The development and verification of a cloud prediction scheme for the ECMWF model

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SUMMARY

This paper describes the development of a fractional cloud cover scheme which was implemented operationally in the ECMWF medium range forecast model in May 1985. The scheme is based on a diagnostic approach in which cloudiness is related empirically to the large-scale model variables, including convective activity. An example of the performance of the scheme is given, showing that a fair degree of skill is achieved in forecasting tropical and extratropical cloudiness. An attempt to verify the results using retrieved cloudiness from Nimbus 7 is described. Considerable difficulties were experienced due to the different height classifications of clouds in the model and in the satellite data. The importance of cloud radiative properties as well as cloud amount is considered briefly, based on a comparison of model earth radiation budget diagnostics with similar data from the NOAA polar-orbiting satellites. The sensitivity of the simulated outgoing long-wave radiance to changes in the prescribed cloud liquid water content is discussed. Two examples of the effects of cloud–radiation interaction on boundary layer processes are described which demonstrate the importance of an integrated approach to the treatment of clouds, radiation and turbulent fluxes.

1. INTRODUCTION

In 1975 Arakawa wrote “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 on both long and short timescales, 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, studies of the climatic or long-term effects of clouds have shown that a model’s simulation of the general circulation is significantly sensitive to the specification of cloudiness (Shukla and Sud 1981; Meleshko and Wetherald 1981). Recent studies of satellite data in conjunction with model results also suggest that the cloud long-wave forcing for the troposphere may be as substantial as the latent heating in deep convective systems such as the Indian summer monsoon (Ramanathan 1987).

For short timescales, e.g. medium range forecasts, the impact of clouds was generally considered to be less important, mainly because radiative timescales tend to be large. However, studies by Geleyn (1981) and Slingo (1984) showed that simplification of the cloud cover parametrisation led to a weakening of the extratropical circulation during the forecast period (10 days), particularly on the synoptic scale. This manifested itself as a weakening of the baroclinic conversion of eddy available potential energy to eddy kinetic energy, suggesting that the clouds provide, through their interaction with the radiation, a positive correlation between warming and rising. Also, in a model which incorporates the diurnal cycle, the correct representation of the tropical cloudiness and its diurnal variation may be important, particularly over land. In a sensitivity study of
cloud–radiation interaction, Tiedtke (1984) showed that the effect of clouds on the tropical diabatic heat sources could have a significant impact on the extratropical flow. In a more general idealized study Simmons (1982) also showed that the tropics could influence the extratropics within 10 days through teleconnections.

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 hydrological and dynamical processes. However, the prediction of cloud amount, height, thickness and optical properties presents major problems. Apart from boundary layer clouds, which have been the subject of several observational studies (Randall et al. 1984), the formation and dissipation of clouds are, in general, poorly understood. Also, bearing in mind that most clouds are subgrid-scale, both horizontally and vertically, there is neither a sound theory nor an observational database which can be used to relate cloudiness to the large-scale variables. Clouds are a product of complicated interactions of moist convective turbulence with larger scale circulations, radiation and microphysical 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 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. Ideally, it would be desirable to find similar relationships between observed variables and cloudiness but this has proved very difficult mainly because areal averages are required. There have been several investigations using sonde ascents which have been largely fruitless (Smagorinsky 1960; Ricketts 1973; Slingo 1980). The sondes sample only a single profile and is therefore not necessarily representative of the large horizontal area covered by a model grid square. For example, with partial cloud cover the relative humidity profile is dependent on whether the sondes ascends through clear or cloudy air. A recent attempt by Curry and Herman (1985) to find relationships between observed cloudiness and large-scale parameters from ECMWF analyses was unsuccessful in the arctic, possibly because of the complex nature of the clouds (Tsay and Jayaweera 1984). A similar study in mid-latitudes might be more rewarding, particularly with better data coverage for the analyses. The main disadvantage of diagnostic schemes is that the clouds are largely divorced from the rest of the model. They can interact with other processes only 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 the cloud water content.

The second method is a prognostic approach, in which the explicit calculation of the cloud water content, involving the formation and evaporation of cloud and rain drops, is made (Sundqvist 1978). It requires an additional model variable to represent cloud water which may or may not be advected. Such a scheme is computationally more expensive than a diagnostic method, although there are clear advantages. It allows proper representation of the thermodynamic effects of subgrid-scale condensation (precipitating and non-precipitating) and also provides a more direct link between the radiative, dynamical and hydrological processes within the model. In addition, since the scheme predicts the cloud water content required by the radiation scheme, it therefore, in principle, allows the prediction of cloud radiative properties as well as cloud cover. The
main problems with such schemes are verification and interpretation. Data on cloud water content are still very limited. 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° latitude. Other data are gradually becoming available, in particular those from the Nimbus 7 Scanning Multi-channel Microwave Radiometer (SMMR) but again only over the oceans (Prabhakara and Short 1984). However, these data are for the liquid component only and so the model should also include a distinction between liquid and ice in its parametrization. Also the model’s cloud water content has to be expressed in terms of cloud thickness and areal coverage 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 (Sundqvist 1978).

ECMWF has had a fractional cloud cover scheme in operation for several years. It was based on a simple dependence on relative humidity (Gleyn 1981), but with the additional constraint that no clouds were allowed in the well-mixed layer. This restriction was introduced to prevent the excessive cloudiness which formed over the subtropical oceans in earlier versions of the model. The scheme performed well in many situations but a detailed assessment (Slingo and Ritter 1985; J. M. Slingo 1985) showed that it had less satisfactory aspects once a diurnal cycle was introduced in the model. In particular, the diurnal variation in cloudiness over the tropical land masses was poorly represented, having a minimum during the daytime whereas in reality there is often an increase in cloudiness associated with convective activity. This was due mainly to the removal of clouds in the well-mixed layer. During the day the boundary layer deepened and penetrated into the drier middle troposphere. As night fell a stable layer formed near the surface, the well-mixed layer restriction no longer applied, and the cloud amount increased in association with the moist lower layers of the model. It should be pointed out, however, that when this scheme was developed it was not intended for use with a diurnal cycle. These results indicated that a link with the convection was probably necessary to represent the diurnal variation in cloudiness over the tropical continents. Other problems with the scheme were too little tropical cirrus and an almost total lack of subtropical low-level cloudiness. This paper describes the development and assessment of a new fractional cloud cover prediction scheme designed to overcome the shortcomings of the original method. Preliminary results from this scheme were presented earlier in J. M. Slingo (1985). The question of verification based on satellite data will be considered in some detail.

2. DESCRIPTION OF THE SCHEME

Despite the drawbacks of diagnostic methods, this approach was chosen as the basis of the new scheme partly because a quick solution was required to remedy the undesirable diurnal variation of the original scheme, and partly because prognostic methods, although having many attractive aspects, have yet to show results which can compete favourably with diagnostic methods (Slingo 1986). The basic requirements of a new operational cloud scheme are that it should provide good medium range forecasts of cloudiness and adequate representation of the radiative forcing for timescales of about ten days. Important factors would be a good simulation of the extratropical cloudiness associated with transient features, a good simulation of cloudiness over land and a good simulation of the diurnal variation in cloudiness. On the other hand, in a model intended for longer term integrations or to be used with an ocean model, one would also require a good simulation of oceanic cloudiness, particularly areas of persistent cloudiness in the eastern
subtropical oceans, and a good simulation of the radiation budget for the whole earth–atmosphere system.

(a) Possible parameters

Bearing in mind that the basis of diagnostic methods is that condensation on the smaller scales is part of a larger scale condensation regime, it should be feasible to parametrize the cloudiness in terms of the large-scale model variables. A list of parameters which might be used for diagnosing cloudiness could include:

a. Relative humidity   d. Atmospheric stability
b. Convective activity  e. Wind shear
c. Vertical velocity   f. Surface fluxes.

Relative humidity, proposed initially by Smagorinsky (1960) as a predictor of cloudiness, has been widely used since, not only in diagnostic methods (e.g. Le Treut 1985; Ramanathan et al. 1983), but also in the closure of prognostic schemes (Sundqvist 1978). Although observational studies have been unable to identify a unique relationship between large-scale cloudiness and relative humidity (Smagorinsky 1960; Ricketts 1973; Slingo 1980), a study of a large number of radiosonde ascents from GATE at least showed that, in the absence of a boundary layer inversion, low clouds almost always occurred with relative humidities in excess of 80% (Slingo 1980). Similarly, the probability of middle level clouds occurring was observed to increase with increasing relative humidities; clear skies were more likely than cloudy skies for relative humidities below 65% (Slingo 1980).

It was clear from the original scheme (Geleyn 1981; Slingo and Ritter 1985) that relative humidity was a good indicator for extratropical frontal clouds. However, the shortcomings of the scheme were largely in regions where convective processes dominate. There is no reason, then, why the relative humidity averaged over the grid square should be an indicator of cloud cover; the thermal structure may be just as important. A link with the model’s convection scheme is the obvious solution. This would also provide greater unity between the various parts of the model’s physics. In the tropics much of the cirrus occurs as a direct result of deep convection; again the model’s convection scheme could be used to predict these clouds.

Vertical velocity is an obvious parameter in that many clouds, particularly along fronts and in tropical disturbances, are associated with large-scale ascent. Subsidence naturally implies drying and warming so that in a sense, relative humidity and vertical velocity are complimentary. However, it will be seen later that vertical velocity can be useful in distinguishing different types of cloud formed by different mechanisms. In particular, this is true for subtropical boundary layer cloud where the subsidence does not necessarily lead to drying because it is offset by evaporation from the sea surface.

The use of atmospheric stability as a predictor for low-level clouds was proposed earlier by Slingo (1980) based on observations from GATE and proved effective in capturing the subtropical stratus/stratocumulus clouds off the western seaboard and associated with the tradewind inversion. These clouds can be vertically subgrid-scale and are therefore seldom represented by the model’s relative humidity structure. Again, a detailed study of a large number of radiosonde ascents through stratocumulus during GATE revealed no obvious relationship between cloud cover and atmospheric stability, although it was shown that cloudy skies occurred almost exclusively in association with a layer whose stability exceeded the moist adiabatic lapse rate. For further discussion on the difficulties of relating observed cloud cover to other observed quantities the reader is referred to Slingo (1980).
Although wind shear and surface fluxes are mentioned here, they have not, so far, been used as predictors. Wind shear implies mechanical turbulence which may be a source (or sink) of layer clouds in the middle and upper troposphere (e.g. altostratus, jet stream cirrus). There are indications from observational studies that surface fluxes of heat and moisture can have an influence on the low-level cloudiness although the results are by no means conclusive (Agee and Lomax 1978; Sheu and Agee 1977). In the case of mesoscale cellular convection it seems that open cells (i.e. small fractional cloud cover) may be favoured by large surfaces fluxes whilst closed cells (i.e. large fractional cloud cover) may be favoured by smaller fluxes.

(b) Basic structure of the scheme

Following the basic cloud configuration originally proposed by Slingo (1980), the scheme allows for four cloud types. These clouds have been given the names convective (cumulus, cumulonimbus), high (cirrus), middle (altostratus, altocumulus) and low (stratus, stratocumulus). Although the radiation code can accommodate cloud in any number of layers, this configuration was chosen for simplicity to aid the development and verification of the scheme. Further complexity could be introduced but was not found to be necessary. Figure 1 shows a schematic representation of the vertical cloud distribution and the division into high, middle and low clouds. The convective cloud can fill any number of layers whilst for simplicity the layer clouds are at present constrained so that they cannot exceed one model layer in thickness. The levels at which these layer clouds can occur is determined by dividing the atmosphere into three parts, as shown. The maximum cloud amount in each part is computed and is ascribed to that layer of maximum cloudiness. No cloud is allowed in the lowest model layer, which is only about 8 mb in depth. This restriction was introduced mainly because the simple representation of the surface and boundary layer exchanges in the model at this stage precludes a realistic representation of the surface layer and therefore of the formation and dissipation of fog. In addition, the radiation scheme assumes maximum overlap of adjacent cloudy layers and random overlap of non-adjacent cloudy layers. This cloud geometry is used in all calculations of total cloudiness.

![Figure 1. Schematic representation of the vertical cloud distribution in the model and the division into high-, middle- and low-level clouds.](image-url)
(c) Cloud prediction equations

Convective cloud cover \((C_C)\) is determined from the time-averaged precipitation rate \((P)\) from the model’s convection scheme:

\[
C_C = a + b \ln P
\]  

(1)

where \(a\) and \(b\) are empirical constants. The precipitation rate is taken as that at cloud base before any evaporation below the cloud and is averaged over the three hours prior to a call to the cloud and radiation routines. The cloud cover implied by the precipitation is derived from a statistical relationship between frequency distributions of observed tropical convective cloudiness and model precipitation rates in a manner similar to that used in Slingo (1980). Table 1 indicates the cloud cover and the corresponding equivalent precipitation rate implied by Eq. (1). The advantage of the scheme is that it is easily transferable between convection schemes and has been used successfully with both the Kuo scheme and the Betts–Miller convective adjustment scheme (Betts 1986; Betts and Miller 1986). The convective cloud base and top are also obtained from the convection scheme; the lowest base and highest top over the three-hour period are used. An upper limit of 80% is placed on \(C_C\) based on results from GATE data (Slingo 1980). Also the simple assumption is made that in cases of deep convection only 25% of the predicted amount is allowed to occupy the full depth, the remaining 75% being treated as low-level shallow convection. This is intended to represent the observed state where cumulonimbus clouds only occupy a small fraction of the sky but coexist with a large amount of lower level convection.

The scheme distinguishes between two different types of cirrus, that associated with outflow from deep convection and that associated with frontal disturbances. In this scheme the anvil cirrus \((C_H)\) is not captured by a dependence on the relative humidity because the Kuo convection scheme does not adequately moisten the upper troposphere in regions of deep, active convection (Slingo and Ritter 1985). This is in contrast to the convection scheme used in the Meteorological Office 11-layer GCM, which produces a high degree of variability in the upper tropospheric relative humidities, the greatest humidities associated with convectively active regions. Thus in that model, relative humidity is a good predictor of anvil cirrus clouds (Slingo 1980). A dependence on convective activity is therefore used here, since the probability of these clouds occurring increases when there is strong, deep convection:

\[
C_H = 2.0(C_C - 0.3)
\]  

(2)

provided that convection extends above 400 mb and the convective cloudiness exceeds 40% (i.e. equivalent precipitation rate of greater than 3.4 mm d\(^{-1}\)).

Extratropical and frontal cirrus \((C_{HF})\) are determined from a function of (fractional) relative humidity \((RH)\):

\[
C_H = [\text{Max}(0.0, (RH - 0.8)/0.2)]^2.
\]  

(3)

The choice of 80% as the threshold relative humidity is somewhat arbitrary and may be model dependent, although for low cloud, at least, GATE data suggest that above this level, cloudy skies are more likely than clear skies.

<table>
<thead>
<tr>
<th>(C_C) (0)</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P) (mm d(^{-1}))</td>
<td>0.14</td>
<td>0.31</td>
<td>0.70</td>
<td>1.6</td>
<td>3.4</td>
<td>7.7</td>
<td>17</td>
<td>38</td>
<td>85</td>
</tr>
</tbody>
</table>
Middle-level clouds \((C_M)\) appear to form mainly in association with tropical disturbances and extratropical frontal systems. In this scheme they are parametrized by

\[
C_M = [\text{Max}[0.0, (RH_e - 0.8)/0.2]]^2
\]

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

\[
RH_e = RH(1.0 - C_C)
\]

assuming that the cloudy part, \(C_C\), is saturated. This essentially allows for the dry subgrid-scale downdraughts in the ‘environment’ in which the layer cloud is free to form.

Low-level clouds are the most difficult clouds to predict because they are so dependent on the structure of the model’s boundary layer and their interaction with the radiation field. Observational studies (e.g. Roach et al. 1982) have shown that these clouds are characterized by a delicate balance between the cloud top entrainment, radiative cooling and surface turbulent fluxes of heat and moisture. These clouds may also be the most crucial ones to be able to predict in the model. This is certainly true for climate studies with an ocean–atmosphere model when, for example, the position of the subtropical stratocumulus fields is vital (Slingo and Wilderspin 1985). It may also be true for a forecast model because these clouds have the greatest and most direct impact on the land surface heat balance and the transport of heat and moisture out of the boundary layer. In addition they are likely to be of great interest to the user because the presence or absence of low-level clouds can have a profound effect on the surface weather.

Low clouds \((C_L)\) 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 characterized by generally moist air and large-scale ascent. These are parametrized using relative humidity and vertical velocity \((\omega)\):

\[
C_L = [\text{Max}[0.0, (RH_e - 0.8)/0.2]]^2
\]

\(C_L = 0\) if there is subsidence, i.e. \(\omega \geq 0\). There is a linear transition up to a weak ascent:

\[
C_L = C'_L(-10 \cdot 0 \omega) \quad \text{for} \quad \omega \geq -0.1
\]

where \(0.1 \text{ Pas}^{-1} = 3.6 \text{ mb h}^{-1}\). Otherwise \(C_L = C'_L\).

Again, \(RH_e\) is the relative humidity of the environmental air after allowing for convective clouds (Eq. (5)). The advantages of using vertical velocity as well as relative humidity can be seen in Fig. 2, where the low clouds have been diagnosed from day 5 of a forecast from 15 January 1984. (Note that the global distributions of model cloud cover are represented schematically by relating the cloudiness to the fractional area of the grid square covered by a black pixel, the grid square being totally black if the cloud cover is 100%. Thus the pictorial representation of model cloudiness is, in effect, a reverse of the satellite images where the clouds are white.) In Fig. 2(a) the clouds are determined only from the relative humidity (Eq. (6)) and the lack of detail, particularly in the extratropics, is marked. The use of a higher threshold relative humidity would not alleviate the problem because the cloud cover is already 100% in most cloudy areas, indicating a relative humidity already at saturation. However, the additional dependence on vertical velocity (Eq. (7)) successfully delineates the frontal clouds in the extratropics whilst in the subtropics it suppresses the excessive cloudiness which would otherwise occur (Fig. 2(b)).
Figure 2. Low-level cloudiness diagnosed from day 5 of a forecast from 15 January 1984 using (a) relative humidity only and (b) relative humidity and vertical velocity.

The second class of low-level clouds is strongly linked to the boundary layer and is invariably associated with low-level inversions in temperature and humidity, for example the tradewind inversion. These clouds are often vertically subgrid-scale and may therefore not be represented by the average relative humidity through a model layer. An initial parametrization is proposed:

$$C_L = -6.67 \Delta \theta / \Delta p - 0.667$$  \hspace{1cm} (8)

where $\Delta \theta / \Delta p$ is the lapse rate (K mb$^{-1}$) in the most stable layer below 750 mb. This type of parametrization was proposed earlier from GATE data and proved successful in the Meteorological Office limited area tropical model (Slingo 1980). It also seems to work well in the global context of the ECMWF model. Figure 3 shows the clouds diagnosed by Eq. (8) for day 10 of a forecast from 15 July 1983. The persistent clouds off the western seabords are well represented as are the summertime arctic stratus clouds and those over the cold waters of the North Pacific. As expected, the clouds produced by Eqs. (6) and (7) and those from Eq. (8) are almost mutually exclusive so that the two
schemes combine without difficulty. An additional dependence on the relative humidity at the base of the inversion \((RH_{\text{base}})\) has been introduced to prevent cloud forming under dry inversions such as those over deserts and the winter pole.

\[
C_L = \begin{cases} 
0 & \text{if } RH_{\text{base}} < 0.6 \\
C'_L \{1.0 - (0.8 - RH_{\text{base}})/0.2\} & \text{for } 0.6 \leq RH_{\text{base}} \leq 0.8 \\
C_L & \text{otherwise.}
\end{cases}
\] (9)

A similar approach has been used by Le Treut (1985) for predicting stratus clouds in the LMD model. 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. Also this method is designed to represent only the stratus type clouds and therefore will not give the extensive areas of trade cumulus or mesoscale cellular convection in cold air outbreaks. These are convective regimes and should be represented by the model's convective parametrization.

3. **Brief description of the ECMWF model**

The cloud prediction scheme described in the previous section was tested extensively in the ECMWF T63 (triangular truncation at 63 wavenumbers) spectral model and was implemented operationally in the T106 (triangular truncation at 106 wavenumbers) spectral model in May 1985. This paper will describe the results from a typical integration with the T63 spectral model (Simmons and Jarraud 1984). The basic features of the model are shown in Table 2. A hybrid vertical coordinate, \(\eta\), is used such that the model levels follow the orography for pressures near the surface pressure but tend towards constant pressure surfaces aloft. Further information on the physical parametrizations can be found in Tiedtke et al. (1979). Extensive modifications have been made to the treatment of convective processes (Tiedtke 1985; Mohanty et al. 1986; Slingo et al. 1987) to improve the performance of the Kuo scheme and also to include a parametrization of the effects of shallow convection. The radiation scheme uses a two-stream approximation
TABLE 2. ECMWF MODEL DESCRIPTION

<table>
<thead>
<tr>
<th>Domain</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variables</td>
<td>$\xi, D, T, q, \ln(p_1)$</td>
</tr>
<tr>
<td>Vertical coordinate</td>
<td>Hybrid, $P_{k+1} = A_{k+1} + B_{k+1}P_k$, 16 layers of variable thickness</td>
</tr>
<tr>
<td>Vertical representation</td>
<td>Finite-difference, energy and angular-momentum conserving</td>
</tr>
<tr>
<td>Horizontal representation</td>
<td>Spectral, with triangular truncation at wavenumber 63</td>
</tr>
<tr>
<td>Horizontal grid</td>
<td>96×192 points on a quasi-regular (1:875°) 'Gaussian' grid</td>
</tr>
<tr>
<td>Time integration</td>
<td>Leapfrog, semi-implicit ($\Delta t = 20$ min), time filter ($\gamma = 0.1$)</td>
</tr>
<tr>
<td>Horizontal diffusion</td>
<td>Linear, fourth-order ($k = 2 \times 10^8 \text{m}^2 \text{s}^{-1}$); diffusion on divergence ($\kappa = 2 \times 10^9 \text{m}^2 \text{s}^{-1}$)</td>
</tr>
<tr>
<td>Orography</td>
<td>Grid-scale average from high resolution data set, enhanced by $\sqrt{2}\times$(standard deviation of subgrid-scale orography), spectrally-fitted</td>
</tr>
<tr>
<td>Vertical boundary conditions</td>
<td>Kinematic</td>
</tr>
<tr>
<td>Physical parametrizations</td>
<td>(i) Boundary eddy fluxes dependent on local roughness length and stability (Monin–Obukhov)</td>
</tr>
<tr>
<td></td>
<td>(ii) Free-atmosphere turbulent fluxes dependent on mixing length and Richardson number</td>
</tr>
<tr>
<td></td>
<td>(iii) Kuo penetrative convection scheme</td>
</tr>
<tr>
<td></td>
<td>(iv) Shallow convection scheme. Enhances vertical diffusion of $T$ and $q$ within moist convectively unstable layers and through cloud base</td>
</tr>
<tr>
<td></td>
<td>(v) Large-scale condensation when grid-square saturated. Evaporation of precipitation</td>
</tr>
<tr>
<td></td>
<td>(vi) Interaction between radiation and model-generated clouds. Albedo dependent on model snow cover</td>
</tr>
<tr>
<td></td>
<td>(vii) Computed land temperature</td>
</tr>
<tr>
<td></td>
<td>(viii) Computed soil moisture and snow cover</td>
</tr>
<tr>
<td></td>
<td>(ix) Fixed, analysed sea surface temperature</td>
</tr>
</tbody>
</table>

of the radiative transfer equation both in the solar and infrared parts of the spectrum (Geleyn and Hollingsworth 1979). Substantial revision of the treatment of gaseous absorption in the infrared spectrum was found necessary (Ritter 1984; Slingo et al. 1987). The radiative effects of clouds are incorporated in the scheme by assuming a typical liquid water content, based on a supersaturation of 1%. The cloud optical depth used in the scattering computations is derived from the integral of the cloud liquid water content over the depth of the cloud, assumed to be a full model layer. The basic cloud geometry of random overlap of non-adjacent cloudy layers and maximum overlap of adjacent cloudy layers is used to combine the clear and cloudy fluxes. The radiation scheme represents the diurnal cycle explicitly. Full computation of the cloud cover and radiative fluxes is made every three hours, whilst the implied effective transmissivities and emissivities are used every timestep to compute surface radiative fluxes and atmospheric heating rates which include changes in the solar zenith angle and temperature.

The results to be described in the next section come from a 10-day forecast using analysed FGGE data for 12 GMT on 11 June 1979 as a starting time, the data being initialized by the operational diabatic nonlinear normal mode procedure. This case has proved very useful for evaluating the model's performance, particularly that of the physical parametrizations, since it covers the period of rapid intensification of the monsoonal flow over India (Mohanty et al. 1986; Slingo et al. 1987).

4. PERFORMANCE OF THE SCHEME

(a) Zonal means

Despite the importance of cloud cover in determining the radiative heating and cooling of the earth/atmosphere system, the availability of data for verification of cloud
prediction schemes remains fairly limited. Although several global cloud climatologies have been compiled there remain considerable discrepancies between them (Hughes 1984). Ground-based observations tend to overestimate total cloudiness because the lateral surfaces of the cloud elements also enter the field of view of the observer. With satellites, the total cloudiness is probably more accurate except over highly reflecting surfaces such as ice and snow.

In Fig. 4 the model's zonal-mean total cloudiness for days 1–10 is compared with two observed estimates, one surface-based (Bolton 1981) and one from the Nimbus 7 satellite (Stowe et al. 1985). Bolton's values are a compilation of published data from Sasamori et al. (1972), Telegadas and London (1954), Rodgers (1967) and London (1957) with information on arctic and antarctic cloudiness from Huschke (1969) and Phillpot (1968). This climatology has been used extensively in the Meteorological Office GCMs and has been shown to give zonal-mean radiation budgets in good agreement with satellite observations (Slingo 1982; A. Slingo 1985). The satellite data are meaned over 28 days for June 1979 from Nimbus 7 (Stowe et al. 1985). The agreement between the surface and satellite observations is surprisingly good in mid-latitudes. However, the tropical maximum appears to be rather weak in Bolton's data. Bearing in mind the very limited number of surface stations at these latitudes, the sampling problems must be considerable. In polar regions the satellite data are probably less reliable because of problems in distinguishing between cloud and snow or ice. The model's cloudiness shows reasonable agreement with the observed data in the northern hemisphere. However, amounts in the southern hemisphere seem consistently too low in the subtropics and mid-latitudes and too high near the pole. The lack of cloudiness in southern mid-latitudes is related to the inability of the scheme to predict the large amounts of mesoscale cellular convection occurring behind cold fronts in the depression belt (see sub-section (b) below). The tropical peak in cloudiness is well simulated by the model although the Nimbus 7 data suggest that it is underestimated. The large tropical cloud amounts indicated by Nimbus 7 may be attributable, in part, to thin cirrus which is included in the satellite data but is not simulated by the model.

A common problem with cloud prediction schemes is an undesirable increase in cloudiness, particularly low-level clouds, during the integration. This is due to the interaction of the scheme with the increased radiative cooling produced by the cloud. In

![Figure 4. Comparison of the zonal-mean total cloudiness for days 1–10 of the forecast from 12 GMT, 11 June 1979 (solid line) with a surface-based climatology for June (dotted line) and with the mean for June 1979 derived from Nimbus 7 data (dashed line).](image)
Figure 5. Zonal-mean total cloudiness from the model for days 1 (dotted line), 5 (solid line) and 10 (dashed line) of the forecast from 12 GMT, 11 June 1979.

reality this is offset by enhanced turbulent mixing which is often not represented in models (see section 6). However, the scheme seems to be relatively free from such problems, partly due to the incorporation of a shallow convection scheme which prevents an unrealistically moist boundary layer forming under a capping inversion, particularly over the subtropical oceans. This can be seen in Fig. 5 where the zonal-mean total cloudiness for days 1, 5 and 10 are shown. There is no indication of an increase in cloudiness, the global-mean total cloud cover of about 50% being maintained throughout the forecast. The scheme has also proved stable in longer integrations out to 60 days.

(b) Geographical distribution of cloudiness

Figures 6–8 show examples of the high-, middle- and low-level cloud distributions predicted by the scheme. The fields are taken from day 5 of the forecast and can be compared with the Meteosat infrared and visible images for the same date (Figs. 9 and 10). Bearing in mind that by day 5 the cloud fields will show the deficiencies inherent in the model's forecast, the extratropical frontal cirrus (Fig. 6) agrees well with that in the Meteosat infrared image (Fig. 9). In the tropics the anvil cirrus associated with the deep
convection along the Atlantic ITCZ is well represented as is the extensive area of high cloud over the Arabian Sea heralding the onset of the summer monsoon over India. The middle-level clouds (Fig. 7) appear reasonable, occurring principally along extratropical fronts and in association with deep convection in the tropics. These clouds are particularly difficult to verify because they tend to form in association with high- and low-level clouds (Hahn et al. 1982, 1984) and are therefore hidden from view both from the surface and from the satellite.

The low-level clouds (Fig. 8) are a combination of the cumuliform and stratiform clouds. Again the agreement with the Meteosat images is good although the cloud is slightly too extensive over southern Africa. Indeed, the transition from the dense frontal clouds of the extratropics to the broken convective regimes of the tropics is striking. Over the tropical oceans much of the cumuliform cloudiness is shallow, the areas of deep convection being implied by the high cloud field (Fig. 6). In the extratropics, cumuliform
and stratiform clouds form together along the fronts although stratiform clouds are also predicted over the cold waters of the North Pacific. The area of stratocumulus over the southern central Atlantic is surprisingly well simulated, as is the clearance between that cloud and the trailing front extending to South America. The scattered cumuli of the NE Atlantic trades are also captured by the scheme. One shortcoming is the lack of shallow cellular convection which often occurs behind cold fronts in the winter hemisphere and accounts for the low values of total cloudiness already noted in the southern hemisphere.

The representation of the diurnal cycle 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). However, it should be noted that the diurnal variation is very dependent on the convection scheme and its response to the surface heating.

5. **Verification of cloud schemes**

Both methods of cloud prediction (diagnostic and 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 fractional cloud cover schemes (Slingo and Wilderspin 1985). 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 in section 4. That being the case, the question of verification assumes greater importance. Until recently, surface-based observations of cloud cover were the main source of data. However, as Hughes (1984) showed, the global distributions are far from reliable mainly because of the non-uniform data coverage. Information on the vertical distribution is also limited by the obscuration of upper-level clouds by lower-level clouds.

In principle, satellites should provide good global datasets of cloud cover and radiative fluxes. Several new cloud and radiation budget datasets will soon be available as the result of the International Satellite Cloud Climatology Project (ISCCP) and the Earth Radiation Budget Experiment (ERBE). However, there are aspects of the satellite cloud data which make their use in model verification not entirely straightforward. Firstly, the cloud amounts and heights are dependent on the cloud model used to interpret the satellite narrow band radiances. Secondly, in contrast to surface-based data, lower-level
clouds are masked by upper-level clouds and clouds have to be classified in terms of the height of cloud top rather than cloud base. Some problems related to these assumptions became evident in attempts to use Nimbus 7 cloud data for verification of the cloud prediction scheme described in section 3. Total cloudiness and cloud amounts at high, middle and low levels were derived from radiance data using the NCLE algorithm for sub-target areas of approximately (160 km)² (Stowe et al. 1985). These cloud amounts were then interpolated on to the horizontal grid of the ECMWF model (1.875° latitude/ longitude) to provide as near a comparison as possible with the model fields. Where multiple passes over a sub-target area occurred, a mean cloudiness for that area was

Figure 11. Distribution of total cloudiness from the model for day 5 of the forecast from 12 GMT on 11 June 1979. Compare with Fig. 12.

Figure 12. Distribution of total cloudiness derived from Nimbus 7 data for 16 June 1979, local noon.
Figure 13. As Fig. 12 but for high-level clouds.

Figure 14. As Fig. 12 but for middle-level clouds.

Figure 15. As Fig. 12 but for low-level clouds.
used. The distributions of total cloud cover from the model and from the satellite should be directly comparable apart from slight temporal differences. The model field is instantaneous at 12 GMT whilst the satellite data are sun-synchronous at local noon. Bearing this in mind and also allowing for errors inherent in the forecast, the model's prediction at day 5 (Fig. 11) agrees quite well with the Nimbus 7 data for the same date (Fig. 12), although overall the model has slightly less cloud (global mean of 49% compared with 56% for Nimbus 7). The morphology of the large-scale cloud fields is surprisingly well simulated and, in principle, it should be possible to make an objective, statistical analysis of the total cloudiness to detect systematic errors in the cloud prediction scheme. However, when more detailed information on cloud height/type is used to assess the discrepancies seen between the model and satellite total cloudiness and to make any necessary modifications to the scheme (e.g. in the SE Pacific), then the incompatibility between the satellite-derived cloud covers and the model diagnostics becomes very evident. Figures 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. 6–8.

Apart from the obscuration factor, which can be overcome by processing the model data as if seen from a satellite, there are clear differences in the classification of the clouds. Indeed, the categorizing of clouds into various height regimes is somewhat arbitrary both for the satellite data and for the model, and will depend on the model's vertical resolution. 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. A good example can be seen in the SE Pacific where low-level stratus/stratocumulus clouds would be expected but are classed as middle-level clouds in the Nimbus 7 data. This difference could be related to the unavoidable use of cloud top height for classification of the satellite data. The choice of 2 km as the altitude of the low/middle threshold, based on the International Cloud Atlas (1956) (Stowe et al. 1985), may well be more applicable to cloud base than to cloud top. However, attempts to re-classify the model clouds using cloud top height and the same thresholds as the satellite data were unsuccessful. This was possibly because the model's vertical discretization was incompatible with the 2 km low/middle threshold. It may also have been indicative of cloud tops which were too low in the model although this is not corroborated by the model's outgoing long-wave radiation (see section 6).

Although this comparison represents the first attempt 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 numerical modellers and those deriving cloud data from satellite measurements. Indeed, model diagnostics may need to be altered to provide data which are more directly related to the actual satellite measurements rather than the retrieved cloud amounts. The use of cloud height, either base or top, for categorizing clouds is historical and presumably was introduced to aid surface observers in reporting the state of the sky and would not have been intended to provide an accurate measure of the cloud height. Its use now in satellite and model diagnostics may well be erroneous because a slight change in height can result in a completely different description of the cloud state. It may be more applicable for the model to produce radiances or cloud top temperatures which are comparable with those measured by the satellite.

Earth radiation budget measurements have been widely used in model verification (e.g. Geleyn et al. 1982; Hansen et al. 1983; Ramanathan et al. 1983). There are uncertainties inherent in the data due to the radiation models used to convert narrow band measurements into broad band data, and the differences related to viewing geometry
(arising from the use of either scanner or flat plate detectors (Stephens et al. 1981)). Nevertheless, the natural variability associated with cloudiness and latitude is sufficiently large that these uncertainties are not, at this stage, significant for model verification. Since it is the radiative effects of clouds rather than the cloud cover alone that ultimately determine the model's simulation, then the verification of the simulated planetary albedo and outgoing long-wave radiation (OLR) can be very important. When used in conjunction with estimates of the cloud cover these fields can also 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. As described in section 3, the LWC is based on the saturation water vapour mixing ratio which in a simple way represents the decrease in LWC with height and with increasing latitude. However, when the model's OLR for 13 June 1979 (day 2 of the forecast) is compared with similar data from the NOAA polar orbiting satellites (Winston et al. 1979; Gruber and Krueger 1984), the well-defined observed minima in the tropics are clearly lacking in the model (Figs. 16 and 17). (13 June 1979 is used for this comparison because the NOAA data were incomplete or missing for other dates.) Nevertheless, the high clouds predicted by the model (Fig. 18) show substantial areas of cirrus which are not apparent in the model's OLR. This suggests that the model's simple representation of LWC grossly underestimates the opacity and hence the emissivity of the tropical cirrus clouds. As a sensitivity study, the model's LWCs were replaced by values based on cloud height and type (Table 3, derived from data of Cox and Griffith (1979) and Stephens (1979)). As a result there is a marked improvement in the model's OLR (Fig. 19), demonstrating the importance of cloud radiative properties as well as cloud cover. The tropical minima are now clearly evident, associated with the cirrus clouds seen in Fig. 18. Comparison with the NOAA data (Fig. 17) shows a good simulation of many features such as the minima over Africa, central Asia, Japan and the NW Pacific. However, there are still substantial areas of disagreement, such as those over the central and eastern Pacific and over the Arabian Sea. Many of these can be identified as errors in the model's prediction of cloudiness and hence in some circumstances to other aspects of the model's simulation. For example, over the Arabian Sea, the high values of OLR are due to the small amounts of high cloud which 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. 1986; Slingo et al. 1987).

<table>
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<th>Cloud type</th>
<th>LWC</th>
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<tr>
<td>Cumulonimbus</td>
<td>2-5</td>
</tr>
<tr>
<td>Cumulus</td>
<td>1-0</td>
</tr>
<tr>
<td>Anvil cirrus</td>
<td>0-035</td>
</tr>
<tr>
<td>Cirrus</td>
<td>0-024ρ</td>
</tr>
<tr>
<td>Altostratus/altocumulus</td>
<td>0-014ρ</td>
</tr>
<tr>
<td>Stratus/stratocumulus</td>
<td>0-05-0-20 dependent on latitude</td>
</tr>
</tbody>
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(Taken from Stephens 1979; Cox and Griffith 1979)
Figure 16. Outgoing long-wave radiation (Wm$^{-2}$) from the model, meaned over the period 12 GMT on 12 June 1979 to 12 GMT on 13 June, for the forecast from 12 GMT on 11 June. Compare with Fig. 17.

Figure 17. Outgoing long-wave radiation (Wm$^{-2}$) derived from NOAA operational polar-orbiting satellite data for 13 June 1979, average of ascending and descending nodes.

6. DISCUSSION

The results described in the previous sections clearly show that a fair measure of skill in forecasting clouds on short timescales can be obtained with a diagnostic approach. As far as a 10-day forecast is concerned, the impact of the new cloud scheme on the rest of the model is not very large. This is partly because radiative timescales themselves are large and partly because the original cloud scheme was already successful at representing the extratropical frontal clouds. The new cloud scheme has its greatest impact on the tropical and subtropical cloudiness and this may feedback into the extratropics only late in the forecast. However, in the wide variety of cases used to test the scheme there was a consistent but modest improvement in skill when this was measured in terms of anomaly correlations and standard deviations. These statistics are commonly used at ECMWF for
assessing the model's performance. In Fig. 20 the height anomaly correlations for days 3, 4 and 5 of ten forecasts with the new cloud scheme are plotted against the respective values for the forecasts with the original method. All points above the diagonal represent an improvement in the forecast when the new cloud scheme is used. The beneficial effects of the new scheme can be clearly seen especially for those cases where the forecast was not particularly good. To put the magnitude of these changes in context, a similar diagram representing the impact of substantial changes to the long-wave radiation code (Ritter 1984) is shown in Fig. 21. These results suggest that, for a forecast model, cloud prediction can be at least as important as the parametrization of radiative transfer.

Either type of cloud prediction scheme (prognostic or diagnostic) is bound to be dependent on the model's simulation. Cloudiness is the manifestation of the effects of a
number of subgrid-scale processes and is therefore very sensitive to the model’s ability to represent the atmospheric structure which results from these processes. Since clouds are subgrid-scale horizontally and/or, more seriously, vertically, the decision has to be made whether the parametrization attempts to overcome the lack of vertical resolution (as may be the case for arctic stratus and subtropical stratus/stratocumulus) or whether it is purely disguising basic shortcomings in the model’s simulation. A good example of this can be seen in Fig. 22 where the low-level clouds have been calculated using relative humidity as in Eq. (6). The upper distribution is from a forecast without shallow convection whilst the lower one is from a forecast which includes shallow convection. The impact on the cloudiness (i.e. boundary layer relative humidity) is dramatic. The excessive cloudiness in the upper distribution can in no way be blamed on the cloud parametrization but is due to the lack of mixing between the boundary layer and the free atmosphere in the model.

Another problem in cloud parametrization which will be common to diagnostic and prognostic approaches is the way in which the interaction between the clouds and the radiation alters the model’s atmospheric structure. Unless there is a compensatory mechanism, this can feed back into the cloud scheme and can be particularly awkward with boundary layer clouds, the enhanced radiative cooling leading to an increase in cloudiness. For regions of trade cumuli the shallow convection scheme provides the necessary mixing to offset the enhanced radiative cooling due to the clouds. This can be seen in Fig. 23 where the area-mean physical tendencies for day 5 from a region in the SE trades (10°S–20°S, 0°W–10°W) are compared for two forecasts; one with all cloud effects included and one with all clouds removed from the radiation calculation for model layers below $\eta = 0.8$. In the control case with all cloud effects, scattered cumuli covered the area (Fig. 8). The vertical profiles of potential temperature and relative humidity show a well-mixed surface layer, a nearly well-mixed cloud layer and an inversion layer above $\eta = 0.9$. It is interesting to note the similarity between the profiles with and without cloud–radiation interaction. This arises because of the compensatory effects of the radiative and convective processes (r.h.s. graphs on Fig. 23). The enhanced radiative cooling in the cloud layer in the control gives rise to more active mixing by the shallow
Figure 22. Low cloud diagnosed using relative humidity from day 5 of forecasts from 15 July 1983, (a) without shallow convection and (b) with shallow convection.

Figure 23. Effect of cloud–radiation interaction on radiative and convective processes in the SE trades for day 5 of the forecast from 12 GMT on 11 June 1979.
convection scheme. The convective moistening is only slightly modified by the cloud-radiation interaction.

However, there are regions of persistent stratocumulus over the colder oceans which do not appear to be driven by buoyant convection from the surface but are rather driven by radiative cooling at the cloud top and the localized turbulent mixing that results. There the shallow convection scheme will not operate. If the compensating mixing is not represented in the model then a common result is an increase in cloudiness as the cloud layer cools radiatively. An example of this can be seen in Fig. 24 where the clouds associated with low-level inversions are calculated using Eq. (8) from two forecasts, one without cloud–radiation interaction and one with cloud–radiation interaction. In the second experiment the clouds have caused the boundary layer to cool radiatively, so increasing the strength of the inversion and thereby the cloudiness. The model is lacking the turbulent mixing processes which should offset this cooling. This may indeed be a case where layer cloud instability as described by Randall (1980) is applicable as a

Figure 24. Low cloud diagnosed from inversion strength from day 5 of forecasts from 15 July 1983, (a) without cloud–radiation interaction and (b) with cloud–radiation interaction.
mechanism for reducing or controlling the cloudiness. Whatever method is used, this is a striking example of the need for an integrated approach to the treatment of clouds, radiation and turbulent fluxes.

The scheme described in this paper was designed for the ECMWF model, and its transferability to other models will involve several considerations. The first is one of resolution. As far as horizontal resolution is concerned, this has not proved critical for the ECMWF model where a change from spectral truncation at 63 wavenumbers (1.875° latitude/longitude) to that at 106 wavenumbers (1.125° latitude/longitude) required no modifications to the scheme. However, a different vertical resolution may need changes, particularly to the dependence on atmospheric stability (Eq. (8)), reflecting the degree to which the model resolves boundary layer inversions. This can be seen in the different constants used in Eq. (8) of this paper and in Eq. (6) of Slingo (1980), associated with the differing vertical resolutions of the ECMWF model and the Meteorological Office 11-layer model. The second consideration involves the physical parametrizations used in the model. As mentioned earlier, any cloud prediction scheme will depend on the model's temperature and humidity structure, in particular the type of convective parametrization. This may mean that some of the empirical constants, such as the threshold relative humidity, may need to be modified, although there is no apparent reason why the form of the relationships between cloudiness and model parameters should not be transferable to other models. Again the reader is referred to Slingo (1980) for fuller discussion of this topic.

7. 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 realized. 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 subgrid-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.

Although this scheme could be criticized for its lack of scientific basis, it has at least provided a reasonable prediction of cloudiness which, hitherto, had not been achieved. By reaching this stage it is then feasible to address the question of the role of clouds and cloud–radiation interaction in the general circulation. Indeed, as shown earlier in Fig. 20, improvements in the cloud distributions have benefits for the forecast as a whole.

Whatever method is used, the prime source of data for verification will come from satellites. The results described in this paper represent the first detailed attempt to use retrieved cloud data to verify both the horizontal and vertical distribution of model
cloudiness. The problems experienced here are unlikely to apply just to the ECMWF model but will undoubtedly be universal because of the nature of the vertical discretization of any model and of satellite data. Earth radiation budget data may, in fact, offer the best method of verification because they represent the combined effects of cloud cover and radiative properties. The solution to this problem is not clear. Indeed, the whole question of the most appropriate way to use the enormous amount of information inherent in satellite observations is in need of urgent attention.

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