PARAMETERIZATION OF CLOUD COVER

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1. INTRODUCTION

In 1975 Arakawa wrote: "The importance of clouds in climate modelling cannot be overemphasized. Clouds, and their associated physical processes, influence the climate in the following ways:

(1) By coupling dynamical and hydrological processes in the atmosphere through the heat of condensation and evaporation and redistributions of sensible and latent heat and momentum.

(2) By coupling radiative and dynamical-hydrological processes in the atmosphere through the reflection, absorption, and emission of radiation.

(3) By coupling hydrological processes in the atmosphere and in the ground through precipitation.

(4) By influencing the couplings between the atmosphere and the ground through modifications of the radiation and the turbulent transfers at the surface.

Although these cloud-dominated processes have long been known to be important in determining climate, clouds have been very poorly formulated in climate models. In particular, the coupling between the radiative processes and the dynamical-hydrological processes through time-dependent cloudiness has been either completely neglected or modelled only in a very crude way, even in the most comprehensive general circulation models."

Since then, although some advances have been made in the representation of clouds and in the understanding of their importance in both long and short time scales, cloud prediction and the relationship between cloudiness and other physical processes is still very much in its infancy. In most cases the coupling between the clouds and the dynamical and hydrological processes occurs indirectly as a result of radiatively induced changes in the large-scale thermal state of the atmosphere.

Nevertheless a number of studies on the climatic or long-term effects of clouds (e.g. Shukla and Sud 1981; Meleshko and Wetherald 1981) have shown that the model's simulation of the general circulation is significantly sensitive to the specification of cloudiness. For shorter time scales, e.g. medium range forecasts, the impact of clouds was generally considered to be less important mainly because radiative time scales tend to be large. However, studies by Geleyn (1981) and Slingo (1984) have shown that simplification of the cloud cover parameterization leads to a weakening of the extratropical circulation during the forecast period (10 days), particularly in the synoptic scale. There is now an increasing effort to improve the representation of clouds in models, not only with respect to their interaction with the radiation field, but also to provide a closer connection with the hydrological and dynamical processes within the model. This paper will describe the approaches commonly used and the problems encountered, and give examples of the quality of results currently available. The question of verification will also be considered.

2. PROBLEMS OF CLOUD PREDICTION AND POSSIBLE APPROACHES

The prediction of cloud amount, height, thickness and optical properties presents major problems because, firstly, the formation and dissipation processes are poorly understood and, secondly, most clouds are sub-grid scale, both horizontally and vertically. Clouds are a product of complicated interactions of moist convective turbulence with larger scale circulations, radiation and micro-physical processes. Clearly the resulting cloud cover will be very dependent on how well these processes are represented in a model. They in turn may well depend on the model's horizontal and vertical resolution.

At present there are two basic approaches to predicting cloudiness. The first is a statistical or diagnostic approach in which cloudiness is predicted empirically from model variables, the functions chosen to represent the probability of cloud occurring under certain atmospheric conditions. The basic premise of such schemes is that condensation on the smaller scale is part of a larger scale condensation regime related to the synoptic scale situation. Qualitative support for this is evident in any satellite picture. A list of parameters which might be used for diagnosing cloudiness could include:

- Relative humidity
- Convective activity
- Atmospheric stability
- Vertical velocity
- Wind shear
- Surface fluxes.

Ideally it would be desirable to find relationships between observed variables and cloudiness which could then be applied in the model. However, this has proved very difficult mainly because areal coverages are required and several investigations using sonde ascents have been largely fruitless (e.g. Smagorinsky 1960; Slingo 1980). The main disadvantage of diagnostic schemes is that the clouds are largely divorced from the rest of the model. They can only interact with other processes through the radiatively induced changes in the temperature field. Another disadvantage, less serious at this stage because of lack of verification data, is that the radiative properties of the clouds have to be prescribed or calculated separately, using some assumptions concerning liquid water content.

The second method is a prognostic approach which involves the explicit calculation of the liquid water content involving the formation and evaporation of cloud and rain drops. It requires the use of an additional model variable to represent cloud liquid water which may or may not be advected. Such a scheme will be computationally more expensive than a diagnostic method. There are clear advantages, however, to prognostic methods. They allow proper representation of the thermodynamic effects of sub-grid scale condensation (precipitating and non-precipitating) and also provide a more direct link between the radiative, dynamical and hydrological processes within the model. In addition, since they predict the cloud liquid water content required by the radiation scheme, they therefore, in principle, allow the prediction of cloud radiative properties as well as cloud cover. The main problems with such schemes are verification and interpretation. Data on cloud liquid water content are very limited. Also the cloud liquid water has to be expressed in terms of cloud thickness and areal coverage which are required in the computation of the radiative fluxes and for verification with observed cloud covers, both surface based and from satellites. This necessitates the use of a statistical cloud model often similar to those which form the basis of diagnostic methods.

3. DIAGNOSTIC METHODS

Two examples of diagnostic schemes will be described, the first designed for an operational forecast model and the second for a climate model.

3.1 ECMWF scheme

The basic philosophy and design of this scheme follows that originally developed from GATE data for the UK Meteorological Office limited area tropical model (Slingo 1980). A full description of the development and assessment of the ECMWF scheme is given in Slingo (1985) and will only be described briefly here. The scheme, which has been used in the operational model since May 1985, allows for four cloud types - convective and three layer clouds (high, middle and low level). Convective cloud cover (C_c) is determined from the scaled time-averaged precipitation rate ($\bar{P}$) from the Kuo convection scheme:

$$C_c = a + b \log \bar{P} \qquad (1)$$

An upper limit of 80% is placed on C_c

Table 1 indicates the cloud cover and the corresponding equivalent precipitation rate implied by Eqn. 1.

Table 1. Relationship between convective cloud cover and precipitation rate (P)

C_c	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
P (mm day^{-1})	.14	.31	.70	1.6	3.4	7.7	17	38	85

Cloud base and top heights are also given by the convection scheme.

The cloud prediction scheme distinguishes between two different types of cirrus (C_H), that associated with outflow from deep convection and that associated with frontal disturbances. When there is strong deep convection

$$C_H = 2.0\ (C_c - 0.3) \qquad (2)$$

provided that convection extends above 400 mb and the cloudiness exceeds 40% (i.e. equivalent precipitation rate of greater than 3 mm day^{-1}). Extratropical and frontal cirrus are determined from a function of relative humidity (RH):

$$C_H = \{\text{Max}\ (\frac{RH - 0.8}{0.2}\ ,\ 0.0)\}^2 \qquad (3)$$

Middle level clouds (C_M) are parameterized by:

$$C_M = \{\text{Max}\ (\frac{RH_e - 0.8}{0.2}\ ,\ 0.0)\}^2 \qquad (4)$$

where RH_e is the relative humidity of the layer after adjustment for the presence of convective clouds:

$$RH_e = RH\ (1.0 - C_c) \qquad (5)$$

assuming that the cloudy part, C_c, is saturated.

Low clouds seem to fall predominantly into two classes; those associated with extratropical fronts and tropical disturbances and those that occur in relatively quiescent conditions and are directly associated with the boundary layer. The first class of clouds are characterised by generally moist air and large scale ascent. These are parameterised using relative humidity and vertical velocity (ω):

$$C'_L = \{\text{Max}\ (\frac{RH_e - 0.8}{0.2}\ ,\ 0.0)\}^2 \qquad (6)$$

$C_L = 0.0$ if there is subsidence, i.e. $\omega > 0.0$

There is a linear transition up to a weak ascent

$C_L = C'_L\ \omega/-0.1$ for $-0.1 < \omega < 0.0$ Pa s^{-1}

where 0.1 Pa s^{-1} $\approx$ 3.6 mb hr^{-1}

Otherwise $C_L = C'_L$ (7)

Again RH_e is the relative humidity of the environment as defined in eqn. 5.

The second class of low level clouds are strongly linked to the boundary layer and are invariably associated with low level inversions in temperature

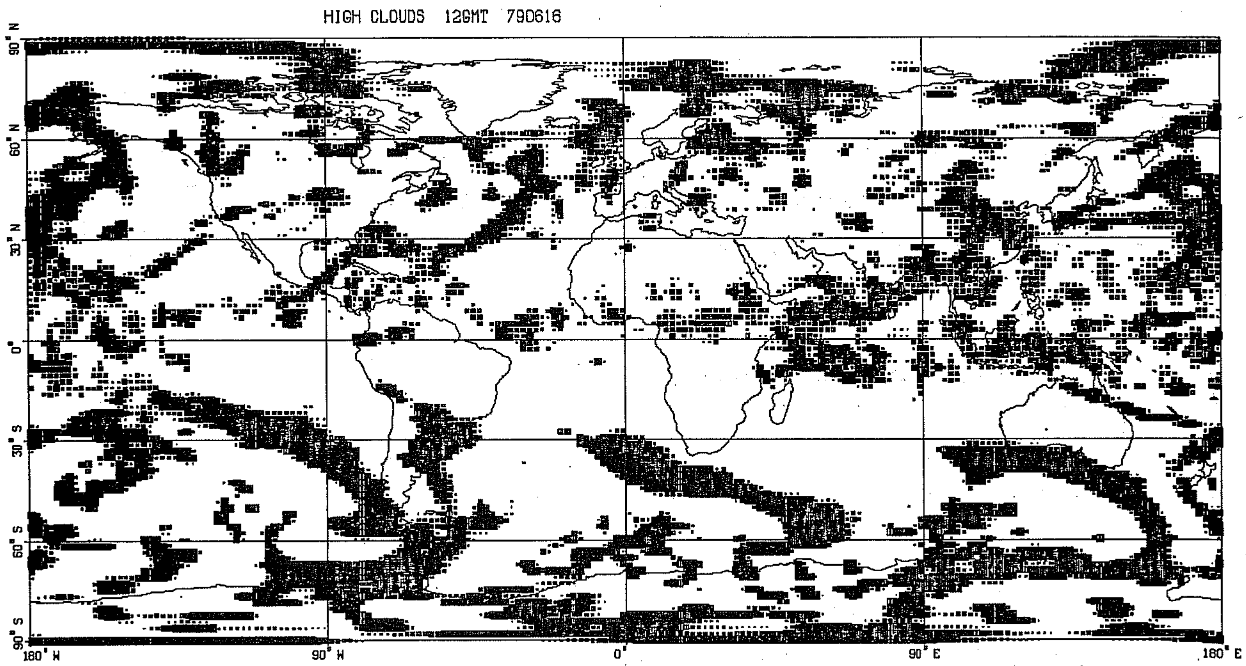

Figure 1: Distribution of high clouds from the ECMWF model for day 5 of a forecast from 12Z 11/6/79.

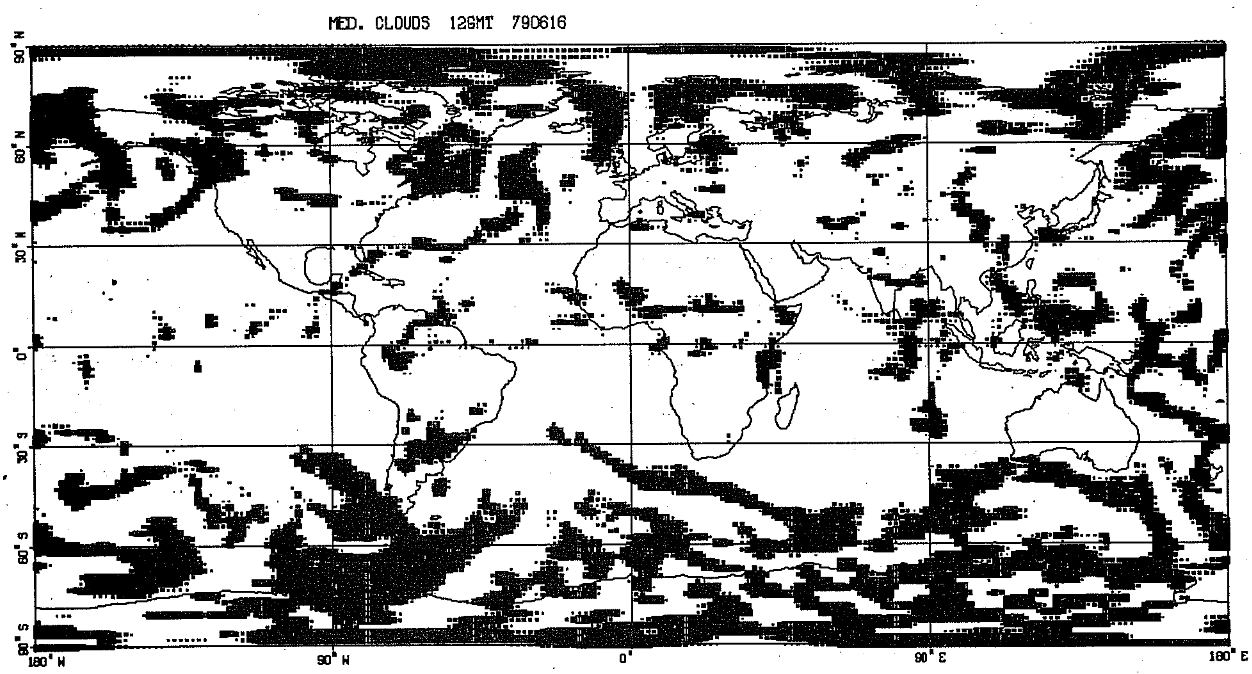

Figure 2: As figure 1 for middle clouds.

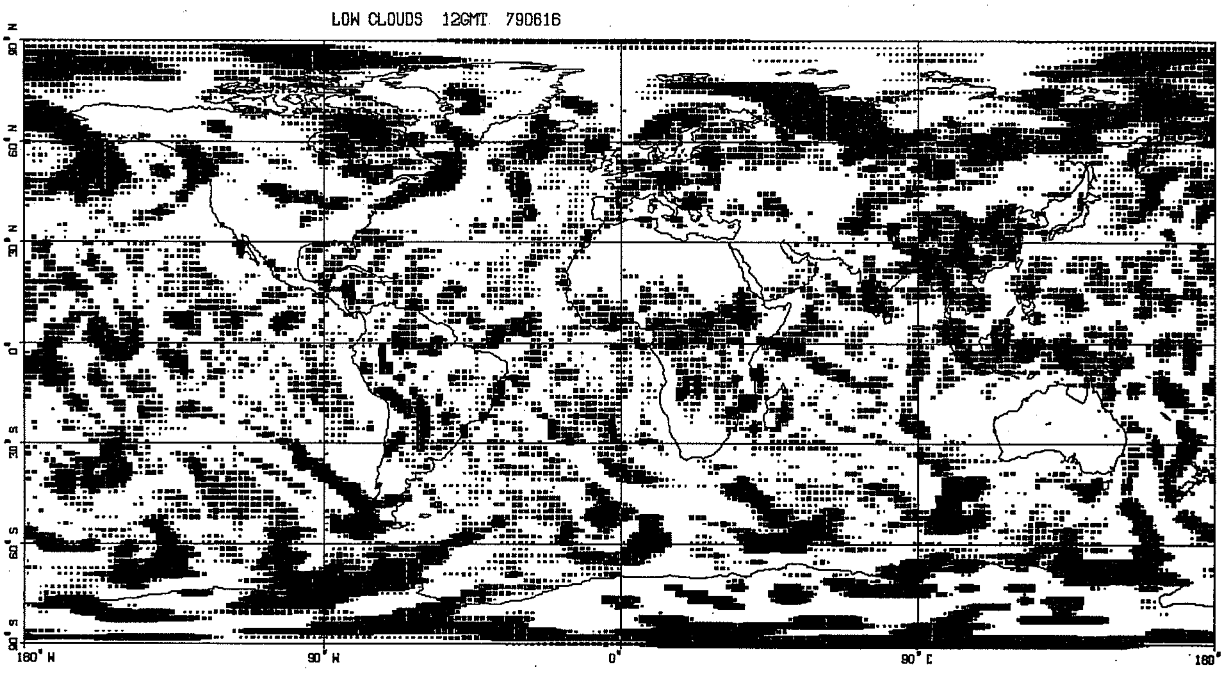

Figure 3: As figure 1 for low clouds (cumuliform + stratiform).

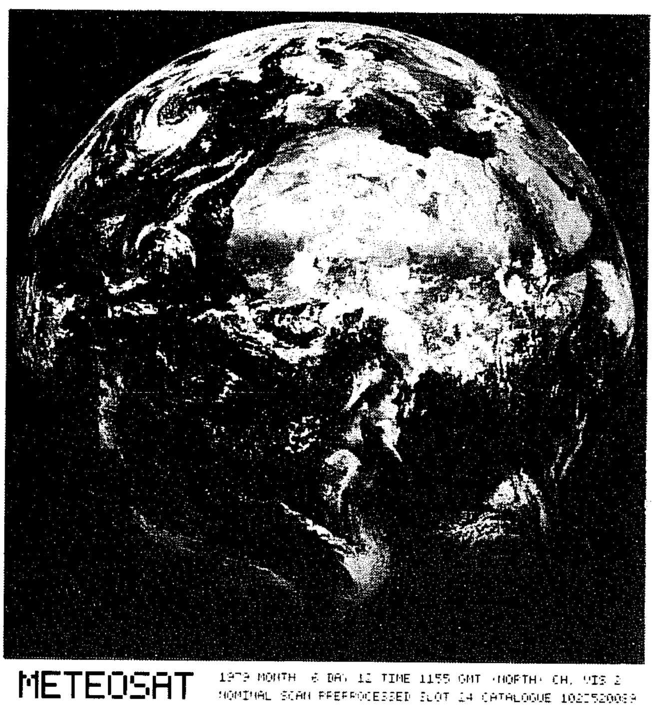

Figure 4: Meteosat visible image for 12Z 16/6/79.

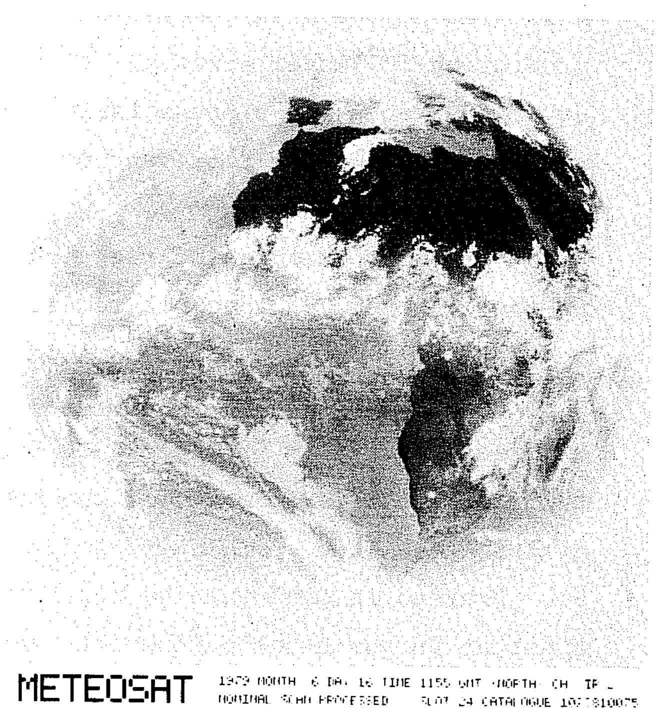

Figure 5: Meteosat infrared image for 12Z 16/6/79.

and humidity e.g. tradewind inversion. They are often vertically sub-grid scale and may therefore not be represented by the average relative humidity through a model layer. An initial parameterization is proposed such that:

$$C'_L = -6.67 \left(\frac{\Delta\theta}{\Delta p}\right)_{min} - 0.667$$

where $\left(\frac{\Delta\theta}{\Delta p}\right)_{min}$ is the lapse rate (K mb^{-1}) in the most stable layer below 750 mb. An additional dependence on the relative humidity at the base of the inversion has been introduced to prevent cloud forming under dry inversions such as those over deserts and the winter pole.

$$C_L = 0.0 \text{ if } RH_{base} < 0.6$$

$$C_L = C'_L * \left(1 - \frac{0.8 - RH_{base}}{0.2}\right) \text{ for } 0.6 < RH_{base} < 0.8$$

$$C_L = C'_L \text{ otherwise} \qquad (8)$$

A similar approach has been used by Le Treut (1985), in the LMD model for predicting low level stratus. It should be stressed here that these equations represent a probability of cloud occurring and should not in any way be thought of as representing a physical process.

Figs. 1-3 show examples of the cloud distributions predicted by the scheme in the 16-level T63 spectral model. (The cloud cover is represented schematically by relating the cloudiness to the fractional area of the grid square covered by a black pixel). The fields are taken from day 5 of a forecast starting from the FGGE analysis for 12Z 11 June 1979 and are typical of the performance of the scheme. In this case they can be compared with the Meteosat visible and infrared images for the same date (Figs 4 and 5). Bearing in mind that by day 5 the cloud fields will show deficiencies inherent in the model's forecast, the extratropical frontal cirrus (Fig. 1) agrees well with that in the Meteosat infrared image (Fig. 5). The high clouds in the tropics, associated with deep convection, are also well represented. The middle level clouds (Fig. 2) appear reasonable although these clouds are particularly difficult to verify because they tend to form in association with high and low clouds (Hahn et al. 1982; Hahn et al. 1984) and are therefore hidden from view both from the surface and from the satellite. Fig. 3 shows the combined low level stratus and cumulus clouds.

Again the agreement with the Meteosat images is good although the cloud is too extensive over S. Africa. The representation of the diurnal variation in cloudiness is satisfactory due mainly to the link with the convection scheme. Over the tropical continents the cloudiness increases as local noon is approached with a maximum cloudiness in the late afternoon. Thereafter the cloudiness decreases again as night falls and convection ceases. This general behaviour agrees with that seen in recent satellite studies (e.g. Gube 1982; Minnis and Harrison 1984).

These results clearly show that a fair measure of skill in forecasting clouds on short time scales can be obtained with a diagnostic approach. The number of parameters required to represent the various types of cloud is not large and can be shown to be justifiable (Slingo 1985).

3.2 UK Meteorological Office climate model cloud prediction scheme

The requirements of this scheme are somewhat different because it is intended for use in a climate model. Here the need is not only for a good forecast of individual synoptic features but also for a good simulation of the climatically important areas of cloudiness. The model is being developed to run with an interactive ocean so that, for example, the persistent areas of low level cloudiness over the eastern sub-tropical oceans are an essential part of the prediction. For a forecast model with a non-interactive ocean, prediction of these clouds, though desirable, is less crucial. In addition simplicity is an essential part of the scheme so that the results can be more readily understood and any deficiencies in the performance of the scheme more easily rectified.

The cloud prediction scheme is currently under development and the version described here is an updated one of that described in Slingo and Wilderspin (1985). The scheme, based on that described in Slingo (1980), is very similar in design to that used at ECMWF with allowance for four cloud types - convective and three layer clouds. Again convective cloud cover and base and top heights are derived from the model's convection scheme, although in this case the cloud cover is related linearly to the moist convective mass flux (Slingo 1980). The three layer clouds (C_H, C_M and C_L) are derived simply from the model's relative humidity (RH).

$$C_H, C_M, C_L = \{\text{Max}\ (\frac{RH - RH_{crit}}{1.0 - RH_{crit}}, 0.0)\}^2 \qquad (9)$$

The threshold relative humidity at which cloud can form RH_{crit}, is 0.95 for the lowest layer, 0.90 for the next layer and 0.85 for the remainder.

The scheme is used in the 11-layer grid point model which has a horizontal resolution of 2.5° latitude by 3.75° longitude. Fig. 6 shows the mean total cloudiness for a 90-day period, September through November. This can be compared with the observed total cloudiness for the same period (Fig. 7) from the atlas of satellite visible images compiled by Miller and Feddes (1971). The availability of global cloud cover climatologies is still fairly limited and there are considerable discrepancies between them (Hughes 1984). This atlas still remains one of the most useful even though there is no adjustment for the high surface reflectivities over the deserts. The model predicted total cloudiness compares quite well with the observed field. The amounts are slightly high but the minima in the subtropics are well represented as are the maxima over Central Africa and along the ITCZ. The break in the cloudiness over the Arabian Sea is also well represented. There is some evidence of the stratus/ strato cumulus in the eastern subtropical oceans.

Of ultimate importance in these models, however, is the radiation budget at the surface and for the whole earth/atmosphere system. That depends not only on the cloud cover but also on the radiative properties of the clouds. For that reason verification and adjustment of the scheme is very much based on earth radiation budget data from satellites rather than derived cloud amounts.

4. PROGNOSTIC METHODS

A prognostic method for predicting sub-grid scale condensation was first proposed by Sundqvist (1978) and it is that scheme which will be described briefly here. More recently Roeckner and Schlese (1985) have developed a scheme based on Sundqvist's approach which has been used with encouraging

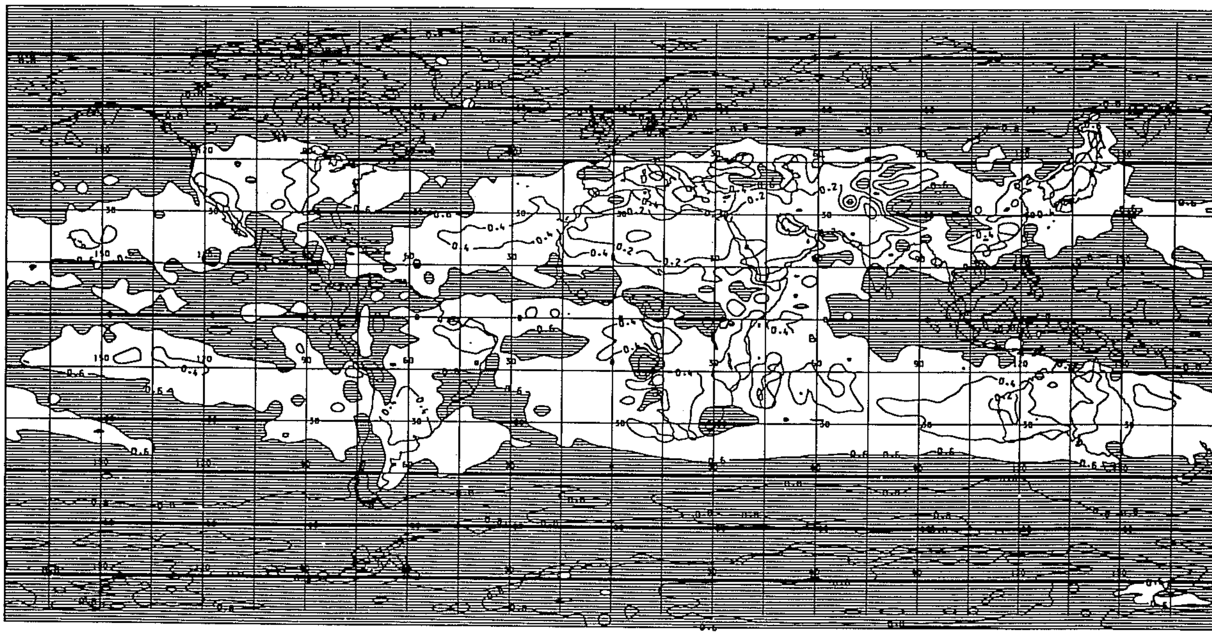

Figure 6: Mean distribution of total cloud for 90-day period, September through November, from the UK Meteorological Office climate model.

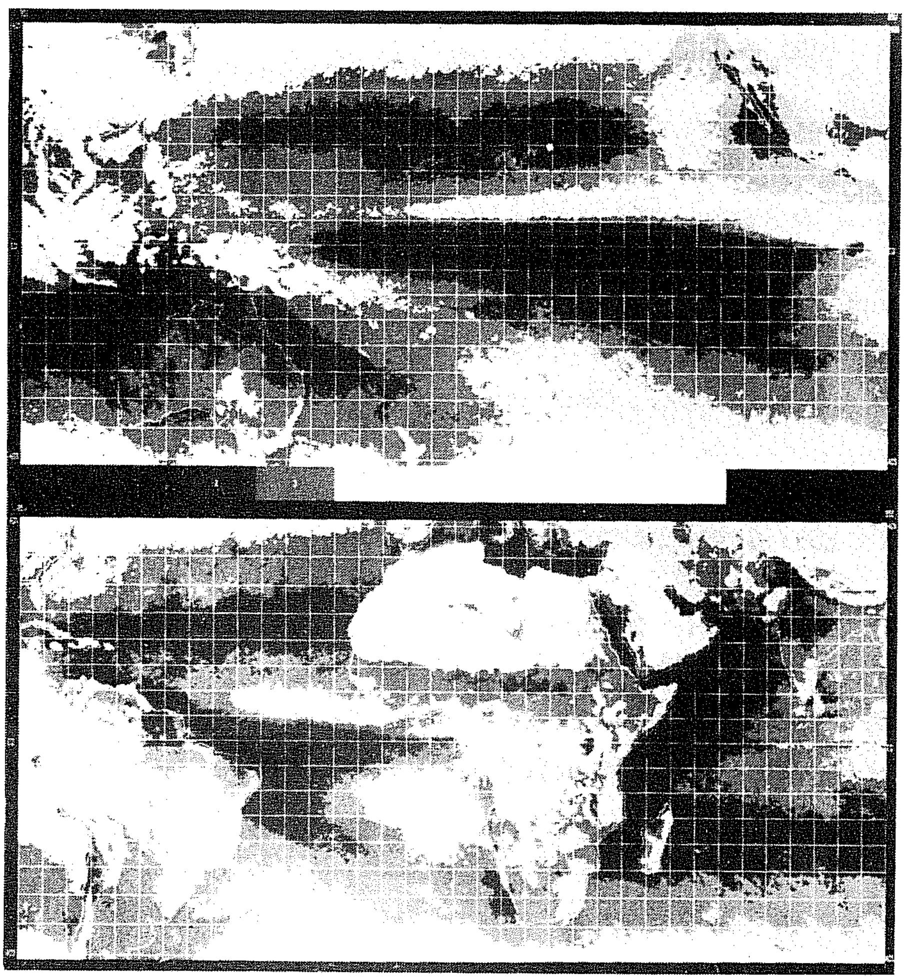

Figure 7: Satellite observed total cloudiness for $40^{\circ}N-40^{\circ}S$, September through November 1967-1970, from Miller and Feddes (1971).

results in the Hamburg University G.C.M. An additional prognostic variable denoting cloud liquid water (m) is required with extra terms in the prognostic equations for potential temperature ($\bar{\theta}$) and humidity ($\bar{q}$) which describe the phase changes from liquid to vapour.

Consider a grid square for which the fraction, a, is cloudy. Then the net heating resulting from condensation and evaporation is given by:-

$$Q = a.Q_c - (1-a)(E_c + E_r) \qquad (10)$$

where Q_c represents condensation and E_c and E_r, the evaporation of cloud and rain drops respectively. The thermodynamic and moisture equations for the whole grid square may then be written as:-

$$\frac{\partial\bar{\theta}}{\partial t} = A(\bar{\theta}) + (\frac{\bar{\theta}}{T}).(\frac{Q}{C_p}) \qquad (11)$$

$$\frac{\partial\bar{q}}{\partial t} = A(\bar{q}) - \frac{Q}{L} \qquad (12)$$

where the operator A represents the convergence by dynamical processes; i.e:-

$$A(x) = -\nabla.\{\underline{v}x\} - \frac{\partial\omega x}{\partial p} - \text{div. of eddy flux of } x \qquad (13)$$

The basic source of cloud water is condensation, the sinks being precipitation and evaporation of cloud drops transported into the clear fraction of the grid box. Thus the rate of change of liquid water (m) is given by:-

$$\frac{\partial m}{\partial t} = A(m) + a\frac{Q_c}{L} - (1-a)\frac{E_c}{L} - P \qquad (14)$$

where P is the formation of precipitation due to coalescence processes.

It is usual to neglect the vertical motion terms in A(m) and to assume that liquid water is only advected horizontally on the scale of the model.

Embodied in the terms P, E_c and E_r are the various assumptions regarding cloud microphysics such as the typical time for conversion from cloud droplets to rain drops, and the water content at which a cloud typically reaches a well developed precipitating state.

If, for the cloudy fraction a, $q = q_s$ and for the clear fraction $(1-a)$, $q = q_o$ then:-

$$a = \frac{\bar{q} - q_o}{q_s - q_o} \equiv \frac{\bar{r} - r_o}{1 - r_o} \qquad (15)$$

where r is relative humidity. Thus the choice of the threshold relative humidity r_o at which condensation can start to occur is a crucial part of the closure of the scheme. Typically $r_o = 0.8$. Also we can see that the rate of change of the mean humidity in the grid square can be expressed as:-

$$\frac{\partial \bar{q}}{\partial t} = a \frac{\partial q_s}{\partial t} + (1-a) \frac{\partial q_o}{\partial t} + (q_s - q_o) \frac{\partial a}{\partial t} \qquad (16)$$

Thus the net change in moisture for the whole grid square has to be partitioned between formation/dissipation of cloud drops within the cloudy fraction, general moistening of the clear fraction and a change in the cloud cover. There is no direct solution to this and some assumptions have to be made which again are a central part of the scheme. Both Sundqvist (1978) and Roeckner and Schlese (1985) assume that the large scale moisture increase/decrease is used to enlarge/reduce the cloud cover and that the relative humidity r_o, of the cloud-free part remains constant.

The scheme described above has been tested in the ECMWF N48 grid point model. As well as the stratiform cloud scheme described above, the model also included changes to the Kuo convection scheme which allowed prediction of cloud liquid water in convective situations (Hammarstrand 1982). Figs. 8-10 show the stratiform cloud distributions at high, middle and low levels from day 5 of an integration from initial data for 12Z, 11 June 1979. They can therefore be compared with the fields shown in Figs. 1-3 and with the Meteosat images in Figs. 4 and 5. The results are promising, bearing in mind that this was one of the first tests of the scheme in a global model. The high clouds (Fig. 8) have a coherent structure and show many features which are common to the results shown in Fig. 1 from a diagnostic method. Amounts are probably slightly large particularly in the tropics. Adjustment of the threshold relative humidity, r_o, may be all that is required to rectify that problem. The

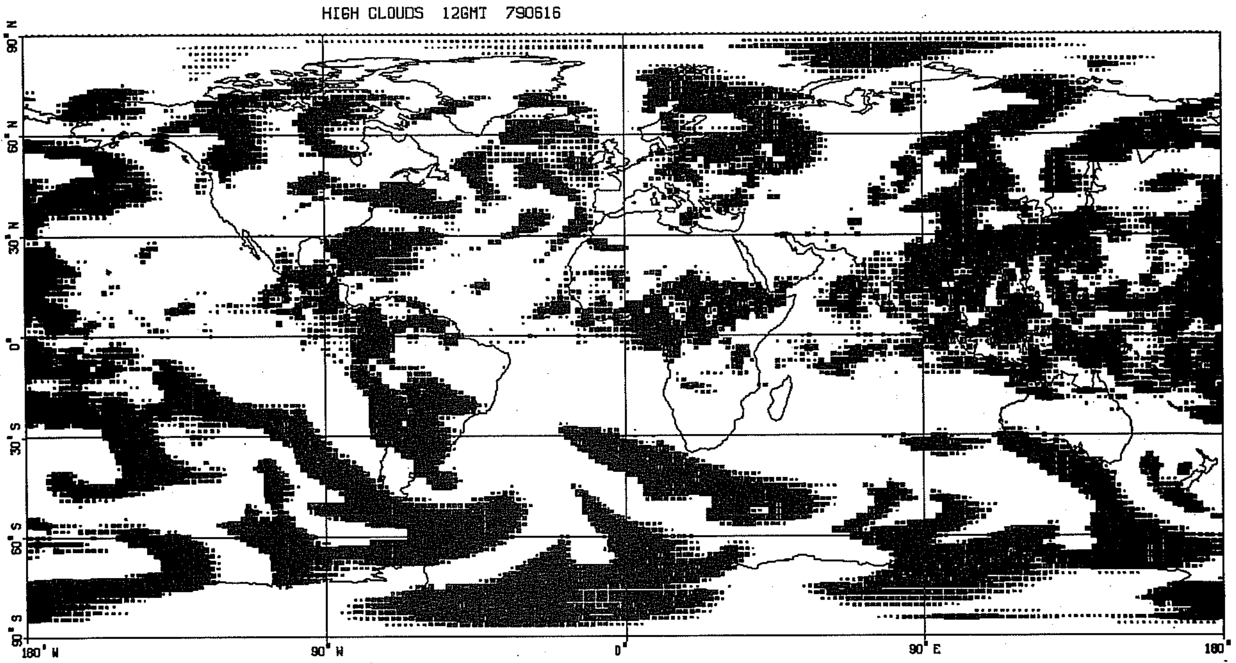

Figure 8: Distribution of high clouds from prognostic cloud scheme for day five of a forecast from 12Z 11/6/79.

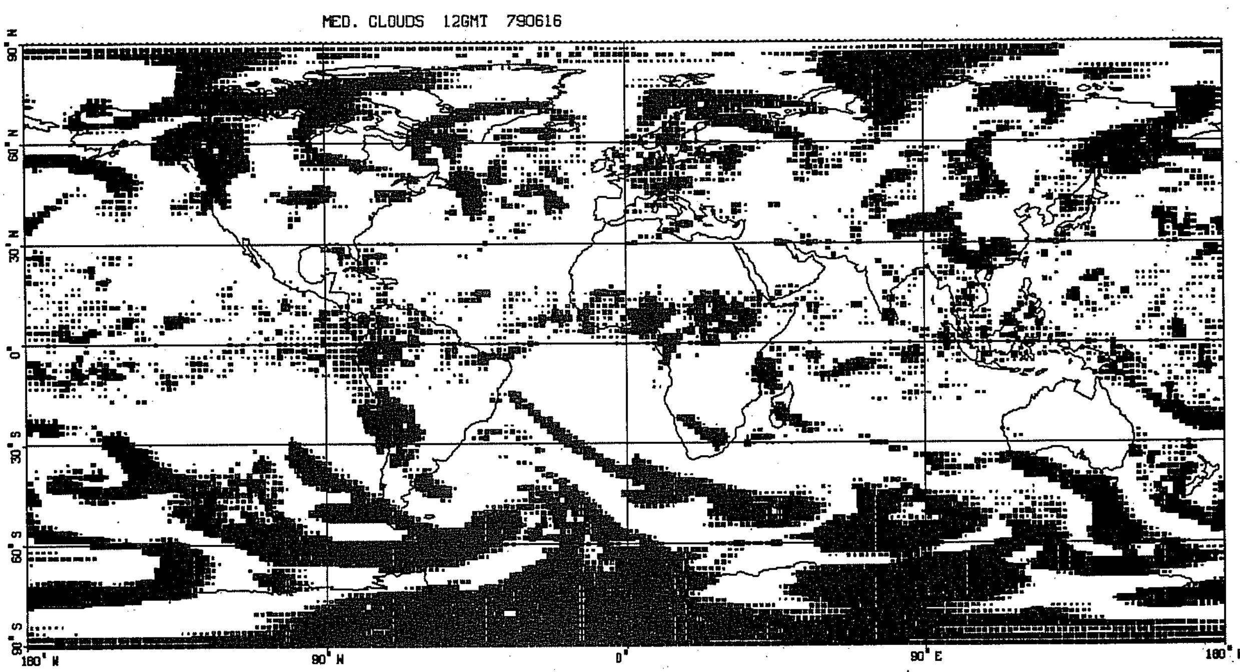

Figure 9: As figure 9 for middle clouds.

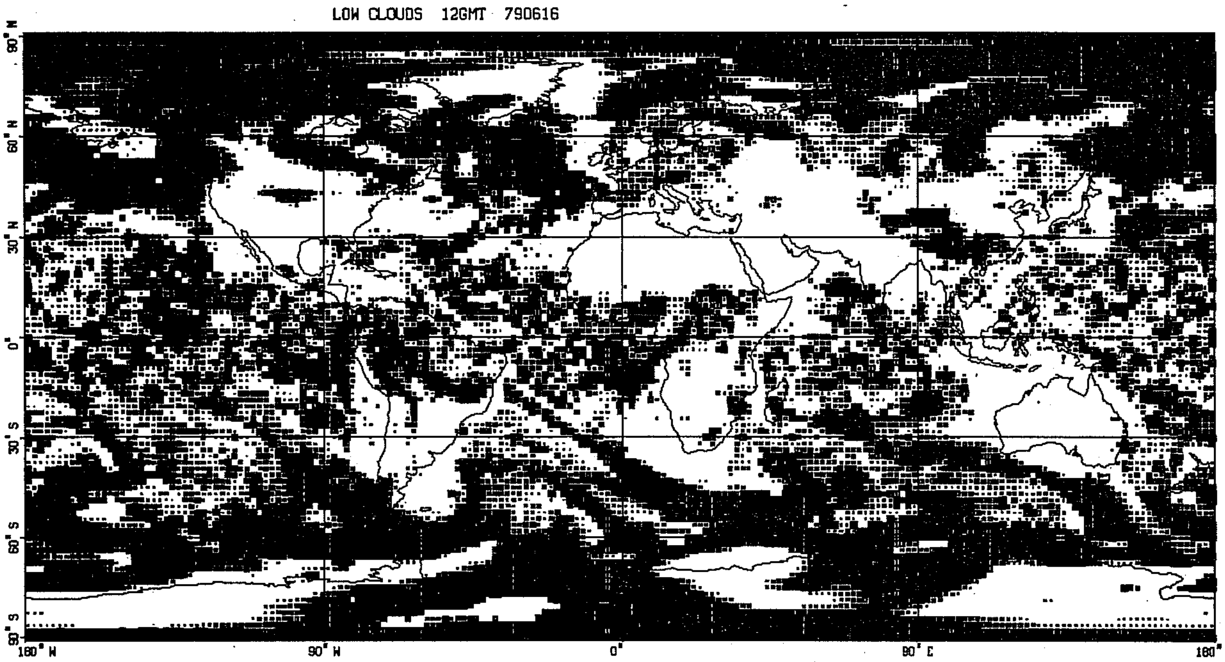

Figure 10: As figure 9 for low clouds.

middle clouds (Fig. 9) also show a good degree of coherence. Amounts are again higher than those obtained with the diagnostic method (Fig. 2) but may well be realistic.

The low level clouds (Fig. 10)) show the greatest problems. They are far too extensive and lacking in structure particularly in the tropics. This may be due in part to the choice of r_o although Roeckner and Schlese (1985) have found that the low level cloudiness, in particular, is sensitive to the choice of the cloud microphysical parameters used in the formation of precipitation. Also the version of the model used here was run without a parameterization of shallow convection (Tiedtke 1985) and in consequence the boundary layer tends to be too shallow and too moist. In addition the interaction between the clouds and the radiation will tend to exacerbate the problem. It is therefore difficult to draw any conclusions about the merits of the cloud scheme until it is tested in a more recent version of the model.

The problems of verifying cloud amounts have already been mentioned. The situation is considerably worse for cloud liquid water. Available data are very limited and so far the most widely used have been estimates by Njoku and Swanson (1983) based on satellite-derived microwave emission over the oceans equatorward of 60^o latitude. Other data are gradually becoming available in particular those from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) over the global oceans (Prabhakara and Short 1984). However, it is this lack of data which may present the most serious restraints on the development of prognostic methods.

5. VERIFICATION

Both methods of cloud prediction (diagnostic or prognostic) necessarily depend on how well the other parts of the model simulate the observed temperature and humidity structures. On occasions this has posed a severe restriction on the development of interactive cloud schemes (e.g. Slingo 1983). However, improvements in the model simulations, both in the forecasting sense and climatically, have meant that cloud prediction has become more skillful as is evident from the results shown

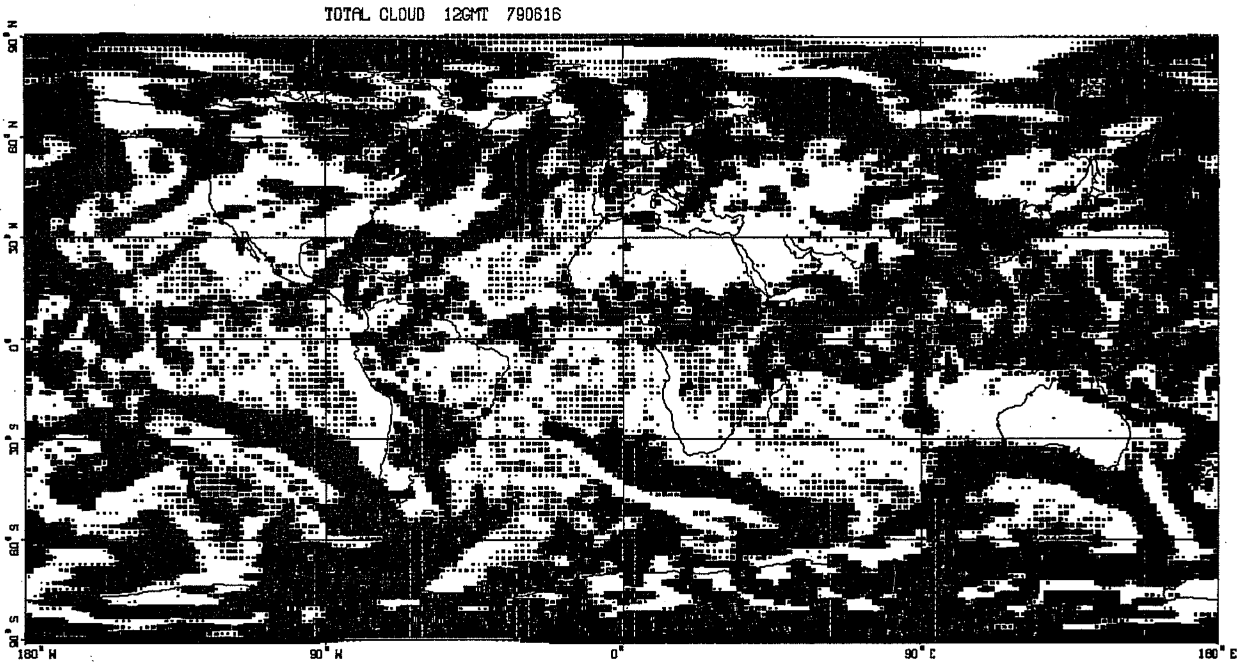

Figure 11: Distribution of total cloudiness from the ECMWF model for day 5 of a forecast from 12Z 11/6/79.

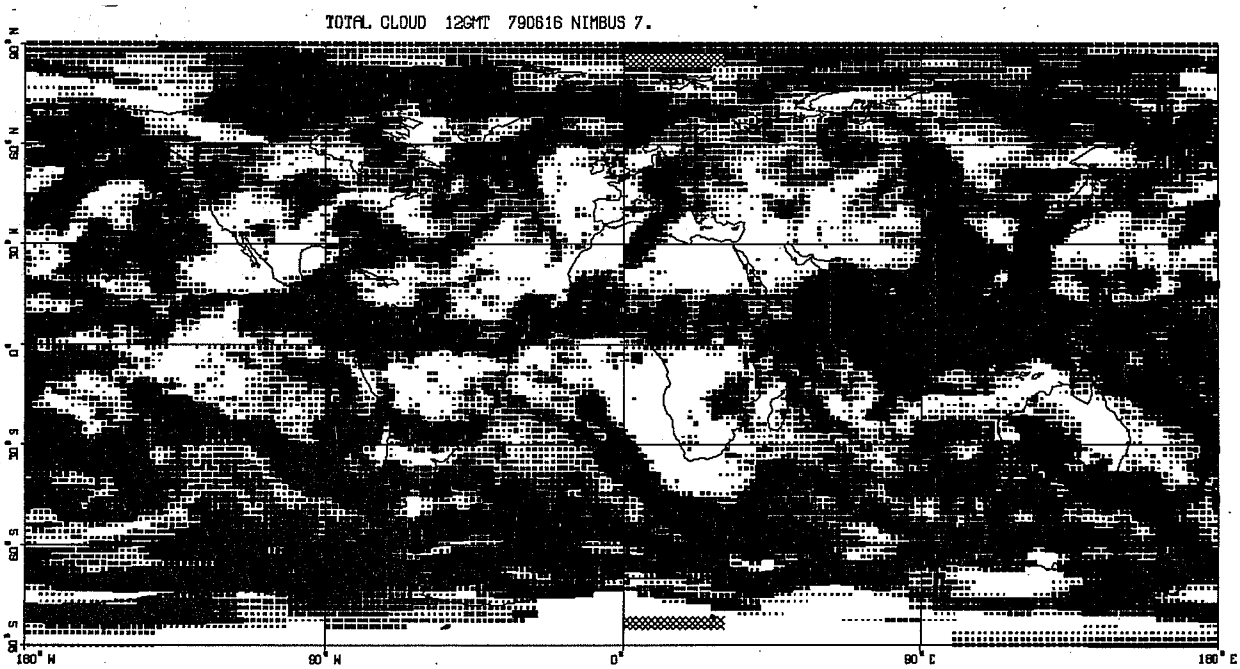

FIgure 12: Distribution of observed total cloudiness from Nimbus 7 for 16/6/79.

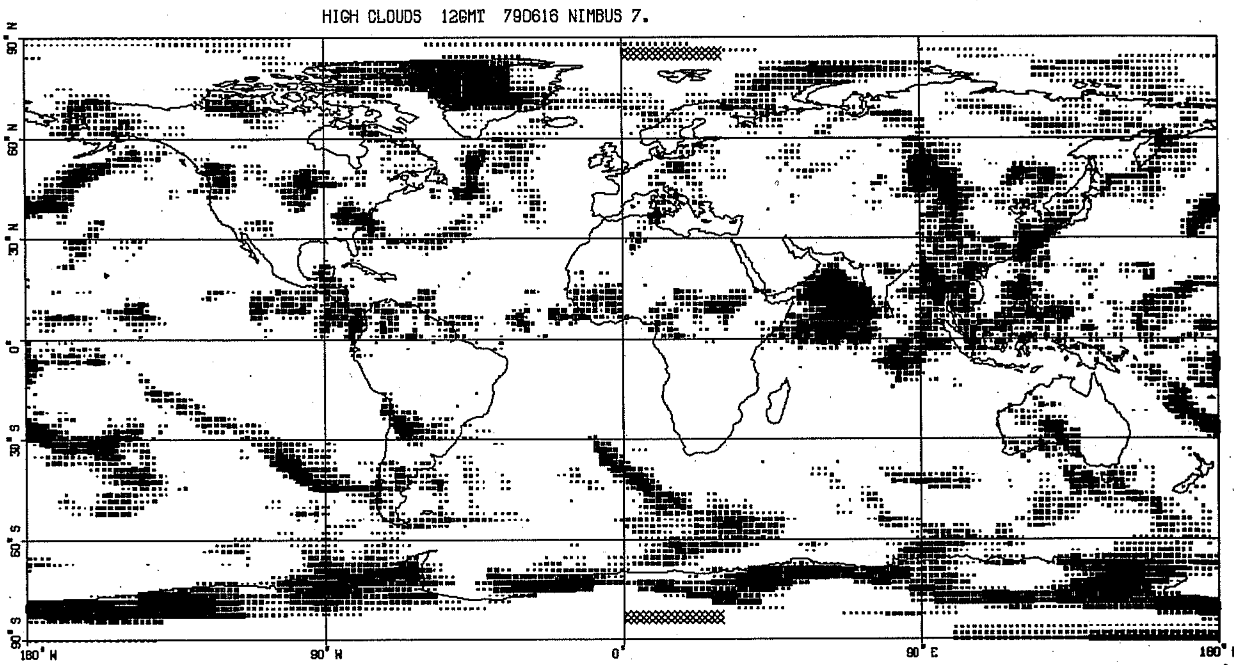

Figure 13: As figure 12 for high clouds.

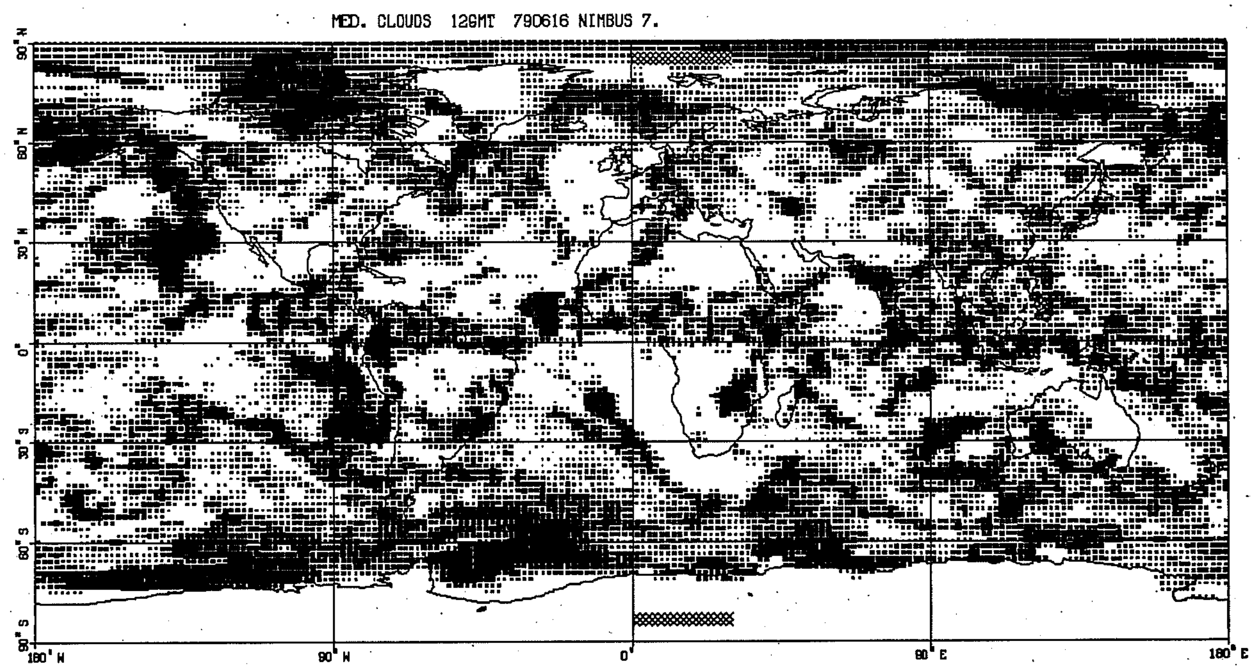

Figure 14: As figure 12 for middle clouds.

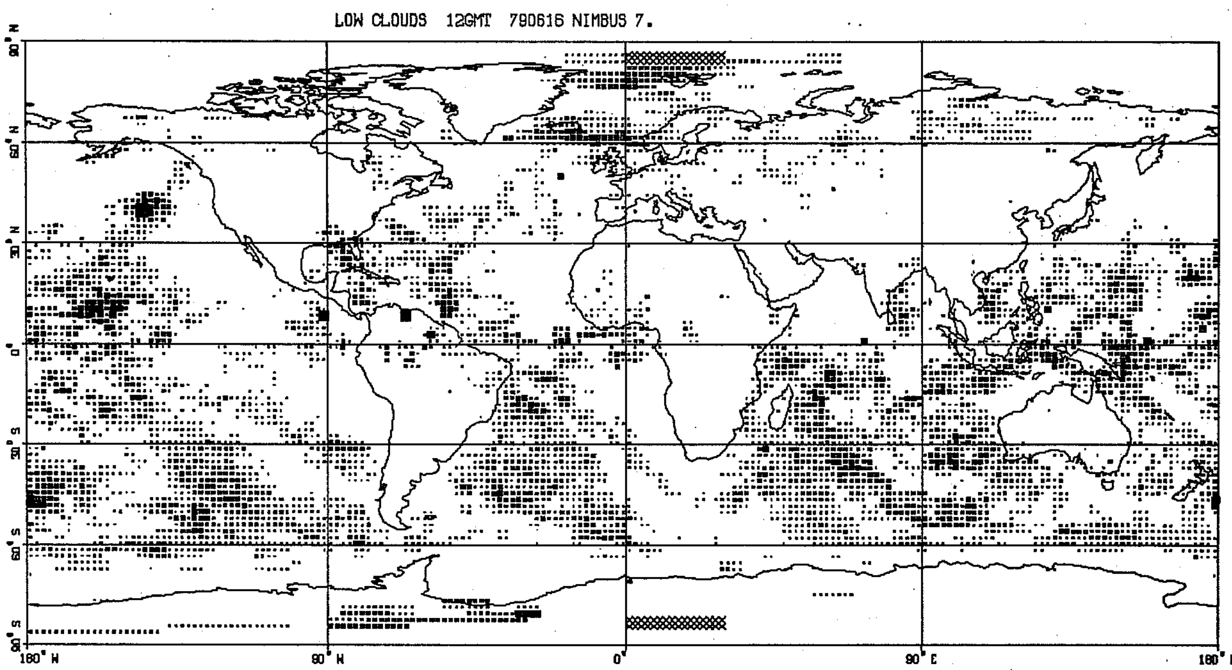

Figure 15: As figure 12 for low clouds.

in sections 3 and 4. That being the case, the question of verification assumes greater importance. Satellites clearly offer the best possibility of global datasets of cloud cover and radiative fluxes. Several new cloud and radiation budget datasets will soon be available as the result of the Earth Radiation Budget Experiment (ERBE) and the International Satellite Cloud Climatology Project (ISCCP).

The use of cloud data from satellites is not entirely straightforward. The cloud amounts and heights are dependent on the cloud model used to interpret the satellite narrow band radiances. Also obscuration of low level clouds by upper level clouds has to be remembered. Some of these problems are evident in recent attempts to use Nimbus 7 data for verification of the ECMWF cloud prediction scheme described in section 3.1. Cloud amounts at high, middle and low levels have been derived from radiance data for sub target areas of approximately $(160\ km)^2$ (Stowe et al 1985). These cloud amounts have then been interpolated onto the grid of the ECMWF model to provide as near a comparison as possible with the model fields. The distributions of total cloud cover from the model (Fig. 11) and the satellite (Fig. 12) should be directly comparable. Subjectively the model's prediction at day 5 of the forecast from 12Z 11 June 1979 agrees quite well with the Nimbus 7 data although overall the model has slightly less cloud (global mean of 49% compared with 56% for Nimbus 7). (The crosses in the Nimbus 7 fields represent missing data). However, where there are discrepancies, such as the S.E. Pacific, then more detailed information on cloud height/type is required if the necessary adjustments to the cloud prediction scheme are to be made. This is where the incompatibility between the satellite derived cloud covers and the model diagnostics becomes very evident. Figs. 13-15 show the high, middle and low level cloudiness derived from the Nimbus 7 data; these can be compared with the model fields shown in Figs. 1-3. Apart from the obscuration factor which can be overcome by processing the model data as if seen from a satellite, there is a clear difference in the classification of the clouds. The Nimbus 7 data show the majority of clouds as middle level whereas, for example, in the tropics and subtropics most of these clouds would be convective, strongly linked to the boundary layer and classed as low level clouds by a surface observer.

Although this comparison represents the first attempt at ECMWF to make a detailed verification of the cloud scheme against satellite data, and clearly it warrants further study, the implications of these results are clear. There must be more cooperation between modellers and satellite researchers. Indeed, model diagnostics may need to be altered to provide data which is more directly related to the satellite measurements. For example, the categorizing of clouds into various height regimes is somewhat arbitrary both for the satellite data and for the model, and will of course depend on the model's vertical resolution. It may be more useful for the model to produce radiances or cloud top temperatures which are comparable with those measured by the satellite. (For further discussion on this topic and on the availabiltiy of satellite data the reader is referred to the Proceedings of the ECMWF Workshop on Cloud Cover and Radiative Fluxes in Large-scale Numerical Models - Design, Validation and Dynamical Impact).

As mentioned earlier in section 3.2, earth radiation budget measurements provide another method of verification. When used in conjunction with estimates of the cloud cover they can give useful guidance on cloud radiative properties or liquid water contents. In the current version of the ECMWF model, the cloud radiative properties are dependent on the liquid water content (LWC) of the clouds. This in turn is based on the saturation water vapour mixing ratio (q_s) such that:-

$$LWC = 0.01\ q_s \qquad (17)$$

Comparison of the outgoing radiance from the model for days 1-2 of the forecast from 12Z 11 June 1979, with similar data from the NOAA polar orbiting satellites (Winston et al 1979, Gruber and Krueger 1984) suggests that equation 17 grossly underestimates the opacity of the tropical cirrus clouds (Figs. 16 and 17). The high clouds predicted by the model (Fig. 18) show substantial areas of cirrus which are not apparent in the outgoing radiance field. However, when the liquid water contents are replaced by values based on cloud height and type (Cox and Griffith 1979; Stephens 1979) then there is a marked improvement in the model's outgoing radiance (Fig. 19) and demonstrates the importance of cloud radiative properties as well as cloud cover. There are still substantial areas of disagreement between Figs. 17 and 19, for example, over the Arabian Sea. By using the

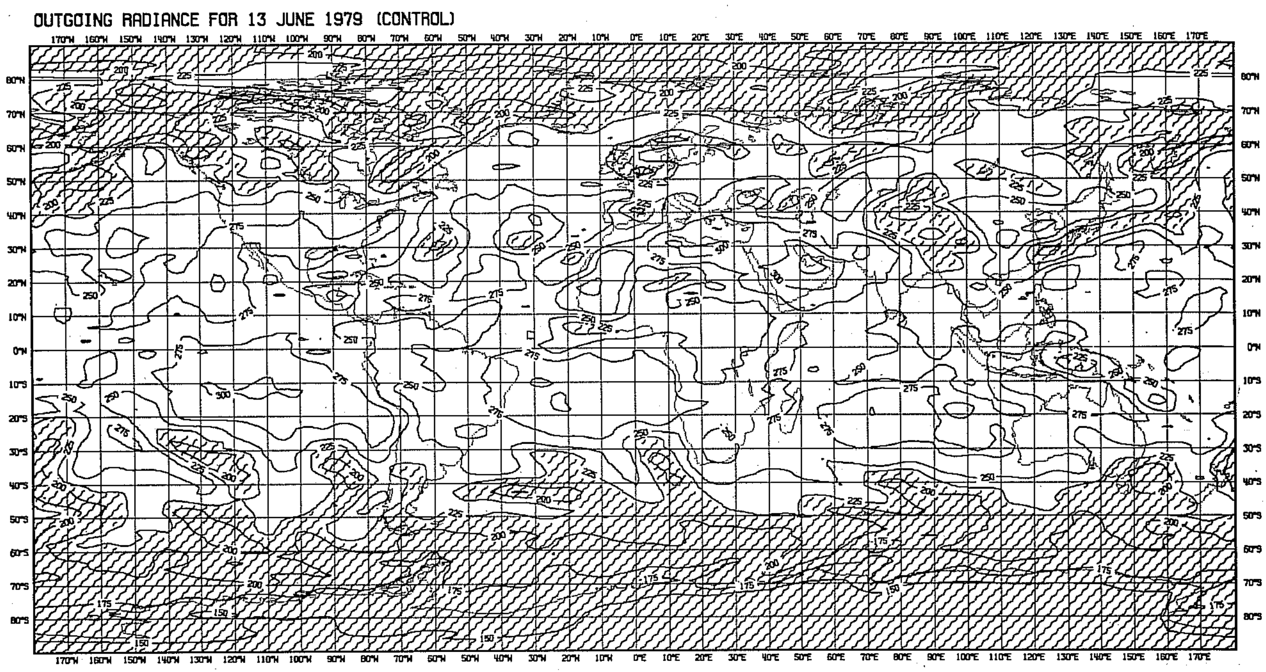

Figure 16: Mean outgoing radiance (Wm^{-2}) for 12Z 12/6/79 - 12Z 13/6/79 from a forecast with the ECMWF model with initial data for 12Z 11/6/79.

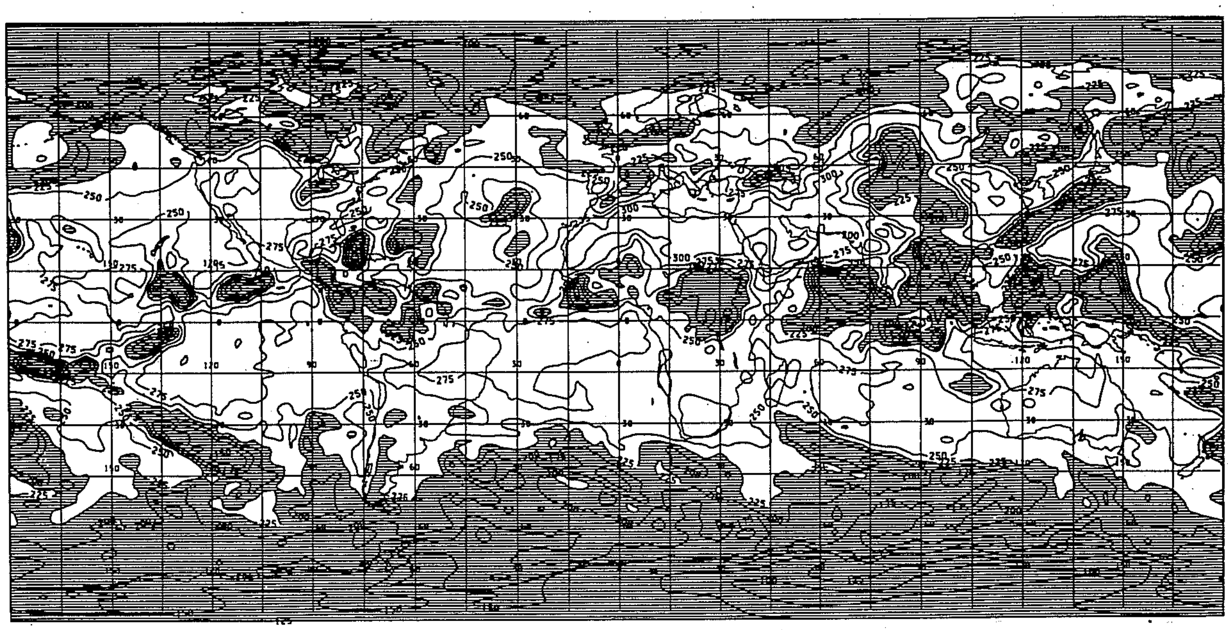

Figure 17: Observed outgoing radiance (Wm^{-2}) from NOAA polar orbiting satellites for 13/6/79.

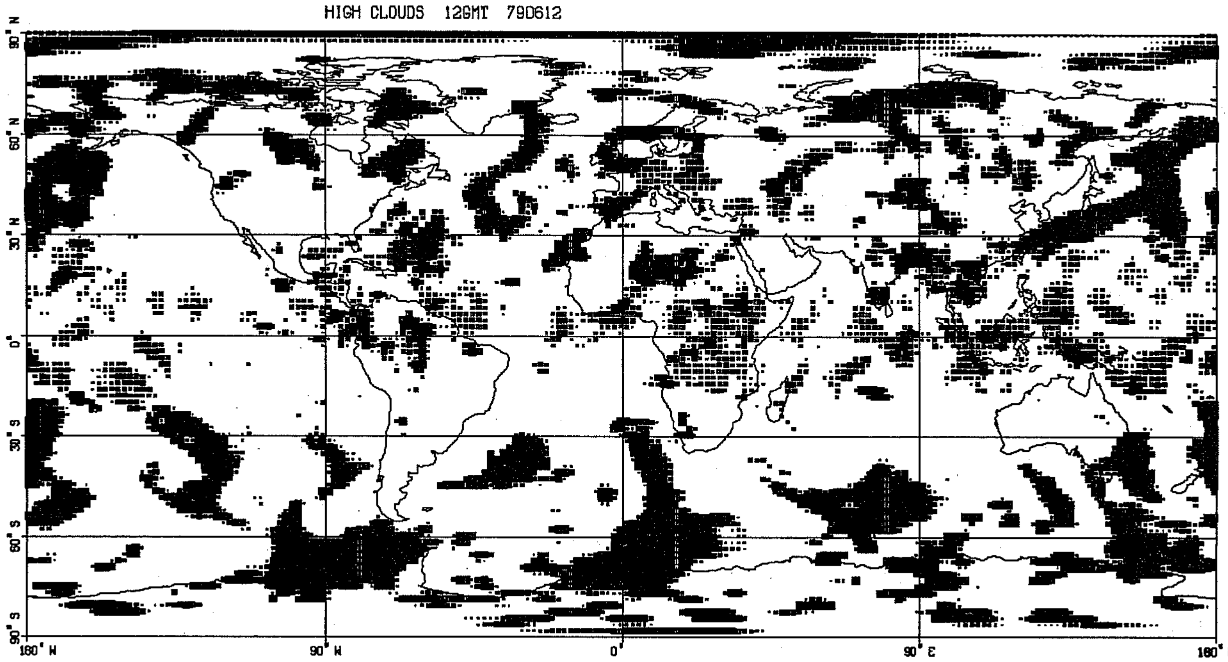

Figure 18: Distribution of high cloud from the ECMWF model for day 1 of a forecast from 12Z 11/6/79.

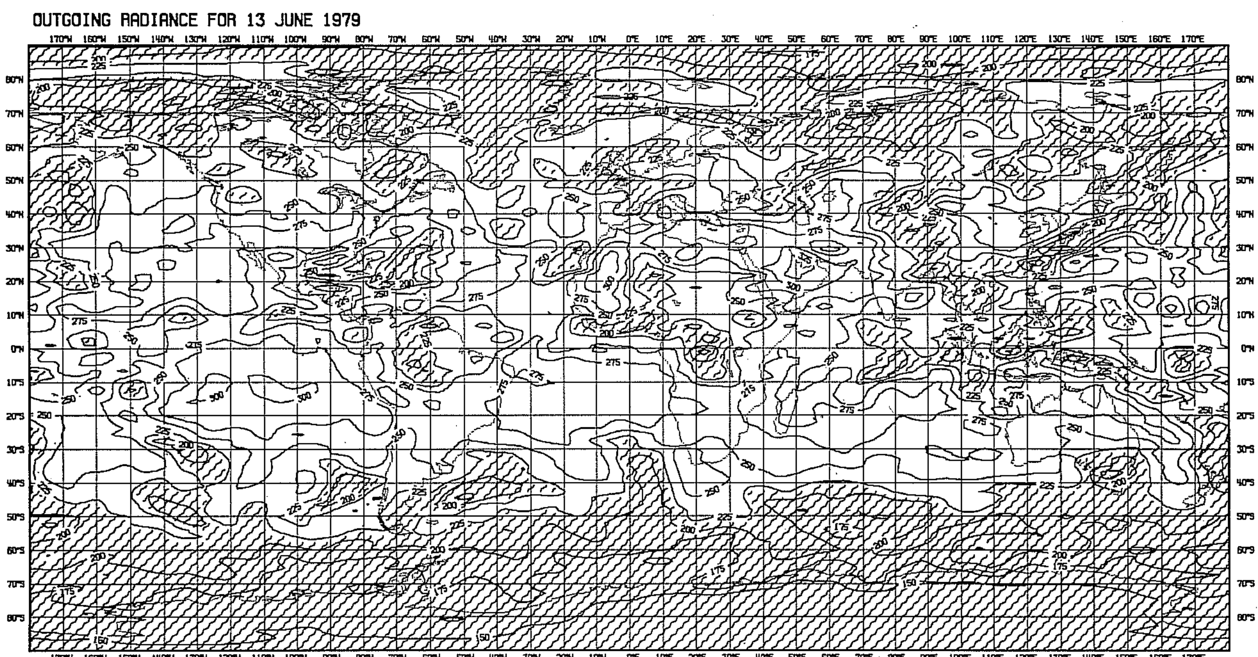

Figure 19: As figure 16 but with revised cloud liquid water contents.

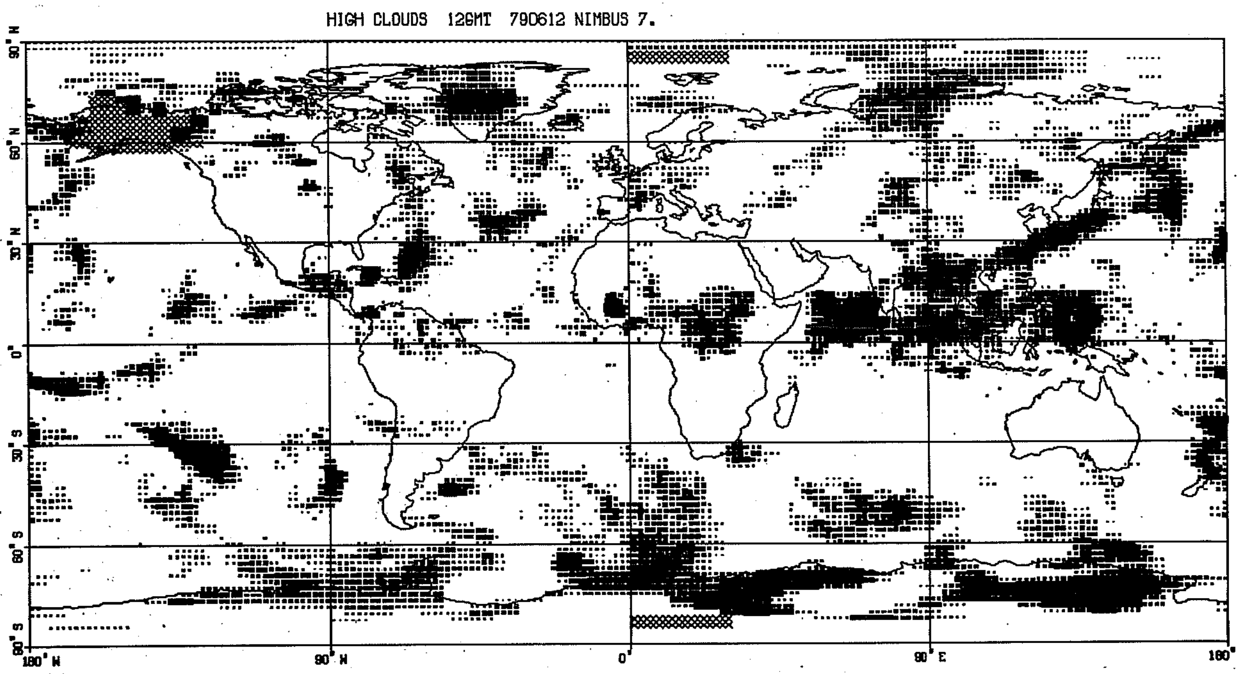

Figure 20: Distribution of observed high cloud from Nimbus 7 for 12/6/79.

Nimbus 7 high cloud amounts (Fig. 20) many of these can be identified as errors in the model's prediction of cloud cover and hence in some circumstances to other aspects of the model's simulation. For example, the small amounts of high cloud over the Arabian Sea are a direct consequence of the lack of deep convection in the model associated with an inadequate intensification of the summer Asian monsoon (Mohanty et al 1985).

The above example has demonstrated the benefits of satellite data in the verification of cloud and radiation schemes. By using the NOAA earth radiation budget data with the Nimbus 7 cloud data it is possible to identify faults in both the radiative properties and liquid water contents of the clouds and in the cloud amounts. These are very preliminary results but they clearly show that there is much to be gained from satellite data which, in the future, should become of increasing importance in model development.

6. CONCLUSIONS

Returning to Arakawa's remarks, the last decade has seen some progress in the prediction of cloudiness and its impact on model performance. The examples given in this paper show that a fair level of skill can now be reached. For diagnostic schemes, which are still relatively simple, this has arisen not so much from our understanding of cloud formative/dissipative mechanisms, but more by virtue of improvements in other aspects of the model, notably resolution and the representation of physical processes (radiation, convection, boundary layer exchanges). The couplings between the various processes described by Arakawa are still some way from being realised. Diagnostic schemes are, by their nature, somewhat divorced from the rest of the model although the use of information from other parts of the model (e.g. convective activity) does provide more unification. Prognostic schemes undoubtedly represent the methods for the future, dependent on adequate verification being available. They come much nearer to representing the couplings between the various processes. However, they do require a cloud model to determine when sub grid scale condensation should occur and to interpret the cloud liquid water content in terms of a geometric cloud cover. It is here that the experience gained from diagnostic schemes may be very useful. The parameters used in these schemes to represent the probability of cloud occurring may be equally applicable to the closure of prognostic schemes. Thus in the near future the progress in cloud prediction should involve development of both methods.

Acknowledgements

The author is grateful to Dr. P. Hwang of NASA/GSFC for supplying a tape of Nimbus 7 NCLE cloud data and to S. Brentnall of the UK Meteorological Office for supplying maps of NOAA earth radiation budget parameters.

References

Arakawa, A., 1975: Modelling clouds and cloud processes for use in climate models, GARP Publication Series No. 16, (ICSU/WMO) pp. 183-197.

Cox, S.K. and Griffith, K.T., 1979: Estimates of radiative divergence during Phase III of the GARP Atlantic Tropical Experiment. J. Atm. Sci., 36 , pp. 576-601.

Geleyn, J-F., 1981: Some diagnostics of the cloud/radiation interaction in ECMWF forecasting model. ECMWF Workshop on Radiation and Cloud-radiation Interaction in Numerical Modelling, 15-17 October 1980, ECMWF, pp. 135-162.

Gruber, A. and Krueger, A.F., 1984: The status of the NOAA Outgoing Longwave Radiation Data Set., Bull. Amer. Met. Soc., 65, pp. 958-962.

Gube, M., 1982: Radiation Budget Parameters at the Top of the Earth's Atmosphere derived from METEOSAT Data. J. Appl. Met., 21, pp. 1907-1921.

Hahn, C.J., Warren S.G., London, J., Chervin, R.M. and Jenne, R., 1982: Atlas of simultaneous occurrence of different cloud types over the ocean. NCAR Tech. Note TN-201+STR, Boulder, Co., 212 pp.

Hahn, G.J., Warren S.G., London, J., Chervin, R.M., and Jenne, R., 1984: Atlas of simultaneous occurrence of differenct cloud types over land. NCAR Tech. Note TN-241+STR, Boulder, Co.

Hammarstrand, U., 1982: A parameterization scheme for convective cloud water and cloud cover. Report DM-40, Dept. Of Met., Univ. of Stockholm.

Hughes, N.A., 1984: Global Cloud Climatologies: A Historical Review. J. Clim. and Appl. Met., 23, pp. 724-751.

Le Treut, H., 1985: Cloud Prediction Experiments with the LMD GCM. ECMWF Workshop on Cloud Cover and Radiative Fluxes in Large-scale Numerical Models - Design, Validation and Dynamical Impact (in press).

Meleshko, V.P. and Wetherald, R.T., 1981: The effect of a geographical cloud distribution on climate: A numerical experiment with an atmospheric general circulation model. Jour. Geophys. Res., 86, pp. 11995-12014.

Miller, D.B. and Feddes, R.G., 1971: Global atlas of relative cloud cover, 1967-1970, based on data from meteorological satellites, Washington NOAA, NESS, Washington Air Weather Service.

Minnis, P. and Harrison, E.F., 1984: Diurnal variability of regional cloud and clear-sky radiative parameters derived from GOES data. Part II: November 1978 Cloud distributions. J. Clim. and Appl. Met., 23, pp. 1012-1031.

Mohanty, U.C., Slingo, J.M. and Tiedtke, M., 1985: Impact of modified physical processes on the tropical simulation in the ECMWF model. ECMWF Tech. Report No.52 (in press).

Njoku, E.G. and Swanson, L., 1983: Global measurements of sea surface temperature, wind speed and atmospheric water content from satellite microwave radiometry. Mon. Weath. Rev., 111, 1977-1987.

Prabhakara, C. and Short, D.A., 1984: Nimbus 7 SMMR derived seasonal variations in the water vapor, liquid water and surface winds over the global oceans. NASA Tech. Memo. 86080, Goddard Space Flight Center, Greenbelt, Maryland.

Roeckner, E. and Schlese, U., 1985: January simulation of clouds with a prognostic cloud cover scheme. ECMWF Workshop on Cloud Cover and Radiative fluxes in large scale Numerical Models - Design, Validation and Dynamical Impact (in press).

Shukla, J. and Sud, Y., 1981: Effect of cloud-radiation feedback on the climate of a general circulation model. J. Atm. Sci., 38, pp. 2337-2353.

Slingo, A., 1983: Clouds and radiation in the Meteorological Office 11-layer general circulation model. Met.O. 20 Tech. Note II/203. (Also appears in WCP-74, WMO, Geneva).

Slingo, A. and Wilderspin, R.W., 1985: Cloud prediction experiments with the British Meteorological Office Climate Model. ECMWF Workshop on cloud cover and radiative fluxes in large-scale numerical models - Design, validation and dynamical impact (in press).

Slingo, J.M., 1980: A cloud parameterization scheme derived from GATE data for use with a numerical model. Quart. J. R. Met. Soc., 106, pp. 747-770.

Slingo, J.M., 1984: Studies of cloud-radiation interaction in the ECMWF medium range forecast model. Proc. of IAMAP International Radiation Symposium, 21-29 August 1984, Italy (in press).

Slingo, J.M., 1985: Cloud cover experimentation with the ECMWF model. ECMWF Workshop on cloud cover and radiative fluxes in large-scale numerical models - Design, validation and dynamical impact (in press).

Smagorinsky, J., 1960: On the dynamical prediction of large-scale condensation by numerical methods. Washington Nat. Acad. Sci., Amer. Geoph. Union, Geoph. Monogr. No. 5, pp. 71-78

Stephens, G.L., 1979: Optical properties of eight water cloud types. Div. Atm. Phys. Tech. Paper No. 36, CSIRO, Australia.

Stowe, L.L. and others, 1985: Use of Nimbus 7 satellite data for validation of GCM generated cloud cover. ECMWF Workshop on cloud cover and radiative fluxes in large-scale numerical models - Design, validation and dynamical impact (in press).

Sundqvist, H., 1978: A parameterization scheme for non-convective condensation including prediction of cloud water content. Quart. J. R. Met. Soc., 104, pp. 677-690.

Tiedtke, M., 1985: The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. ECMWF Workshop on convection in large-scale numerical models, 28 Nov. - 1 Dec. 1983, ECMWF, pp. 297-316.

Winston, J.S. and others, 1979: Earth-atmosphere radiation budget analysis derived from NOAA satellite data, June 1974 - February 1978, Vols. 1 and 2, NOAA, U.S. Dept. of Commerce.