THE SENSITIVITY OF THE TIME-MEAN LARGE-SCALE FLOW TO CUMULUS CONVECTION IN THE ECMWF MODEL

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The effect of cumulus convection and cloud radiation interaction on the time-mean flow corresponding to a mean February circulation has been studied in the ECMWF general circulation model. The study consists of three 'sets' of sensitivity experiments. In the first set the effect of penetrative cumulus convective heating is studied by comparing three standard cumulus convection schemes (Manabe et al., 1965; Kuo, 1974; Arakawa and Schubert, 1974). In the second set the interaction of model generated cumulus clouds with radiation is examined and in the last set the effect of shallow cumulus convection is studied. All integrations start from identical conditions and are run for 50 days. The experiments were carried out with the ECMWF T40 spectral model (Baede et al., 1979). The atmosphere is vertically resolved by 15 irregularly spaced levels as in the ECMWF operational forecast model (Hollingsworth et al., 1980). The subgrid-scale processes which are parameterized include radiation, large-scale condensation, dry and moist convection, boundary layer turbulent fluxes, land surface and ground hydrological processes. All processes are parameterized in the way described by Tiedtke et al. (1979), except for cumulus convection and cloud-radiation interaction which, for the purpose of this study, are parameterized in various ways. The parameterization of shallow convection is described in Section 2.

1. PENETRATIVE CUMULUS CONVECTION AND CLOUD RADIATION INTERACTION

1.1 Introduction

The experiments on penetrative cumulus convection and cloud-radiation interaction are described in detail in a separate paper (Tiedtke, 1984) and therefore are only briefly summarized here.

Cumulus convection is parameterized by either using one of the conventional schemes or ignored altogether:

1. Moist adiabatic adjustment (Manabe et al., 1965).
2. Kuo-scheme (Kuo, 1974).
3. A-S scheme (Arakawa-Schubert, 1974).
4. No parameterization of convection.

The MAA-scheme is a simple adjustment scheme, where the large-scale temperature and moisture fields are adjusted towards a moist adiabat in a moist conditionally unstable layer. The Kuo- and the A-S scheme have been designed particularly for parameterizing penetrative convection. In the fourth experiment (NO CONV), parameterization of cumulus convection has deliberately been omitted and therefore condensational heating can now only occur in saturated flow with a scale which is resolved by the model. Consequently, cumulus convection which provides most of the diabatic heating in the tropics is replaced by large-scale condensation. Although this model assumption appears unrealistic, this experiment is significant in view of the uncertainty in parameterizing cumulus convection. In fact, the results of this study showed that one of the convection schemes i.e. the MAA scheme, provides diabatic heating fields which are more similar to those obtained in the experiment without cumulus parameterization than with the two penetrative convection schemes KUO and A-S.

The effect of cloud-radiation interaction on the large scale flow is studied by using a fully interactive scheme. Therefore, model generated cumulus cloudfields are used as input for the radiation calculation. The cumulus cloud cover is derived from the convective precipitation. Three formulations of the convective cloud cover are used. In the first experiment it is assumed that convective clouds do not interact with radiation. This is ensured by imposing a zero cloud cover

$$C^c = 0$$

In the second experiment we choose the other extreme of maximum possible interaction and assume that convective clouds fill the whole grid column of the convectively unstable layer whenever the convective precipitation rate exceeds the threshold value of 1 mm/day

$$C^c = \begin{cases} 1 \text{ if } P^c \geqslant 1 \text{ mm/day} \\ 0 \text{ if } P^c < 1 \text{ mm/day} \end{cases}$$

In the third experiment a more realistic fractional cloud cover is derived from the convective precipitation

$$C^c = \begin{cases} 0.1 + 0.07\, P^c \text{ if } P^c \geqslant 0 \\ 0 \qquad\qquad\quad \text{ if } P^c = 0 \end{cases} \quad (P^c \text{ in mm/day})$$

Besides convective clouds we also consider stratified clouds. These are identically specified in all experiments from the large-scale relative humidity field as

$$C^L = \begin{cases} 1 & \text{if RH} \geq 100\% \\ 0 & \text{if RH} < 100\% \end{cases}$$

Thus, stratified clouds exist only if the whole grid column becomes saturated.

1.2 Results

Results of the experiments are also presented in Tiedtke (1984) and therefore will be summarized here. The main results are:

1. Planetary scale divergent circulation is strongly linked to the diabatic heat sources in the tropics.

2. The intensity of the heat sources and the associated circulation is effectively reduced by cumulus convective heating in all areas of diabatic heating (i.e. Western Pacific and over the tropical continents), except along the ITCZ where the diabatic heating is intensified. The two penetrative convection schemes (Kuo and A-S) are similar in their overall performance but yield different diabatic forcings in some areas. These differences are found to be statistically significant as they are larger than those due to the inherent variability.

3. Cumulus cloud-radiation interaction has a controlling influence on the zonal asymmetry of the diabatic heat sources, and the associated circulation, through feedback loops between clouds, radiation, cumulus convective heating and the large-scale flow. The sign of the feedback loop is determined by the dominance of either the albedo effect (over land) or the "greenhouse" effect (over sea). We find that the feedback is positive over the sea and negative over land. The large-scale flow enters the feedback loop through the moisture convergence caused by

diabatically driven circulations. It effectively reduces the heat source and the circulation itself over the tropical continents, and increases their amplitudes over the sea.

4. Cloud-radiation interaction also affects the surface hydrology through the large-scale moisture convergence, and can cause the reduction of the runoff by as much as 50%.

5. The study of the extratropical mean flow indicates that cloud-radiation interaction may have, through its influence on the zonal asymmetry of the tropical heat sources, a significant effect on the intensity and position of the long standing Rossby waves. This response occurs through a) the modification of the subtropical flow associated with changes in the Hadley type circulation and b) the subsequent wave propagation producing teleconnection patterns which are similar to observed patterns.

The statistical significance of the results is demonstrated by showing that the response changes are much larger than the inherent variability of the model deduced from an extended integration over 2 years.

From these experiments we may draw the following conclusions concerning the role of parameterization of cumulus convection in large-scale models. The results indicate that the major role of cumulus convection in large-scale models is to modify the diabatic heat sources which also exist if cumulus convection is ignored but then occur in connection with other diabatic processes, i.e. latent heat release due to large-scale vertical motion. This study shows further that conventional schemes for penetrative cumulus convection (here represented by the Kuo and the A-S scheme) are similar in performance. They both seem to underestimate the diabatic forcing of the mean divergent circulation but we cannot say from this study, if this is due to common deficiencies in the convection schemes or to deficiencies in other parts of the model.

The large sensitivity of the tropical heat sources and of the mean flow to the cloud-radiation feedbacks suggests that the parameterization of the interaction between cumulus cloud fields and radiation is important and must be improved in large-scale models. Here, the main problem is to relate the total convective cloud cover to the convective activity given by the model's convection scheme. A more realistic method compared to that used in this study would therefore be needed to define the cloud cover. A scheme which in some way is based on the prediction of the large-scale cloud water would probably be the most suitable.

The results have important implications for the problem of long range forecasts. Shukla (1981) showed in a recent study that the monthly mean flow may be predictable up to one or probably two months. The prospect of useful forecasts will, however, largely depend upon the model's ability to realistically simulate the quasi-stationary component of the flow. The large response changes obtained in this study suggest that this prospect for useful long range forecasts is largely diminished by the uncertainties that exist with regard to the parameterization of cumulus convection and cloud-radiation interaction.

2. SHALLOW CUMULUS CONVECTION

Work on the parameterization of shallow convection at ECMWF was initiated in response to deficiencies found in global integrations which can be related to a lack of shallow convection. Both the operational forecasts and extended integrations show a weakening and a north-east displacement of the Azores high. It has been argued that this error is related to the lack of an intertropical convergence zone over the Atlantic due to an insufficient moisture supply in the trade wind areas. It was also found that the trade wind boundary layer is too shallow with little evidence of a cloud layer at the top of the mixed layer. Observational studies for the undisturbed trades during BOMEX (Holland and Rasmussson, 1973) and during ATEX (Augstein et al., 1973) support the idea that shallow convection ensures that water vapour is accumulated in the cloud layer below the inversion and transported downstream. The convective fluxes of heat and moisture thus counteract the drying and warming effects of the mean downward motion.

2.1 A simple scheme to parameterise shallow convection

The large-scale budget equations for a non-precipitating cloud layer in terms of dry static energy s, moisture content q and liquid water content ℓ are (see, for example, Betts, 1975):

$$\frac{\partial \bar{s}}{\partial t} + \bar{V}.\nabla\bar{s} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{w's'}) + L\,(C-E) + Q_R$$

$$\frac{\partial \bar{q}}{\partial t} + \bar{V}.\nabla\bar{q} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{w'q'}) - (C-E) \qquad (1)$$

$$\frac{\partial \bar{\ell}}{\partial t} + \bar{V}.\nabla\bar{\ell} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{w'\ell'}) + (C-E)$$

(Q_R = radiative source term; C,E = condensation, evaporation rate; L = latent heat). For cumulus cloud layers as in the trades, the time change and the advection of liquid cloud water by the large-scale flow are typically small and the balance is between the turbulent transport of liquid cloud water and condensational processes

$$\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho}\ \overline{w'\ell'}) = C-E$$

The effect of shallow cumulus convection can therefore be described by the turbulent fluxes of heat, moisture and liquid cloud water.

$$\left(\frac{\partial \bar{s}}{\partial t}\right)_{cu} = -\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left(\bar{\rho}\ (\overline{w's'} - L\overline{w'\ell'})\right)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = -\frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left(\bar{\rho}(\overline{w'q'} + \overline{w'\ell'})\right) \qquad (2)$$

Observational studies show that the turbulent transports of liquid cloud water and, respectively, the condensation and re- evaporation of cloud water play only a minor role for the heat and moisture balance of the cloud layer. Furthermore, they act in the same way as the turbulent processes of heat and moisture - that is to dry and warm the lower part of the cloud layer and to moisten and cool its upper part.

A shallow convection scheme has therefore been developed for the ECMWF model based on the assumption that the net effect by convection can be attributed to the turbulent fluxes of heat and moisture

$$\left(\frac{\partial \overline{T}}{\partial t}\right)_{cu} = \frac{1}{\overline{\rho} c_p} \frac{\partial H}{\partial z}$$

$$\left(\frac{\partial \overline{q}}{\partial t}\right)_{cu} = \frac{1}{\overline{\rho}} \frac{\partial W}{\partial z} \qquad (3)$$

The fluxes are parameterized on the basis of the mixing length theory

$$H = c_p \overline{\rho} \left(\frac{p}{p_o}\right)^{\kappa} K \frac{\partial \overline{\theta}}{\partial z}$$

$$W = \overline{\rho} K \frac{\partial \overline{q}}{\partial z} \qquad (4)$$

(4) is applied at model layer which are moist convectively unstable. Various methods of defining K have been investigated, including one where K was assumed to depend on the thermal stratification in terms of the vertical gradient of the equivalent potential temperature. However, the scheme performed best when K was set constant throughout the cloud layer

$$K = \begin{cases} 25 \text{ m}^2/\text{sec} & \text{in cloud layer} \\ 0 & \text{elsewhere} \end{cases}$$

This value is the one that reproduces the ATEX and BOMEX data.

The cloud base is assumed to be the condensation level for surface air and the cloud top the level of non-buoyancy, but not higher than 750 mb.

The whole cloud layer may consist of several model layers. The top and bottom layers (which contain the cloud base and cloud top) also include the subcloud air and the air above the inversion respectively. By applying (4) at the top layer we take into account the mixing of cloud air and air above the inversion - that is the entrainment of warm dry air into the cloud layer and the moistening and cooling of air above the inversion due to the evaporation of clouds. Sensitivity experiments with BOMEX and ATEX data have shown that excluding the mixing through the inversion from the scheme leads to a destruction of the cloud layer (subsidence of the inversion) due to the effects of large-scale subsidence. Therefore cloud top entrainment is important for maintaining convective cloud layers and must be adequately represented in a parameterization scheme for shallow cumulus convection. The importance of cloud top entrainment for deepening cloud layers has recently been stressed by Randall (1984).

The coefficient has been fixed so that the scheme reproduces the ATEX and BOMEX data.

This scheme is universal as it can be applied under a large variety of synoptic situations. Up to now it has been used on one-dimensional experiments using ATEX, BOMEX and GATE data and in a general circulation study. Results of these experiments are presented in Sections 2.1 for ATEX and in 2.2 for general circulation studies.

2.2 Studies of shallow cumulus convection for ATEX

This section describes the results of a prognostic study using data from ATEX. The data refer to an undisturbed period of the Atlantic tradewinds (7-12 February 1969), where shallow convection was the only type of cumulus convection that was observed. The synoptic flow was steady throughout the period and the trade wind boundary layer was essentially maintained by a balance of mean atmospheric sinking and turbulent and convective mixing from below. This period is therefore suitable for testing cumulus parameterization schemes and we performed a series of experiments to see how well the thermal state of the boundary layer is maintained if turbulent and convective processes are parameterized. For this purpose we prescribe all but turbulent and convective processes, and use a one column model for the experiments. The model equations (10) are identical to those used for the GATE experiments. The prescribed adiabatic processes, which refer to the whole period, are taken from Wagner (1975). Turbulent processes are parameterized by the Centre's boundary layer scheme and cumulus convection by various schemes - the Kuo-scheme, the A-S scheme and the shallow convection scheme described above.

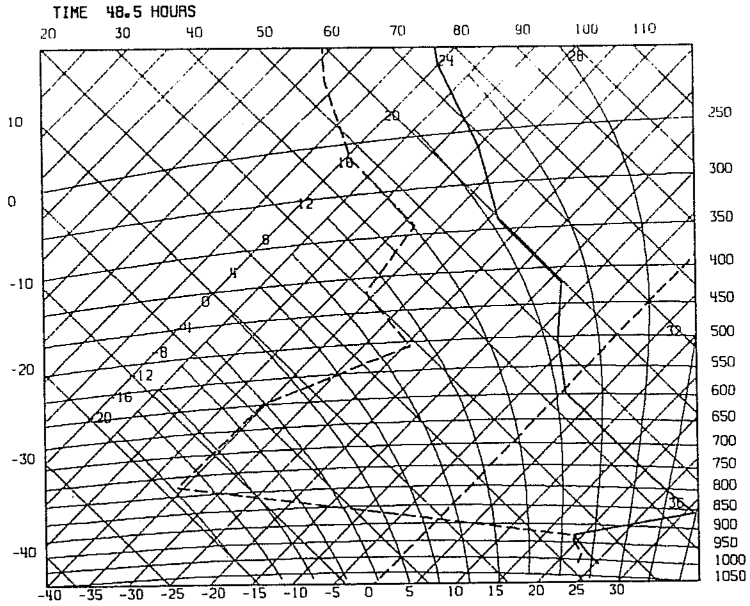
The initial data correspond to the observed time mean flow of that period and the forecasts are also verified against this mean flow (we have assumed steady conditions). Fig. 1 shows the thermal state after 2 days for two of the experiments. The integrations, where cumulus convection was parameterized by the Kuo- or the A-S scheme, showed that neither the Kuo-scheme nor the A-S scheme can provide enough vertical mixing of sensible heat and moisture to counterbalance the effects due to large-scale sinking. In the integrations with these schemes we find that the height of the inversion descends, within 2 days, from 850 mb to 925 mb and at the same time sharpens (see Fig. 1 for the A-S experiment). The lack of convection in the Kuo-scheme is not surprising in view of the closure assumption that cumulus convection is maintained by the net moisture supply into a grid-square due to large-scale plus turbulent processes; the failure of the A-S scheme is not so obvious but appears to be in agreement with the experience of other groups (S.W. Payne, personal communication).

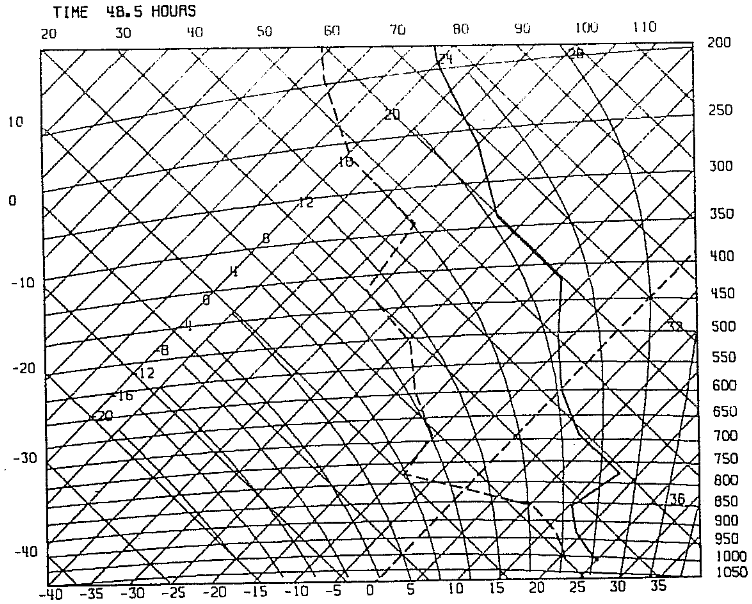
The integration with the shallow convection scheme on the other hand gave a realistic forecast (Fig. 1); the inversion height is not displaced to lower levels and is not intensified. In particular the simple diffusion scheme seems to maintain the characteristic structure of a tradewind boundary layer, that is we find a well mixed layer next to the surface and topped with a cloud layer. A diagnosis of the diabatic processes in the cloud layer (850 mb) shows that cumulus convection provides for a cooling and moistening of 4K/day and 3.5 g/kg/day, respectively, to balance the effects by large-scale sinking.

In summary, we find that the two convectional (penetrative) convection schemes, Kuo and A-S, fail to simulate shallow convection but that the effects of shallow convection on the large-scale flow can effectively be represented by simple schemes based on a vertical diffusion scheme.

2.3 General circulation study - shallow cumulus convection

In order to study the possible impact of parameterized shallow cumulus convection on the large-scale flow a general circulation simulation was carried out. Two 50-day integrations which differed only with respect to cumulus parameterization were carried out and intercompared. A control integration was performed using the present operational parameterization package whereas in the second experiment a shallow convection scheme described





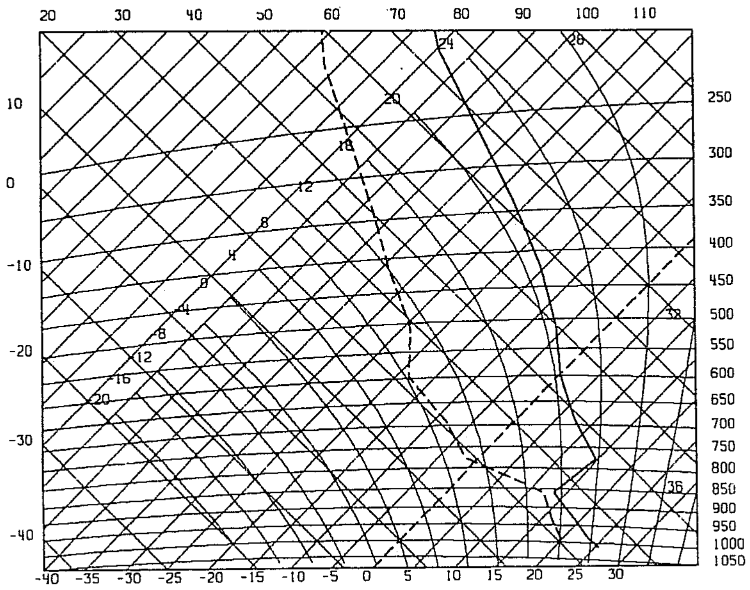


Fig. 1 Vertical distribution of temperature and dewpoint for ATEX (undisturbed period).
Top left: 48h forecast with A-S scheme
Top right: 48h forecast with shallow convection scheme
Bottom: Observed mean state.

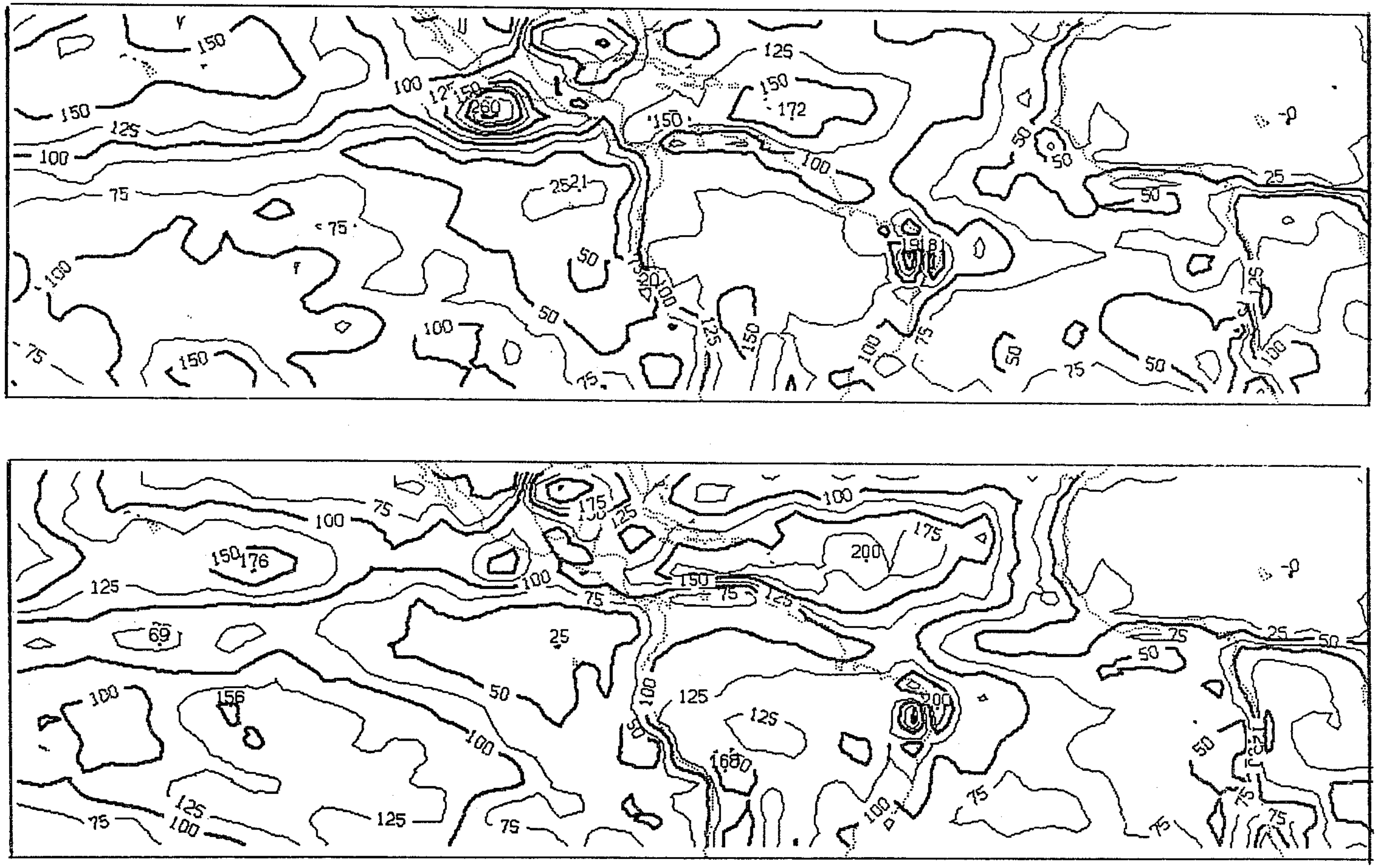


Fig. 2 (20-50)d mean surface evaporation rate (W/m^2) for shallow convection experiments. Top: control run (A-S scheme); bottom: run with shallow convection scheme.

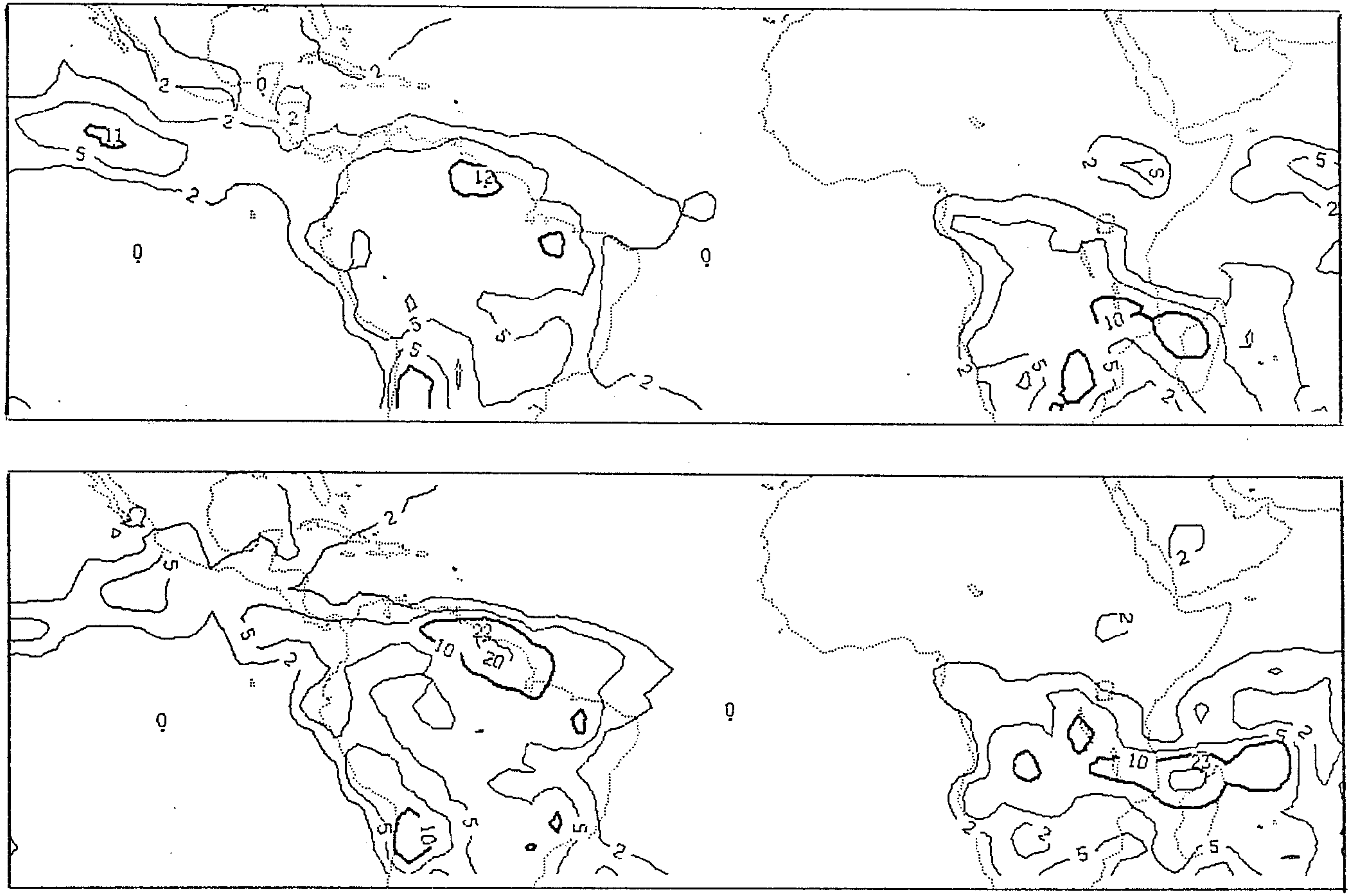


Fig. 3 As Fig. 2 but for precipitation (mm/day).

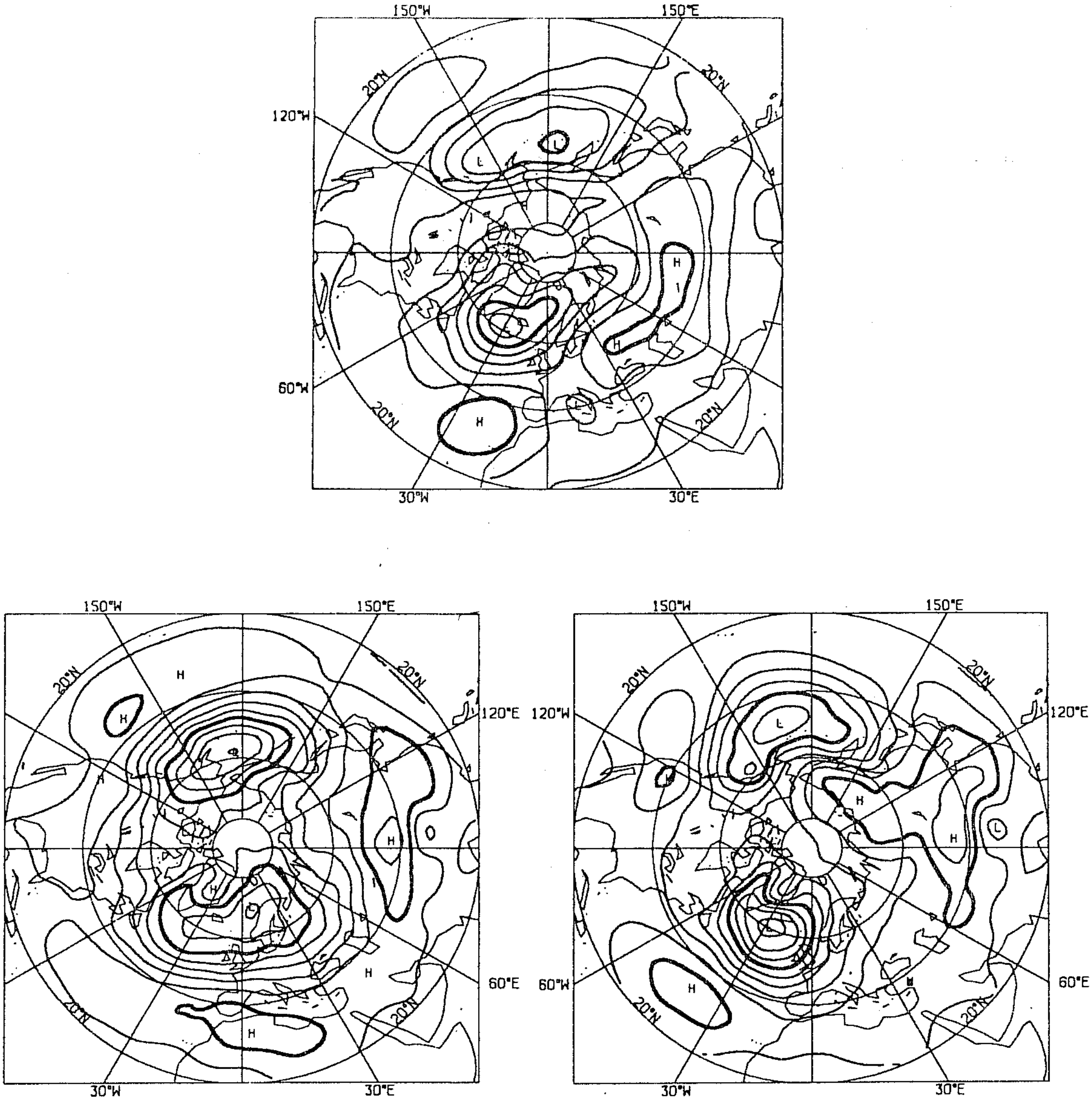


Fig. 4 (20-50)d mean 1000 mb height fields for the Northern Hemisphere for shallow convection experiments. Top: observed during February 1979, bottom left: control run (A-S scheme), bottom right: run with shallow convection scheme.

above was used in addition to the operation KUO convection scheme. The integrations were in all other respects identical to those described previously, i.e. T40 spectral model integrations carried out from initial conditions for 21 January 1979. The main results of this study are summarized in Figs. 2-4 which show geographical distributions of surface evaporation and precipitation as well as the mean surface pressure field.

(a) Surface evaporation

If shallow convection has an impact on the large-scale flow we expect this to occur mainly through modification of the hydrological cycle. A diagnosis of the hydrological cycle in the two simulations does indeed show considerable changes due to shallow convection. We found that the moisture which is supplied globally to the atmosphere through surface evaporation increased from the equivalent of 65 W/m^2 to 70 W/m^2, that is nearly 10%. The largest contributions came from the subtropical oceans where the surface evaporation rate increased locally by as much as 50 W/m^2 (Fig. 2). A closer examination of the geographical distribution of the surface evaporation revealed, however, large geographical differences at lower latitudes. We found:

(i) an increase of the surface evaporation in the subtropical belt between 10°N and 30°N and 10°S and 30°S, respectively;
(ii) a decrease outside this region.

Both effects are such as to enhance the geographical differences in surface evaporation, which is most strongly marked over the Northern Hemisphere oceans.

(b) Precipitation

Precipitation, being the other "end" of the hydrological cycle, is also markedly altered by the effect of shallow convection. From Fig. 3 it can be seen that the intensity of the precipitation has changed in many areas. The largest differences occur over Madagascar and the Indian Ocean, North Brazil and the Atlantic, where shallow convection enhanced the precipitation by up to 10 mm/day. The increase over Brazil and the Atlantic is a direct result of the increased moisture being supplied over the Atlantic tradewind area and advected towards lower latitudes by the mean low level wind. Unfortunately, it was not possible to study the boundary layer structure for the simulated mean flow (due to loss of model level data) but it is presumably similar to that obtained in the single column study for ATEX described in Section2.1.

(c) Response of the large-scale extratropical flow

In this section we describe its response to shallow convection as it occurred in this experiment. For this purpose we consider, as previously, the time mean surface pressure distribution for the Northern Hemisphere. From Fig. 4 it appears that the mean flow reacted surprisingly strongly to shallow convection- this can be judged from the intensity and position of the major pressure systems. The largest differences are observed over the Atlantic. In the control run the Atlantic anticyclone is displaced eastward over North Africa, whereas in the shallow convection experiment it is situated over the middle of the Atlantic. This westward position is presumably related to the intense diabatic heat source over North Brazil and the Atlantic which depends, as shown above, on the occurrence of shallow convection over the Atlantic which is more intense in the shallow convection experiment.

The main results from this study are:

Shallow cumulus convection plays an important role for the mean atmospheric flow since:-

(i) shallow cumulus convection enhances the moisture supply to the atmosphere within the trades;

(ii) shallow convection enhances, as a direct result of (i), the diabatic heat sources downstream in the tropics and the associated Hadley circulation;

(iii) shallow convection influences through its effect on the Hadley circulation, the subtropical flow and in particular the position of the Atlantic High.

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