CLOUD COVER EXPERIMENTATION WITH THE ECMWF MODEL

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1. INTRODUCTION

There are several reasons why some effort has been made in recent months to improve the cloud cover prediction in the ECMWF model. Firstly cloud cover is a forecast product routinely sent out to the Member States. Secondly the impact of cloud cover on the quality of the forecast through its interaction with the radiative fluxes may not be negligible. Both Geleyn (1981) and Slingo (1984) showed that simplification of the cloud cover parameterization led to a weakening of the extratropical circulation during the forecast period, particularly in the synoptic scale. This manifested itself as a weakening of the baroclinic conversion of eddy available potential energy to eddy kinetic energy; clearly the clouds provide, through their interaction with the radiation, a positive correlation between warming and rising. Thirdly the operational model now incorporates the diurnal cycle and the correct representation of the tropical cloudiness and its diurnal variation may be important, particularly over land. Tiedtke (1984) showed in a sensitivity study of cloud-radiation interaction, that the effect of clouds on the tropical diabatic heat sources could have a serious 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.

ECMWF has had an interactive cloud scheme in operation for several years. It performs acceptably in both short and long time scales and there are no indications of undesirable feedbacks between the clouds and the radiative fluxes. That being the case it was important that a full study of the existing scheme should be made to identify any shortcomings. A complete description of this study is given in Slingo and Ritter (1984). A new cloud scheme should of course rectify those less satisfactory aspects of the operational scheme. This paper will describe briefly the results of this study. The remainder of the paper will concentrate on the approach and methodology of the new cloud prediction scheme and its impact and performance in a 10-day forecast.

2. THE OPERATIONAL CLOUD COVER SCHEME

The current operational scheme is based on a simple function of relative humidity (RH). Cloudiness (CC) is allowed at any model level and is given by:

$$CC = \left[\max\left(\frac{RH - RH_{crit}}{1 - RH_{crit}},\ 0\right)\ 0\right]^2$$

where RH_{crit} is the critical relative humidity above which cloud can form (Geleyn, 1981). It is itself a function of height through the generalised pressure coordinate, η, of the model such that:

$$RH_{crit} = 1 - 2(\eta - \eta^2) + \sqrt{3}\ \eta\ (1 - 3\eta - 2\eta^2)$$

The form of this function is shown in Fig. 1 which also shows the variation of CC with RH for two values of η. An important constraint is also applied to the cloud cover, namely that no cloud is allowed in the well mixed layer. This was introduced to prevent widespread cloudiness over the tropical and sub-tropical oceans associated with the excessively moist boundary layer of the model. For the calculation of the radiative fluxes and of the total cloudiness the assumption of maximum overlap for adjacent cloudy layers is used, otherwise random overlap of non-adjacent layers is assumed.

Study of the performance of the operational scheme revealed four major shortcomings.

(i) Too many deep clouds

(ii) Too little tropical cirrus

(iii) Too little subtropical cloudiness

(iv) Poor representation of the diurnal variation in cloudiness particularly in the tropics.

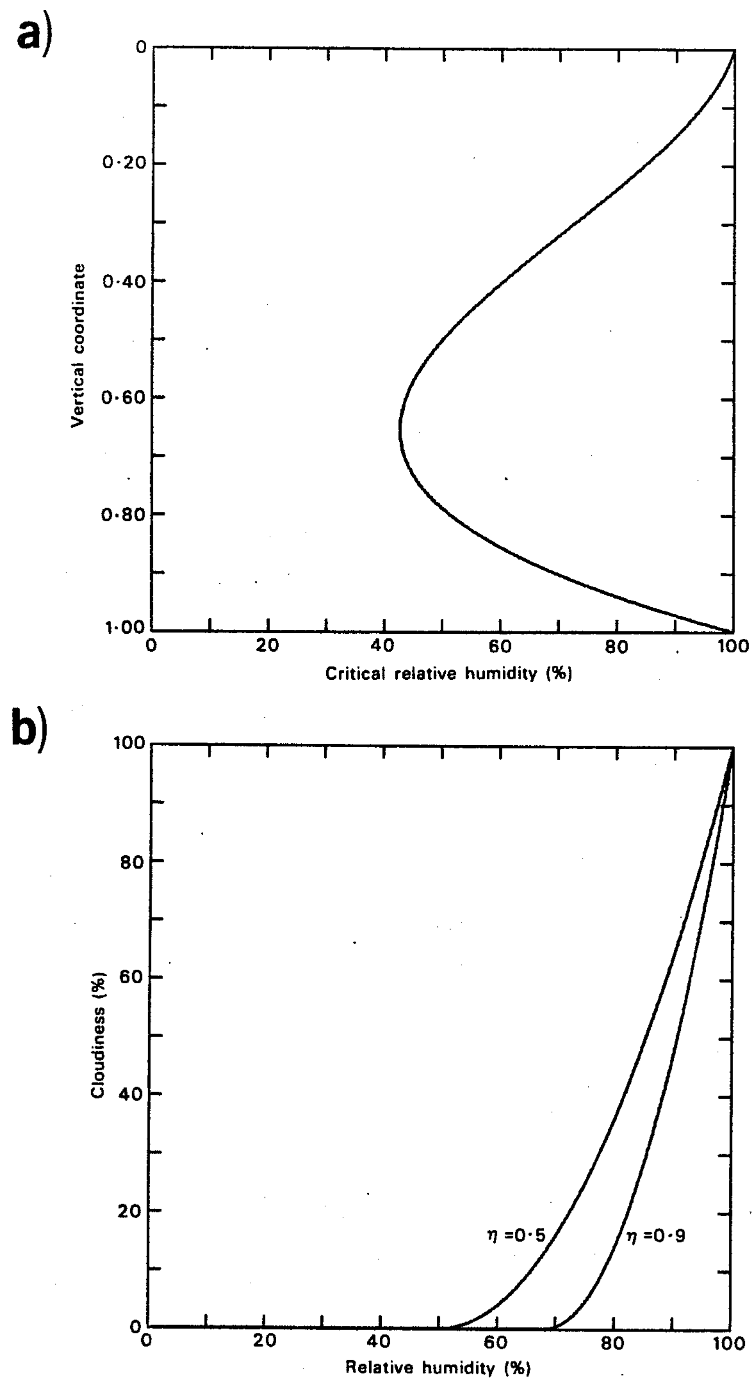


Fig. 1 Operational cloud prediction scheme:
(a) Variation of critical relative humidity with height,
(b) variation of cloud cover with relative humidity for two values of η.

A typical cloud distribution for day 5 of a forecast from 15/7/83 (Fig. 2) amply demonstrates (i), (ii) and (iii). For the purposes of comparison with climatologies the cloudiness has been subdivided vertically into low, medium and high clouds. High clouds are assumed to occur in the model layers 1-7 (i.e. approx. 0-450 mb), medium clouds belong to layers 8-11 (i.e. approx. 450-800 mb) and low clouds are associated with layers 12-16 (i.e. approx. 800 mb-surface). The cloud cover is represented schematically by relating the cloudiness to the fractional area of the grid square covered by a black pixel. Thus, for example, the grid square will be totally black if the cloud cover is 100%. The freedom to allow clouds in any layer of the model has resulted in a large number of deep clouds with tops in the middle troposphere. This can be seen in the similarity between the distribution of low and middle cloud. The lack of tropical cirrus in the convectively active regions of the ITCZ and S.E. Asia is due to a lack of moistening of the upper troposphere by the Kuo convection scheme. The complete absence of low clouds in the subtropics is a consequence of the removal of clouds in the well mixed layer. In reality, of course, many of the clouds in this region are shallow cumuli or stratocumuli and are either in the boundary layer or closely linked to it. It it well recognised that these clouds, particularly over the cold eastern oceans, are difficult to predict (e.g. Randall 1985). However, it should be emphasised, that, despite these criticisms, the scheme does perform well in the extratropics where the frontal clouds are well described by the relative humidity formulation.

The poor diurnal variation of cloudiness is most apparent in the low level clouds and arises mainly from the removal of clouds in the well mixed layer. Fig. 3 shows the low cloud distributions through day 5 of a forecast from 15/7/83. Over the tropical land masses the cloudiness has a minimum during

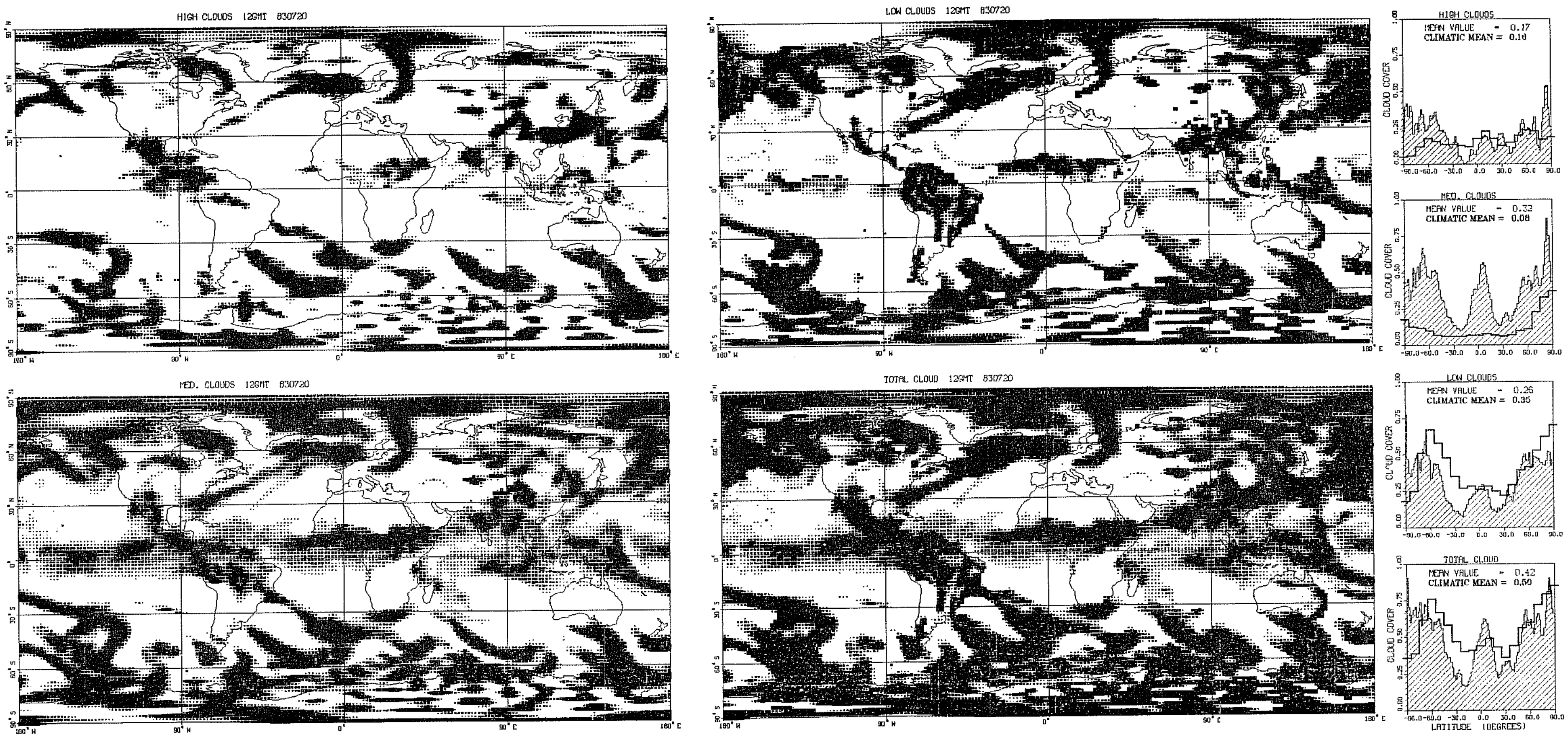


Fig. 2 Total, low, middle and high cloudiness from the operational cloud scheme for day 5 of a forecast from 15/7/83.

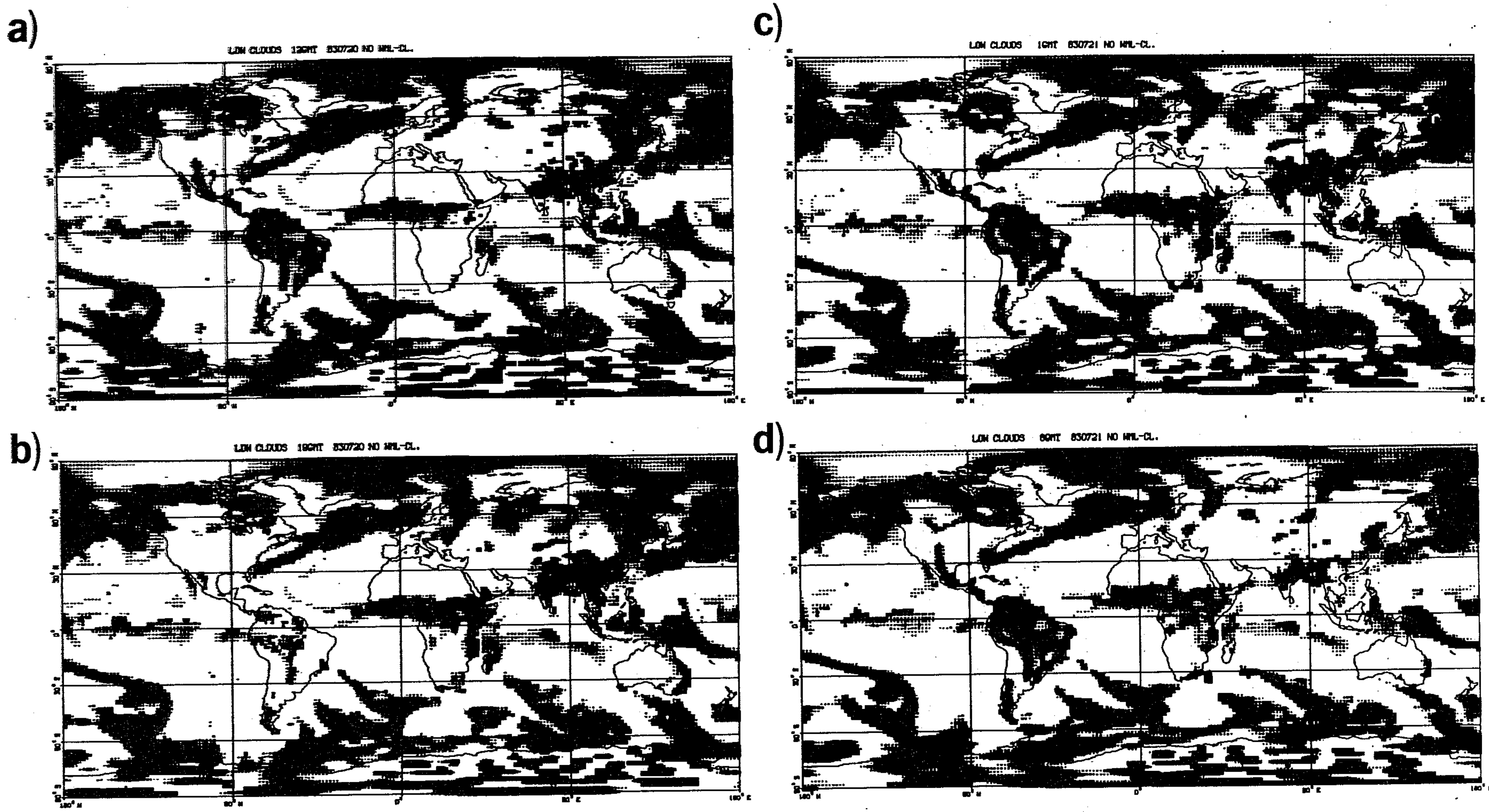


Fig. 3 Diurnal variation in low cloudiness from the operational cloud scheme through day 5 of a forecast from 15/7/83. (a) 12 GMT 20/7/83, (b) 18 GMT 20/7/83, (c) 01 GMT 21/7/83 and (d) 08 GMT 21/7/83.

the daytime whereas in reality there is an increase in cloudiness due to convective activity. This is particularly noticeable over S. America, S.E. Africa and S. E. Asia. During the day the boundary layer deepens and penetrates into the drier middle troposphere. However as night falls a stable layer forms near the surface, the well-mixed layer restriction no longer applies, and the cloud amount increases in association with the moist lower layers of the model. A similar effect can be seen over the northern hemisphere continents where there is a marked build up of cloud at night over Russia and Canada. It should be pointed out however that when this scheme was developed it was not intended for use with a diurnal cycle. These results indicate that a link with the convection is probably necessary to represent the diurnal variation in cloudiness over the tropical continents.

3. THE NEW CLOUD COVER SCHEME

3.1 Possible approaches

There are two basic approaches to cloud prediction. The first is a statistical or diagnostic approach in which the cloudiness is predicted empirically from model variables, the functions chosen to represent the probability of cloud occurring under certain atmospheric conditions. The second method involves an explicit calculation of the liquid water content involving the formation and evaporation of cloud and raindrops. Although this method has many attractive aspects it has yet to show results which can compete favourably with diagnostic methods. It also has two serious drawbacks. The first is problems of verification and the second is interpretation of the cloud liquid water content in terms of a geometric cloud cover required by the radiation scheme. Partly for these reasons and partly because a quick solution was required to remedy the undesirable diurnal variation of the existing scheme, a diagnostic approach was chosen as the basis of the new scheme.

3.2 Possible parameters

With the new scheme, the premiss is made that condensation on the smaller scales is part of a larger scale condensation regime related to the synoptic scale situation. In other words it is feasible to parameterize the cloudiness in terms of the large-scale model variables. A list of parameters which might be used for diagnosing cloudiness could include:

(i) Relative humidity

(ii) Convective activity

(iii) Atmospheric stability

(iv) Vertical velocity

(v) Wind shear

(vi) Surface fluxes

It is clear from the operational scheme that relative humidity is 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 and will also provide the desirable unity between the various parts of the model's physics. In the tropics much of the cirrus occurs as a result of deep convection; again it would be reasonable to use the model's convection scheme to predict these clouds.

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 seaboards 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. A comparison of frequency distributions of observed cloudiness, relative humidity and potential temperature lapse rate from two GATE stations (Fig. 4) demonstrates the feasibility of using

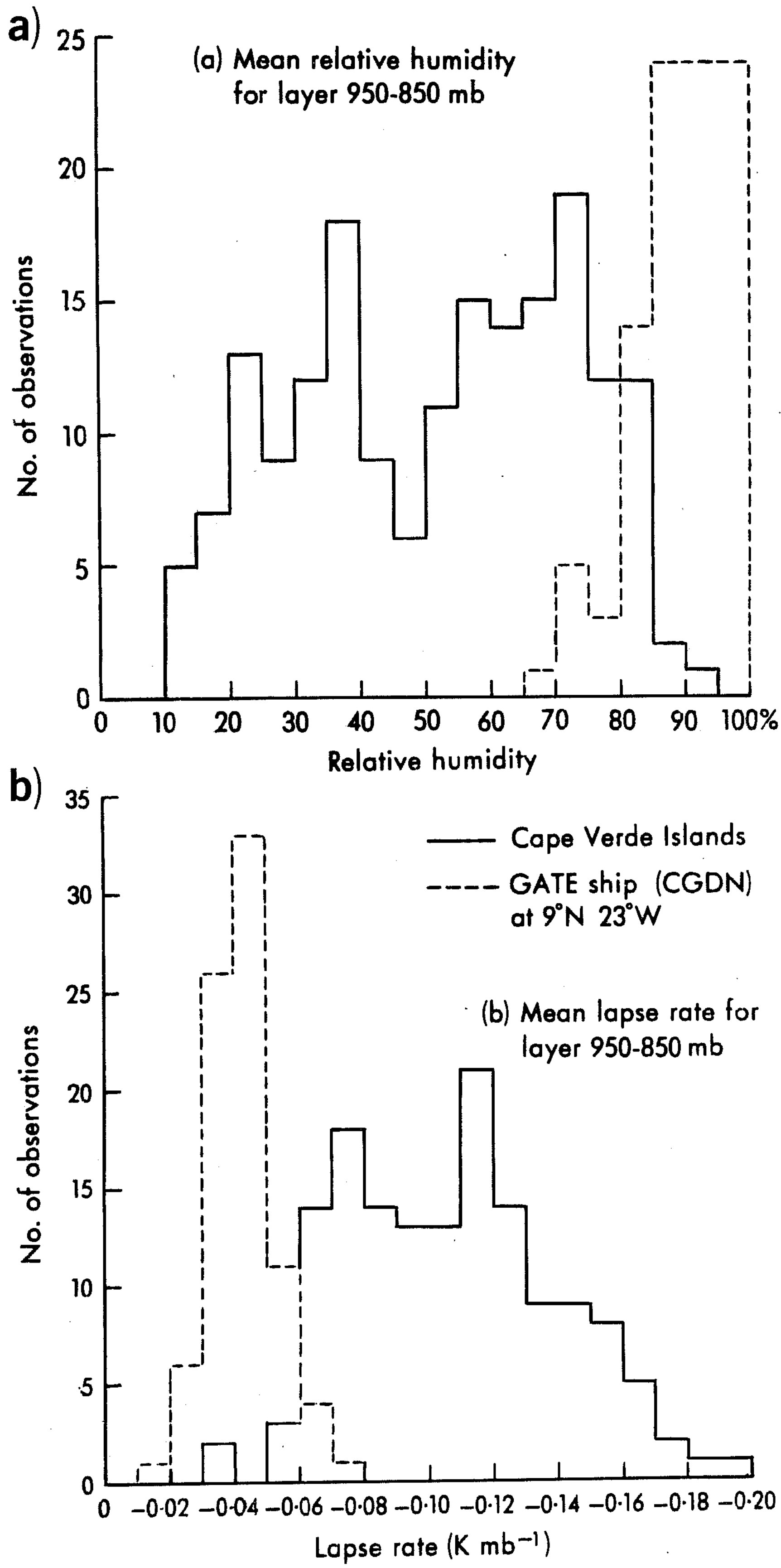


Fig. 4 Comparison of frequency distributions in the presence of low layer cloud of (a) mean relative humidity in the layer 950-850 mb and (b) mean lapse rate in the layer 950-850 mb from Sal, Cape Verde Islands, and GATE ship (CGDN) at 9°N, 23°W (from Slingo 1980).

atmospheric stability as a predictor. GATE ship (CGDN) was positioned in the convectively active part of the ITCZ whilst the Cape Verde Islands experienced persistent stratocumulus throughout the GATE period. The difference in the two regimes is clear. The probability of cloud occurring with relative humidities in excess of 80% would predict most of the clouds in the ITCZ zone but would capture almost none of the clouds at Sal, Cape Verde Islands. In contrast, those clouds are most probable when a low-level inversion is present and lapse rate is clearly a useful indicator.

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 which would suppress cloudiness. Thus, in a sense, relative humidity and vertical velocity are complimentary. However it will be seen later than vertical velocity can be useful in distinguishing different types of cloud which are 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.

Although wind shear and surface fluxes are mentioned here they have not, so far, been used in the new scheme. Wind shear implies mechanical turbulence which may be the source (or sink) of layer clouds in the middle and upper troposphere (e.g. altostratus, jet stream cirrus). There are indications from observational studies (e.g. Agee and Lomax 1978; Sheu and Agee 1977) that surface fluxes of heat and moisture can have an influence on the low level cloudiness although the results are by no means conclusive. In the case of mesoscale cellular convection it seems that open cells (i.e. small cloudiness) may be favoured by large surface fluxes whilst closed cells (i.e. large cloudiness) may be favoured by smaller fluxes.

3.3 Basic structure of the scheme

The scheme allows for four cloud types - convective and three layer clouds (high, middle and low level). The convective cloud can fill any number of model layers, its depth being determined from the convection scheme. The layer clouds are at present constrained so that they cannot exceed one layer in thickness. The levels at which these clouds occur is determined by dividing the atmosphere into three parts and the maximum cloud amount in each part ascribed to that layer of maximum cloudiness. Fig. 5 shows a schematic representation of the vertical cloud distribution and the division into high, middle and low clouds. No cloud is allowed in the lowest model layer.

3.4 Cloud prediction equations

(i) Convective cloud (C_c)

This is determined from the scaled time averaged precipitation rate ($\bar{P}$) from the model's convection scheme using:

$$C_c = a + b \operatorname{Log}_e \bar{P} \qquad (1)$$

This relationship was derived from a statistical relationship between frequency distributions of tropical observed convective cloudiness and model precipitation rates in a similar manner to that used in Slingo (1980). The advantage of the scheme is that it is easily transferable between convection schemes and has been used successfully with the Arakawa-Schubert scheme. 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

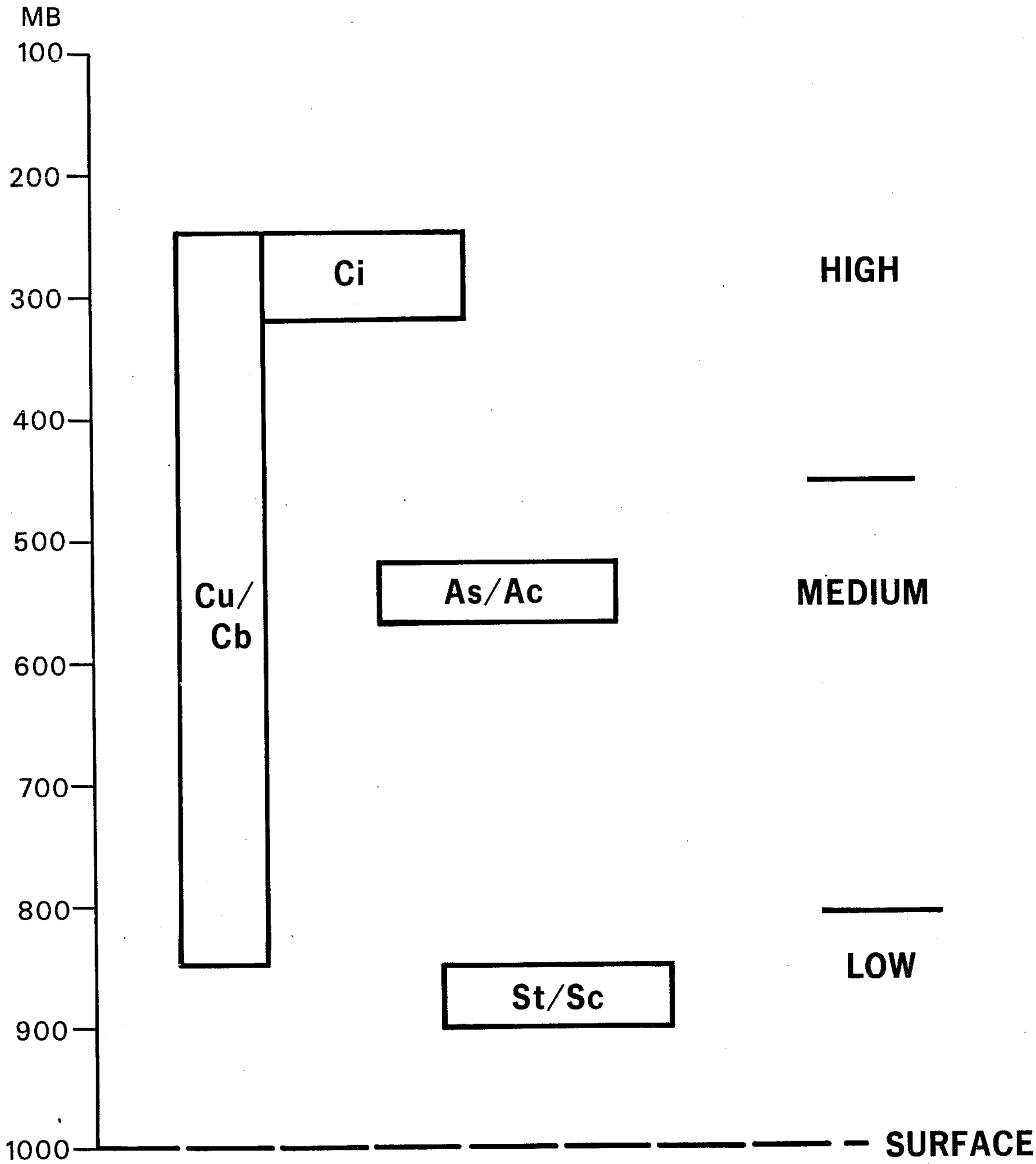


Fig. 5 Schematic representation of the vertical cloud distribution and the division into high, middle and low clouds for the new cloud prediction scheme.

(ii) High cloud (C_H)

The scheme distinguishes between two different types of cirrus, that associated with outflow from deep convection and that associated with frontal disturbances. As already mentioned the anvil cirrus is not captured by a dependence on the relative humidity because the Kuo convection scheme does not adequately moisten the upper troposphere. A dependence on convective activity is therefore used since the probability of these clouds occurring increases 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) similar to that used in the operational scheme:

$$C_H = \left\{\mathrm{Max}\left[\frac{RH - 0.8}{0.2}\ ,\ 0.0\right]\right\}^2 \qquad (3)$$

(iii) Middle cloud (C_M)

Very little is known about these clouds, how and why they form. They occur mainly in association with tropical disturbances and extratropic frontal systems. In this scheme they are parameterized by:

$$C_M \left\{\mathrm{Max}\left[\frac{RH_e - 0.8}{0.2}\ ,\ 0.0\right]\right\}^2 \qquad (4)$$

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. This essentially allows for the dry subgrid scale downdraughts in the 'environment' in which the layer cloud is free to form.

(iv) Low cloud (CC_L)

These 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 1985). It may also be true for a forecast model because these clouds have the greatest and most direct impact on the 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 dramatic effect on the surface weather.

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):

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

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

There is a linear transition up to a weak ascent

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

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

Otherwise $C_L = C'_L$ (7)

Again RH_e is the relative humidity of the environmental air after allowing for convective clouds (Eqn.5). The advantages of using vertical velocity as well as relative humidity can be seen in Fig. 6 where the low clouds have been diagnosed from day 5 of a forecast from 15/1/84. In Fig. 6(a) the clouds are determined only by the relative humidity (Eqn.6) and the lack of detail particularly in the extratropics is marked. However the additional dependence on vertical velocity (Eqn.7) has proved successful in delineating the frontal clouds in the extratropics whilst in the subtropics it suppresses the excessive cloudiness which would otherwise occur (Fig. 6(b)).

The second class of low level clouds are strongly linked to the boundary layer and are invariably associated with low level inversions in temperature and humidity e.g. tradewind inversion. They are often vertically subgrid scale and may therefore not be represented by the average relative humidity through a model layer. An initial parameterization is proposed such that:

$$C_L = -6.67 \left(\frac{\Delta\theta}{\Delta p}\right)_{min} - 0.667 \quad (8)$$

where $\left(\frac{\Delta\theta}{\Delta p}\right)_{min}$ is the lapse rate (K mb^{-1}) in the most stable layer below 750 mb. Further refinement of this parameterization may be necessary. However it should be stressed here that this equation represents a probability of cloud occurring and should not in any way be thought of as representing a physical process. This type of parameterization was proposed earlier from GATE data and proved successful in UKMO limited area tropical model (Slingo 1980). It also seems to work well in the global context of the ECMWF model. Fig. 7 shows the clouds diagnosed by Eqn.8 for day 10 of a forecast from 15/7/83. The persistent clouds off the western seaboards are well represented as are the summertime Arctic stratus clouds and those over the cold waters of the North Pacific. It is interesting to note that the clouds produced by Eqns. 6

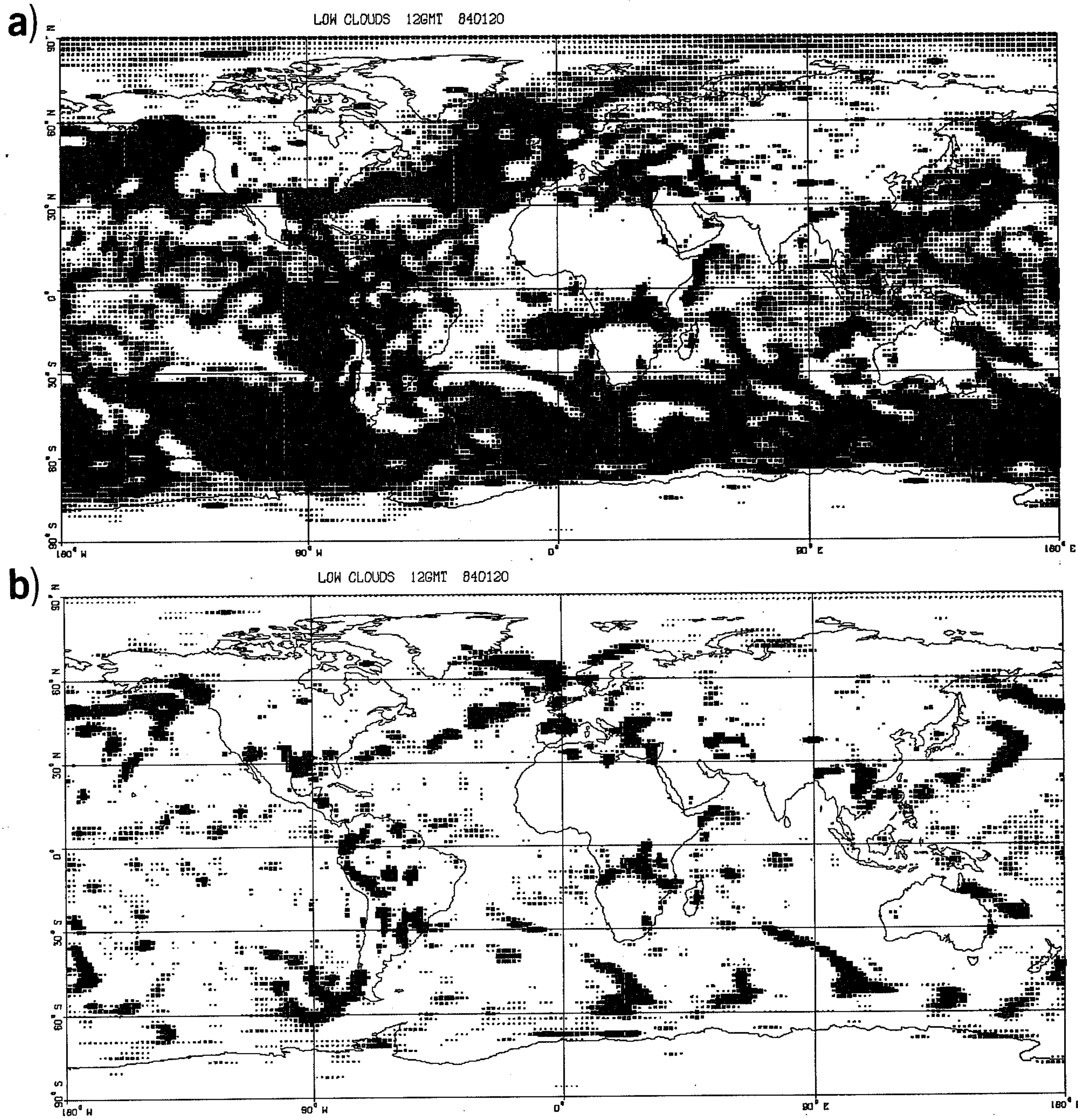


Fig. 6 Low level cloudiness diagnosed from day 5 of a forecast from 15/1/84 using (a) relative humidity only (b) relative humidity and vertical velocity.

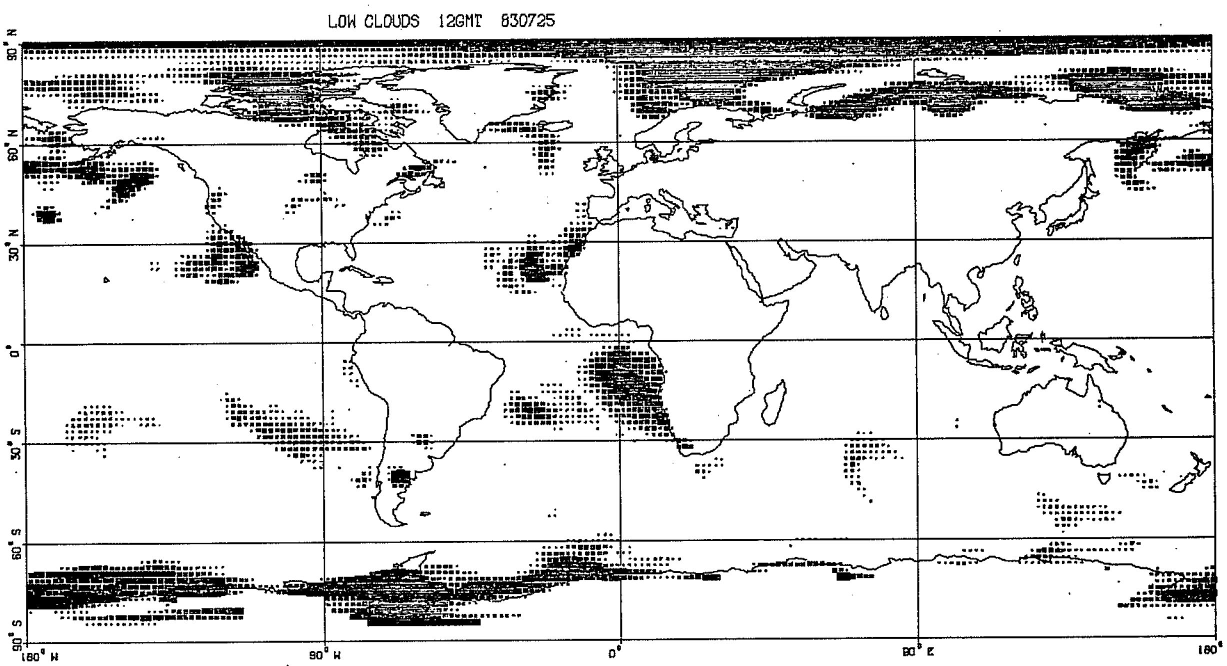


Fig. 7 Low level cloudiness diagnosed from day 10 of a forecast from 15/7/83 using inversion strength as an indicator.

and 7 and those from Eqn.8 are almost mutually exclusive so that the two schemes combine without any difficulty. This method is designed only to represent 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 parameterization.

4. DESCRIPTION OF THE MODEL AND THE EXPERIMENT

The cloud scheme described in the previous section has been tested in a number of 10-day forecasts with the T63 spectral model (Simmons and Jarraud 1984). The model has 16 levels in the vertical based on a hybrid coordinate system η such that:

$$\eta_{k+\frac{1}{2}} = A_{k+\frac{1}{2}}/P_o + B_{k+\frac{1}{2}}$$

Variables A and B are chosen so that the coordinate system follows the orography for pressures near the surface pressure but tends towards constant pressure surfaces for upper levels. Fig. 8 shows the vertical coordinate system. The model includes a comprehensive representation of the physical processes as described by Tiedtke et al. (1979) but with some modifications outlined below.

(i) A modified Kuo convection scheme is used in the tropics (30°N to 30°S) in which the partitioning between the heating and moistening of the environmental air is altered to give more convective heating and less moistening.

(ii) A shallow convection scheme has been included in which the vertical diffusion is enhanced when a shallow convective cloud layer exists within the boundary layer. This leads to a marked improvement in the structure of the tradewind boundary layer (Tiedtke 1985).

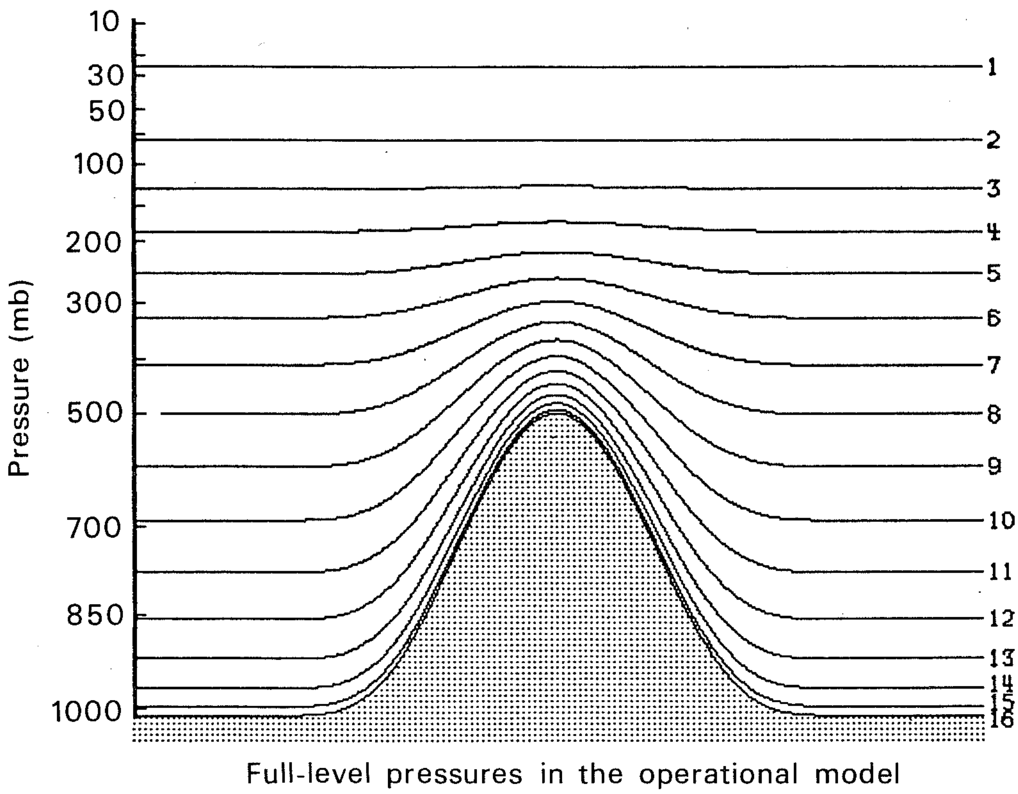


Fig. 8 Vertical hybrid coordinate system of the operational model.

(iii) A modified infrared radiation scheme is used in which the gaseous effects are treated using the technique of exponential sum fitting (Ritter 1984). This version was found to correct the errors of the effective absorber method (Geleyn and Hollingsworth 1979) particularly the interaction with clouds (Slingo 1983) and was introduced into the operational model on December 4, 1984.

(iv) Cloud liquid water contents were increased from the current operational value of 0.2% supersaturation to 1% supersaturation. This gives more realistic values particularly for upper levels clouds and has a significant effect on the radiation budget (see Sect. 6).

The cloud scheme has been tested on several dates with operational analyses and one date with the latest FGGE analysis (11 June 1979). This was prepared from a data assimilation which included the modifications (i) to (iii) to the physical processes described earlier in this section. The results described here will concentrate on the 11 June 1979 case partly because the new analysis is good particularly in terms of humidity and partly because it covers the sudden intensification of the monsoon and is therefore a good test of the model (Mohanty et al. 1985).

5. RESULTS

5.1 Cloud cover

The cloud amounts predicted by the model after 24 hours have been compared with the METEOSAT image (Fig. 9) and the GOES image (Fig.10) for the Indian Ocean given in Krishnamurti et al. (1983). The 24 hour forecast was chosen partly because the model's initial adjustment should be almost complete and partly because beyond day 1 the comparison is progressively biased by errors in the model forecast.

Fig. 11 shows the distribution of high cloud for the new scheme and the operational scheme. The extratropical frontal cirrus is very similar in both cases and agrees well with that in the METEOSAT infrared image (Fig. 9b). However the new scheme shows a marked improvement in the tropics with high cloud being predicted in the Atlantic and off S. America as seen in the METEOSAT image. The high clouds over the Indian Ocean (Fig. 10), heralding the onset of the monsoon are captured by the new scheme. Basically the scheme now represents those cirrus clouds which are the result of convection as, for example, over Eastern Europe.

The middle clouds (Fig. 12) show a general reduction in cloudiness. 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.

For the purposes of comparison with the operational scheme, Fig. 13 shows the combined low level stratus and cumulus clouds from the new scheme. There is a marked increase in subtropical cloudiness with the new scheme and the transition from the dense frontal clouds of the extratropics to the broken convective regimes of the tropics is striking. In particular the scheme has been successful in capturing the areas of subtropical low level cloudiness off the western seaboards of the major continents. Comparison with the METEOSAT infrared image shows that the scheme has achieved a fair degree of skill in representing the tropical cloudiness and similar results were obtained for the other cases. The reduction in cloudiness over South America is due to the use of vertical velocity in the scheme in place of a restriction on clouds in the well mixed layer. This has led to a marked improvement in the diurnal cycle over the tropical continents (see later). One shortcoming of the scheme is the excessive cloudiness over the winter pole. This is related to the overly simple form of Eqn.8 which does not include any information on relative humidity or the structure under the inversion. However the effect of these clouds on the model will be very slight because they are optically very thin.

It is instructive to consider the partition between cumuliform and stratiform clouds for the low level cloudiness. This is shown in Fig. 14. Over the tropical oceans much of the cumuliform cloudiness is shallow, the areas of deep convection being implied by the high cloud (Fig. 11; Eqn. 2).. Over the cold water of the eastern subtropical oceans the cloud is stratiform but changes to cumuliform as the sea surface temperatures increase. In the extratropics cumuliform and stratiform clouds form together along the fronts although stratiform clouds are also predicted over the cold oceans of the North Pacific. One shortcoming is the lack of shallow cellular convection which often occurs behind cold fronts in the winter hemisphere.

The representation of the diurnal variation in cloudiness is much improved with the new scheme. Fig. 15 shows the distribution of low level cloudiness (cumuliform and stratiform) for four times through day 5 of the forecast from

a)

Fig. 9 METEOSAT image for 12Z 12/6/79 (a) visible (b) infra red.

b)

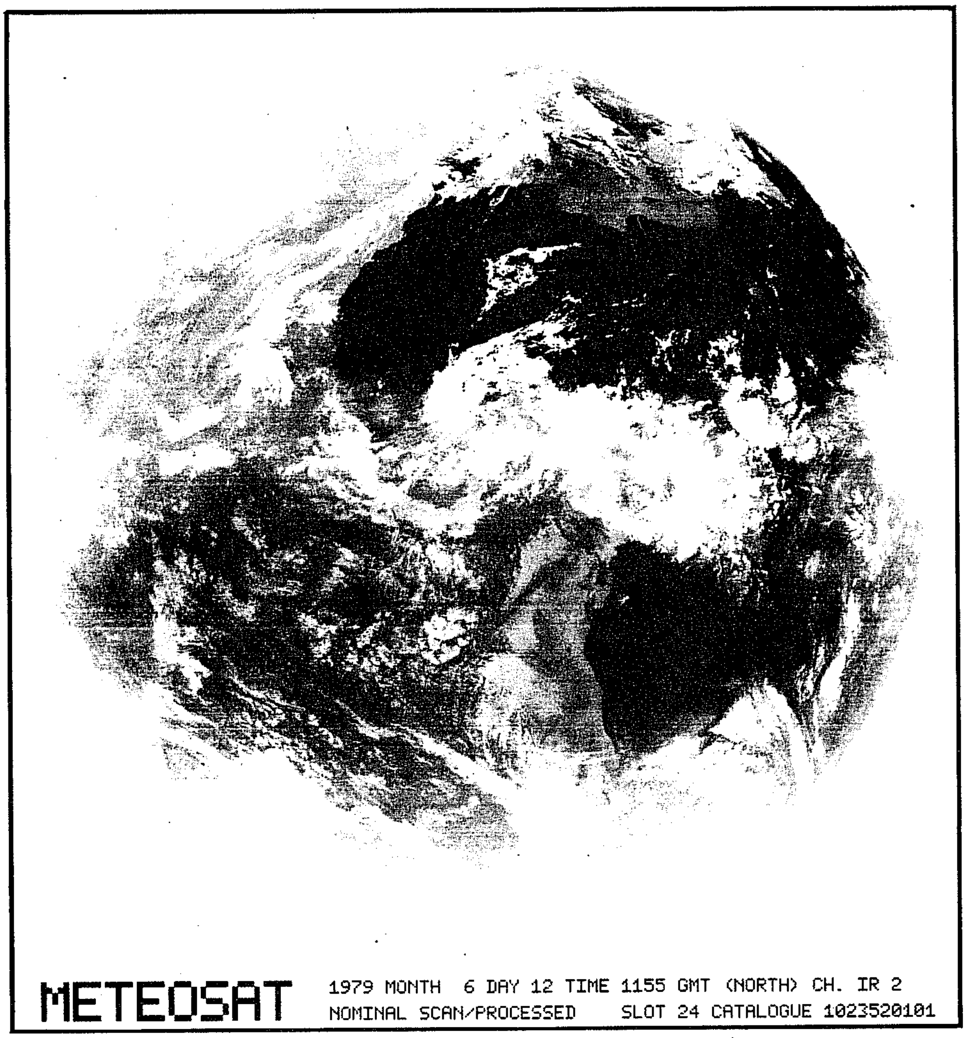


Fig. 9 Continued

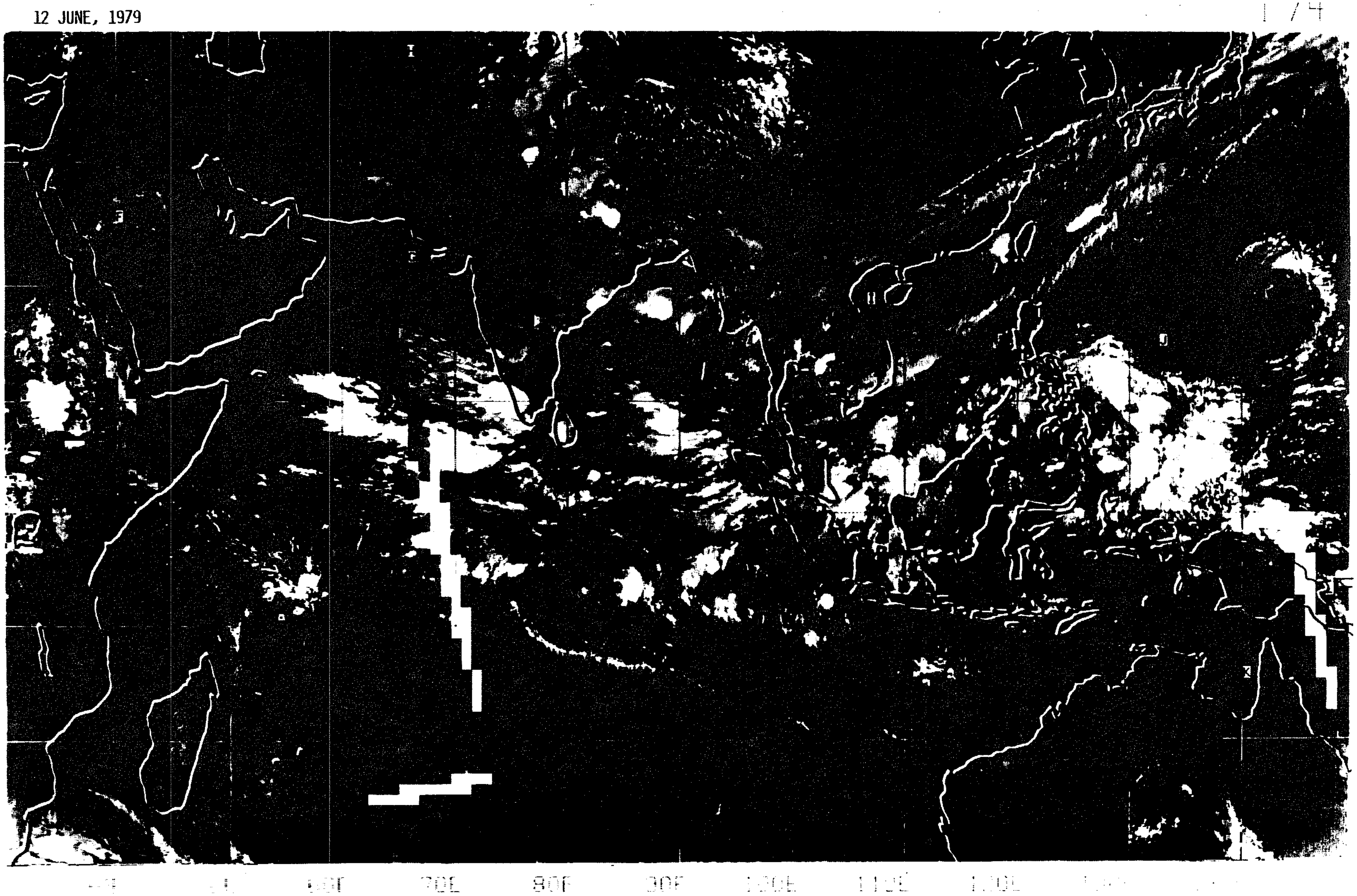


Fig. 10 GOES infrared image for the Indian Ocean for 12Z 12/6/79 from Krishnamurti et al. (1983)

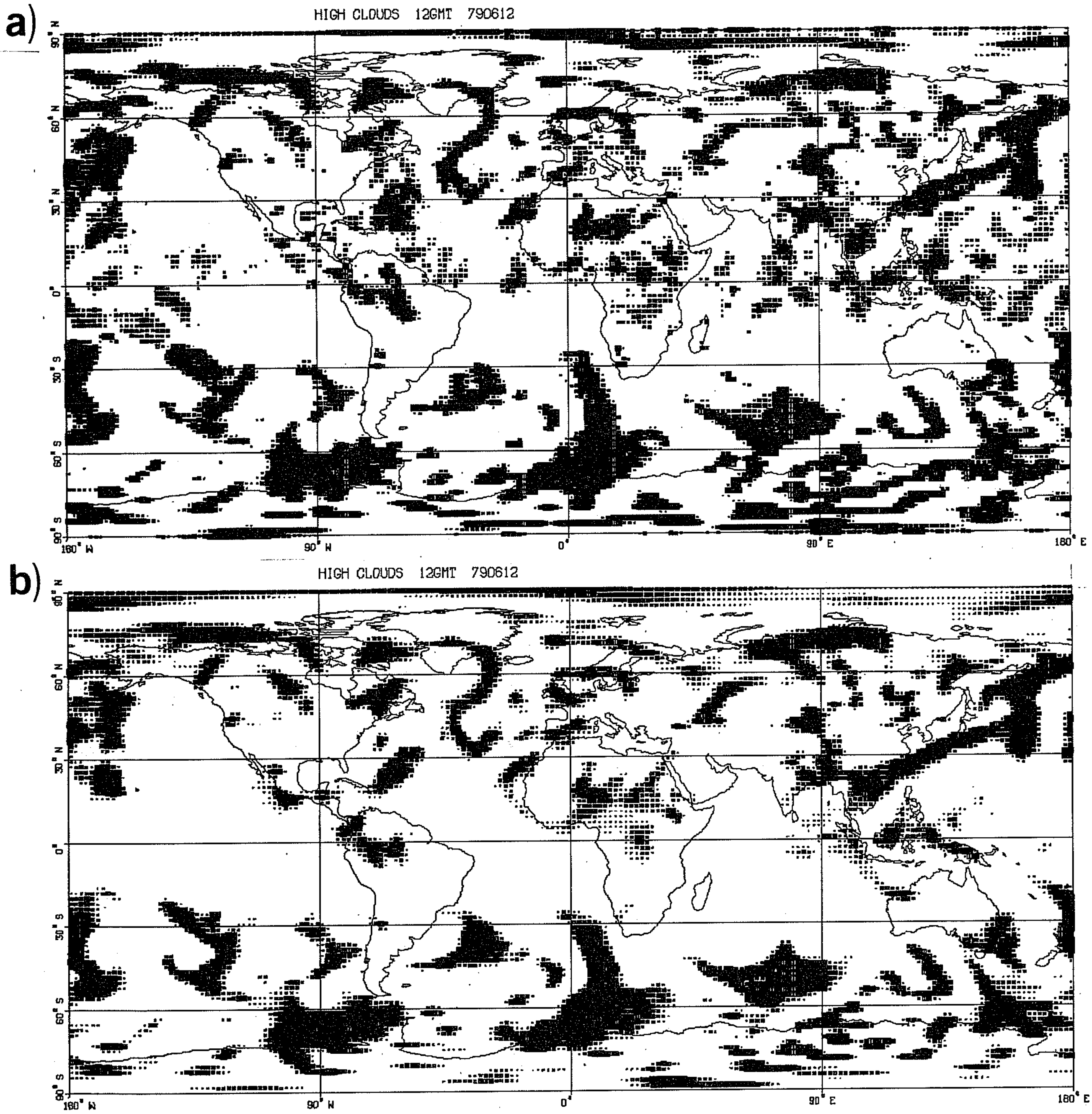
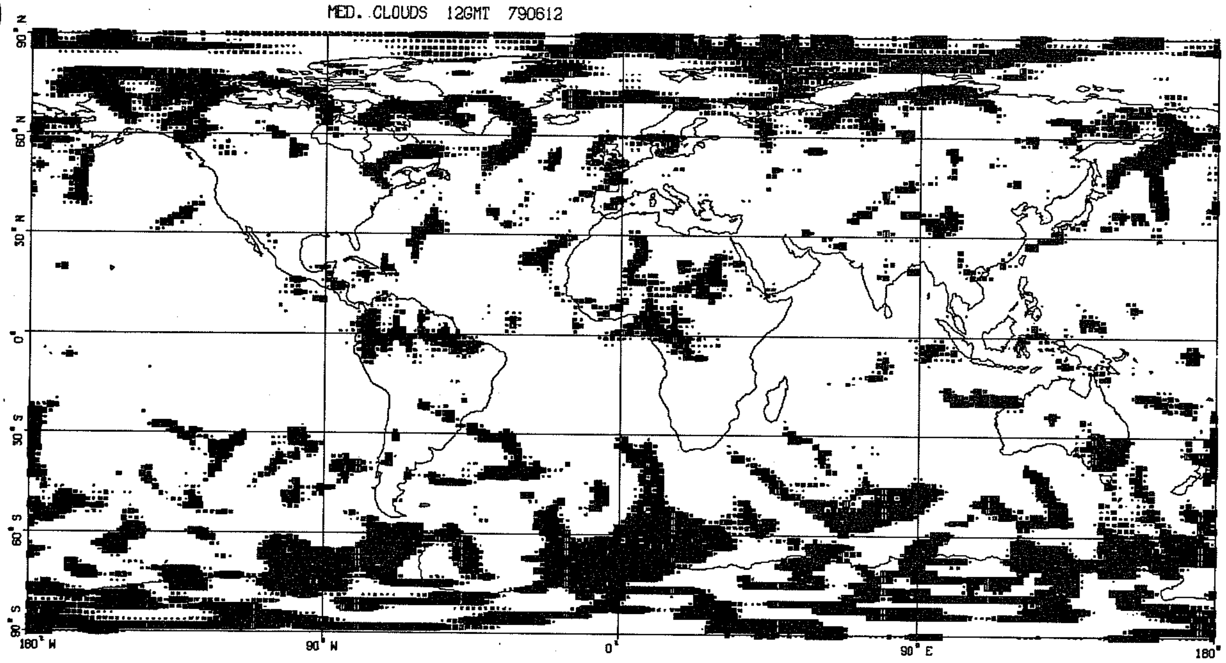


Fig. 11 Distribution of high cloud for day 1 of forecast from 11/6/79. (a) new scheme (b) operational scheme.

a)



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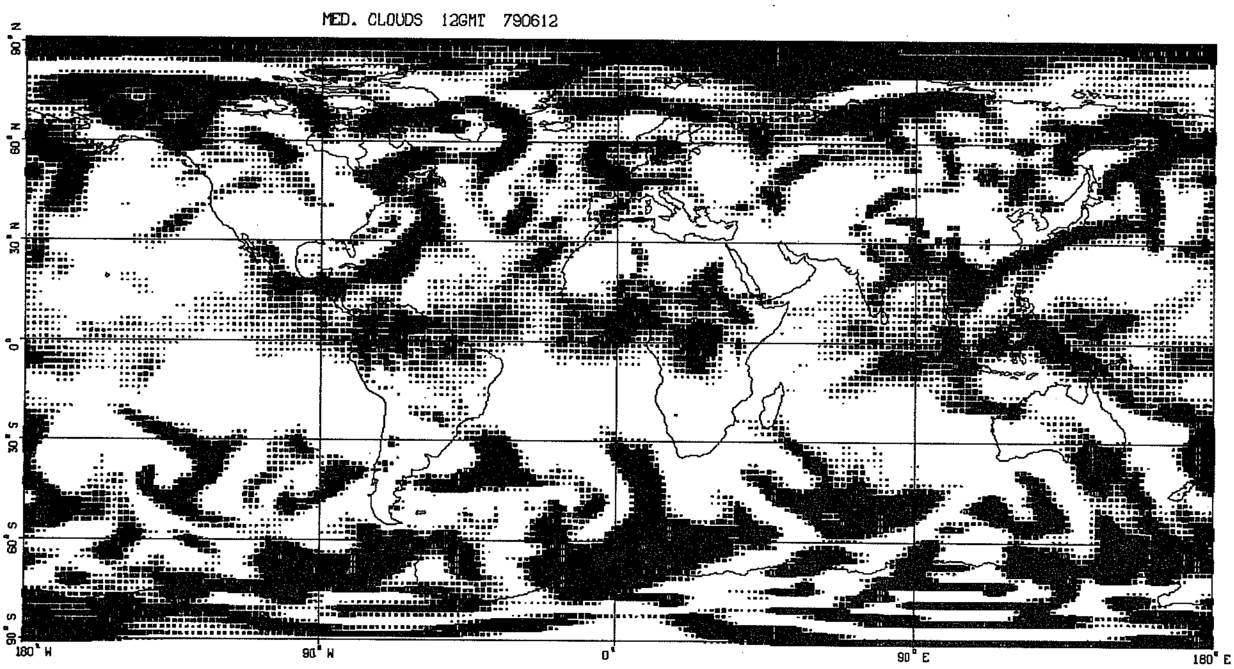


Fig. 12 As Fig. 11 for middle cloud.

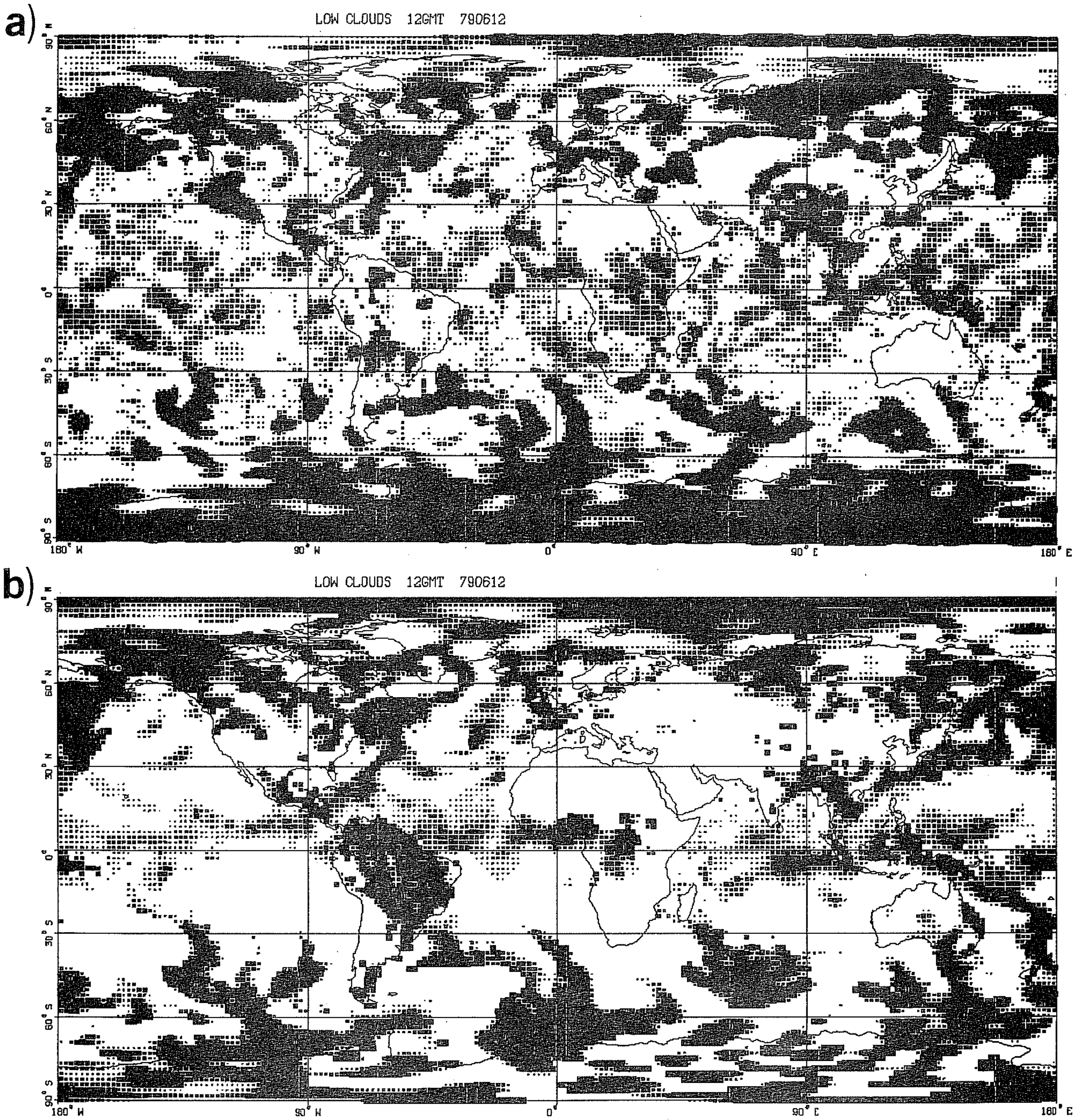


Fig. 13 As Fig. 11 for low level cloud (i.e. stratiform plus cumuliform for the new scheme).

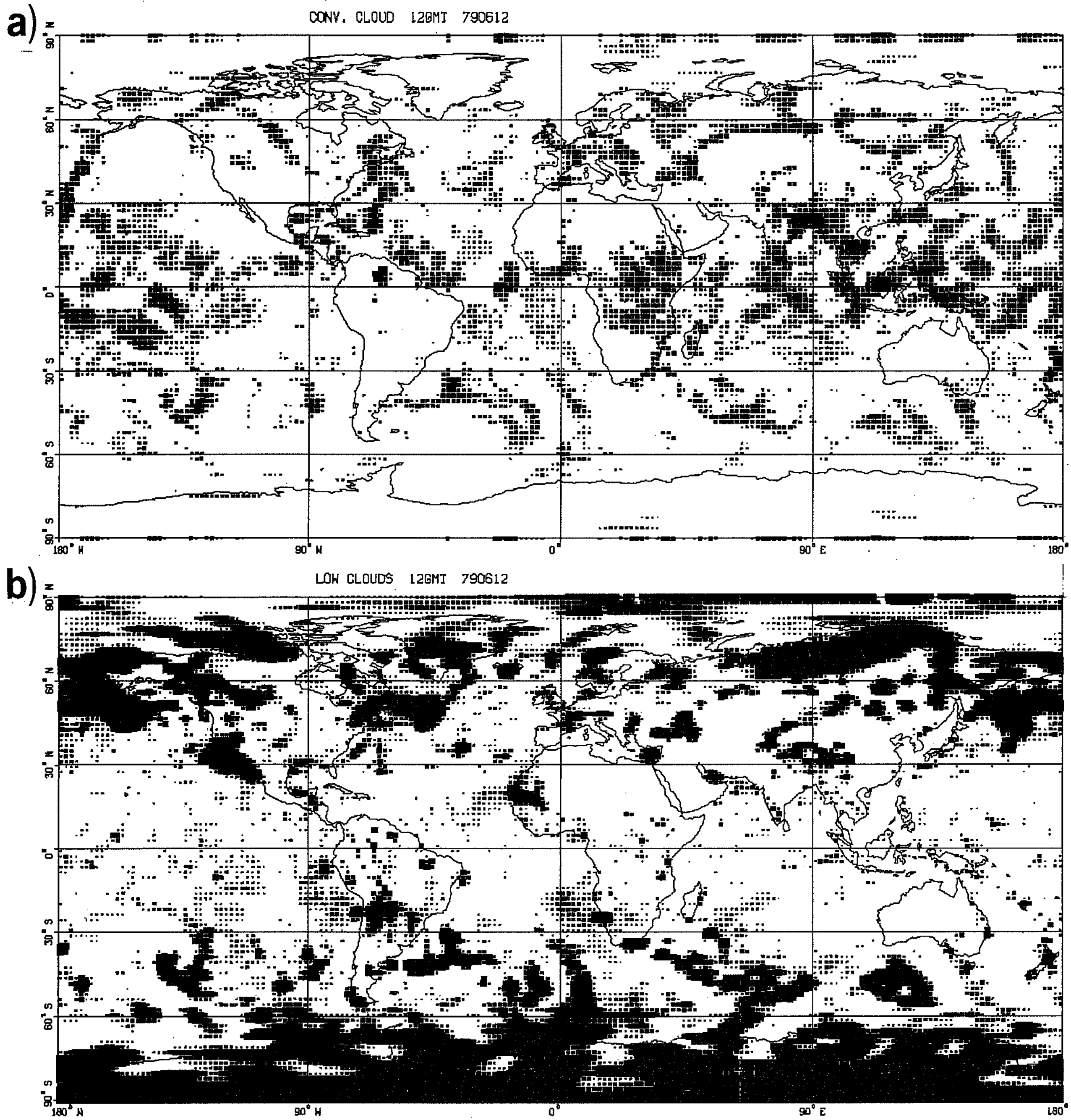


Fig. 14 Partition between (a) cumuliform and (b) stratiform low level clouds from the new scheme for day 1 of forecast from 11/6/79.

11/6/79. Over South America the variation in cloudiness shows an increase between 12 and 19 GMT as local noon is approached. By 1 GMT the cloudiness has decreased again as night falls and convection ceases. A similar variation is seen over central and West Africa with more cloud at 12 and 19 GMT than at 1 and 8 GMT. The undesirable variation in cloudiness over the summer continents, related to the well mixed layer restriction, appears to be rectified. However it should be noted that the diurnal variation is very dependent on the convection scheme and its response to the surface heating.

A common problem with cloud prediction schemes is an undesirable increase in cloudiness, particularly for low clouds, during the integration. This is due to the interaction of the scheme with the enhanced radiative cooling produced by the cloud which in reality is offset by turbulent mixing. The scheme described here 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 extensive sub-tropical oceans. This can be seen in Fig. 16 where the zonal mean cloud amounts for days 5 and 10 of the forecast from 15 July 1983 are compared with a climatology compiled by Bolton (1981) from various published surface based climatologies. Again the low clouds are a combination of cumuliform and stratiform clouds. As can be seen there is no indication of an increase in cloudiness, the total cloud cover of 51% being in good agreement with observed estimates. The scheme predicts more high and middle cloud particularly in the southern hemisphere depression belt. However Bolton's climatology must be questionable here because upper level clouds are often obscured by low level stratus; satellites indicate a greater occurrence of middle and high cloud (Stowe 1985). The lack of low cloud between 30° and 60°S may be due to the scheme's inability to represent cellular convection behind cold fronts as already mentioned.

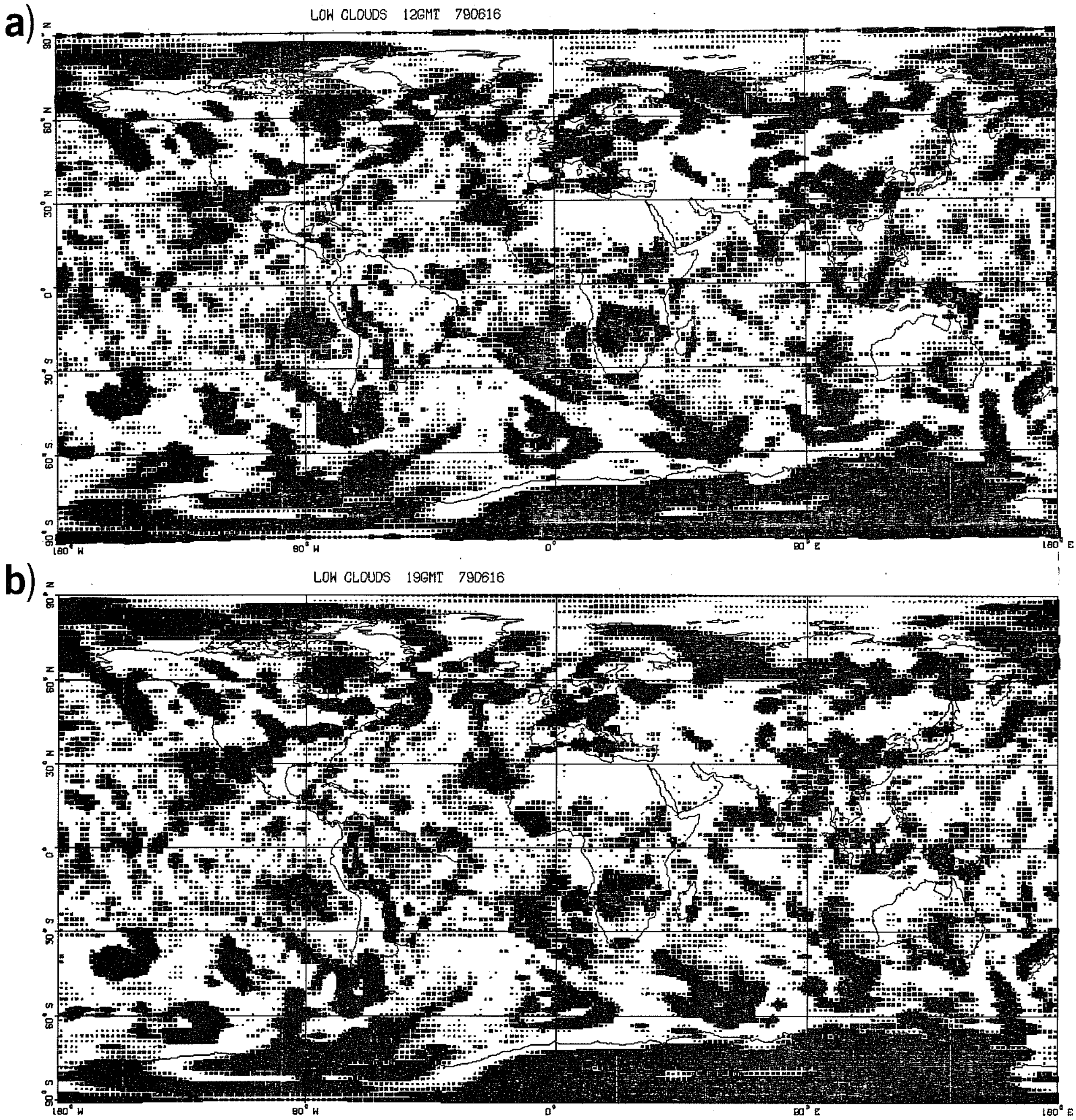
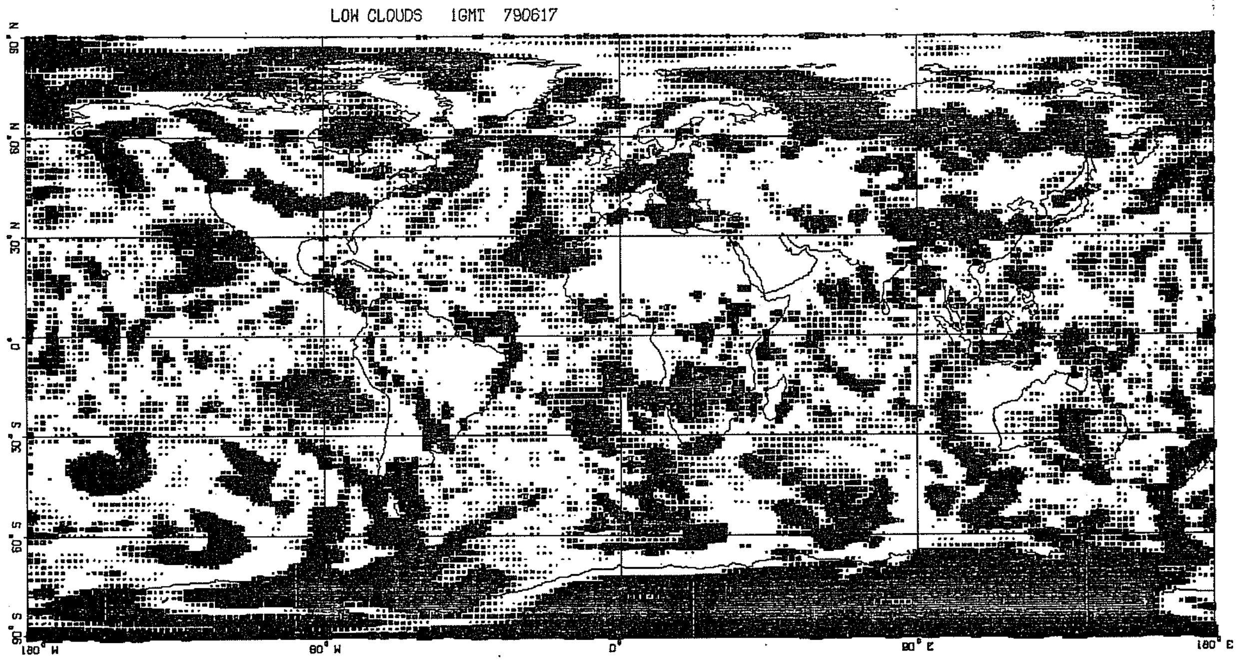


Fig. 15 Diurnal variation in low level cloudiness from the new scheme through day 5 of the forecast from 11/6/79, (a) 12 GMT 16/6/79, (b) 19 GMT 16/6/79, (c) 01 GMT 17/6/79 and (d) 08 GMT 17/6/79

c)



d)

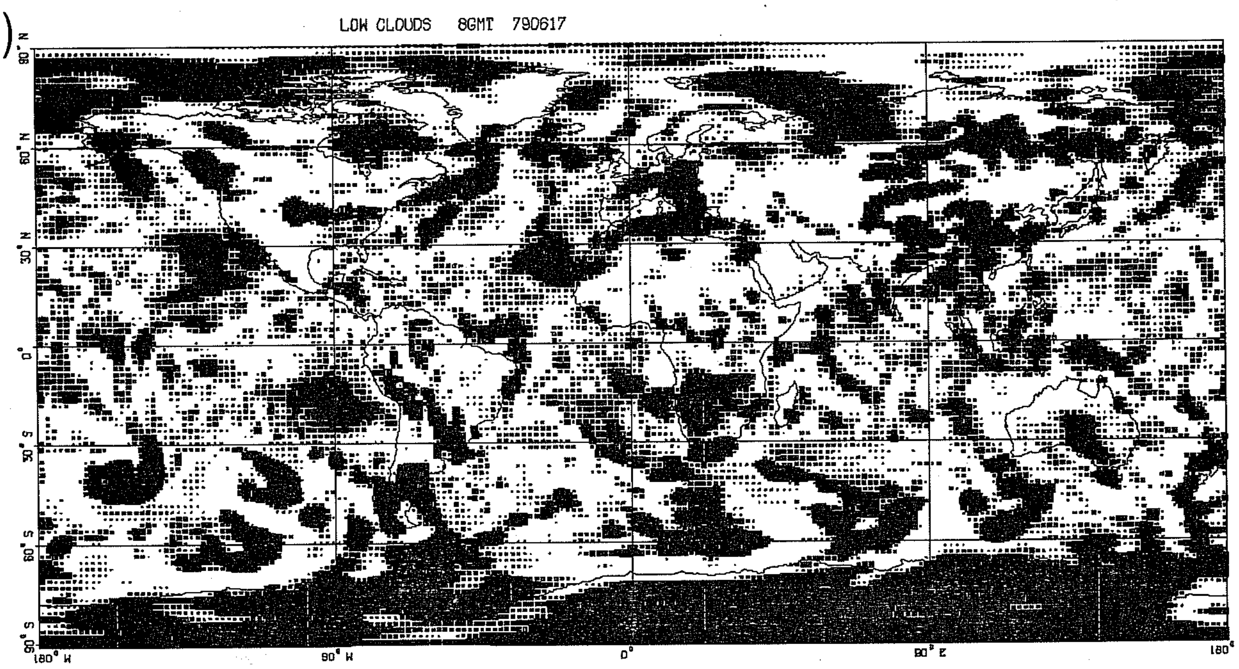


Fig. 15 Continued

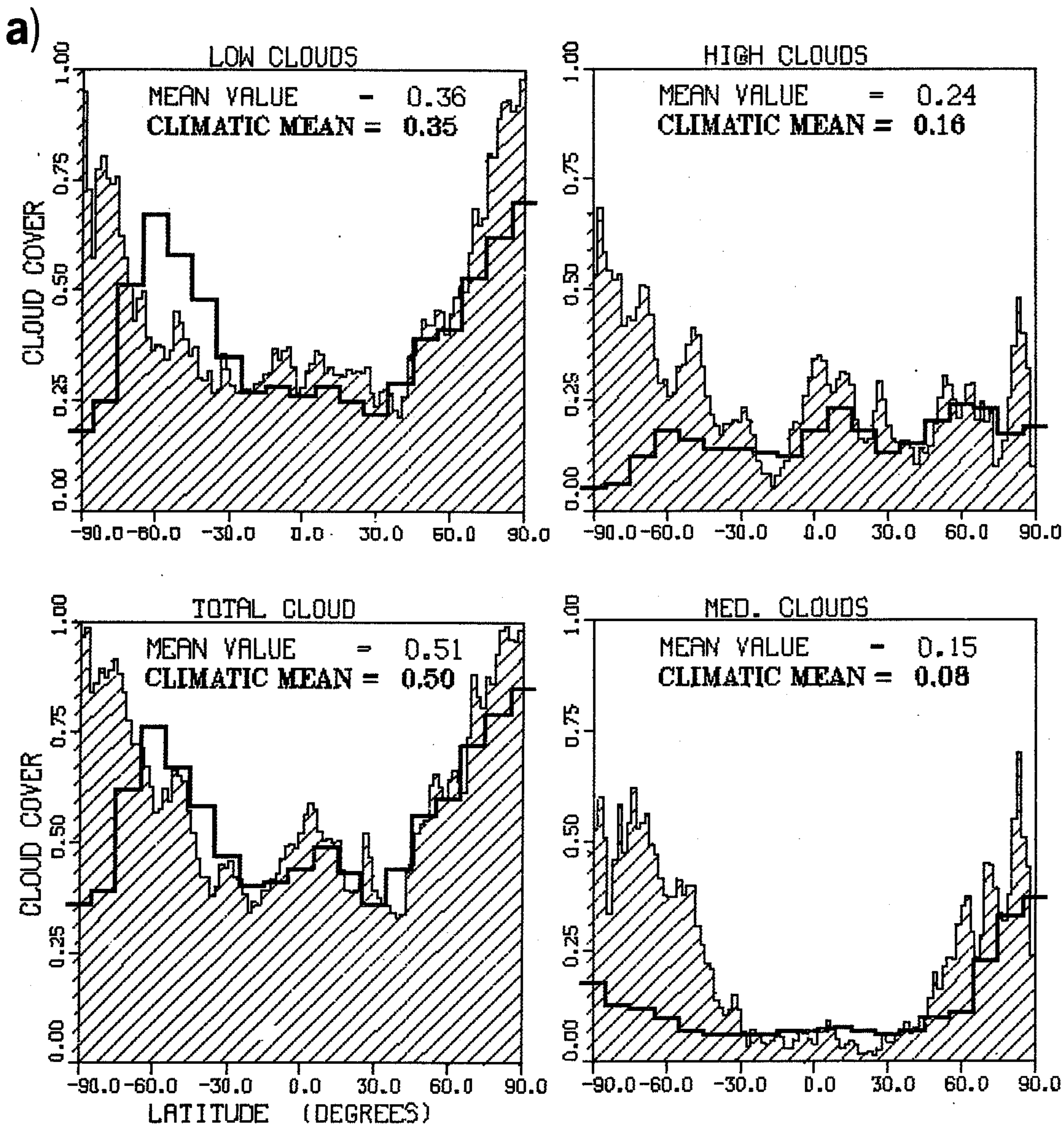


Fig. 16 Comparison of zonal mean cloud amounts for (a) day 5 and (b) day 10 of forecast from 15/7/83 with a climatology compiled by Bolton 1981. (Solid line is climatology, hatched area is model).

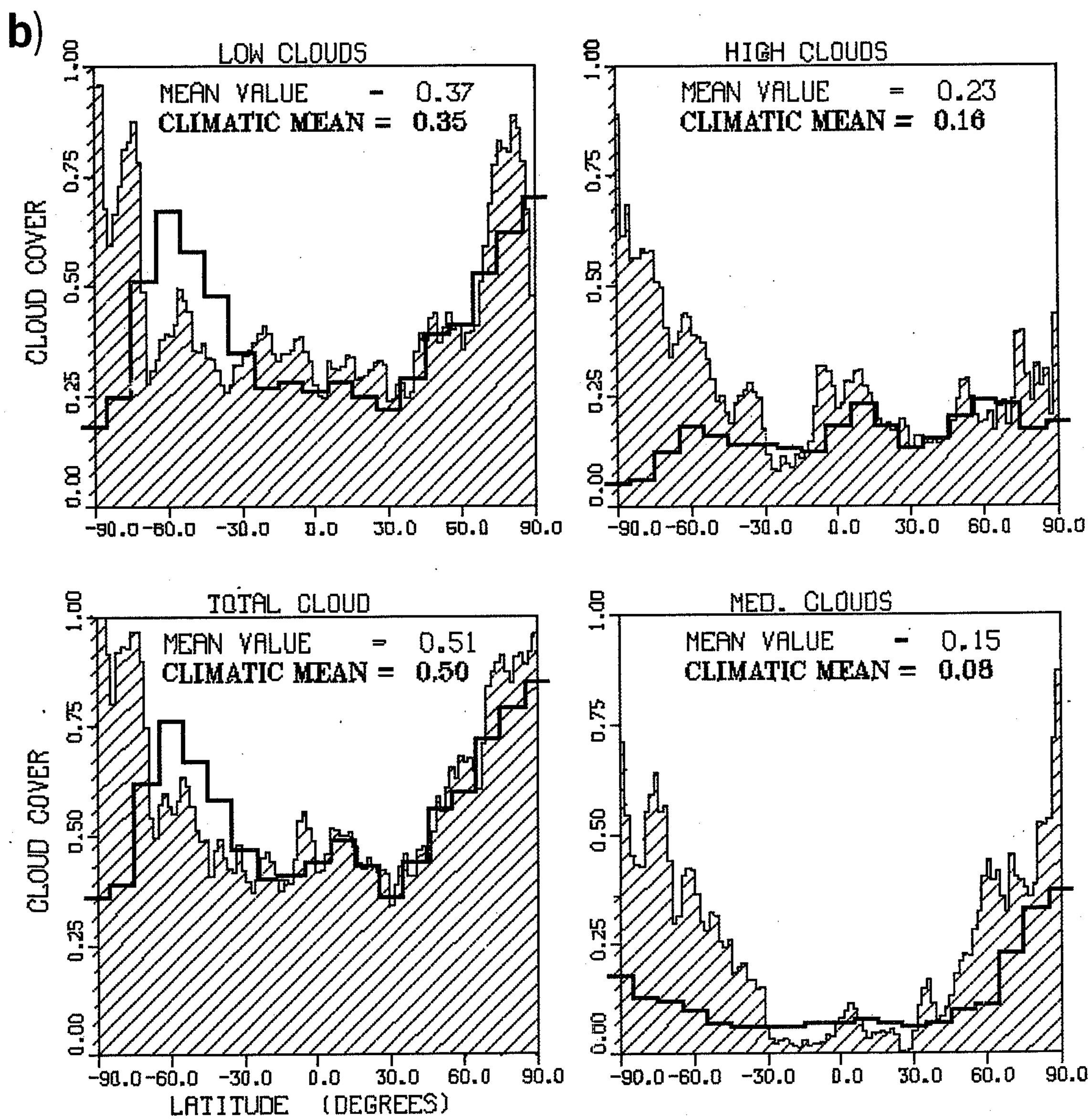


Fig. 16 Continued

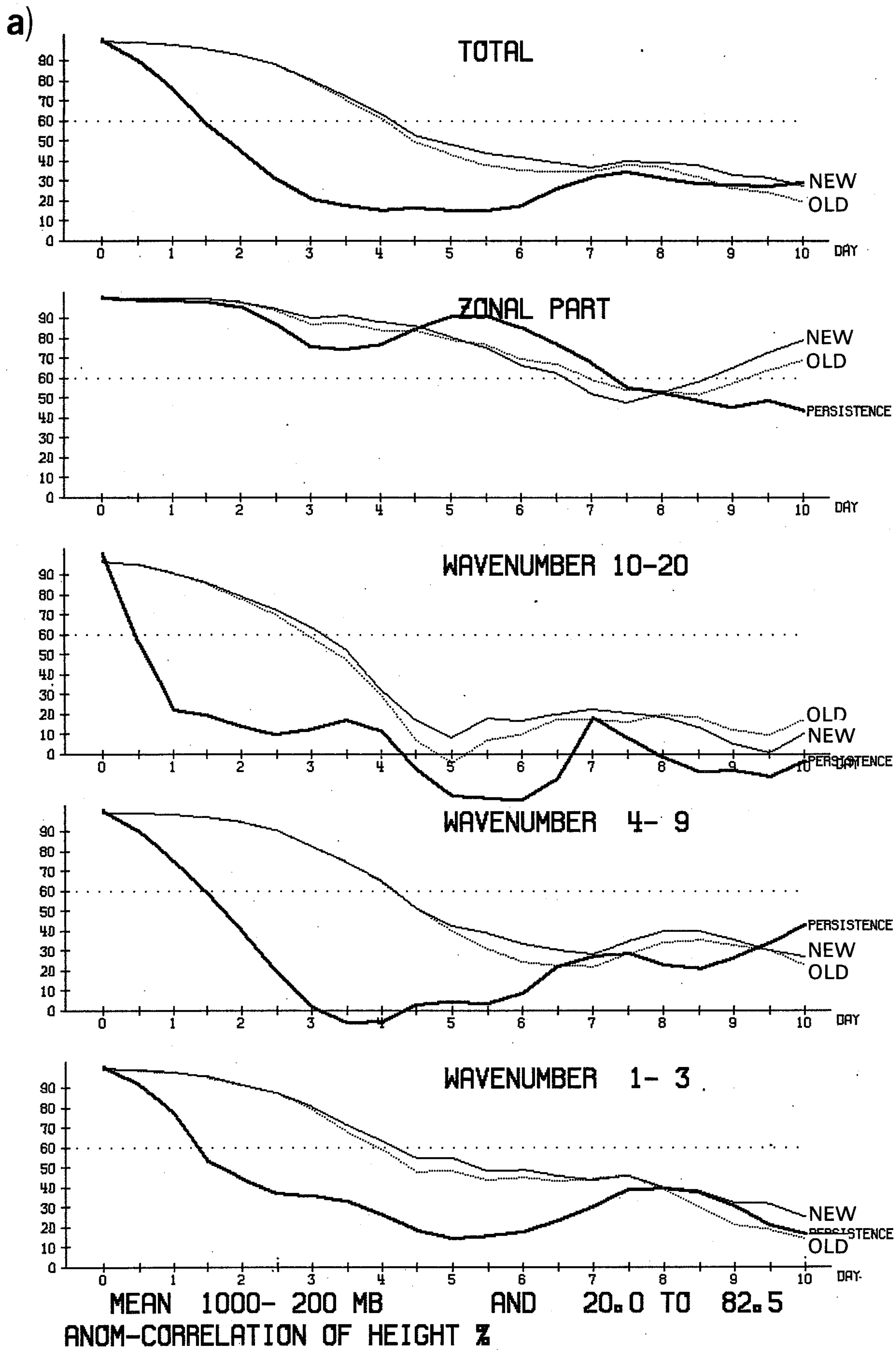


Fig. 17 Anomaly correlations of height for forecasts with the new scheme versus forecasts with the operational scheme for (a) 11/6/79 case and (b) 15/1/84 case.

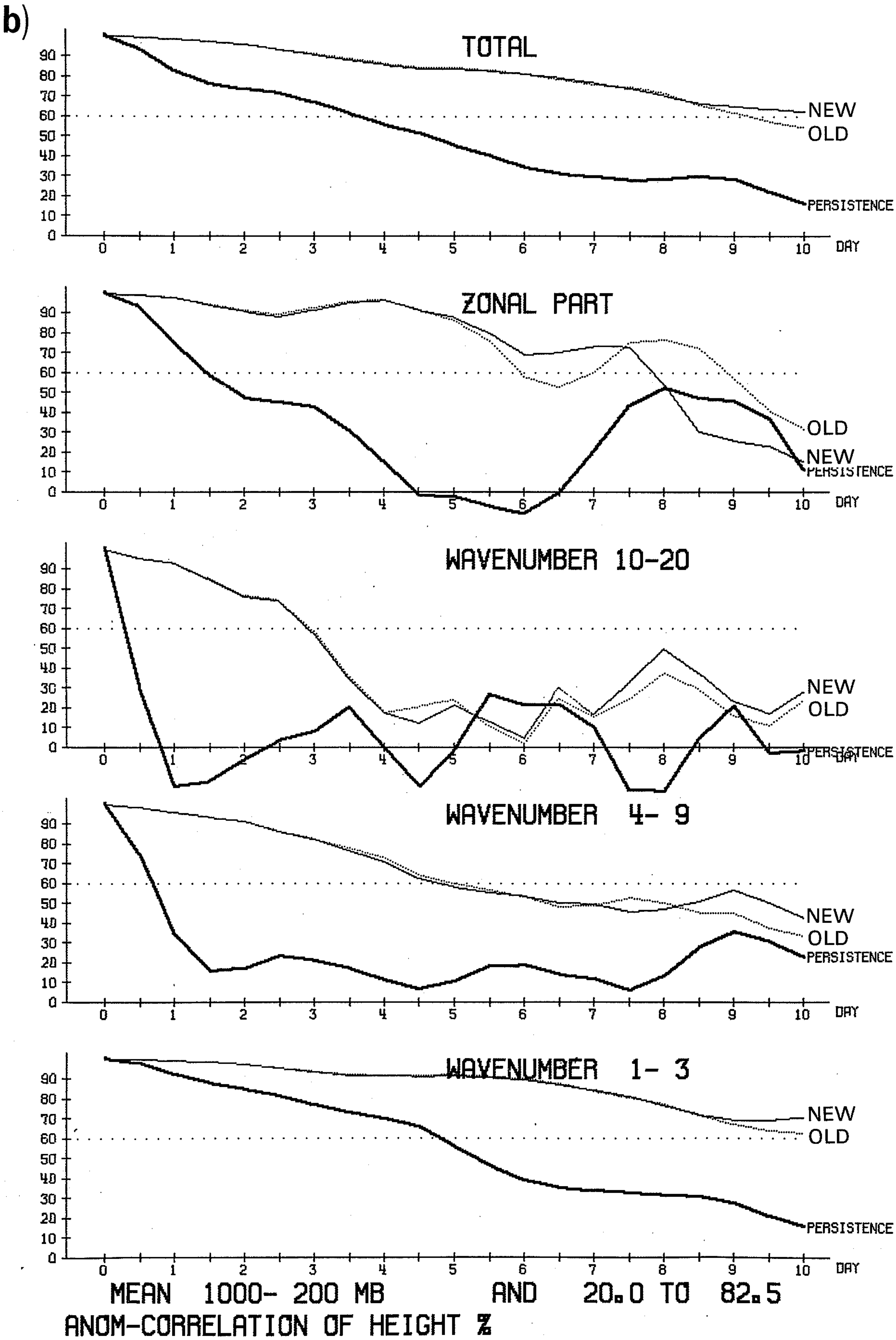


Fig. 17 Continued

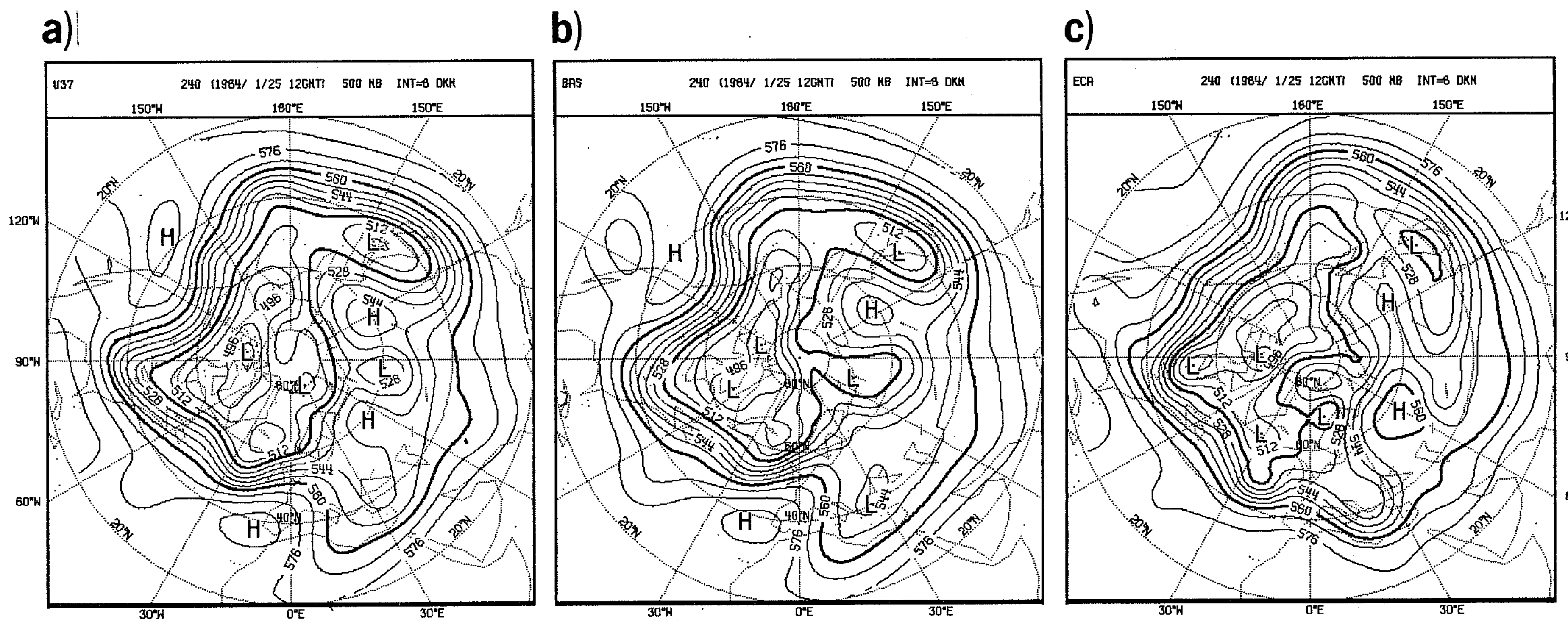


Fig. 18 500 mb height fields for day 10 of forecasts from 15/1/84
(a) new scheme (b) operational scheme and (c) analysis.

5.2 Impact of the cloud scheme on the model's performance

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 time-scales themselves are large and partly because the operational cloud scheme was already successful at representing the extratropical frontal clouds. The new cloud scheme has its greatest impact on the tropical and sub-tropical cloudiness and this may only feed-back into the extratropics late in the forecast. Also it would be unwise at this stage to draw any conclusions about the effect of the scheme on the model's systematic errors because it is still in the development stage particularly with respect to the radiative properties of the clouds (see Sect. 6).

However all the cases show that the scheme gives a slight improvement in skill when this is measured in terms of anomaly correlations and standard deviations. These statistics are commonly used at ECMWF for assessing the model's performance. For anomaly correlations of forecast heights versus actual heights the 60% level is taken as the minimum level at which the forecast shows some skill. In Fig. 17 the anomaly correlations of height for the forecasts from 11/6/79 and 15/1/84 are shown. Both show a slight improvement in the total scores which is due mainly to the long waves. For 15/1/84 case for example the zonal part is unimportant. It is interesting to see what these scores actually imply in terms of the height fields. The forecast from 15/1/84 was particularly good and the height fields at day 10 can be compared with the analysed field (Fig. 18). The increase in skill for that time with the new cloud scheme can be seen in the improved orientation of the trough over southern Europe, the ridge north of the Caspian Sea and in the orientation and sharpness of the trough over Canada and the United States.

6. DISCUSSION AND CONCLUSIONS

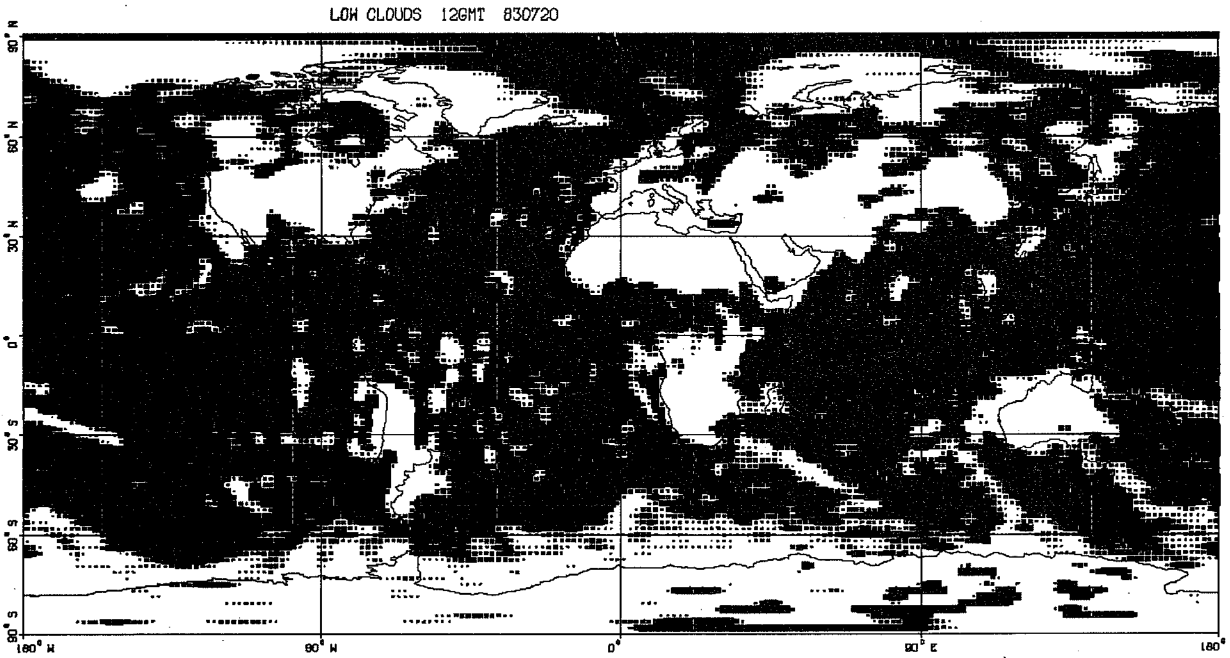
The results of the scheme have shown that a fair degree of success can be obtained with a diagnostic approach at least in the short term. The scheme is of course very dependent on the model's simulation and resolution. Since clouds are sub grid scale horizontally and/or, more seriously, vertically, the decision has to be made whether the parameterization attempts to overcome the lack of vertical resolution (as may be the case for Arctic stratus and subtropical stratus/strato cumulus) or whether it is purely disguising basic shortcomings in the model's simulation. The model cannot, because of its vertical discretization represent the highly stratified nature of the summertime Arctic (Tsay and Jayaweera 1984) nor the sharp inversions and the shallow cloud layer frequently observed in the subtropics.

It is important to remember that the equations used in the scheme represent probabilities and not a specific physical process. Ideally, it would be desirable to find similar relationships between observed variables and cloudiness but that 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 sonde is only observing at a single point and is 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 sonde ascends through clear or cloudy air. However it was possible to show from GATE data, that for low cloud at least, cloudy skies were more likely for relative humidities above 80% than below. 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. A similar study in mid-latitudes might be more rewarding.

Either type of 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 sub grid scale processes and is therefore very sensitive to the model's ability to represent the atmospheric structure which results from these processes. A good example of this can be seen in Fig. 19 where the low level clouds have been calculated using relative humidity as in Eqn.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. the boundary layer relative humidity) is dramatic. The excessive cloudiness in the upper distribution can in no way be blamed on the cloud parameterization but is due to the lack of mixing between the boundary layer and the free atmosphere in the model. It would have been wrong to try and mask this deficiency by raising the threshold relative humidity in the cloud prediction scheme.

Another problem in cloud parameterization 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. This can then feedback into the cloud scheme and can be particularly awkward with boundary layer clouds, the enhanced radiative cooling leading to an increase in cloudiness. An example of this can be seen in Fig. 20 where the clouds associated with low level inversions are calculated using Eqn.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 and this indicates that a

a)



b)

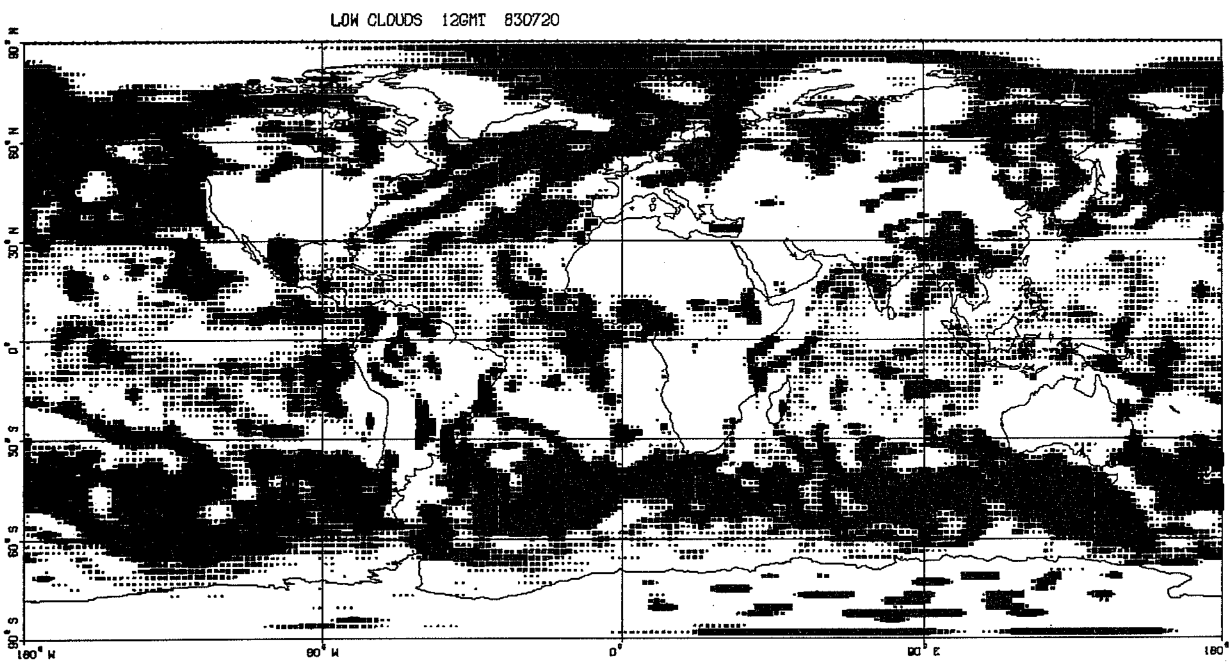


Fig. 19 Low cloud diagnosed from relative humidity from day 5 of forecasts from 15/7/83 (a) without shallow convection and (b) with shallow convection.

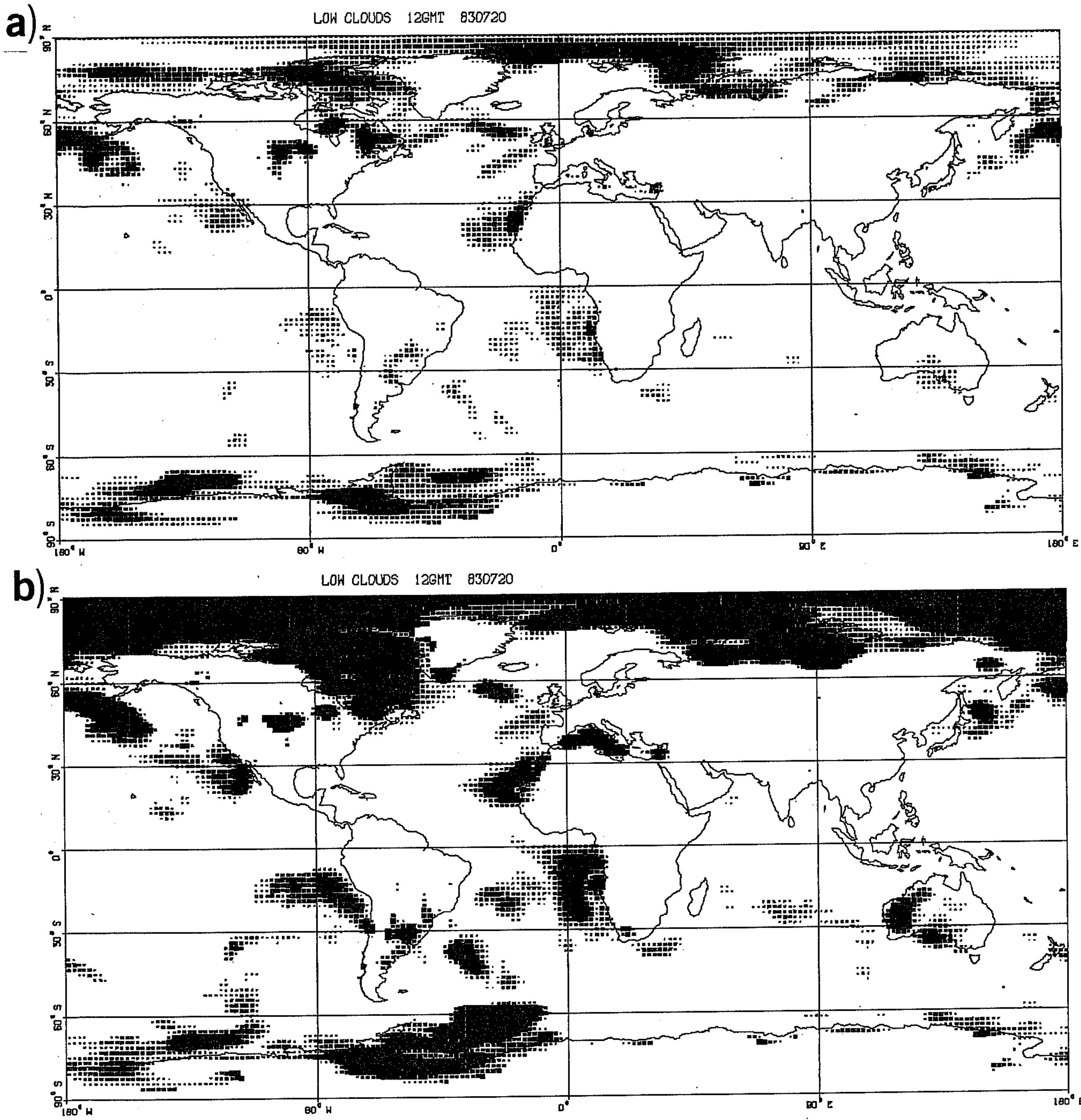


Fig. 20 Low cloud diagnosed from inversion strength from day 5 of forecasts from 15/7/83 (a) without cloud-radiation interaction and (b) with cloud-radiation interaction.

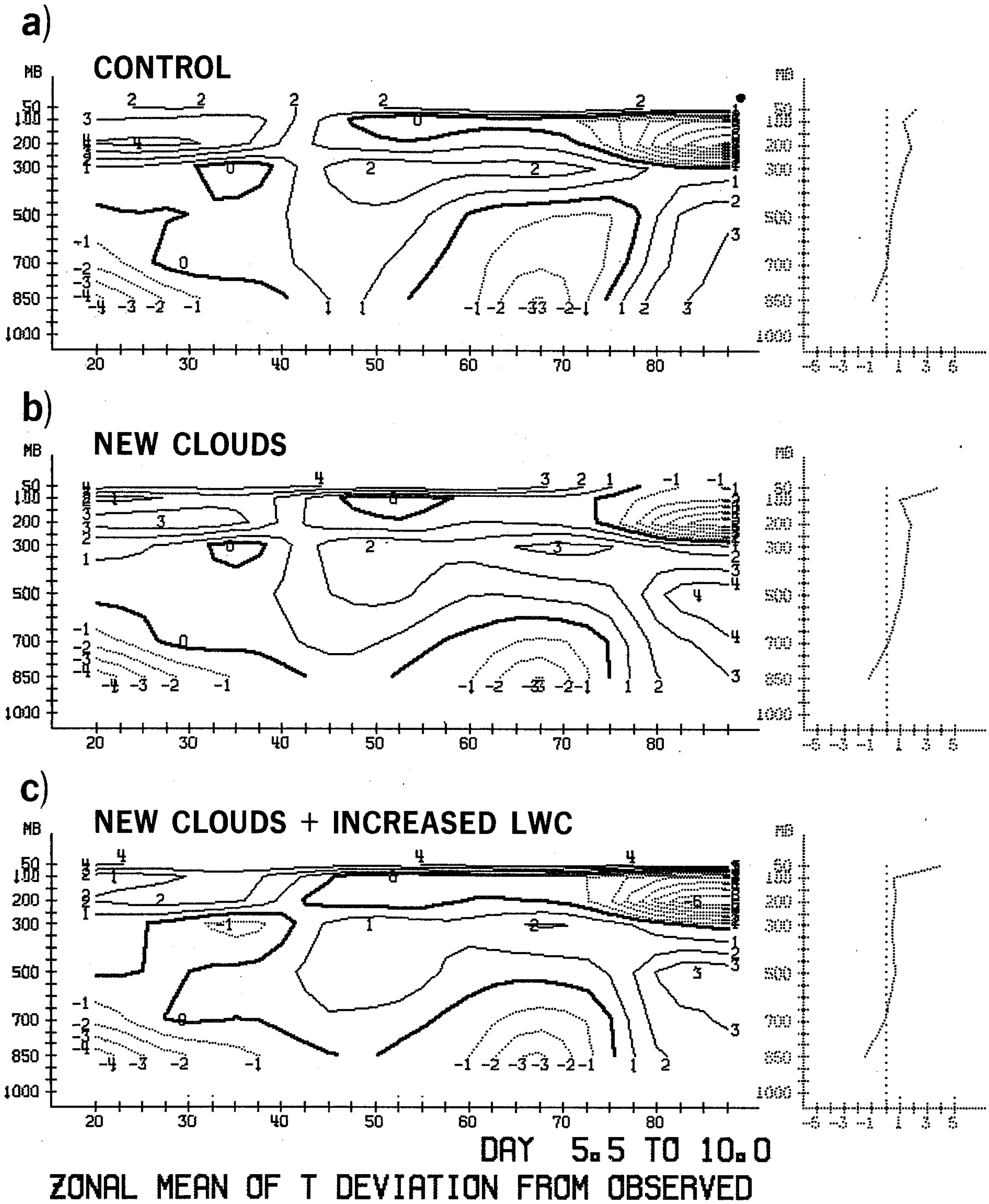


Fig. 21 Vertical cross-sections of zonal mean temperature error for days 5-10 of forecasts from 15/7/83
(a) Operational cloud scheme
(b) New cloud scheme, unchanged liquid water content and
(c) New cloud scheme plus enhanced liquid water contents.

closer link with the boundary layer/shallow convection schemes would be advisable. This may indeed be the case where layer cloud instability as described by Randall (1985) is applicable as a mechanism for reducing the cloudiness.

The question of the radiative properties of the clouds has only been touched on here. They are of course just as important but the prediction of cloud cover is seen as a more tractable problem because the verification is easier. As mentioned earlier the liquid water contents of the clouds were increased from 0.2% to 1% supersaturation. The impact of this change on the model's systematic temperature error is shown in Fig. 21 for forecasts from 15/7/83 where it can be compared with the impact of a change in the cloud prediction scheme. The increased liquid water contents have reduced the warming in the middle and upper troposphere by as much as 1K. They also significantly improve the model's radiation budget as shown in Table 2 (observed values are taken from Slingo, 1982).

Table 2. Effect of changing the liquid water content (LWC) on the model's radiation budget at the top of the atmosphere.

	Cloud (%)	Planetary Albedo (%)	Outgoing Radiance (Wm^{-2})	Net Radiation (Wm^{-2})
LWC=0.2% supersaturation	51.5	26.6	249	-3
LWC=1.0% supersaturation	51.6	32.5	242	-16
Observed	50-60	30-31	235-240	-15 - -3

The outgoing radiance is still somewhat too high probably because even 1% supersaturation does not give high enough emissivities for tropical cirrus clouds. Further research on this aspect of the scheme is planned in the near future possibly with typical liquid water contents ascribed to each cloud type.

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