TECHNICAL MEMORANDUM

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First studies with a prognostic cloud generation scheme

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Abstract

A prognostic scheme has been designed to predict the cloud condensed water content for non convective clouds as a new state variable of the ECMWF model. This permits an evaluation of the cloud optical depth on a sounder physical basis than is presently done and also constitutes a useful framework for a consistent treatment of cloud/turbulence interaction. Some sensitivity experiments have been carried out, both with the 1-D version of the GCM and with the 3-D global model (in resolutions T21 and T106). The scheme gives a better latitudinal dependence of the cloud properties than the parametrization presently used, with thicker clouds at high latitudes. Stratus clouds appear in the Eastern part of the oceans (especially off the coast of Angola). A more detailed evaluation of the scheme is nevertheless needed, to assess the relative role of the analysis and the cloud scheme in determining the vertical structure of cloudiness, especially at the tropopause where we get in some cases a layer of thin clouds that seems too widespread.

1. INTRODUCTION

The simulation of cloud cover and cloud optical properties has become one of the most important issues in climate modeling and climate sensitivity experiments, because clouds are clearly one of the main components of the atmospheric system that can amplify or dampen the climate response of for example the current CO_2 increase (Schlesinger and Mitchell, 1987). The impact of cloud radiation interaction on the atmospheric general circulation at the timescale of medium range weather forecasting, although more difficult to assess, has also been demonstrated by a few studies (Geleyn, 1981; Slingo, 1987). Moreover, clouds are an important model output for the users.

Therefore, there is a clear need of improvement in the treatment of cloudiness within numerical weather prediction models, and since so much remains to be done it can only be a step by step process. In this note a brief description is made of a parametrization which can constitute a first step toward a more consistent treatment of cloudiness within models, i.e. the inclusion of a prognostic equation for cloud condensed water content. The first studies in this direction were made by Sundquist (1981). Similar approaches have subsequently been developed by Smith (1985) or Roeckner and Schlese (1985). The prediction of cloud condensed water permits the estimation of cloud optical depth using a simplified representation of cloud spectra. Also, predicting total cloud water, rather than the vapour phase only, is essential for the treatment of cloud/turbulence interaction in the boundary layer.

2. DESCRIPTION OF THE SCHEME

2a) General description

The scheme was originally developed for a climate model, in order to ensure the consistency between the various representations of clouds in the model, as was necessary for cloud-feedback climate sensitivity studies (Le Treut and Li, 1988). In principle, it may provide a framework for a consistent treatment of latent heat release, cloud/radiation interactions and cloud/turbulence interactions. The first objective in the context of ECMWF, however, is to predict a reasonable cloudiness input (cloud fraction + cloud optical thickness) to radiation codes.

Two kinds of assumptions have to be made: the first ones concern the representation of unresolved scales, and the second ones concern the cloud microphysics processes.

We first assume that, inside a given model grid-box, there exists some statistical equilibrium such that the fraction of the grid on which clouds occur may be diagnosed from large scale variables, such as:

q: specific humidity

q_l: condensed water specific content

($q_t = q + q_l$ will represent the total water specific content)

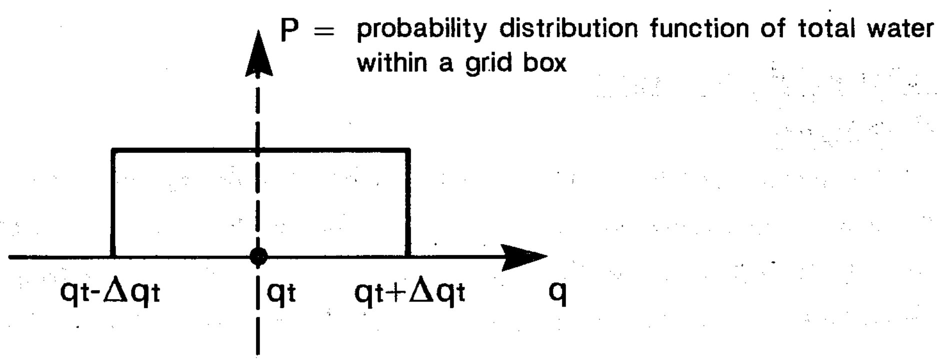
and some estimate of Δq_t (or σ_{qt}), i.e. the sub-grid variability of total water within the grid-box, which is itself assumed to depend on large scale parameters.

The description of these subgrid scale processes would best be achieved through a higher order closure model. As this is presently not available we must rely on a simple closure. We propose that:

$$\Delta q_t \sim \sigma_w \frac{\partial q}{\partial z} \Delta t$$

with $\sigma_w = \dfrac{a+b\ |\ w\ |}{\ell n(1.+\max(0,Ri)},$

where w is the grid-scale vertical velocity and Ri the grid-scale Richardson number (this formula is due to Heise, personal communication). The distribution of q_t is assumed to be a top-hat one, as stated below:



We assume that precipitation occurs following the law:

$$\frac{dq_l}{dt} = -\frac{\mathrm{Max}\,(q_l - q_o,\ 0)}{\tau}$$

where the threshold for precipitation q_o and the time-scale τ are tunable parameters.

Two sets of values have been chosen.

- for clouds with temperature < 260K:

$q_o \simeq 0$ $\tau \simeq$ more than 1 hour

- for clouds with temperature > 273.15 k

$q_o \simeq 0.1$ g/kg and $\tau \simeq$ ½ hour $\simeq$ model time step.

They correspond respectively to warm clouds which precipitate through coalescence of cloud droplets and to clouds which contain ice, at least in their top levels (Bergeron-process). Evaporation of rain in unsaturated subcloud layers is parametrized by means of Kessler's scheme, noting that precipitation occurs only on a fraction of the grid. The coefficient has been set constant (no dependency on pressure).

2b) Procedure for the calculation

The calculation at a given time step is done in three steps:

- re-evaporation of clouds from previous time step (no advection!)
- calculation of new cloud field and condensation rates
- precipitation of part of the condensed water.

The equations for these 3 steps are the following:

(1) Re-revaporation

Increments for T (temperature), q, and q_l are the following:

$$\delta_1 T = -\frac{L}{C_p} q_l$$

$$\delta_1 q = q_l$$

$$\delta_1 q_l = - q_l$$

(2) Condensation

We define q_s, saturation water vapour mixing ratio as q_s $(T + \delta_1 T)$ then the cloud fraction is the probability for $q > q_s$, so according to the assumptions:

$$f = \frac{q_t + \Delta q - q_s}{2\Delta q}$$

with $0 < f < 1$

The mean total water mixing ratio over the cloudy area is

$$q_{cloud} = \frac{q_t + \Delta q + q_s}{2} \qquad \text{if } 0 < f < 1$$

or $\quad q_{cloud} = q_t \qquad \text{if } f = 1$

then $\delta_2 \, q_l = f \dfrac{q_{cloud} - q_s}{1 + \dfrac{L}{C_p} \dfrac{\partial q_s}{\partial T}}$

$$\delta_2 \, q = - \, \delta_2 \, q_l$$

$$\delta_2 \, T = \frac{L}{C_p} \, \delta_2 \, q_l$$

(3) Conversion of cloud water into precipitation we assume that precipitation occurs following

$$\frac{dq_l}{dt} = - \frac{\mathrm{Max}((q_l - q_o), 0)}{\tau}$$

where q_o and τ are disposable parameters. The equation for precipitation is integrated for a time interval Δt, starting from $q_l + \delta_1 \, q_l + \delta_2 \, q_l$ ands its solution may be approximated by:

$$\delta_3 \, q_l = - \, \mathrm{Max} \, (q_l + \delta_1 \, q_l + \delta_2 \, q_l - q_o, 0) \, . \, \mathrm{Min} \, (\frac{\Delta t}{\tau}, 1)$$

We have also:

$$\delta_3 \, q = 0$$

$$\delta_3 \, T = 0$$

q and T being unaffected by the conversion of cloud into rain water.

As noted earlier q_0 and τ have fixed values above 273.15 K and below 260 K and a linear interpolation of q_0 and τ is made between 260 K and 273.15 K. A refinement would be to consider the temperature of cloud top to determine q_0 and τ.

All those processes have been included in a new version of the routine for non-convective precipitation, COND. This new routine is named CONDST.

2c) Remarks about the scheme

a) It is useful to state briefly the main differences with Sundquist (1981)'s parametrization.

- Sundquist assumes that relative humidity of the clear air is a model parameter. It gives a well defined threshold for the formation of cloudiness, which can be made a function of height and/or humidity. In the present model clear air relative humidity is predicted from the assumed statistical law. Sundquist also uses an integrated formula for precipitation, valid for any cloud: we use simpler precipitation laws, which can be differentiated depending on the type of cloud under consideration.

b) Stability of the scheme

In our scheme the cloud fraction is a function of the total water. Then condensation occurs and the total water content is changed. We can show analytically, under some assumptions, that this procedure converges. This is also apparent from 1-D simulations shown afterwards. Let us assume that there is no precipitation.

Starting from q, q_l, T, one defines a cloud fraction $f(q, q_l, T)$ and then updated values of

$$q', q_l', T'$$

The scheme is stable if it converges toward an equilibrium value

$$q_e, q_{le}, T_e$$

It can also be shown analytically, with the approximation $\frac{L}{C_p} \frac{\partial q_s}{\partial T} << 1$.

$q_{le} = \delta q + \Delta q + 2s\sqrt{\delta q\, \Delta q}$ with $\delta q = q_s - q$ and $s = -1$ or $+1$

therefore cloud fraction $f = 1 + s\sqrt{\frac{\delta q}{\Delta q}}$

which means $s = -1$.

It can also be shown that this solution is stable provided

$$q > q_s - \Delta q.$$

The scheme therefore should converge toward a solution where $q_s - \Delta q < q < q_s$. (But one should note that the proof is not mathematically perfect).

c) The prognostic nature of the equation

Sensitivity experiments have shown that the prognostic nature of the equation is essential to the maintenance of the cloud fields. These experiments have been carried out in the framework of the 1-D model, in the absence of any large-scale advection terms. The cloud is maintained by radiation, vertical diffusion and surface evaporation. After a few days an "equilibrium" is reached (see Section 2b), which means that the same characteristic temporal behaviour is maintained throughout time. If all cloud water is suddenly precipitated there is a complete destruction of this equilibrium, the cloud amount being drastically reduced, or disappearing completely. This examplifies the role of the prognostic nature of the equation, which is almost impossible to evidence in 3-D simulations due to the large-scale water vapour advection.

3. COUPLING WITH OTHER PHYSICAL PARAMETRIZATIONS

a) Coupling with radiation

Its treatment is quite straightforward since the radiation schemes used at ECMWF need as input the cloud fractional cover and the cloud liquid water content. This is true both for the operational scheme (up to May 1989) and the new scheme developed by J-J Morcrette.

b) Coupling with diffusion scheme

In the presence of clouds the test of buoyancy which is made in the parametrization of the diffusion (in the computation of the Richardson number) should be made assuming that the air parcels follow a moist adiabat, rather than a dry adiabat.

In the version of the model I have used the computation of the Richardson number between two layers k and k+1 is done in the following way:

$$T_{\text{virtual up}} = \left(T_k + \frac{d(gz)}{2\, C_{pd}} \frac{1}{1+\delta_2 q_k} \right) (1+\delta_1 q_l)$$

and

$$T_{\text{virtual low}} = \left(T_{k+1} - \frac{d(gz)}{2\, C_{pd}} \frac{1}{1+\delta_2 q_{k+1}} \right) (1+\delta_1 q_{k+1})$$

with $\frac{d(gz)}{2\, C_{pd}}$ = semi-difference in geopotential between the 2 levels.

In totally cloudy conditions $\frac{d(gz)}{2\, C_{pd}\ (1+\delta_2 q_k)}$ should be replaced by the corresponding moist adiabatic slope

$$\frac{d(gz)}{2\, C_{pd}\ (1+\delta_2 q_k)} \frac{1}{\left(1 + \frac{L}{C_{pd}(1+\delta_2 q_k)} \left(\frac{\partial q_s}{\partial T}\right)_{T_k}\right)}$$

and one may also replace $(1+\delta_1\ q_k)$ by $(1+\delta_1\ q_k - q_l)$ to include the liquid water loading.

When conditions are partly cloudy we use the formula:

$$\frac{d(gz)}{2\, C_{pd}\ (1+\delta_2 q_k)} \frac{1}{\left(1 + \frac{f_k}{C_{pd}(1+\partial_2 q_k)} \left(\frac{\partial q_s}{\partial T}\right)_{T_k}\right)}$$

with f_k the cloud fraction).

When this scheme is used, the shallow convection scheme is skipped. Note that the proper simulation of these effects should also include the fact that total water and liquid water potential temperature are now the variables that should be mixed within the turbulent layer.

c) Coupling with convection

Convective sources of liquid water are presently lacking in the scheme. Specifying them means some coupling between the convective and non-convective cloud and precipitation schemes. No specific work on that issue has been done yet at ECMWF.

4. MAIN RESULTS

4.1 Experiments with the 1-D version of the model

These experiments were done to explore the model sensitivity.

In Fig. 1 we show some examples of the typical behaviour that was obtained. All simulations start from the analysis of the 23 May 1988, at 52N and 5E (which is approximately Amsterdam). The 1-D model is integrated without any forcing from large-scale advection.

In Fig. 1a the model is integrated with the cloud water prognostic equation, without any coupling with radiation or turbulence. There appears a cirrus cloud, and, after a while, a stratus cloud. The smooth time behaviour is the indication that the scheme is stable, as already mentioned. A first sensitivity experiment (not shown here) was to suppress the prognostic character of the cloud equation: cloudiness then disappears very quickly, because condensed water is automatically precipitated as rain. To have a prognostic equation for liquid or total water is therefore essential for clouds which have a local development as in this case.

In Fig. 1b and 1c, clouds were made to interact respectively with the operational and the LOA radiation schemes (developed by J-J Morcrette). We can see that this leads to a thickening of the cloudiness. In Fig. 1d, we have added the interaction with the new radiation scheme and turbulence: after some time, increased turbulence is able to disrupt the cloud deck. These behaviours are in accordance with "a priori" ideas on the mechanisms which control cloud formation or dissipation.

4.2 Experiments at T21-16 levels resolution (starting on 1 July 1983)

A number of 10-day forecasts starting on 1 July 1983 were made as a first 3-D test of the cloud model.

The main problems encountered came from the spectral truncature of the humidity field. Zonal means of the occurrence of negative humidities were computed on the initial and subsequent states: in such areas as high altitudes or latitudes it could reach as much as 30 or 40%. Therefore the subroutine that ensures the positivity of q was called before condensation occurs.

The mean zonal values of cloudiness are found in Fig. 2a and Fig. 2b for two experiments:

- In INT (name in the archive), the cloud prognostic equation was used alone, without coupling with radiation.

- In IRZ (name in the archive), clouds interact with the old (operational) radiation scheme.

An equilibrium for mean zonal cloudiness is reached after a few days. In the case of interaction with radiation there is a marked increase of low cloudiness, as was to be expected from the 1-D simulations shown earlier.

The mean zonal values of cloud liquid water content is shown in Fig. 2c and Fig. 2d respectively for the INT and IRZ experiments. One should note that clouds appear in the tropical regions at the beginning of the experiment and then tend to disappear: this corresponds to a feeding of non-convective cloudiness by convection and advection of water vapour, which is probably not sustained throughout the integration.

4.3 Experiments at T21 - 19 levels resolution (starting on 15 January 1987)

In these experiments diagnostic tools developed by J-J Morcrette were used to make a first evaluation of the cloud scheme over the Meteosat area.

In Figs. 3a, b, c, d, e and f the distribution of cloudiness and cloud liquid water content after 24 h are given at three levels (low, middle and high) for both the operational scheme (plots labeled OP1) and the present scheme (plots labeled HL1). Cloud water contents are summed over the model levels, cloudiness is determined assuming random distribution within each layer (for consistency with radiation). In experiment HL1, generated clouds interact with the new radiation scheme developped by J-J Morcrette, but not with turbulence.

The main remarks to be done are the following:

- the prognostic scheme produces more low cloudiness in high altitudes, with a higher liquid-water content. These two features are more realistic than with the operational scheme. At the same time there appears some stratus clouds which are not present in the operational scheme (see Fig. 4).

- the middle cloudiness is very much the same as in the operational scheme, except in the Tropics where we do not have the convective clouds because they were not included in the scheme at this stage. Again at high latitudes clouds have larger water contents, because water content is not a function of temperature only, as in the operational model.

- there is too much - and above all too little organized - high cloudiness occurring in this series of experiments. But these clouds carry little water and the cloud liquid water pattern is organized in a physically reasonable manner. The distribution of the zonal mean cloudiness show clearly where this high cloudiness appears (Fig. 5). Results for the infrared brightness temperature (Fig. 6) also show that these high clouds have no effect on radiation due to their small water content.

A comparison of low cloud amounts from experiments HL1, where clouds interact with radiation, with low cloud amounts from experiment HL2, where clouds do not interact with radiation and with low clouds from experiment HL6, where clouds interact with both radiation and turbulence, show that clouds maintained by large-scale advection of water vapour do not depend too critically on the coupling with radiation or turbulence. This is no longer true for clouds that have a more local development, as stratus clouds (Figs. 7 and 8), or, in the present case, high clouds. Other sensitivity experiments not reported here show that the precise formulation for Δq matters for the same type of clouds essentially. It was also shown that - consistently with sensitivity experiments made with the LMD GCM - the values of q_0 and τ have more effects on the cloud liquid water content than on the cloud fraction.

4.4 T106 experiments

Three 3-days T106 experiments were done, starting from the 15 April 1985 (first ERBE data set).

They are the following (using the name in the archive):

ISZ: no interaction with radiation or turbulence
IVS: interaction with radiation (new scheme)
IW8: interaction with radiation and turbulence

Only preliminary results are mentioned here. Zonal means after 24 hours are shown in Figs. 9 and 10. One of the main features to be noted is that there is no spurious high cloudiness as in the previous T21 experiments. Also there is no cloudiness in convective areas. Finally, it must be mentioned that negative values are produced by the post-processing, not by the cloud routine.

Examination of the cloud fields (not shown here) show that they are well organized throughout the integration, but the post-processing or the spectral truncature of the humidity fields generate some noise.

Interaction with radiation tends to increase low cloudiness in sub-tropical regions, as already noted in T21 experiments. Interaction with turbulence, by enhancing vertical diffusion of moisture tends to increase the high cloudiness, which has a distribution very reminiscent of the second series of T21 experiments analyzed in this note.

5. CONCLUSIONS

The prognostic cloud scheme presented in this note presents some advantages over the operational one, as far as can be judged from the few experiments presented here:

- better estimation of the cloud optical properties, especially at high latitudes.

- better performance for polar or subtropical stratus clouds

It is therefore very possible that introducing it in the forecast model in its present state would improve some aspects of the forecast. But more research is needed to assess the performance of this scheme in various situations, and to develop aspects of its interaction with the physics that have been neglected. The recommended steps could be the following:

- tune the optical properties of mid-latitude clouds by comparison with ERBE data, by varying q_0 and τ.

- couple the scheme with a scheme for convective cloudiness.

- evaluate the impact on stratus development when coupling with radiation and turbulence is included, for various values of q_0 and various parametrizations of Δq, as well as various parametrizations of the vertical mixing processes.

Acknowledgements

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APPENDIX A

Time filtering

The time filtering of the cloud liquid water content is the same as the time filtering of the water vapour content.

As CONDST (the programme that replaces COND) is presently the only programme that modifies the cloud liquid water content, it was possible to introduce only two 3-D fields:

QLIM1 ⟷ equivalent of QM1 but for condensed water
QL1 ⟷ equivalent of Q but for condensed water

It was not necessary to introduce QLIF (⟷ QF) or QLIME (⟷ QME)

All the changes are done in subroutine TF1.

The filtering operates in the following way:

time = t_o

	Time t_o		COND		Time t_o		Variables changed		Filtering
QLIM1 :	$\overset{\approx}{q}_l(t_o-1)$	→	$q_l(t_o+1)$	→	$q_l(t'_o)$	→	$\tilde{q}_l(t'_o-1)$	→	$\overset{\approx}{q}_l(t'_o-1)$
QL1 :	$\tilde{q}_l(t_o)$	→	$\tilde{q}_l(t_o)$	→	$\tilde{q}_l(t'_o-1)$	→	$q_l(t'_o)$	→	$\tilde{q}_l(t'_o)$

with $\overset{\approx}{q}_l$ = filtered variable

$\tilde{q}_l$ = semi-filtered variable

Filtering the cloud water in accordance with what is done for water vapour is more consistent physically, but it prevents it to being exactly equal to 0.

APPENDIX B

Codes

Three updates on .PAR.PUBLIC. contains the update modifications necessary to use this new cloud model (valid on cycle 30).

UP1 contains the update modifications to run with no interaction with radiation.

UP2 contains the update modifications to run with interaction with new radiation.

UP3 contains the update modifications to run with interaction with new radiation and turbulence.

In all cases COND, the subroutine for large-scale condensation is replaced by a new routine CONDST.

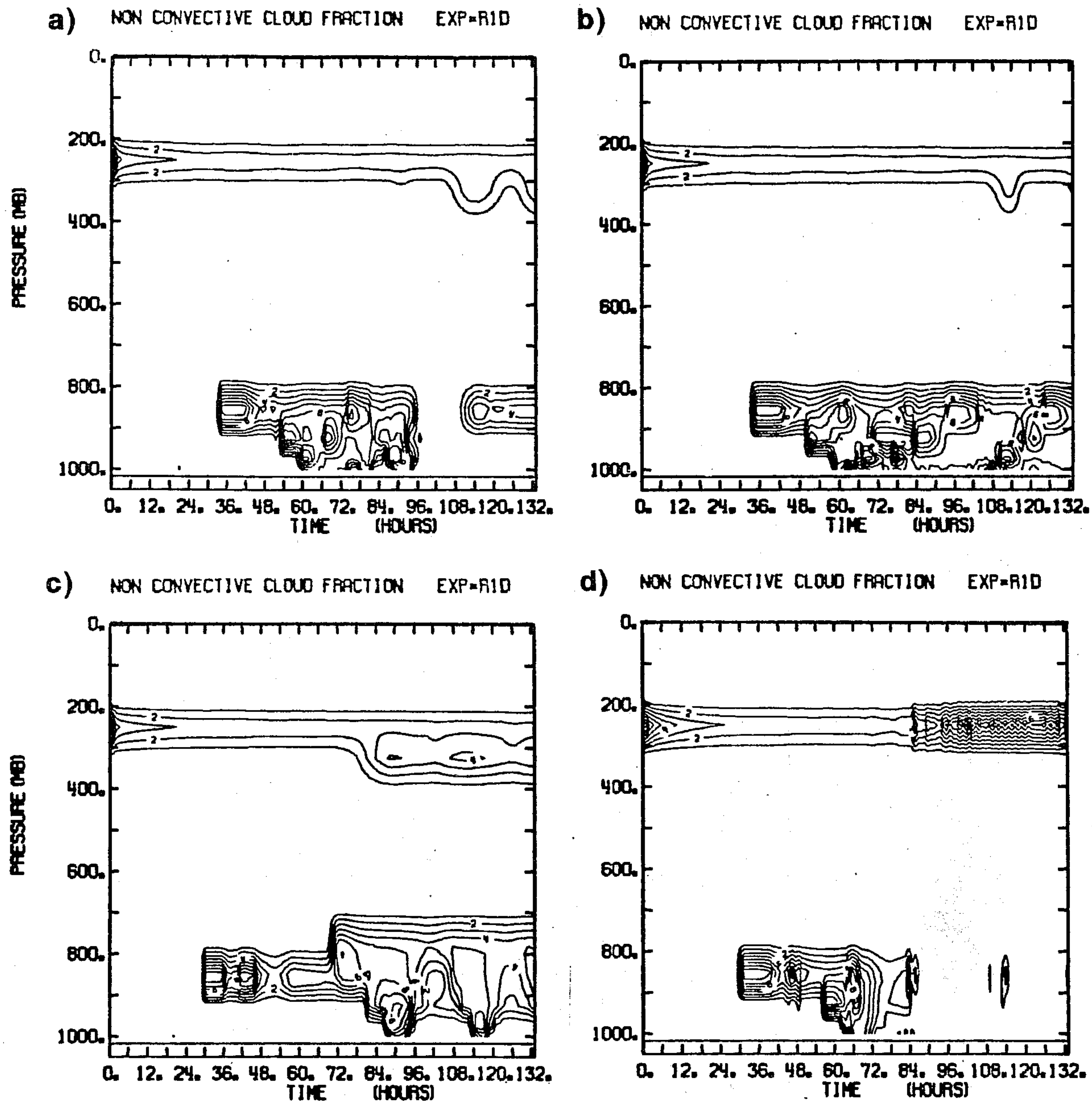


Fig. 1 1-D integrations of the cloud prognostic equation.

(a) No interaction
(b) Interaction with old radiation scheme (operational radiation scheme)
(c) Interaction with new radiation scheme (LOA scheme)
(d) Interaction with new radiation and turbulence (SCV yanked)

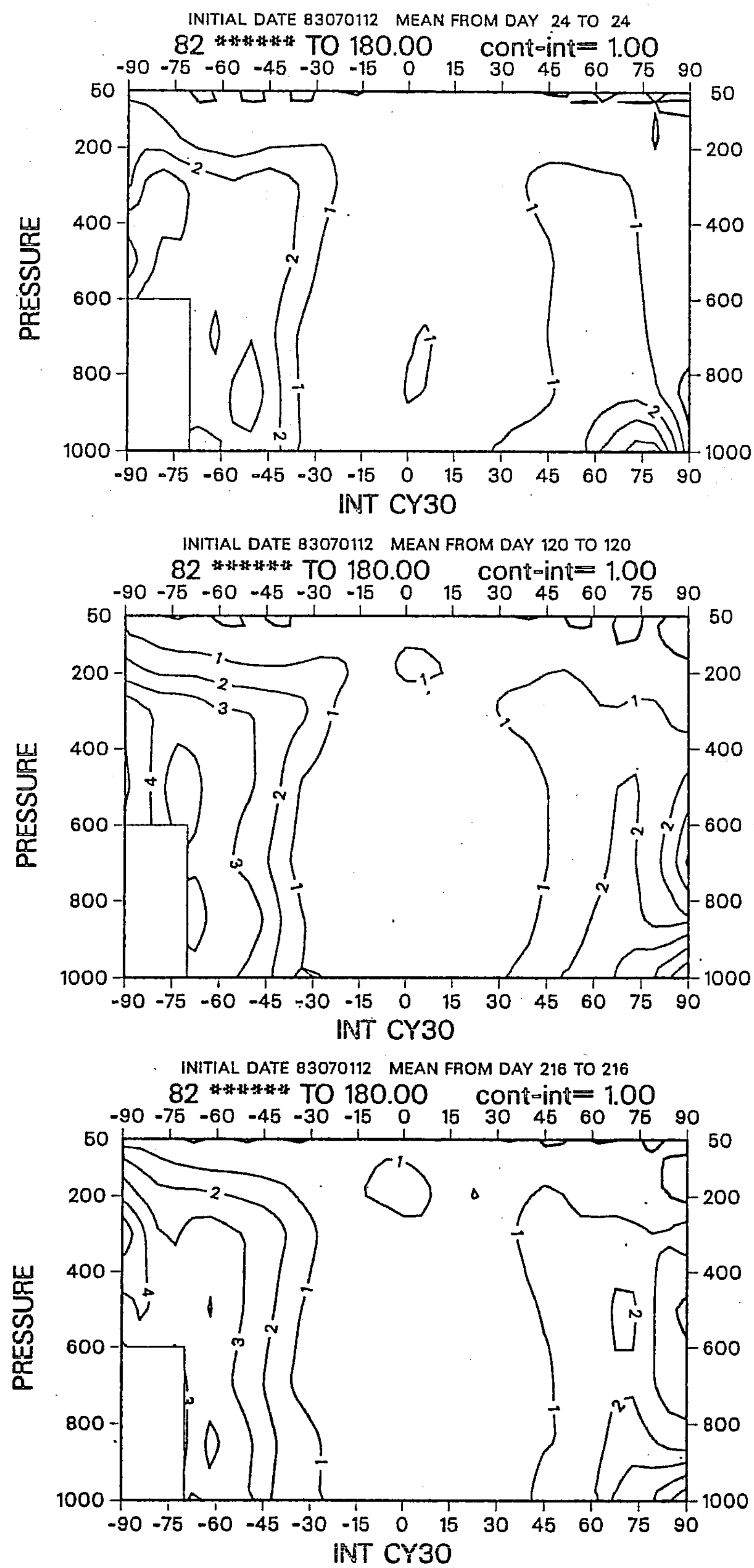


Fig. 2(a) Zonal mean cloudiness for experiment INT after 1, 5 and 9 days.

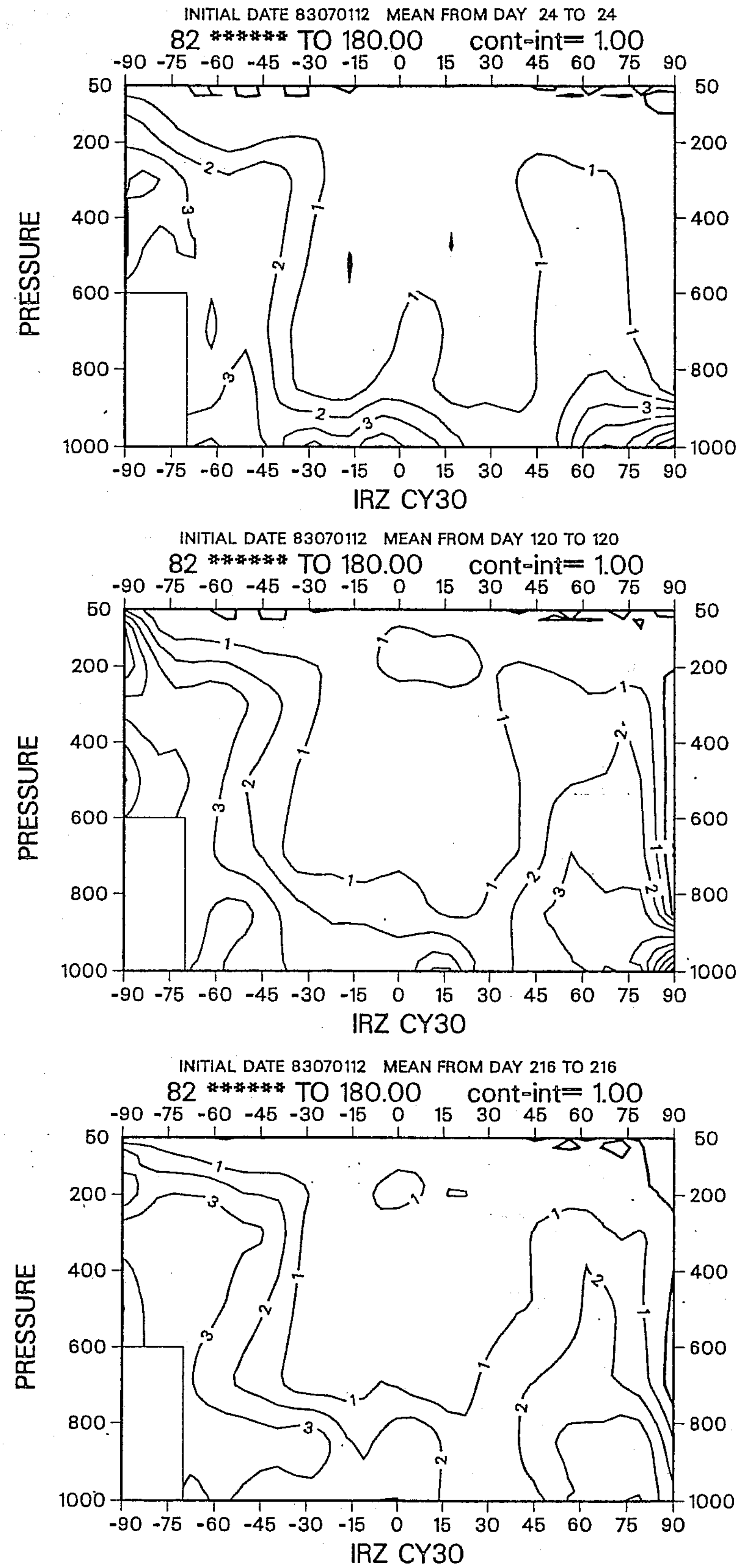


Fig. 2(b) Zonal mean cloudiness for experiment IRZ after 1, 5 and 9 days.

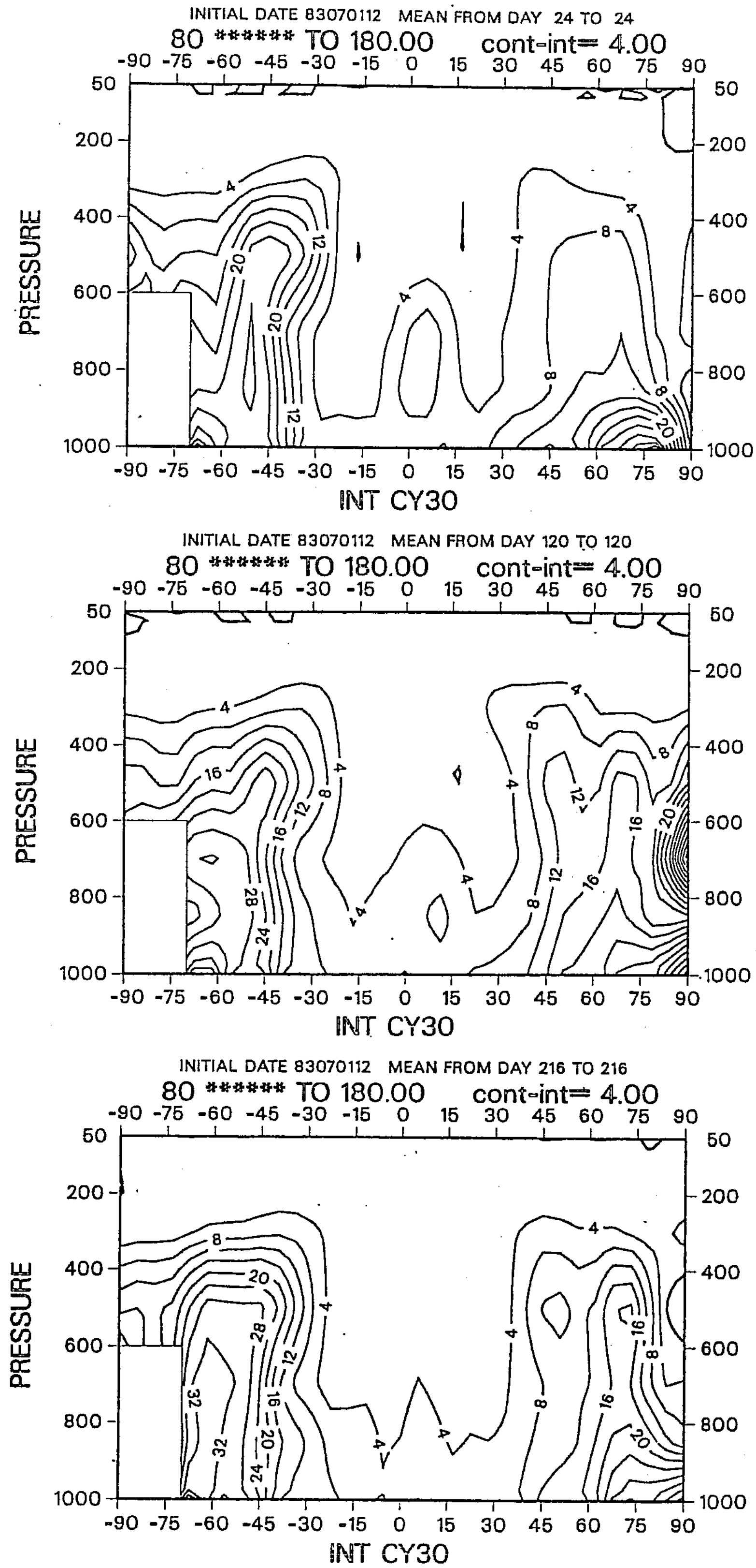


Fig. 2(c) Mean zonal cloud liquid content for experiment INT after 1, 5 and 9 days.

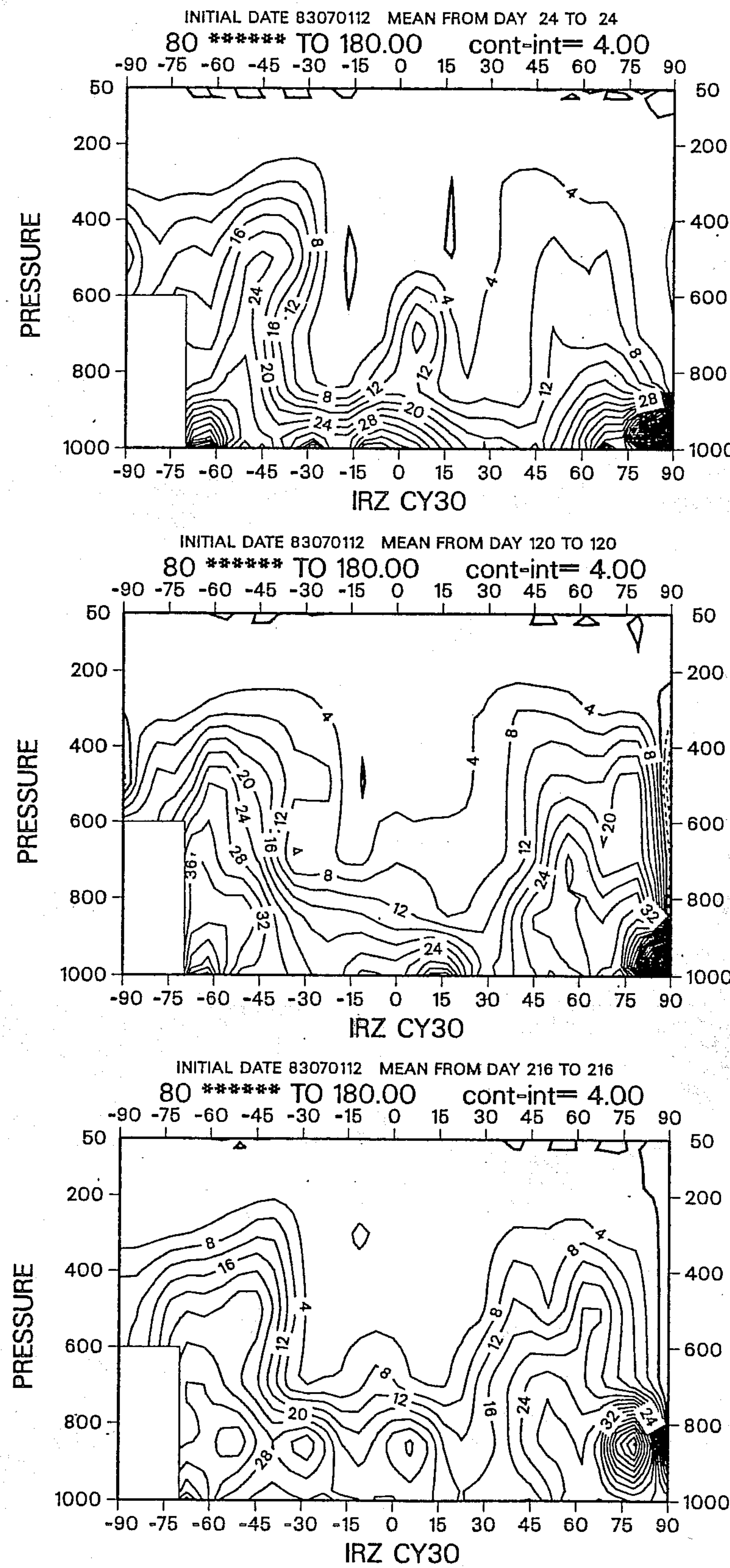
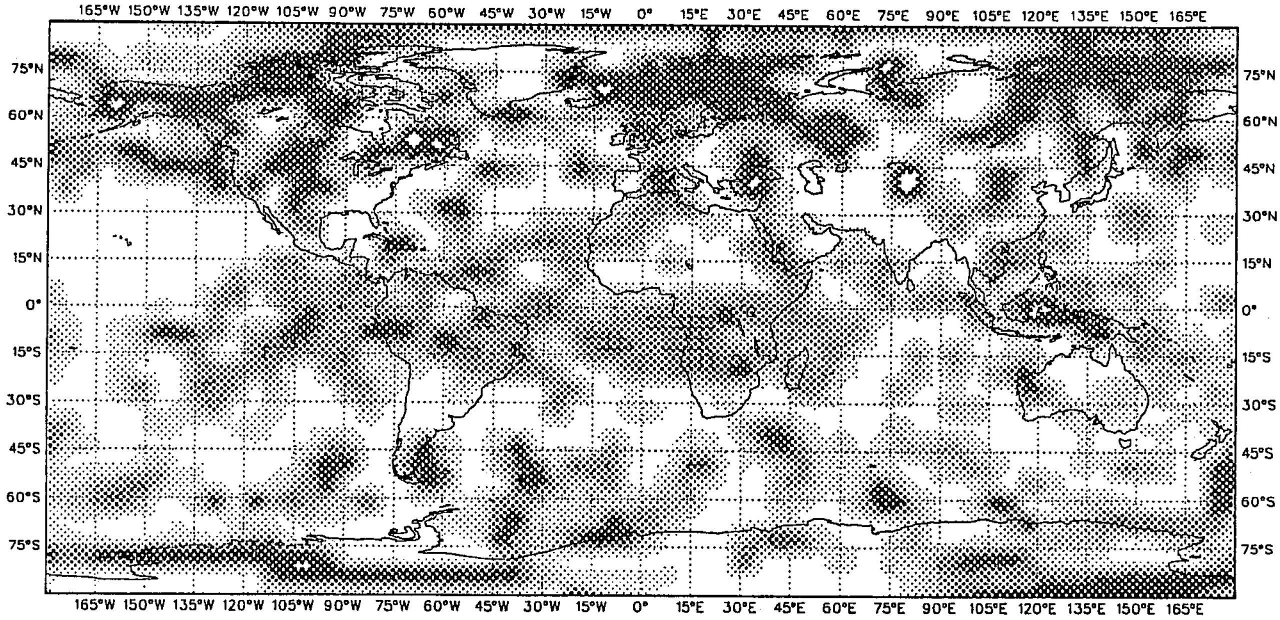


Fig. 2(d) Mean zonal cloud liquid water content for experiment IRZ after 1, 5 and 9 days.

Low level cloudiness
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



Low level cloudiness
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

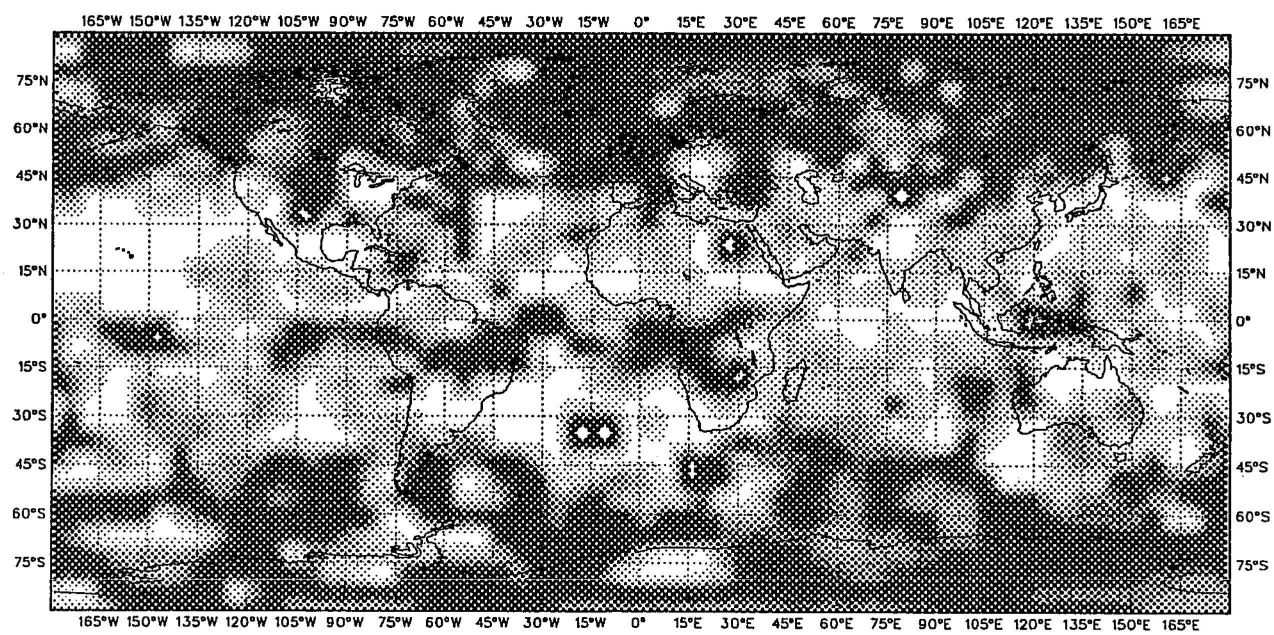
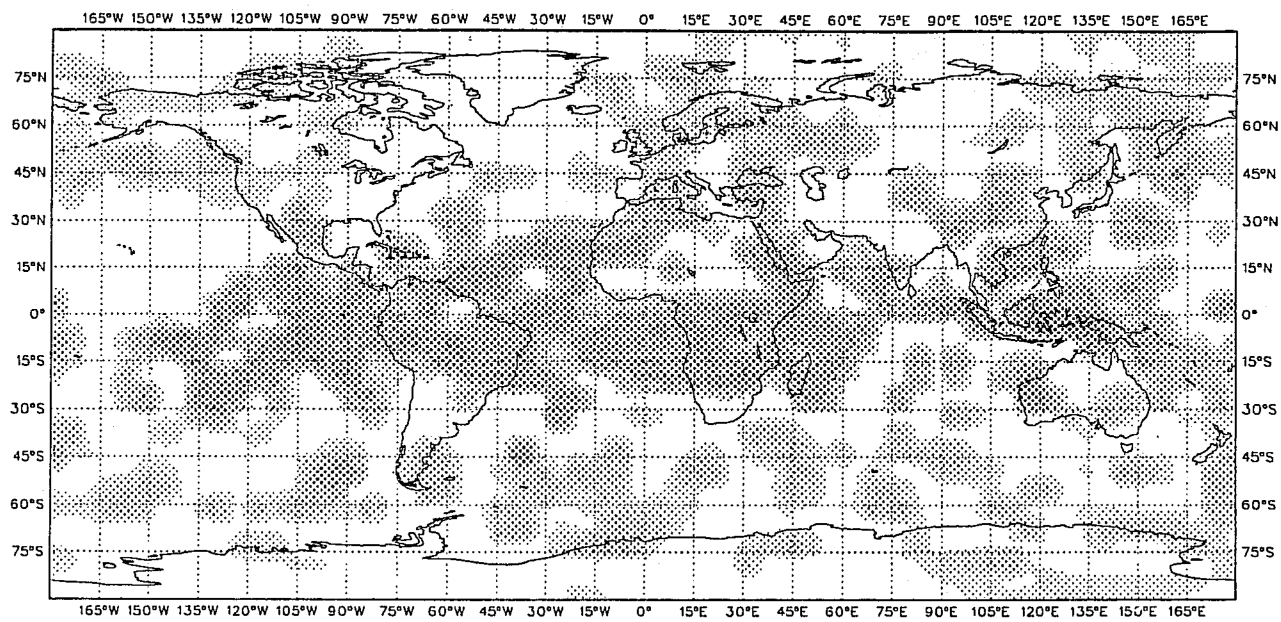


Fig. 3(a) Low cloudiness for a T21 experiment starting on 15/01/81, after 24 hours OP1=operational model, HL1=present scheme. In both cases cloud interact with radiation.

Liquid water (kg/m2 x 1.e+3) low clouds
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



Liquid water (kg/m2 x 1.e+3) low clouds
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

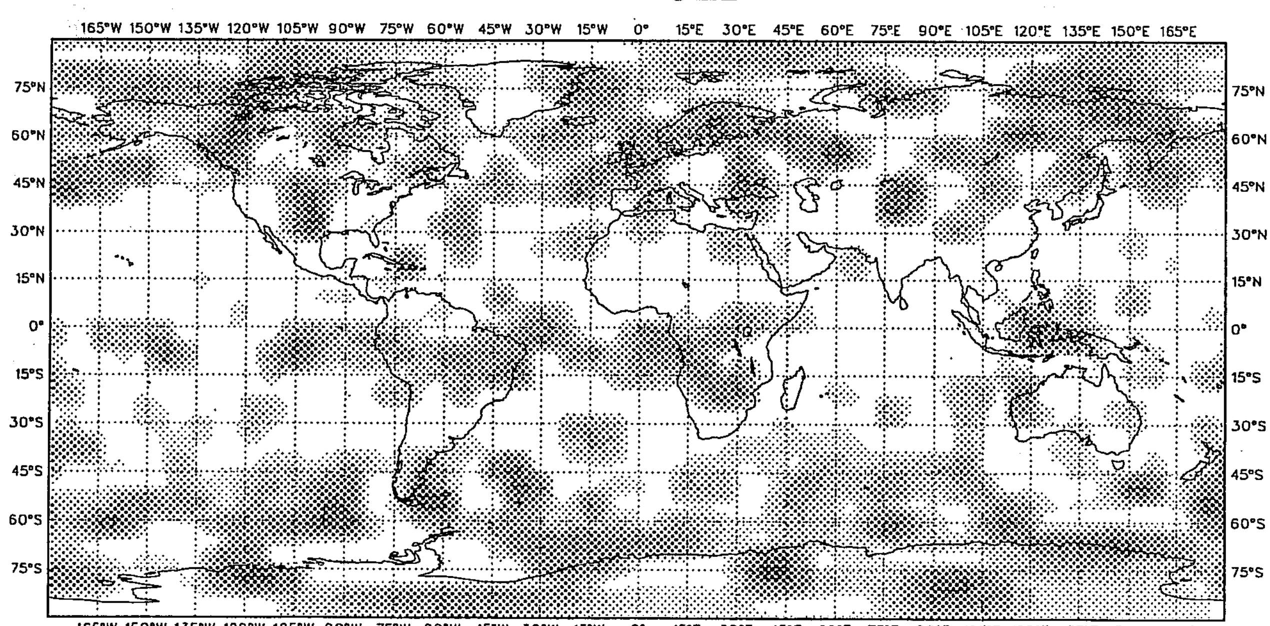
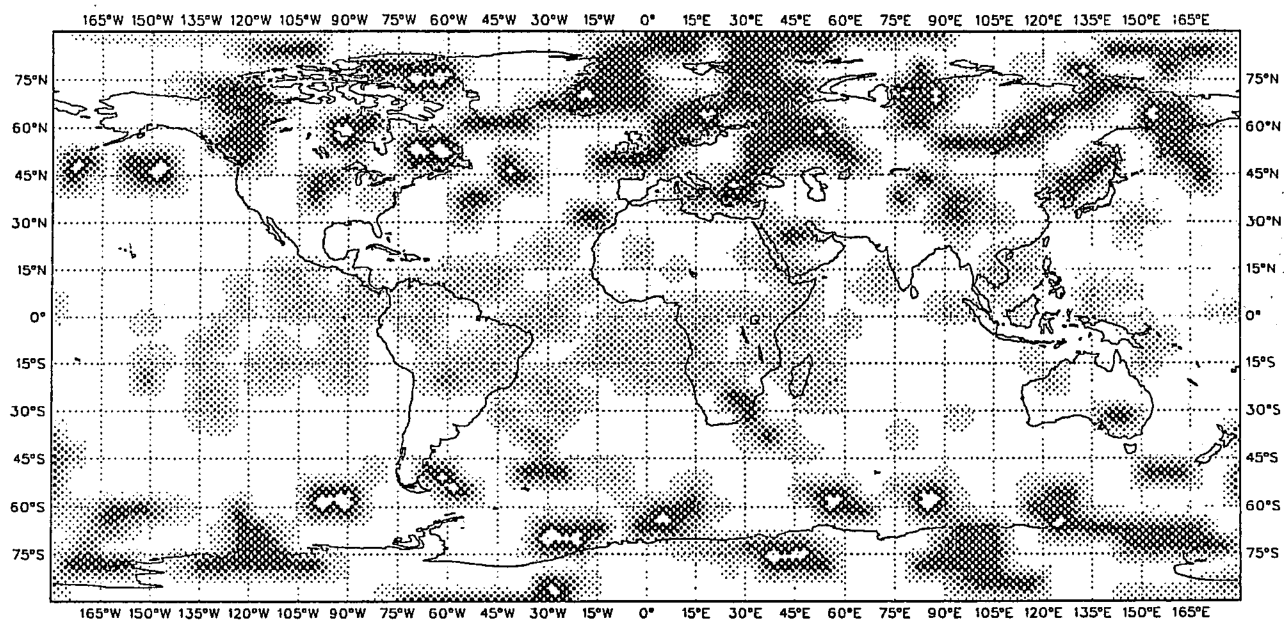


Fig. 3(b) Same as Fig. 3(a) but for low liquid water contents.

Medium level cloudiness
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



Medium level cloudiness
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

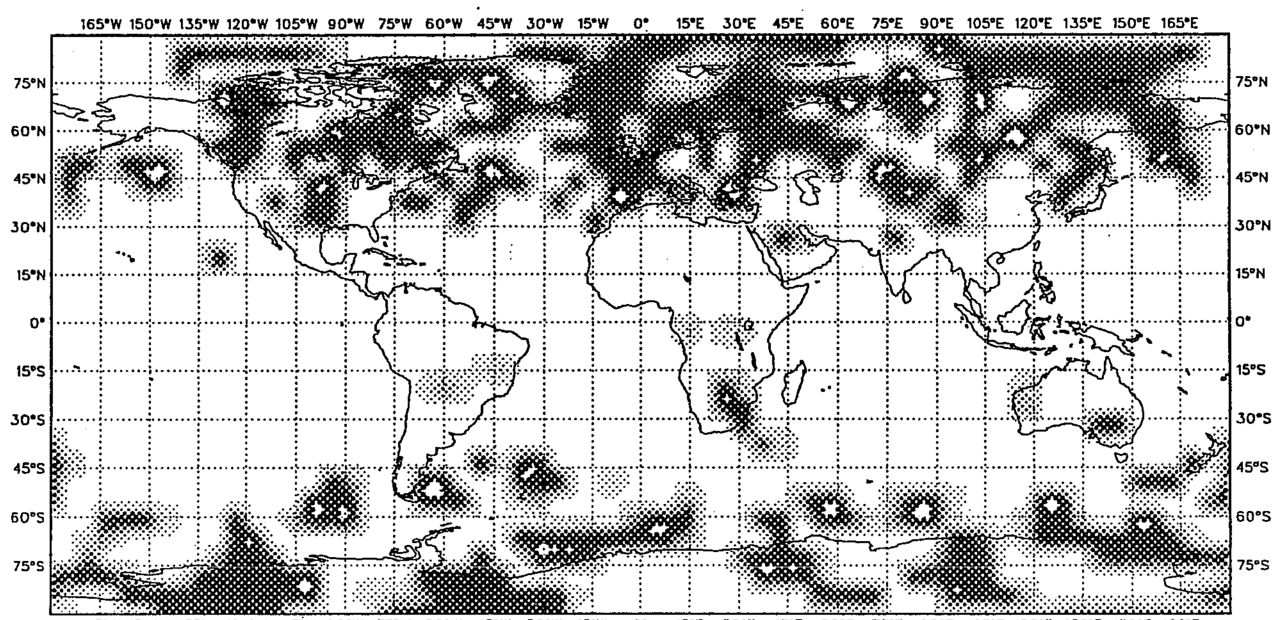
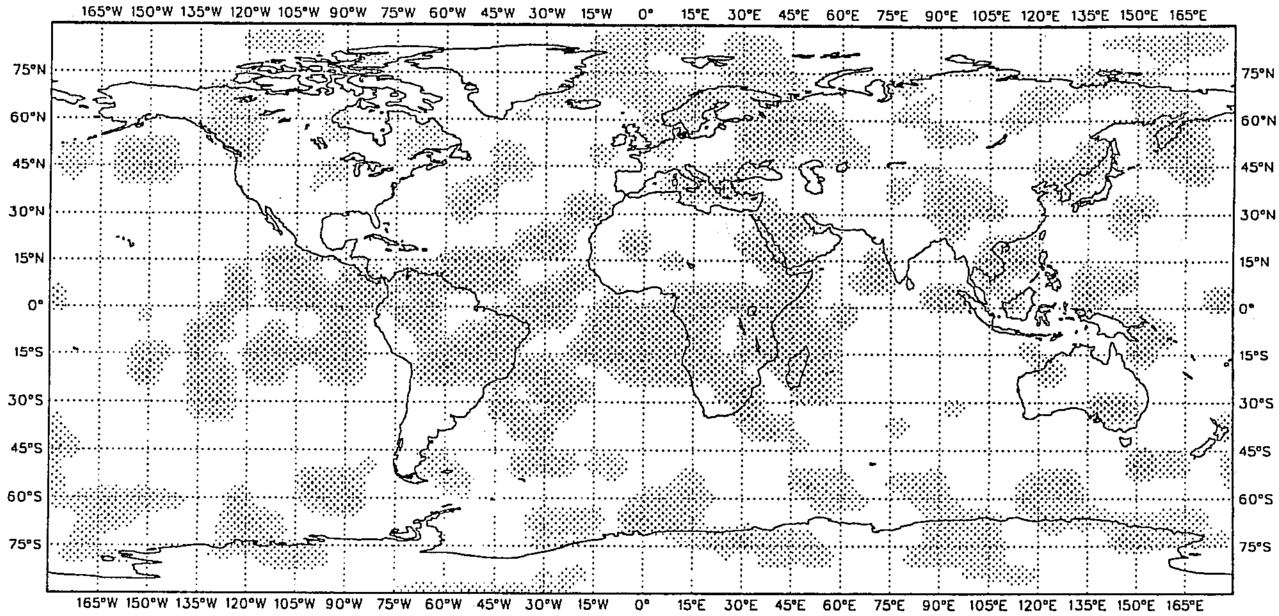


Fig. 3(c) Same as Fig. 3(a) but for middle level cloudiness.

Liquid water (kg/m2 x 1.e+3) Medium clouds
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



Liquid water (kg/m2 x 1.e+3) Medium clouds
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

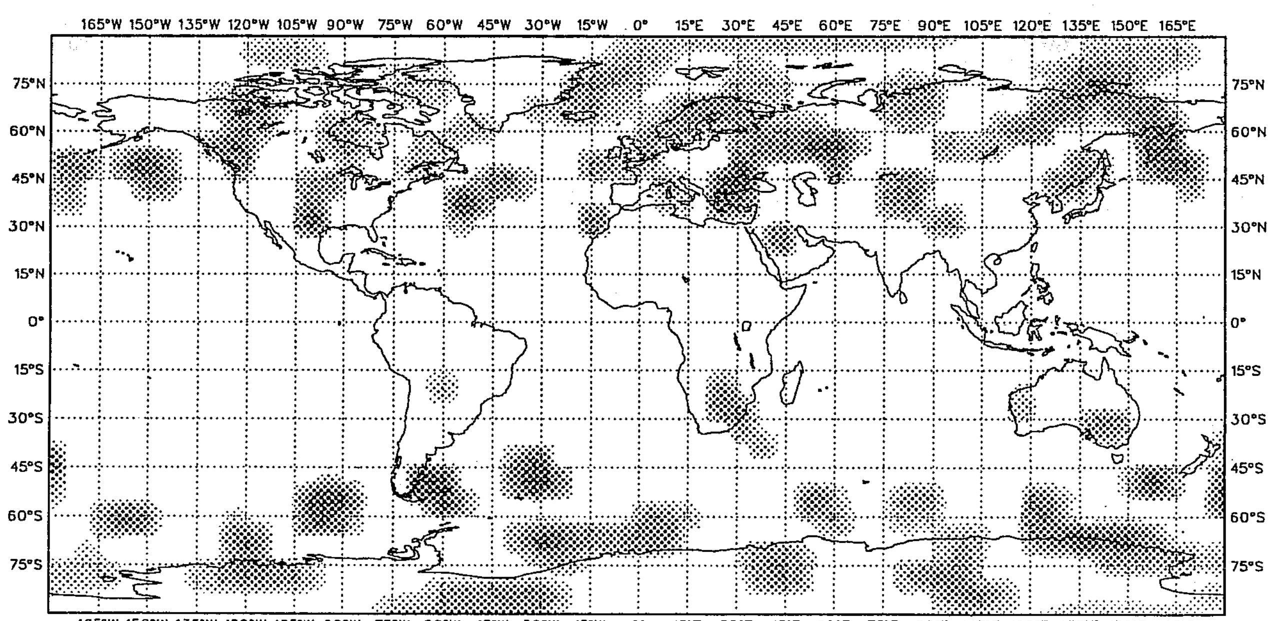
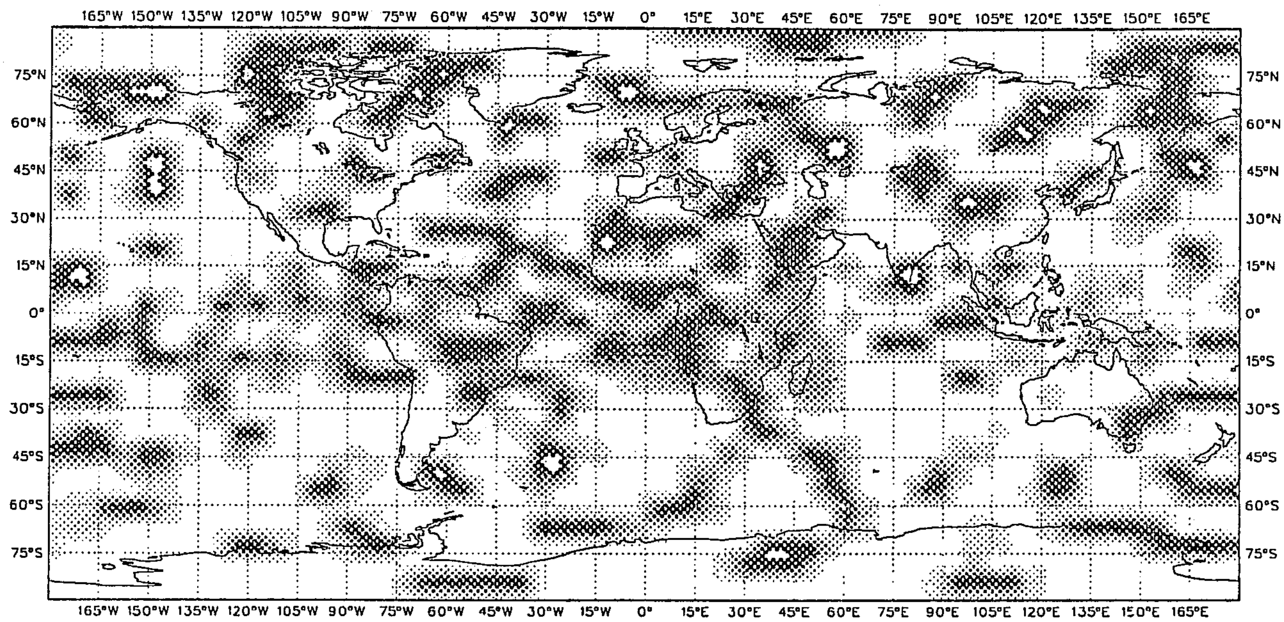


Fig. 3(d) Same as Fig. 3(a) but for middle level liquid water content.

High level cloudiness
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



High level cloudiness
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

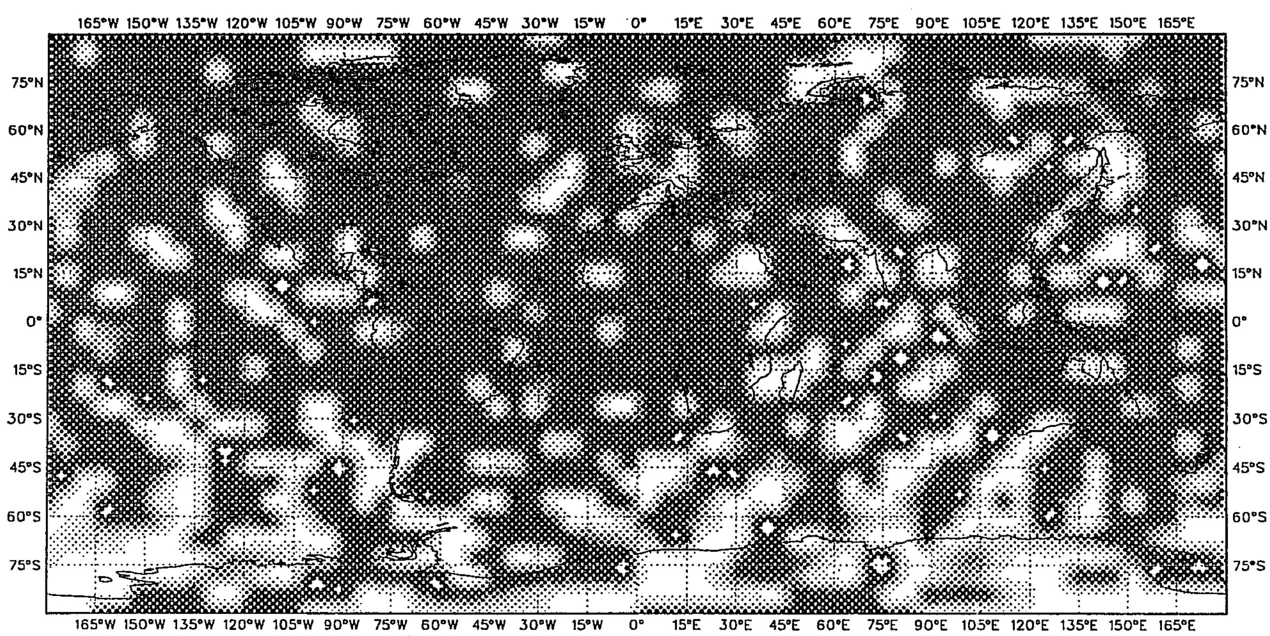
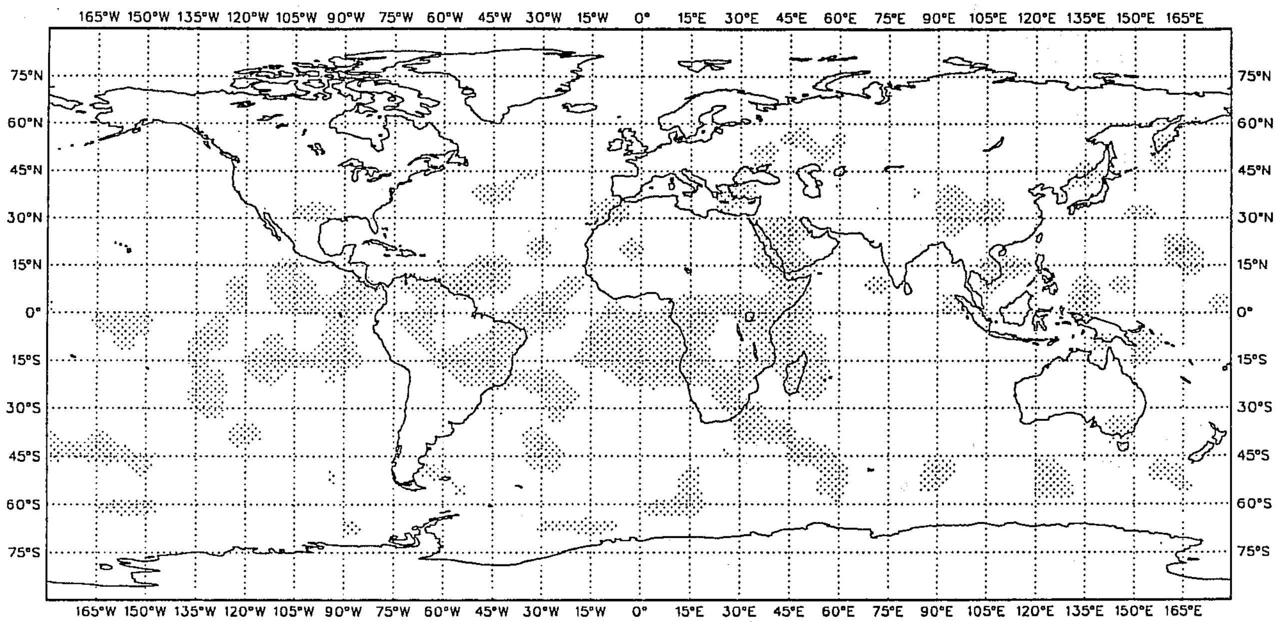


Fig. 3(e) Same as Fig. 3(a) but for high level cloudiness.

Liquid water (kg/m2 x 1.e+3) High clouds
+24H PO1 1987 01 15 12UTC

Operational scheme PO1.CLD



Liquid water (kg/m2 x 1.e+3) High clouds
+24H HL1 1987 01 15 12UTC

Present scheme HL1.CLD

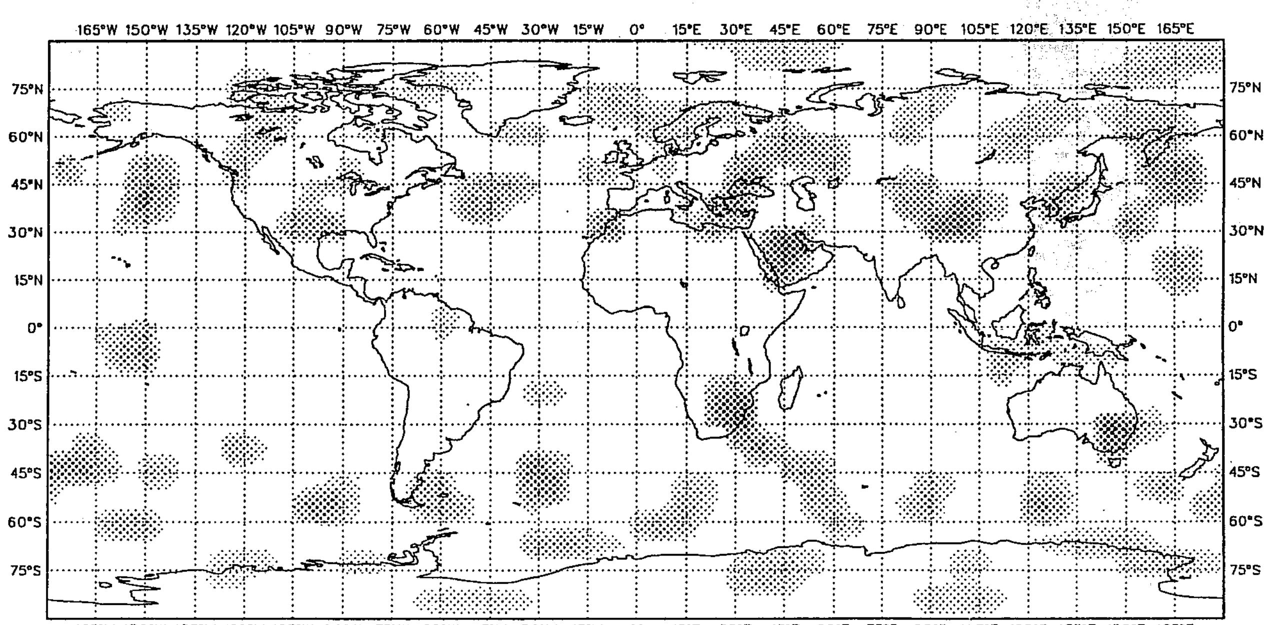


Fig. 3(f) Same as Fig. 3(a) but for high level cloud liquid water content.

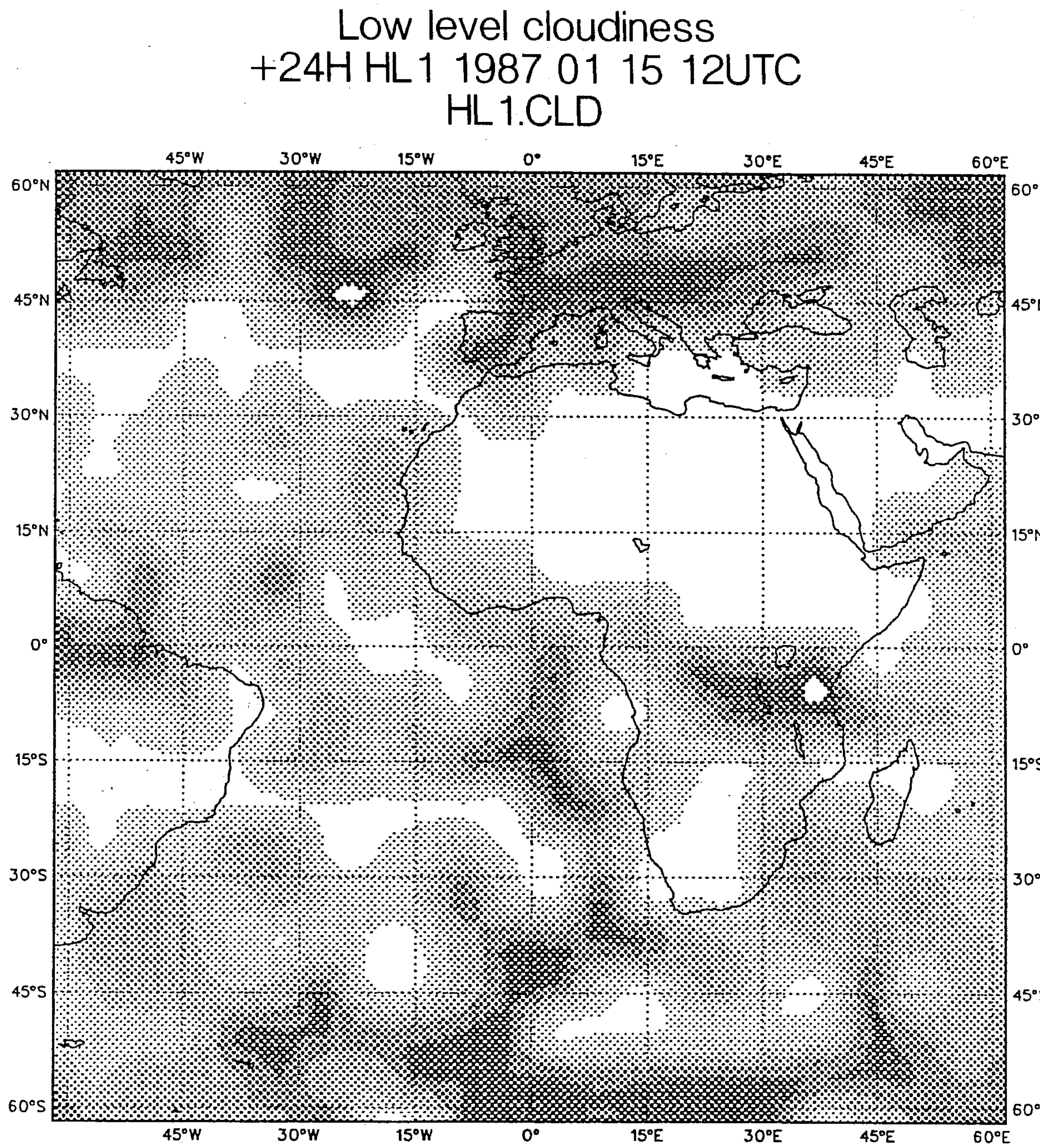
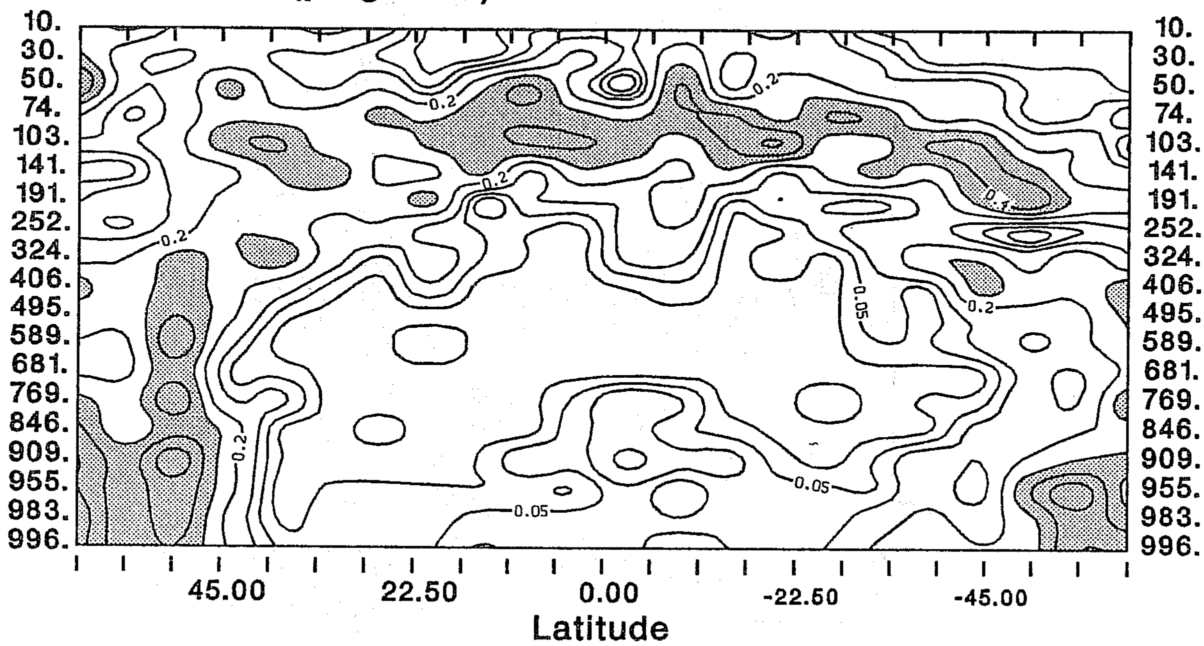


Fig. 4 Detailed view of low cloudiness over the Meteosat area (same conditions as Fig. 3), which shows the clear occurrence of stratus cloud. Although its development begins roughly at the end of local night there is no appearance of a marked diurnal cycle. Further analysis is needed to ascertain this feature.

Zonal Mean over Meteosat FOV of Cloudiness
+24H HL1 1987 01 15 12GMT

Present scheme (prognostic) HL1 .CLD



Zonal Mean over Meteosat FOV of Cloudiness
+24H P01 1987 01 15 12GMT

Operational scheme P01 .CLD

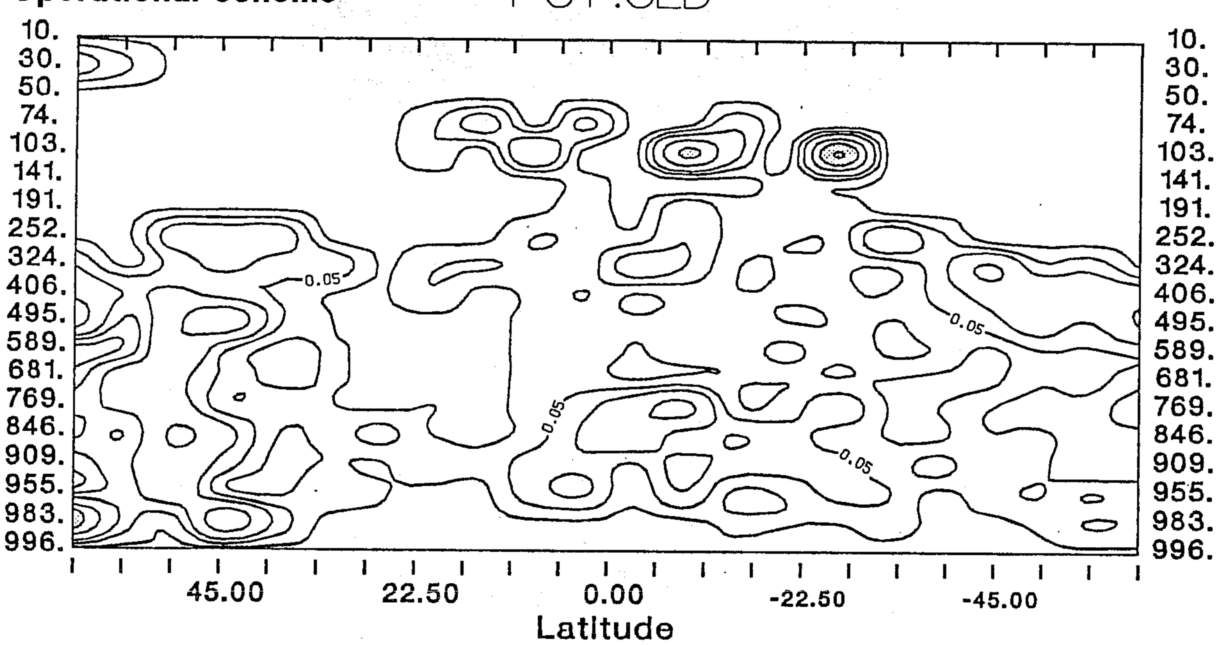
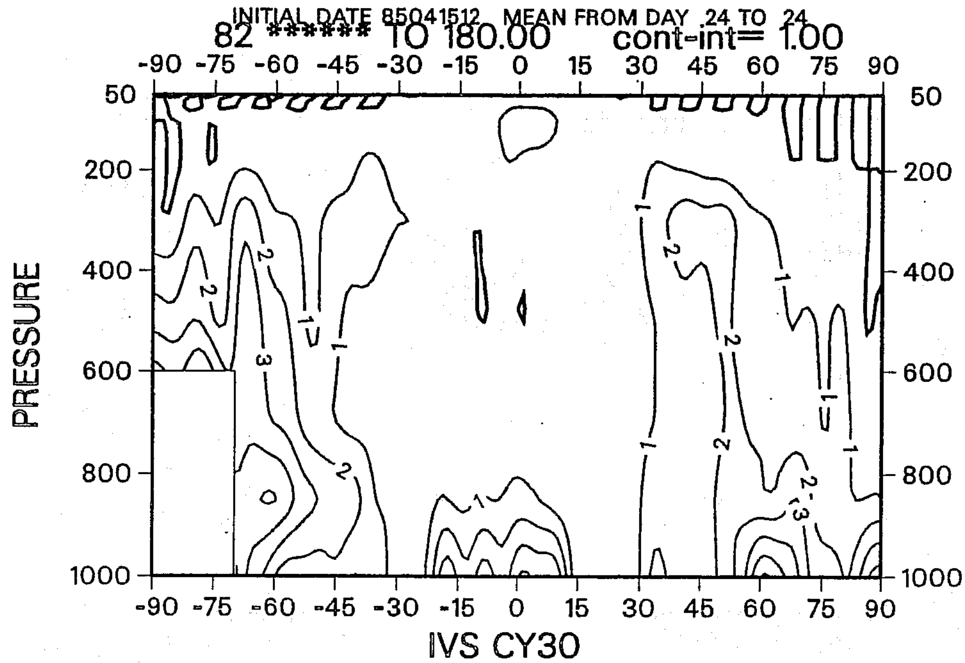


Fig. 5 Mean zonal cloudiness after 24 hours, for a T21 experiment starting on 15 January 87.



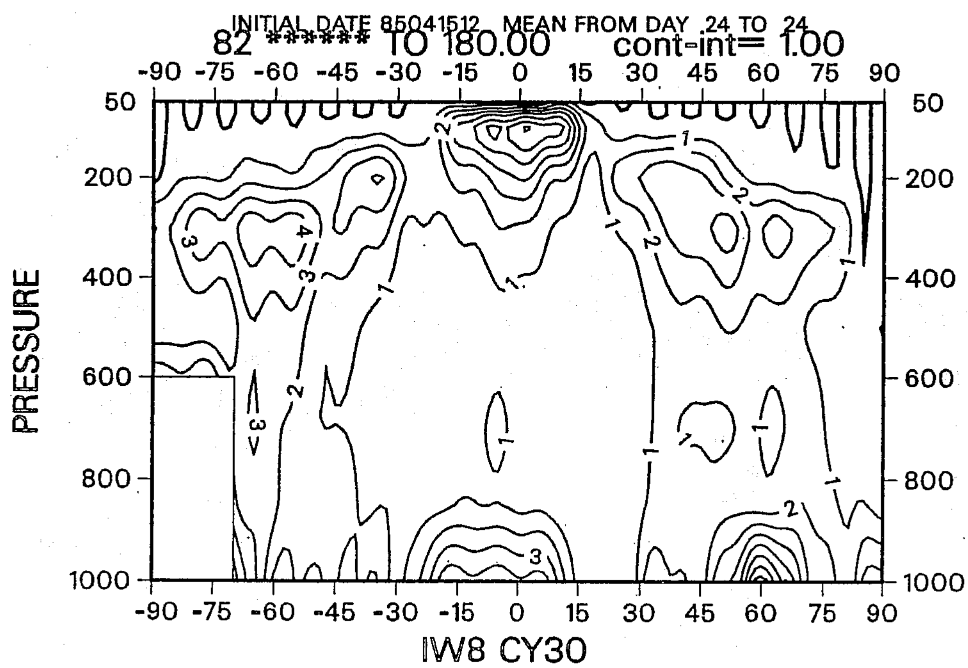


Fig. 10 Same as Fig. 9(a), i.e. mean zonal cloudiness after 24 hours for a T106 experiment starting on 15 April 85, but for experiment IVS (interaction with radiation) and IW8 (interaction with radiation and turbulence).