INTRODUCTION

Cloud cover is one of the main quantities to be predicted by an atmospheric forecast model. It is in itself a meteorological product which is required by the user, especially the general public for whom the cloudiness and sunshine forecasts are of considerable interest. As a physical parameter, cloudiness is a link between several of the processes represented in a numerical model; it is a key element of the hydrological cycle which in turn affects turbulent exchanges between the various atmospheric layers as well as the radiative budget of the earth's surface and of the whole atmosphere. The effect on surface temperature and moisture, and thus on the incidence of frost and fog, is the main short-term meteorological impact of cloudiness. However, its longer term impact on the atmospheric circulation is less well understood; it is certainly large on the time-scales of interest to climate modelling but, according to recent experience at ECMWF, is not negligible on time-scales of interest for medium range weather forecasting.

The formation, maintenance and dissipation of clouds, as well as their organisation, are the product of complex interactions between small-scale turbulent processes, larger-scale circulations, radiation and microphysical processes. One important problem is to assess how much of this complexity is required in a forecast model, in order to represent the main effects of cloudiness on the atmospheric circulation and, at the end, to make a useful forecast of cloud cover and related quantities.

At the same time, cloud formulations are difficult to validate and are very sensitive to uncertainties in several model variables, especially temperature and moisture. This was and remains one of the main limitations to their development.

The purpose of the workshop was to initiate an exchange of views among modellers and specialists in satellite data about the various approaches to the parameterization of cloud cover, the available validation methods and data, and the impact of cloudiness on the atmospheric circulation.

Apart from the oral presentations, three working groups discussed the following topics:

- Representation of clouds in numerical models
- Validation of GCM cloud parameterizations
- Importance of clouds in the dynamics of large-scale numerical models

The following three sections summarize the discussions and recommendations of these working groups. The remainder of the proceedings contains the text of the papers presented at the workshop.

IMPORTANCE OF CLOUDS IN THE DYNAMICS OF LARGE-SCALE NUMERICAL MODELS

1. INTRODUCTION

Operational weather forecasting centres have not regarded cloud forecasting as a serious business until quite recently, even though a number of forecast models, including that of ECMWF, have been predicting cloud fields for some years. The recent interest in cloudiness as an important climate feedback mechanism has focused attention on the ability of GCMs to predict cloud distributions, and this has led to heightened interest in the cloud forecasting problem, and in the possible influence of cloudiness on day-to-day weather changes. Nevertheless, the refereed literature still contains little or no discussion of current operational cloud forecast skill.

2. INITIALISATION

Clearly, accurate initialization of the moisture and divergence fields is necessary for successful cloud forecasting. In a four-dimensional data assimilation system, there is a strong inter-dependency of the moisture and divergence fields through the model's parameterization of convection. This is particularly true for the ECMWF scheme which is formulated in terms of moisture convergence. If the moisture convergence is initially wrong so will be the parameterized precipitation, which in turn further deteriorates the moisture field; this then becomes the first-guess for the subsequent analysis. A good moisture analysis, quite apart from the need for moisture data, therefore requires a good analysis of the divergence field and the use of a physically sound convective parameterization. Within the ECMWF system both the initialisation and the analysis itself act as filters on small scale features in the divergence field. The forecast model takes some time to recreate divergence on these scales (spin-up) and the model convection (which is partly driven by intense small-scale convergence) is initially too weak.

The use of partially divergent structure functions offers some hope of capturing divergence in the analysis, but in the absence of sufficiently dense high quality conventional observations it may be necessary to incorporate further non-conventional data. One possibility is the use of infra-red data to define the divergence field in the regions of high level clouds.

Analysis of the humidity field itself presents a problem due to its spatial inhomogeneity, lack of sufficiently dense conventional observations and uncertainty as to the quality of satellite observations.

3. EFFECTS OF CLOUDS ON RADIATION AND DYNAMICS

The effect of clouds on the radiation field manifests itself in two distinct ways. The first is by modifying the surface radiative flux, and the second is by a redistribution of atmospheric radiative cooling both horizontally and vertically. Surface effects, particularly due to obscuration, can be large (~ 100 Wm^{-2} or more) and certainly comparable with the surface turbulent fluxes, whilst within the atmosphere the effects are a localised response of the order of tens of Wm^{-2} and can be an order of magnitude less than, say, the heating due to convection. Nevertheless, sensitivity studies have shown that the atmospheric effects of clouds can have an impact on the forecast within 10 days; homogenisation of the cloud distribution, particularly in the horizontal, leads to a weakening of the extra-tropical synoptic scale cirlculations. This is evident in a weaker baroclinic conversion of A_E to K_E; clearly the spatial variation in cloudiness provides an important correlation between warming and rising.

The above arguments are supported by computations of the cloud radiative forcing in the UCLA model, in which the model's radiative fluxes with clouds are compared with those that would be obtained if no clouds occurred. The results show that the clouds warm the atmosphere radiatively in regions of large-scale ascent and deep convection, and cool the atmosphere radiatively in regions of large-scale descent and low stratiform cloudiness. Evidently the radiative effects of the clouds act to reinforce the existing large-scale vertical motion patterns that give rise to them. This is a positive feedback mechanism. Similar results have been seen in other studies.

The sensitivity of the model to the surface radiative effects of clouds can be very large. Long integrations performed at ECMWF have shown that clouds initiate through their albedo effect a negative feedback which couples cloud cover, evaporation, and the large-scale convergent flow, whereby precipitation is effectively reduced over the tropical continents by up to 50%. Another process stressed in Le Treut's presentation at this workshop is the climatological effect of stratus on the energetics of the atmosphere. These results are significant in view of the thermal forcing of planetary scale flow, and consequently an effort should be made to validate model-generated cloud cover and surface radiation over land. Poor representation of the diurnal variation of tropical cloudiness can lead to a similar result. A direct coupling between convective activity and cloudiness is needed to properly simulate the role of cloudiness in regulating the hydrological cycle.

The simulation of the diurnal cycle of cloudiness and precipitation has not been widely considered. The UCLA GCM includes the diurnal cycle and produces more cloudiness at night than during the day. It also shows a nocturnal maximum of convective precipitation over the oceans in qualitative agreement with observations. This is presumably due to the daytime warming of the upper levels of the atmosphere by absorption of solar radiation, which tends to increase static stability and thus limits the intensity of convective precipitation. However, these processes are not well understood and further study of the impact on the diurnal cycle over land and sea is required.

Clouds strongly influence the distribution of turbulence in the atmosphere. Practically all clouds are turbulent, because condensational heating at cloud base, evaporative cooling at cloud top, radiative warming at cloud base, and radiative cooling at cloud top all tend to drive convection in the cloud layer. In addition, the strong shear often found near cloud tops tends to produce mechanically driven turbulence. The turbulence modifies the cloud by entraining warm dry air, and by transporting moisture up from below. The interaction of clouds and turbulence in the boundary layer has been widely studied, but the corresponding interactions in the free atmosphere are almost entirely unknown.

Recent ECMWF results with a simple representation of the enhanced mixing due to shallow convective clouds have shown a marked improvement in the simulation of the trade-winds and the monsoon circulation. At present the turbulent mixing is not dependent on the radiative cooling or cloud amount. However, the sensitivity of the model to such a process suggests that this could be an important interactive mechanism, and indicates the need for a more unified approach to boundary-layer cloudiness and turbulent exchanges.

This is also relevant to the effect of radiative fluxes on the clouds. The radiative coling in the clouds leads to a positive feedback, and so cloudiness increases when turbulent exchanges are neglected. No mechanism exists in the ECMWF model to destroy these clouds, particularly boundary-layer clouds under stable inversions. Cloud-top entrainment instability may be relevant here.

GCM-dependent effective cloud amount fields may be useful for some applications. They are constrained, locally, by the observed shortwave and longwave radiative fluxes. Here, in contrast to externally generated observed cloud amount fields, they are implicitly tuned to GCM cloud-radiation models and surface albedo fields. Gordon finds effective cloud amount fields to be moderately sensitive, locally, to surface albedo, observed satellite-derived shortwave radiation data and the analysis of water vapour and/or temperature. Even so, they bear more resemblance to each other than to the 3-D Neph and surface-based analyses of observed cloud amount.

The effect of clouds on the radiative fluxes may be as much determined by the cloud optical properties as by the cloud amount. This may be particularly true of high-level cirrus clouds, whose liquid/ice water path length may vary by several orders of magnitude. Shortwave albedo and longwave emissivity can therefore vary widely.

4. RECOMMENDATIONS

(a) Efforts should be made to improve the analyses of moisture and divergence, perhaps by making use of satellite-observed cloud fields.

(b) Model development should focus on an attempt to unify the treatment of all cloud-related processes, including radiative interactions, precipitation, and turbulence. Use of liquid water as an explicit model variable is essential for this unification. Model experiments should focus on the role of clouds in modulating the roles of precipitation and evaporation, particularly in the diurnal cycle.

(c) The effects of clouds on the vertical profile of radiative heating should be investigated. In view of the apparent difficulty to verify these effects, ECMWF should perform single column integrations for selected atmospheres of various cloud cover and relative humidity profiles and do a comparison study with other radiation schemes. This is consistent with the international radiation comparisons now underway.

REPRESENTATION OF CLOUDS IN NUMERICAL MODELS

1. INTRODUCTION

The problem of predicting the cloudiness in a numerical model is not well posed and has no clear solution. A pragmatic approach is thus necessary in which various methods for predicting and treating clouds need to be explored to find the optimum scheme for a particular application.

Present cloud schemes may conveniently be divided into two classes:

(a) Diagnostic or statistical schemes, in which the cloudiness is derived from other variables within the model such as the relative humidity, vertical velocity, atmospheric stability or lifting condensation level.

(b) Prognostic schemes which include an extra model variable or variables to represent clouds and to model their formation/dissipation, and in some cases advection through the model.

The advantages and disadvantages of these methods are discussed below. In both classes convective cloud is commonly related to the precipitation rate given by the convective parameterization, or to the (closely related) saturated mass flux.

2. DIAGNOSTIC AND STATISTICAL APPROACHES

The most common parameter for predicting stratiform cloud is the relative humidity, and other factors taken into account include the atmospheric stability and vertical velocity. In the Sasamori scheme a statistical approach is utilised which involves the mean and standard deviation of the vertical velocity, in addition to the temperature and moisture fields.

Two main advantages of such schemes were identified:

- Simplicity - they are usually easy to program, economic and (relatively) easy to tune to give viable predictions.

- They are relatively independent of the rest of the model. They may thus be largely unaffected by other model changes (e.g. substitution of different convection schemes), though some re-tuning may be needed. It is also relatively easy to substitute other diagnostic schemes into the same model.

Some disadvantages should also be listed:

- There is often a degree of arbitrariness in their formulation. It may be very difficult to justify the physical basis of such schemes or the values of the tunable constants employed (reasonable-looking cloud fields do not necessarily prove that a scheme makes physical sense).

- Diagnosed clouds are often used solely by the radiation scheme and thus do not interact with other parts of the model where cloudy processes should influence the calculations (e.g. of turbulent processes).

- The radiative properties of the clouds have to be prescribed or calculated separately, sometimes from a liquid water path calculated on the basis of some ad hoc parameterization, although this is not the case for the statistical scheme developed by Sasamori.

3. PROGNOSTIC SCHEMES FOR CLOUD VARIABLES

The most well-known prognostic method for predicting the cloudiness is that which uses an additional model variable to represent cloud liquid water. However, such methods do not necessarily include either the horizontal or vertical advection of the liquid water.

There are several reasons why prognostic schemes are attractive:

- In principle, they allow a better physical representation of clouds and their effects on the thermodynamic, turbulent and radiative fields, because these effects can be related directly to the predicted liquid water content and its temporal evolution. They therefore have the potential for including more detailed formulations of cloudy processes.

- They can provide consistency in the treatment of clouds between the component parts of the model.

- They predict variables which in principle are measurable, either by airborne instrumentation or remote sensing techniques.

- Once a cloud model which relates the liquid water content to the cloud cover has been chosen, the cloud radiative properties are largely defined.

There are, however, problems with such schemes:

- They involve more programming changes and storage area, both in the model itself and its diagnostic package.
- There may be numerical difficulties, such as in calculating the advection of cloud liquid water if this is required.
- They cannot be run separately from the rest of the model to allow diagnostic studies.
- The radiative properties of clouds are not uniquely defined by the liquid water path as the cloud geometry (e.g. the cloud cover fraction) is also important. It is thus necessary to include additional assumptions as to the cloud cover or a statistical cloud model to retrieve the cloud cover required by the radiation scheme in addition to the liquid water path
- There may be problems initialising such a scheme.
- At present there is no reliable climatology or global measurement programme of cloud liquid water content with which one can validate such a scheme.

4. PARTICULAR PROBLEM AREAS

The prediction of low level, i.e. boundary layer, cloudiness is particularly difficult. Both the diagnostic/statistical and prognostic methods have problems in predicting the low cloud field. This is not entirely surprising as it is recognised that boundary layer cloudiness is often the manifestation of a subtle balance between turbulent processes (including entrainment), synoptic scale development and radiative cooling/heating.

It seems reasonable to demand that such clouds be treated in as consistent a way as possible by the various parameterization schemes, in particular the cloud amount used in the radiation scheme should be consistent with that used to compute turbulent transport in the boundary layer scheme. While prognostic cloud schemes show considerable potential in this area it may also be possible to obtain reasonable results from a diagnostic scheme if this condition can be met. Randall's approach to the cloud cover scheme is built into the PBL parameterization and provides input for both turbulent and radiative computations, thus overcoming some of the defects of diagnostic schemes. Smith's proposal also deserves special attention as it allows a coherent treatment of turbulent and radiative process within the PBL.

The relationship between "stratiform" and "convective" cloud in the boundary layer may pose some problems. Randall demonstrated that inclusion of cloud top entrainment instability to model the break-up of stratocumulus cloud was an important factor in determining the low cloud distribution over the sub-tropical oceans in the UCLA model. In the ECMWF Workshop on "Convection in Large-scale Numerical Models" (1983), Tiedtke presented results in which he showed marked improvements in the ECMWF model's trade wind boundary layer structure when a shallow convection scheme was included. In both models the thermodynamic structure of the marine boundary layer in suppressed conditions is controlled by an entrainment rate dependent on cloud cover, but in the first example this is modelled as stratiform whereas in the second it is convective. In reality, both processes may operate but in different geographical locations. It may not be easy to define the point at which the transition between these cloud regimes occurs.

5. RECOMMENDATIONS

(a) Given the inherent difficulties associated with predicting cloudiness in numerical models, ECMWF should pursue several approaches to the problem. In particular, they should develop a prognostic cloud scheme whilst continuing their work on diagnostic schemes. The work already being carried out in this area by groups in the Member States of ECMWF should be taken into account. Parallel experiments with various cloud schemes should be carried out.

(b) Work should be directed towards ensuring compatibility between the cloud scheme and other areas of the model. In particular, cloud amounts diagnosed in the boundary layer should be consistent with those used to model turbulent and convective processes.

(c) The diagnostic cloud scheme developed at the Centre by J.M. Slingo showed encouraging skill in short forecast integrations. Further forecasting and assimilation tests are needed, and in addition longer integrations would be valuable to establish the cloud cover climatology, with a view to including this scheme operationally. Attempts should be made to minimise the number of predictors used to determine the cloud cover by assessing the relative importance of the predictors and removing redundancy.

(d) The development of cloud schemes should be accompanied by an adequate strategy for the verification of the hypotheses involved, using, for example, the results from field experiments such as F.I.R.E. and simulations by "large-eddy" models.

(e) The limited area high resolution version of the ECMWF model could be used to assess the potential of a scheme based on the statistical approach which may require higher order information.

(f) The comparison of cloud schemes initiated by WGNE should be pursued and should include verification of radiative flux output, humidity fields and other relevant variables.

VALIDATION OF GCM CLOUD PARAMETERIZATIONS

1. INTRODUCTION

This discussion is limited to the issues involved in validating the cloud parameterizations used in GCMs using satellite-based cloud information. Although there are other types of atmospheric models and other sources of cloud information, GCMs and satellite data present the most comprehensive and challenging problems. The objective of the research recommended is termed "validation" to signify that this study will serve to provide error estimates; improvement of cloud parameterization schemes requires more difficult iterative studies of model testing and data comparison. Cloud parameterization in GCMs actually involves two related, but distinct, types of cloud models: cloud prediction schemes derive several cloud properties from the model's current atmospheric state, whereas cloud radiative schemes derive radiative flux divergences from some of these cloud properties. Both cloud models are important, but their validation can require different strategies.

2. SATELLITE DATA

Several satellite-based data sets which provide cloud distribution information are currently available for use in model validation studies. These include:

NEPHOS (University of Lille): The NEPHOS data set consists of AVHRR bi-dimensional histogram cloud analyses (with up to 5 levels of cloud), HIRS radiances from NOAA satellites and ECMWF meteorological analyses. The domain is 37.5°W-37.5°E, 18.75°N-71.25°N and the data is for the period 1 February 1982-31 December 1983.

NIMBUS-7 cloud climatology and radiation budget (NASA/GSFC and NOAA/NESDIS, USA): Provides twice daily, global low, middle and high cloud amount, cloud top temperature, cloud UV reflectivity (daytime only), mean and variance of cloud and clear sky narrow band (11.5 µm) radiances, broadband solar and thermal fluxes, and surface temperature. Global coverage is at ~500 km resolution starting April 1979.

U.S. AIR FORCE 3-D NEPH (NOAA/NCDC, USA): This operational product has been studied most carefully for the FGGE year; it provides information on cloud amount and cloud altitude. Global coverage is at a resolution of 40 km every 3 hrs.

ESA, JMA and NOAA operational products: ESA and JMA offer operational cloud cover amounts over their region every 12 hrs. NOAA produces radiation budget quantities from the polar orbiter radiometer data every 12 hrs.

GOES cloud analysis (NASA/Langley, USA): Provides hourly cloud information at 250 km resolution in GOES-EAST area for selected months of FGGE year. Parameters reported include cloud cover fraction for total, low, middle and high clouds, mean temperature and albedo for these cloud types, and mean surface temperature and albedo.

NOAA 5 cloud analysis (NASA/GISS, USA): Provides global cloud information once per day (daytime) for selected months in 1977. Parameters reported include cloud cover fraction, optical thickness, top temperature and altitude for total, low, middle, high, "deep convective", and "thin cirrus" clouds at resolutions ranging upward from 100 km. Also provided are mean narrowband (0.6 - 11 µm) radiances, surface temperature and reflectivity.

TIROS-N sounder cloud analysis (NASA/GSFC, USA): Provides global cloud information at 250 km resolution two to four times per day for selected mont in the FGGE year. Parameters reported include fractional cloud cover, cloud top temperature and altitude, atmospheric temperature and humidity profiles, and surface temperature and emissivity.

Several new cloud and radiation budget related data sets will soon appear as the result of ERBE* (radiation budget measurements from two or three satellites), ISCCP* and field studies such as FIRE*. The ISCCP cloud climatology will provide global cloud information at 3 hr intervals starting with July 1983. Parameters reported at 250 km resolution include cloud cove fraction, optical thickness, top temperature and pressure for total, low, middle, high, "cirrus" and "deep convective" clouds, mean total and clear sk narrowband (0.6 - 11 m) radiances, surface temperature and reflectivity, atmospheric temperature and humidity profiles, and ozone column abundance.

All of these data sets will provide useful information for cloud parameterization validation studies, but two important facts must be stresse Since these data are derived from satellite radiance measurements, cloud radiation models are employed in the analyses. These models differ from dat set to data set and may be different from the radiative models used in the GCMs. Validation of these data sets is necessary and such efforts are underway. Because of the view of clouds afforded by satellites and the necessity for radiative models to link measurements to cloud properties, man kinds of desirable information about clouds are not available. Model diagnostics may need to be altered to provide satellite and model quantities which are compatible with the different data sets.

*ERBE - Earth Radiation Budget Experiment
ISCCP - International Satellite Cloud Climatology Project
FIRE - First ISCCP Regional Experiment

3. MODEL STUDIES

Model validation studies have begun, but they must be considered preliminary due to the uncertainties in data quality. Types of studies which are underway are: (1) comparisons of model generated cloud and radiation budget distributions to both cloud and radiation budget climatologies, and analyses at specific times and locations, (2) comparisons of cloud distributions generated in a single GCM utilizing different cloud prediction (and radiation) schemes, and (3) comparisons of cloud distributions and cloud types in different GCMs. These studies allow important conclusions about model parameterizations of clouds and cloud types, but for further improvement more quantitative studies are needed. Objective methods for comparison of different cloud distributions are lacking.

The observed diurnal and seasonal variability of cloudiness are very strong signals, which stand out above uncertainties in an observed cloud climatology. Any successful cloud forecasting model should be able to reproduce these signals with good fidelity. Ensemble n-day forecasts have the potential to reveal systematic drifts in the model simulated cloud climatology, and so they should also be considered as an important method of verification.

4. RECOMMENDATIONS

(a) Various satellite-based cloud property data sets are available now with sufficient coverage, resolution and detail to challenge the GCM parameterizations. Even though validation of the accuracy of these data sets is still in progress, they can be used to develop the methods and procedures involved in the validation of GCMs. Such studies will allow definition of both the data and model diagnostics best suited to testing the performance of model parameterizations and allow the solution of several problems which arise in the comparison of data and models. Foremost among these problems are: (1) compatibility of spatial resolution and mapped parameters between data and models, (2) compatability of time of occurrence or time averaging between data and models, and (3) compatibility of cloud properties defined by the satellite view and model structures.

(b) Cloud distributions and variations are spatially and temporally complex. Proper testing of a parameterization scheme therefore requires that comparisons between data and models be made on more than one space and time scale. Comparisons should be made on both *regional* (1000 km) and *global* scales to test particular processes (case studies) and general validity. Comparisons should be made in both *forecast* and *time-averaged* mode to test processes and general statistical agreement. This approach is necessary to isolate the cloud parameterization schemes from other physical processes in the GCM.

(c) The three quantities which should initially receive most attention are total cloud amount and the solar and thermal fluxes at the top of the atmosphere. Comparisons of all three will lead to conclusions about the basic validity of current parameterizations and suggest studies for improvement of these schemes. The spatial and temporal variation of cloud amount (space scales at least as small as 500-1000 km, time scales including diurnal and seasonal) should be compared in addition to space and time averaged values. *This comparison must be quantitative*, including calculations of correlation coefficients, difference maps, etc.

Though care in interpretation of both data and model should be exercised, it is particularly crucial to look at specific cloud type situations. Examination of simple case studies, defined either by the data or the model patterns of cloud distribution, can be revealing of model shortcomings. One example of this strategy is examination of cloud amounts in the subtropical, marine stratocumulus regions.

(d) Though not crucial for early model validation studies, regional cloud observational projects (e.g. FIRE) will become more important in attempts to improve model cloud parameterizations. First order comparisons between satellite-observed and model-calculated cloud amounts will allow significant progress, but more refined understanding of cloud processes and cloud-radiative effects will require more detailed regional observations to validate the remote sensing data and the model parameterizations.

(e) Cloud cover data should be associated with adequate complementary data sets in order to allow global forecast verifications.