# CUMULUS PARAMETRIZATION:
# THERMODYNAMIC ASPECTS

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## 1. INTRODUCTION

There are three ways in which cumulus convection can influence the large-scale atmospheric flow, i.e.

(i) through diabatic heating due to latent heat release in penetrative convection,

(ii) by vertical turbulent transports of heat, moisture and momentum and

(iii) through interaction of cumulus clouds with radiation.

Diabatic heating due to penetrative convection plays an important role in the maintenance of the tropical energy budget and the mean flow and is also the primary source of energy for tropical disturbances.

Turbulent transports by cumulus convection is associated with all types of cumulus clouds and is particularly significant in connection with non-precipitating cumulus clouds in the trade wind region as they provide the vertical transports of heat and moisture necessary to maintain the observed thermodynamic structure of the lower troposphere in those areas (Betts, 1975).

The interaction of cumulus cloud fields with radiation plays a major role in determining the planets radiation budget and therefore its climate. This occurs through all types of cumulus clouds, ranging from penetrative clouds to stratocumulus cloud checks which cover large areas of the oceans.

While the above examples demonstrate the importance of cumulus convection for the large-scale flow and thus the need for adequate representation through parametrization in large-scale models, existing cumulus parametrization is still uncertain and may largely contribute to forecast errors. Difficulties arise mainly because (a) the interaction of cumulus convection with the large-scale flow is not well understood and (b) the complexity of convective processes (e.g. updrafts, downdrafts, precipitation processes) can only be crudely represented by means of parametrization. Some progress in understanding of cumulus convection and its effect on the large-scale temperature and moisture fields has been made through observational studies but parametrization has benefited only slowly from this progress. In this paper we discuss recent activities at ECMWF which led to some improvements in cumulus parametrization. In section 2 we briefly describe the two parametrization schemes that were recently developed, that is the generalized adjustment scheme and the massflux scheme. The latter became operational in May 1989. In section 3 results from 10 day forecasts and extended integrations are shown which demonstrate the significance of cumulus parametrization for the large-scale flow. The discussions will be limited to thermodynamic aspects of cumulus convection but the effects of convective cloud-fields on radiation transfer are excluded. Section 4 contains a short summary of ongoing and future developments at ECMWF.

## 2. PARAMETRIZATION OF CUMULUS CONVECTION

### 2.1 General aspects

Parametrization of cumulus convection in large-scale model implies the interaction of the synoptic flow, individual clouds and possible organization in meso-scale cloud complexes with well developed circulations. Although there seems to be sufficient evidence from observational and numerical studies that cumulus convection is basically parametrizable in spite of the existence of meso-scale organization, large uncertainties exist as to the appropriate closure assumptions and modelling of cloud fields; presently applied closures fall into one of two categories (Arakawa and Chen, 1987):

(i) Specification of convective warming and moistening to maintain equilibrium states

This type of closure implies that convection exerts a strong influence on the large-scale flow such that under convective situations the thermal structures rapidly approach certain equilibrium states. This type of closure is applied in simple adjustment schemes such as the moist adiabatic adjustment scheme (Manabe et al., 1965) and the generalized adjustment scheme (Betts, 1986), but also in the highly sophisticated Arakawa-Schubert scheme (Arakawa and Schubert, 1974).

(ii) Coupling of convective heating and moistening to advective (and boundary layer) processes

Here the assumption is that penetrative convection occurs in response to large-scale processes in particular the low level large-scale moisture convergence as, for example, in the Kuo scheme (Kuo, 1965 and 1974) which is widely used in large-scale models.

Both closures seem to be supported by observational data and it is presently not possible to give preference for one against the other. Nor is it even clear whether these distinct closures are sufficient to describe properly the range of convective phenomena requiring parametrization.

In addition to the uncertainty about the basic closure there is little agreement among modellers as to whether and to what degree the cloud fields should be modelled. Those who advocate the use of adjustment schemes generally argue that the convective cloud fields and their associated circulations cannot be inferred with sufficient accuracy from the large-scale flow and therefore are best bypassed. On the other hand the representation of cumulus cloud fields and their associated circulations in the context of massflux-schemes appears justified on the basis of observational studies which show that realistic profiles of convective heating and moistening can be derived using very simple cumulus cloud models representing 1-dimensional entraining plumes.

In view of these large uncertainties the Centre has developed convection schemes of these various types and tested them in global models, and during recent years a number of conventional schemes were assessed (Tiedtke, 1988). We found that none of these schemes has significant advantages over the operationally used Kuo-scheme and consequently the first change to the operational model in May 1985 consisted of a modification to the Kuo-scheme together with the introduction of a new scheme for shallow convection (Tiedtke et al., 1988). Although this change led to significant improvements in the Centre's forecasts and analyses in various aspects (Tiedtke et al., 1988), there still remained large deficiencies in the simulated flow which in all likelihood are connected to cumulus parametrization and so there remains a strong motivation for further studies in cumulus parametrization. Since the changes in May 1985 we have concentrated on the development of only two schemes:

(1) the generalized adjustment scheme
(2) a massflux scheme in connection with a moisture convergence closure.

The closures and physical concepts of the two schemes are fundamentally different and, in view of the given uncertainty in cumulus parametrization, it seemed desirable to retain this flexibility.

The basic features of the two schemes may be summarized as follows.

### 2.2 Generalized adjustment scheme

The scheme is based on the observational evidence that in convective situations there exists a quasi-equilibrium between the cloud fields and the large-scale forcing Betts (1986). This implies the existence of characteristic temperature and moisture profiles which can be observed and used as the basis for adjustment schemes for shallow (non-precipitating), deep and middle-level convection. Given suitable profiles the large-scale temperature and moisture fields can then be simply adjusted as

$$\left(\frac{\partial \overline{T}}{\partial t}\right)_{cu} = \frac{T_{ref} - \overline{T}}{\tau} \qquad (1)$$

$$\left(\frac{\partial \overline{q}}{\partial t}\right)_{cu} = \frac{q_{ref} - \overline{q}}{\tau} \qquad (2)$$

In our scheme the lapse rates of the reference profiles of temperature $T_{ref}$ and moisture $q_{ref}$ are defined from observational data in the tropics (Betts, 1986) and are applied over the whole globe. An important feature of the reference temperature profiles is that for situations of penetrative convection in accordance with observed tropical soundings the lower troposphere is conditionally unstable whereas the higher levels are stable (Fig. 1). The scheme is therefore much more realistic than the moist adiabatic adjustment scheme where the reference profile is that of a moist adiabat. The reference moisture profile is defined assuming typical degrees of subsaturation. For the case of shallow convection the reference lapse rates are those of a mixing line through the air below cloud base and the air above the level of non-buoyancy.

The relaxation time is a disposable parameter which has been determined from 1-dimensional experiments using special observational data sets (Betts and Miller, 1986) which were used to test thoroughly both deep and shallow schemes. An important aspect which is central to the adjustment philosophy is that the difficulties in representing the wide range of cloud and subcloudscale processes are effectively bypassed. Nevertheless, the scheme relies heavily on observational data to provide realistic reference profiles and relaxation times under various conditions. Particular difficulties arise for the boundary layer. Due to the strong interaction of the boundary layer flow and the convective-scale flow, the definition of reference profiles in the boundary layer and in particular the relaxation time-scale is of crucial importance. A local adjustment time is defined from the local moisture budget such as to either maintain the subcloud moisture content and equivalent potential temperature values or to allow systematically higher ones. The present scheme, with only one reference lapse rate for penetrative convective situations may be considered a preliminary version. In fact an observational study by Betts (1974) shows that there is considerable variation in the quasi-equilibrium states depending on the convective regimes (Fig. 1). As the flow becomes more disturbed and convective activity increases the thermal state becomes colder and moister. These changes in the quasi-equilibrium states ought to be represented in the scheme.

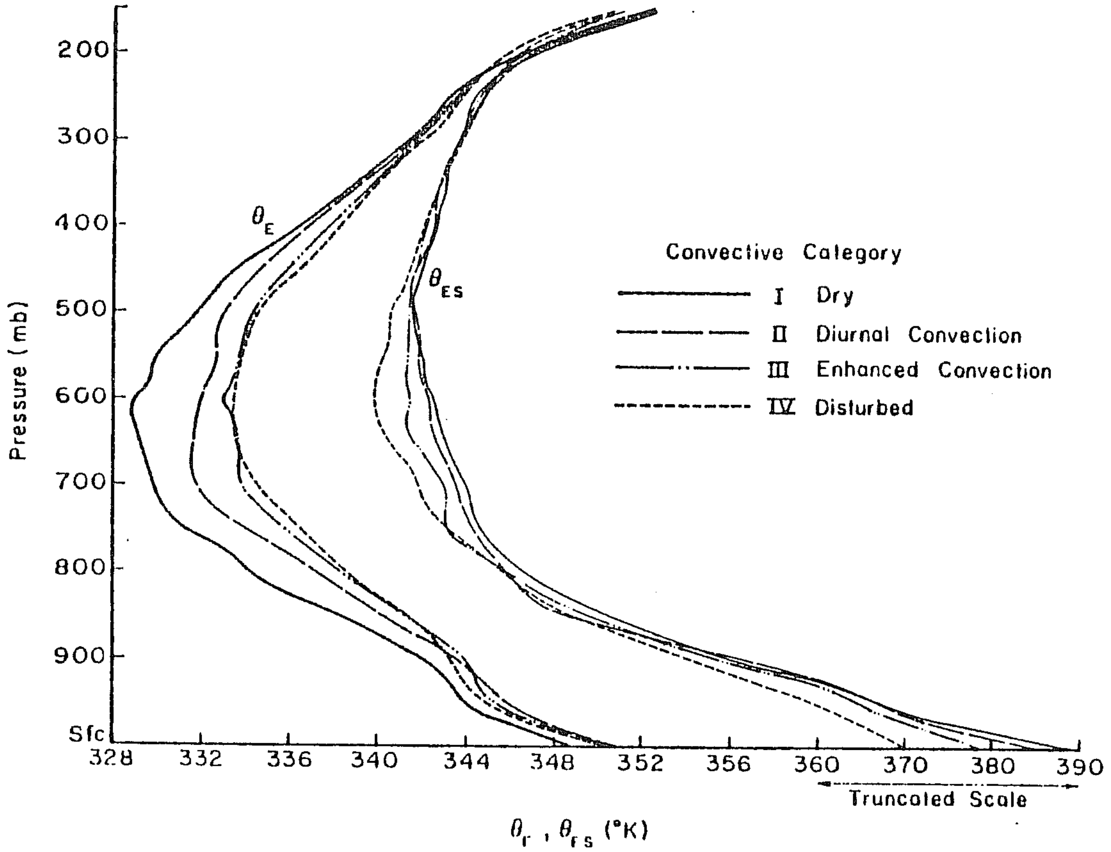


Fig. 1 Vertical profiles of equivalent potential temperature ($\theta_e$) and saturation equivalent potential temperature ($\theta_{ES}$) for four convective regimes: dry, diurnal convection, enhanced convection, and disturbed (Betts, 1974).

## 2.3 Massflux-scheme

The scheme is very different from the adjustment scheme as the interaction between the large-scale flow and the cumulus cloud fields are explicitly modelled. The scheme is described in detail in Tiedtke (1989) and is therefore only briefly summarized here.

Clouds are represented as a bulk model following earlier studies by Yanai et al. (1973 and 1976) who prior to the introduction of spectral cloud ensembles in diagnostic studies applied a bulk model and obtained realistic contributions from convection to the large-scale budgets of heat and moisture.

The large-scale budget equations are in the usual notation (s = dry static energy):

$$\frac{\partial \bar{s}}{\partial t} + \bar{v}.\nabla\bar{s} + \bar{w}\frac{\partial \bar{s}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\ \overline{w's'}) + L(\bar{c} - \bar{e}) + \bar{Q}_R \qquad (3)$$

$$\frac{\partial \bar{q}}{\partial t} + \bar{v}.\nabla\bar{q} + \bar{w}\frac{\partial \bar{q}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\ \overline{w'q'}) - (\bar{c} - \bar{e}) \qquad (4)$$

where the cumulus transports are given as

$$(\bar{\rho}\ \overline{w's'}) = (M_u s_u + M_d s_d - (M_u + M_d)\,\bar{s}) \qquad (5)$$

$$(\bar{\rho}\ \overline{w'q'}) = (M_u q_u + M_d q_d - (M_u + M_d)\,\bar{q}) \qquad (6)$$

($M_u/M_d$ = updraft/downdraft massflux, index u/d refers to updrafts/downdrafts).

The conceptual idea of the cumulus clouds is that adopted in many diagnostic studies. Cumulus clouds are assumed to be embedded in the large-scale environment, share the same cloud base but extend to various heights. They are defined by updraft and downdraft mass fluxes and by their thermal properties as dry static energy s, moisture q and cloud water content $\ell$. They are modelled as one-dimensional entraining plumes and the bulk of the clouds are assumed to be in a steady state. Then the equations for the bulk of updrafts are

$$\frac{\partial M_u}{\partial z} = E_u - D_u$$

$$\frac{\partial (M_u s_u)}{\partial z} = E_u \bar{s} - D_u s_u + L \bar{\rho} c_u$$

$$\frac{\partial (M_u q_u)}{\partial z} = E_u \bar{q} - D_u q_u - \bar{\rho} c_u \qquad (7)$$

$$\frac{\partial (M_u \ell)}{\partial z} = \quad - D_u \ell + \bar{\rho} c_u - \bar{\rho} G_p$$

($E_u/D_u$ = entrainment/detrainment rates,
$c_u$ = condensation rate in updrafts,
$G_p$ = generation of precipitation water).

Downdrafts are considered to be associated with convective precipitation from the updrafts and originate from cloud air influenced by the injection of environmental air. The equations for the bulk of downdrafts are the same as for the updrafts except now describe a saturated descent hence

$$\frac{\partial M_d}{\partial z} = E_d - D_d$$

$$\frac{\partial (M_d s_d)}{\partial z} = E_d \bar{s} - D_d s_d + L \bar{\rho} e_d \qquad (8)$$

$$\frac{\partial (M_d q_d)}{\partial z} = E_d \bar{q} - D_d q_d - \bar{\rho} e_d$$

($e_d$ = evaporation rate of convective precipitation to maintain saturated descent).

The scheme represents 3 types of convection, i.e. penetrative convection in connection with large-scale convergent flow, shallow convection in suppressed conditions associated with tradewind cumuli and mid-level convection associated with potentially unstable air above the boundary layer and large-scale ascent. The closure assumptions for determining the bulk cloud massflux are essentially of the moisture convergence type: penetrative convection and mid-level convection are maintained by large-scale moisture convergence via dynamical entrainment of environmental air through cloud base and cloud edges and shallow convection is maintained by supply of moisture through the cloud bases in response to surface evaporation. In addition there is turbulent entrainment/detrainment depending on cloud size in accordance with observational data.

New features of the scheme which are not included in the Centre's operational Kuo scheme are the additional processes of mid level convection and cumulus momentum transport.

Mid-level convection, that is convective cells which have their roots not in the boundary layer but originate at levels above the boundary layer, often occur in rainbands at warm fronts and in the warm sector of extratropical cyclones (Browning et al., 1973; Houze et al., 1976; Herzegh and Hobbs, 1980). These cells are probably formed by the lifting of low level air until it becomes saturated (Wexler and Atlas, 1959) and the primary moisture source for the clouds is from low level large-scale convergence (Houze et al., 1976). Often there exists a low level temperature inversion which inhibits convection to start freely from the surface and therefore convection seems to be initiated by lifting low level air dynamically to the level of free convection. The present parametrization considers the finding of the diagnostic studies in a simple way. We assume that convection is activated when there is large-scale ascent at lower levels, the environmental air is sufficiently moist, i.e. of relative humidity in excess of 90%, and a convectively unstable layer exists above. The free convection level is determined by lifting a parcel of environmental temperature and moisture content

$$T_u = \overline{T}, \quad q_u = \overline{q} \tag{9}$$

adiabatically, allowing for condensational heating, and then checking for buoyancy. The upwards massflux is set equal to the vertical mass transport by the large-scale flow at that level

$$(M_u)_B = \overline{\rho}_B \, \overline{w}_B \tag{10}$$

which ensures that the amount of moisture vertically advected through the cloud base by the large-scale ascent is fully available for generation of convective cells. Mid-level convection has a strong influence on the vertical profile of heating as is apparent in a case of intense convection in connection with severe storms over central USA during SESAME-79 (Fig. 2). When mid-level convection is not included, the heating at higher levels is not reproduced. The occurrence of mid-level convection can be widespread in the extratropics, in particular during winter as is indicated in a 24hr forecast over USA during November 1986 (Fig. 3) and therefore is likely to have a significant impact on forecast quality. This has indeed been verified for a few cases where the forecast quality improved when mid-level convection was included.

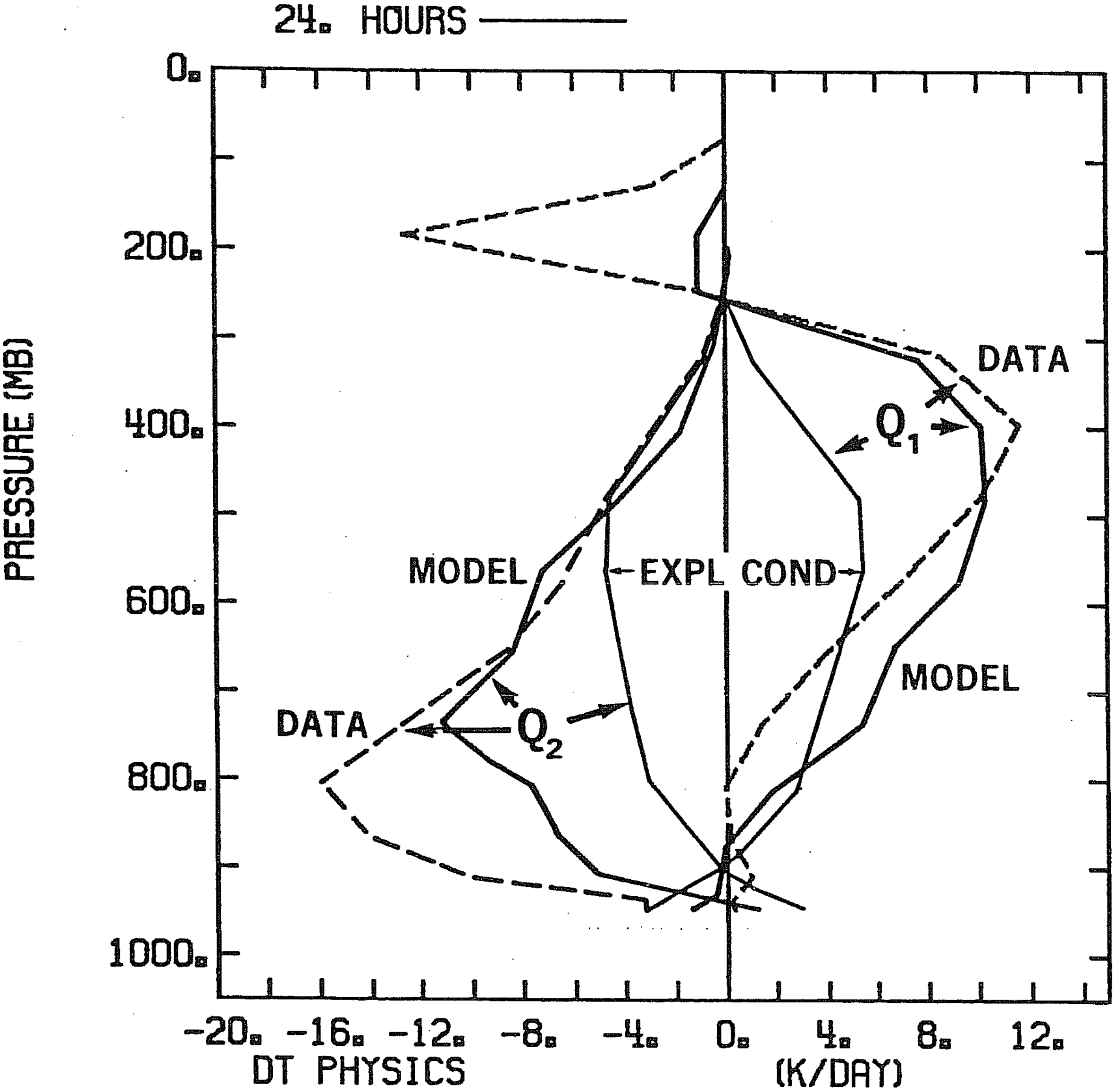


Fig. 2 SESAME - simulations:
Vertical profiles of 24 h time averaged diabatic heating $Q_1$ and diabatic moistening $Q_2$ for integration with massflux scheme (solid lines), for integration with "explicit condensation" (thin lines) and diagnosed from data by Kuo and Anthes (1984).

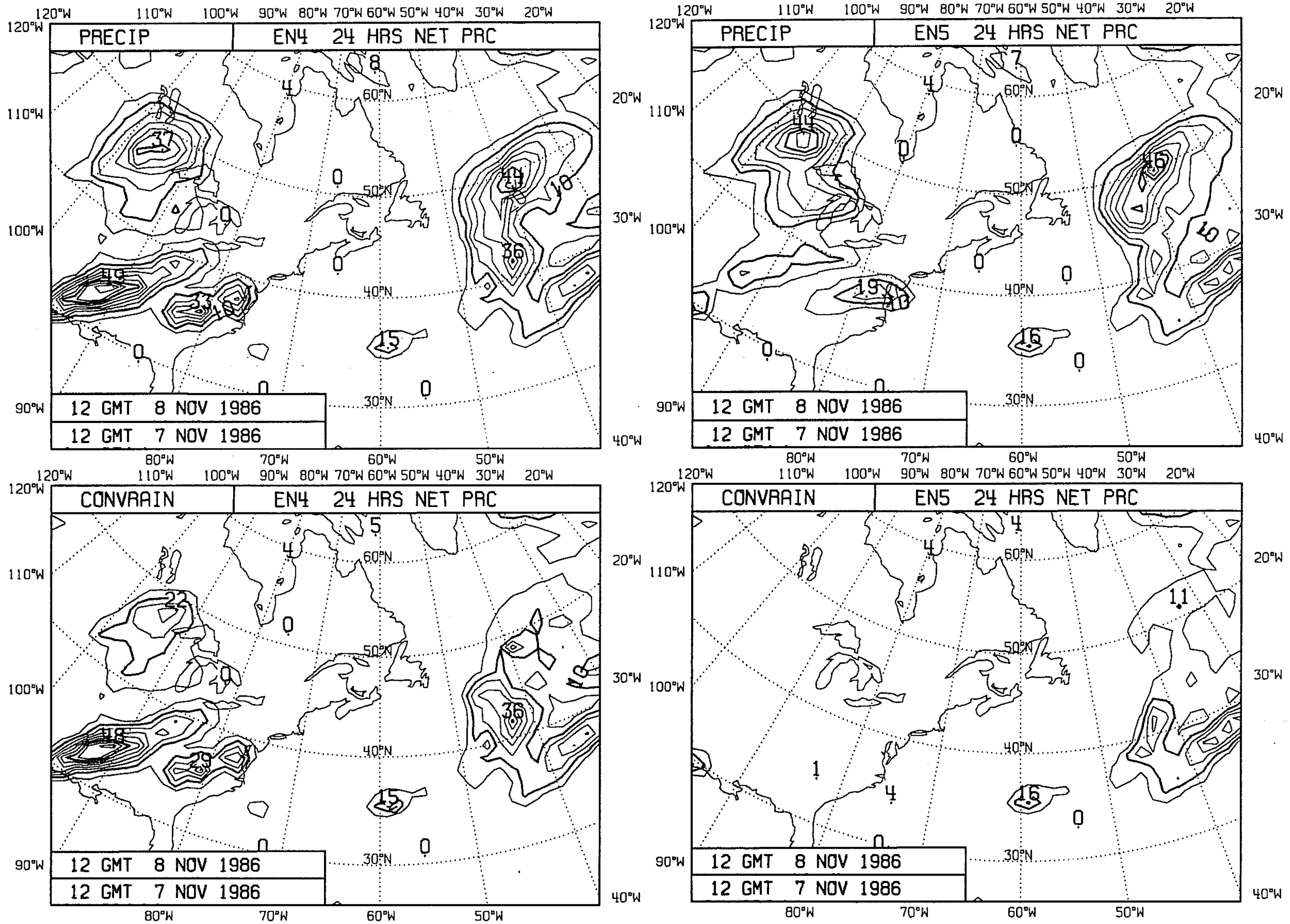


Fig. 3 24-hour accumulated convective precipitation (right) and total precipitation (left) for forecasts from 7 Nov. 1986 with massflux scheme without mid-level convection (top) and with mid-level convection included (bottom).

Parametrization of cumulus momentum transports is very uncertain and therefore is often neglected in large-scale models. A simple scheme where cumulus effects are expressed in terms of convective massfluxes (Schneider and Lindzen, 1976, Esbensen et al., 1987) is adopted here. This parametrization is very crude as it assumes zero pressure drag on the clouds for calculating the vertical profiles of u and v within the clouds which may influence the cloud momentum profile above 500 mb (Shapiro and Stevens, 1980). However, it represents the dominant effects of cumulus convection. By effectively producing downgradient momentum fluxes in the tropics by penetrative convection it acts to decelerate the large-scale zonal wind in the upper troposphere which is confirmed by diagnostic studies (e.g. Sui and Yanai, 1986). Further support for the parametrization is provided by a comprehensive data study for tropical cloud clusters (Lee, 1984).

The introduction of cumulus momentum transport has been found to have little effect on the divergent flow, neither in terms of the zonal averaged Hadley circulation nor the intensity of their regional branches, but the rotational flow appears to be strongly affected (Tiedtke, 1989).

### 2.4 Assessment of adjustment scheme and massflux scheme on special datasets and in global forecasts

Before applying the schemes in global forecasts both scheme were extensively tested using single column data sets from tropical field experiments (GATE, Marshall Island, ATEX, BOMEX) and from SESAME-79 for extratropical organized convection (only with massflux scheme). The verifications show that the fields of convective heating and drying were realistically reproduced as can be seen in Fig. 2 for the example of extratropical convection (SESAME) with the massflux scheme. Results obtained with both schemes are presented in detail by Miller and Betts (1986) and by Tiedtke (1989), respectively.

Assessment of the schemes in global forecasts is more difficult because of feedbacks with other processes such as boundary layer turbulence and radiative transfer. Still, the forecasts show significant improvement for both schemes against the operational Kuo scheme in various aspects (Tiedtke and Miller, 1988):

(i) a more realistic Hadley circulation which for example does not collapse over the Indonesian area as with the Kuo scheme,

(ii) more intense tropical cyclones in forecasts and in data assimilation,

(iii) reduced spin-up in convective heating.

The comparison of the two schemes appears to favour the massflux scheme as it produces more realistic vertical profiles of convective heating, better balanced conditions in the initial flow (less spin-up) and less of a tendency for producing intense tropical cyclones. The massflux scheme was on the basis of these results chosen to replace the operational Kuo scheme and the shallow convection scheme in May 1989.

## 3. SIGNIFICANCE OF CUMULUS PARAMETRIZATION FOR NUMERICAL FORECASTING

### 3.1 Introduction

Since cumulus convection plays a dominant role in the maintenance of the large-scale flow we must expect that its parametrization is equally significant for the simulation of the large-scale flow and eventual deficiencies will induce errors in the flow. A perfect parametrization for cumulus convection is beyond our reach, but some progress in cumulus parametrization has been achieved at ECMWF which is clearly reflected in a reduction of errors in the large-scale flow and increased forecast quality. This has been shown for the first set of changes in the operational convection parametrization made in May 1985, as reported in a previous Seminar (Tiedtke, 1985) and in Tiedtke et al. (1988). Improvements resulted mainly from the introduction of a shallow convection scheme which had the effect to increase the moisture flux out of the subtropical boundary layer, thereby increasing the surface evaporation, and hence the moisture source for deep convection. This increased moisture source together with a reduced moistening parameter in the Kuo scheme produced greater rainfall amounts and the increased convective heating changed the tropical temperature bias from a systematic cooling to a warming. These changes resulted in improved ITCZs, a more intense Hadley circulation and more intense and realistic subtropical highs: the resulting reduction in model systematic errors particularly in the tropics and sub-tropics was marked and an overall improvement in forecast skill was seen at all latitudes. Despite the significant improvements there remained still major shortcomings especially in the maintenance of the tropical mean flow and the forecasting of tropical transient eddies. There is an easterly wind error in the tropics which is most prominent in the Northern Hemisphere winter. This error extends through much of the upper troposphere with a large latitudinal extension. Likewise the forecasts fail to maintain the strength and location of the large-scale divergent circulations. Also, transient eddies in the tropics are not deepened and/or maintained well and there is a strong 'spin-up' whereby the convective precipitation is excessive during the first three days of the forecast and then regains a reasonable balance but with too dry and warm a tropical troposphere.

In the following we discuss the impact of the recent change in May 1989 (= replacement of Kuo scheme for penetrative convection and shallow convection scheme by massflux scheme) on these aspects of the forecasts.

### 3.2 Convective forcing and time-mean tropical flow

The primary aim of convection parametrization is to produce realistic profiles of convective heating. Unfortunately, adequate data to verify these profiles are not available and therefore convection is often assessed in terms of zonal means of the time averaged heating. The zonal mean values obtained from the two convection schemes (i.e. previous operational scheme and the massflux scheme) show (Fig. 4) that both schemes produce a strong heating by convection in the ascending branch of the Hadley cell and a second maximum in the mid-latitude belts of baroclinic disturbances. Cooling by convection occurs in the subtropics at the trade inversion in connection with shallow convection and in the sub cloud layer with the Kuo scheme due to evaporation of rain. The massflux scheme does not produce a net cooling below cloud base as the evaporative cooling is compensated by heating due to a net downward convective heat flux at cloud base which is not represented in the Kuo scheme. The convective heating in mid-latitudes is stronger with the new scheme as a result of mid-level convection which again is not included in the previous scheme. However, the differences in convective heating are largest in the tropics. The tropical heating with the Kuo-scheme appears somewhat unrealistic as it is largest below 800 mb and rather small at higher levels, whereas the massflux scheme produces profiles more typical for penetrative convection with maximum values at higher levels.

The effect of convective heating on the large-scale flow is most pronounced in the divergent part and, consequently, it is there that we see the largest impact from the new scheme. In agreement with the stronger heating extending over a deeper layer we find that the divergent flow at higher levels is much stronger in the integrations with the massflux scheme (Fig. 5). In particular we notice that the collapse of the circulation over the Indonesian area and West Pacific, which is typical for the previous operational model, disappears and there is now better agreement with the analysed divergent flow.

However, the impact on the rotational flow is much smaller leaving the errors in the zonal wind in winter for example rather unaffected by cumulus parametrization. However, the error seems to be more sensitive to momentum forcing by cumulus convection as we infer from the extended summer integrations where the massflux scheme was run a) with momentum transports and b) without momentum transport. This is further discussed in the paper by M. Miller in these proceedings.

### 3.3 Spin-up

An important problem in numerical forecasting is the specification of well balanced initial conditions. In the presence of diabatic processes like convective heating this balance is rather complex as it involves not only the thermal and dynamical state but also the diabatic forcing from parametrization. Any mismatch between convection as indicated by the observations on the one hand and by the parametrization scheme on the other hand will initiate strong adjustments until balance is approached. This is in particular the case in connection with cumulus parametrization and there is often a strong spin-up of convective

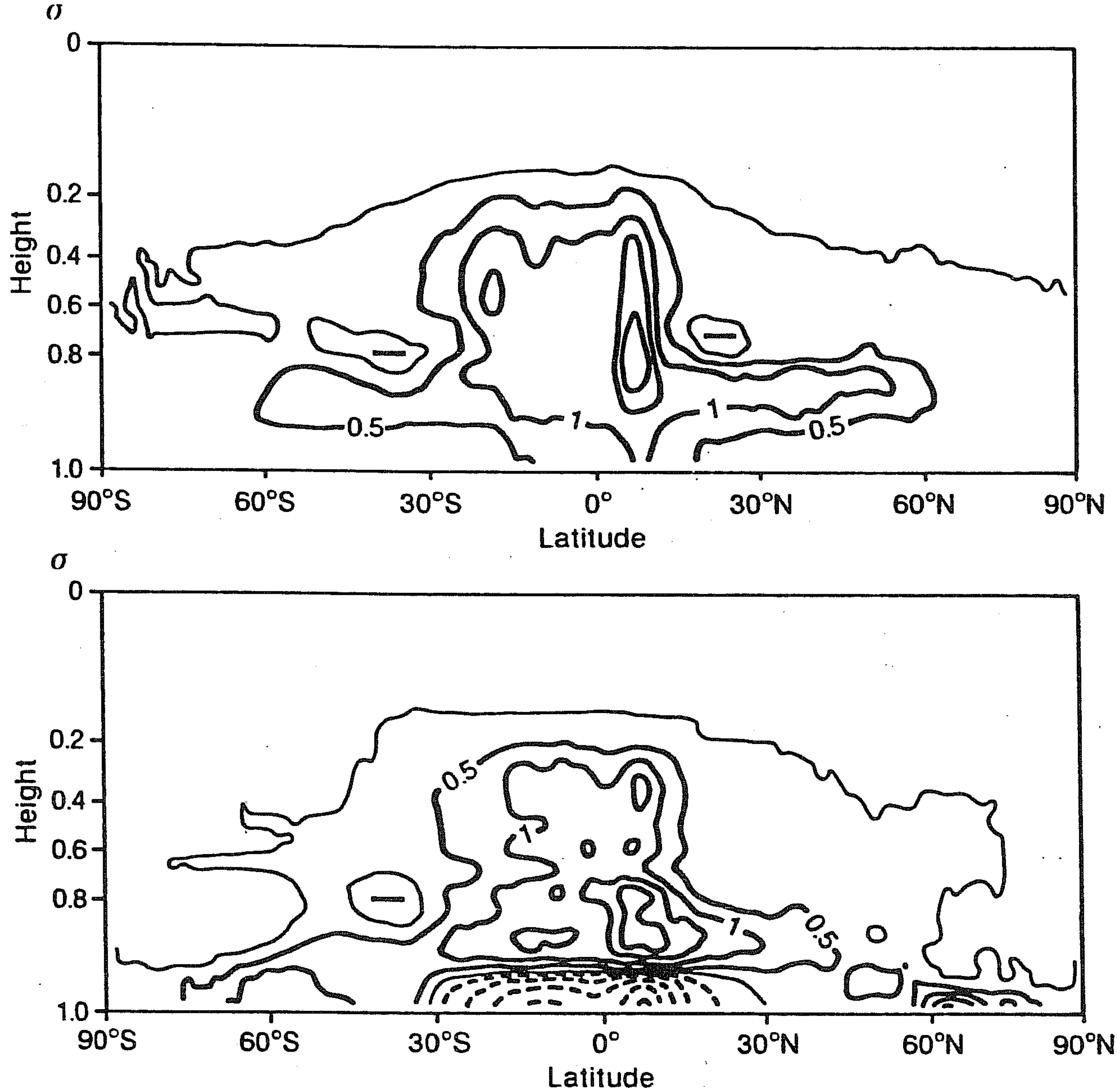


Fig. 4 30 day mean convective heating (K/day) zonally averaged over all model grid points for 30 day integrations from 17.1.88, 12Z. Vertical coordinate is normalized pressure. Plotting interval is 0.5 K/day, dashed lines for convective cooling.
Top: massflux scheme
Bottom: ECMWF previous operational convection scheme (before May 1989).

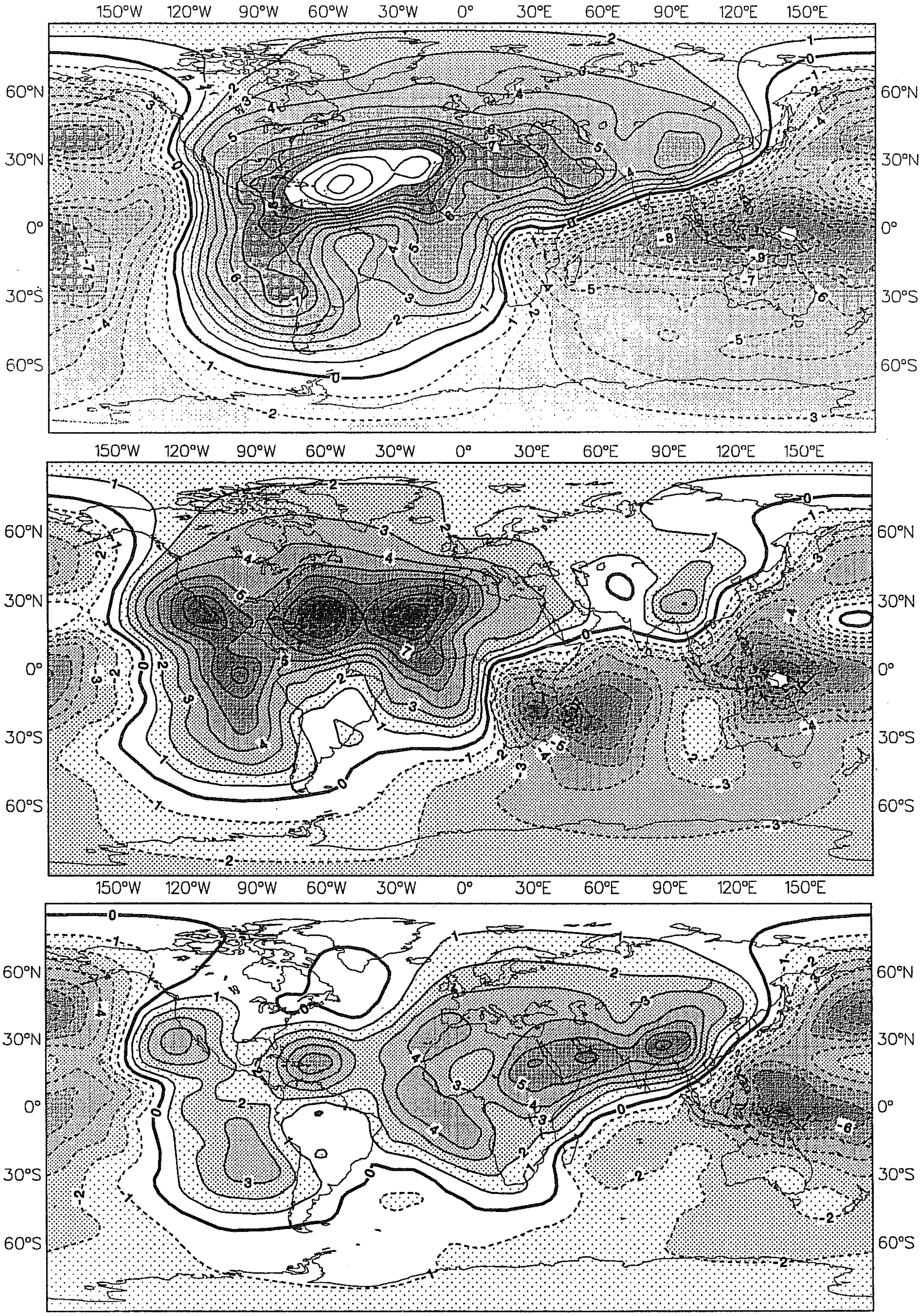


Fig. 5 30 day mean velocity potential ($10^6 m^2/sec$) at 200 mb for the integrations with ECMWF previous operational convection scheme (bottom), the massflux scheme (middle) plus analysed field (top).

heating during the early stages of a forecast. Earlier studies have shown that the spin-up depends strongly on the convection scheme (Illari, 1987) and this has been confirmed in operational forecasts with the new massflux scheme as the typical strong spin-up/spin-down with the Kuo-scheme is replaced by a spin-down with somewhat too large values at the beginning of the forecasts (Fig. 6). The reduced spin-up implies that the massflux scheme is more compatible with observational data. As the spin-up is mainly associated with penetrative convection it occurs predominantly in tropical areas. The geographical distribution of rain during the early stages of the forecasts (Fig. 7) shows that the rainfall with the new scheme is less widespread and more confined to the ITCZ which appears more realistic. The enhancement of the rain along the ITCZ is important for the maintenance of the divergent flow in the tropical belt which is strongly enhanced in the analysis and in the forecasts with the new massflux scheme (K. Arpe, 1989).

### 3.4 Tropical temperature forecasts

Imbalance in the net diabatic heating has a direct effect on temperature forecasts and therefore as a result of the large spin-up with the Kuo scheme there is an overall erroneous warming of the tropical troposphere, within one day by up to 1.5 K. As the spin-up is reduced with the massflux scheme so is the spurious warming (Fig. 8).

### 3.5 Forecasts of tropical cyclones

The impact of cumulus parametrization on the analysis and forecast of tropical cyclones was studied in data assimilation/forecast experiments where the data assimilation suite was rerun with the new scheme and forecasts run from these reanalyses.

As might be expected the forecasts of tropical disturbances including cyclones/hurricanes are highly sensitive to the convection scheme. Forecasts with the Kuo scheme typically fail to deepen and maintain tropical cyclones. The new convection scheme appears to improve this aspect as more intense disturbances are predicted in the forecasts. As an example we show the forecast of tropical cyclone 'Orson' to the north east of Australia during April 1989 (from a parallel data assimilation/forecast suite prior to the operational change). The 72 hour forecasts (Fig. 9) predicted a central pressure of 984 hPa against 100 hPa with the Kuo scheme (ship observation near centre gave 948 hPa) and a maximum wind speed of 37 m/sec against 21 m/sec at 850 mb.

The results from parallel runs were confirmed by recent operational forecasts with the new convection scheme, which for the hurricane season of this year did not show, as in previous years, the tendency to suppress the tropical cyclones and tropical storms within the forecasts. Although a conclusive picture about the model's performance with respect to forecasting tropical storms and hurricanes can only emerge from a detailed study over a

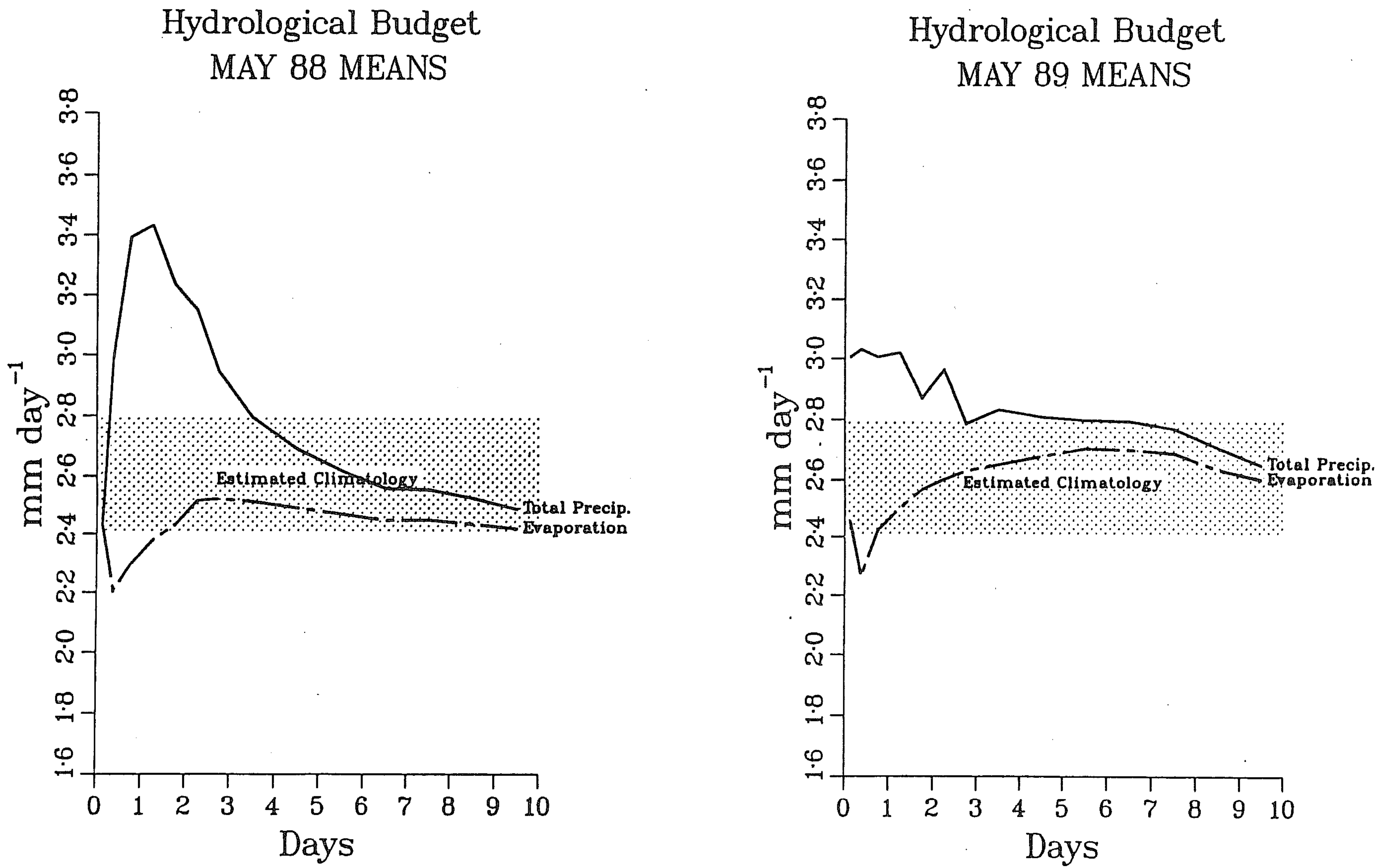


Fig. 6 Time evolution of global precipitation and evaporation rates in ensemble of all forecasts for May 1988 (previous ECMWF convection scheme) and for May 1989 (massflux scheme).

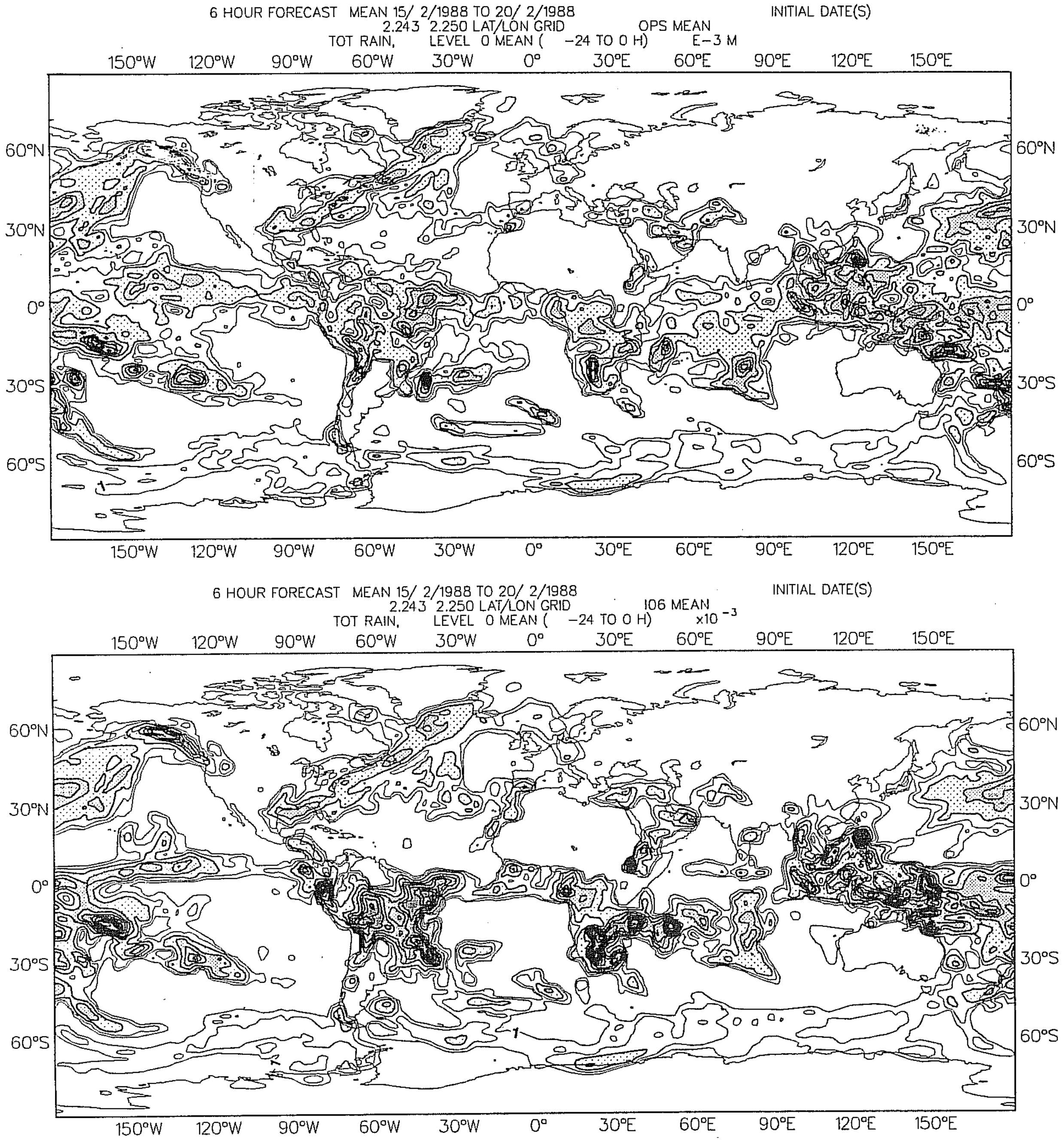


Fig. 7 Global distribution of precipitation rate averaged over all 6-hour forecasts in data assimilation from 15.2.88, 12Z to 20.2.88, 12Z for previous operational physics (top) and for new physics (bottom). Intervals are: 1, 2, 4 (shaded, 12, 16 .... mm/day).

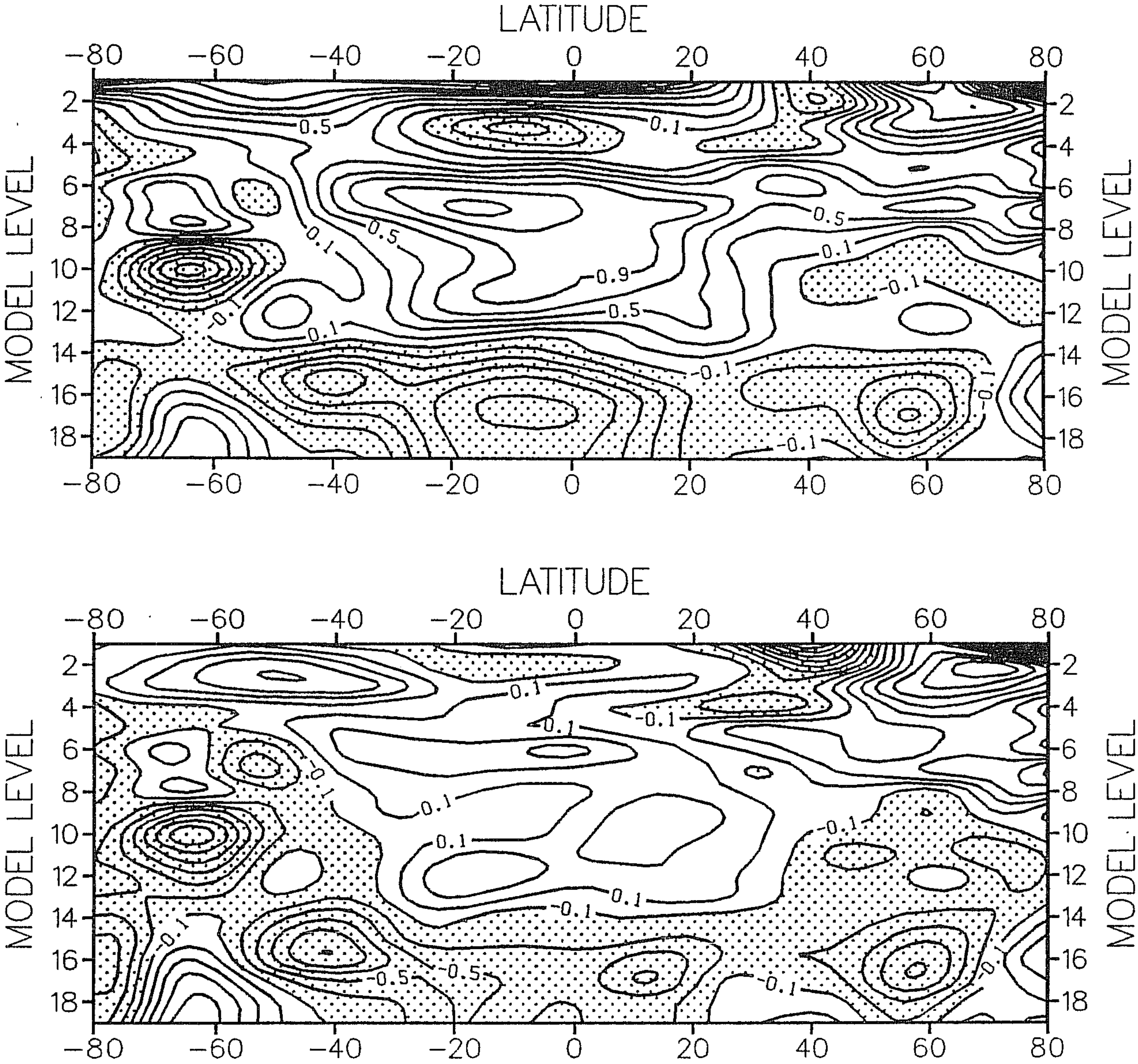
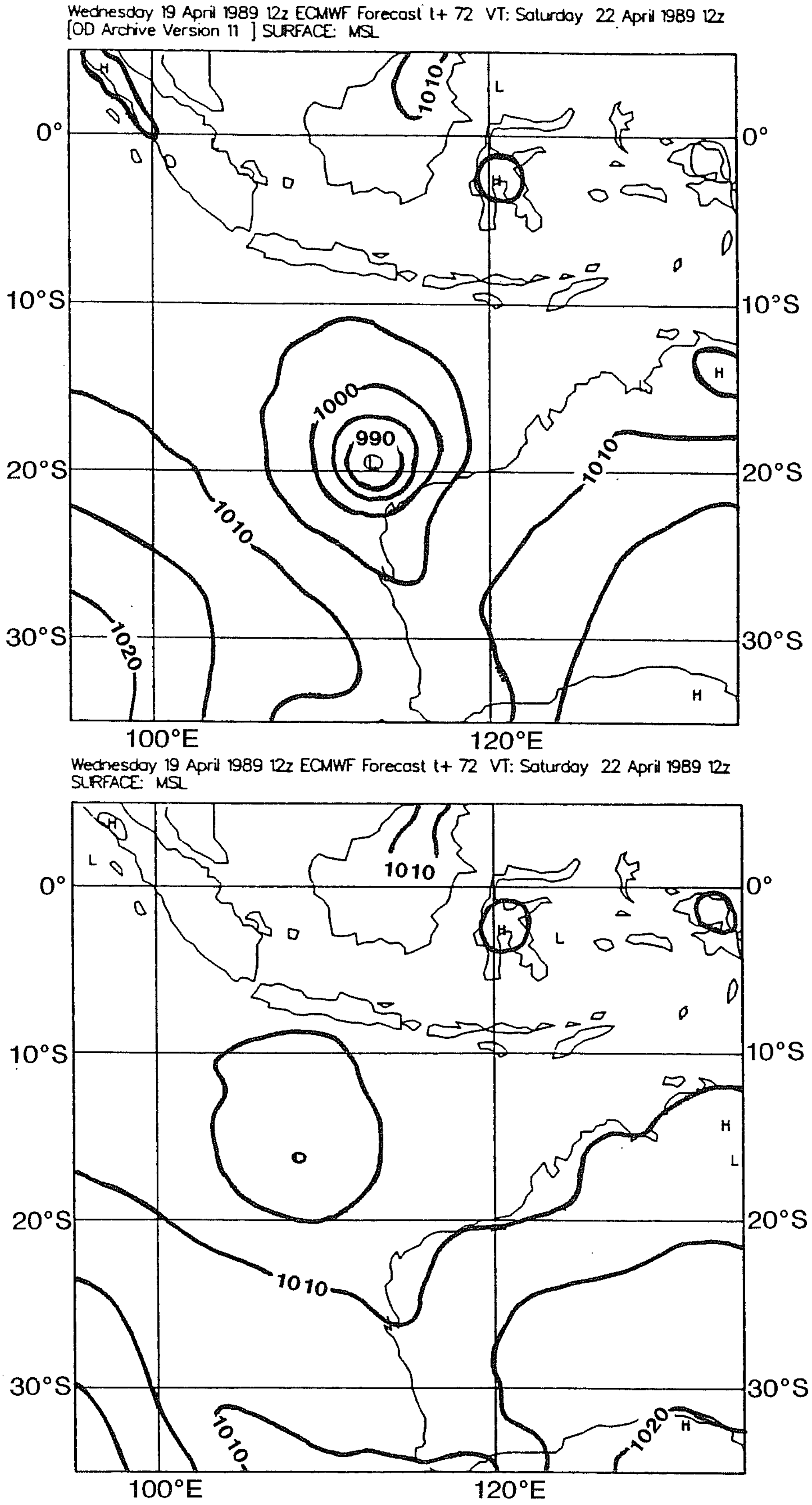


Fig. 8 Zonal mean 1-day temperature error (K/day) for an ensemble of 5 1-day forecasts with previous operational physics (top) and new operational physics (bottom) for period 15.2.88 to 20.2.88. Forecasts with new physics start from reassimilated data.



Wednesday 19 April 1989 12z ECMWF Forecast t+ 72 VT: Saturday 22 April 1989 12z
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Fig. 9 3 day forecasts for tropical cyclone 'Orson' from 19 April 1989 with previous ECMWF operational physics (bottom) and with new scheme (top).

longer period, subjective verification of the Centre's tropical forecast indicate, that given realistic initial conditions useful forecasts of tropical storms and hurricanes are produced for a few days ahead. Two examples of successful forecasts with the new convection scheme were those for hurricane 'Gabrielle' and 'Hugo', which were realistically predicted as to generation and storm track. In case of 'Hugo' the Centre's medium range forecasts provided realistic timing and location of land fall near Charleston (USA). An an example we show predicted and observed storm tracks for 'Grabrielle' which occurred over the Atlantic during the time of this Seminar. The agreement between predicted and observed tracks of Gabrielle (Fig. 10) is good except for the fact that the predicted track is displaced northeastwards by 200 km (apart from day 9 and 10). As predicted phase-speed and direction of movement are realistic the displacement of the track is presumably due to errors in the initial position of the disturbance. The model is also successful in reproducing the development of the storm as it develops the weak initial disturbance within two days into a tropical storm which then intensifies further to become a hurricane at day 8 with windspeeds of 35 m/sec. However, predicted windspeeds are considerably smaller than observed values which is not surprising in view of the coarse resolution of the model (i.e. spectral truncation T106). In fact, forecasts made at higher resolution but using the same physics package produce more intense tropical storms (Dell'Osso, personal communication).

### 3.6 Extra-tropical forecasts

The diabatic forcing from convection influences synoptic systems directly through deep convection at fronts and through mid-level convection and slantwise convection and indirectly through extra-tropical response to tropical convection. Extensive medium-range forecast experimentation carried out at ECMWF shows a mean improvement in extra-tropical forecast skill for the generalized adjustment scheme and the massflux scheme (Tiedtke and Miller, 1988) and there are indications that both the direct and indirect response are important. Although forecasts improve on average with advanced cumulus parametrization there is a spread in forecast quality as forecast quality diverges with forecast time. In a number of cases the skill scores are deteriorated for the more advanced schemes. In view of the results of predictability and forecast 'spread' studies this should not be too surprising since, as forecasts lose skill in predicting low-frequency long-wave patterns which in turn define the storm tracks, improving diabatic forcing of baroclinic eddies does not necessarily gain forecast skill but the reverse. Still, in the majority of cases the differences in skill were rather small and are as such reflected only in small differences in the synoptic flow. However, in some cases the impact of cumulus parametrization are large and on occasions already evident after a few days. A case where the impact was particularly large is the forecast from 17 January 1988. (Fig. 11). Differences are already noticeable at day 2 in the intensity of a cyclone over the Atlantic which become very large by day 8 over large areas of the northern hemisphere, the massflux scheme producing the more accurate forecast.

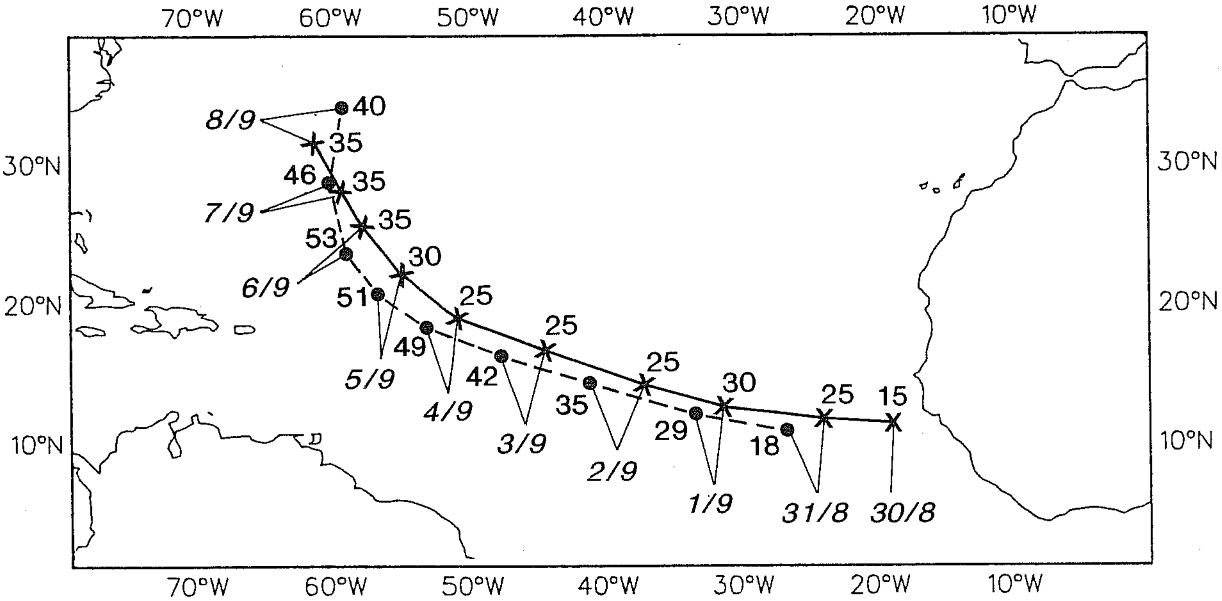

Fig. 10 Observed (●---●) and predicted track (X——X) of hurricane Gabrielle with new operational model, initial date is 30.8.89, 12Z. Values indicate observed maximum sustained windspeed and predicted mean windspeed at 850 mb level. Note that Gabrielle was first reported on 31.8.89.

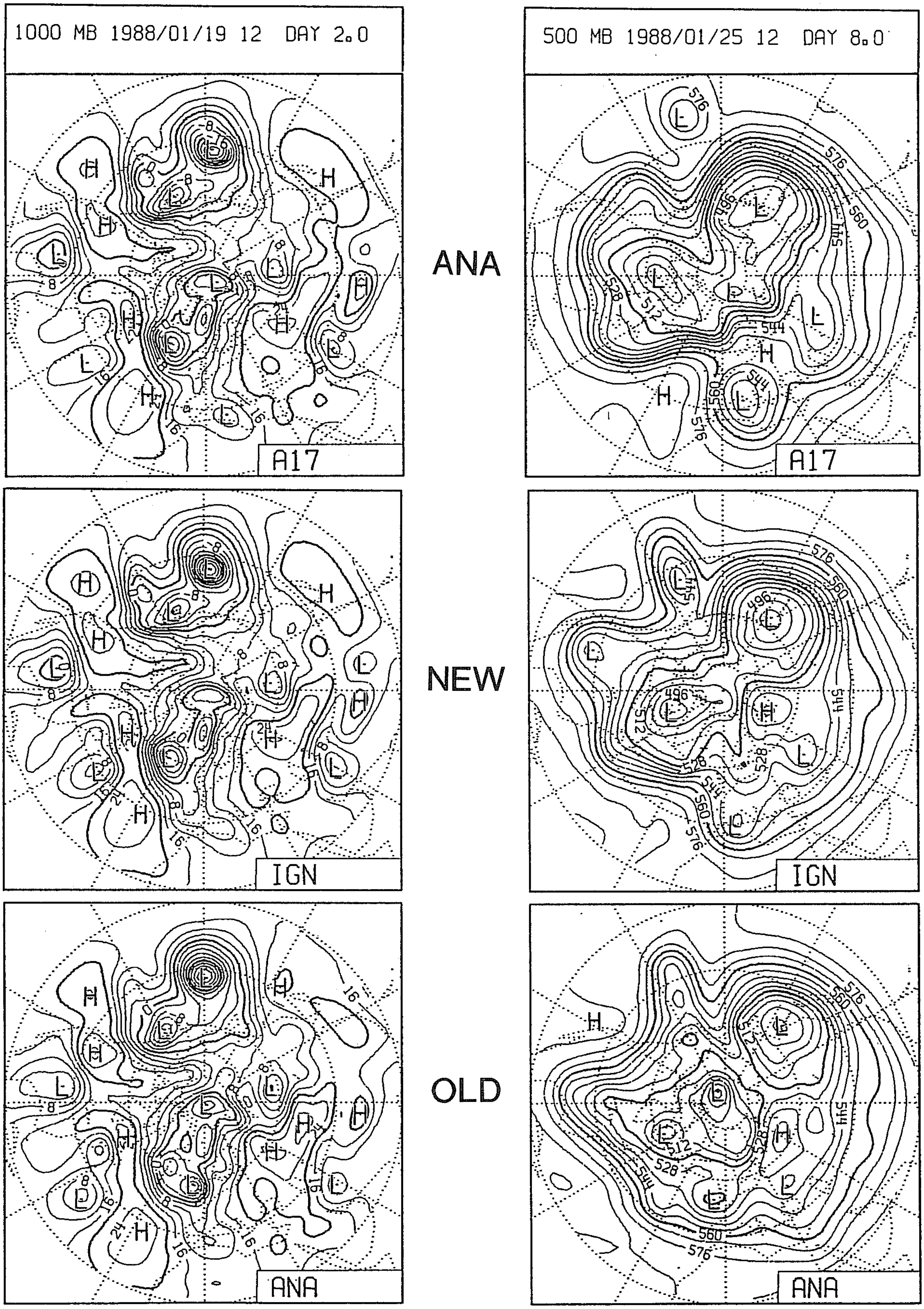

Fig. 11 Analysed and predicted height fields at day 2 (left) and at day 8 (right) for forecasts starting 17.1.88, 12Z. Marked areas are those with largest differences between forecasts with previous operational physics and new physics.

## 4. CONCLUSIONS AND FUTURE DEVELOPMENTS

We have reviewed the work on convective parametrization at ECMWF during recent years. It confirms the fundamental role of cumulus parametrization for numerical weather forecasting, particularly in the tropics even at short time-scales and in the extra-tropics mainly in the medium- and extended-range but occasionally also at shorter time-scales. Although much progress has been made, mainly through diagnostic studies, in the understanding of convective organisation and its interaction with the large-scale flow, the advance in cumulus parametrization has been slow and must still be considered a partly unsolved problem. Some progress has been made at ECMWF in recent years by first isolating critical aspects of parmetrization and by subsequently improving the corresponding parametrization schemes. Thus changes to the operational cumulus parametrization in May 1985, in particular the introduction of a scheme to represent the effects of shallow convection, had a beneficial effect on the diabatic forcing of the large-scale flow. This, in turn, significantly improved the operational forecasts, especially, in the tropics and subtropics. The replacement, in May 1989, of the Kuo scheme and the shallow convection scheme by a comprehensive massflux scheme has brought further improvements in particular with regard to

(i) the maintenance of the Hadley circulation which does not collapse over the Indonesian area as previously with the Kuo scheme,

(ii) the spin-up in convective heating which is considerably reduced with the new massflux scheme indicating better compatibility of the parametrization with observations,

(iii) the forecast of tropical cyclones, which the Kuo scheme typically failed to deepen and to maintain in forecasts.

Despite the significant improvements there are still major deficiencies in the simulation of the large-scale flow which strongly point towards remaining errors in the diabatic forcing in the flow. Most outstanding is the easterly wind error in the tropics and subtropics which extend through much of the upper troposphere. Some evidence that the tropical wind errors are indeed connected to erroneous diabatic forcing has been provided by Mohanty (personal communication). Mohanty has shown that the wind errors are largely reduced (Fig. 12) when the models diabatic forcing in the tropics is replaced by fields which have been derived from the analysed flow (Klinker and Sardeshmukh, 1988). The study seems to indicate that while the thermal forcing is of primary importance momentum forcing plays also a role for the generation of tropical wind errors. While Mohanty's study cannot provide conclusive evidence as to which parts of the parametrization are incorrect, cumulus parametrization, because of its dominant role, is a strong candidate for the large errors in the tropical flow. Therefore, cumulus parametrization remains a major research project in

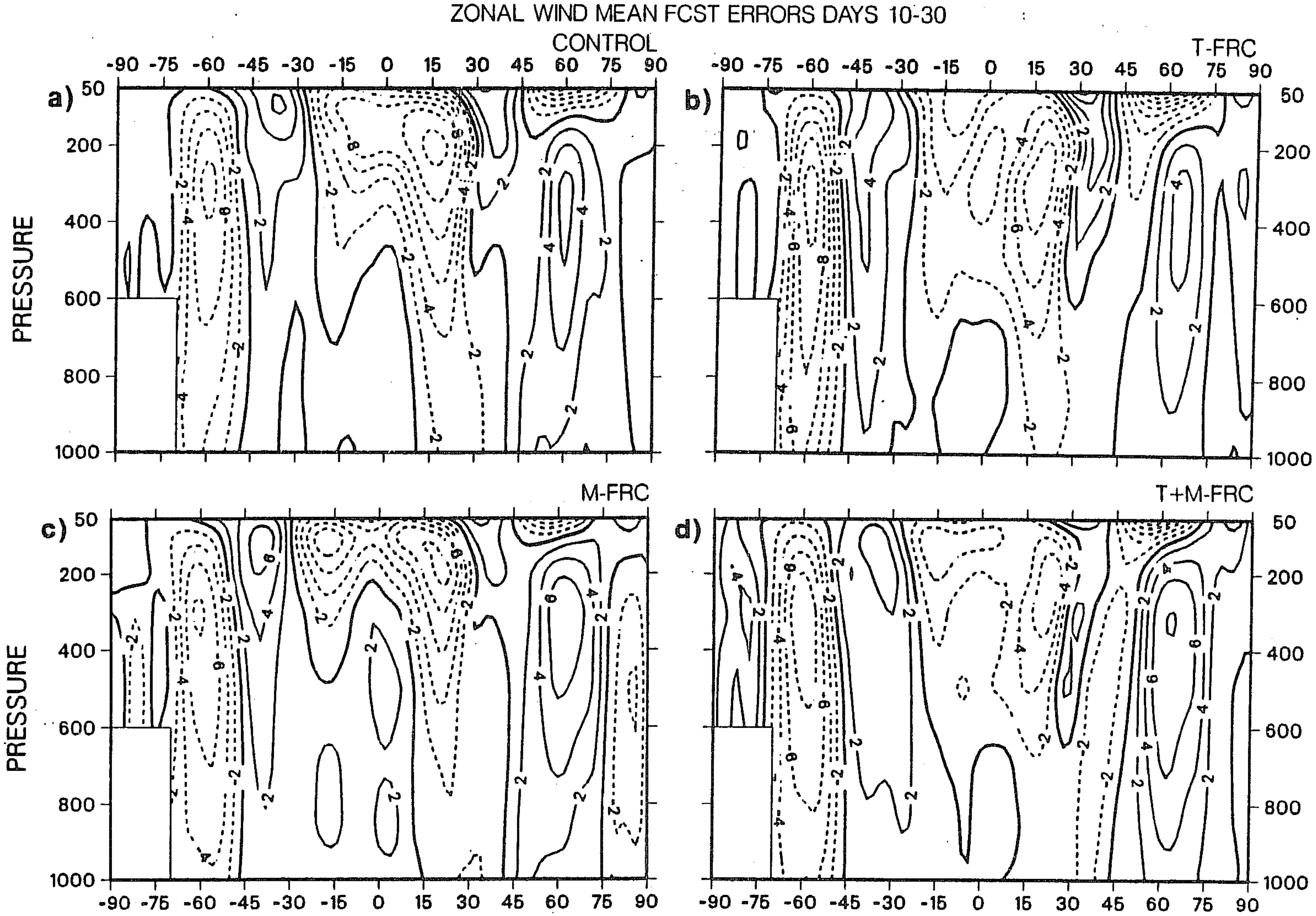

Fig. 12 Zonal mean error of zonal wind for day 10-30 for T42 integrations from 15.1.88 with a) operational scheme, b) momentum forcing, c) temperature forcing, d) momentum + temperature forcing. M- and T-forcing are derived from analysed flow and are applied only in topics (from Mohanty, personal communication).

research at ECMWF. The following parametrization aspects listed below are presently being addressed or will be considered in the near future:

(i) Closure assumption:
This is a fundamental problem. Here we will test and intercompare the two main closures (i.e. moisture convergence and adjustment concept) within the same framework of the ECMWF massflux scheme.

(ii) Convective scale downdrafts:
Refinement of the parametrization will include the introduction of a shear dependent evaporation efficiency for precipitating updrafts.

(iii) Inclusion of water loading on buoyancy:
The importance of water loading on the buoyancy of convective clouds (normally ignored in parametrization schemes) has recently been stressed by Betts (1982) and Xu and Emanuel (1989).

(iv) Introduction of kinetic energy equation for convective updrafts:
This is to improve the parametrization of convective elements overshooting the level of zero buoyancy (particularly important for tradewind cumuli).

(v) Prediction of convective cloud fields via prognostic equations for cloud area and cloud liquid water content:
This is to improve the cloud parametrization for radiative transfer.

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