THE IMPACT OF THE NEW CLOUD SCHEME ON ECMWF'S INTEGRATED FORECASTING SYSTEM (IFS)

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1. INTRODUCTION

A new prognostic cloud scheme has recently been developed at ECMWF (*Tiedtke*, 1993). It is based on prognostic equations for both cloud liquid water and cloud fraction. The scheme treats all cloud related processes in a consistent way by coupling the time evolution of the cloud fields directly to model processes: such as large-scale ascent/descent, turbulent transports, cumulus convection and radiative heating/cooling.

With the introduction of additional prognostic variables the problem of defining their initial conditions arises. How to initialize cloud variables is an open question. However, the refined treatment of condensation and cloud processes leads to a growing importance of realistic and balanced initial humidity and cloudiness fields to keep model spin-up to a minimum in the assimilation cycle. An assimilation of cloud information on a global scale seems unfeasible. This is partly due to a lack of operationally usable observations of cloud water content and three dimensional cloud fraction and partly due to missing algorithms to use the available information. Progress has recently been made in the latter aspect by using the variational approach (*Phalippou*, 1995). Possible solutions to the problem of cloud initialization for regional models have been reported by *Kristjansson* (1991), *Huang and Sundqvist* (1993) and *Ballard et al* (1993).

This paper describes how the prognostic cloud scheme has currently been implemented in the data assimilation system at ECMWF and shows the impact on analysis and short-range forecast results. Furthermore the impact on a longer-term analysis is investigated in the context of the reanalysis project currently carried out at ECMWF.

2. THE SCHEME

The cloud scheme used in this study is described in detail in *Tiedtke* (1993). However there are a few modifications made to the scheme which are described below.

2.1 Mixed phase

In the scheme only one equation for cloud water/ice content is employed. In order to account for the thermodynamics associated with the occurrence of both phases we diagnose cloud water and ice from temperature by defining the partition of water α in the total condensate as T_0 and T_{ice} are chosen as 273.16 K and 250 K respectively. The same formulation is applied to describe the transition from liquid water saturation thermodynamics to ice saturation thermodynamics so that the latent heat of phase changes becomes

$$\alpha = 0 \qquad T < T_{ice}$$

$$\alpha = \left(\frac{T-T_{ice}}{T_0-T_{ice}}\right)^2 \quad T_{ice} < T < T_0$$

$$\alpha = 1 \qquad T > T_0$$

$$L = \alpha L_w + (1-\alpha)L_i$$

and the saturation specific humidity is

$$q_{sat} = \alpha(q_{sat})_w + (1-\alpha)(q_{sat})_i$$

2.2 Ice precipitation

The scheme originally used a parametrization of precipitation following *Sundqvist* (1988) for all phases (water and ice). Verification of OLR against satellite measurements show an overestimation of OLR in tropical regions indicating optically too thin anvil clouds (Rizzi, personal communication). It was thought that this might be due to over-efficient release of precipitation in these clouds, therefore the parametrization of precipitation of ice was reconsidered. The loss of cloud ice due to sedimentation is now represented as where

$$\left(\frac{\partial l}{\partial t}\right)_{sedim.} = \frac{1}{\rho}\frac{\partial(\rho v_i l)}{\partial z}$$

$$v_i = 3.29(\rho l_c)^{0.16}$$

is the mean fall speed of the ice particles following *Heymsfield and Donner* (1990). ρ is the density and $l_c = l/a$ the cloud ice content per cloud area as defined in *Tiedtke* (1993).

Initially we assumed that ice falling through the lower boundary of a model layer may appear as a source for ice content of the next model layer below (in case of overlapping cloud area) or is converted directly into precipitation (when falling into cloud-free area). However this assumption led to erroneously high ice contents (especially in Tropical anvil cirrus) and has later been relaxed so that all ice leaving a model layer is subsequently treated as precipitation.

The release of precipitation from pure water and mixed phase clouds is still treated following *Sundqvist* (1988).

2.3 Cloud top entrainment

Validation of the original version of the scheme showed that it failed to dissipate low level clouds fast enough and may also produce spurious rain from low level clouds over the sea. One important dissipation process for these clouds is cloud top entrainment. The effect of this process is currently considered only as a result of buoyancy production by turbulent processes within the mixed layer. The effect of longwave radiative cooling on the cloud top entrainment is not directly included so far because of large uncertainties in its treatment. To correct the above mentioned bias towards excessive boundary layer cloudiness the scheme has been extended by introducing entrainment due to radiative cooling following *Stull* (1988)

$$(w_e)_{rad} = \beta \frac{c_p\ \Delta F}{\Delta s_v}$$

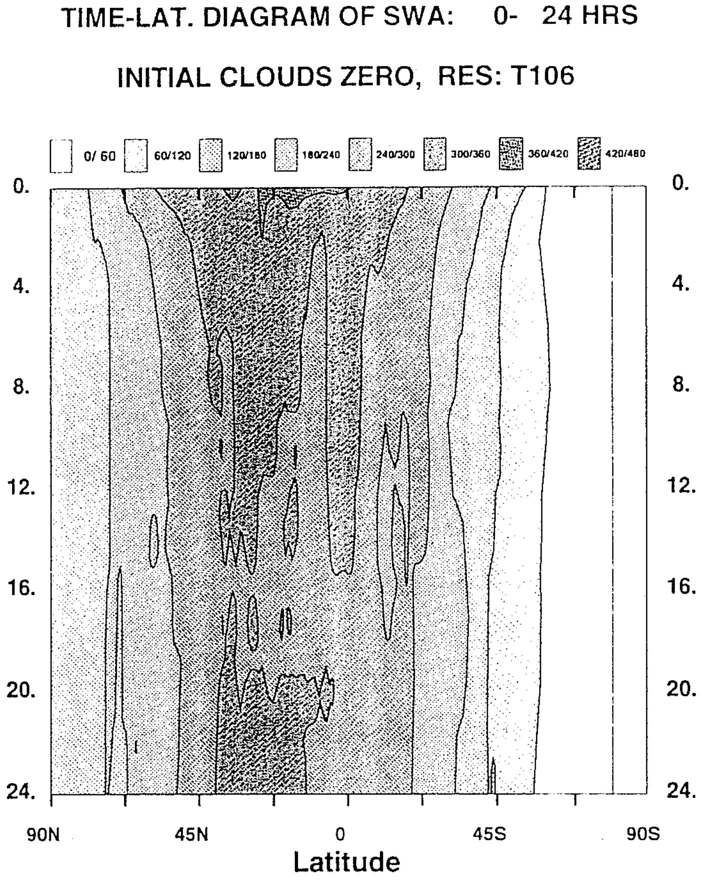
where ΔF is the change of longwave radiative flux between the model levels below and above cloud top, Δs_v the respective change in virtual dry static energy and $\beta = 0.5$.

Several significant modifications have been carried out to the convection scheme. A detailed discussion of these changes is beyond the scope of this paper and will be included in a future paper.

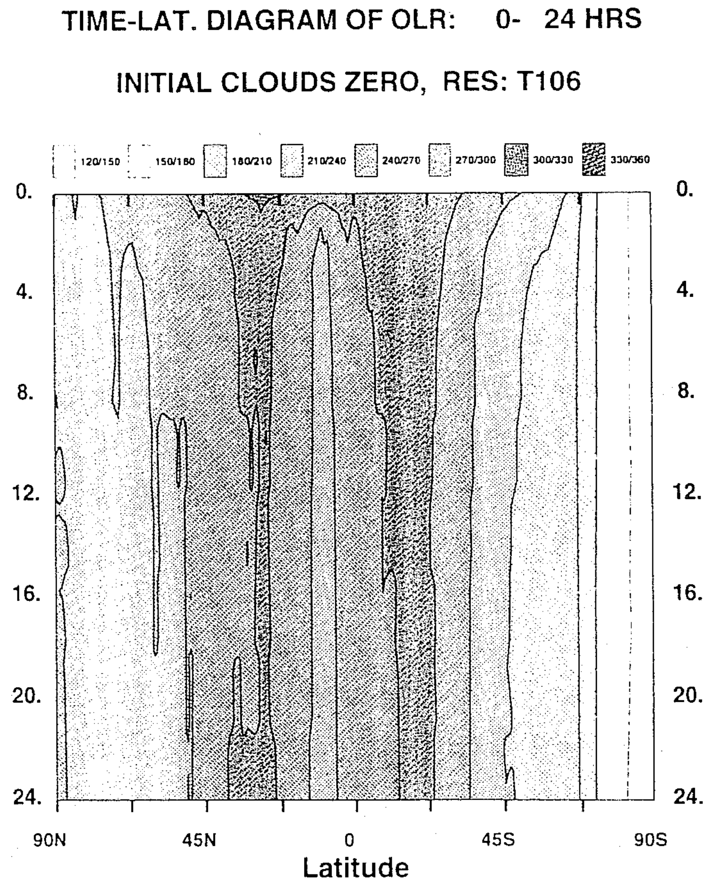
3. IMPLEMENTATION INTO DATA ASSIMILATION

The easiest way to initialize cloud variables in a prognostic scheme is to start the forecast with no clouds at all. However, this leads to a considerable spin-up as clouds slowly build up during the forecast. This is clearly evident in the time evolution of zonal mean top shortwave and top thermal radiation in the first 24 hours of a forecast in which the cloud fields are set to zero at initial time (Fig 1). It takes up to ten hours to reach a quasi-equilibrium state in these radiation fields. This kind of spin-up might be acceptable for medium range forecasts but not for the six hour forecasts providing a first guess for the analysis. Hence an eventual operational implementation of the scheme requires more realistic initial values for cloud liquid water and cloud fraction.

To provide non-zero initial conditions for the cloud fields we follow one of the suggestions made in *Kristjansson* (1991) and supply the first guess results as cloud initial state for the next first guess or forecast respectively. This method is outlined in Fig 2. At the end of a first guess forecast the cloud fields are in balance with the humidity field. However, since the thermal state is altered in the course of the analysis this balance might be destroyed in the forecast initial state when applying the technique described above. Kristjansson tried to overcome this problem by adjusting the humidity field according to the introduced cloud fields. There are two major objections for us not to apply a similar method. Firstly in our scheme clouds can exist within a wide range of relative humidity even if there generation is limited to values above a threshold. So there is no "simple" relationship between clouds and relative humidity which would allow to change the latter according to the model clouds. Secondly the initial humidity field is analysed, i.e. observations are used in its determination, so that any adjustment towards model clouds would lead to a loss of valuable observation information. Instead we make the assumption, that the processes necessary to adjust


TIME-LAT. DIAGRAM OF SWA: 0- 24 HRS

INITIAL CLOUDS ZERO, RES: T106


TIME-LAT. DIAGRAM OF OLR: 0- 24 HRS

INITIAL CLOUDS ZERO, RES: T106

Fig 1: Time evolution of zonal mean net shortwave (upper panel) and outgoing longwave (lower panel) radiation at the top of the atmosphere in the first 24 hours of a forecast started with no clouds.

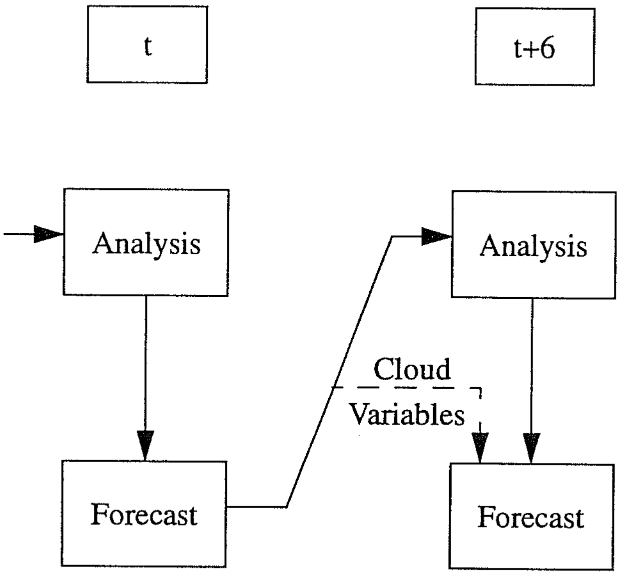


Fig 2: The treatment of the cloud variables in the data assimilation system.

cloud and humidity fields (which are in balance before the analysis of humidity is performed) are fast and it therefore takes only a few time steps to achieve a new balance in the moisture related variables.

4. RESULTS

4.1 Spin-up

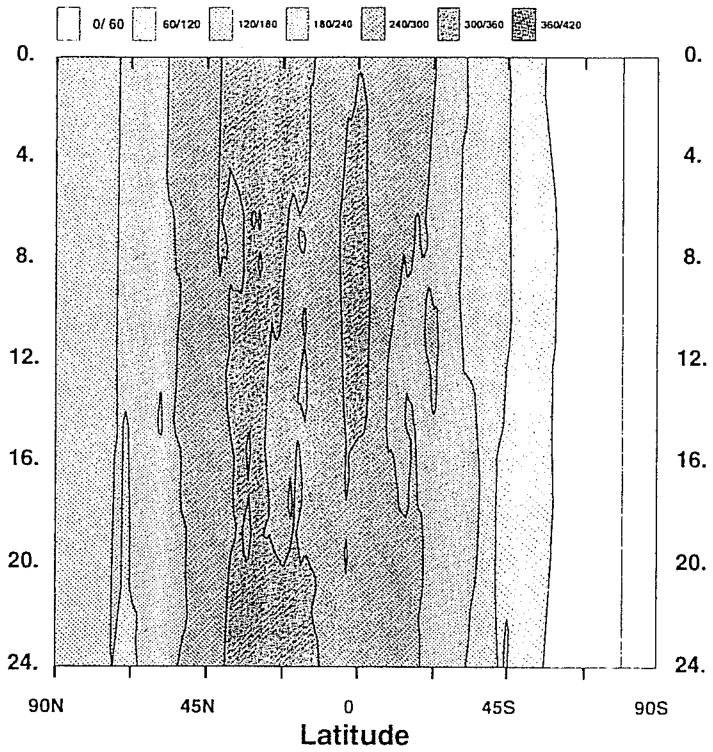
The technique described above was implemented into the data assimilation system at ECMWF. One of the main results is a notable reduction in spin-up times for many variables. Fig 3 shows the time evolution of zonal means of top shortwave and thermal radiation similar to those in Fig 1, but this time with initially non-zero cloud fields. It is evident that there is no significant spin-up in those fields any more. In outgoing longwave radiation on the contrary a spin-down seems to occur in the deep Tropics. This may indicate excessive cloud ice contents in anvil cirrus produced by the scheme which seem to have accumulated during the analysis. The cloud ice contents are significantly reduced (not shown) when changing the assumption on the treatment of cloud ice leaving a model layer in the layers below (see section 2).

A considerable reduction in spin-up is also recognizable for precipitation. Fig 4 shows the difference of 24h precipitation to 6h precipitation for forecasts starting with zero and non-zero clouds.

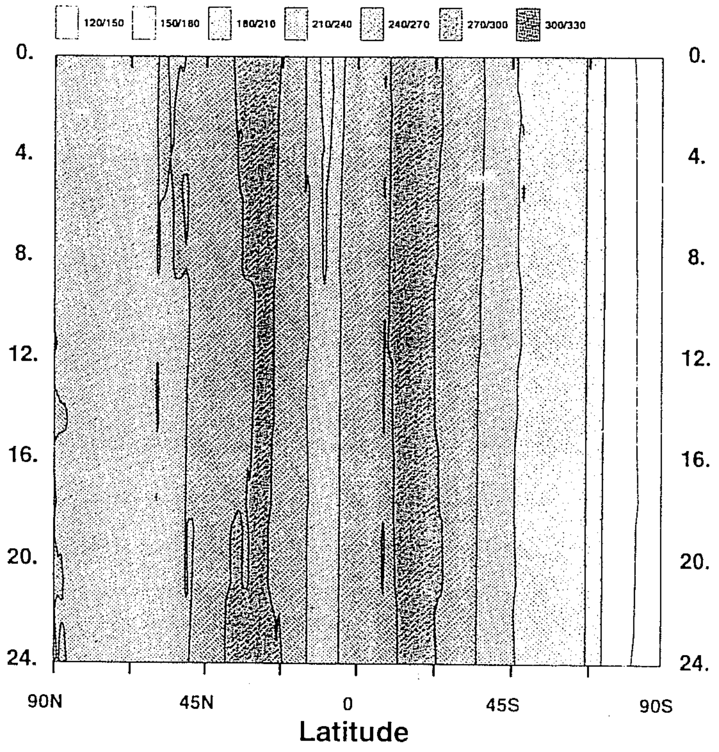
4.2 Weather parameters

To assess the impact of the scheme on the data assimilation system it is useful to evaluate its short range forecast performance. A known problem of the currently operational cloud scheme (after *Slingo*, 1987) is its underestimation of cloudiness over land. Fig 5 shows the mean cloud cover of thirteen 24h-forecasts run with this scheme at T106L31 resolution for 18 to 30 August, 12UTC. The model cloudiness is compared to SYNOP observations over Europe. The numbers are forecast errors in octas. In most areas the cloud cover is underestimated by 2 to 4 octas. This underestimation significantly contributes to a warm bias in two-metre temperature at the same forecast time (Fig 6). These biases, noticeable already in the short range, lead to substantial errors in the surface energy balance and influence the performance of the whole data assimilation and forecasting system, as experienced in spring/summer 1994 when the model's land surface started to dry out affecting even the medium-range objective forecast scores.

The new scheme improves the cloud cover forecast over land substantially. Fig 7 and Fig 8 show cloud cover and two-metre temperature errors similar to Fig 5 and Fig 6 but from forecasts run with the new scheme from an analysis performed in the way described above. The improved cloud cover leads to a substantial decrease in the two-metre temperature bias.


TIME-LAT. DIAGRAM OF SWA: 0- 24 HRS

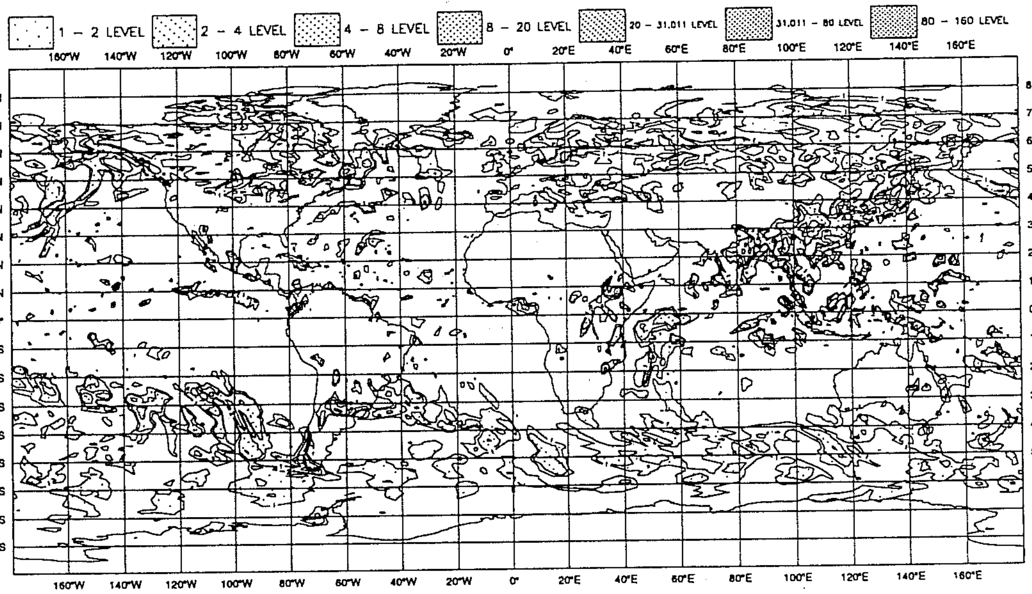
INITIAL CLOUDS NON-ZERO, RES: T106


TIME-LAT. DIAGRAM OF OLR: 0- 24 HRS

INITIAL CLOUDS NON-ZERO, RES: T106

Fig 3: As Fig 1 but for a forecast started with clouds from the previous first guess forecast.

Mean Diff. 24h minus 6h Precip. - 18-30 August 93
Initial Clouds zero



Mean Diff. 24h minus 6h Precip. - 18-30 August 93
Initial Clouds non-zero

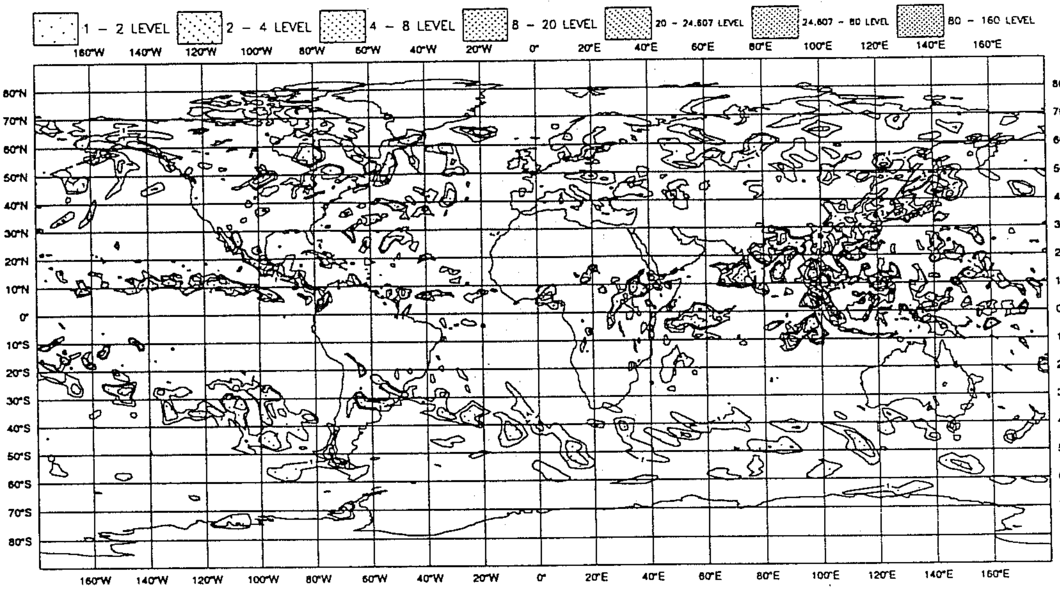


Fig 4: Mean difference (13 cases) of t+24h and t+6h precipitation (mm/day) for forecasts started with no clouds (upper panel) and with first guess clouds (lower panel).

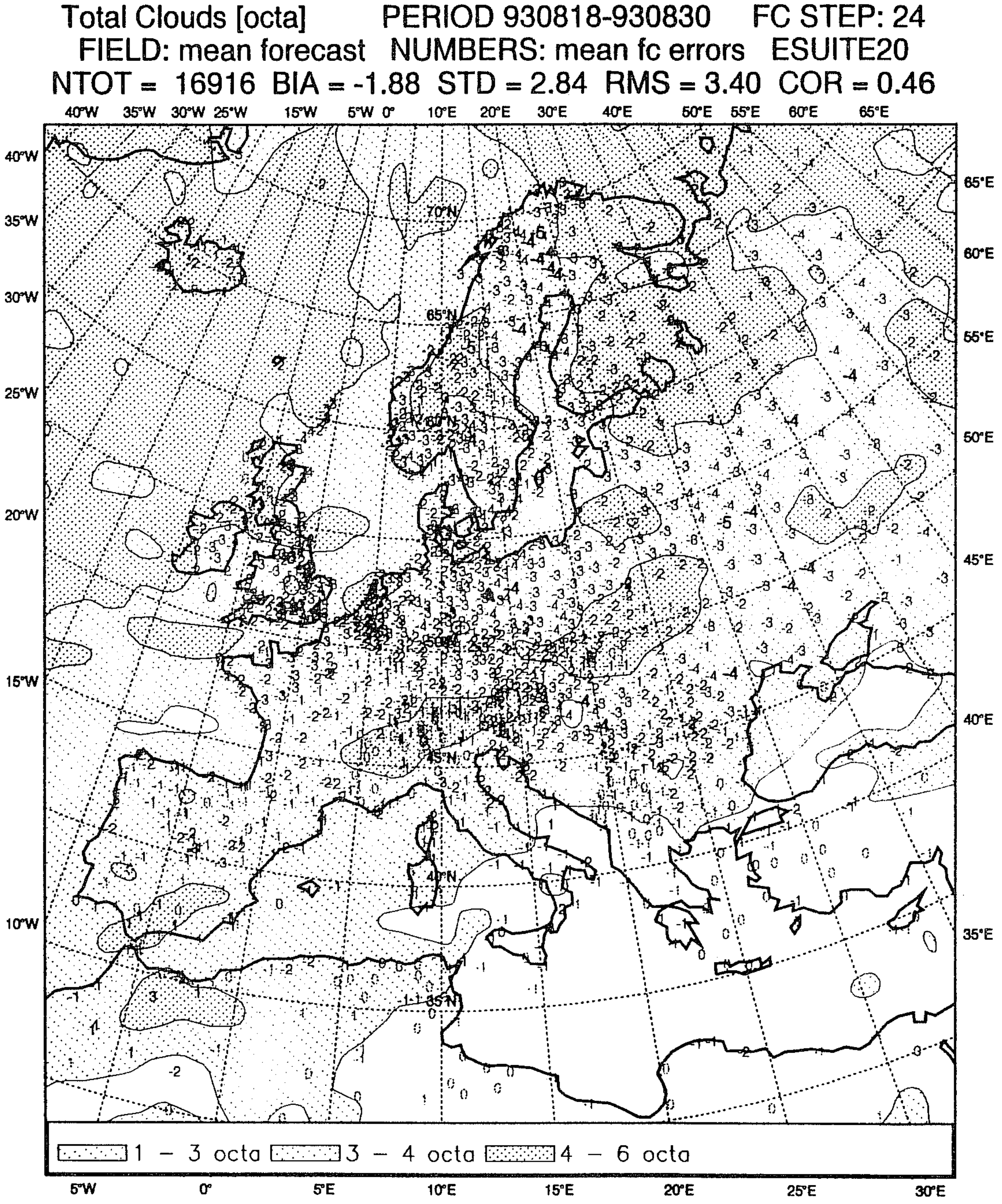
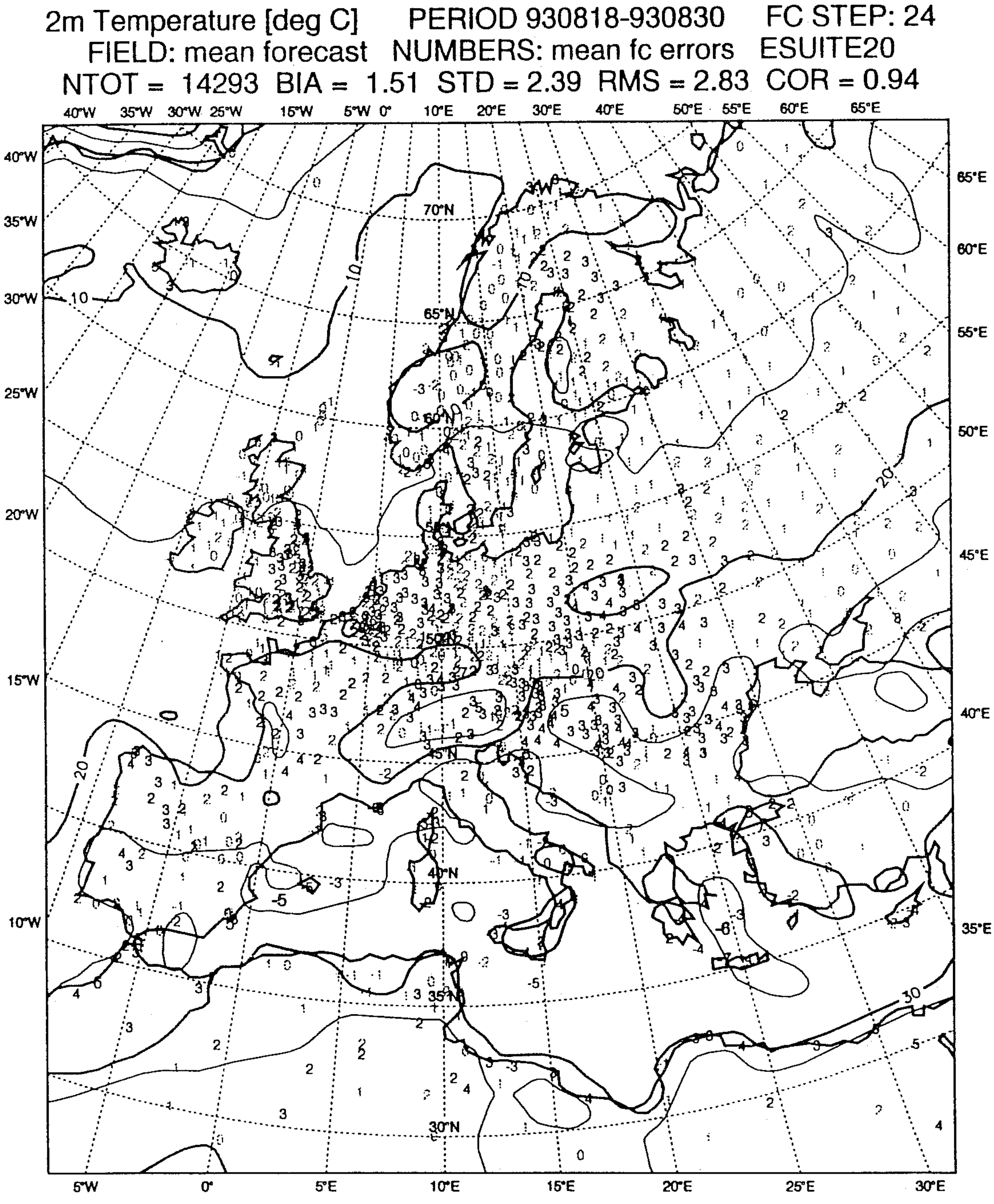


Fig 5: Mean t+72 forecast and forecast error of total cloud cover for thirteen T106L31 forecasts (930818-930830) run with the diagnostic cloud scheme.



2m Temperature [deg C] PERIOD 930818-930830 FC STEP: 24
FIELD: mean forecast NUMBERS: mean fc errors ESUITE20
NTOT = 14293 BIA = 1.51 STD = 2.39 RMS = 2.83 COR = 0.94

Fig 6: As Fig 5 but two-metre temperature.

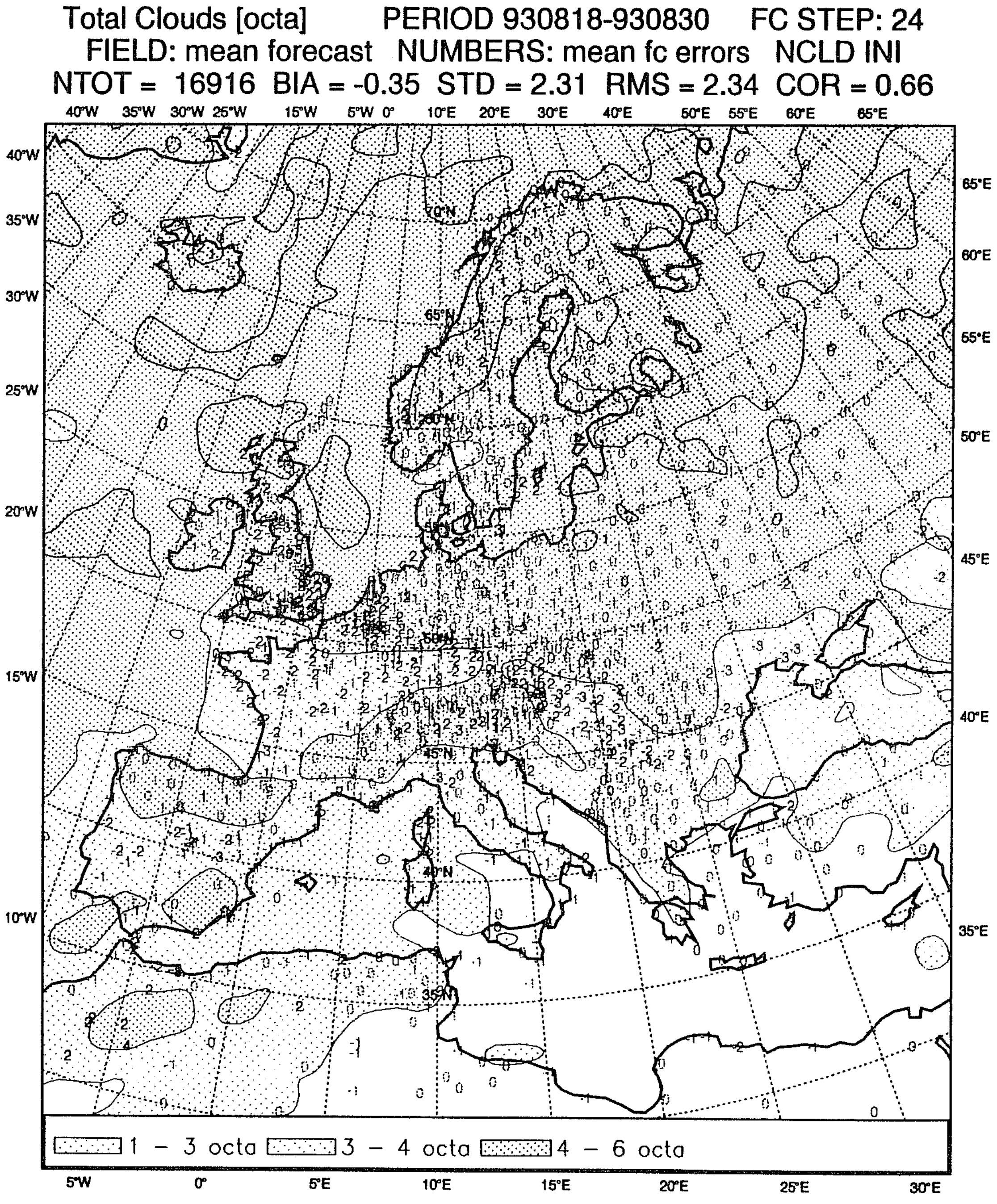


Fig 7: As Fig 5 but run with the prognostic cloud scheme with initial clouds from the first guess.

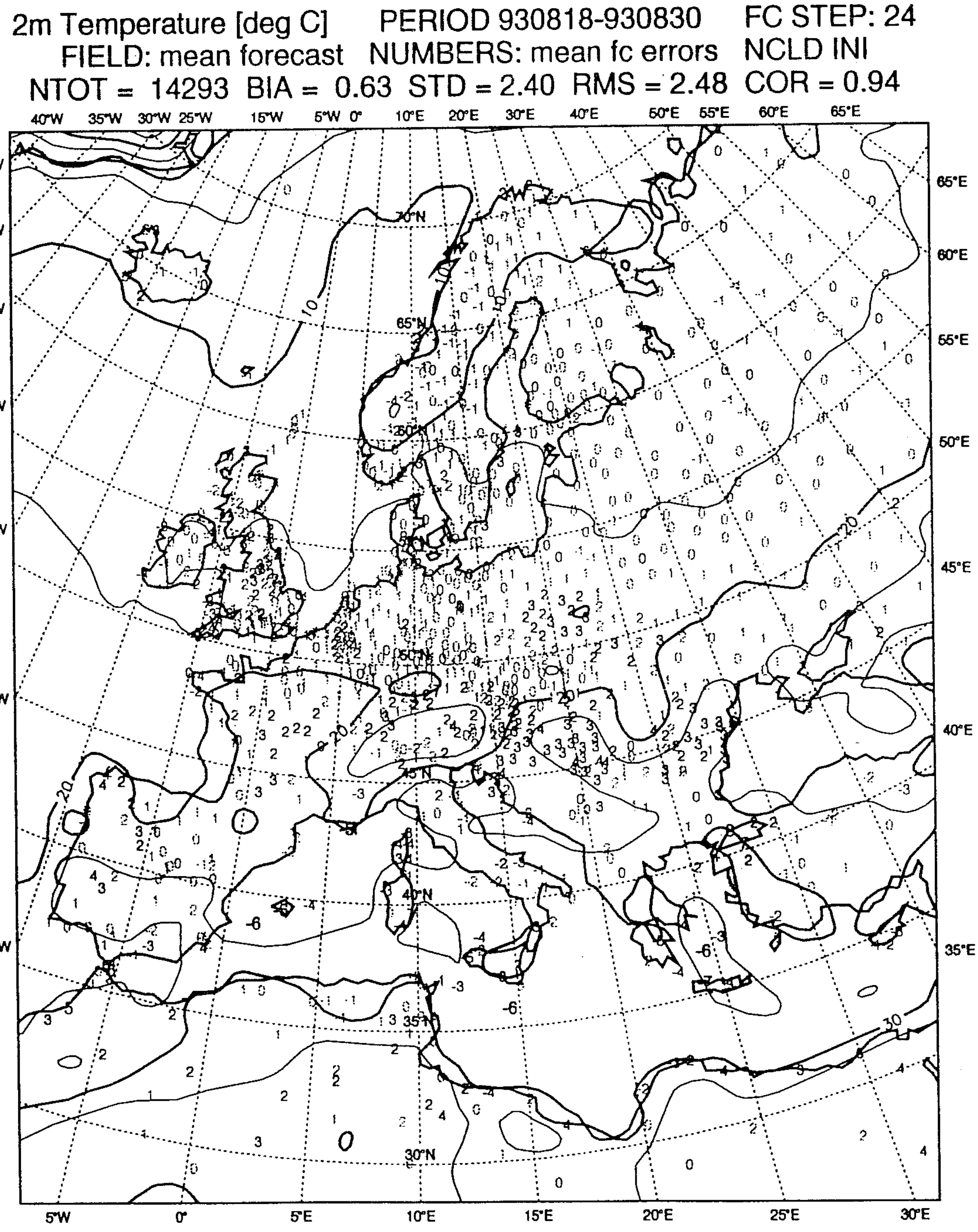
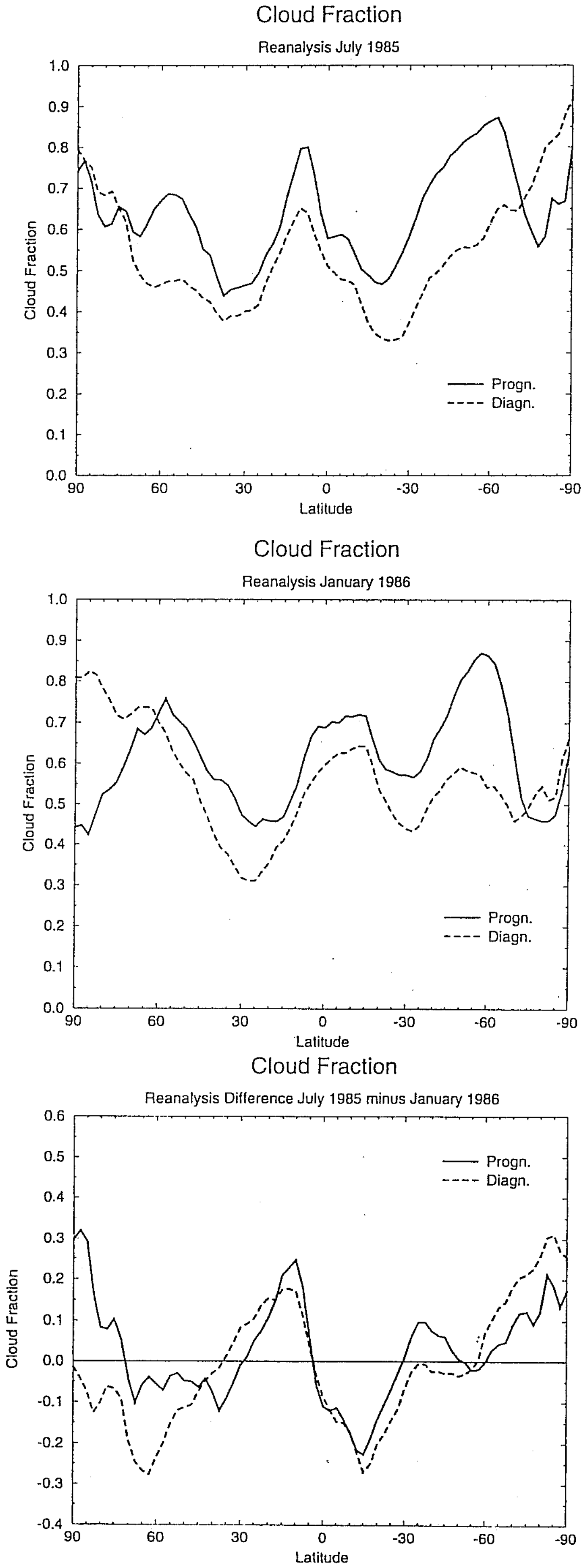


Fig 8: As Fig 7 but two-metre temperature.



Cloud Fraction

Reanalysis July 1985

Cloud Fraction

Reanalysis January 1986

Cloud Fraction

Reanalysis Difference July 1985 minus January 1986

Fig 9: Zonal mean of total cloud cover from reanalysis for July 1985 (upper panel), January 1986 (middle panel) and July 1985 minus January 1986 (lower panel). Prognostic cloud scheme - solid line, diagnostic cloud scheme - dashed line.

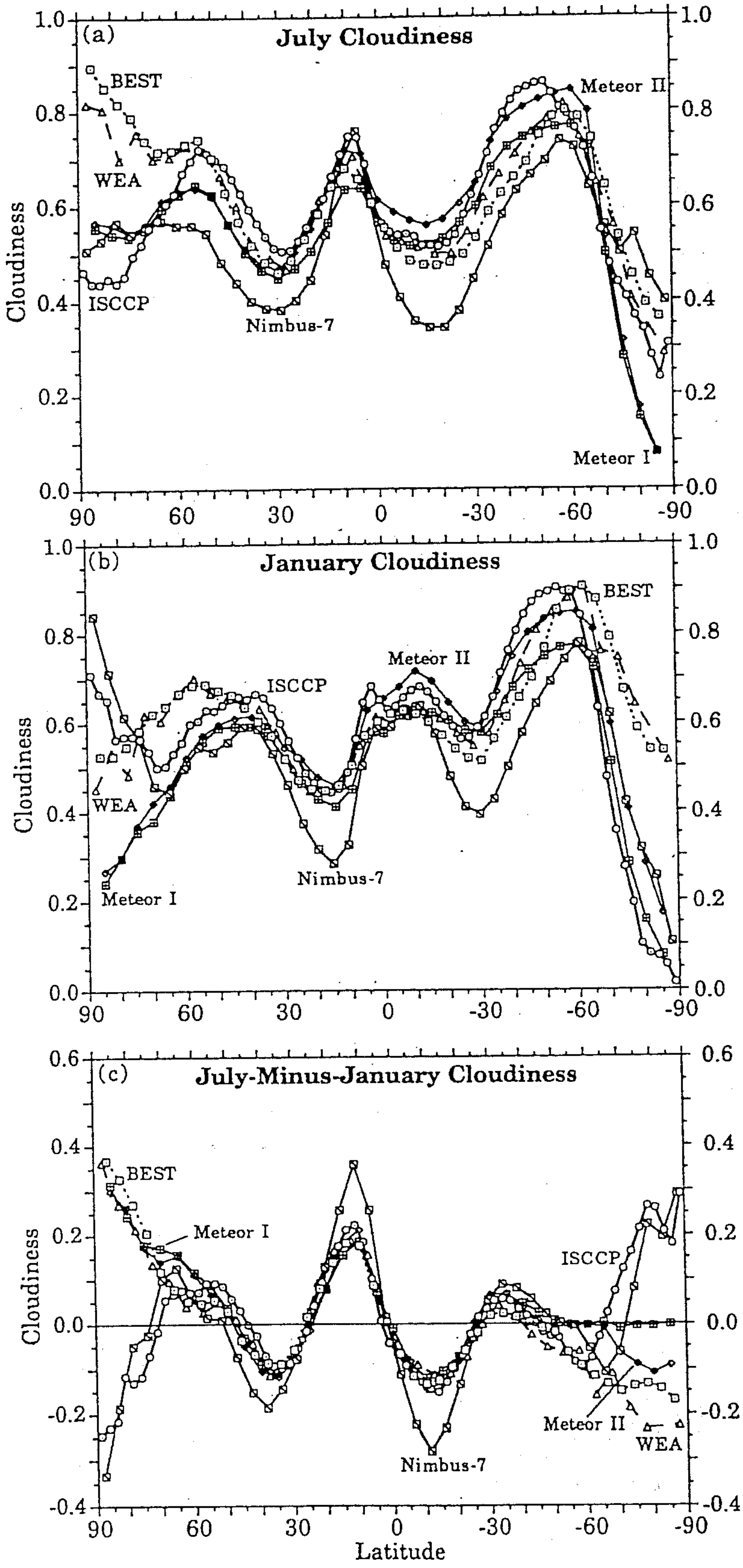


Fig 10: Observed zonal mean of total cloud cover from several climatologies for July, January and July minus January (from *Mokhov and Schlesinger*, 1994).

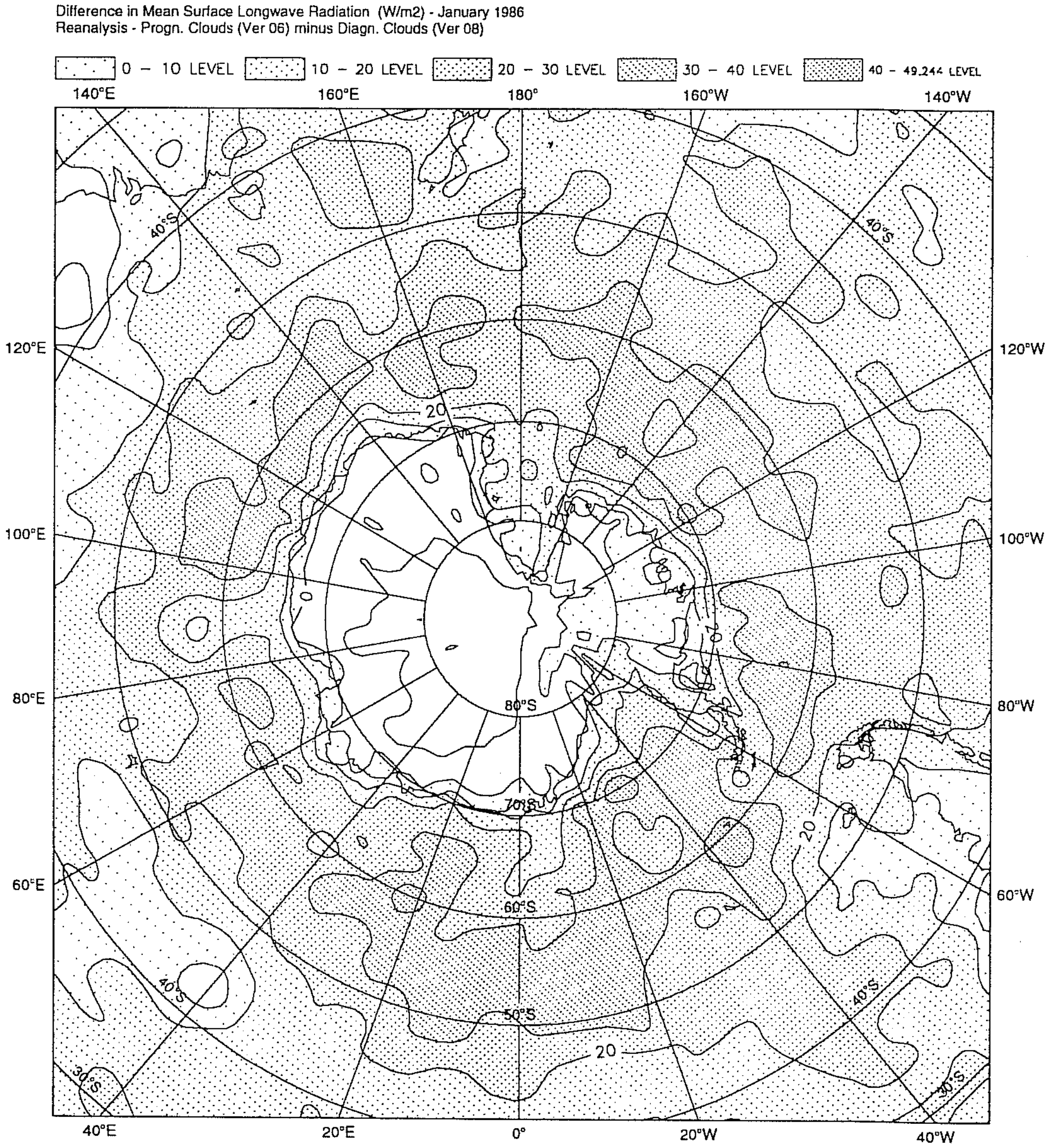


Fig 11: Difference in net longwave radiation at the surface between analyses carried out with the prognostic and the diagnostic cloud scheme (January 1986).

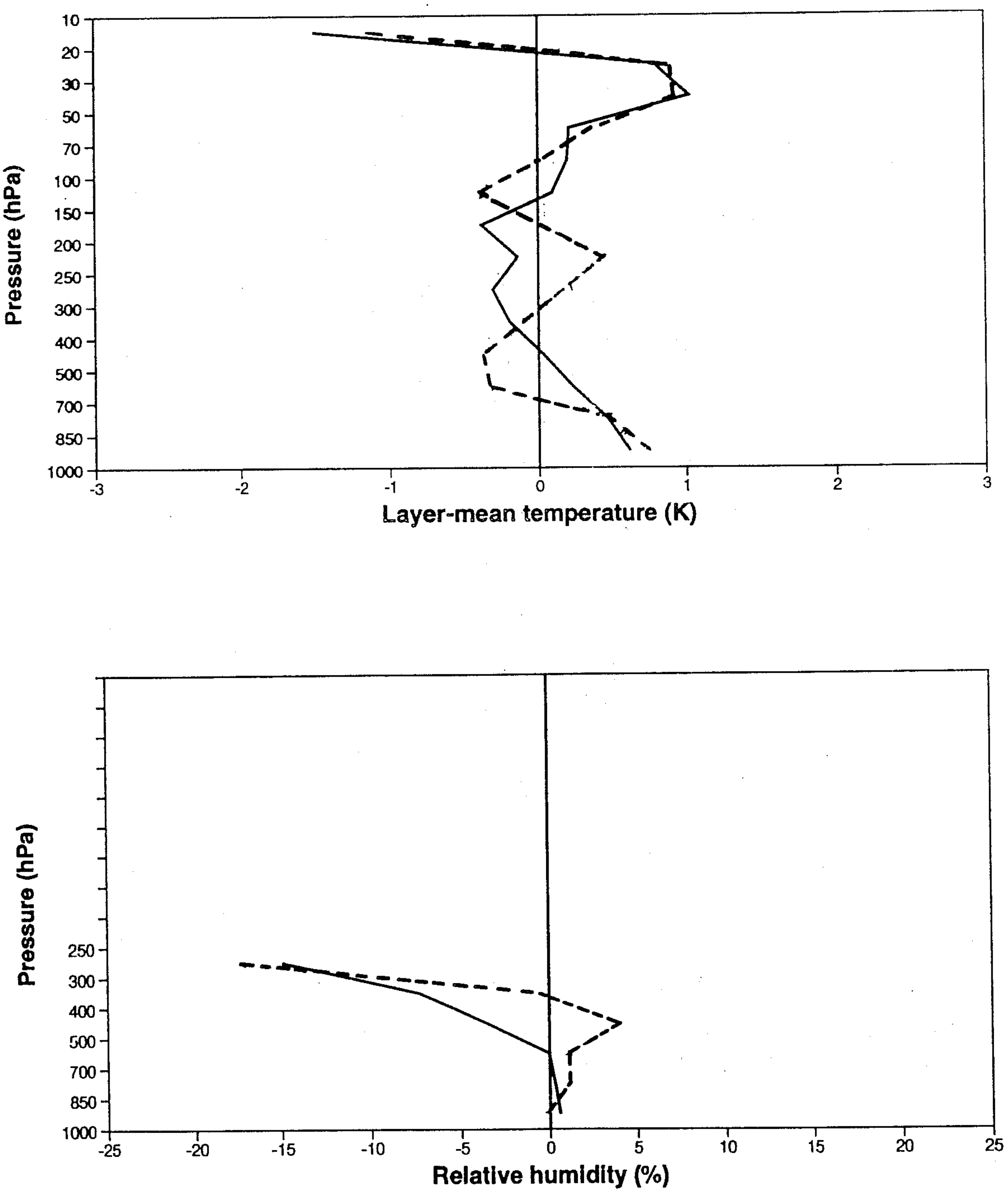


Fig 12: Collocated mean biases of temperature (upper panel) and relative humidity (lower panel) of first guess results for July 1985. Prognostic cloud scheme - solid line, diagnostic cloud scheme - dashed line.

4.3 **Reanalysis**

To assess the performance of the scheme in a longer term analysis two months of analysis (July 1985 and January 1986) were carried out in the context of ECMWF's reanalysis project. Fig 9 shows the zonal mean cloudiness for these experiments in comparison to experiments carried out with the diagnostic scheme. Shown are both months as well as the July minus January difference. Fig 10 shows the same parameters for several climatologies (*Mokhov and Schlesinger*, 1993). It is evident that there is a significant improvement in the model's cloudiness especially in the Southern Hemisphere. This improvement, as well as changes in cloud water/ice content and its vertical distribution, have a significant impact on the energy balance of both atmosphere and surface. As an example, Fig 11 shows the difference in the mean net thermal radiation at the surface between two analyses carried out with the different cloud schemes for January 1986 over the Southern Hemisphere. There is a remarkable increase in this parameter between 50°S and 65°S when using the new scheme. This is caused by an increased downward radiation due to low and middle level clouds which were under-represented in the diagnostic scheme.

Fig 12 shows the fit of the first guess forecasts of temperature and relative humidity to radiosonde data in the Tropics for July 1985. The vertical structure of the temperature bias in the troposphere has changed significantly removing a warm bias at around 500 hPa and changing the sign of the bias between 400 hPa and 150 hPa. There is a reduction in the lower troposphere relative humidity bias but a 15% moist bias in the upper troposphere still persists.

5. CONCLUSIONS

A simple method to initialize cloud variables was adopted to implement a fully prognostic cloud scheme in the ECMWF data assimilation system. Results of the first guess forecast are used as to initialize cloud liquid water and three-dimensional cloud fraction in the analysis cycling and in forecasts. No major problems seem to occur when applying this method. The introduction of the scheme using this technique leads to considerable reduction in model spin-up and to an improved prediction of cloudiness. There is a significant change in the thermal structure of the atmosphere as well as in the surface energy balance. This leads to a reduced two-metre temperature bias over land. The beneficial impacts of the new scheme led to its implementation into ECMWF's reanalysis system.

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