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CLOUD PREDICTION IN THE ECMWF MODEL

by

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Abstract

This report describes a detailed assessment of the performance of the current operational cloud scheme (at the time of writing). Comparison of zonal mean cloud amounts with climatological estimates reveal several shortcomings of the scheme. In the light of these results various changes to the scheme are proposed. The report includes some assessment of the cloud scheme in terms of the model's radiation budget. The sensitivity of the model to cloud-radiation interaction is also briefly considered.

CONTENTS

1. INTRODUCTION

An assessment of the performance of the cloud parameterization scheme was initiated to form the basis of the development of a new scheme and also for the Centre's participation in an intercomparison of cloud schemes organised by the WMO Working Group on Numerical Experimentation. This study has concentrated mainly on comparing zonal mean cloud amounts with climatological estimates, with particular emphasis on the vertical distribution of cloudiness. The geographical distribution has also been studied to investigate whether the model has any systematic errors in the location of the clouds. The use of satellite data as an additional method for verifying cloud amounts and heights has also been considered. Since the calculation of radiative fluxes and heating rates are, at present, the only place where the diagnosed cloud amounts are used, the cloud scheme should be evaluated together with the radiation scheme. Direct comparisons of computed and observed planetary albedo and outgoing radiance are thus an obvious part of this study. Some discussion on the variation between the different sets of satellite and cloud data has been included to form a basis for any future comparative studies.

While this study was being undertaken a revised radiation code was completed which made some substantial changes in the cloud-radiation interaction. It seemed appropriate that the sensitivity of the cloud prediction scheme to such a change in the radiation parameterization should be studied. It is also important to understand the role played by cloud-radiation interaction in the forecast and to this end a series of sensitivity experiments were completed and are described as part of this report.

2. THE ECMWF CLOUD SCHEME

In the ECMWF model cloud amounts are diagnosed from the prognostic variables temperature and specific humidity using a relative humidity criterion as follows:

$$CLC_k = \left[\max\left(\left(\frac{RH_k - RH_{crit_k}}{1 - RH_{crit_k}}\right), 0\right)\right]^2 \qquad k = 1, NLEV$$

where

$$RH_{CRIT_k} = 1 - 2\sigma_k + 2\sigma_k^2 + \sqrt{3} * \sigma_k * (1 - 3\sigma_k + 2\sigma_k^2)$$

RH_k is the relative humidity at level k, and σ_k is the ratio of the pressure at level k to the surface pressure.

The relative humidity criterion was adjusted to give a good agreement with globally observed total cloud amounts and also with the global figures of outgoing radiance and planetary albedo. Other amendments and restrictions to the scheme were found to be necessary, namely, a smoothing of relative humidity in the vertical before calculation of CLC_k and the suppression of clouds in the well mixed boundary layer. Cloud overlap is assumed to be random except for adjacent cloudy layers where maximum overlap is assumed (Geleyn, 1981).

The cloud fields presented in this study are based on model results from a winter and a summer integration with the latest version of the N48 gridpoint model (Hollingsworth et al. 1980). The model includes parameterization of the sub-grid scale processes as described in Tiedtke et al. (1979). The initial conditions were from FGGE data for 21st January 1979 and 11th June 1979. For the purpose of this report we distinguish between cloud cover in three different slabs. High clouds are assumed to occur in the model layers 1-6 (i.e. approx. 0-380 mb), medium clouds belong to layers 7-11 (i.e. approx.

380-800 mb) and low clouds are associated with layers 12-15. To compute the cloudiness for these slabs the assumption of maximum cloud overlap in adjacent layers was used in the same way as in the radiation scheme for the total cloudiness. For non-adjacent layers random overlap of clouds is assumed. In this study maps of the global distribution and diagrams of zonally averaged amounts for the three cloud types and the total cloudiness have been produced. For the global distributions the cloud cover was 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%. This type of representation provides a good visual impression of the cloud cover although quantitative analysis is not really possible.

3. ASSESSMENT OF THE PERFORMANCE OF THE CLOUD PREDICTION SCHEME

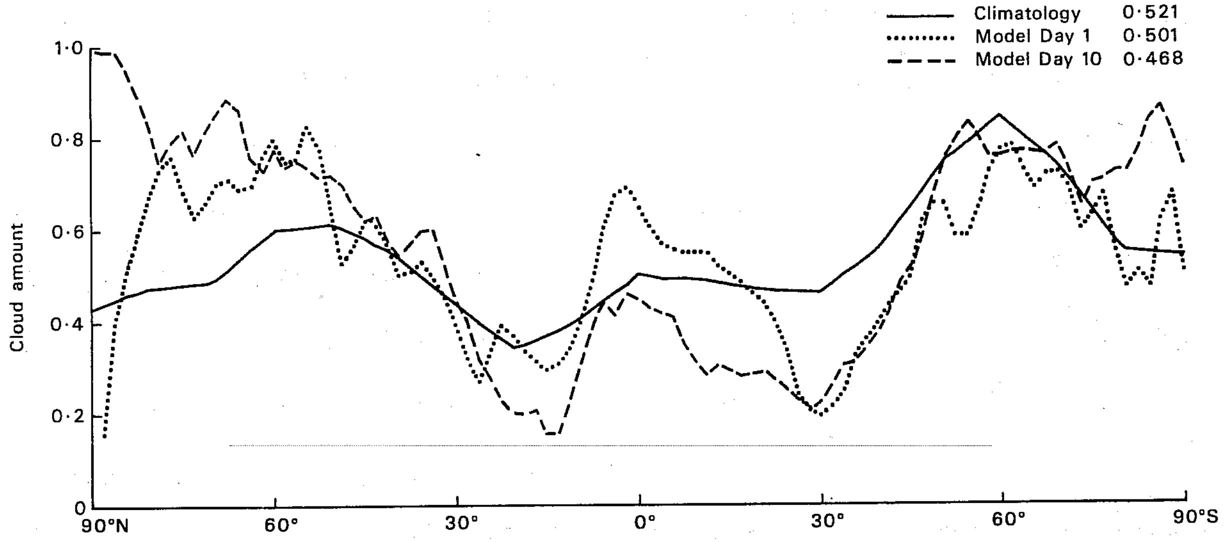
3.1 Zonal mean amounts

Zonal mean amounts for the total cloudiness and the three types, low, medium and high, have been computed for days 1 and 10. The results of this analysis are shown in Figs. 1 and 2. The cloud climatology used for comparison is that prepared by Bolton (1981) based on the data of 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 U.K. Met. Office GCM's and has been shown to give radiation budgets in good agreement with satellite observations (Slingo, 1982).

Results from day 1 and day 10 have been considered to see if the cloud scheme displays any drift through the integration. The total cloudiness for both

January

a) High



b) Total

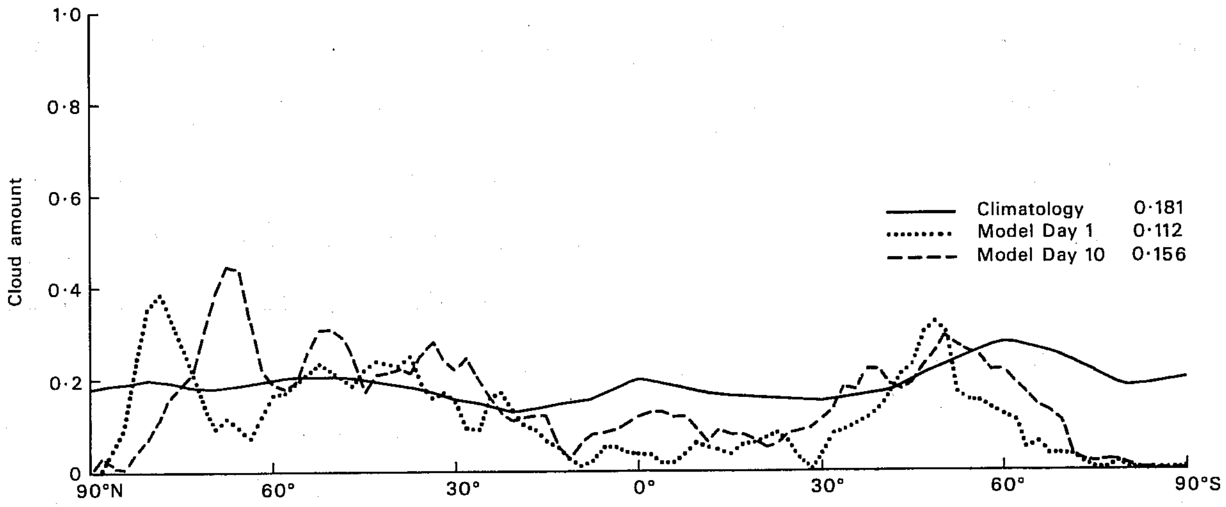
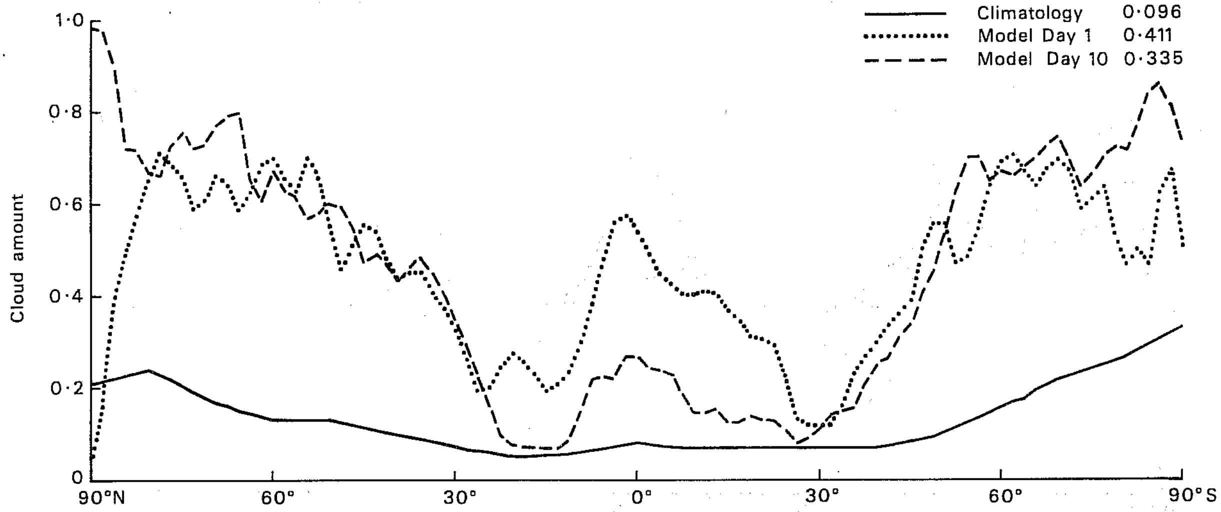


Fig. 1 Zonal mean cloudiness for January case (a) Total (b) High

January

c) Middle



d) Low

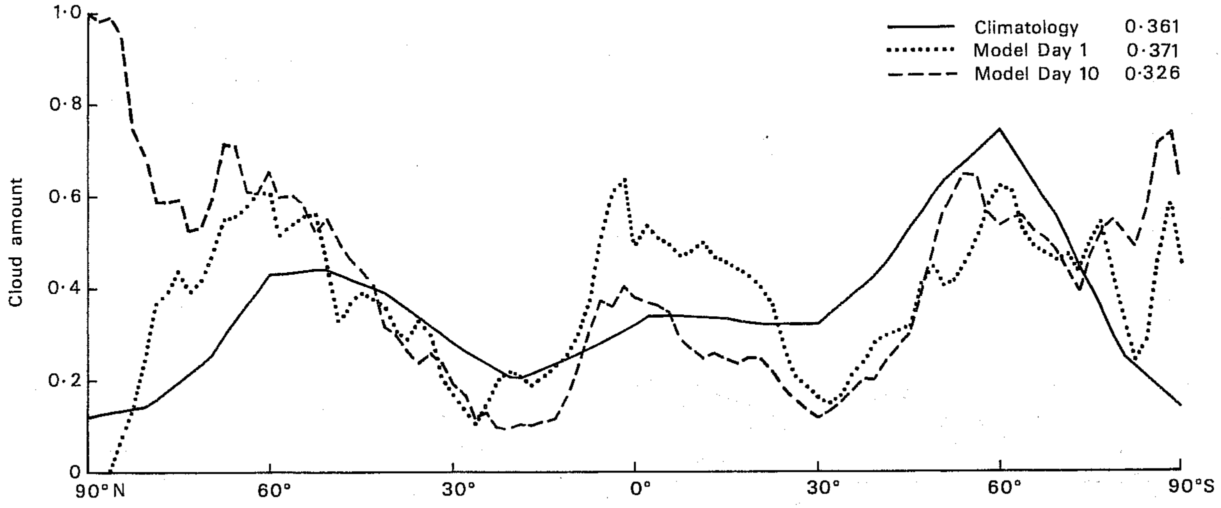


Fig. 1 (continued) (c) middle (d) low

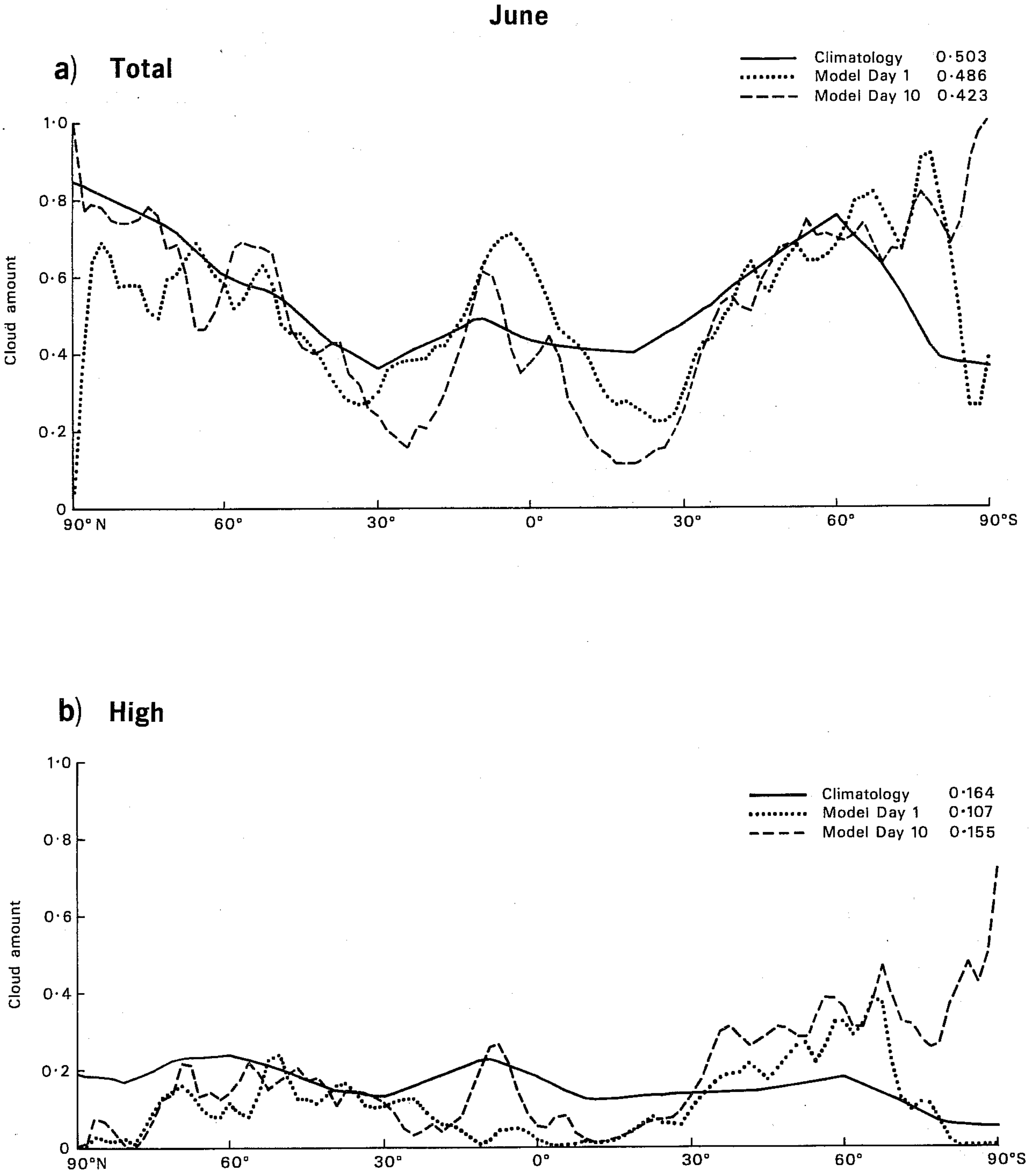
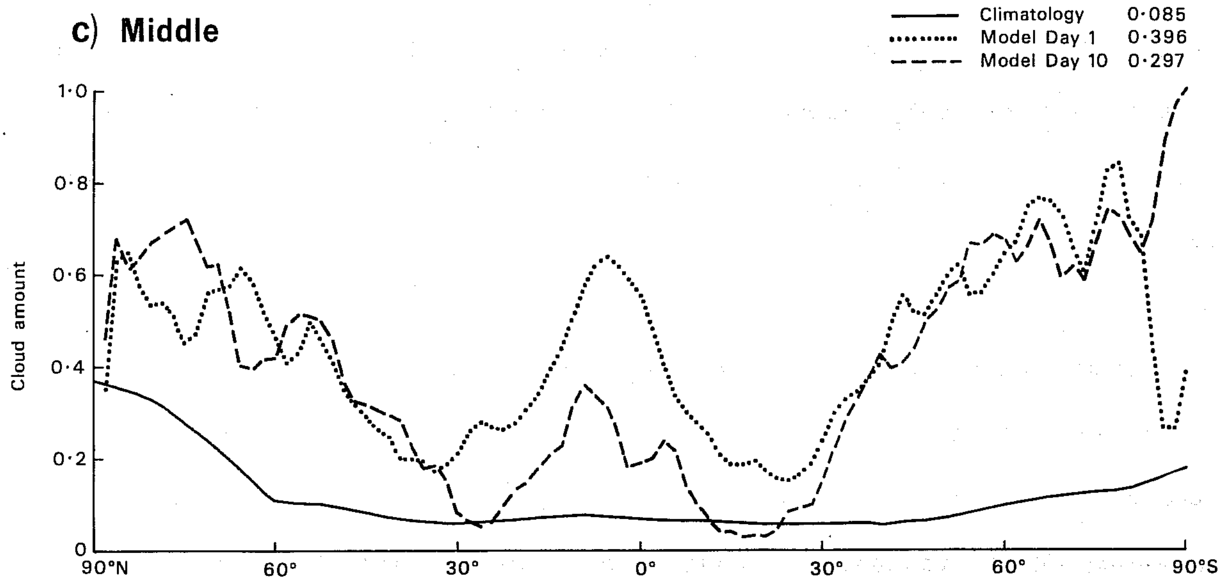


Fig. 2 As Figure 1 for June case

June

c) Middle



d) Low

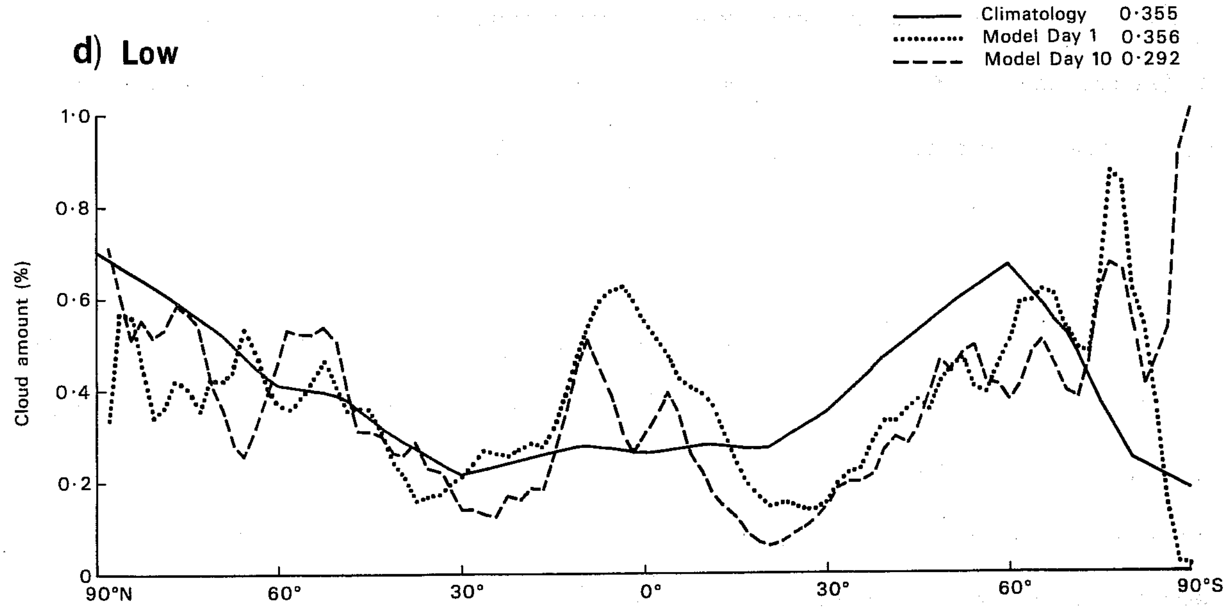


Fig. 2 (continued)

January and June (Figs. 1(a) and 2(a)) show a decrease in cloudiness during the forecast, mainly in the tropics. However, the total cloudiness shows reasonable agreement with climatology bearing in mind that the model results are for one day only. Both cases show a tendency for too little cloud in the sub-tropics of the southern hemisphere and a poor simulation over the winter pole by the end of the forecast.

For both January and June, global mean amounts of high cloud show good agreement with climatology (Figs. 1(b) and 2(b)). The main deficiency is in the tropics where the model has consistently too little cloud. This is probably due to the model's failure to develop a sufficiently strong intertropical convergence zone (ITCZ) so that too little moisture is transported to the upper troposphere by the convection. Also the 'Kuo' convection scheme is not designed to represent explicitly the detrainment of moisture that occurs at the top of a cumulonimbus. It may be necessary therefore to specify an anvil cirrus cloud when strong, deep convection exists independent of the model's humidity structure.

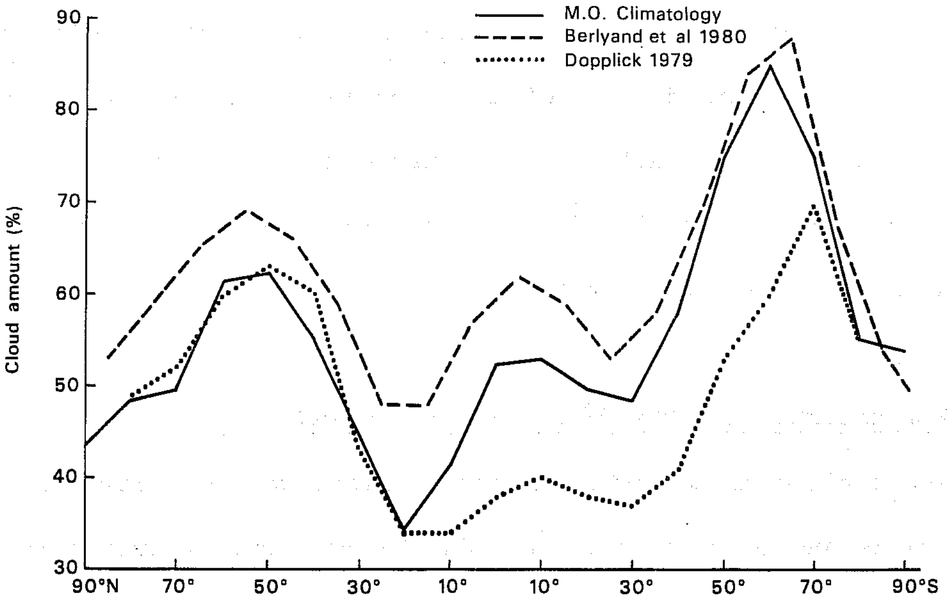
The main deficiency of the cloud prediction scheme is in the amount of medium cloud which is considerably greater than climatology for January and June (Figs. 1(c) and 2(c)). It is interesting to note the similarity between the curves for medium and low clouds (Figs. 1(d) and 2(d) which suggests that the scheme is giving a lot of deep clouds. The assumption of maximum overlap for adjacent cloudy layers is no doubt the cause of this. The model's prediction of low cloud is in reasonable agreement with climatology except in the tropics at the beginning of the forecast. There also seems to be too little cloud on the equatorward side of the depression belt in the southern hemisphere.

In conclusion the scheme seems to give reasonable amounts of total cloud with no unsatisfactory tendencies through the forecast. However, the vertical distribution of cloudiness is seriously in error. There are too many deep clouds with cloud tops in the middle troposphere and too little cloud in the upper troposphere. The scheme seems unable to produce stratified layers of cloud, in particular the low level layer clouds which are the major contribution to the total cloudiness.

3.2 How reliable are the cloud climatologies?

In any comparison of the model against climatology the reliability of the observations has to be considered. Cloud cover, and in particular the vertical distribution of cloudiness, has always been difficult to measure. 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. On the other hand, upper level clouds are bound to be underestimated because they can be masked by low level clouds. With satellite measurements, the total cloudiness is probably more accurate except over highly reflecting surfaces such as snow and ice. In principle, the satellite should give better estimates of high level clouds at the expense of low level clouds. However, there are problems here in distinguishing the different grey scales and in dealing with partial cloud cover. For example, a broken field of high cloud might be taken as medium level cloud. There may also be problems in determining low level cloud amounts at night-time since the infrared flux may be very similar to that from the surface.

a) January



b) June

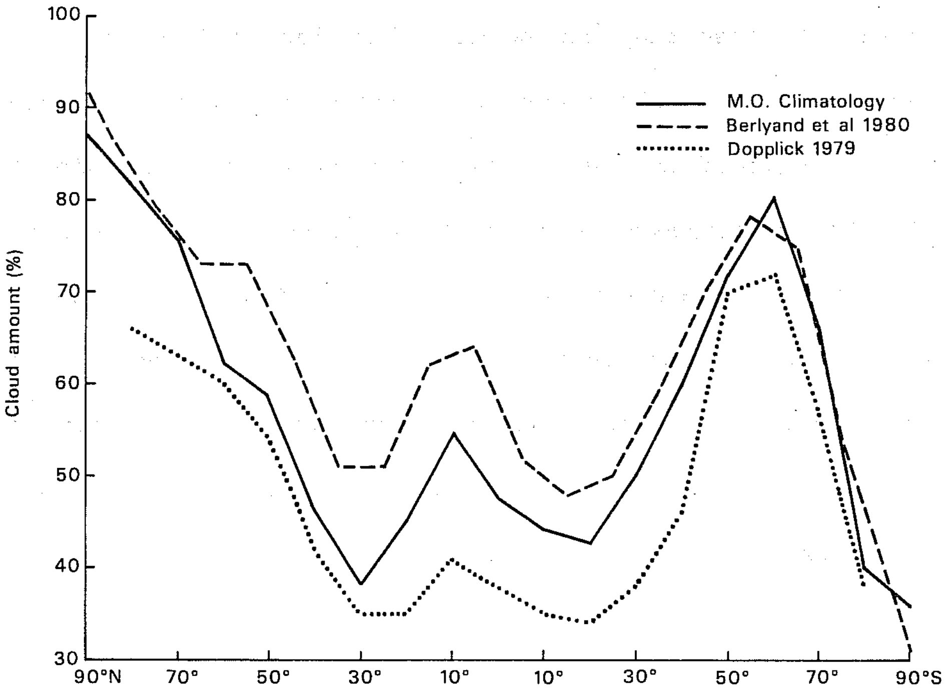


Fig. 3 Comparison of observed zonal mean total cloudiness from different sources
(a) January (b) June

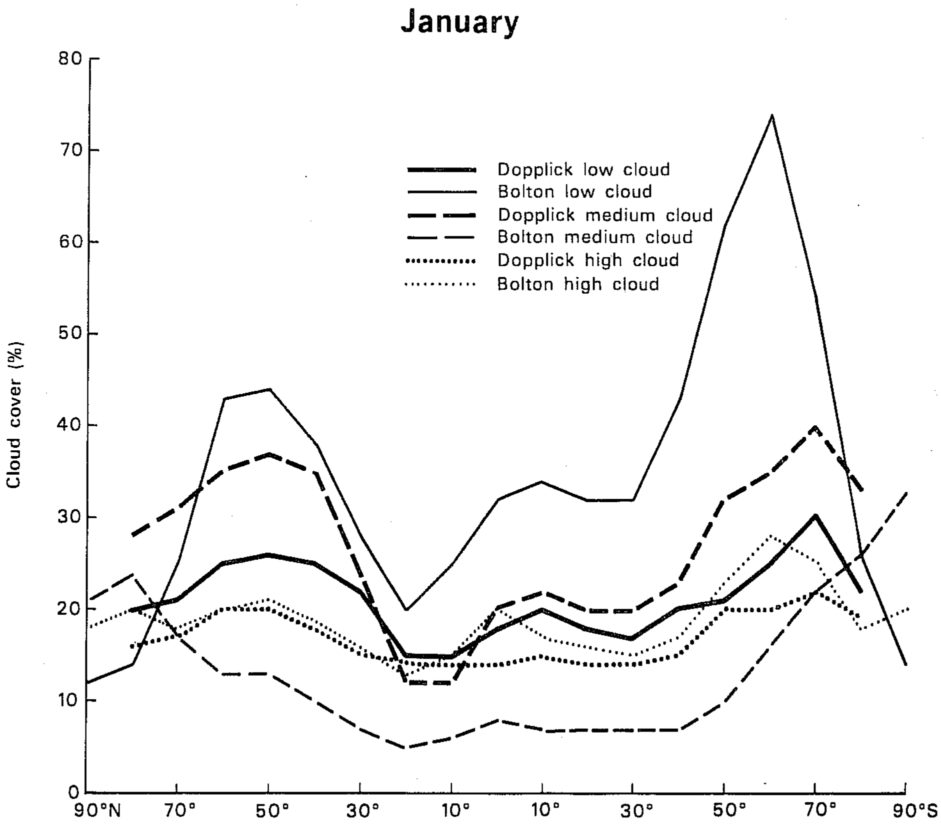


Fig. 4 Comparison of the observed vertical distributions of cloudiness for January

In Fig. 3 the total cloudiness for January and July from three different sources are compared. As can be seen there are considerable differences between them. Beryland et al. (1980) calculated their values from a wide range of observations over a long time period. They are mainly from surface based observations so that there will be a tendency for over estimating cloud cover. They do not, however, give any information on the vertical distribution of cloudiness. Apart from the polar regions, Dopplick's (1979) values are taken from a short-term study of satellite data but seem anomalously low at some latitudes.

There is very little information on the vertical distribution of cloudiness. When preparing the cloud climatology for the U.K. Meteorological Office GCM's Bolton (1981) used data from various sources (see Section 2) to derive amounts of high, medium and low cloud. Dopplick (1979) has a similar analysis and the results for January are compared in Fig. 4. The amounts of high cloud are very similar which is slightly surprising since Dopplick's values are mainly from satellites and Bolton's are from ground-based data. However, there are significant differences for medium and low cloud. At most latitudes Dopplick has more medium cloud than low cloud. This is probably just a question of classification. Satellites view cloud tops and some clouds, particularly cumulus, may have their tops in the middle troposphere whilst their bases are at the top or within the boundary layer and would be classed as low clouds by a surface observer. A similar discrepancy has been noted by Stowe et al. (1984) with Nimbus 7 data. This difference in classification needs to be borne in mind when these climatologies are used.

3.3 Geographical distribution of cloudiness

For the intercomparison of cloud schemes organised by the WMO Working Group on Numerical Experimentation, maps of high, medium, low and total cloudiness were prepared for four days from the initial dates 21/1/79 and 11/6/79. Again the evolution of the model's cloudiness with time was studied. Figures 5-7 show the cloud maps for analysis time, day 1 and day 4 for the forecast from 21/1/79, and Figures 8-10, the same maps for the forecast from 11/6/79. In both cases the same deficiencies can be seen. There is hardly any high cloud at analysis time which may be due to the sparcity and unreliability of upper air humidity observations and also because above 300 mb there is no analysis and the humidities are extrapolated towards stratospheric background values. As the forecast progresses the high cloud increases except in the tropics. In general the high cloud associated with extratropical systems is fairly well represented. However the tropical anvil cirrus clouds are almost completely lacking as already noted in Sect. 3.1. Most of the spin-up in cloud amounts, particularly high cloud, takes place during the first day as can be seen in Figs. 5 and 6, and Figs. 8 and 9.and is associated with a rapid moistening of the upper troposphere which takes place mainly during the first day.

As already noted, the mean deficiency of the scheme is the overestimation of medium cloudiness. The distribution of clouds seems reasonable being mainly in convective areas in the tropics and in frontal disturbances in the extratropics. Cloudiness in the lower layers is fairly well represented except in the sub-tropics where the stratocumulus and fair weather cumulus of the trade winds are lacking. This is due partly to the restriction of no clouds in the well-mixed layer (see Sect. 2). Also these sub-tropical clouds are associated with sub-grid scale convection rather than the large-scale humidity structure and for reasons to be discussed later, may need a separate treatment.

January - analysis

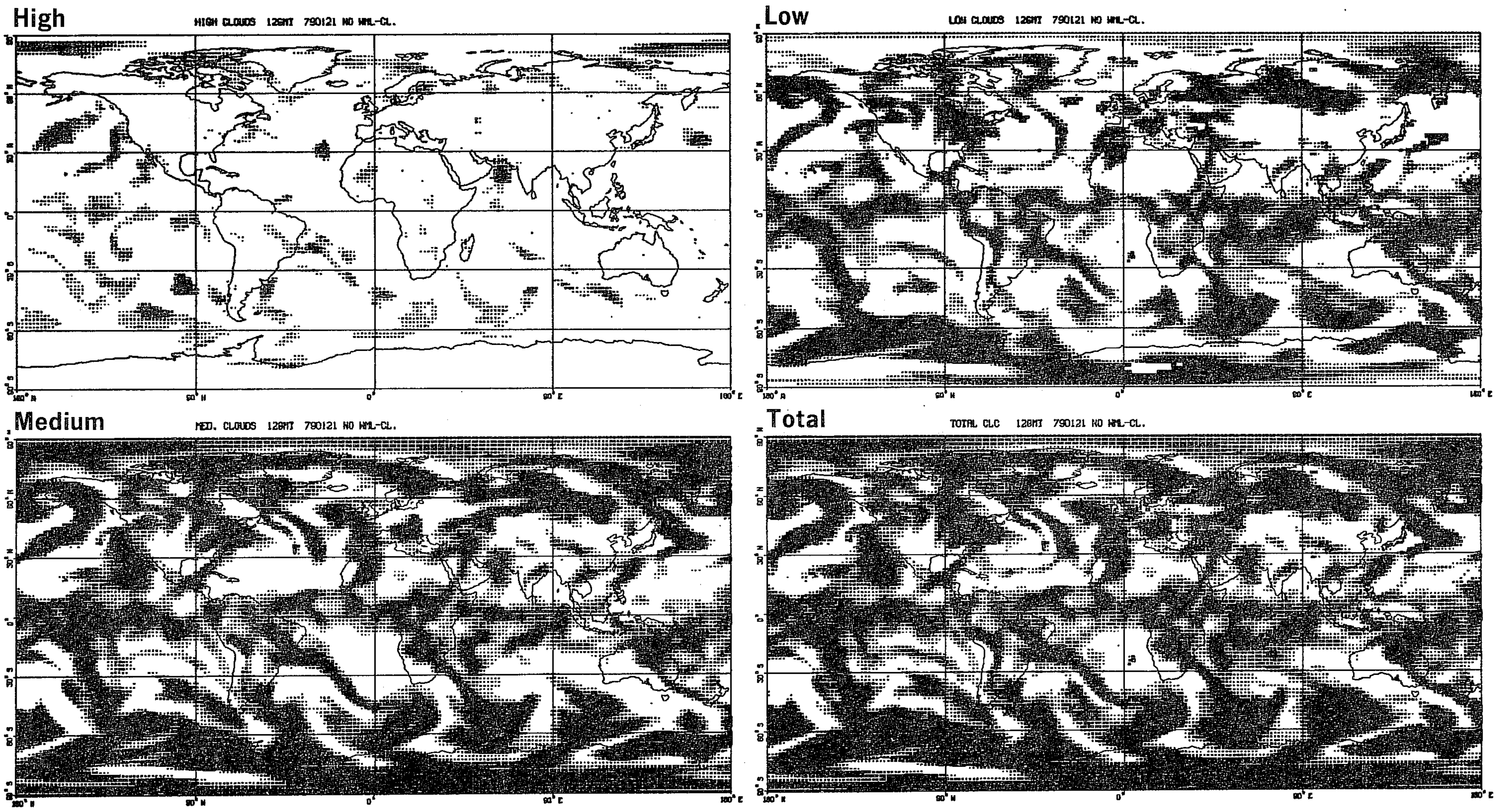


Fig. 5 Geographical distribution of total, low, middle and high cloudiness for analysis time for the January forecast (21.1.79)

January - day 1

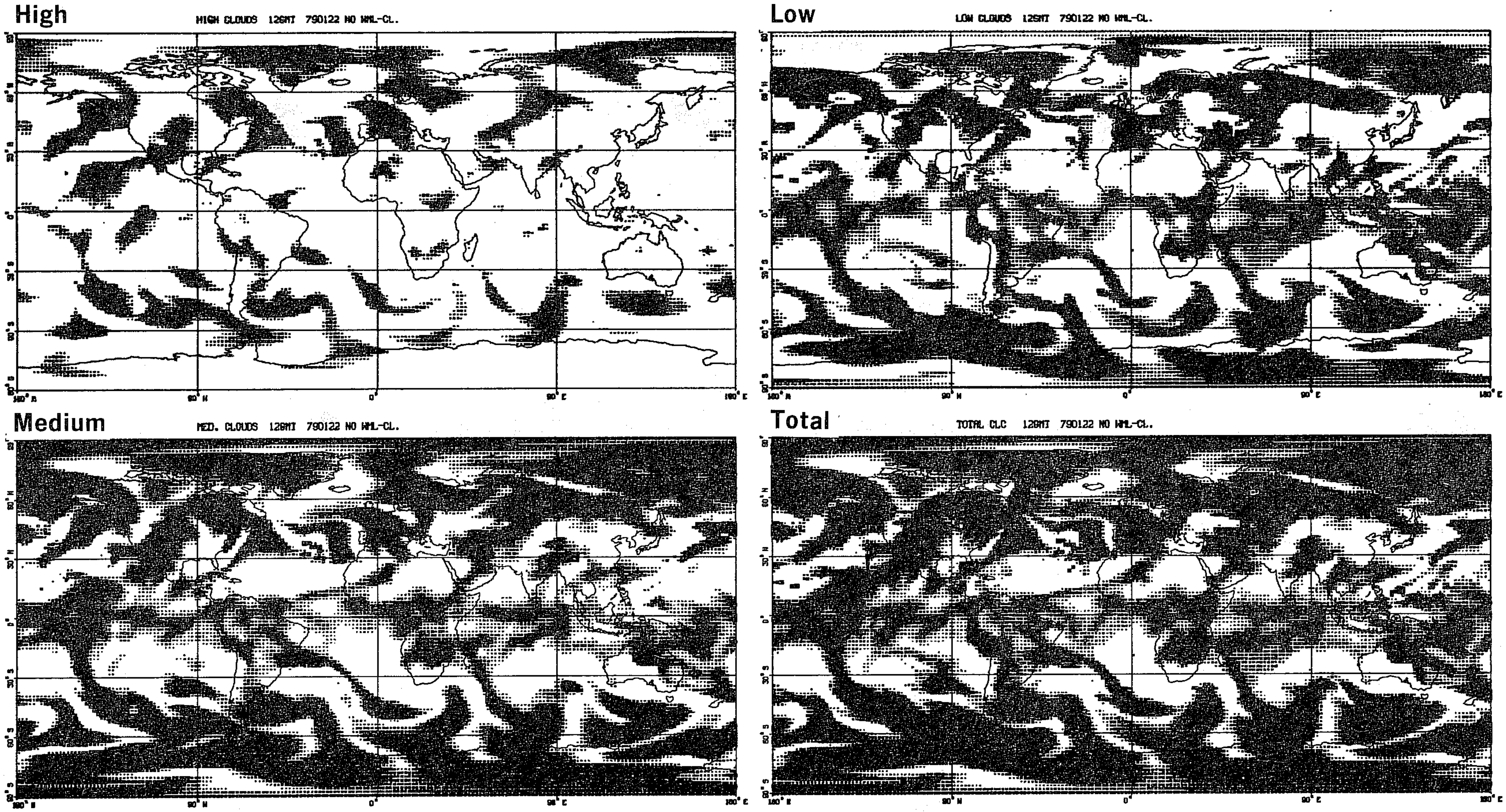


Fig. 6 As Figure 5 for day 1 (22.1.79) of January forecast

January - day 4

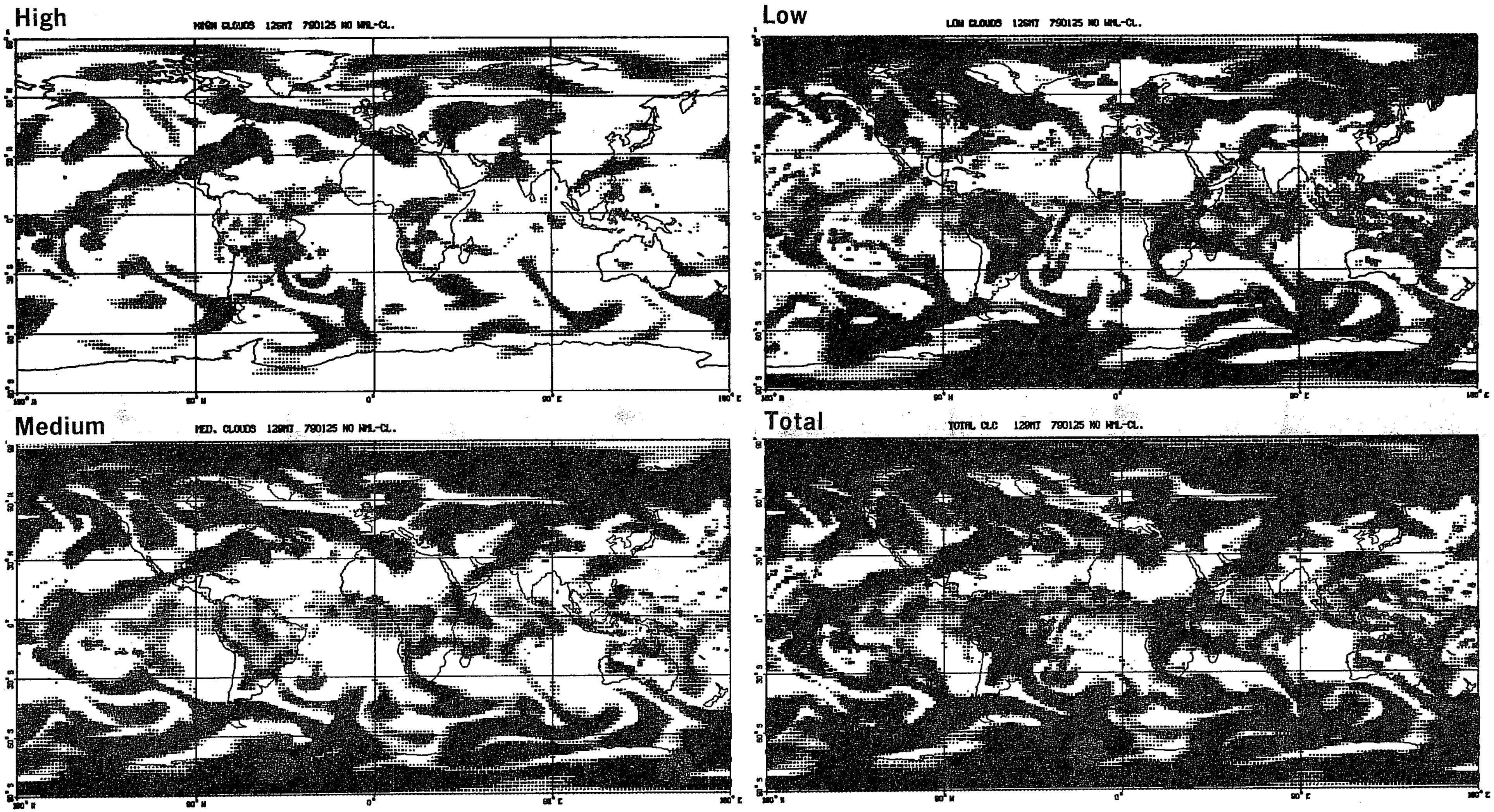


Fig. 7 As Figure 5 for day 4 (25.1.79) of January forecast

June - analysis

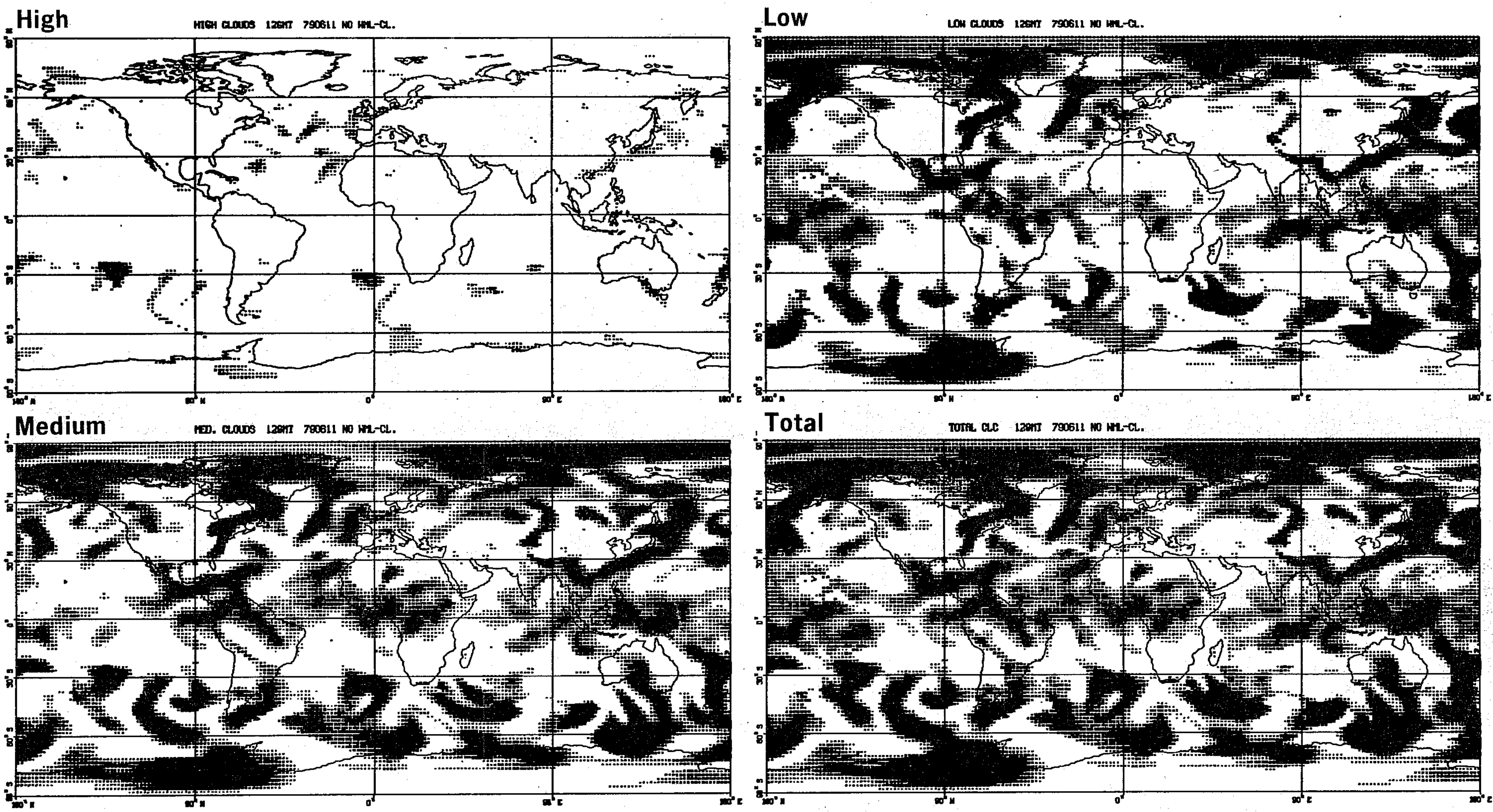


Fig. 8 As Figure 5 for analysis time (11.6.79) of June forecast

June - day 1

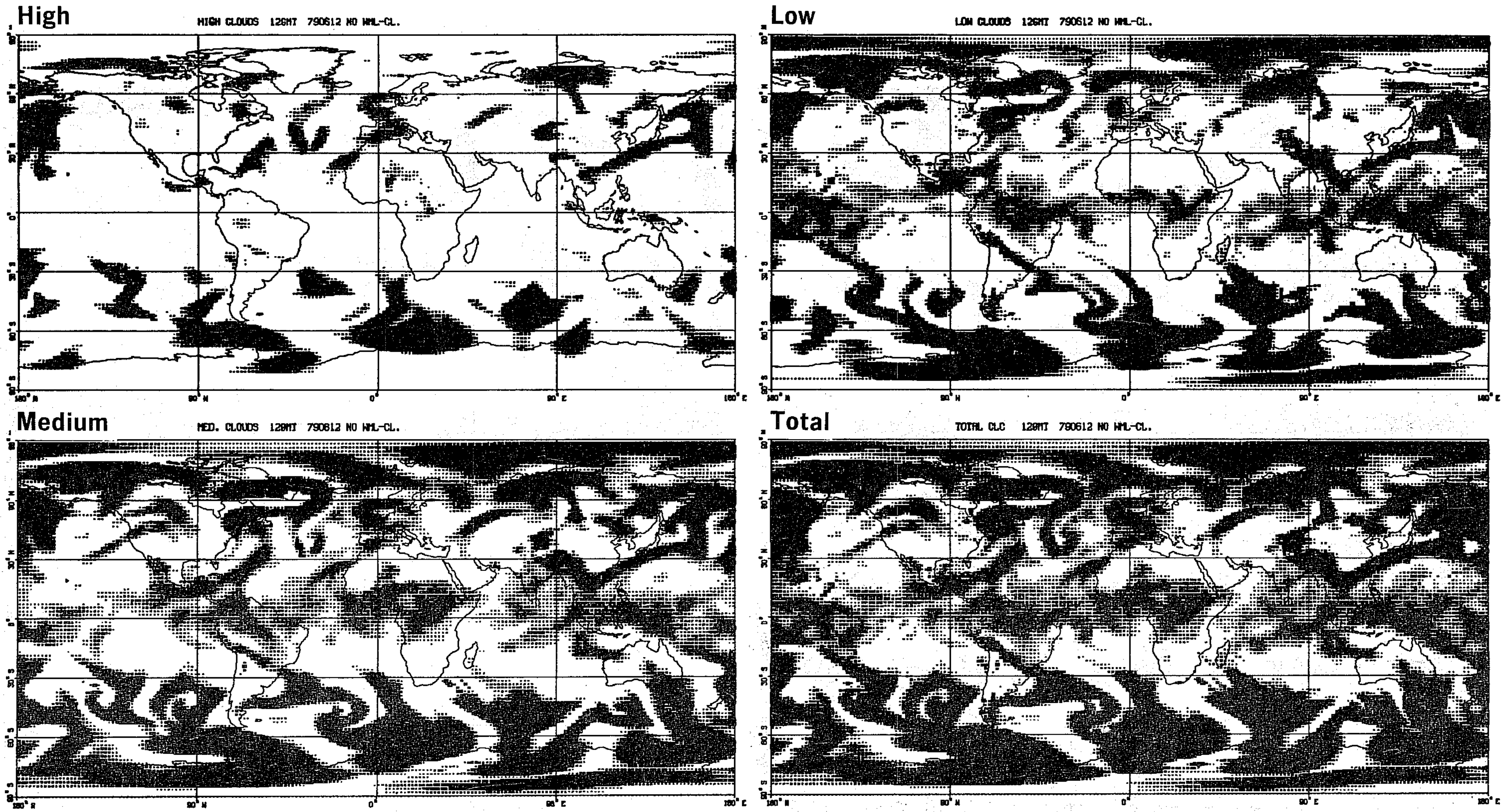


Fig. 9 As Figure 5 for day 1 (12.6.79) of June forecast

June - day 4

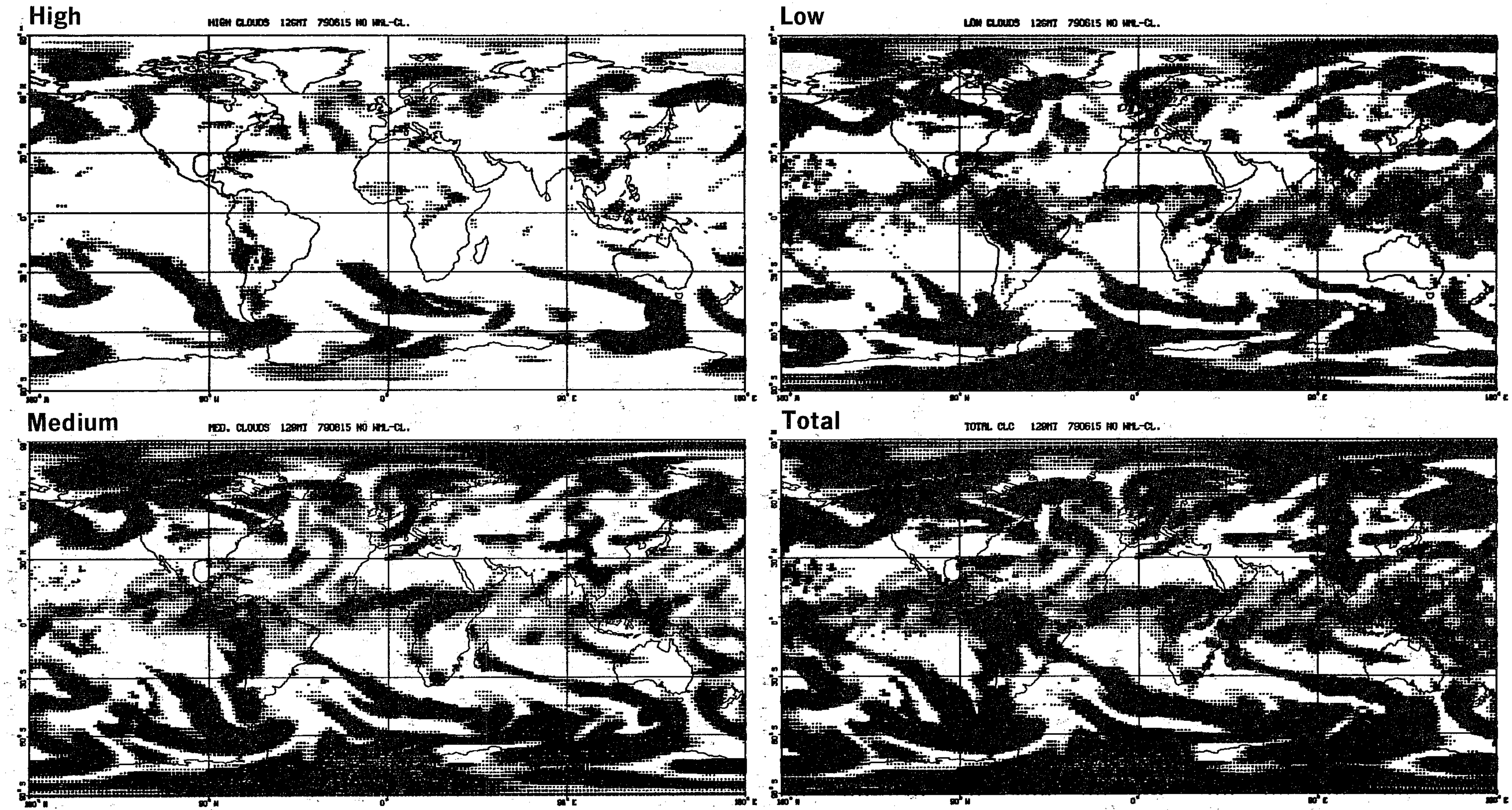


Fig. 10 As Figure 5 for day 4 (15.6.79) of June forecast

4. SATELLITE DATA AND ITS USE IN MODEL VERIFICATION

Another method of verifying a cloud prediction scheme is to compare the model's radiation budget with that from satellites. A comparison of planetary albedo, for example, should reveal systematic errors in total cloudiness, provided of course that surface and cloud reflectivities are reasonably represented. Outgoing radiance also gives information on cloud heights in addition to some indication of total cloudiness. These fields can also provide useful verification of the radiation scheme itself (Geleyn et al, 1982).

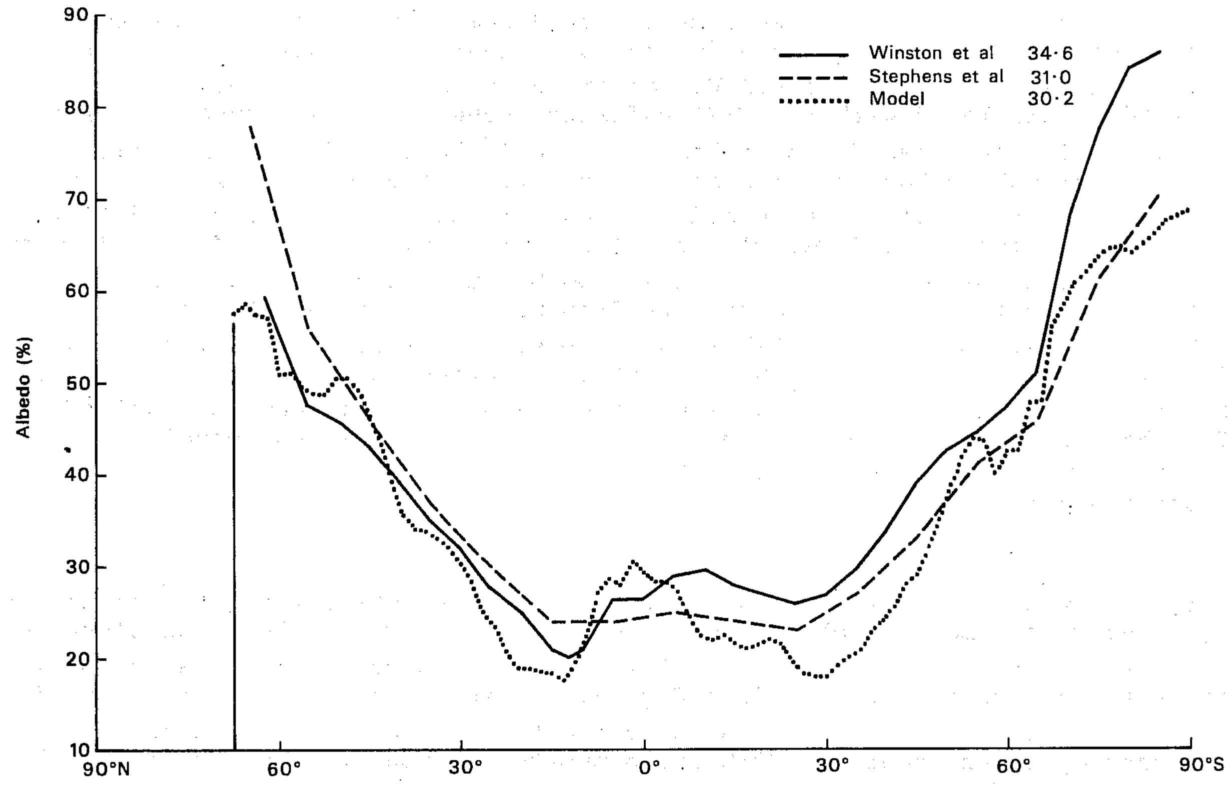
Measurements of the earth's radiation budget by satellites have been made for many years and the literature now contains several compilations of monthly mean values of the global radiation budget. There are still considerable discrepancies between the various estimates due to the different methods used to process the satellite data, different instruments and different observing times (Slingo, 1982). In this study two sets of satellite data have been used for comparison with the model's radiation budget. The first is a compilation by Winston et al (1979) of 44 months of NOAA satellite data. These data are from the scanning radiometers which sense only in a narrow band width (0.5-0.7μm, for the shortwave spectrum and 10.5-12.5μm for the longwave spectrum). The extrapolation of these measurements to the whole spectrum involves several assumptions which introduce uncertainties in the final radiation budget (Slingo, 1982). The other satellite data used in this study were from a compilation by Stephens et al. (1981) from several different satellites for a total of 48 months. All these observations were from broad band sensors so that there was no need for any extrapolation to obtain total fluxes. They ought therefore to be more accurate than those of Winston et al. It is interesting to note, however, that Stephens et al have an imbalance of 9 Wm^{-2} in the annual mean net radiation whilst Winston et al. have -12 Wm^{-2}.

The outgoing radiance and planetary albedo have been calculated from day 10 of the model results from the experiments for January and June. These fields have been calculated with the ESFT radiation scheme (Ritter, 1984) since the operational scheme has deficiencies in its calculation of outgoing radiance particularly for upper level clouds. These are shown in Figs. 11 and 12 where they can be compared with the results from Winston et al and Stephens et al. The discrepancy between the two sets of observations is striking, particularly for the outgoing radiance, and makes it difficult to draw any conclusions about the model's performance.

For January the model's planetary albedo is too low where the total cloudiness is less than the climatology (see Fig. 1). This is particularly apparent in the subtropics and south of 30°S and supports the use of Bolton's data rather than Dopplick's as a cloud climatology against which to compare the model. At the south pole the values of Winston et al are almost certainly too high since the assumption that the narrow band albedo is representative of the whole spectrum leads to an overestimation over snow in particular (Slingo, 1982). The difference between the two sets of satellite data are so large for the outgoing radiance that it is difficult to draw any firm conclusion about cloud heights. The model's outgoing radiance tends to be too high in the tropics where there is too little cloud. South of 30°S the agreement between the model and observations is good for probably the wrong reasons. Fig. 1 suggests that the total cloudiness is too low in this region although what clouds there are, are too high. Thus the net effect is an outgoing radiance which is near the observed. In the northern hemisphere the effect of too much medium cloud is less apparent.

January

a) Planetary albedo



b) Outgoing radiance

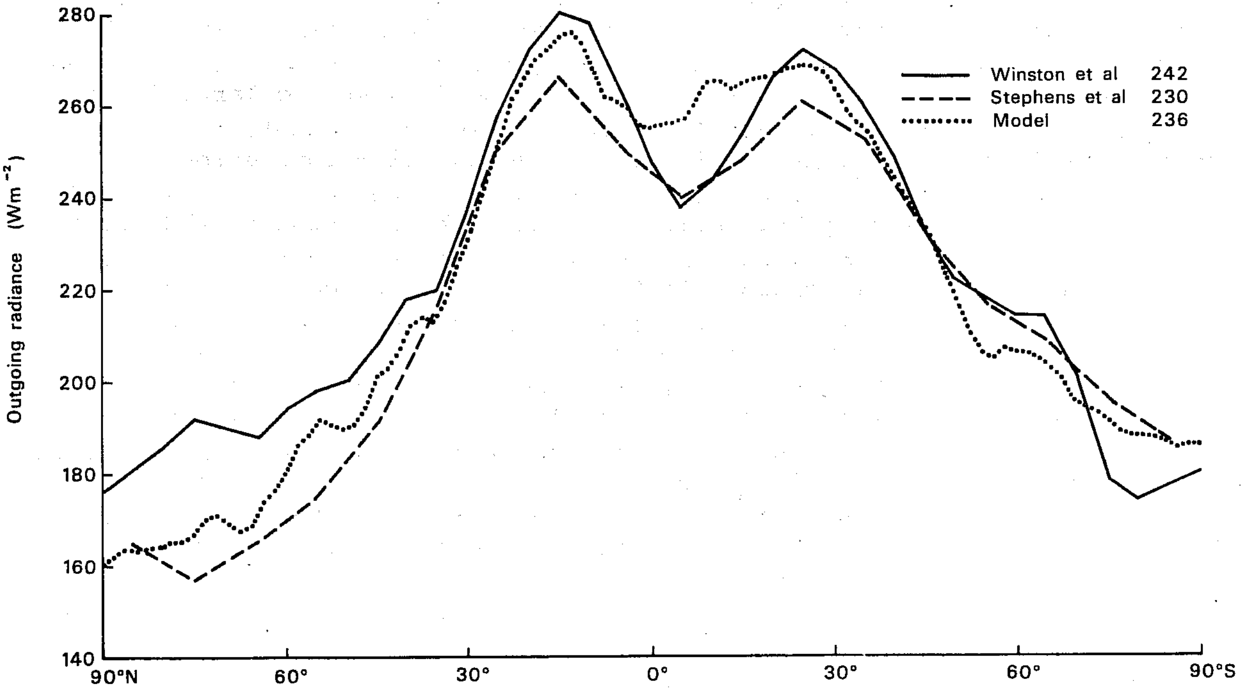
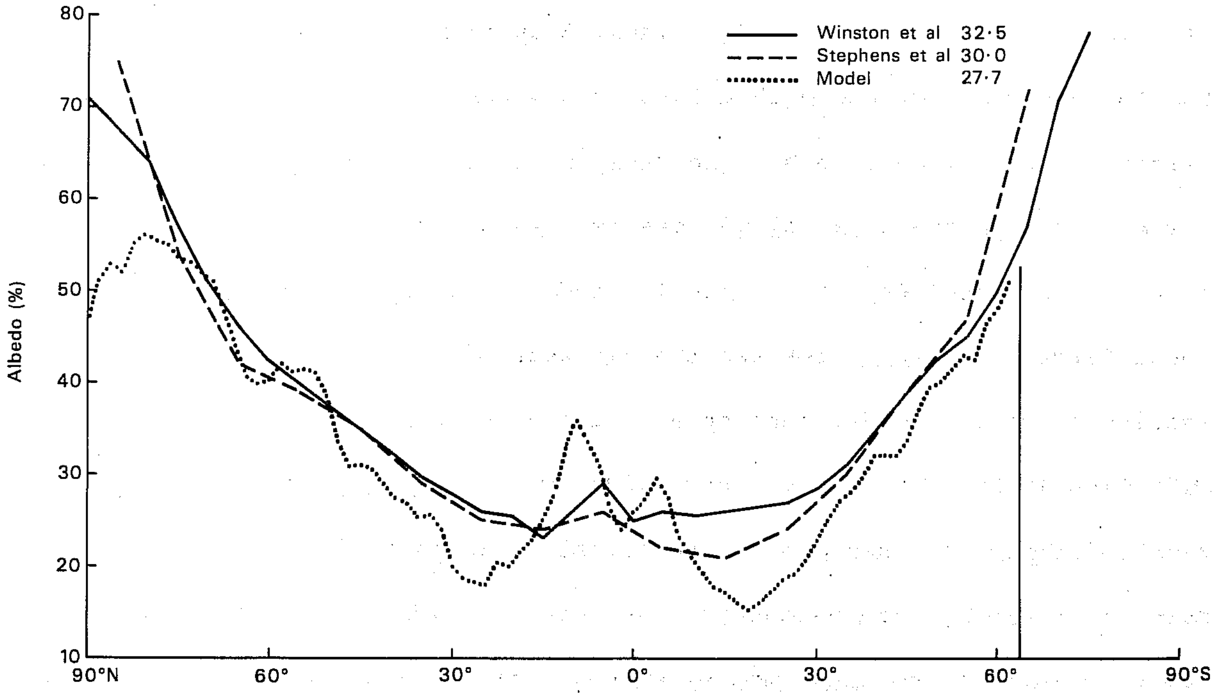
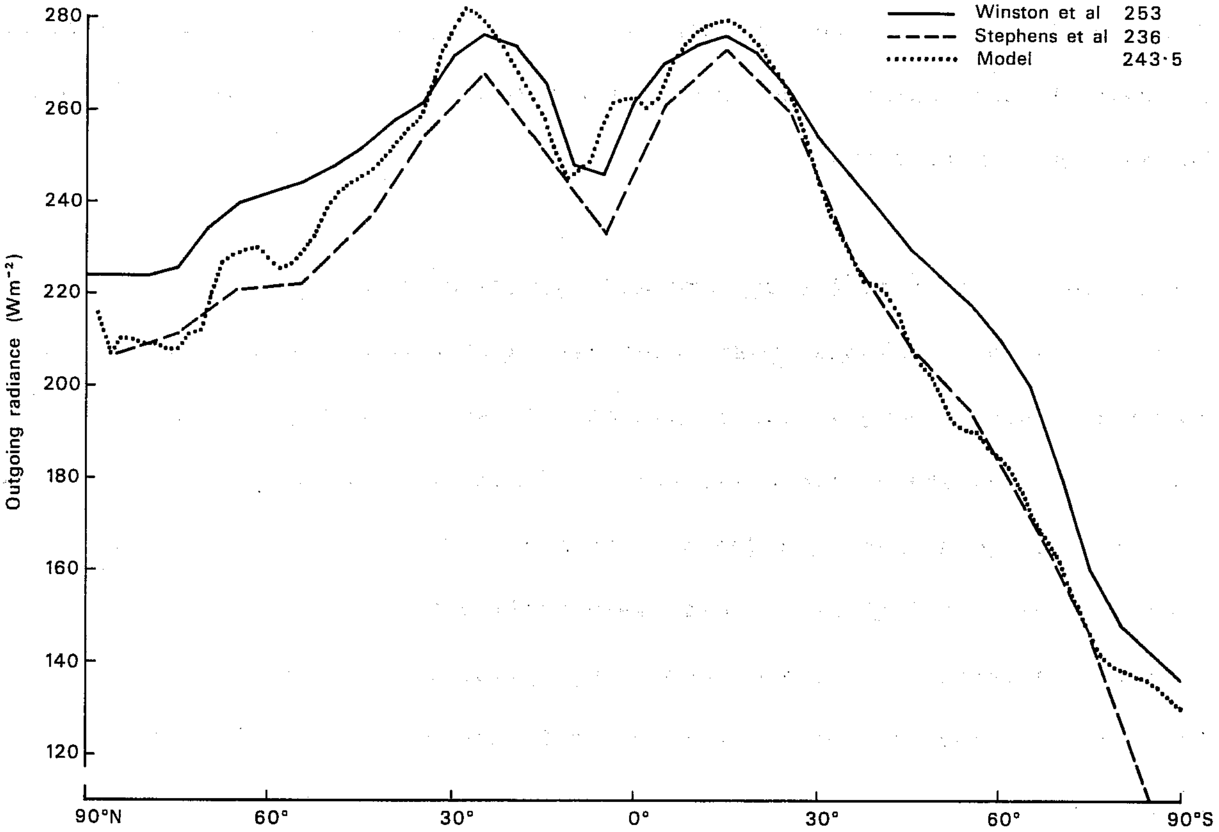


Fig. 11 Comparison of model and observed zonal mean radiation budgets for January (a) planetary albedo (%) (b) outgoing radiance (Wm^{-2})

June



a) Planetary albedo



b) Outgoing radiance

Fig. 12 As Figure 11 for June case

For June (Fig. 12) the planetary albedo again shows the errors in total cloudiness seen in Fig. 2. The global mean planetary albedo of the model is too low being associated with a total cloud cover of 42% rather than the climatological value of 50%. The model's values at the north pole seem rather low even though the total cloudiness is reasonable. This may be an example in which the reflectivity of the model clouds is too low. The outgoing radiance shows large differences between the two sets of observations at all latitudes. Bearing in mind that Stephens et al. have an annual mean net radiation of 9 Wm^{-2} then it is likely that their values of outgoing radiance are too low, particularly since they quote a reasonable planetary albedo of 30%. Thus the model is probably underestimating the outgoing radiance in the southern hemisphere due to too much medium cloud. Again the agreement in the tropics is probably fortuitous as in January, due to the wrong total cloud cover at the wrong height. This conclusion is supported by the planetary albedo which shows good agreement with the total cloudiness. North of 30°N it is difficult to draw any conclusions about cloud height because of the large difference between the observations.

The outgoing radiances for January and June raise the question of the accuracy of the cloud climatologies particularly with respect to medium cloud. Is there more middle level cloud than these climatologies imply? As will be seen the difference between the observations of outgoing radiance is more than the change in outgoing radiance due to a change in cloud height. Even though a change in cloud height has a relatively small effect on the zonal mean outgoing radiance it can have important implications for the model because of the change in the vertical profile of radiative cooling as discussed in Section 6.

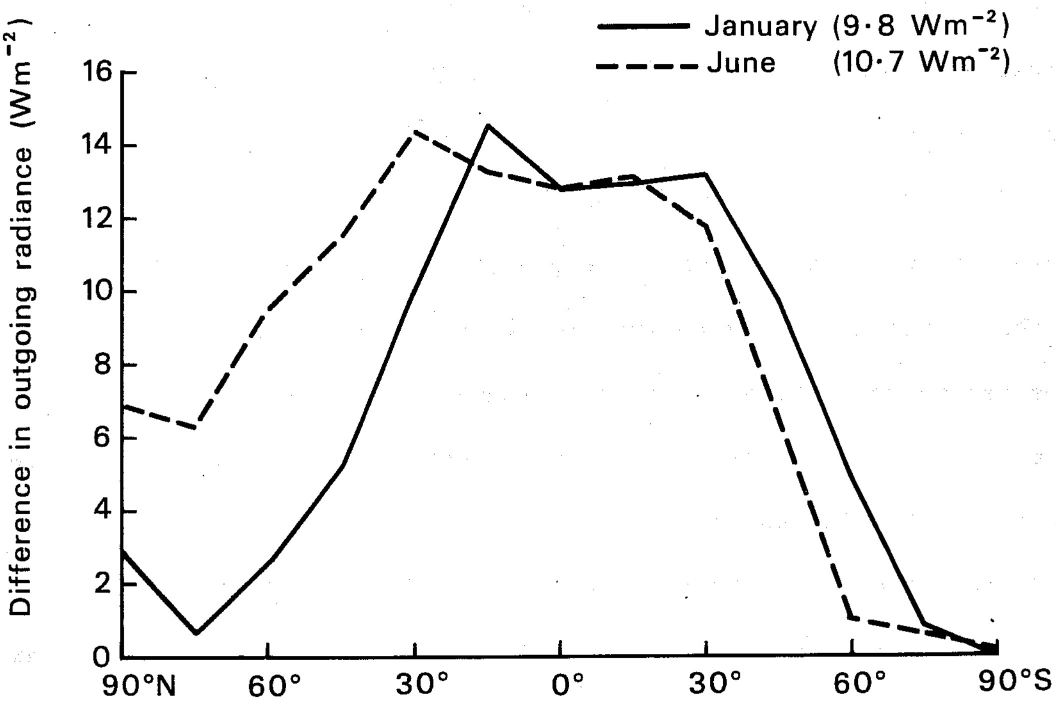


Fig. 13 Change in zonal mean outgoing radiance due to a change in cloud height

With such large differences between the two sets of observations the question arises as to whether the sensitivity of the outgoing radiance to a change in cloud height is greater than the error in the observations. As a simple test the outgoing radiance for January and June was calculated for two different cloud fields. In the first a cloud cover of 50% was prescribed at level 12 ($\sigma = .845$) for the whole globe. In the second, the cloud cover was prescribed at level 9($\sigma = .588$). The difference in outgoing radiance between the two cases is shown in Fig. 13. The differences are greatest in the tropics where the temperature gradient is the most steep. It is interesting to note that the sensitivity to cloud height is greater in the northern hemisphere summer than the southern hemisphere, presumably because the northern hemisphere land masses become much warmer in summer. However, for both January and June the sensitivity to such a change in cloud height would only be significant in parts of the tropics and in the southern hemisphere in January. Elsewhere the difference between the observations is considerably larger. Thus the use of satellite measurements of outgoing radiance as a verification of cloud height is limited particularly for zonal mean values. However, Slingo (1983) has shown that they can be useful in verifying the geographical distribution of cloudiness on individual days. In these circumstances the natural variations in outgoing radiance are considerably larger than those being discussed here.

5. THE SENSITIVITY OF THE CLOUD PREDICTION SCHEME TO A CHANGE IN THE RADIATION SCHEME

The radiation scheme currently in use in the operational model uses the method of pseudo-optical depths in which the fluxes for a scattering atmosphere without gaseous absorption are used to derive the effective gaseous absorber amounts encountered by the photons (Geleyn and Hollingsworth, 1979). It was developed and chosen for its computational efficiency. The method works well for solar radiation but the approximations necessary to make the method computationally viable lead to inaccuracies for the thermal fluxes, in particular the treatment of the emission terms in the atmosphere. The scheme gives excessive cooling rates in the layers with small amounts of cloud and has an unrealistic treatment of upper tropospheric clouds. The formulation also prevented proper inclusion of the e-type absorption in the atmospheric window although some allowance is made for this effect in the computation of the transmission functions.

A new method for the treatment of longwave fluxes has recently been developed. Gaseous absorption is incorporated by using the technique of exponential sum fitting of transmission (ESFT). Each exponent behaves like a monochromatic optical depth which can be easily incorporated into the multiple scattering form of the existing radiation scheme. This method also allows the e-type absorption to be included as an additional term since its transmission follows the simple exponential law. With this new treatment of gaseous absorption the cooling rates for cloudy atmospheres are more realistic (Ritter, 1984).

The effect of these changes on the model's global mean radiative cooling profile can be seen in Fig. 14. The e-type effect accounts for the enhanced cooling near the surface whilst the decrease in cooling in the middle and upper troposphere is due to a more realistic response of the radiation scheme to partial cloud cover.

The sensitivity of the model to such a change in the radiation code has been studied in a 10-day forecast from 21 January 1979. For the purposes of this study only the cloud fields at day 4 will be discussed (Fig. 7 and 15). They show a slight increase in total cloudiness from 44% to 49% with the revised radiation code. There is an increase in cloudiness at all levels but most

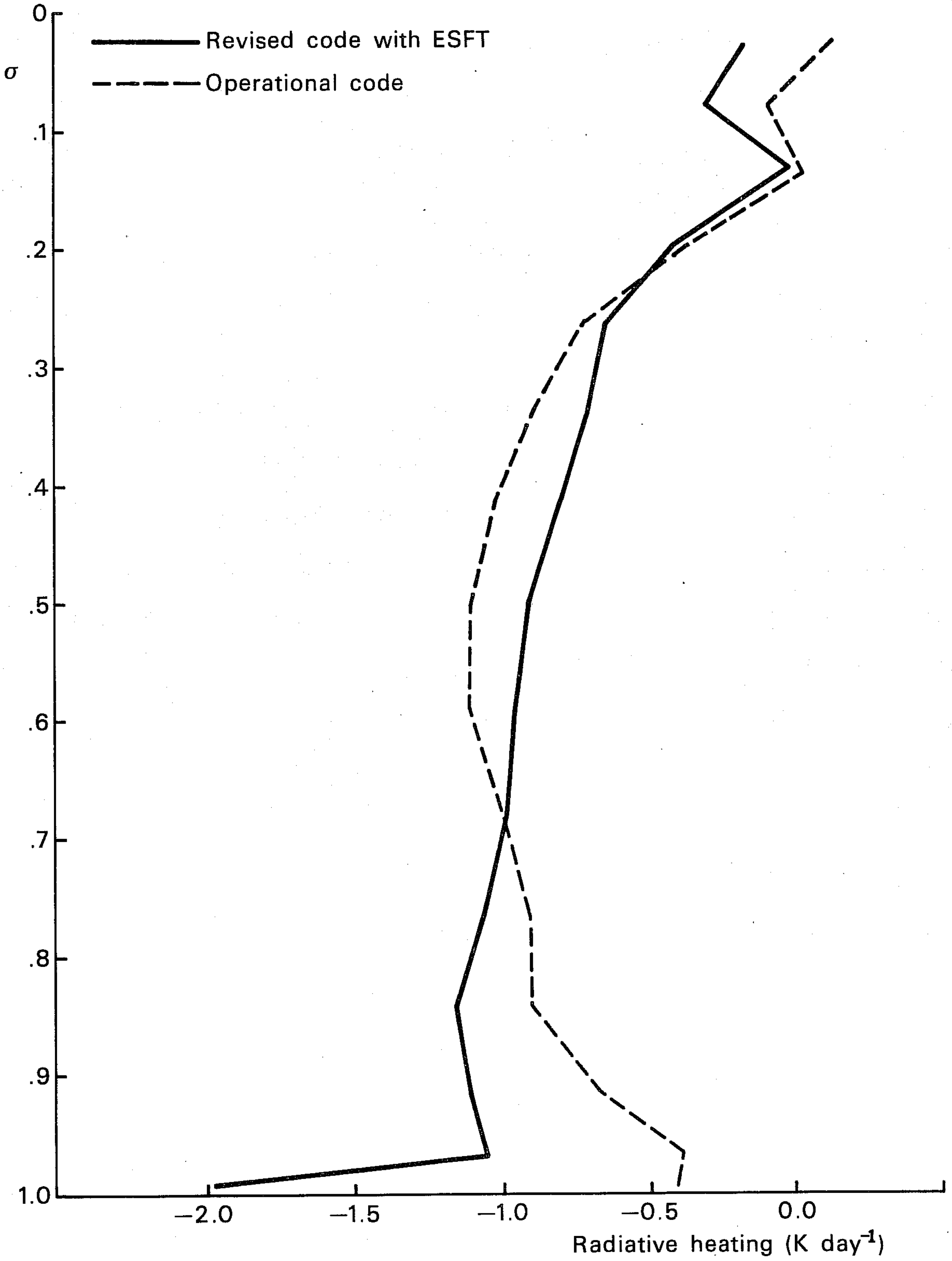


Fig. 14 Comparison of global mean radiative cooling profile for the operational radiation scheme and the ESFT scheme

January - day 4

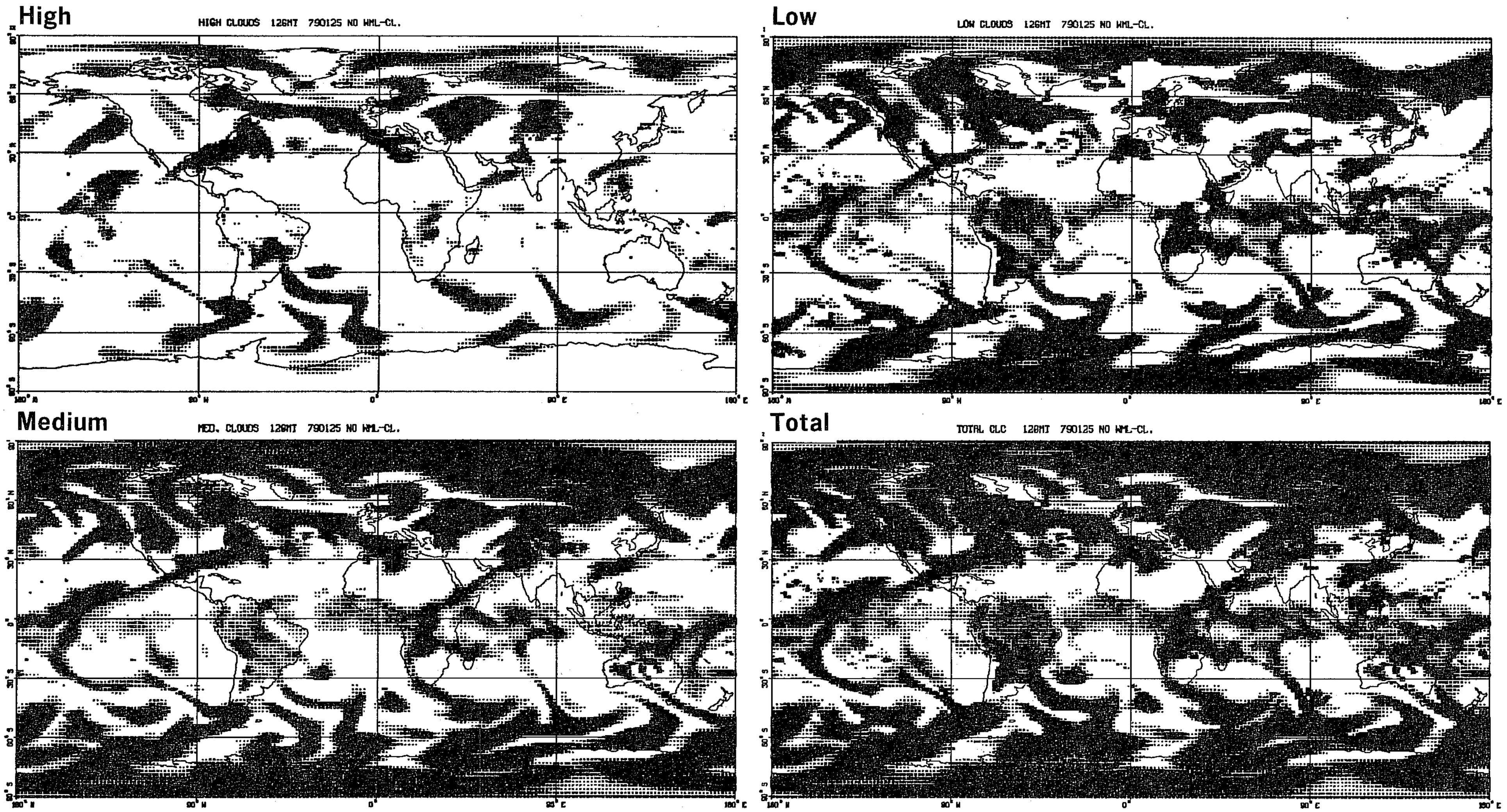


Fig. 15 Cloud distribution for day 4 (25.1.79) of January experiment with the ESFT radiation scheme.

noticeably in the high clouds, particularly in the tropics. There is now some indication of the cirrus clouds associated with the ITCZ which has strengthened due mainly to the introduction of the e-type effect. This enhances the radiative cooling near the surface leading to more evaporation and thus promoting a more intense hydrological cycle.

The overall pattern of cloudiness is very similar in both experiments at this stage in the forecast, particularly in the extratropics. This suggests that in the short term the model's relative humidity structure is fairly insensitive to the radiative cooling profile except in the tropics where convective processes dominate.

6. THE SENSITIVITY OF THE MODEL TO CLOUD-RADIATION INTERACTION

As part of this study the sensitivity of the model's performance to the cloud prediction through its interaction with the radiation scheme has also been considered. There are two main processes by which clouds can influence the atmospheric circulation. The first is by modifying the surface radiative flux and the second is by a redistribution of atmospheric radiative cooling both horizontally and vertically. A series of 10-day forecasts with the N48 grid-point model were run to try to assess the relative roles of the two processes concentrating on the extratropics. The results might give some guidance on the degree of complexity required in the cloud scheme. For example, is it necessary to know the vertical structure of cloudiness or is it sufficient to know only the total cloud cover so that the surface heating is reasonably defined? The experiments were all run from the FGGE analysis for 12Z, 21/1/79 and were:

(A) Control - all cloud effects included.

(B) No cloud effects in the atmosphere, i.e. clear sky cooling but cloud effects on surface flux included.

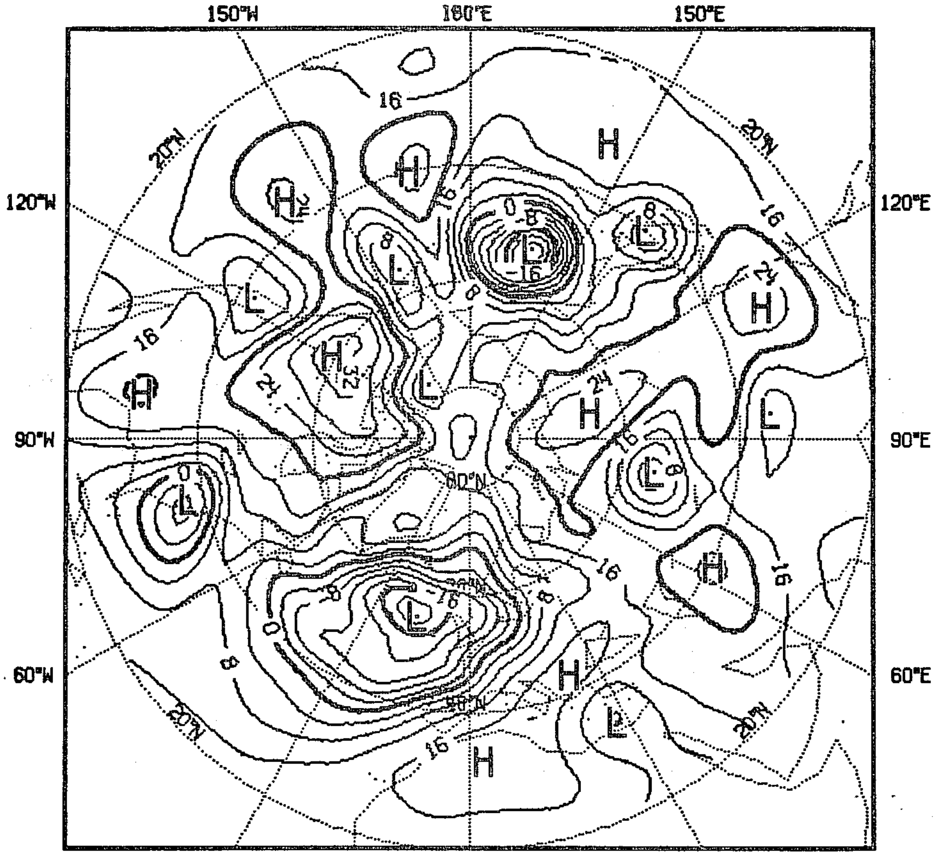
(C) As (B) but considering the vertically integrated effects of clouds by modifying the cooling rates to give the net cooling in the vertical column as in (A).

(D) All clear skies (surface and atmosphere)

(E) Fixed zonal mean clouds - cloud amounts derived from day 10 of (A).

Comparison of experiments A and B indicate that when the atmospheric part is removed, the initial effect is one of a general weakening of the synoptic scale circulation. This is well demonstrated in 1000 mb height fields for day 7 (Fig. 16) where the cyclones are weaker by 6-8 dkm and the anticyclones by about 4 dkm. There is no obvious phase shift at this stage. A similar response is also seen at 500 mb. Beyond day 7 the forecasts begin to diverge more rapidly and the shape of the flow begins to change so that it becomes more difficult to estimate the cloud effects. As expected this change can be clearly seen in an analysis of the energetics, with a reduction of 20% in the eddy kinetic energy (K_E) of wave numbers 4-9 and 10-15. This is associated with a large decrease (~40%) in the baroclinic conversion from eddy available

a) Experiment A



b) Experiment B

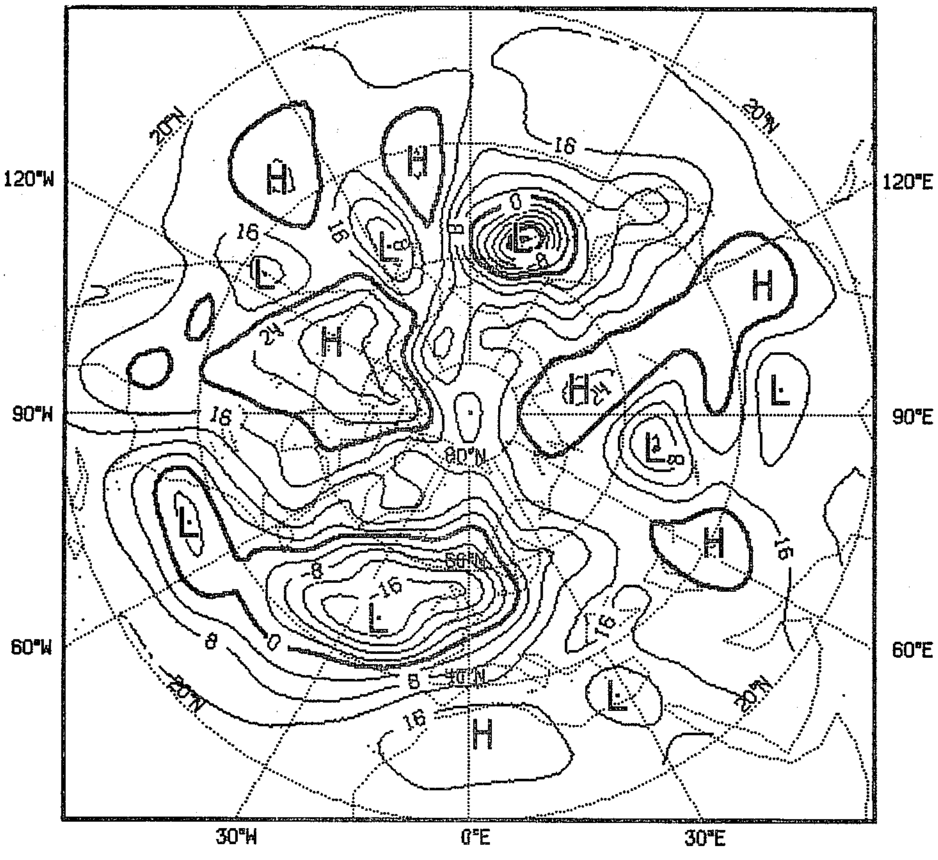


Fig. 16 1000 mb height fields for day 7 of (a) control (experiment A) (b) clear sky atmospheric cooling (experiment B)

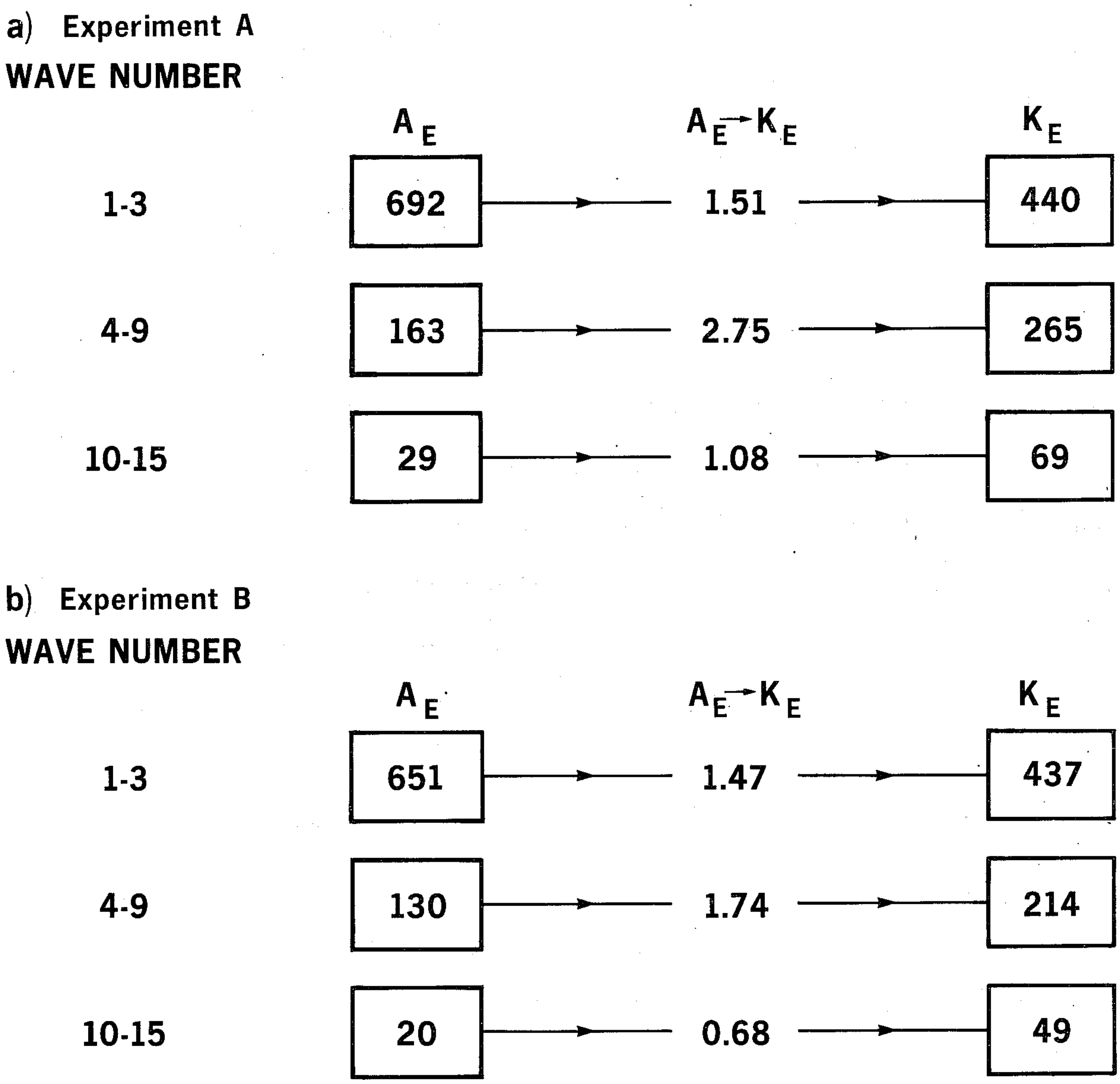


Fig. 17 Energetics analysis for days 1-10 for (a) control (experiment A) (b) clear sky atmospheric cooling (experiment B)

potential energy (A_E) to K_E for these wave numbers (Fig.17).

A possible cause of the weakening of the circulation could be a decrease in the mean meridional temperature gradient associated with a slight decrease in the mean radiative cooling. Certainly the poleward flux of heat by wave numbers 4-9 is reduced although the majority of this flux is accomplished by the long waves (1-3) which appear to be unaffected by changes in cloud-radiation interaction at least for a winter forecast. To ascertain whether the weakening of the circulation was due to the change in meridional temperature gradient, experiment C was run which restored the gradient. Nevertheless the 1000 mb height field remains similar although the general weakening of the circulation is not so marked (Fig.18). The poleward heat flux is now similar to the control A although the energetics still show a weakening of the baroclinic conversion of A_E to K_E.

The effect on the forecast of the surface component is not so marked for a winter simulation (experiment D). At day 7 the flow pattern is very similar to experiment B (Fig.19). However by day 10 there is a substantial change in the forecast over Europe (Fig.20) which might be due to the tropical influences. Tiedtke (1984) has shown that cloud-radiation interaction, particularly over the tropical land masses, can have a marked effect on the diabatic heating patterns which may easily influence the extratropics via teleconnections within a few days. Of course, it is probable that the surface effects of the extratropical land masses would be evident much earlier in the forecast for a summer case.

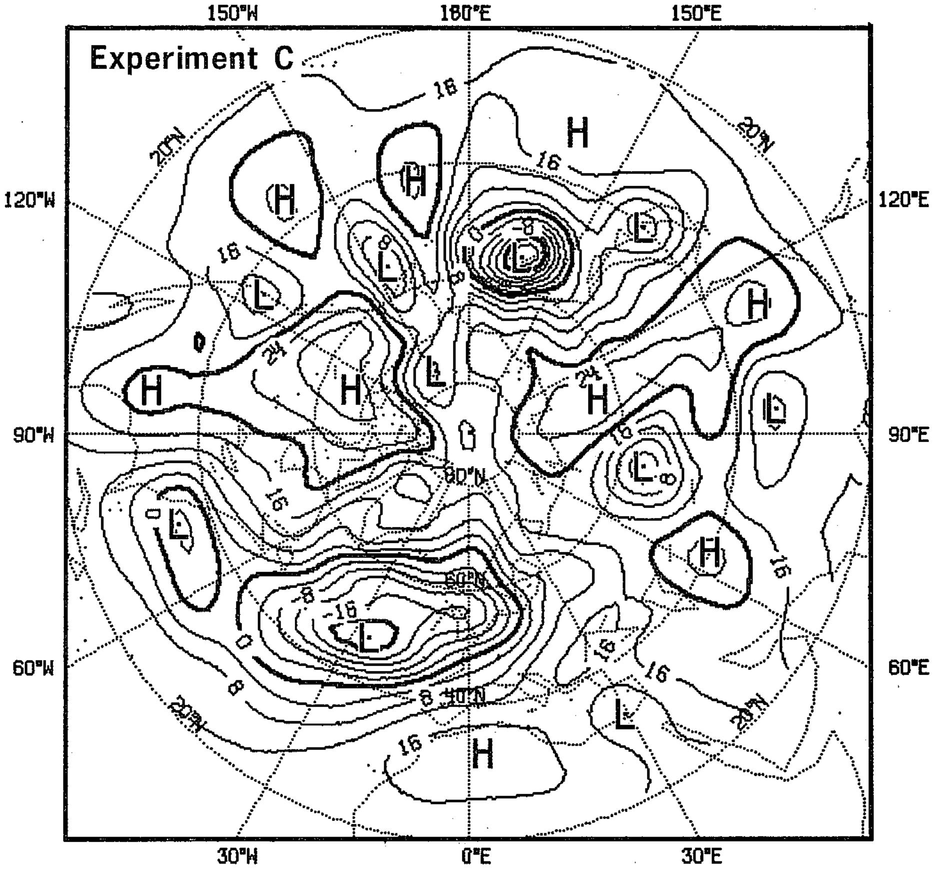


Fig. 18 1000 mb height field for day 7 of adjusted clear sky cooling (experiment C)

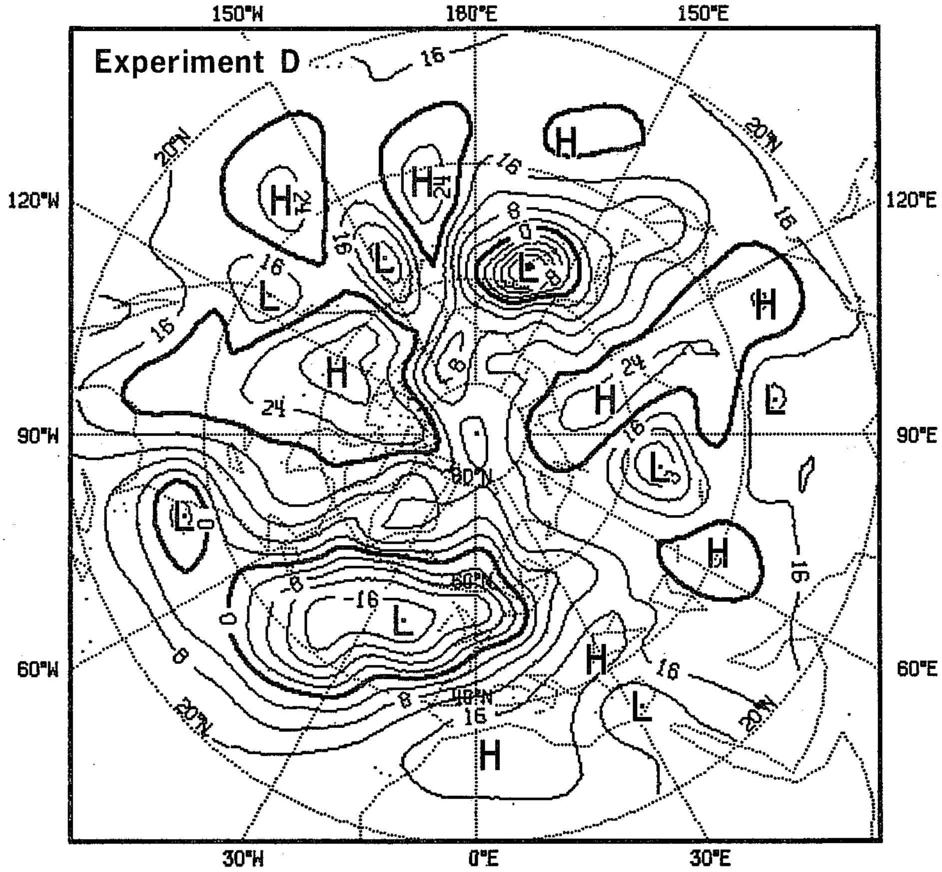
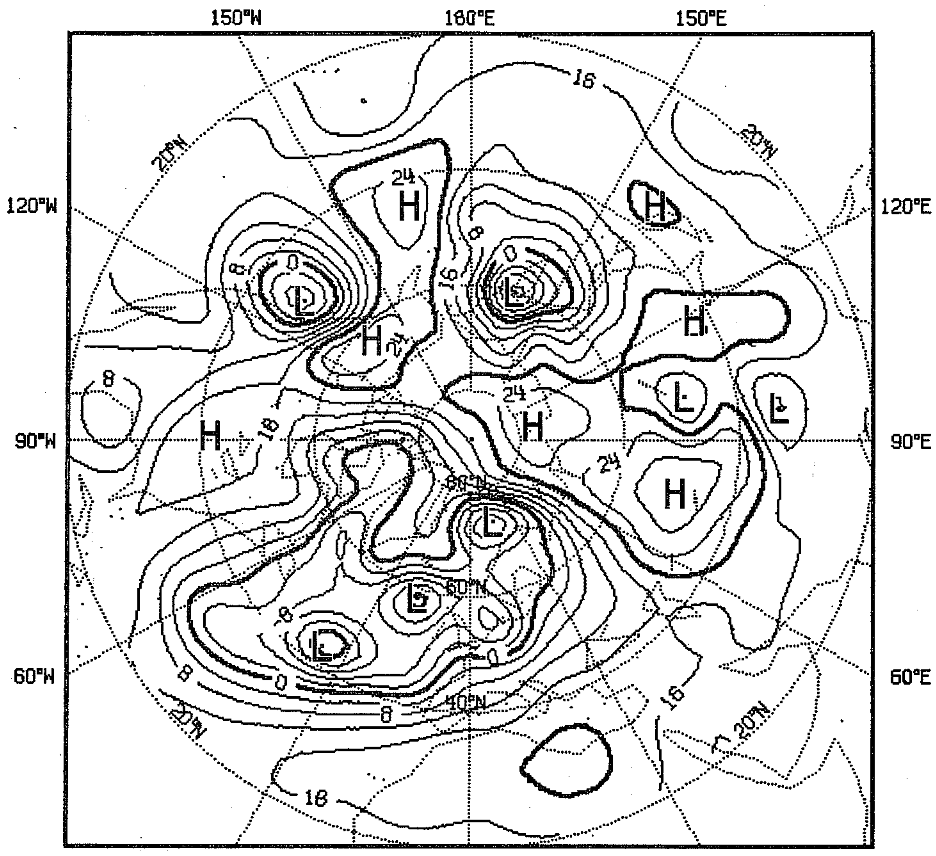


Fig. 19 As Figure 18 for all clear skies (experiment D)

a) Experiment B



b) Experiment D

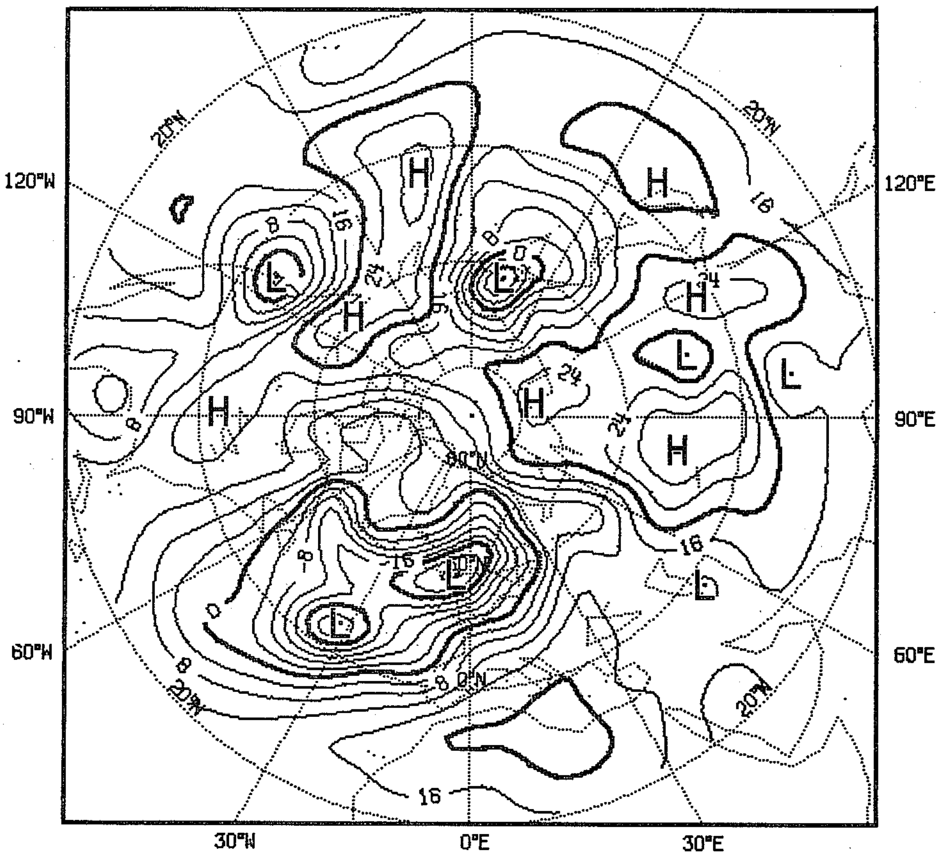


Fig. 20 1000 mb height fields for day 10 of (a) clear sky atmospheric cooling (experiment B) and (b) all clear skies (experiment D)

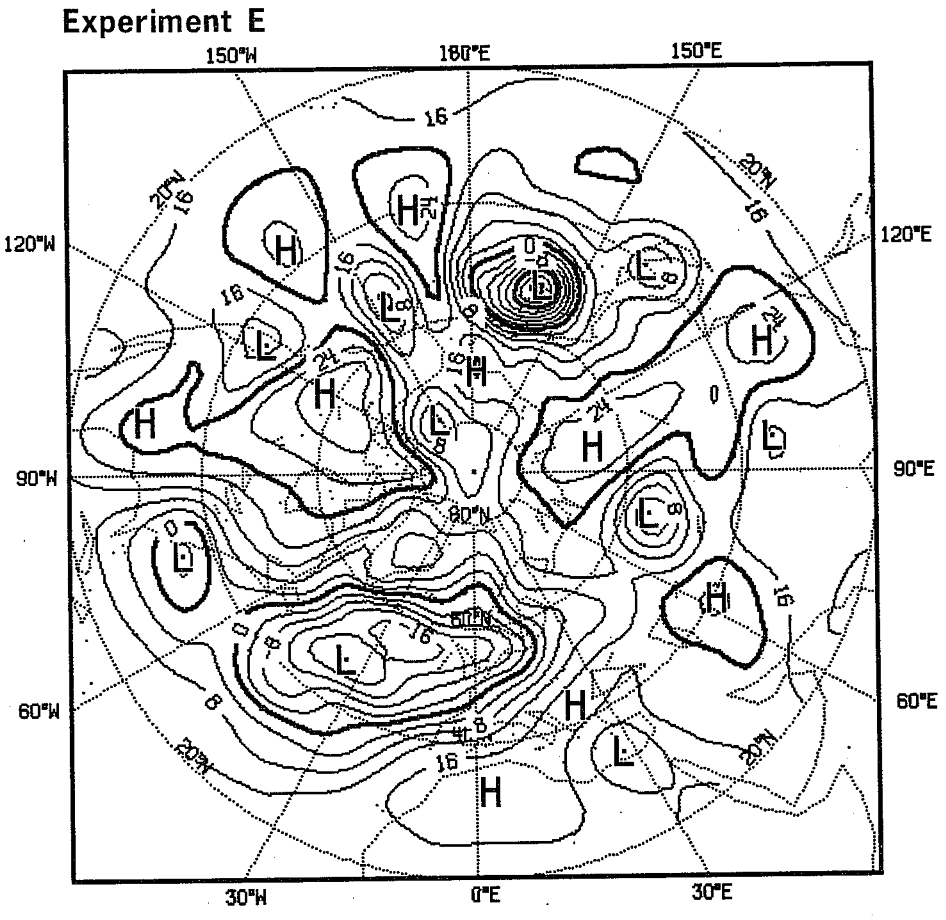

Experiment E

Fig. 21 As Figure 18 for zonal mean clouds (experiment E)

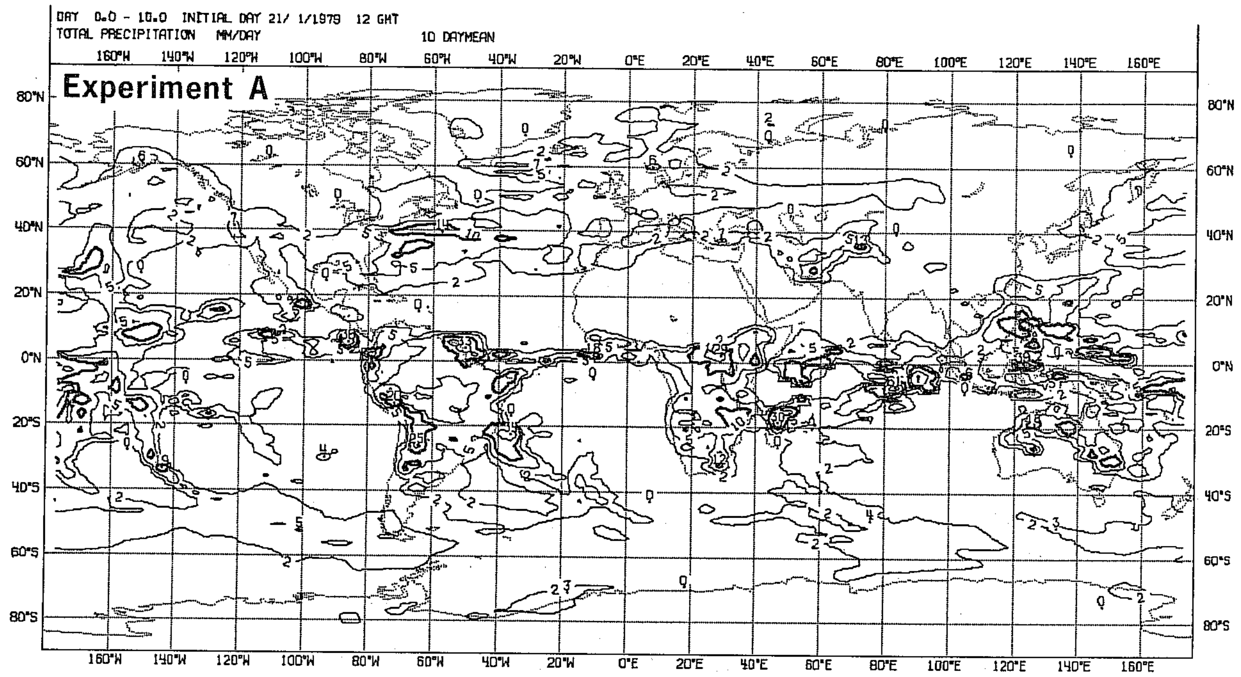


Fig. 22 Total precipitation for days 0-10 for control (experiment A)

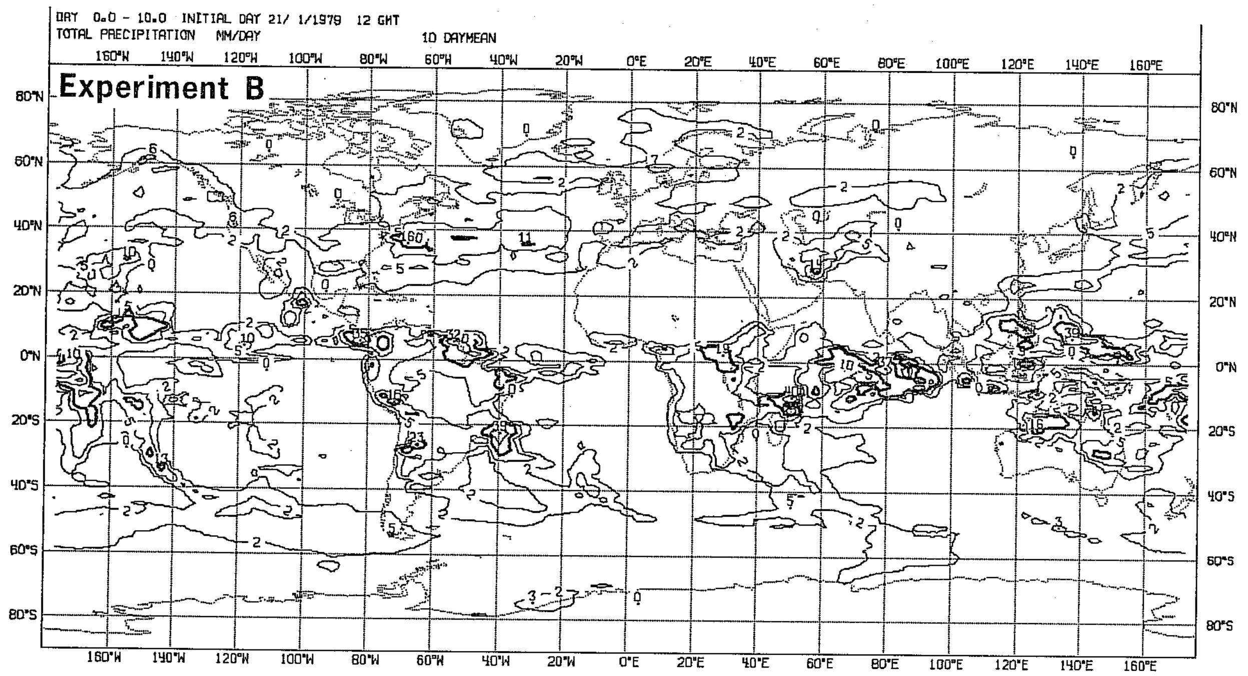


Fig. 23 As Figure 22 for clear sky atmospheric cooling (experiment B)

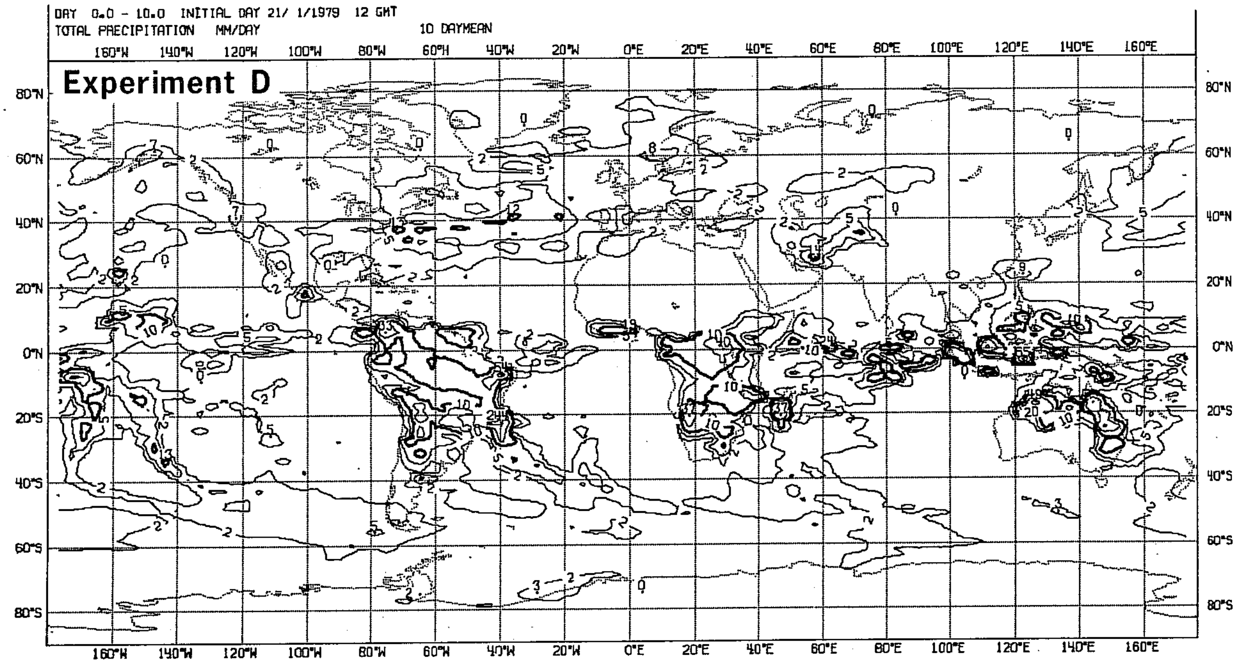


Fig. 24 As Figure 22 for all clear skies (experiment D)

Experiment E with zonal mean clouds was designed to assess the sensitivity of the model to spatially varying clouds. Again the 1000 mb height fields show a greater similarity to experiments B and C than to the control A with a weakening of the circulation particularly over the Atlantic (Fig.21). The baroclinic conversion of A_E to K_E is again weaker suggesting that the spatial variation in cloudiness provides an important correlation between warming and rising as noted by Geleyn (1981).

In the tropics the precipitation responds rapidly to the radiative effects of clouds. The radiative effects in the atmosphere enhance precipitation over land and sea (Figs. 22 and 23) whilst the surface effect suppresses it over land (Fig.24). Over land the surface effect dominates.

It should be emphasised that these results are from only one set of experiments and may therefore not be typical. However, where applicable, they do agree with those of Geleyn (1981) and are a clear indication that it would be unwise to oversimplify the representation of clouds in a forecast model. The results suggest that representing the surface effects only by means, say, of a total cloudiness would be inadequate and that both the horizontal and vertical variation in atmospheric radiative cooling can affect the circulation within a few days.

7. DISCUSSION AND CONCLUSIONS

The results of this study have shown that a relative humidity criterion of the kind used in the existing cloud scheme is reasonably successful at predicting many features of the total cloudiness especially in the extratropics.
However one problem with this kind of method is that the humidity field is by

far the least known of all the analysed prognostic variables. In particular, this is true for the high layers of the model as there is no reliable data source for moisture in this region. This aspect might improve in future with increasing reliability of satellite measurements and the development of more accurate retrieval methods although there is still the problem that humidity data have a shorter horizontal scale and therefore may need higher resolution in the analysis scheme. Also any cloud scheme based solely on the relative humidity will be very dependent on the way in which the model's convection scheme redistributes the moisture in the vertical.

In the tropics and subtropics the scheme is less successful because deep and shallow convection are the main sources of clouds. All the experiments reported here were run without a diurnal cycle. However, the diurnal variation in cloudiness may be large, particularly over the tropical land masses, and is generally associated with convective activity. There is therefore a clear need for a direct link with the convection scheme for determining cloud cover in this region. Another deficiency of the scheme in the tropics is the lack of high cloud, particularly anvil (or outflow) cirrus. This is improved slightly with the new radiation code but is due mainly to the general lack of moistening of the upper troposphere by the Kuo convection scheme. It may therefore be necessary to parameterise these clouds in terms of convective activity rather than relative humidity.

The lack of boundary layer clouds is very evident in the subtropics. These clouds pose serious problems because they represent a delicate balance between the surface fluxes of heat and moisture, turbulent entrainment through the top of the well mixed layer and radiative processes within the cloud. Unless all these processes are properly represented, serious feedback problems between cloud cover and radiative cooling arise (e.g. Slingo, 1983). It is unlikely that a simple formulation based on relative humidity would solve this problem. Some success in representing the stratocumulus fields over the cold oceans off the western seaboards has been obtained using the strength of the trade wind inversion as a predictor (Slingo, 1980, Le Treut and Laval 1984). However the extensive areas of fair weather cumulus in the subtropical highs and those of mesoscale cellular convection in extratropical cold outbreaks are yet to be satisfactorily represented. At present the model's boundary layer is far too moist so that there is little chance of relative humidity being a sensible indicator. This should improve with the introduction of a shallow convection scheme (Tiedtke 1984) but even then it will probably be necessary to use other indicators, such as information from the scheme itself to predict cloudiness. The shallow convection scheme should also provide the necessary enhanced entrainment at the top of the well mixed layer to compensate for the radiative cooling associated with the cloud.

The other major deficiency of the existing cloud scheme is in the vertical distribution of cloudiness. The freedom to allow clouds in any layer has resulted in a large number of deep clouds. Experiments have shown that the model is sensitive to the atmospheric radiative cooling profile and thus the vertical distribution of clouds should be correctly specified. It will probably be necessary to force the layer clouds to be stratified because the model is unlikely to reproduce the complex relative humidity structure often observed.

The verification of a cloud prediction scheme cannot easily be done. There are few cloud climatologies available and they generally lack detail on the geographical or vertical distribution of cloudiness. This may improve with the results from the International Satellite Cloud Climatology Program (ISCCP). Earth Radiation Budget (ERB) data also provide useful verification although ideally they need to be used with the relevant cloud distribution to be able to properly verify cloud amounts and heights. Data from Nimbus 7 (Stowe et al. 1984) currently becoming available may provide such a facility. Another method of verification is to make a detailed regional comparison on individual days of observed and model cloud fields. Such a comparison is planned using cloud retrievals from METEOSAT over West Africa and the South Atlantic. Details on the diurnal variation of cloudiness should also be available from this study. This comparison has to be done with care due to problems of model bias. The initial state of the model is not a perfect meteorological picture of the atmosphere and is biased by defects of the observational network and features of the analysis method. As already discussed the model shows a pronounced spin-up during the first day whilst beyond day 1 the comparison is progressively biased by errors in the model forecast.

At the moment diagnostic methods for cloud prediction probably offer the best chance of representing the global cloudiness. Relative humidity is a good indicator for frontal cloudiness and it is hoped that other parameters, such as information from the convection scheme, will give equally good results in the tropics. One drawback of such schemes is that the cloud is partially divorced from the rest of the model. It can only respond to the radiation field it produces through changes in the large scale temperature field and subsequently the parameters (e.g. relative humidity) used as predictors. In reality however the strong radiative cooling at the cloud top induces changes in droplet growth and turbulent mixing which may maintain or dissipate the cloud. Methods based on the explicit calculation of the liquid water cycle (e.g. Sundqvist 1978) are physically more realistic in that they allow a direct link between the clouds and the radiative fluxes. They also include the latent heat release involved in cloud formation and dissipation which is lacking in diagnostic methods. However such methods are still in the development stage and should be considered as a longer term solution. They are of course computationally more expensive and are more difficult to verify. They either require direct observations of liquid water content or the model values have to be interpreted in terms of a geometric cloud cover. There may be as many uncertainties in this step as in the simple diagnosis of cloud cover directly from model variables.

In conclusion several shortcomings of the existing cloud scheme have been identified. However the results have shown that a diagnostic approach to cloud prediction can be successful and in the short term should be used as the basis of a new scheme. A more direct link with the other physical processes, particularly convection, is recommended for representing clouds especially in the tropics.

REFERENCES

Berlyand, T.G., L.A. Strokina and L.E. Greshnikova, 1980: Zonal cloud distribution on the earth. Soviet Meteorology and Hydrology, No. 3, 9-15.

Bolton, J.A., 1981: The estimation of zonally averaged climatological cloud data for use in the 5-level model radiation scheme. UK Met. Office, Met O 20 Tech. Note No. II/136.

Dopplick, T.G., 1979: Radiative heating of the global atmosphere: Corrigendum. J. Atmos. Sci., 36, 1812-1817.

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

Geleyn, J-F. and A. Hollingsworth, 1979: An economical analytical method for the computation of the interaction between scattering and line absorption of radiation. Beitr.Phys.Atmosph., 52, 1-16.

Geleyn, J F., A. Hense and H.J. Preuss, 1982: A comparison of model generated radiation fields with satellite measurements. Beitr.Phys. Atmosph., 55, 253-286.

Hollingsworth, A., K. Arpe, M. Tiedtke, M. Capaldo, and H. Savijärvi, 1980: The performance of a medium range forecast model in winter - Impact of physical parameterization. Mon.Wea.Rev., 108, 1736-1773.

Huschke, R.E., 1969: Arctic cloud statistics from "air calibrated" surface weather observations. RAND Corp. Memo. RM-6173-PR.

Le Treut, H. and K. Laval, 1984: Sensitivity of the climate simulated by a G.C.M. to the parameterisation of stratus clouds. Proceedings of the IAMAP International Radiation Symposium, 21-29 August, Italy. (in press).

London, J., 1957: A study of the atmospheric heat balance. College of Engineering, New York Univ., Final Rep., Contract No.AF 19 (122)-165.

Phillpot, H.R., 1968: A study of the synoptic climatology of the Antarctic. Melbourne Inst. Ant. Met. Res. Centre Tech. Report No. 12.

Ritter, B., 1984: The impact of an alternative treatment of infrared radiation on the performance of the ECMWF forecast model. Proceedings of the IAMAP International Radiation Symposium, 21-29 August, Italy (In press).

Rodgers, C.D., 1967: The radiative heat budget of the troposphere and lower stratosphere. MIT Dept. of Met., Planetary Circ. Project, Report No. A2.

Sasamori, T., J. London, and D.V. Hoyt, 1979: Radiation budget of the southern hemisphere. AMS Met. Mono., Vol. 13, No. 35, American Met. Society, 9-23.

Slingo, A., 1983: Clouds and radiation in the Meteorological Office 11-layer general circulation model. UK Met. Office, Met O 20 Tech. Note No. II/203.

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

Slingo, J.M., 1982: A study of the earth's radiation budget using a general circulation model. Quart.J.R.Met.Soc., 108, 379-405.

Stephens, G.L., G.G. Campbell and T.H. Vonder Haar, 1981: Earth Radiation Budgets. J.Geoph.Res., 86, No. C10, 9739-9760.

Stowe, L.L., P.P. Pellegrino, and P.H. Hwang, 1984 Validation of Nimbus 7 cloud products. Proceedings of the IAMAP International Radiation Symposium, 21-29 August, Italy (In press).

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

Telegadas, K. and J. London, 1954: A physical model of the northern hemisphere troposphere for winter and summer. NY Univ. Sci., Report No. 1, Contract No. AF 19(122)-165.

Tiedtke, M., 1984: The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. ECMWF workshop on convection in large-scale numerical models, 28 Nov.-1 Dec.1983, ECMWF, 297-316. (in print)

Tiedtke, M., J.-F. Geleyn, A. Hollingsworth and J.-F. Louis, 1979: ECMWF model: Parameterization of subgrid-scale processes. ECMWF Tech.Rep.No.10.

Winston, J.S., A. Gruber, T.I. Gray Jr., M.S. Varnadore, C.L. Earnest and L.P. Manello, 1979: Earth-atmosphere radiation budget analyses derived from NOAA satellite data, June 1974-February 1978. Volumes 1 and 2, NOAA S/T 79-187, NOAA Nat. Environmental Satellite Service.

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