EFFECT OF PHYSICAL PARAMETERISATION ON THE LARGE-SCALE FLOW IN THE ECMWF MODEL

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1. INTRODUCTION

Diabatic processes affect the atmospheric flow on a large variety of temporal and spatial scales. In the case of medium range forecasts we are only concerned with the forcing of large-scale transient disturbances and the slowly varying long waves. Although the forcing of these scales is generally considered important, a comprehensive theory to substantiate this statement is not presently available. As far as extratropical transient disturbances are concerned, diabatic effects would therefore best be studied in the framework of the baroclinic instability theory which when applied at mid-latitudes, say latitude ϕ, relates the growth rate G of a disturbance of wavelength L to the vertical wind shear ΔU and the vertical stability S of the basic flow

$$G = G\,(\Delta U,\ S,\ \phi,\ L)$$

The growth or decay of baroclinic disturbances may then be affected by diabatic processes in two ways:

(a) Through processes directly linked to the eddy flow itself (e.g. release of latent heat in large-scale ascent and surface friction).

(b) Indirectly through their effect on the basic flow (i.e. by diabatic heating in the tropics and radiative cooling at mid and high latitudes).

A systematic study which would clarify how diabatic processes and their parameterisation influence baroclinic developments through (a) has so far not been carried out at ECMWF. Instead, most of the work during the last few years has been devoted to the forcing of the quasi-stationary flow in the tropics. This work was motivated by the experience that the simulated tropical time-mean flow exhibits large systematic errors in the Centre's forecasts (Heckley, 1985) which points to deficiencies in the diabatic forcing. Also there was increasing concern that this erroneous tropical forcing may significantly affect the extratropical forecasts.

In particular, errors in the major quasi-permanent tropical heat sources (Indonesia, South America, Africa) may be responsible for a large part of the errors in the tropical flow and are likely to affect also the extratropical flow; for example the jet streams over North America and Eastern Asia which are largely maintained by the meridional circulation associated with these heat sources (Bjerknes (1969), Blackmon et al. (1977)). Besides, forecast experiments performed at ECMWF and discussed below indicate that the subtropical anticyclones respond to erroneous diabatic heating in the tropics.

Recent parameterisation studies at ECMWF have revealed that the intensity and location of the major tropical heat sources are most sensitive to the parameterisation of the following processes:

- penetrative cumulus convection
- cloud-radiation interaction
- shallow cumulus convection

and continuous effort is being made to improve their parameterisation in our global model.

In this paper I will summarise results from:

- extended integrations
- medium range forecasts

which demonstrate the effect of parameterisation of these processes on the time-mean flow, as well as its impact on medium range forecasts.

The results presented are obtained with the full model, which includes non-linear processes and feedbacks between the various components of the models, and are therefore difficult to interpret. Consequently, in order to provide some guidance for the interpretation of the flow response to parameterisation changes in the full model we will first consider a simple analytic model which describes the response of the tropical flow to prescribed diabatic forcings.

2. SIMPLE EXAMPLES OF FLOW RESPONSE TO DIABATIC HEATING IN LOW LATITUDES

The response of the large-scale flow in low latitudes to diabatic forcing has been investigated in various studies using simple models. Webster (1972) determined the response to realistic but prescribed diabatic heating and orography in a linear two-layer model. He found that most of the induced time-independent flow compared well with the observed flow in the tropics, but elsewhere there was less agreement and this points to a more complex forcing mechanism outside the tropics.

The nature of the response in the tropics has been explored by Webster (1972), Gill (1980), Lau and Kim (1982) and Heckley and Gill (1984) who investigated the response to simple forms of imposed diabatic heating in linear analytic models; such studies added much to our understanding of the phenomena involved. Two examples taken from Gill (1980) and Heckley and Gill (1984) are shown in Fig. 1, namely

- for a symmetric local heating at the equator;
- for a local heat source at 20°N.

The flow induced by these heat sources represent two basic types of flow observed in the tropics. Depending on the geographical position of the heat source, either a Walker type circulation (flow in east-west direction) or

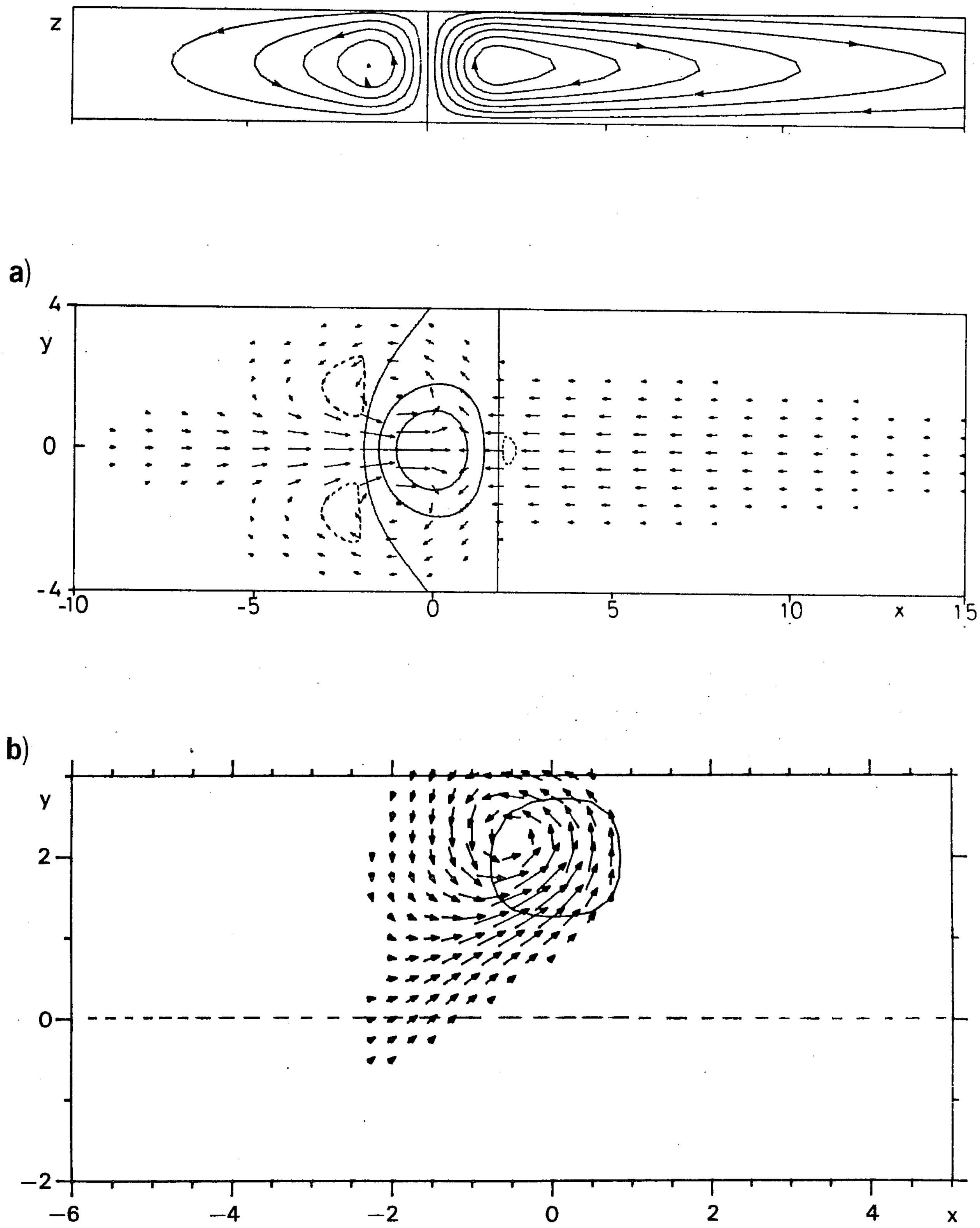

Fig. 1 Analytic solutions for prescribed heating
a) symmetric about the equator (top and middle) after Gill (1980)
b) at 20°N (bottom) after Heckley and Gill (1984)
top: vertical circulation; middle and bottom: low level flow

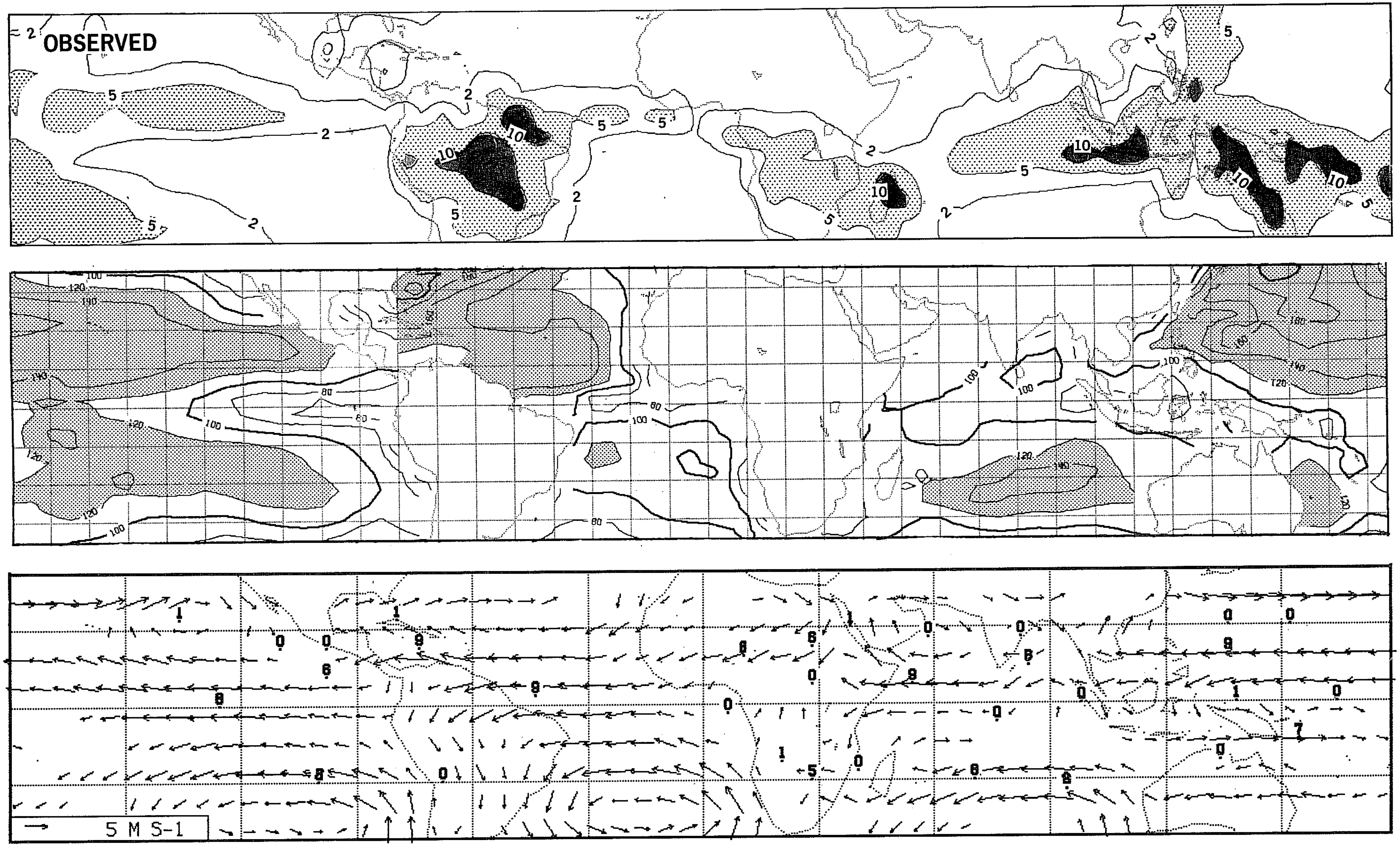

Fig. 2 Climate estimates of precipitation (top), evaporation over oceans (middle) and 850 mb flow (bottom) for February. Precipitation rates (mm/day) after Jaeger (1976), evaporation rates (W/m^2) after Esbensen and Kushnir (1981) and 850 mb flow as analysed at ECMWF (1980-1985).

a Hadley type circulation (meridional flow) predominates; the first is induced by diabatic heating symmetric around the equator and the second by an asymmetric heat source. In both cases a direct circulation is induced with rising motion within the heat source, low level convergent flow into the heat source, divergent flow at upper levels and subsidence outside the area of heating.

Even though solutions obtained with the analytic models apply to idealised conditions, they have been tentatively compared with reality by Lau and Kim (1982) and by Gill (1984) using realistic estimates of diabatic heating. Remarkable agreement with the observed flow was found in some cases. In particular, Lau and Kim (1982) were able to reproduce some important features of the Asian Winter Monsoon which develops as a result of the strong heat source over the Indonesian region and the heat sink over the Asian continent.

An essential assumption made in analytic models is the a priori specification of the diabatic heating. However, in a forecast model or a GCM, the heating has to be determined internally and this involves the parameterisation of various processes. The parameterisation of cumulus convection is crucial since the heating is largely through condensational heating in convective clouds. Also, since the release of latent heat is maintained by the moisture convergence into the heat source by the low level flow, the parameterisation of moisture supply through turbulent processes into the atmosphere from the oceans and tropical continents is important. This is illustrated in Fig. 2 which shows for the month February estimates of the climate diabatic heating (in terms of precipitation rates), surface evaporation rates and the mean low level flow over the tropical and subtropical oceans. Note that there are three major condensation heat sources, i.e. over the Indonesian region, South America and Africa, plus the less intense heat sources along the ITCZ over the

Central Atlantic and Pacific. The moisture being advected into the heat sources by the low level wind has been supplied to the atmosphere in regions far from the heat sources. In fact, most of the moisture is supplied over the subtropical oceans and is advected into the heat source by the trade winds. From these considerations we can already infer that the parameterisation of the following processes is significant:

- penetrative cumulus convection
- processes which affect the surface evaporation

In the study of processes which affect the surface evaporation we will demonstrate the effects of:

- shallow cumulus convection in the trades
- cloud-radiation interaction through its influence on the surface energy balance over the tropical continents.

3. SENSITIVITY OF THE TIME-MEAN FLOW TO THE PARAMETERISATION OF PENETRATIVE CUMULUS CONVECTION, CLOUD RADIATION INTERACTION AND SHALLOW CONVECTION IN A GCM

The effect of the parameterisation 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 and 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 a previous version of the ECMWF operational forecast model (Hollingsworth et al., 1980). The subgrid-scale processes which are parameterised include radiation, large-scale condensation, dry and moist convection, boundary layer turbulent fluxes, and land surface and ground hydrological processes. All processes are parameterised 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 parameterised in various ways.

3.1 Penetrative cumulus convection

Release of latent heat by penetrative cumulus convection is the dominant source of energy in the tropics and much effort went into its parameterisation during the last decades. Several parameterisation schemes have been designed which differ considerably in their basic design. Though there have been many comparisons of these schemes, it is still not possible to be confident about which one is most realistic and accurate. Therefore, in order to see how the simulated flow depends on the parameterisation of convection, a set of three experiments was carried out in which three of the most frequently used schemes were used; in addition a fourth experiment was performed with the parameterisation of convection discarded altogether.

- Moist adiabatic adjustment (Manabe et al., 1965) - MAA.
- Kuo-scheme (Kuo, 1974) - KUO.
- Arakawa-Schubert scheme (Arakawa-Schubert, 1974) - A-S.
- No parameterisation of convection - NO CONV.

The MAA-scheme is a simple adjustment scheme in which 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 parameterising penetrative convection. In the fourth experiment (NO CONV), parameterisation 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 parameterising 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 parameterisation than with the two penetrative convection schemes KUO and A-S.

3.1.2 Results

Results of the convection experiments are presented in Tiedtke, (1984b) and therefore are only summarised here:

- The simulated tropical heat sources and associated circulation are sensitive to the choice of the parameterisation scheme.
- The moist adiabatic adjustment scheme produces similar heating rates and circulations as obtained when parameterisation of convection is altogether ignored - the heat source over Indonesia and its associated circulation are much too strong, whereas the ITCZ over the Pacific and Atlantic are much too weak (Fig. 3 and Fig. 4).
- The two penetrative convection schemes (KUO and A-S) are similar in their performance but yield different diabatic forcing in some areas (Fig. 3). The overall effect of using the KUO or the A-S scheme is to reduce the intensity of the three major heat sources (Indonesia, South America, Africa) and to intensify the ITCZ. Heat sources and the circulation are more realistic than with the MAA scheme and in the absence of convection (NO CONV), but appear too week (Fig. 3 and 4).

The reasons for the large diversity in the four simulations, in particular in the Indonesian area, are not clear but may be related to differences in the simulated static stability within the heat sources for the following reason.

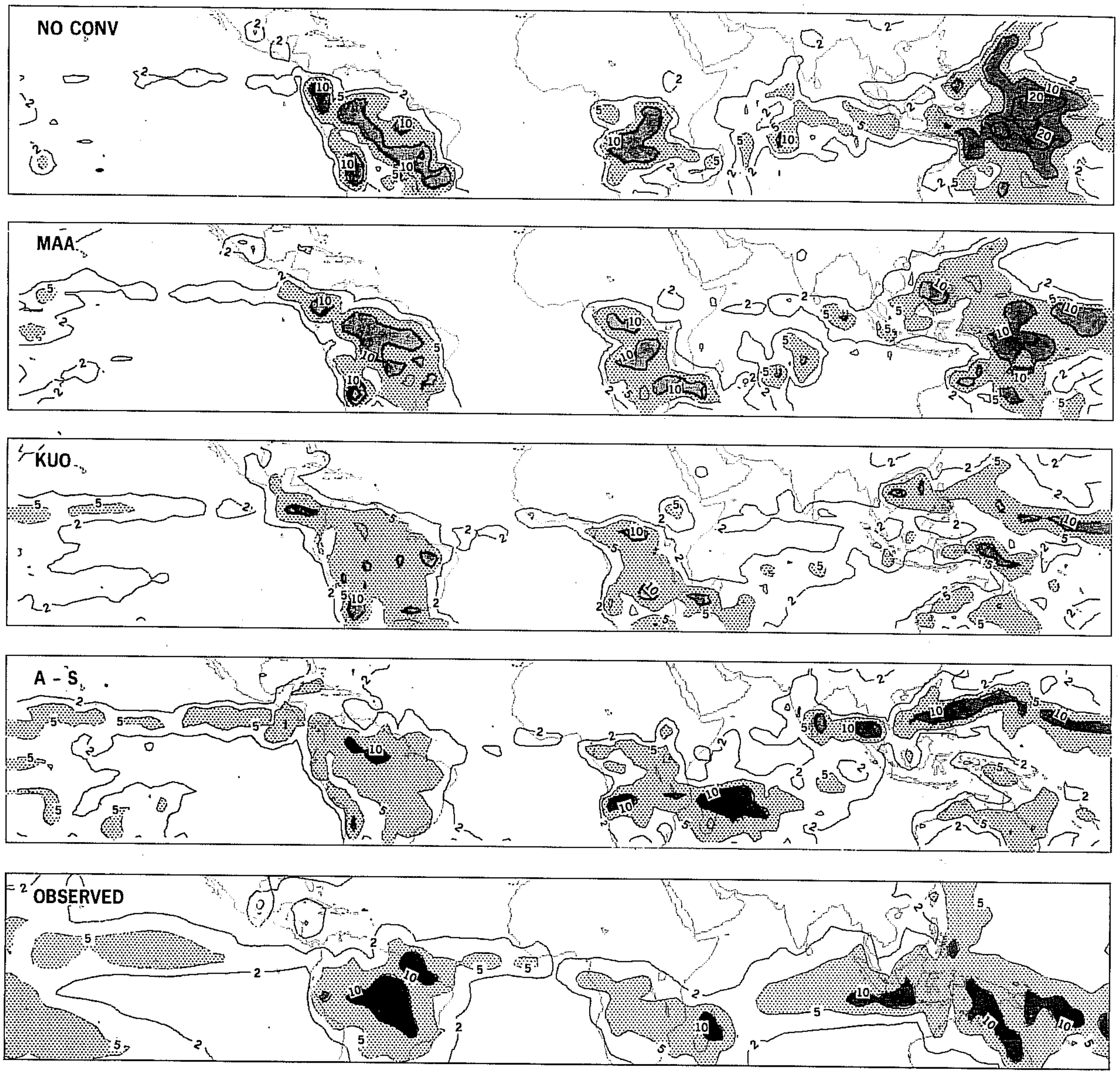

Fig. 3 (20-50) day mean precipitation rate (mm/day) for cumulus convection experiments and climate values for February after Jaeger (1976). Values above 5 mm/day are dotted, over 10 mm/day are black.

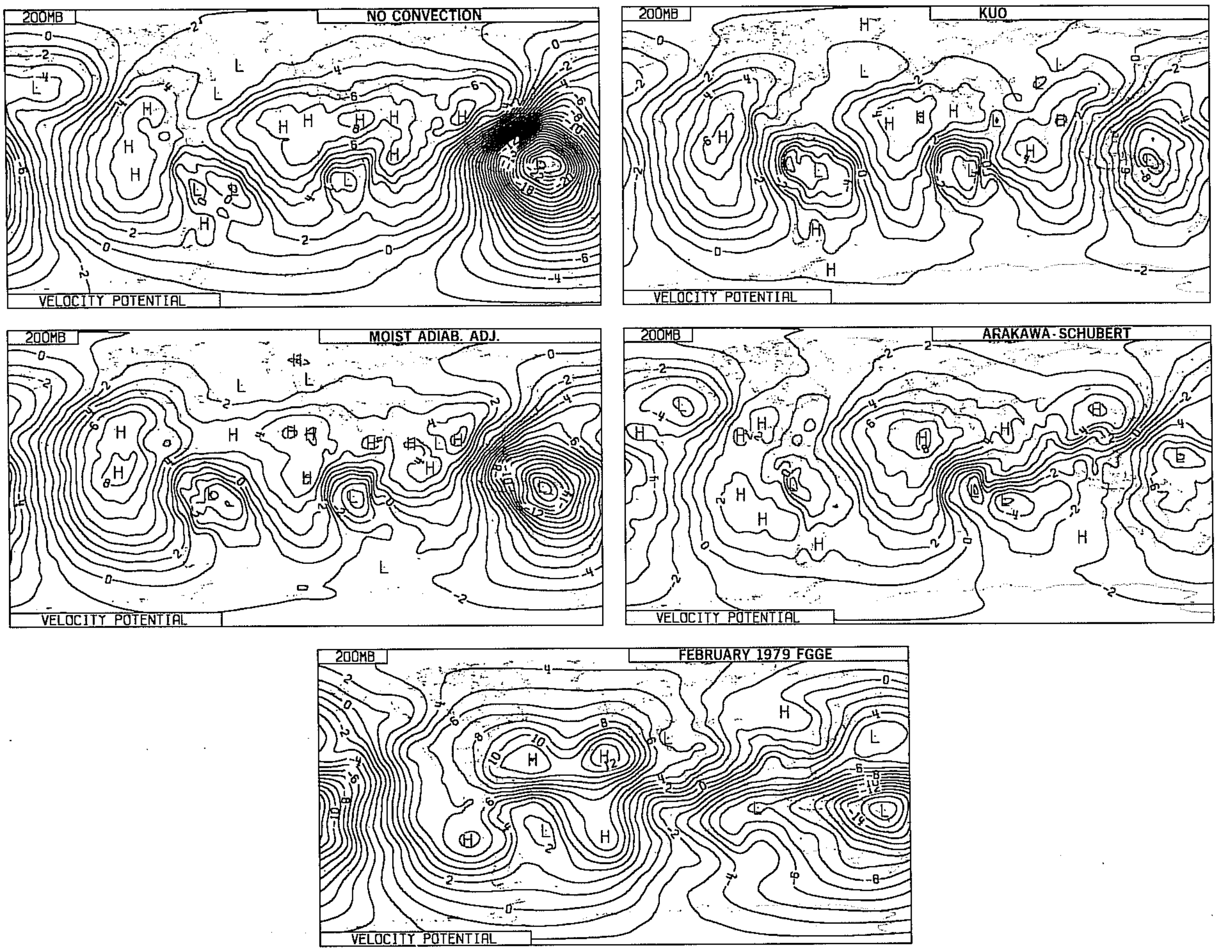

Fig. 4 (20-50) day mean velocity potential $\chi(10^6\ m^2/sec)$ at 200 mb for cumulus convection experiments and observed mean distribution during February 1979 (analysed at ECMWF). The irrotational component of the wind is perpendicular to the contours from lower to higher values, the intensity being proportional to the gradient of χ.

In steady state conditions the balance in the heat sources is between convective heating/drying, adiabatic cooling/moistening due to vertical ascent and moisture supply by horizontal advection:

$$\omega \frac{\partial\theta}{\partial p} = S_T$$

$$\underline{V}.\nabla q + \omega \frac{\partial q}{\partial p} = S_q$$

where the symbols have the usual meaning and S_T and S_q denote convective heating and moistening.

Integrating over the whole heat source we obtain

$$\int \omega \frac{\partial\theta_e}{\partial p}\, dpdF = - \frac{L}{C_p} \int \left(\frac{P_o}{p}\right)^{R/C_p} \underline{V}.\nabla q\, dpdF$$

The balance is now between vertical advection of equivalent potential temperature and the convergence of moisture; this indicates that the intensity of the vertical ascent (and consequently moisture convergence and convective heating) depends on the magnitude of the moist static stability ($\sim \frac{\partial\theta_e}{\partial p}$). We are therefore lead to the conclusion that realistic diabatic heat sources, and in turn a realistic circulation, can only be obtained if the convection scheme used provides realistic static stabilities. This is presumably more easily achieved by the KUO and the A-S schemes than the MAA scheme or when convection is ignored.

3.2 Cloud-radiation experiments

The interaction of clouds with radiation may have a profound influence on the forcing of the atmospheric flow. With the advance of GCM's there has been an increased interest in the study of cloud-radiation feedback processes. Unfortunately, very little is known about the temporal and spatial distribution of clouds, and therefore clouds are treated rather crudely in models. Sometimes only a zonally aeraged cloud cover is used (Holloway and Manabe, 1971), but such studies cannot add much valuable information to our understanding of the interaction of clouds and atmospheric motion. Therefore interactive cloud-radiation schemes have recently been deployed to study certain aspects of the atmosphere's general circulation and climate (Herman et al., 1980; Shukla et al., 1981; Hunt, 1982). The net effect of clouds depend upon two competing cloud-radiation feedback mechanisms; these are connected to the albedo effect (i.e. decrease of radiation budget by reflection of solar radiation) and greenhouse effect (i.e. increase of radiation budget by absorption and re-emission of thermal radiation). Results obtained by Herman et al. (1980) suggest a positive feedback loop over the sea where the greenhouse effect dominates and a negative feedback loop over land where the albedo effect is dominant. The existence of such feedback loops would further suggest that cumulus convection and cloud-radiation interaction cannot be treated independently in models if the diabatic forcing of the large-scale flow is to be realistic. The interaction between cumulus cloud fields and radiation is especially important in view of the dominant role cumulus convection plays in the diabatic forcing of the atmospheric circulation.

3.2.1 Parameterisation of cloud cover

In present models parameterisation of cloud-radiation interaction has not been adequately resolved. The main obstacle to progress arises from the difficulty of specifying realistic cloud amounts from the model's convective activity, as it is directly connected only to the active cumulus clouds but not to the total cumulus cloud amount. Therefore at this stage we study the effect of cumulus cloud-radiation interaction on the large scale flow by investigating its sensitivity to the extreme cases of non-interaction and maximum interaction.

The effect of cloud-radiation interaction on the large scale flow is studied by using a fully interactive scheme. Therefore, model generated cumulus cloud fields are used as input for the radiation calculation. The cumulus cloud cover is derived from the convective precipitation. Two 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

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

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

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

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

3.2.2 Results of cloud-radiation experiments

Results of the cloud-radiation experiments are again presented in Tiedtke (1984b). Although cloud-radiation interaction affects the zonal mean, as well as the zonally asymmetric diabatic forcing, we will discuss only the effects on the major tropical heat sources.

Cloud radiation interaction has a large effect on the tropical heat sources and the circulation (Fig. 5 and Fig. 6). The effect is of opposite sign over sea and land.

Over the sea we find that cumulus convection is increased along the ITCZ over the Pacific and Atlantic (although to a lesser degree), and also over the Indian Ocean; however, the heat source over the Western Pacific remains unchanged. The increase over the oceans is presumably related to the "greenhouse" effect of cumulus clouds which initiates a positive feedback loop between cumulus convection, radiative cooling at cloud top levels and the large-scale flow.

Over the tropical continents, cloud-radiation interaction has the opposite effect and causes the convective precipitation to decrease over large areas by more than 5 mm/day. Part of this decrease is explained by the dominance of the albedo effect over the "greenhouse" effect, which causes the downward radiation flux to decrease at the surface, locally by up to 100 W/m^2 (Fig. 7) and globally by 29 W/m^2. Consequently, less radiant energy is available for evapotranspiration which in turn reduces the precipitation by an equivalent amount of 3 mm/day. The precipitation is further decreased because of a weakening of the large-scale convergent flow which then transports less moisture onto the tropical continents. As the moisture transport by the large scale flow has not been directly calculated, it has been indirectly diagnosed from the precipitation P and the surface evaporation E. For steady state conditions, as apply for the time scale considered here, the difference P-E equals the moisture converged into the area in question. The experiments show that in the presence of cloud-radiation interaction, moisture convergence is reduced by 3 to 5 mm/day over large areas.

Thus, we find that convective heat sources depend on cloud-radiation interaction in two ways: thermally through the albedo and "greenhouse" effects, and indirectly through its effects on the large scale flow.

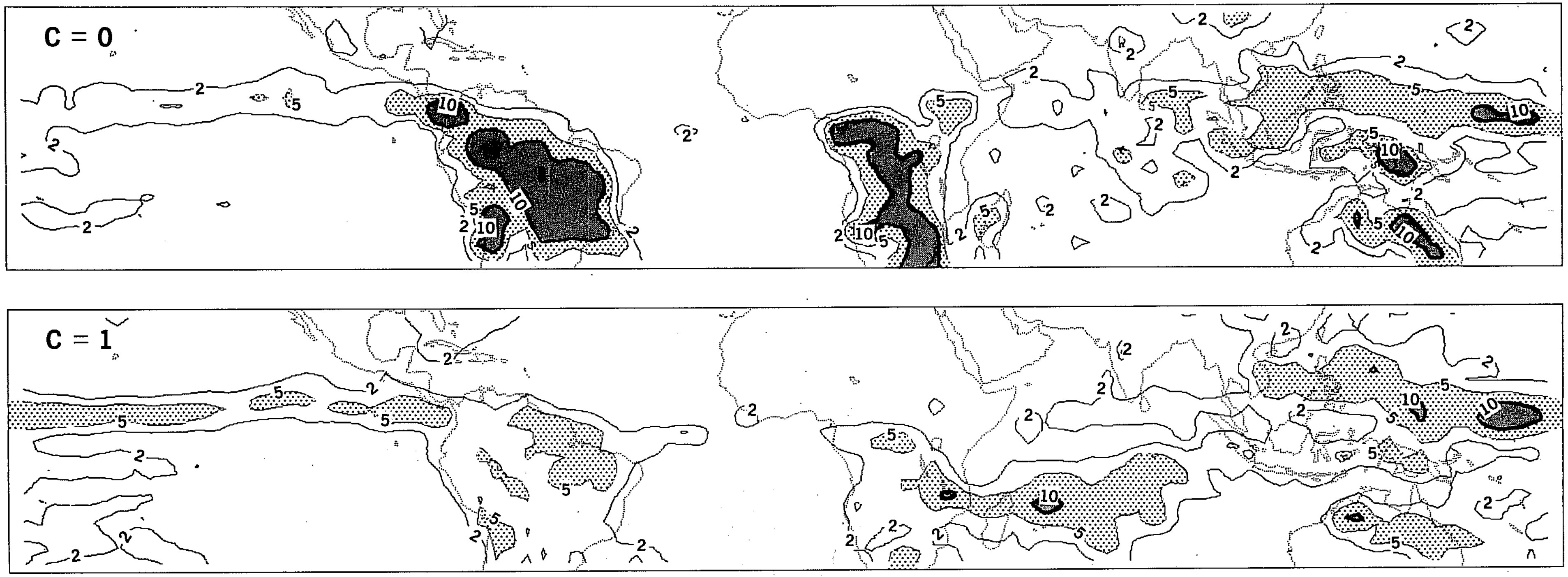

Fig. 5 (20-50) day mean precipitation rate (mm/day) for cloud-radiation experiments.

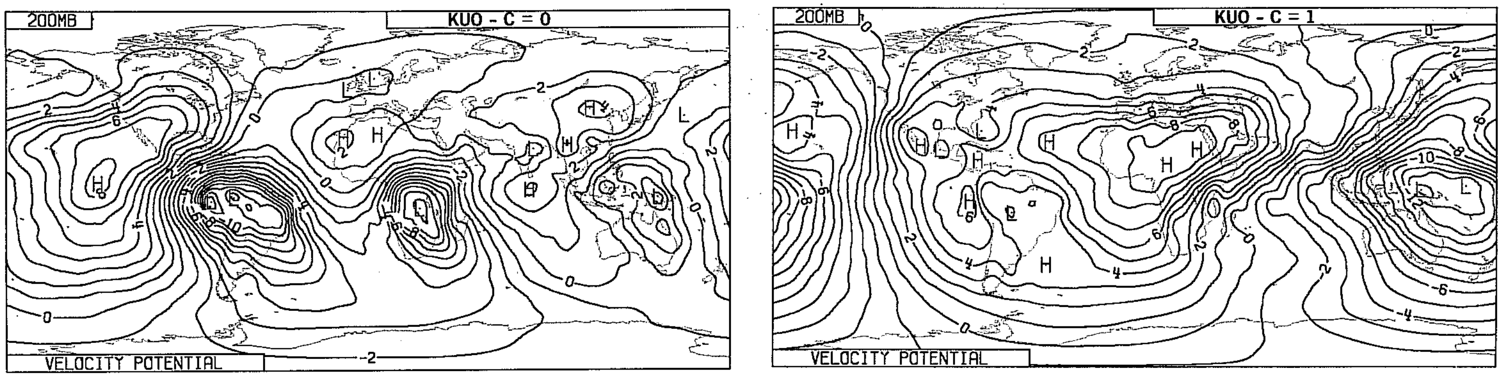

Fig. 6 (20-50) day mean velocity potential (10^6 m^2/sec) at 200 mb for cloud radiation experiments.

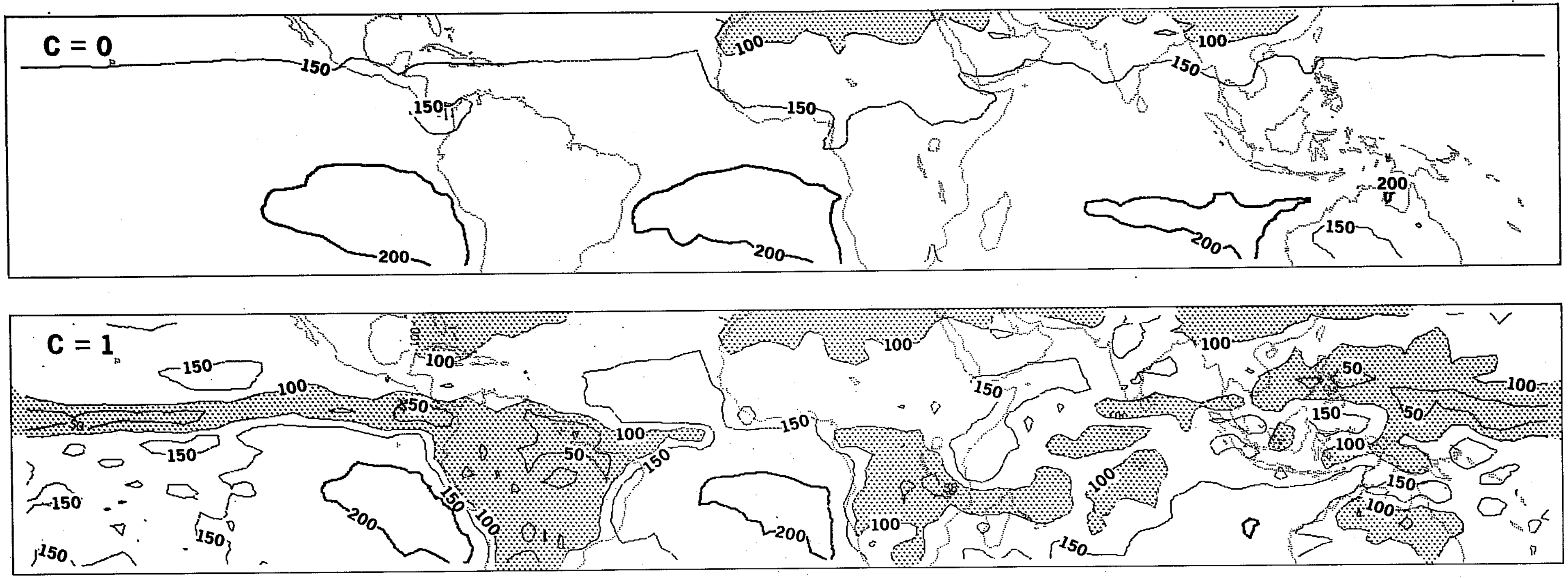

Fig. 7 (20-50) day mean net downward surface radiation flux (W/m^2) for cloud-radiation experiments. Values below 100 W/m^2 are dotted.

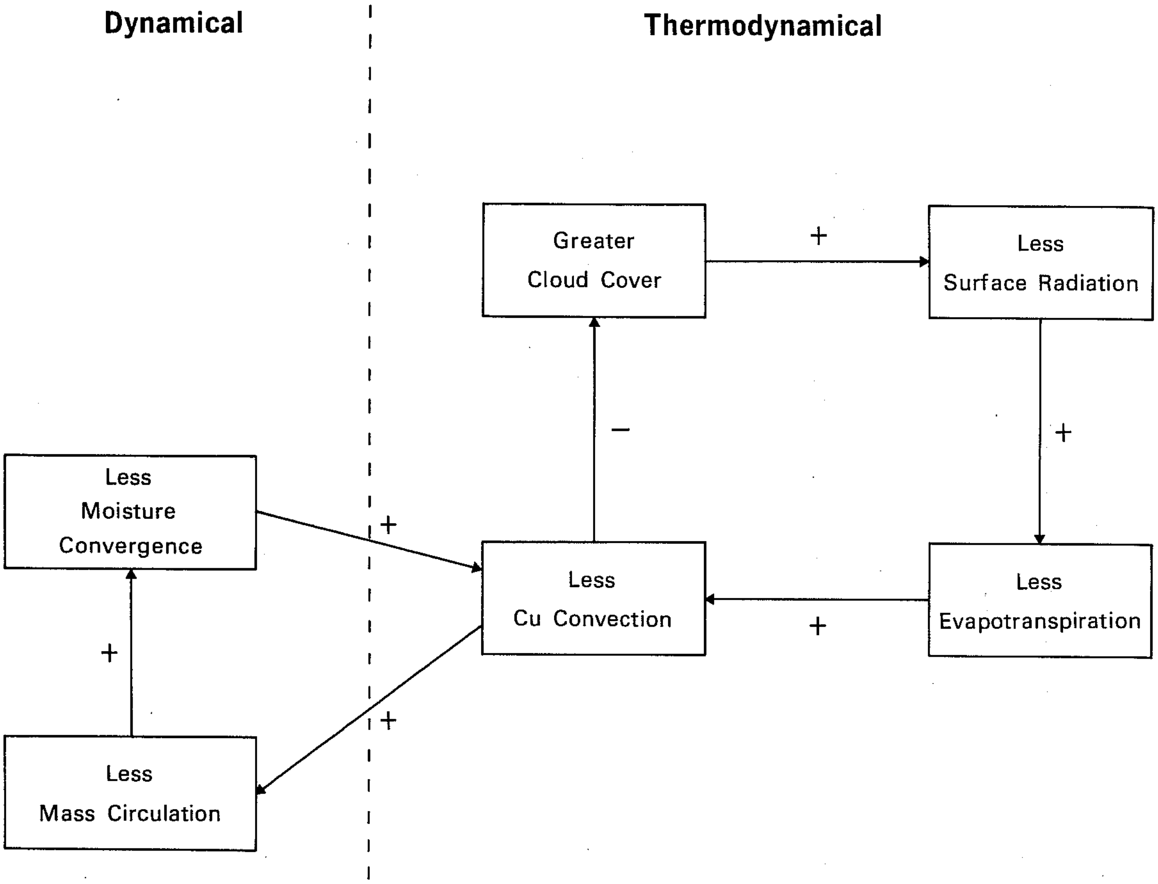

Fig. 8 Schematic diagram of feedback loop for cloud-radiation interaction, surface evaporation, cumulus convective heating and large-scale moisture supply.

The situation over land is illustrated schematically in Fig. 8: an increase in the cumulus cloud amount is followed by changes in surface radiation, evapotranspiration, cumulus convective heating and large-scale moisture convergence which in turn leads to a reduction in the cloud amount. This is a negative feedback loop which tends towards an equilibrium through the combined action of all the components, including the dynamics. The results show that the dynamical part of the feedback contributes more to the total feedback than the part involving clouds, radiation and convection. A similar but positive feedback loop is evident over the sea where the "greenhouse" effect, cumulus convective heating and large-scale flow are involved.

From these experiments we must conclude that errors in the convective cloud cover can lead to large errors in the diabatic heating over the tropical continents and the associated circulations.

3.3 Shallow cumulus convection

Shallow cumulus convection is generally not parameterised in large-scale models for two main reasons. Firstly, the effects of shallow convection on the large-scale flow has probably been underestimated. Secondly, the vertical resolution of large-scale models is generally too coarse to resolve the cloud layer associated with shallow convection; the ECMWF vertical grid spacing probably being just near the critical resolution.

Shallow convection has primarily a local effect on the thermal state as it ensures that water vapour is accumulated in a cloud layer at the top of the well mixed boundary layer. This is most pronounced in the trades and has been confirmed by observational studies during BOMEX[1] (Holland et al. 1973) and during ATEX[2] (Augstein et al. 1973). Through this local effect it may exert a significant influence on the hydrological cycle in the tropics and consequently on the diabatic forcing of the large-scale flow. In fact diagnosis of the Centre's forecasts revealed deficiencies in areas which point directly to the lack of shallow convection over the subtropical oceans.

3.3.1 Parameterisation scheme

A shallow convection scheme has recently been developed, in which the turbulent transports of sensible heat and moisture are represented by vertical diffusion within moist convectively unstable layers, through cloud base and the level of non-buoyancy. A full description of the scheme is given in Tiedtke (1984a) but is briefly summarised here.

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[1] BOMEX = Barbados Oceanographic and Meteorological Experiment, 1969
[2] ATEX = Atlantic Trade Winds Experiments, 1969

The effects of non-precipitating cumulus convection on the large-scale heat and moisture budget can be described by the turbulent fluxes of sensible heat, moisture and condensation processes:

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

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = - \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho}\ \overline{w'q'}) - (C-E)$$

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

where $\bar{s} = c_p\bar{T} + gz$ is the dry static energy, C and E are the condensation and evaporation rates, respectively. For non-precipitating cumulus convection the time change and advection of liquid cloud water ℓ by the large-scale flow are typically small; consequently the balance is between the turbulent transport of liquid cloud water and the result of the condensation-evaporation process

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

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

In the present version of the scheme the turbulent transports of liquid cloud water are ignored and the turbulent fluxes of heat and moisture are parameterised by means of the mixing length theory. The diffusion coefficient is assumed to be constant throughout the cloud layer and a value has been chosen so that the scheme gives the best reproduction of ATEX and BOMEX data. The scheme effectively transports moisture from the cloud free part of the boundary layer into a cloud layer above. This is most pronounced in the trades, where shallow convection counteracts the drying and warming by the large-scale subsidence. A typically ascent in the trade winds (Fig. 9 for undisturbed period during ATEX) shows that with shallow convection the well mixed boundary layer is capped by a conditionally unstable cloud layer with a realistic moisture content slightly below saturation over a few layers. This

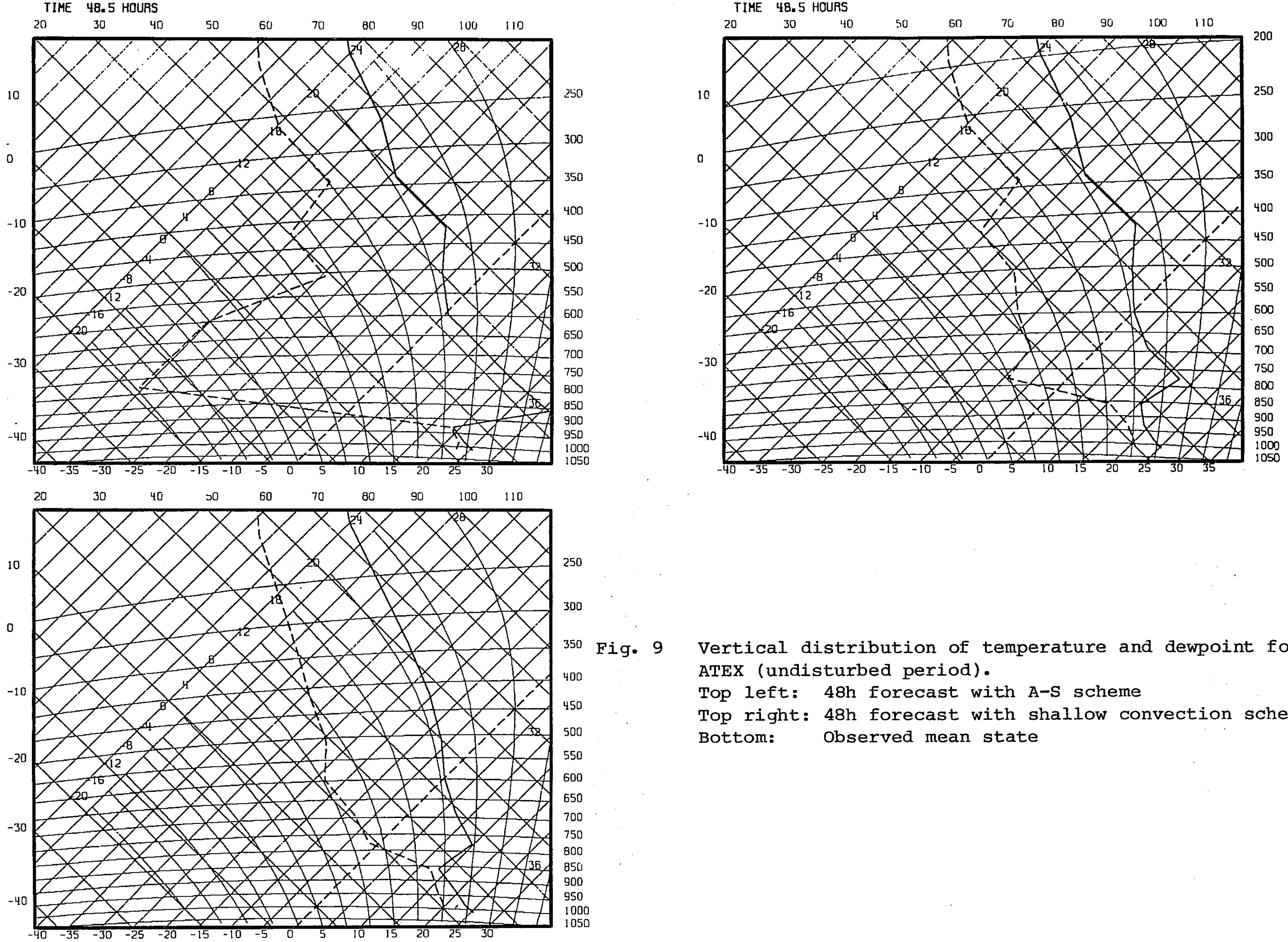


Fig. 9 Vertical distribution of temperature and dewpoint for ATEX (undisturbed period).

Top left: 48h forecast with A-S scheme

Top right: 48h forecast with shallow convection scheme

Bottom: Observed mean state

has to be compared with the shallow almost saturated boundary layer predicted in the absence of shallow convection (Fig. 9).

3.3.2 Results of shallow convection experiments

The effect of shallow convection on the time-mean flow has again been studied in the Centre's GCM by comparing simulations, with and without the shallow convection scheme included. Results are presented in Tiedtke (1984a).

In summary we find that shallow convection has a strong impact on the time-mean flow through intensifying the hydrological cycle which occurs through

- enhancing the moisture supply into the atmosphere within the trades;
- enhancing the moisture transport into the tropics and thereby enhancing the tropical heat-sources;
- intensifying the anticyclonic flow over the subtropical oceans (including the trades).

This situation is illustrated in Fig. 10 showing schematically a vertical cross-section along the trades and the ITCZ, e.g. from northeast to southwest over the Atlantic.

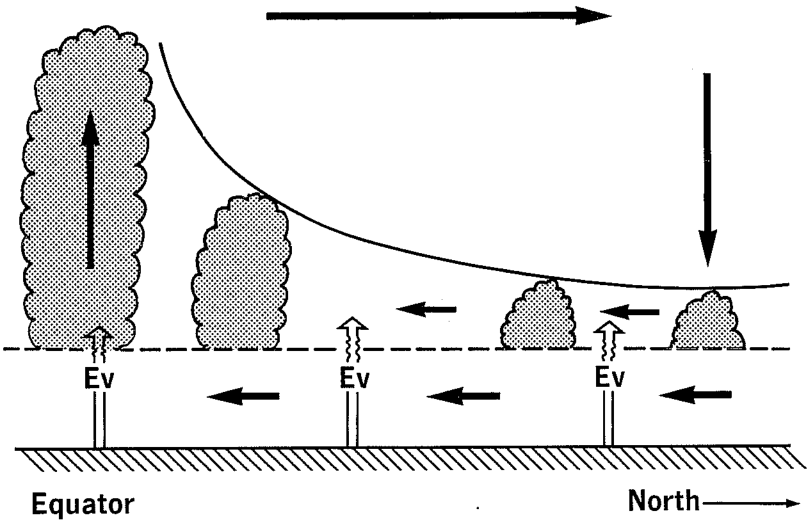


Fig. 10 Schematic cross-section through trades and ITCZ illustrating circulation, boundary layer and cumulus layer.

The effect on evaporation, precipitation and large-scale flow are evident from Fig. 11-13. Surface evaporation (Fig. 11) is increased by as much as 50 W/m^2 over large parts of the subtropical oceans. Precipitation (Fig. 12) increased by up to 10 mm/day, with the largest differences occurring over Madagascar and the Indian Ocean, North Brazil and the Atlantic; the increase over Brazil and the Atlantic being a direct result of the increased moisture supply over the Atlantic trade wind area. The response of the large-scale flow was found to be surprisingly strong (Fig. 13), with the largest differences observed over the Atlantic. In the control run (no shallow convection) the Atlantic anticyclone is displaced eastward towards 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 more intense diabatic heat source over North Brazil and the Atlantic as shown before. This strong response is confirmed by further forecast experiments discussed below.

4. EFFECT OF PARAMETERISATION ON MEDIUM RANGE FORECASTS

The effects of parameterisation of convection and cloud-radiation interaction have also been studied in medium range forecasts with the Centre's model. Revised parameterisation schemes were tested in a series of forecast experiments. These showed a positive impact on forecast quality and subsequently the parameterisation schemes were implemented in the Centre's operational model on 1 May 1985. Results from the forecast experiments will be summarised and some results from recent operational forecasts presented.

4.1 Parameterisation modifications

Two modifications have been made to the operational Kuo-scheme for penetrative convection. Firstly, the cloud base is redefined as the condensation level for surface air (lowest model level) rather than that for air with the mean characteristics of the sub-cloud layer. This change enhances the occurrence

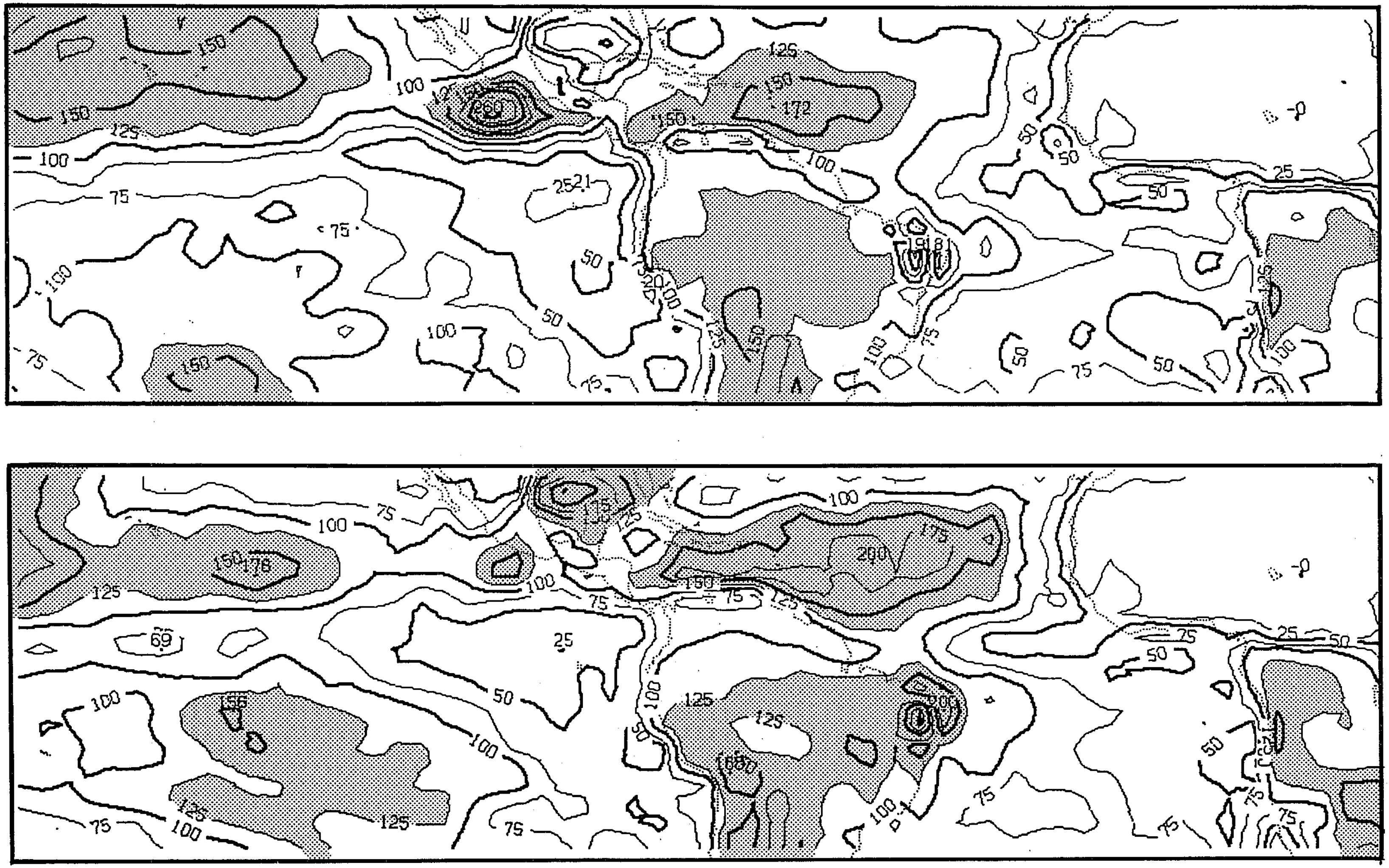


Fig. 11 (20-50) day mean surface evaporation rate (W/m^2) for shallow convection experiments. Top: control run; bottom: run with shallow convection scheme.

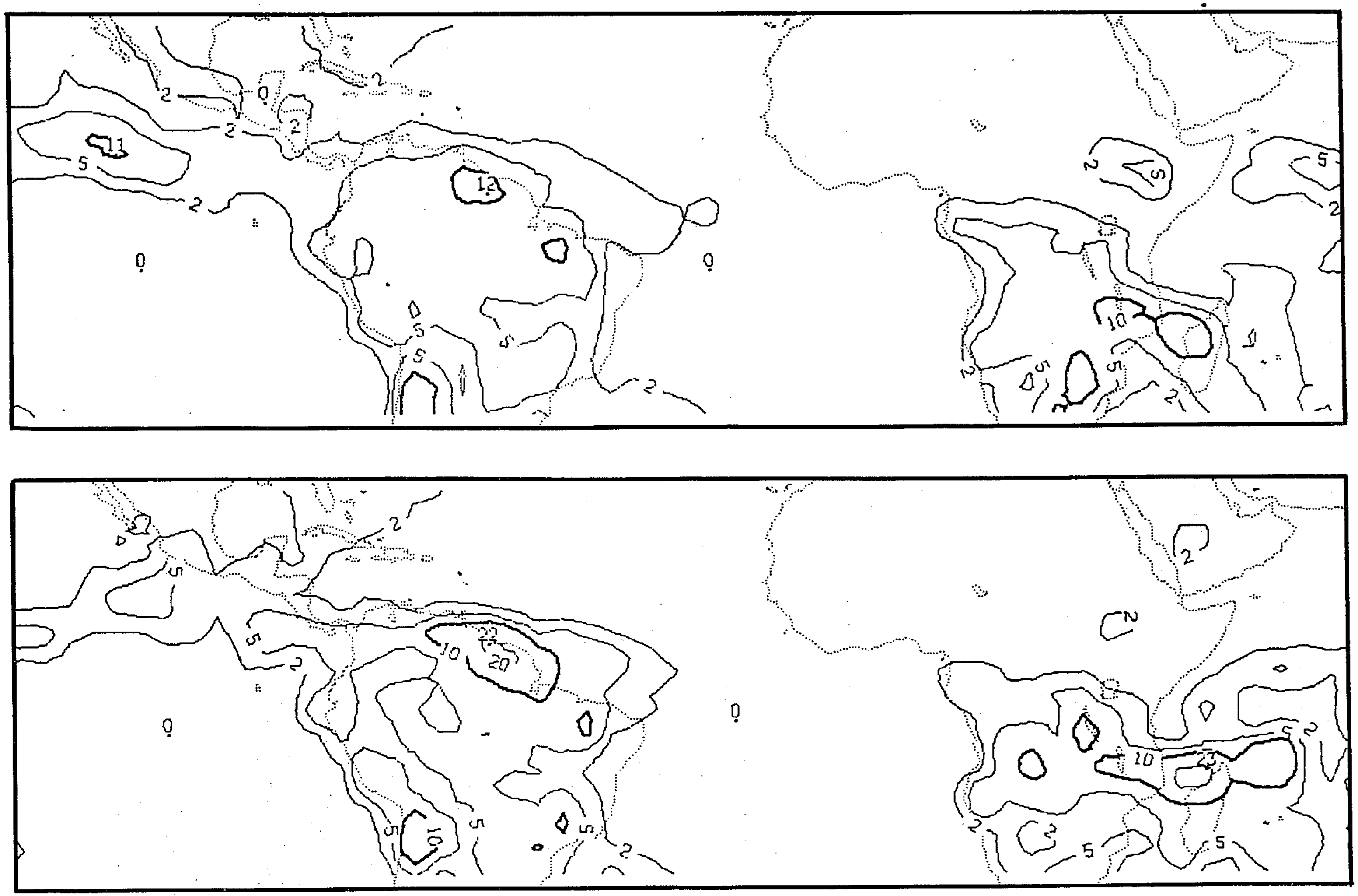


Fig. 12 As Fig. 11 but for precipitation (mm/day).

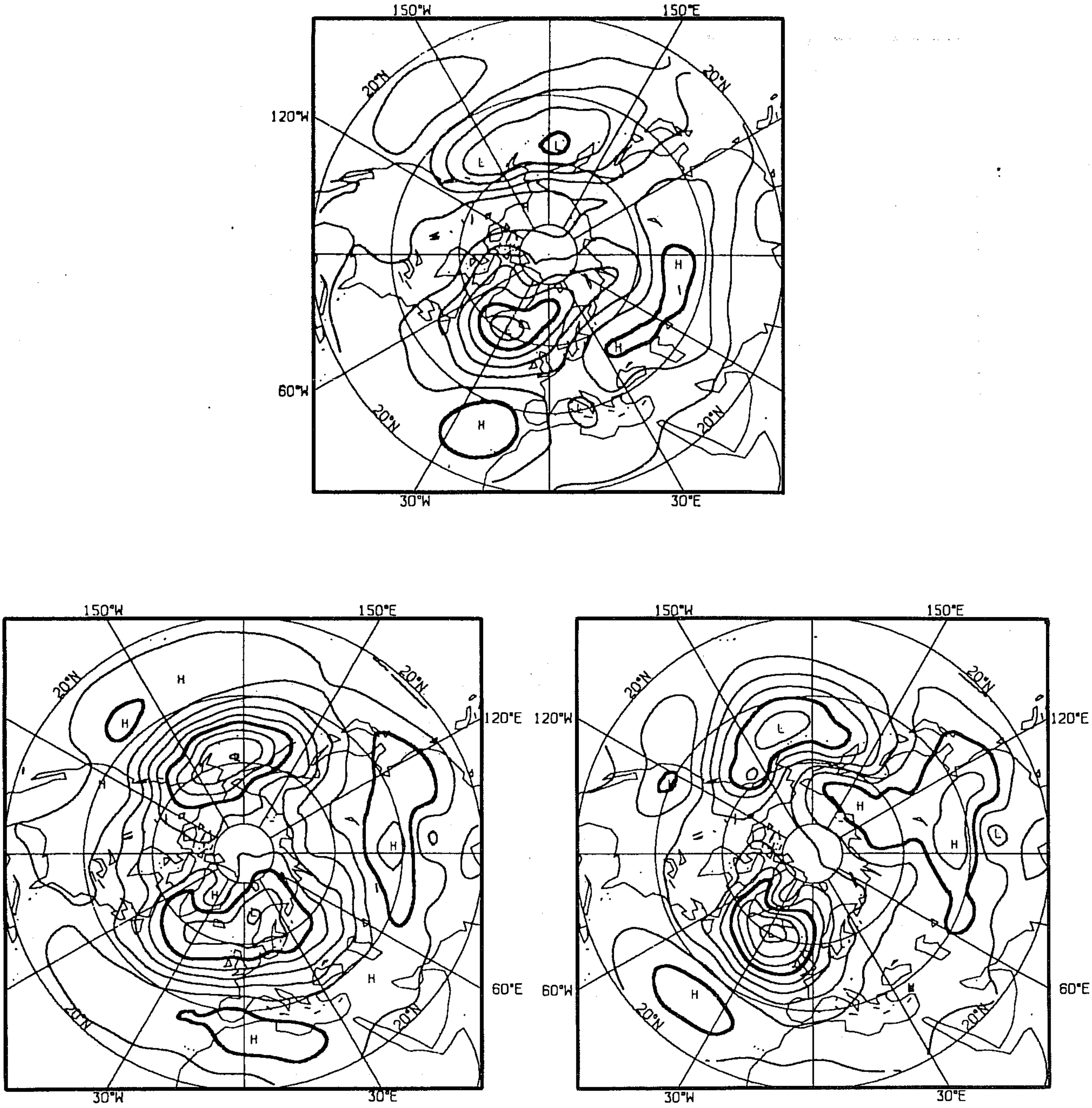


Fig. 13 (20-50) day mean 1000 mb height fields for the Northern Hemisphere for shallow convection experiments. Top: observed during February 1979; bottom left: control run; bottom right: run with shallow convection scheme.

of cumulus convection which was previously underestimated, and gives a more realistic response by the convection to the dinural cycle in surface heating over the continents. The second change involves the moistening parameter β, which determines the partitioning between convective heating and moistening. In the previous scheme β was assumed to depend linearly on the environmental saturation deficit. From experience it was found that this formulation tended to overestimate the moistening and underestimate the heating by latent heat release. This deficiency was particularly noticeable in a simulation of intense convection during GATE (using the composite data for Phase III, Thompson et al., 1979). The simulation was much improved when β was replaced by β^3 which provides less moistening and more heating through a stronger dependency on the saturation deficit, and as a result a more realistic thermal state.

Shallow convection, which was previously not considered, is parameterised by the vertical diffusion scheme already described in Section 3.3.

In order to improve cloud-radiation interactions, a new cloud scheme developed by Slingo (1985) has been introduced (see seminar paper by J. Slingo). The scheme allows for several cloud types. Convective clouds and anvil cloud are determined from the convective activity (i.e. convective precipitation rate from the Kuo-scheme); high, middle and low layer clouds are determined from the relative humidity field and boundary layer clouds associated with low level inversions are determined from the intensity of the inversion and the relative humidity under the inversion. The scheme has been tested on a variety of cases. It appears to give more realistic cloud distributions than the previous scheme. However, its impact on a 10-day forecast is not very large, certainly not as large as that due to the changes in the convection parameterisation. This is mainly because the radiative time-scales themselves are large.

In addition to these changes, minor modifications were made to the parameterisation of evaporation of large-scale precipitation and melting of snow.

4.2 Results from numerical forecast experiments and recent operational forecasts

Assessment of medium range forecasts shows that the flow response to the parameterisation changes found in the time mean flow already occurs on much shorter time-scales, i.e. below 10 days. This was first noted in a series of forecast experiments (Tiedtke and Slingo, 1985) and was then confirmed in recent operational forecasts with the revised scheme. In view of the similar response, we will briefly summarise the results and illustrate some of them by comparing recent forecasts made with the revised physics (June 1985) with earlier forecasts with the original scheme (June 1984). The parameterisation changes primarily affect the diabatic forcing in the tropics and therefore influence initially the tropical flow. Here we will first consider the tropics and subtropics, and then the extratropics.

4.2.1 Tropics and subtropics

The main effects in the tropics and subtropics are as follows:

(a) The tropical diabatic heat sources are stronger because of an intensified hydrological cycle due to moisture supply in the subtropics. This is evident from the comparison of the mean evaporation of the mean evaporation and precipitation rates for June 1984 and June 1985 averaged over the first 5 days of all forecasts for June (Fig. 14 and Fig. 15).

(b) The model's tendency to cool the tropical and subtropical troposphere is removed (see Tiedtke and Slingo, 1985).

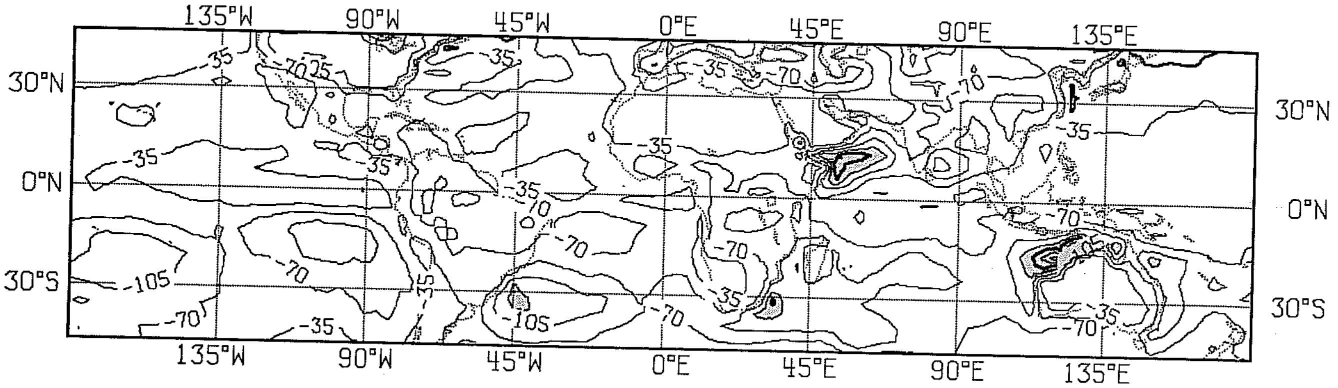
(c) The Hadley circulation is stronger as a result of the stronger diabatic forcing, as can be seen from the upper level divergent wind denoted by the velocity potential at 200 mb (Fig. 16).

(d) The quasi-stationary subtropical anticyclones are stronger and more realistic. Also deficiency in the production of upper level vorticity in the subtropics is largely removed. As a consequence tropical and subtropical forecasts are considerably improved.

The strengthening of the subtropical anticyclones is evident from the comparison of the mean forecast errors of the rotational flow at day 5 for June 1984 and June 1985 (Fig. 17). The weakening of the subtropical anticyclones, noted in the forecasts for June 1984 over the Atlantic and Pacific in both hemispheres, appears as spurious cyclonic circulations in the forecast error field. These cyclonic circulations have largely disappeared in the forecasts with the revised physics, and in particular have lead to stronger and more realistic trades over the Atlantic and the Pacific in both hemispheres. In addition, the spurious westerly low level flow over Africa which is a typical feature in previous forecasts has also disappeared (Fig. 17). Similar improvements are found in the upper troposphere; we find that the forecasts with the original physics are characterised by large anticyclonic errors in the subtropics (Fig. 18) which may be interpreted as a poleward shift of the subtropical jet steams and the occurrence of a too strong easterly flow at the equator.

These errors are much reduced with the revised physics. The changes result presumably from an increased production of anticyclonic vorticity at lower levels and cyclonic vorticity at upper levels, in connection with the more intense Hadley circulation due to the stronger tropical diabatic heat sources. The improved tropical and subtropical flow essentially follow from a reduction of the systematic errors and as such improve the overall forecast quality as revealed in the verification of single forecasts as well as forecast

JUNE 1984



JUNE 1985

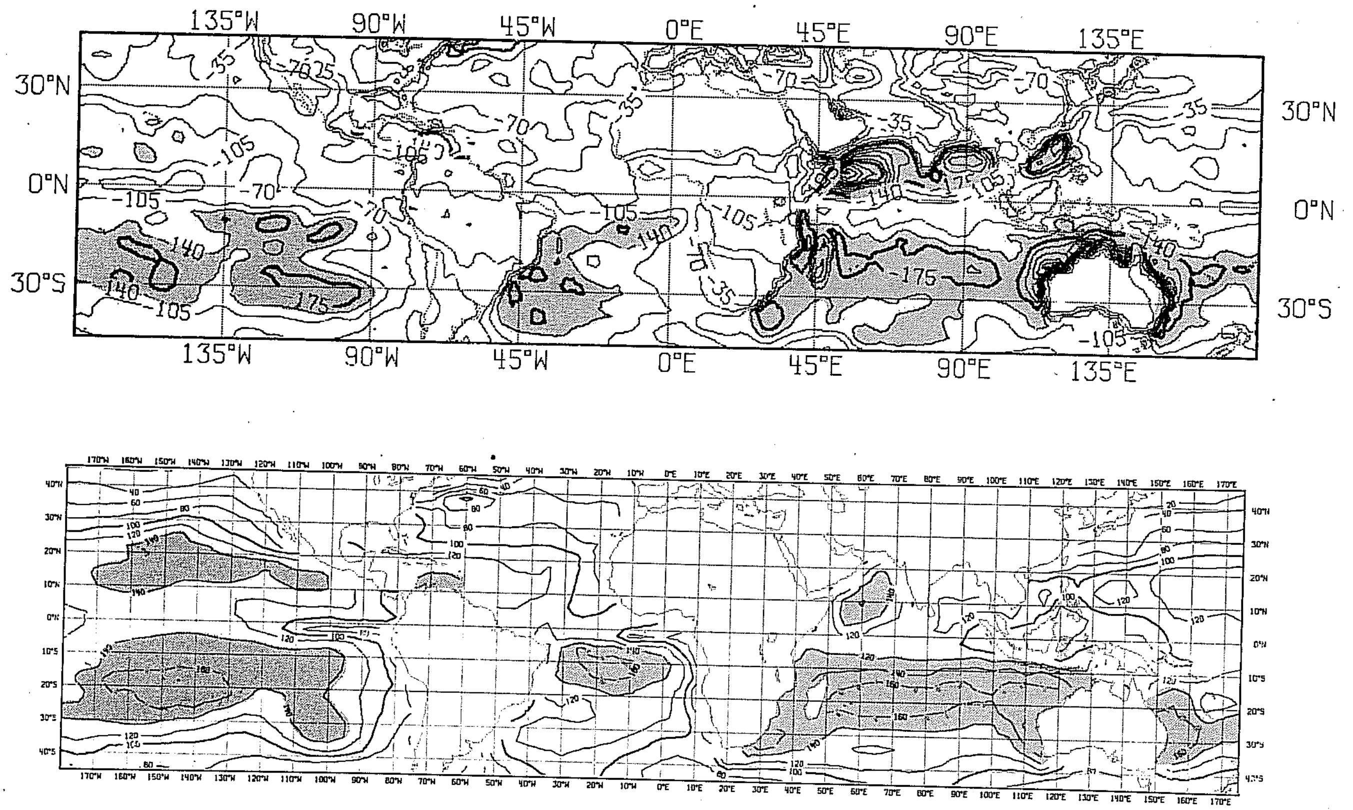


Fig. 14 Mean evaporation rates (W/m^2) during the first 5 days of ECMWF operational forecasts for June 1984 and June 1985 and climate values over the oceans for June after Esbensen and Kushnir (1981).

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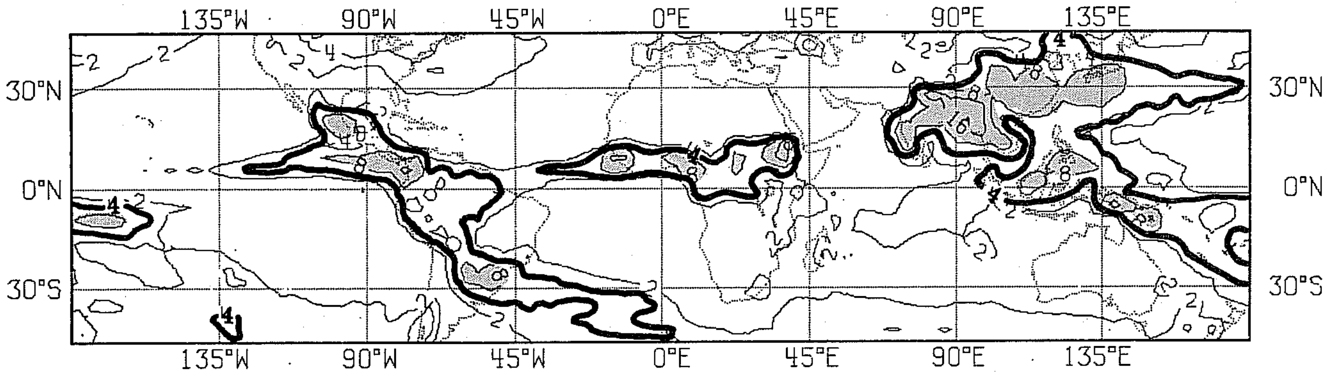

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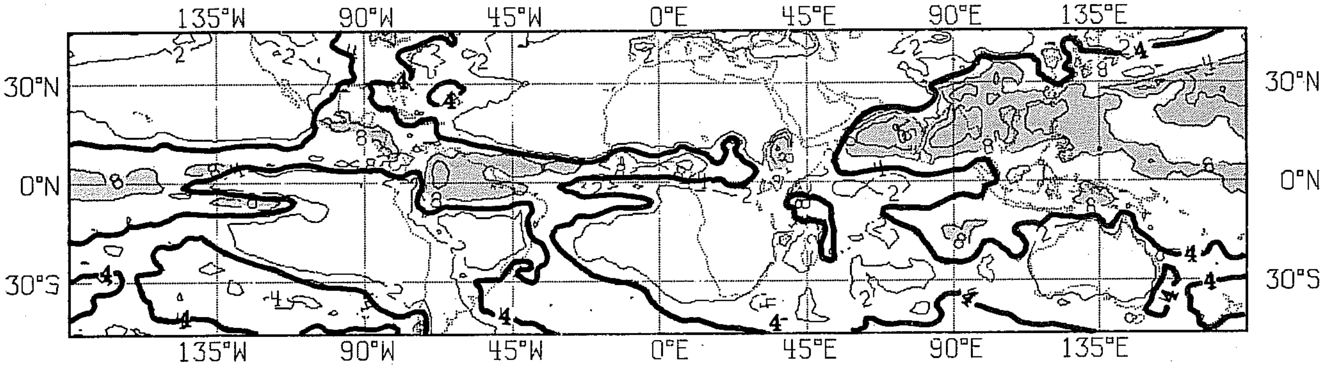

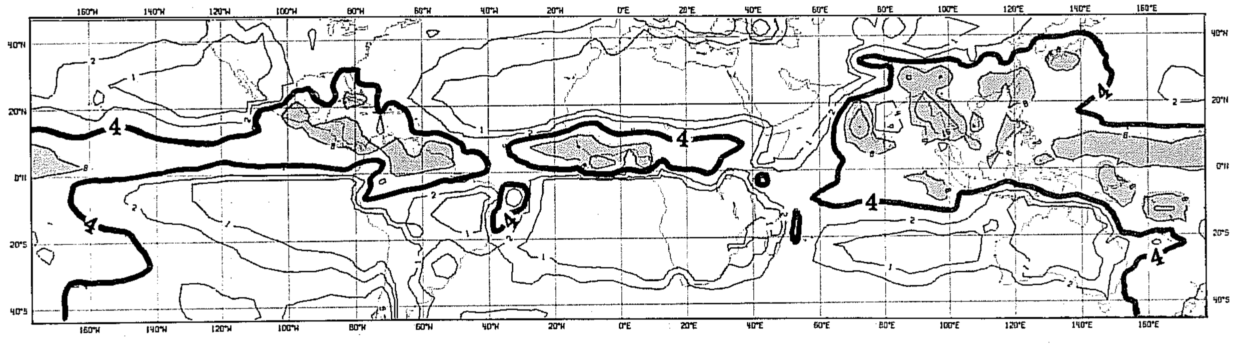

Fig. 15 Mean precipitation rates (mm/day) during the first 5 days of ECMWF operational forecasts for June 1984 and June 1985 and climate values for June after Jaeger (1976).

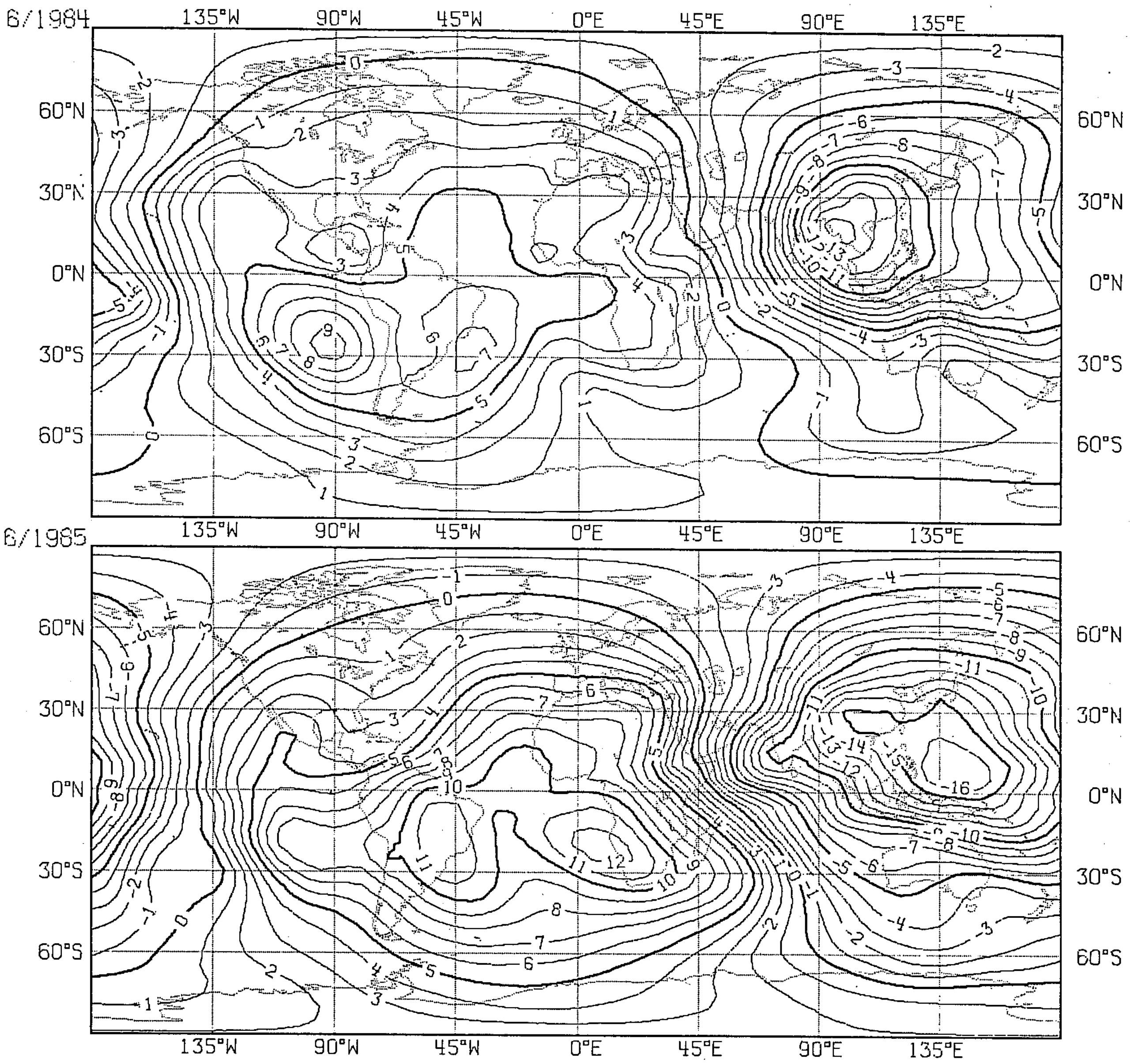

Fig. 16 Velocity potential field (10^6 m^2/s) at 200 mb of 5 day ECMWF operational forecasts for June 1984 and for June 1985

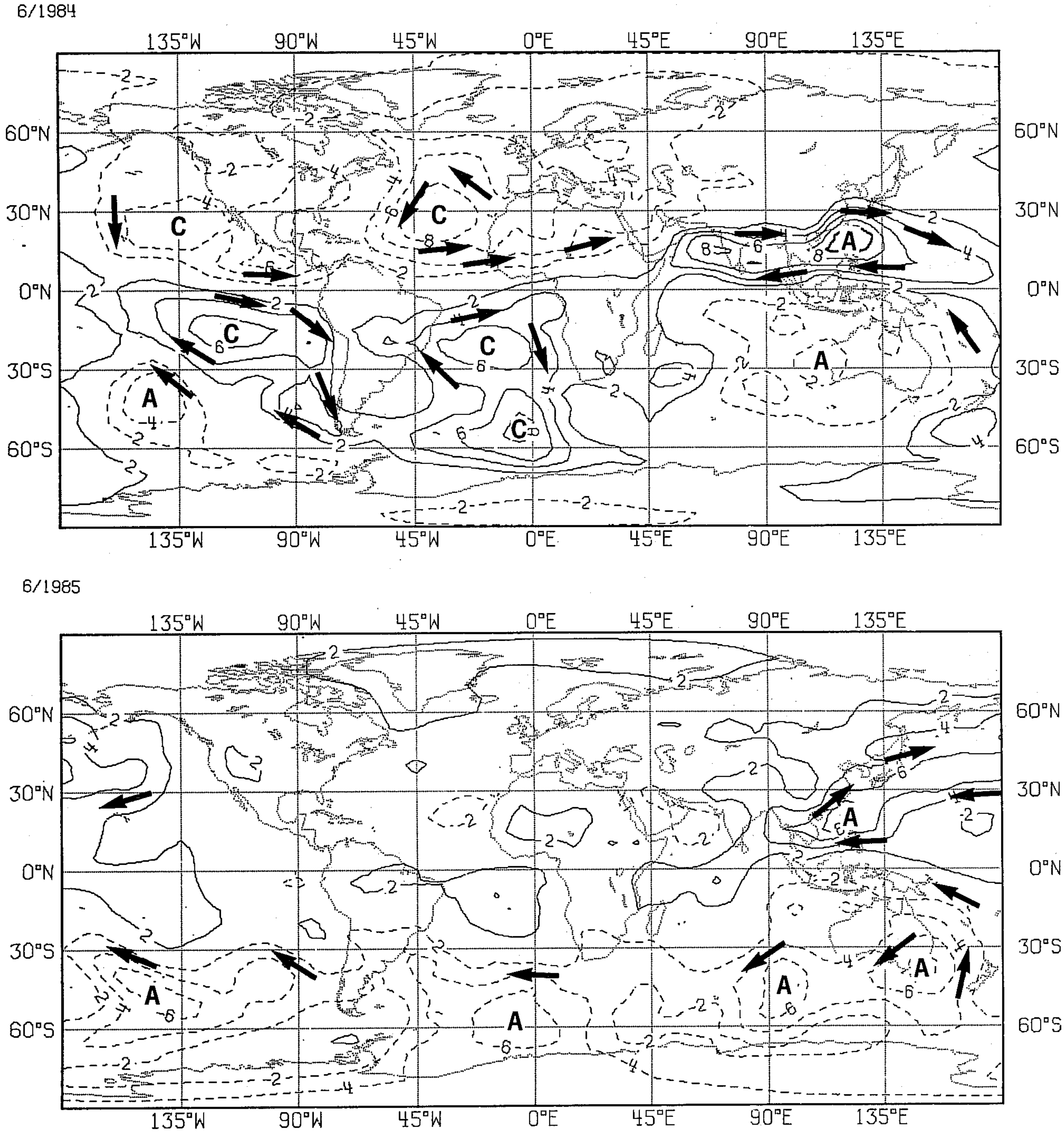

Fig. 17 Mean error in stream function (10^7 m^2/s) at 850 mb of 5 day ECMWF operational forecasts for June 1984 and for June 1985

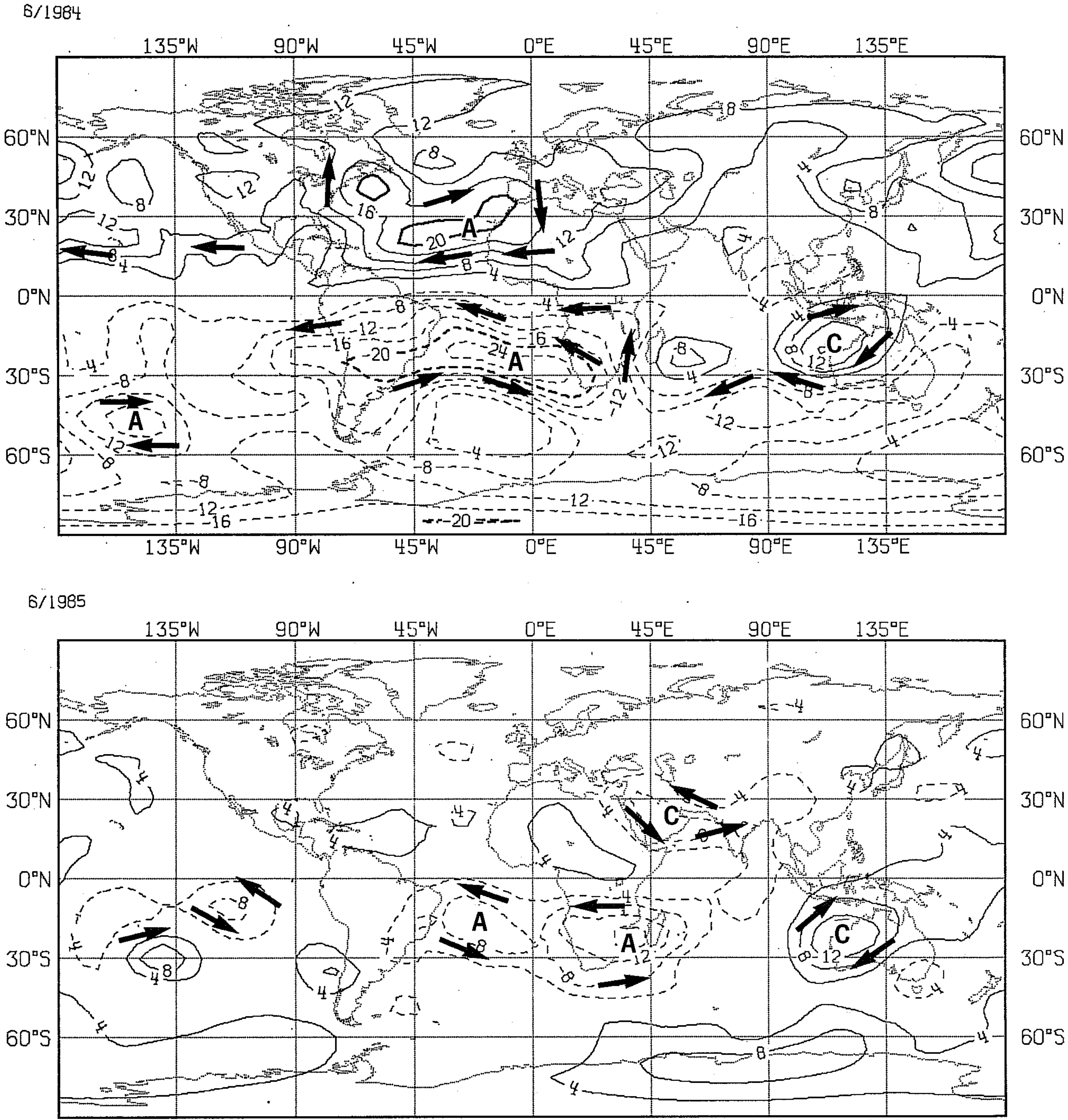

Fig. 18 As Fig. 17 but for 200 mb

ensembles. They show that the improvements occur on average between day 2 and day 4, and almost reach their final level at day 4 (Tiedtke and Slingo, 1984).

4.2.2 Extratropics

The impact of the parameterisation on the extratropical flow is less clear in its systematic nature and therefore will not be discussed here in length; instead we refer to the discussion in Tiedtke and Slingo (1985). They found that the impact of introducing the revised scheme becomes significant in the later stages of the forecasts, and is more pronounced and of a positive nature in the forecasts with increased horizontal resolution (i.e. T106 as compared to T63). However, it is not clear whether the impact is mainly from the tropics or evolves directly in the extra-tropics. With regard to the tropical forcing, it is found that the increased tropical diabatic heating leads to an increase in the production of zonal available potential energy which in turn intensifies baroclinic energy conversions. It may also be argued that the more realistic treatment of the quasi-stationary subtropical anticyclones may eventually improve the midlatitude stormtracks.

5. CONCLUDING REMARKS

In this paper we studied the role of parameterisation for the diabatic forcing of the large-scale flow in numerical models. We found that the major tropical diabatic heat sources strongly depend on the choice of the parameterisation schemes for penetrative convection, cloud-radiation interaction and shallow convection. Therefore we must conclude that the uncertainty which still exists about the quality of the various schemes introduces an element of ambiguity into numerical modelling. This is particularly true when it comes to simulating the atmospheric general circulation, but is already significant on shorter time scales which effect medium range forecasts.

Some progress in parameterisation has recently been made at ECMWF by first isolating critical aspects of parameterisation and by subsequently improving the corresponding parameterisation schemes. In particular the introduction of the effects of shallow convection into the Centre's model appeared to have a beneficial effect on the diabatic forcing of the large-scale flow. This in turn significantly improved the medium range forecasts, especially in the tropics and subtropics. However, there still remains large uncertainties about the parameterisation schemes presently used and further studies are needed to investigate their effects on the large-scale flow. These studies should also include an examination of the transient flow which has been neglected in our study.

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