited sample of ETAC cloud analyses might serve as the best way to verify predicted cloudiness.

6. CONCLUSIONS

The recommendations of the four groups indicates what were the main points of consensus among workshop participants: Some immediate action should be taken to try to remedy the known shortcomings of the ECMWF radiation parameterization so that one can start assessing the influence of cloud-radiation interaction on medium range forecasts; this assessment should lead to a more balanced system where the treatment of one physical effect is weighted in terms of its influence; cooperation with modellers and experimentalists outside ECMWF is essential for the success of this effort; comparison with real data should always be done both globally and locally by means of global - and single column - numerical experiments.

The contributions printed in this volume will give the reader of these Proceedings a deeper insight into the problems mentioned in the above sections. Unfortunately many interesting points raised in the discussions following the talks could not be treated in the group discussions, mainly because of lack of time.

Effort will now start at ECMWF to implement as many of the recommendations formulated here as manpower and technical facilities will allow, and it is hoped that cooperation with other groups, and especially with those who took part in the workshop, will be part of this programme.

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LIST OF ACRONYMS

Alpex	Alpine Experiment
ECMWF	European Centre for Medium-Range Weather Forecasts
ERB	Earth Radiation Budget
ESA	European Space Agency
ETAC	Environmental Technical Application Center
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Programme
GARP JOC	GARP Joint Organising Committee
GARP WGNE	GARP Working Group on Numerical Experimentation
GTS	Global Telecommunication System
IAMAP	International Association of Meteorology and Atmospheric Physics
ISCCP	International Satellite Cloud Climatology Project
KonTur	"Konvection und Turbulenz" Experiment
NASA	National Aeronautic and Space Administration
Nephos	Etude de l"Influence radiative de la Nebulosité étendue".
NOAA	National Oceanic and Atmospheric Administration
NSSDC	National Space Science Data Centre
RC	Radiation Commission
WDC	World Data Centre