Sensitivity and validation studies with a prognostic cloud generation scheme.

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1. Introduction:

The widespread recognition that cloud/radiation feedbacks constitute some of the most important and complex features that affect the climate sensitivity (Cess et al, 1990) has put emphasis on the need to improve the cloud parameterizations of the present general circulation models. There are also clear indications that a precise treatment of the cloud/radiation interaction is necessary for accurate medium-range weather forecasts (Slingo, 1987; Morcrette, 1990). In the search of more physically based cloud parameterizations, the so-called "prognostic cloud models" (Sundquist, 1981; Smith, 1985, 1990; Roeckner and Schlese, 1985; Le Treut, 1985) have become widely used. Indeed by predicting cloud condensed water through a budget equation, they provide a consistent framework in which it is possible to add progressively more cloud physics. At the present stage, however, these models remain rather crude, because the various physical processes which are important for the development and dissipation of cloud systems are known qualitatively only.

The purpose of the present paper is precisely to discuss in more details the accuracy with which the cloud/radiation processes are treated in a GCM through a number of sensitivity and validation studies. The cloud scheme used for those experiments was first developed for use in the LMD GCM (Le Treut and Li, 1991), and was then adapted to the ECMWF model (Le Treut, 1988).

2. Description of the cloud generation scheme.

In a prognostic cloud scheme the cloud condensed water is a new state variable of the model: it evolves through various processes which can be considered separately. We can review them briefly and state the simplifications attached to their parameterization:

. advection by the large scale circulation

This term is included when the cloud scheme is used in the LMD GCM. For technical reasons it was not included in the ECMWF experiments. It is usually thought that the condensed water large-scale advection is negligible compared to the water vapour advection, although this may no longer be true for specific cloud regimes (cirrus) and when the resolution increases.

. *diffusion or turbulent transport*

In the boundary layer (and perhaps also for cirrus clouds) the vertical transport of total water (condensed+ vapour) by turbulent processes is an important term for the maintenance of a cloud layer. At the same time, in a cloud layer, the release of latent heat associated with condensation (or the cooling associated with evaporation) may change the nature of the turbulence. In the experiments with the LMD GCM these effects are neglected. They were intoduced in a simple manner for some of the experiments run with the ECMWF GCM: the parameterization of these effects, and the impact on the predicted cloud and radiation fields, will be shown in Section 3.

. *condensation and reevaporation*

Convective clouds will be essentially ignored in the present studies. In the LMD GCM we have considered both convective and non-convective sources of cloud liquid water: this is somewhat arbitrary because convection is treated by both a Kuo scheme and a moist adiabatic adjustment, used in sequence, neither of which provide any information on the level at which water is condensed. Some assumptions are therefore required and we have decided to have a vertical profile of condensation proportional to the vertical profile of water vapour removal, when positive. This might lead to some underestimation of the height of convective clouds. In the experiments with the ECMWF GCM the source of cloud water from convective clouds was not included and convective clouds were determined with the usual diagnostic scheme (Slingo, 1987).

If we turn now to stratiform clouds, a first difficulty for their modelling comes from the fact that they, too, generally do not cover a whole GCM gridbox, and require a representation of the sub-grid scale processes. There may be two general approaches of this problem: one is to try to describe as explicitely as possible the sub-grid scale circulations and their effect on the cloud fields, this leading in principle to the definition of cloud cover as a model prognostic variable; the other is to use a statistical approach of these processes: we have chosen this attitude, because it seemed more adapted to our present knowledge of the processes which determine the non-convective cloud cover. In that sense our scheme can be considered as semi-prognostic only, since the cloud liquid water only, and not the cloud cover, is considered a prognostic variable.

In fact we consider both the condensation and evaporation terms in the same simple formulation: we suppose that within a grid box, the cloud water gets evaporated and condensed again, at a time scale which is near or inferior to the model time step, due to subgrid circulations. The cloud fraction as well as the net amount of condensed water are determined by this equilibrium between the condensation and evaporation of cloud droplets: we have taken here an approach which corresponds to a simplification of the ideas presented originally by Deardorff and Sommeria (1977). Our scheme is also similar to the one developed by Smith (1990) for the

UKMO model. To describe the effect of those subgrid circulations, it is more suitable to use variables conserved through water phase changes: the total water (q_t) and the liquid water temperature (T_t):

$$q_t = q + l$$

$$T_t = T - \frac{L\,l}{C_p}$$

Let us assume that the temperature varies little within a given grid box, while total water varies with a probability distribution $P(x)$, then it is possible to determine the fraction of the grid on which water vapour will exceed saturation and to determine the amount of water which will be condensed and precipitated, assuming that condensation and precipitation of water occur over the cloudy part only. Such a scheme works partly as an adjustment scheme.

Finding the distribution $P(x)$ is obviously the difficulty of this approach. Bougeault (1981) showed through the analysis of results from a high resolution dynamical cloud model that for low clouds at least, $P(x)$ was not symmetrical. At this stage we have used the most simple approach, assuming an uniform distribution of q between the values (q_t - Δq) et (q_t + Δq). This approach gives a very simple analytic and easily understandable formula for the cloud fraction:

$$f = \frac{q_t + \Delta q \; - \; q_s}{2\,\Delta q} \quad \text{or 0 or 1}$$

Similarly one may compute a mean water vapour amount, before condensation and precipitation, on the clear and overcast part of the model grid box, as, respectively:

$$q_t^c = \frac{q_s + q_t - \Delta q}{2} \quad \text{or } q_t \text{ or } 0$$

and

$$q_t^o = \frac{q_s + q_t + \Delta q}{2} \quad \text{or } 0 \text{ or } q_t$$

The cloud water vapour is then in excess of the saturation level whenever the cloud fraction f is positive: there must therefore occur a condensation process which can be treated as the usual supersaturation process, but over the cloudy part only. This procedure splits the total water over the cloudy area into a vapour part -- which corresponds to the saturation value for the temperature in the cloudy part at the end of the process -- and a liquid part. The difference between the liquid water content obtained at the end of this procedure and that used at the beginning of it gives a source or sink of liquid water which will be used in the general budget equation.

The determination of the parameter Δq is of course an essential point for the cloud generation scheme. In the LMD GCM, $\Delta q = \gamma q_t$ and γ is a adjustable parameter of the model, which was set to 20%. This means that clouds begin to form when the relative humidity reaches a value of 83%: this happens to be slightly lower, but roughly consistent with the value used by Smith (1990). In the ECMWF GCM we have used an empirical dependance of Δq on the mean vertical velocity w, the Richarson number Ri and the vertical gradient of water vapour (Le Treut, 1989)

. precipitation

By precipitation process, we mean the transformation of cloud water into rain water. This process largely determines the amount of liquid water which remains stored within the clouds, and hence, their cloud optical properties. Sundqvist (1981) has designed a formula which basically sets a quick precipitation rate for LWC larger than a given value and a slower precipitation rate when LWC becomes lower than this threshold. To respect our general spirit of simplicity, we represent this process by two parameters: a threshold valuel_c above which all LWC is precipitated and under which all LWC is retained in the atmosphere, and a precipitation time scale τ corresponding to the rate at which the amount of water above the threshold is being precipitated.

For warm water clouds the value for l_c is set to 0.1 g/kg. This value gave the best match between simulated and analyzed optical properties when we compared our model results with ISCCP analyses (Le Treut and Li 1988; Li and Le Treut 1989). A review of the precipitation schemes in various models show values ranging from 0.1 to 0.5 g/kg for l_c or equivalent parameters. The value of τ was chosen in both the LMD and ECMWF model as small enough for the precipitation of all water above l_c to take place in a single time step.

The physics of ice clouds is very different and if we want to use the same kind of formulation we must at least use a different set of parameters. It is generally thought that cirrus clouds produce very efficiently particles large enough to precipitate, but that the terminal fall speed of ice crystals is smaller that that of water rain drops. This is clearly a very simple image which needs to be precised. In the LMD experiments considered in the present paper, we simple set l_c to the minimum of .001 g/kg and 0.2 q. In the present experiments with the ECMWF model, values may be slightly more realistic are used: $l_c = 0$ and $\tau = 7200$s. Another important point is to be able to distinguish water and ice clouds, since we know that water is still present at temperatures lower than 0°C. This appears to be a critical process as far a climate sensitivity is concerned: experiments with the LMD GCM (Li and Le Treut, 1991, in preparation) have shown that the choice of a temperature range to distinguish water and ice clouds has a very strong impact on the climate sensitivity.

. interaction with radiation

The parameterization of the interaction between cloud and radiation is also subject to many assumptions. The role of the overlap of different cloud layers will be emphasized later. When using the present solar radiation scheme one also needs to prescribe a cloud droplet effective radius, which is used together with the cloud water amount to compute its optical thickness (in principle other parameters of the radiation scheme, such as the asymmetry factor for the diffusion, may also depend on the cloud type). In the experiments using the ECMWF model we have used a uniform value of 15µ for this parameter; in the experiments with the LMD GCM a formula due to Stephens (78), which gives a dependance of the cloud radius on the total water amount was used: it seems to bring too small values and is clearly not valid for all cloud types. In the infrared, the interaction of the cloud with radiation is described by an absorptivity coefficient k= 0.13 m2/g. Again this coefficient should depend on the cloud type

3. Simulated distribution of clouds and radiative fluxes

Our cloud generation scheme was first developed for use in the LMD GCM. The LMD GCM is a grid-point model. Its usual resolution is 64 points in longitude and 50 points in sine of latitude, with 11 vertical layers. The basic physical package includes a simple ground hydrology (bucket model; a refined ground and vegetation hydrology was developed by K. Laval and N. Ducoudré, it is not used in the present experiments), a boundary layer where turbulent transports are described as a diffusive process, and the simultaneous use of both a Kuo scheme and a Moist Adiabatic Adjustment scheme for the treatment of convective precipitation. The radiation scheme is the same as the operational ECMWF scheme (Morcrette, 1990) (for more details see Le Treut and Li, 1990, and references herein).

The cloud cover and cloud liquid water content simulated for a perpetual July integration is shown in Figure 1. The model predicts correctly the main qualitative features of the observed climatology, except for the stratus cloud cover in the eastern part of the oceans.

A series of experiments have also been run with the ECMWF model, using the cloud prognostic cloud scheme described above. These experiments were 10-day forecasts at the T42 resolution, starting on the 15 April 1985 and some 30-day forecasts at the T63 resolution, starting on the 15 July 88. One of the main benefit of this scheme is to be able to simulate more accurately the cloud liquid water content: the mean zonal cloud cover (computed assuming respectively a random or maximum overlap of the cloud layers) and the mean liquid water content are shown in Figure 2 for the two April and July reference cases (convective clouds are excluded from those results). As could already be noted in Figure 1.b, the cloud liquid water is able to increase with latitude, which is never the case when it is diagnosed as a function of temperature. The order of magnitude of the peaks is consistent with the results deduced from SSMR by Njoku and Swanson (1983)

We have plotted in Figure 3 the thermal and solar fluxes at the top of the atmosphere as

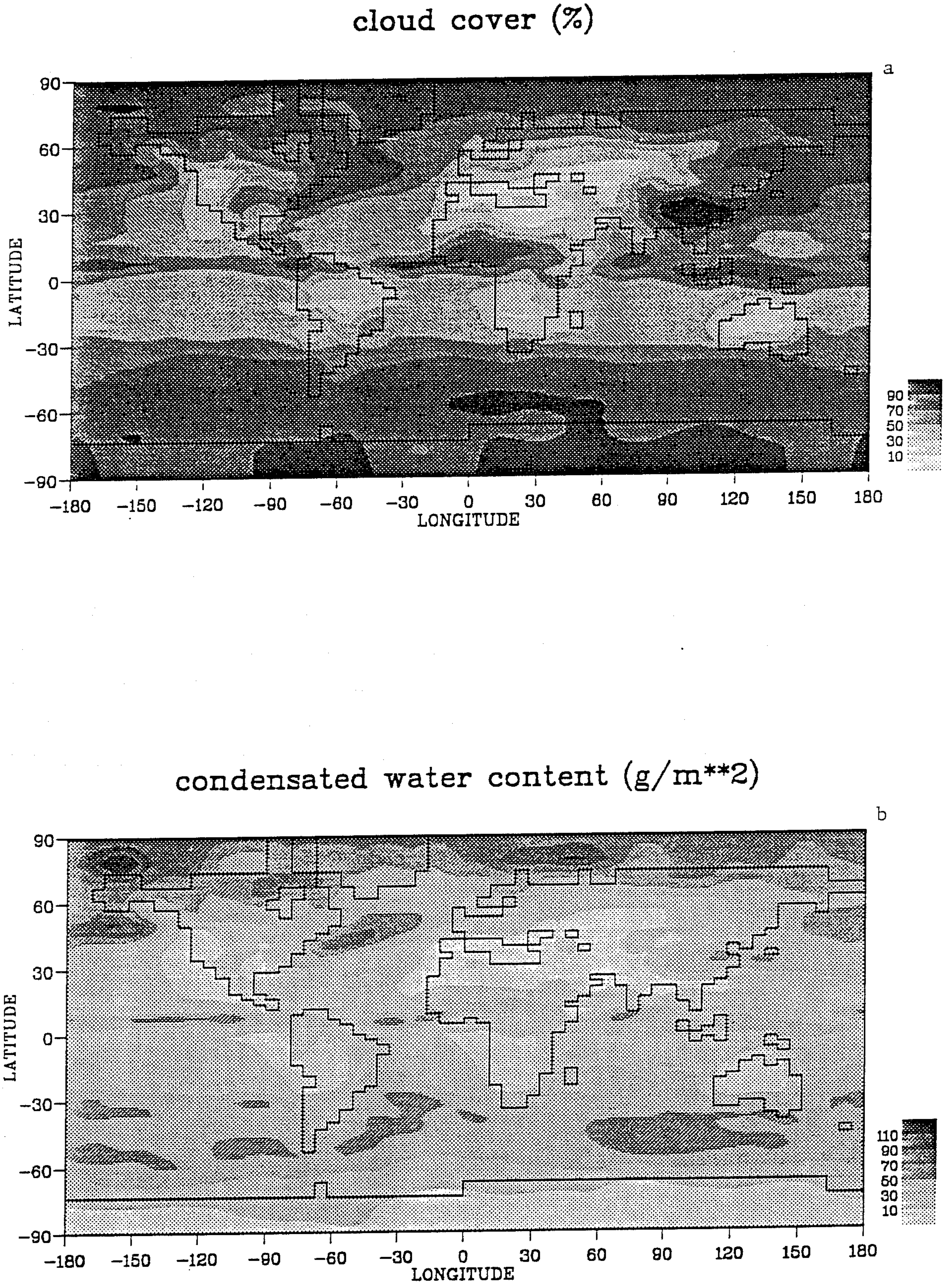

Figure 1: Cloud cover (top) and cloud liquid water content (bottom) from a July perpetual experiment with the LMD GCM (Le Treut and Li, 1991)

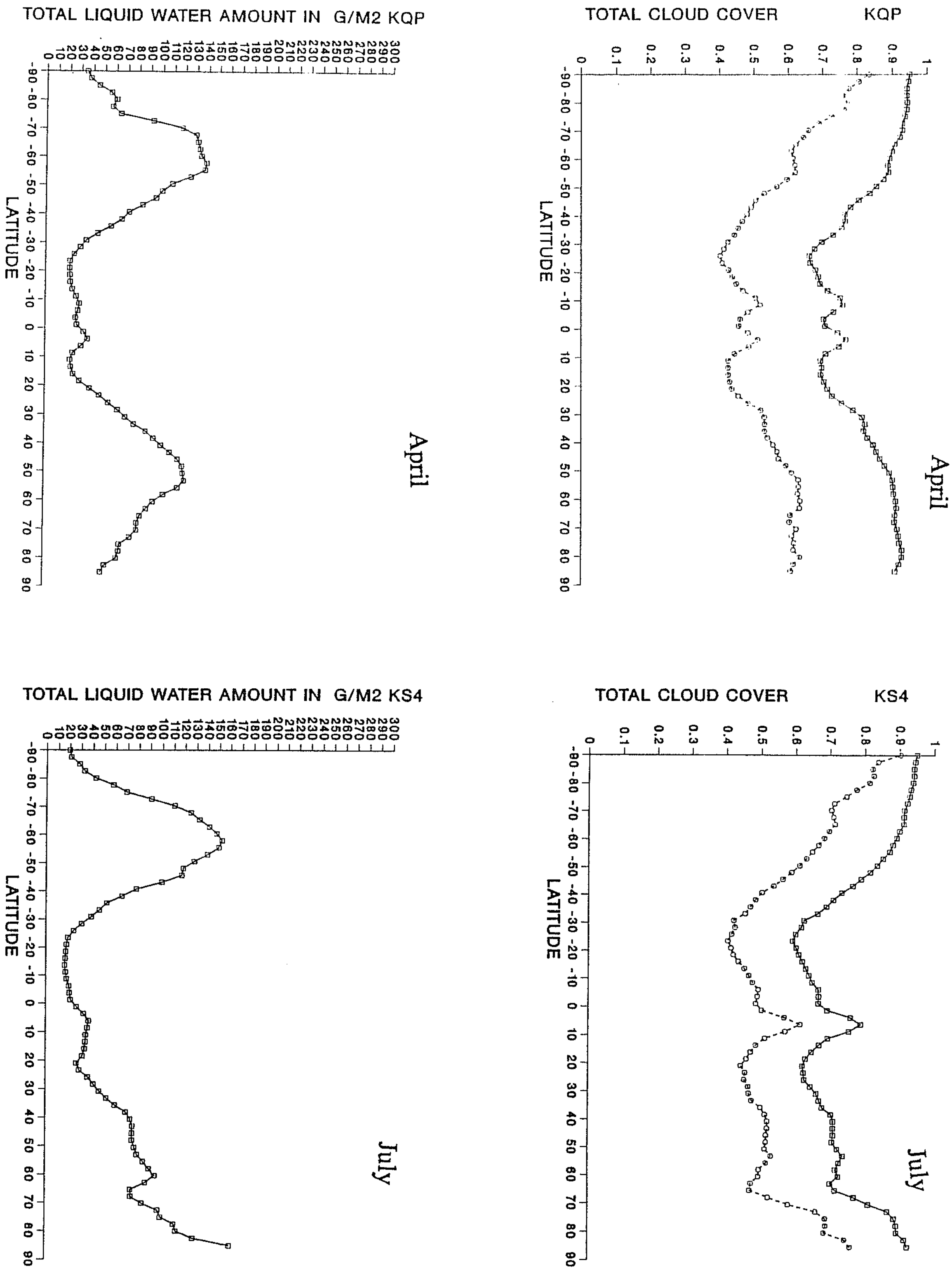

Figure 2: Mean zonal cloud cover and cloud liquid water content, from two experiments with the ECMWF GCM using a prognostic cloud generation scheme (April and July conditions - see text). The cloud cover is computed using both a random or a maximum overlap assumption.

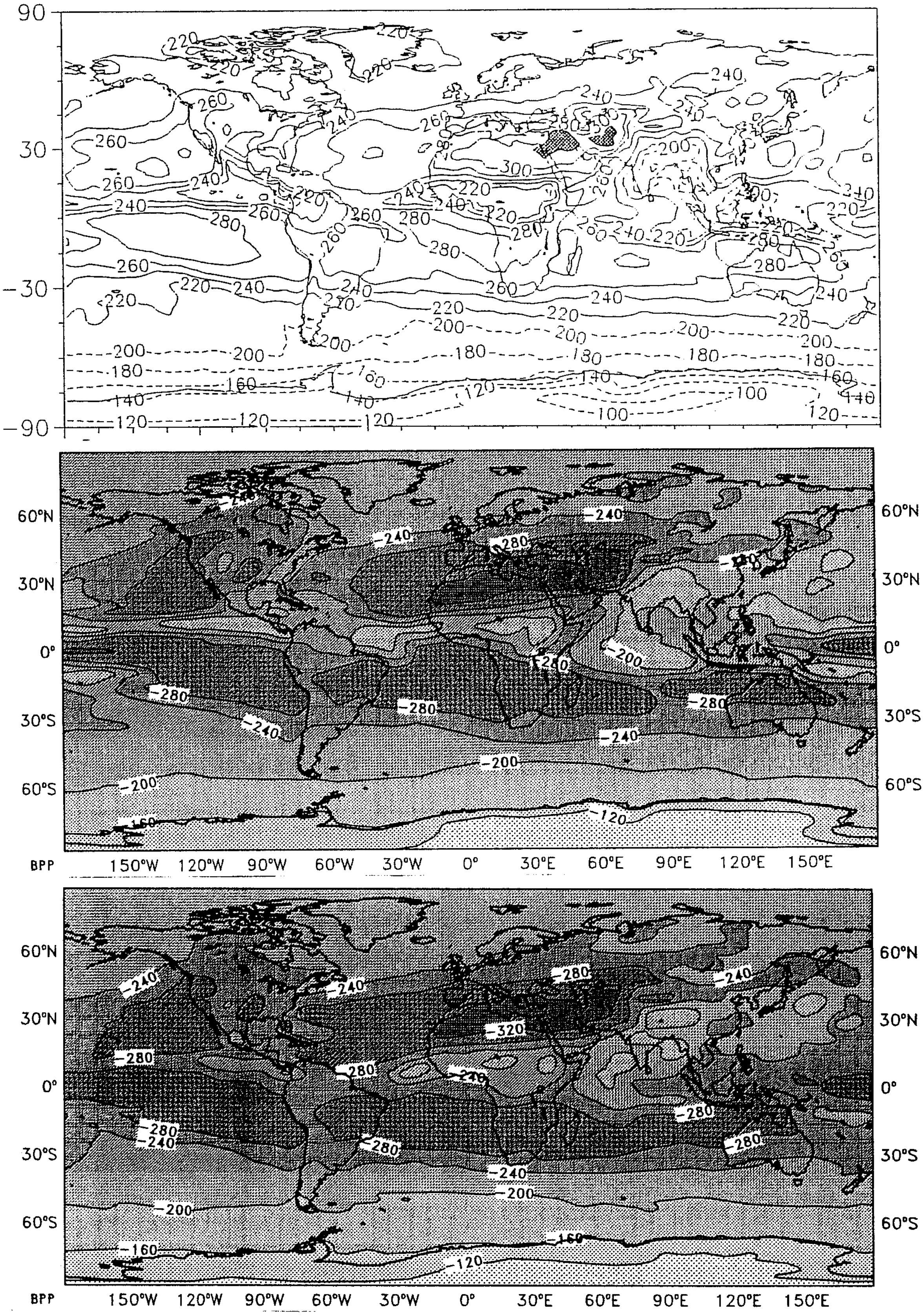

Figure 3.a: Mean thermal radiation at the top of the atmosphere from ERBE data for July 85 (top), from a perpetual July integration with the ECMWF model using a prognostic cloud scheme (middle), from a perpetual integration with the ECMWF model using the standard cloud algorithm (bottom).

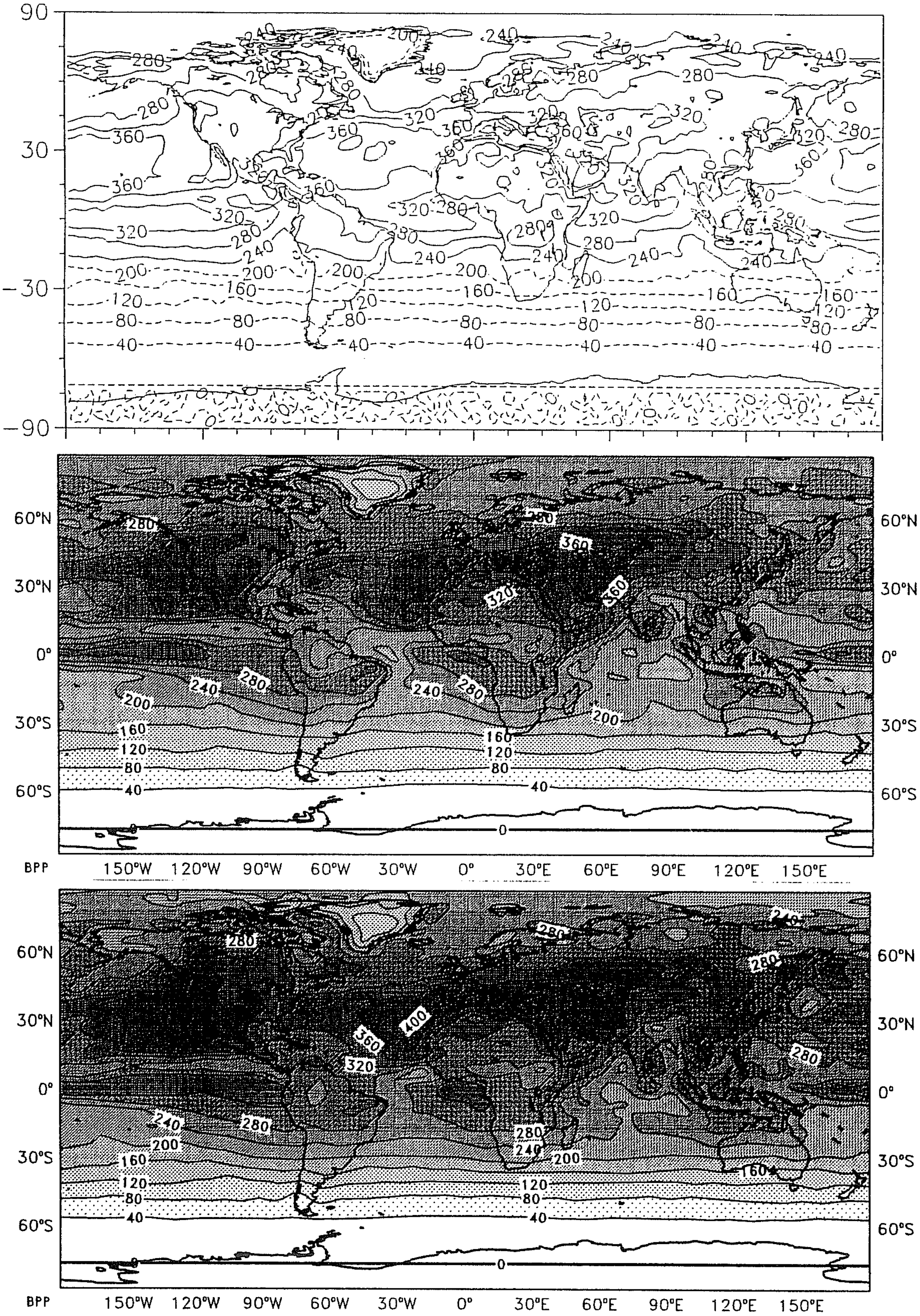

Figure 3.b: same as Figure 3.a but for solar radiation at the top of the atmosphere.

measured by ERBE (July 85) and simulated in a 30-day forecast by the ECMWF model using either the cloud prognostic scheme or the operational diagnostic scheme. The same fields are shown in Figure 4 in zonal means: it is hard to distinguish a better version of the model. We will show in the next section that, moreover, this success in simulating good radiative fields in the presence of clouds can very easily be the result of compensating errors.

4. Sensitivity of the results to various physical processes.

How accurate are the present models? The radiative impact of various model assumptions was diagnosed. A few of them are briefly reviewed here, to note the order of magnitude and the sign of the effect they can have on the simulated radiative fluxes.

4.a: Overlap of the cloud layers and interaction with radiation:

The results of Figure 2.a show that assuming a random overlap of the cloud layers, with this version of the cloud scheme, means a strong overestimation of the mean cloud cover. The total cloud cover is in that case a function of the number of layers in the model. Changing to a maximum overlap assumption means a diminution of the cloud greenhouse effect and a mean increase of the outgoing longwave radiation by about 30 Wm-2. The impact on the solar radiation is much less.

A similar sensitivity, this time for the shortwave flux, is obtained when the equivalent radius of the cloud droplets used in the radiation code is changed from 5 to 15 micons.

4.b: Representation of the subgrid scale motions.

They are very crudely represented in our model by the parameter Δq. When Δq is diminished the cloud cover tends to become 0 or 1 and the two defintions of the total cloud cover (due to random or maximum overlap) tend to converge towards a mean value. This means that the incertitude associated with the parameterization of this term is potentially as large as that described in 4.a. This also means that when Δq is decreased, for example, the sign of the radiative impact of this change will also depend on the assumption made for the cloud overlap (because the cloud cover will increase in one case and decrease in the other).

4.c: Cloud-turbulence interaction

This process was generally neglected in the experiments described here. It was introduced in some simulations in the following manner:

- when there is some cloudiness we define a moist Richardson number which serves to determine the mixing coefficient in the turbulent mixed layer rather than the usual dry Richarson number (in fact we use an average of the two weighted by the cloud fraction). This enhances the mixing in the presence of clouds.
- the cloud liquid water is mixed as temperature or water vapour (with no source or sink from the ground).

The two main cloud types which are affected by the introduction of this new mechanism are the low stratiform clouds and the cirrus clouds which are strongly reduced; this is illustrated

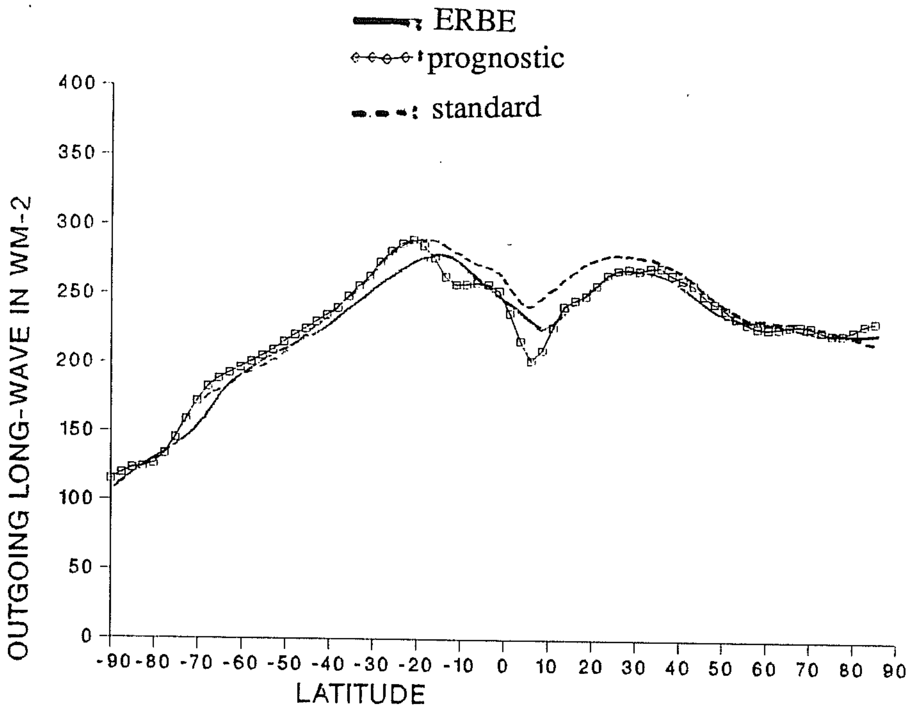

Figure 4.a: same as Figure 3.a but for zonal means

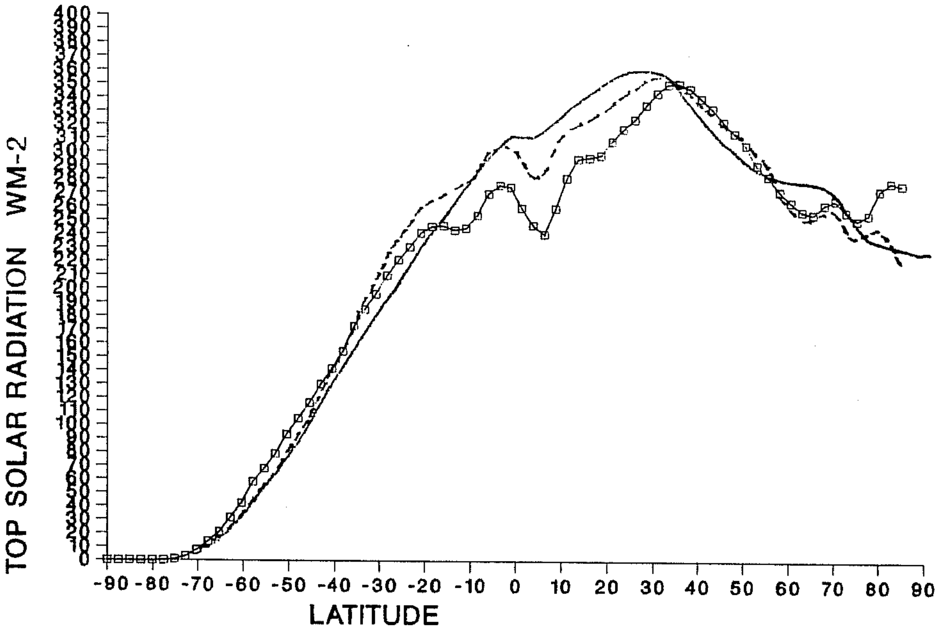

Figure 4.b: same as Figure 3.b but for zonal means

in Figure 5. The low clouds which are disrupted by the turbulence are generally unwanted and the introduction of this parameterization seems beneficial, although it also correponds to a crude treatment of complex processes.

4.d: Cloud liquid water precipitation mechanisms.

Although the order of magnitude of the basic parameters used to describe the precipiation mechanism are known, the detailed values are not. These processes determine the cloud thickness, and, hence, its optical thickness. The related incertitude on the fluxes at the top of the atmosphere has also the same order of magnitude (some 10 Wm-2). As mentionned earlier these processes were found to be very critical in the context of climate sensitivity.

5. Validation studies

It is clear from the above discusion that there remains a large number of uncertain processes in the treatment of the cloud/radiation interaction in the models. The present use of the satellite data is not compelling enough, and there remain too many degrees of freedom for the tuning of the models. In Section 3 we have shown that we did achieve to tune our cloud scheme in a way that allows a correct reproduction of the main cloud regimes and of the mean radiative fluxes at the top of the atmosphere: but there are still various manners to achieve that result. More diagnostics have to be extracted from the data to provide a stonger constraint on the cloud algorithms. We give here two results from the work done at LMD in that direction:

5.a: Study of the day to day variability :

The Figure 6 is taken from a sudy by Yu et al (1991). Both images represent the day-to-day variability of the radiance in the infrared window. In one case it is simulated by the model, using a simple algorithm, described in Li and LeTreut (1988) to obtain this radiance from the model results. In the other case it is obtained from the ISCCP analysis of the Meteosat measurements: they have been first averaged to the model resolution, and then the day-to-day variability was computed. We see that the model simulates quite well the observed structure of the variability, and if anything, underestimates slighltly the observed variability. This is certainly a good test of the prognostic aspect of the cloud scheme. This work is being pursued at LMD in collaboration with G. Seze and M. Desbois.

5.b: Study of the seasonal variability

As part of a collaboration of the LMD model group with R. Kandel and J.P Duvel, we have begun to use the ERBE data to evaluate the seasonal variability of the model by comparison with the observations. The Figure 7 (due to S. Bony) is an early result of this work: we have divided the fluxes at the top of the atmosphere in a term of forcing (the seasonal variations of the insolation) and a term of response (the variations of the net solar flux due to the change of the planetary albedo and the thermal radiation). This response term (in zonal mean) is plotted as a function of latitude and month for the LMD model results and the observed ERBE data . Again the model performs realistically, with the clear exception of subtropical

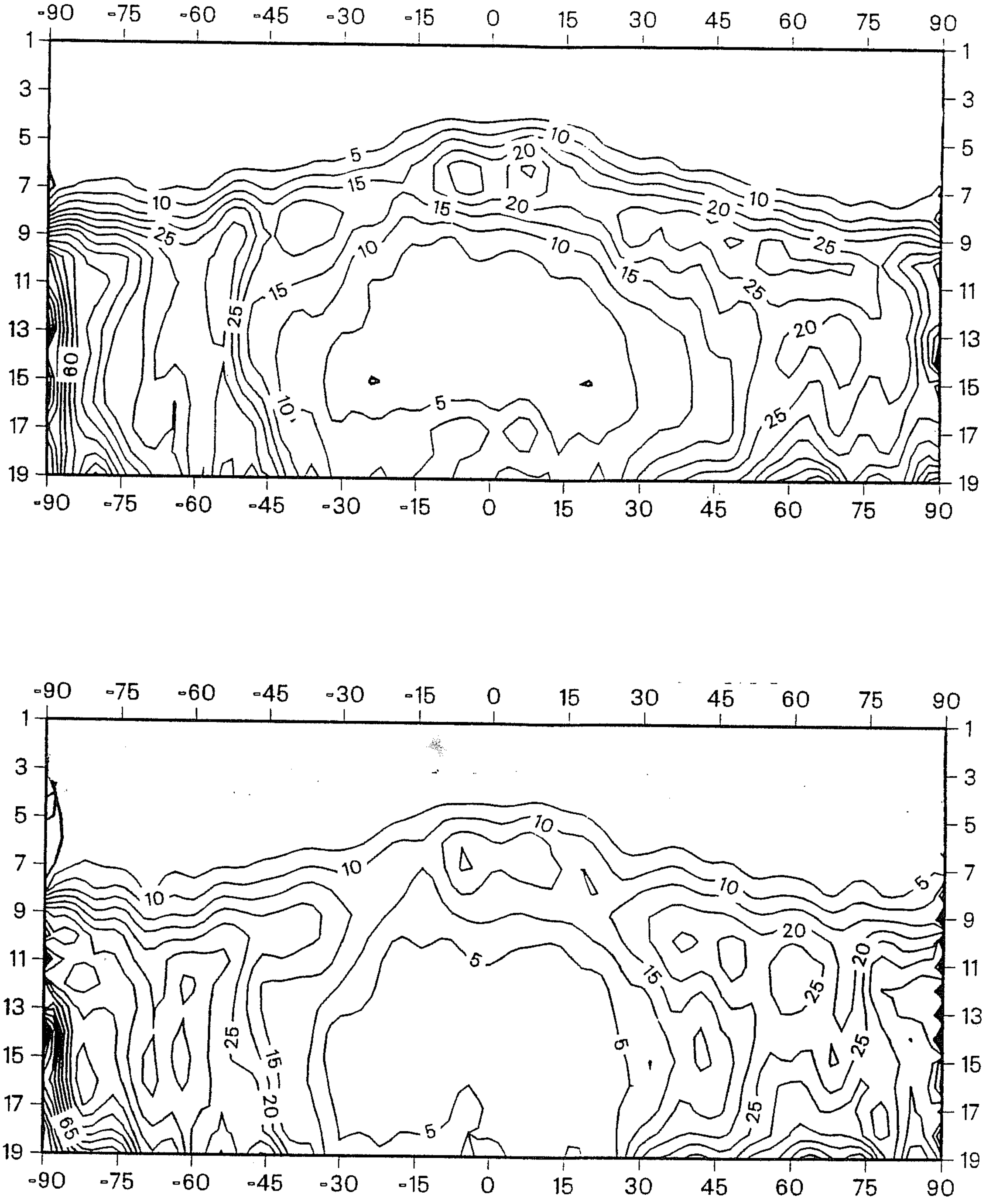

Figure 5: Mean zonal cloud cover for an April 10-day forecasy:

(top) model with the prognostic cloud scheme and no representation of the cloud/turbulence interaction

(bottom) model with the prognostic cloud scheme and a representation of the cloud/turbulence interaction.

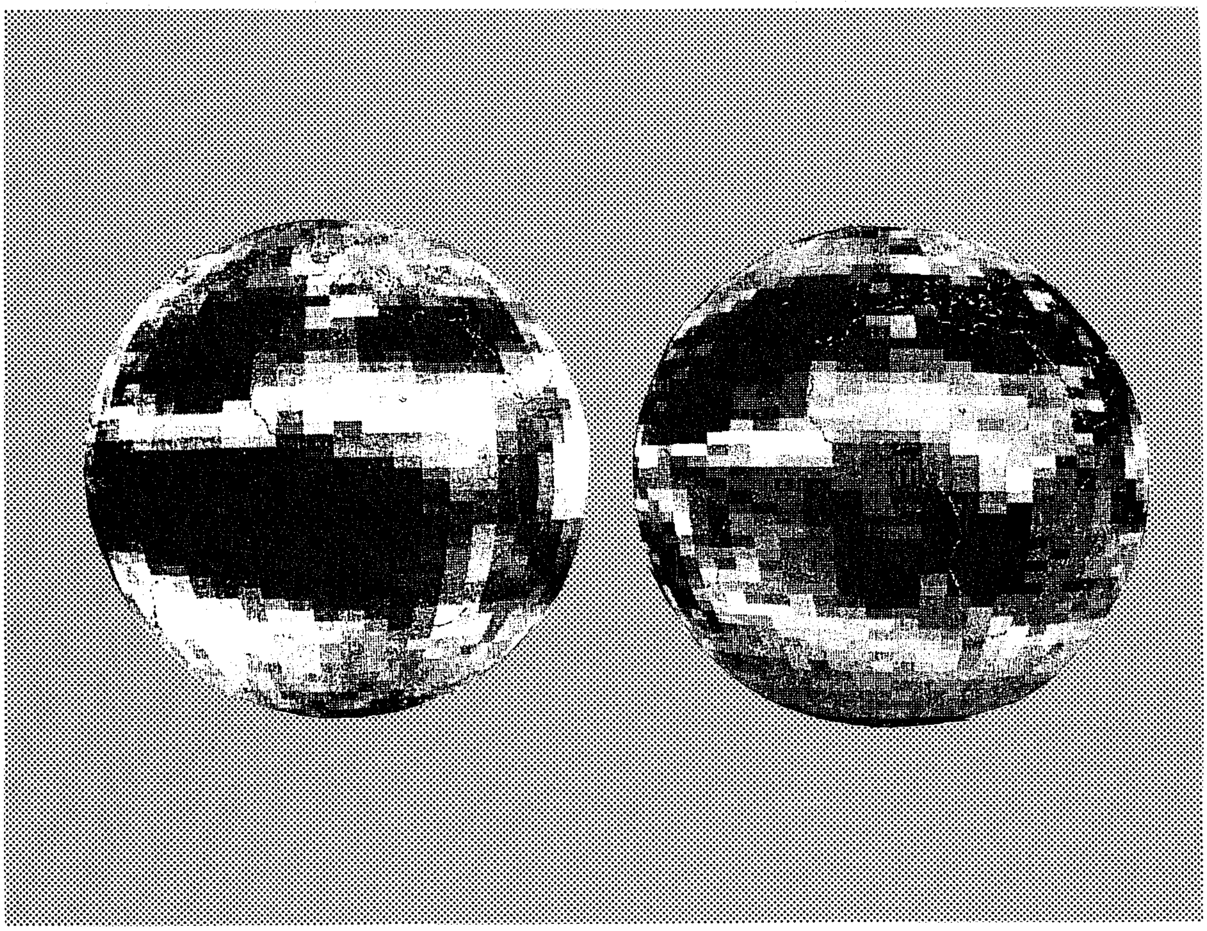

Figure 6: Observed and simulated day-to-day variability of the radiances in the infrared atmospheric window. Yu et al (1991)

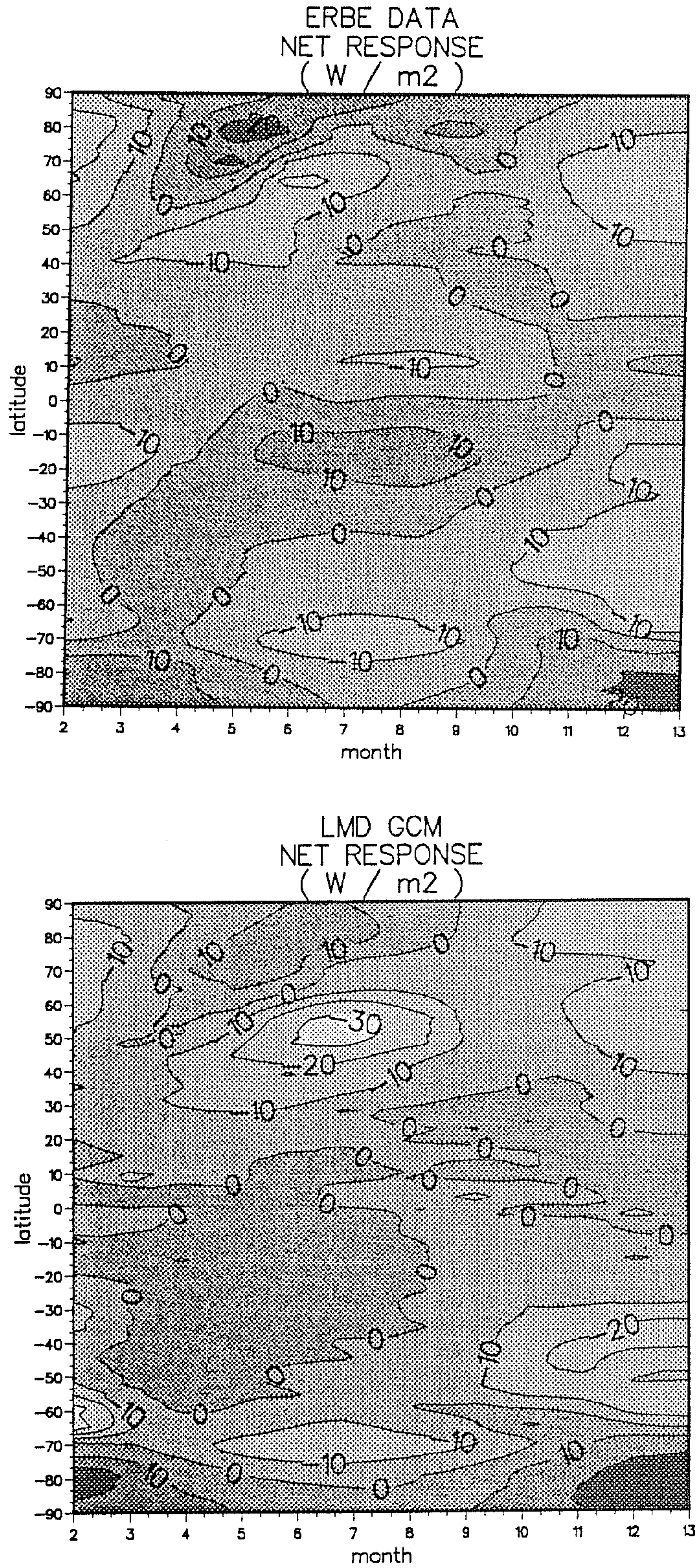

Figure 7: "Response term" (see text) of the radiative fluxes at the top of the atmosphere, from ERBE data and LMD GCM simulations. (due to S. Bony)

latitudes (which may be the result of the bad simulation of the stratocumulus regimes).`

5. Conclusions

The representation of the clouds in the general circulation models will certainly become less and less empirical in the years to come. One has to be cautious, however, that this will introduce a wide range of new physical processes which are presently known in a qualitative way only. The careful validation of these new cloud schemes will therefore be one of the most important aspects of the work to be done.

Acknowledgements:

Many of the experiments with the ECMWF model were done with the assistance of and in collaboration with Lodovica Illari, also with the help and advice of J.J. Morcette.

The GCM experiments and validation studies at LMD constitute a team work. I have tried to give in the text a proper credit to the work of the various involved persons, and special thanks are also due to Z.X. Li.

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