ASPECTS OF CUMULUS PARAMETRIZATION

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Summary

The general problem of cumulus parametrization is reviewed. Conventional schemes are classified according to closure assumption and cloud model and uncertainties in various parametrization aspects are discussed. For example the effect of water loading on buoyancy which is ignored in conventional schemes is shown to have a substantial effect on the tropical mean thermal state.

It is argued that only parametrizations based on the mass flux concept can provide a realistic framework for studies such as vertical transports of gas tracers in pollution and climate models and the simulation of cumulus cloud fields.

Convective mass transports obtained from the ECMWF operational model convection scheme are presented. The results show that cumulus clouds transport on average more mass upward than the large scale flow; penetrative clouds in areas of large scale ascent and shallow clouds more widespread providing the only means through which in regions of large scale descent boundary layer air is exchanged with the air above. Uncertainties in the model derived mass transports are discussed including a comparison with results from other models.

The problem of representing convective cloud fields in large scale models is discussed. A new parametrization developed at ECMWF to predict cloud area and cloud water content is presented. Clouds are formed as a result of the detrainment of cloud air from convective updrafts into environmental air (predicted by the mass flux scheme) and they are dissipated by adiabatic and diabatic heating, formation of precipitation and turbulent mixing of cloud air and unsaturated environmental air at cloud edges. Advantages of the new cloud scheme against diagnostic schemes are discussed and demonstrated on results.

1. INTRODUCTION

Cumulus convection can have an important effect on the diagnosis and energetics of larger scale atmosphere circulations through

i) diabatic heating due to latent heat release in penetrative convection.

ii) vertical transports of heat, moisture and momentum and

iii) through the interaction of cumulus cloud fields 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 transport 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, but it can affect the large scale flow already on much shorter time scales relevant for short and medium range forecasts.

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 parametrization is still uncertain and may 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 formation of cloud fields) can only be represented crudely by means of parametrization.

Some progress in the understanding of cumulus convection and its effect on the large scale temperature and moisture fields has been made through observational studies which benefited parametrization but previous observations did not provide measurements for critical quantities such as cloud mass fluxes and cloud properties which are needed for developing and verifying parametrizations and therefore progress in parametrization had been rather slow. Besides, research had focused mainly on the problem of diabatic forcing by penetrative convection while other aspects related to convective transports and cumulus cloud fields had received little attention in comparison. In fact numerous contributions were made towards the parametrization of penetrative convection (see for example review papers by Frank, 1983; Arakawa and Chen, 1987 and Tiedtke, 1988) and therefore little will be added here (section 2). Instead we shall address in more detail the question of convective transports and present results for the Centre's convection scheme (section 3) and we shall also discuss the problem to represent cumulus cloud fields in large scale models and present a new cloud scheme developed at ECMWF to predict cloud area and liquid water content (section 4).

2. BASIC ASSUMPTIONS IN CONVENTIONAL PARAMETRIZATION SCHEMES

In order to represent the affects of cumulus convection in large scale models assumptions must be made as to how the "subgrid scale" cumulus convection depends on the "resolved" large scale flow and how it in return interacts with the resolved flow. As we are rather ignorant on both accounts it is not surprising to find quite a number of schemes based on different assumptions. In Fig. 1 we present a simple classification of parametrizations with regard to their two main components that is the closure and the cloud model. As far as conventional schemes are concerned the closure appears to be based either on the adjustment concept (e.g.

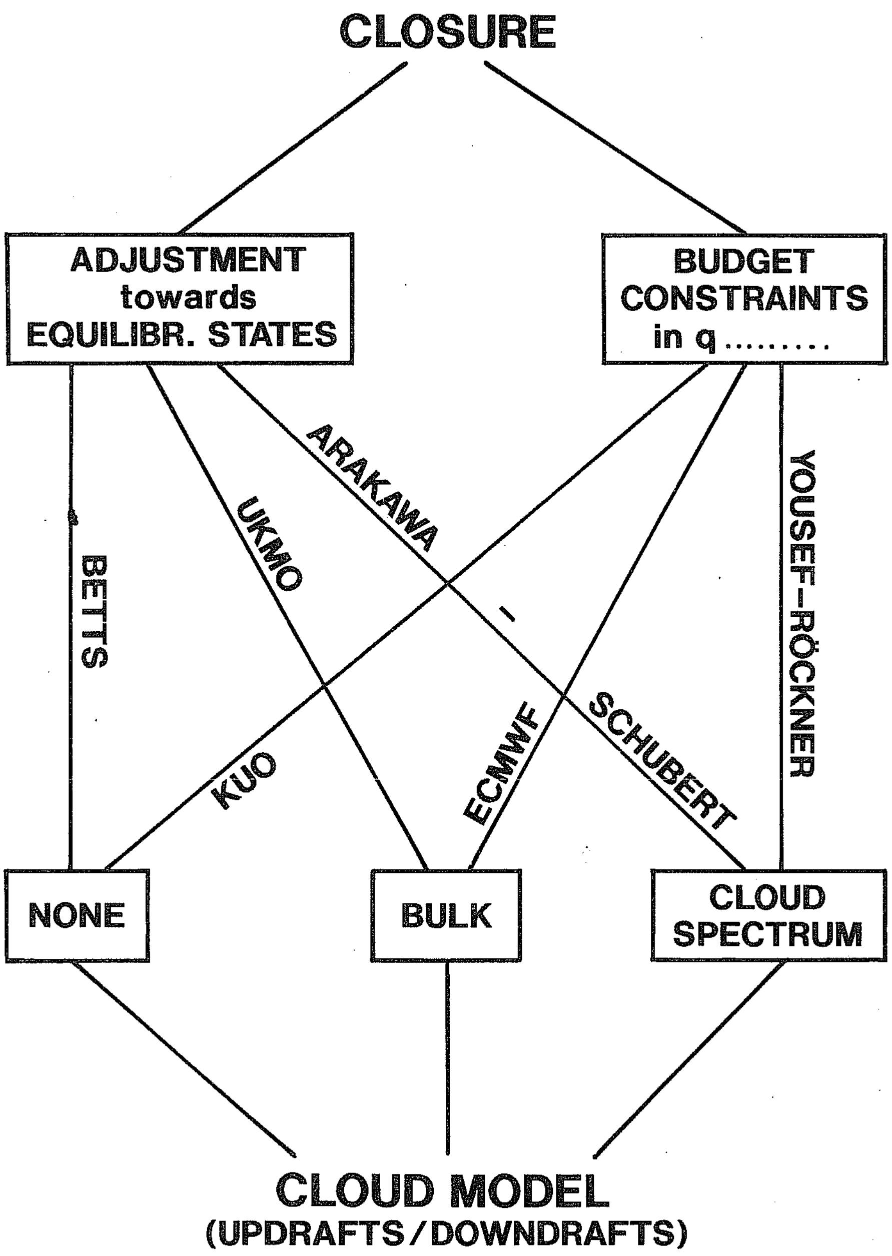

Fig. 1 Classification of conventional cumulus parametrizations.

Betts, 1986; Arakawa and Schubert, 1974) or a moisture budget constraint (e.g. Kuo, 1965 and 1974). In the case of the adjustment closure the assumption is that convective activity is strongly determined by the production of cloud available potential energy and thus the degree of conditional instability generated by adiabatic and diabatic processes during one time step is the relevant input parameter. Other schemes such as Kuo's consider the supply of moisture through large scale convergence and turbulent fluxes from below as a relevant indicator for cumulus convection. As it is at present not clear which one of the two closures is more realistic or whether alternate closures would be more appropriate it is difficult to give any parametrization preference over others as far as the closure is concerned.

The cloud model provides the variables through which cumulus clouds modify the environment. It is now widely accepted that convective heating and drying occurs predominantly through cumulus induced circulations (Ooyama 1971, Arakawa and Schubert 1974) and real-data diagnostic studies carried out for periods of tropical convection (e.g. Yanai et al., 1973; Ogura and Cho, 1973; Nitta, 1978; Johnson, 1976 and 1980; Chen, 1985; review article by Houze and Betts, 1981 on convection during GATE) and for tradewind cumulus convection (e.g. Nitta, 1975) have shown that in order to reproduce the contributions from convection to the large scale apparent heat and moisture sources it is sufficient to describe the cloud population by a highly idealised ensemble of clouds where the clouds are represented by simple prototypes of one-dimensional entraining plumes. In these studies the cumulus ensemble is either represented by a spectral cloud ensemble comprising clouds of various sizes or simply as a bulk (e.g. Yanai et al., 1973) which appears to be adequate for representing realistic contributions from convection to the large scale budgets of heat and moisture. Since a bulk representation of cumulus clouds makes the parametrization task so much simpler it has been adopted in various schemes (e.g. the operational schemes of ECMWF and UKMO). Recent studies (e.g. Johnson, 1980; Chen, 1985) indicate that besides convective updrafts cumulus-scale downdrafts and the organization of penetrative cells in meso scale cloud clusters and squall lines with well developed meso scale circulations on their own can also be important for the large scale heat and moisture budgets. However, there is presently little understanding how cumulus downdrafts and meso scale organization depend on the large scale flow and consequently parametrizations are either tentative as in the case of cumulus downdrafts (i.e. Fritsch and Chappell, 1980; Tiedtke, 1989; Cheng, 1989) or not available at all as for meso scale effects. Further extensive diagnostic studies are required to enhance progress in this area.

The representation of cloud physical processes is an essential prerequisite for cumulus parametrization but, unfortunately, contains many uncertainties. For example the assumption about the conversion from cloud droplets to rain drops within cumulus updrafts, which is not well based, has a strong bearing on rain efficiency and therefore on the net convective heating. Cloud water and rain water content can affect the buoyancy of convective elements.

$$B = T_c\,(1 + 0.608q_c) - \bar{T}\,(1 + 0.608\bar{q}) - T_c\,(l_c + l_r) \qquad (1)$$

where T_c, $\bar{T}$, q_c, $\bar{q}$ are temperature and specific humidity of cloud air and environmental air, respectively and l_c and l_r are cloud and rain water content. Conventional parametrizations ignore the effect of water loading and buoyancy is then determined purely by the excess of virtual temperature of the cloud element against its environment. However, as pointed out by Betts (1982) and Emanuel (1988) water loading can cause a substantial reduction in buoyancy which can have important implications for the thermal state maintained by cumulus convection. Water loading is difficult to include in models as the estimate of rainwater requires knowledge of its fall out which depends on the vertical velocity field in updrafts which is normally not available. Therefore in order to study the significance of water loading the global ECMWF model (T42 resolution) is integrated for 30 days first without and then with water loading included. Rainwater is calculated ignoring the effect of fall out (~ reversible moist adiabatic) but only 25% of its value is assumed to contribute to the water loading in (1) (which implies that effectively 75% of the rain water fell already out below the level in question). The 25% assumption gives, for tropical convection, values of up to 5g/kg at higher level which is probably a realistic upper limit for water loading in strong updrafts. The effect of water loading on the tropical mean thermal state is larger than expected (Fig. 2). The tropical troposphere is colder by more than 0.5K and the cooling is not only restricted to the convectively active regions where substantial cooling was anticipated but has also spread to the subtropics. This experiment confirms that the effect of water loading on buoyancy has important implications for the large scale thermal state and therefore must be included in cumulus parametrizations.

Turning back to the question of representing clouds we note that conventional parametrizations apply cloud models of various degree of complexity (Fig. 2). Simple schemes such as Bett's and Kuo's do not represent cumulus scale circulations and therefore convective heating and drying is not expressed in terms of cumulus induced circulations but instead by relaxing temperature and moisture towards prescribed equilibrium states. It is worth noting that Kuo's schemes is also of this type as the equilibrium state are moist adiabates and the relaxation time is inversely proportional to the moisture supply by large scale convergence and surface fluxes. It is sometimes argued that in order to represent the contribution of convection to the large scale heat and moisture budgets it is not necessary to include in parametrizations details about convective circulations. While this may be true as long as convective heating and drying are concerned it is also obvious that the simpler schemes are rather limited in their scope for further developments. In the following two sections we will discuss two of those areas, i.e. convective transports and the simulation of convective cloud fields.

3. VERTICAL TRANSPORTS BY CUMULUS CONVECTION

There is a genuine interest in knowing how much cumulus convection contributes to vertical transports in

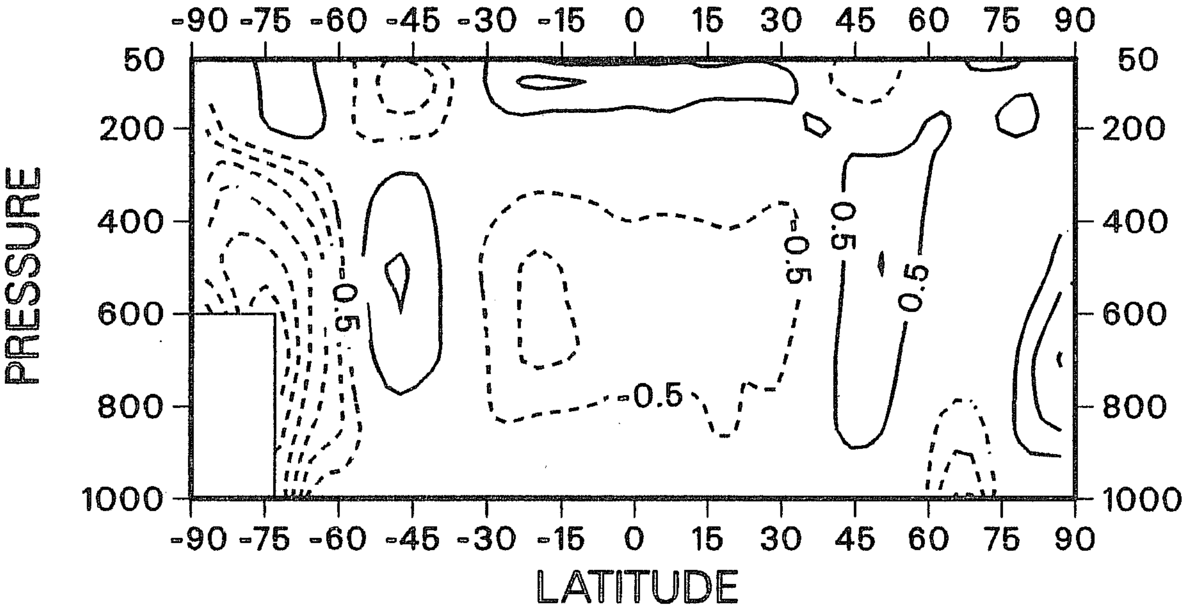

Fig. 2 Meridional height cross-section of zonal mean of temperature difference between forecasts with and without waterloading in buoyancy calculation for day 15 to 30 of T42 integrations for 16.4.85, 12Z.

the atmosphere, for example in the context of pollution studies or the dispersion of trace gases in the climate context. As it is practically impossible to measure convective transports over large areas estimates can only be obtained from cumulus parametrization schemes applied to real data as for example in forecast models. The accuracy of these estimates is affected by uncertainties in cumulus parametrization but as forecast models have improved over the years and produce now realistic forecasts even for tropical regions where cumulus convection plays a fundamental role there is reason to believe that convection schemes should be able to provide realistic estimates of convective transports. In the following we will study the convective transports by penetrative and shallow convection produced by the Centre's model in particular in comparison with the large scale transports with regard to magnitude and geographical distribution.

Cumulus convection contributes to the vertical transport of a quantity x (e.g. heat, specific humidity, trace gas concentration) through updrafts and downdrafts and cumulus induced subsidence as

$$\frac{\partial \overline{\rho}\,\overline{x}}{\partial t} = \frac{\partial}{\partial z}(\overline{\rho w x}) - \frac{\partial}{\partial z}\left(M_u x_u + M_d X_d - (M_u + M_d)\,\overline{x}\right) \qquad (2)$$

where the first term of the right hand side represents the large scale transport and M_u, M_d are the total mass fluxes from all updrafts and downdrafts, respectively. The vertical distribution of the mass flux and the updraft and downdraft values x_u and x_d are determined by entrainment of environmental air E and detrainment of cloud air D (besides phase changes as for T and q); for example in the case of updrafts entrainment occurs through cloud base and cloud edges at lower levels and detrainment occurs at higher levels where buoyancy is lost (Fig. 3)

$$\frac{\partial M_u}{\partial z} = E - D$$

$$\frac{\partial M_u x_u}{\partial z} = E\overline{x} - D x_u + C(x_u) \qquad (3)$$

As updrafts and downdrafts occupy only small fractions of the whole grid area, typically only a few percent, they transport mass much more efficiently than the large scale motion; updrafts of penetrative clouds carry boundary layer air to the upper troposphere with an hour rather than days. It is also important to note that cumulus induced subsidence counterbalances the large scale ascent which for the case of perfect cancelling implies that the area mean mass transport originates entirely from updrafts and downdrafts. This condition is most likely to exist in situations of intense penetrative convection such as in tropical storms, because then the balance is between adiabatic cooling by vertical ascent and convective heating

$$\overline{\rho w}\frac{\partial \overline{\theta}}{\partial z} \approx M\frac{\partial \overline{\theta}}{\partial z} \qquad (4)$$

as other processes such as radiation and horizontal advection are small in comparison to either of these two

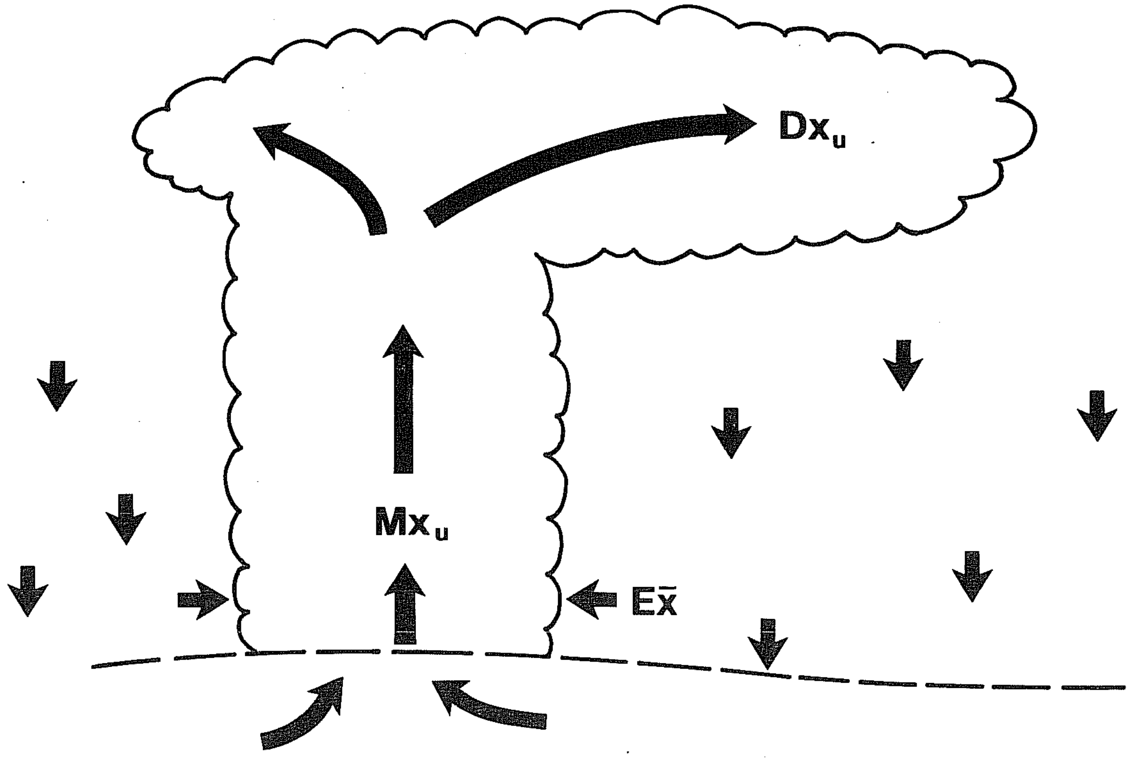

Fig. 3 Schematic diagram showing cloud circulations associated with cumulus updrafts.

processes and convective heating is determined largely by the cumulus induced subsidence.

Model diagnosed convective mass fluxes are shown in Figs. 4-8. In situations of penetrative convection updrafts entrain mass through cloud base as well as laterally, on average up to 700 hPa (maximum of M) and detrain above (Fig. 4). The depth of the convective layer increases towards the tropics (Fig. 5) detrainment of cloud air into the environmental being concentrated between level 10 (~ 400 hPa) and level 7 (~ 750 hPa).

Shallow convection provides a larger transport of boundary layer air than penetrative convection as its globally averaged transport by updrafts through cloud base (level 17 ~ 950 Hpa) is more than twice as large (Fig. 4) but updraft air detrains already within the lower troposphere. Also, the largest contribution comes from the extratropics (Fig. 5) whereas in the tropics cloud base mass fluxes are comparable in magnitudes to those for penetrative convection.

Of particular interest, for example in the context of pollution studies, is the transport of mass through the top of the boundary layer as it represents the rate at which boundary layer air is processed. We note that an average transport of $10\ g\ m^{-2}\ s^{-1}$ is roughly equivalent to the replacement of the whole boundary layer air within one day. Our results (Figs. 6 and 7) show that convective updrafts carry considerably more mass from the boundary layer to higher levels than the large scale flow. Since penetrative convection is closely linked to the large scale convergence (as is ensured already in the closure of the ECMWF parametrization) updrafts and downdrafts provide a net upward transports in the same regions as the large scale flow, that is along the ITCZ, over the tropical continents and in the extratropics in connection with cyclones. The already quite large mass flux is further enhanced by the contributions of shallow convection, in many areas by a factor of 2. Besides, shallow convection provides large transports in areas where there is large scale subsidence, that is over the subtropical oceans and in connection with air mass transformation in cold air outbreaks. The presence of convective updrafts in these areas is highly significant as they provide the only means by which boundary layer air is exchanged with air above. A striking example of their importance is the moisture transport in the trades which has been found to have a large effect on the thermal state, the global hydrological cycle and the maintenance of the large scale flow (Tiedtke et al. , 1988).

Since cumulus parametrization is still uncertain model generated mass fluxes must be considered as preliminary estimates. In order to have confidence in our estimates a comprehensive verification would be required for convection under different types of synoptic conditions. Unfortunately this is not possible as convective transports are not observed and only a few diagnostics from special observational data sets are available for tropical convection. A previously undertaken verification of model generated mass fluxes against diagnosed values over the Atlantic during Phase III of GATE and over the Pacific (Tiedtke, 1989)

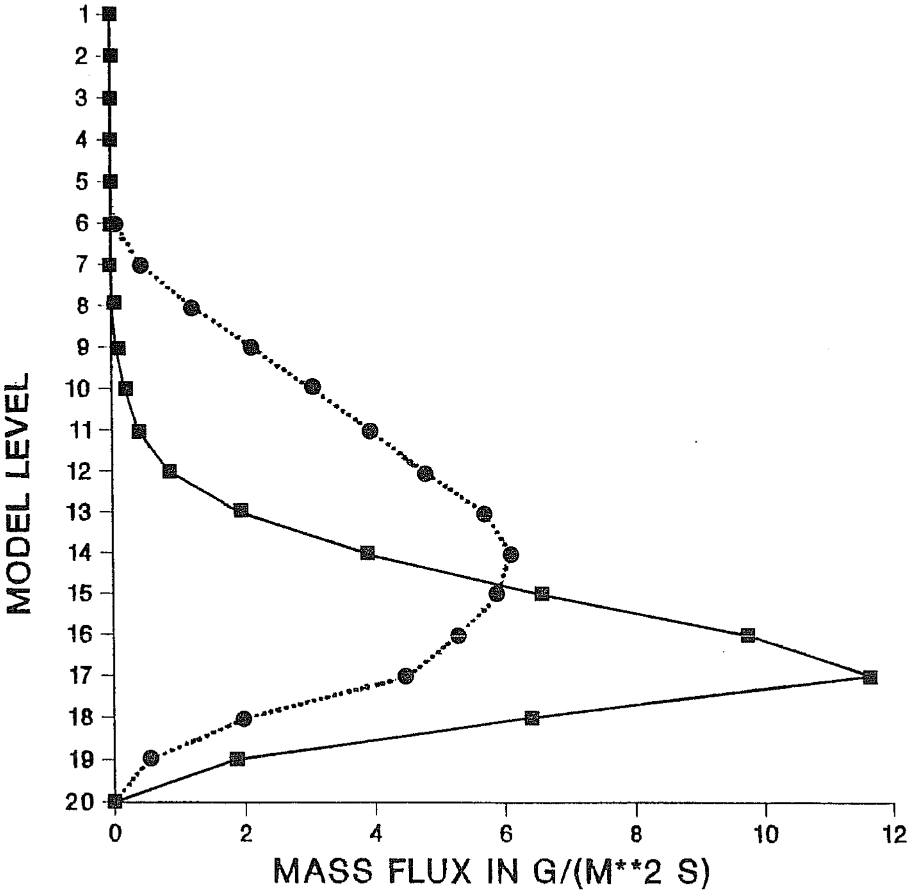

Fig. 4 Vertical profiles of 10-day mean globally averaged mass fluxes $M = M_u + M_d$ by penetrative convection (dotted line) and by shallow convection (full line) for T106 forecast from 15.1.90, 12Z.

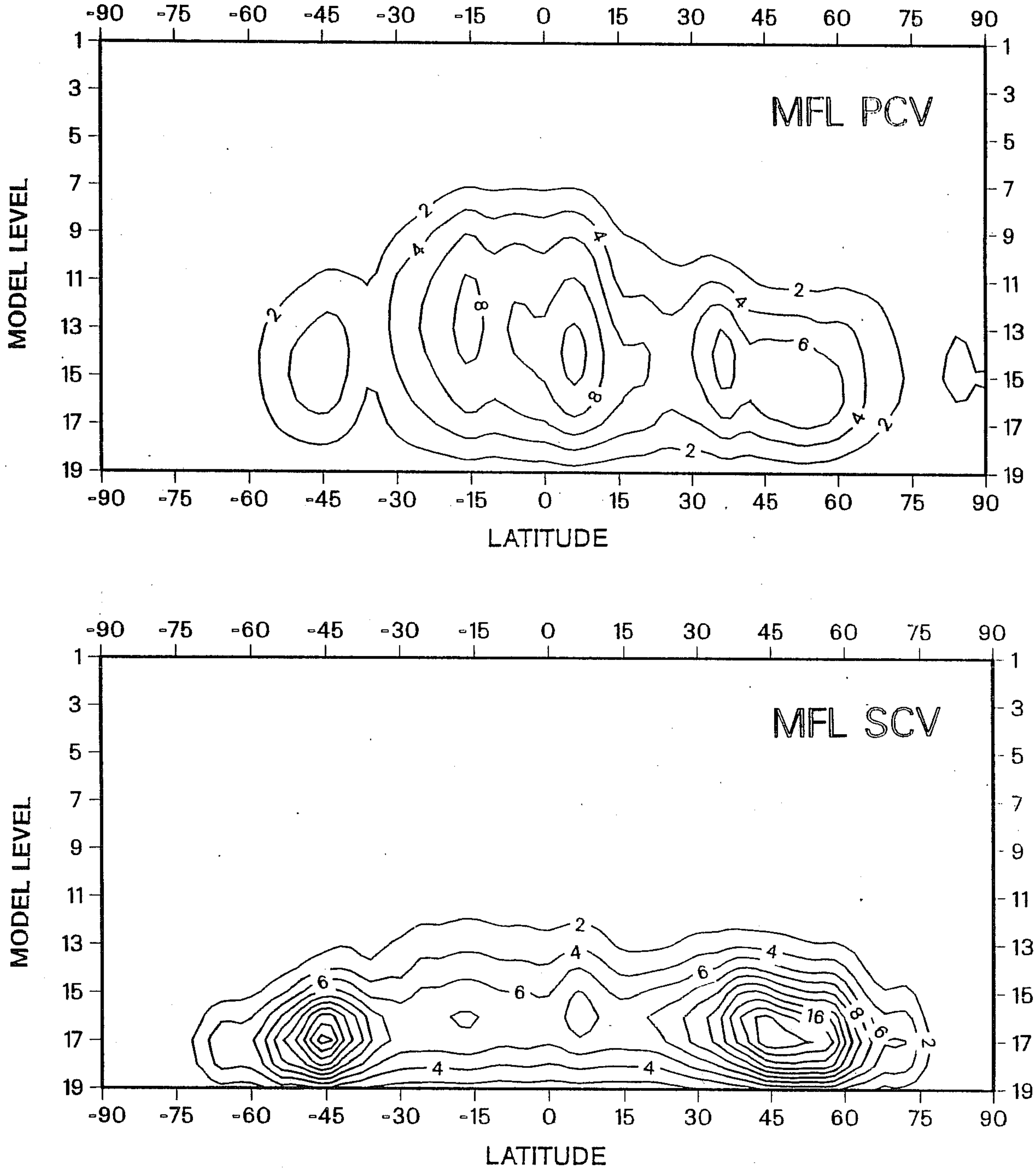

Fig. 5 Meridional height cross-section of 10-day mean zonally averaged mass fluxes $M = M_u + M_d$ for penetrative convection (top) and shallow convection (bottom) for T106 forecast from 15.1.90, 12Z.

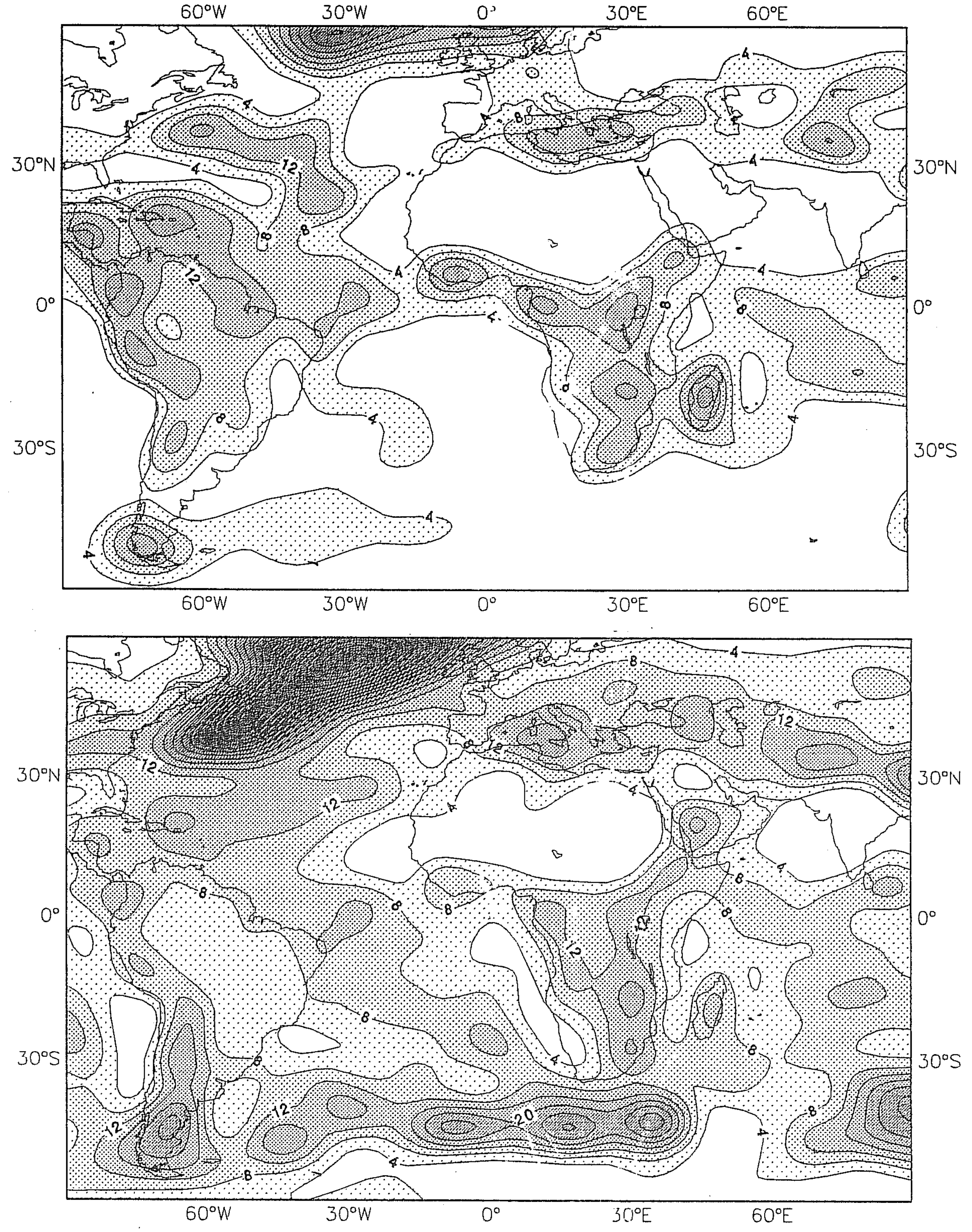

Fig. 6 10-day mean convective mass flux $M = M_u + M_d$ $(gm^{-2}s^{-1})$ at level 16 (~900 Hpa) for T106 forecast from 15.1.90, 12Z. Fields have been spatially smoothed for plotting purposed.

Top: penetrative convection
Bottom: shallow convection,

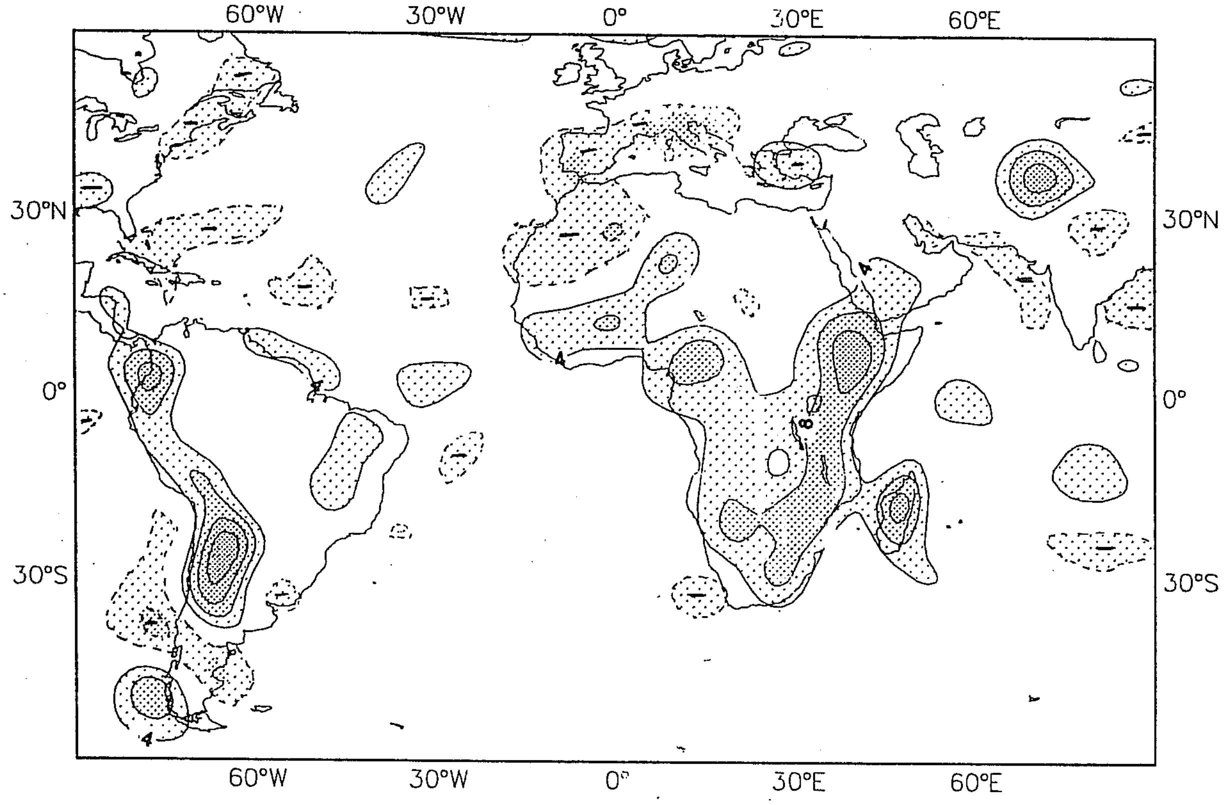

Fig. 7 as Fig. 6 but for mass flux by large scale vertical motion. Dotted lines and "---" indicate downward motion.

showed for penetrative convection good agreement with regard to magnitude, vertical profile and time-evolution of its mass flux but for shallow convection an underestimate of cloud base values. As this is the only verification available at this time we must assume that the contributions from shallow convection to the transport of mass shown in Fig. 4-5 might also be underestimated.

Brost (1990) has recently compared globally averaged convective mass fluxes obtained by various authors (Fig. 8) and noticed a large spread of estimates indicating a high level of uncertainty in their values. However, at closer examination it appears that a direct comparison of those estimates is not possible as some include contributions from penetrative and shallow clouds, others only penetrative clouds and one (labelled $\zeta = 0.5$ in Fig. 8) has been derived from another one $\zeta = 1$ by dividing its values by 2. Our estimated total mass flux (labelled EC in Fig. 8) has a similar profile as that of Prather et al. (1987) but has larger values in the lower and middle troposphere. Besides, the profile obtained for penetrative convection alone (Fig. 4) is similar to that of Feichter and Crutzen (1990) for precipitating clouds (FC in Fig. 8). Thus apart form the two estimates FR (which may be typical for some tropical regions but certainly not the whole globe) and $\zeta = 0.5$ (which is not an independent estimate) we find fair agreement between different model estimates, which supports our results in particular with regard to the vertical mass flux profile for penetrative convection and the large contribution from shallow convection to the mass transport across the boundary layer top.

Finally we add that our results on the relative contribution from convection and large scale ascent to the vertical mass transport are significant in the context of trajectory models used in pollution studies. Given that in convective situations in particular for penetrative convection more mass is being transported vertically by cumulus updrafts than by the large scale ascent and that the transport occurs over much deeper layers within the same time interval there is doubt whether trajectory models based on mean winds are appropriate. Therefore we conclude that pollution studies ought to be carried out with 3-dimensional models which include the mass transport by convection.

4. SIMULATION OF CONVECTIVE CLOUD FIELDS

Simulation of clouds in large scale models has not been given the same attention as other modelling aspects until quite recently although a number of forecast models, including that of ECMWF, have been predicting cloud fields for some years. The recent interest in cloudiness as an important climate feedback mechanism has focused attention on the ability of GCMs to predict cloud distributions and this has let to increased interest in the cloud forecasting problem and in the influence of clouds on the flow on shorter time scales. Still, clouds are presently poorly represented, often by means of a diagnostic scheme such as that of ECMWF in which the cloudiness is derived from other model variables such as the relative humidity, vertical velocity,

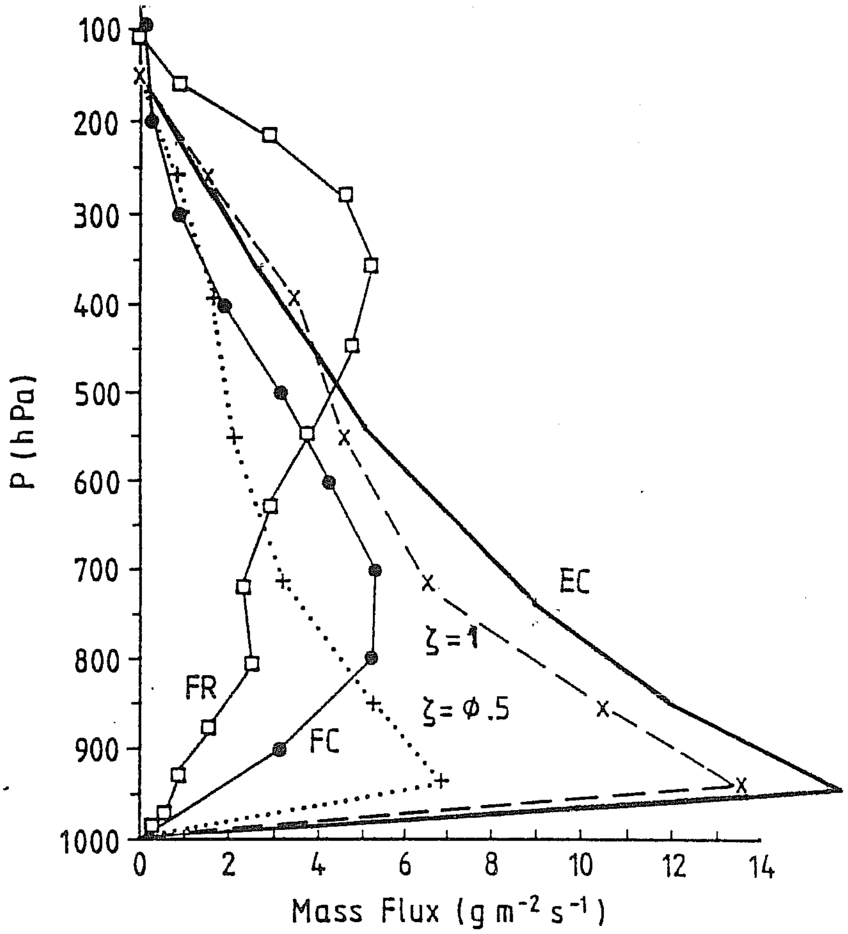

Fig. 8 Global average vertical profile of mass fluxes. FC is Feichter and Crutzen (1990). Two curves are the GISS convection statistics (including shallow clouds and clear air PBL turbulence) as used by Prather et al. (1987, curve $\zeta = 1$) and by Heimann and Keeling (1989, $\zeta = 0.5$). FR is Feichter et al. (1990). From Brost (1990). EC is the total mass flux by convective updrafts and downdrafts for penetrative and shallow convection for the EC-scheme.

static stability or convective precipitation rate. Only recently has there been a more systematic approach by means of prognostic schemes which include one or more extra variable to represent clouds and to model their formation, dissipation and advection. These schemes have the advantage that they a) provide a better physical representation of clouds and their effect on other fields through their relation to cloud water content, b) provide a consistent treatment of cloud processes in the various components of the model and c) predict variables like cloud water content which are measurable. Some progress has been made in predicting non-convective clouds (Sundquist, 1978) but the prediction of convective cloud fields remains an unsolved problem. As the formation of convective clouds depends on the occurrence of cumulus updrafts they ought to be represented by means of a parametrization as an extension of the already existing model's convection scheme. Although this can be done in a rather straight-forward way in case cumulus convection is parametrized through a mass flux scheme, as then the source term for the formation of cloud fields can be readily expressed in terms of available model variables, it has so far not been tried as far as we know. Therefore we have developed such a scheme at ECMWF which is prescribed here and include results from a 10 day forecast experiment to demonstrate its advantages over a purely diagnostic scheme. The concept behind the scheme is that the cloud field is formed as cloud air is detrained from the cumulus updrafts into the environmental air (Fig. 3). The source terms for the cloud water content and cloud mass are fully determined by the detrainment terms in the equations for the updrafts (underlined terms in equations (5))

$$\frac{\partial Ml}{\partial z} = -\underline{Dl} + \bar{\rho} c - \bar{\rho} P_l$$

$$\frac{\partial M}{\partial z} = E - \underline{D} \tag{5}$$

where the parametrization assumptions concerning detrainment D, entrainment E, condensation c and precipitation P_l are discussed in Tiedtke (1989). Dissipation of clouds occurs mainly through evaporation of cloud water and conversion of cloud water into precipitation. Therefore the evolution of total liquid water content l is given by

$$\frac{\partial \bar{l}}{\partial t} = \frac{D}{\bar{\rho}} l - e_H - e_T - P_l \tag{6}$$

where e_H, e_T are the evaporation rates of cloud water due to heating and turbulent mixing of cloud air and unsaturated environmental air, respectively, and P_l is the conversion of cloud water into rain. The total transports by the large scale flow are presently ignored.

The cloud fraction a is determined from the mass balance equation applied to the total cloud area ignoring large scale transports

$$\bar{\rho}\frac{\partial a}{\partial t} = \oint \bar{\rho} \; v_u \, ds \tag{7}$$

v_u represents the displacement of the cloud boundaries due to expansion ($v_u>0$) as the result of the outflow from updrafts and/or shrinking ($v_u<0$) in connection with evaporation of cloud air at cloud edges

$$\bar{\rho} \; \frac{\partial a}{\partial t} = \oint \bar{\rho} \; v_n^+ ds + \oint \bar{\rho} \; v_n^- \, ds \tag{8}$$

In order to specify the expansion of clouds in connection with mass detrainment from updrafts assumptions must be made as to how the outflow changes outside the updrafts. First, we note that because updrafts are counterbalanced by cumulus induced subsidence in the environmental air within the same grid box (parametrizations assumption in convection scheme) the mass transport from updrafts must decrease towards zero at the grid boundaries. Here we assume that the mass transport across the boundaries of area a around the updrafts decreases as the area increases as

$$\oint \bar{\rho} \; v_n^+ \, ds = (1 - a) \, Du \tag{9}$$

We are aware that this parametrization is rather crude but we believe it can be refined when adequate data from observations or high resolution models become available. Finally we note that parametrization (9) ensures realistic limits at zero cloud cover (only detrainment into cloud free area) and at cloud cover 1 (only detrainment into already existing clouds). Reduction of the cloud area represented by the last term of equation (8) occurs as a result of evaporation of cloud water in connection with heating and turbulent mixing of cloud air and environmental air discussed below.

As to the evaporation of clouds due to heating e_H we consider presently only the contributions due to large scale vertical motion $\bar{\omega}$ and cumulus induced subsidence M as

$$e_H = a \, \frac{dq_s}{dt} \approx \left(\bar{\omega} + gM\right) \frac{dq_s}{dp} \tag{10}$$

We note that this term represents a sink by evaporation of cloud water in regions of subsidence (e.g. trades) but a source by condensation in the presence of ascent (e.g. anvils).

Evaporation due to turbulent mixing of clouds with unsaturated environmental air is uncertain. Here we assume that it is proportional to the saturation deficit of environmental air

$$e_T = aK(q_s - \bar{q}) \tag{11}$$

where $\bar{q}$ is the specific humidity of the environmental air. For the parametrization of the conversion from cloud water into rain we follow Sundquist (1978)

$$P_l = a\,C_o\left(\frac{\bar{l}}{a}\right)\left(1 - e^{-\left(\frac{\bar{l}}{a}/l_{crit}\right)^2}\right) \tag{12}$$

where C_o and l_{crit} are disposable parameters.

Before discussing results we add some general remarks concerning the new cloud parametrization. The scheme deals only with clouds connected with cumulus convection but it represents the various types which typically occur over the subtropical oceans (trade wind cumuli), over the continents in summer, in cold air outbreaks, in the tropics (cumulonimbus with anvils and cirrus), in extratropical cyclones in the presence of midtropospheric layers of convective instability. As the parametrization represents the various processes which can contribute to cloud formation and dissipation it reproduces realistically the time evolution of the various cloud fields noting that clouds are controlled by different processes depending on synoptic conditions; for example anvils and cirrus are affected largely by cloud physical processes (e.g. release of precipitation) whereas trade wind cumuli dissipate due to evaporation in connection with heating by the large scale downward motion. The scheme prognoses cloud water content and cloud area. It differs in this respects from convectional parametrizations for stratiform clouds where only one prognostic equation, that is for cloud water content, is used.

The new cloud scheme has been tested and compared with the diagnostic scheme of the ECMWF operational model at T42 resolution. Although experimentation was limited to only one forecast experiment it clearly shows how the two schemes perform and how they differ. Here we present only results showing the time evolution of convective cloud fields over land and predicted average cloud water contents, as it is in these fields that we noticed the largest differences. The new scheme produces more realistic cloud fields over land as is shown in Fig. 9 for a region of central Africa: cloud base occurs on average at 950 Hpa (level 16) rather than close to the surface and penetrative clouds extend to higher levels than with the diagnostic scheme which seems to predict tops systematically too low as noticed by Morcrette (1989) in a diagnostic study using ERBE data. But the most striking difference is in the time evolution of the high clouds. For the new scheme the maximum cloud cover occurs in the afternoon (~15 h local time) rather that at noon and the cloud persist after convection has ceased; for example during the first two days when convection was particularly strong some clouds persisted throughout the whole night. The diagnostic scheme fails to reproduce a realistic time evolution of cloud fields because the cloud cover is assumed to be directly linked to the convective activity (precipitation rate) and therefore clouds cannot persist beyond the time of convective activity.

The representation of liquid water content (LWC) of cumulus cloud fields in models is particularly difficult for various reasons such as its large variability in space and time, poor knowledge of cloud physical processes

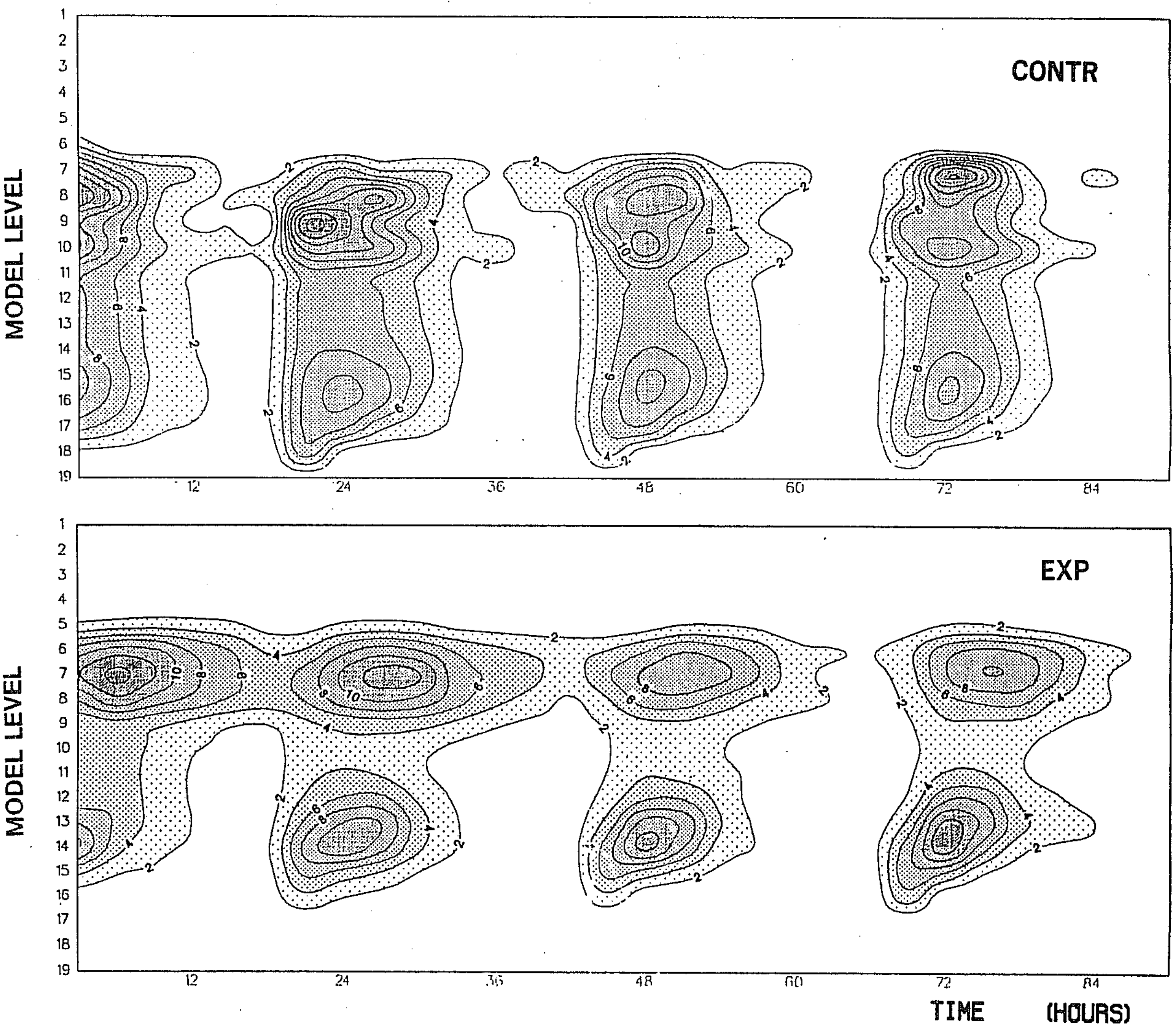

Fig. 9 Time evolution of area mean convective cloud fields processed in 3 hr intervals for Central Africa (15 E - 45 E, 10 N - 20 S) for T42 integrations from 16.4.85, 12Z.

Top:	ECMWF operational scheme (CONTR)
Bottom:	Predictive cloud scheme (EXP)

and the difficulty to verify model results because of lack of adequate observational data. It is therefore not surprising that the two schemes produce so different values of LWC. The diagnostic scheme produces largest values near cloud base below 900 Hpa whereas the new scheme gives an increase with height up to around 820 hPa (level 14) and a decrease above (Fig. 10). Since the liquid water content in cumulus clouds typically increases with height the vertical profile obtained with the diagnostic scheme appears unrealistic. This becomes even more evident when we consider the liquid water content per cloud air which is shown in Fig. 11 for the global average over all clouds. Again the profile obtained with the predictive scheme appears much more realistic. In the lower troposphere LWC increases from small values at cloud base to 0.6g/kg at 750 hPa (level 13) similar to observed profiles for non precipitating cumuli (Warner, 1955). The values obtained for high level clouds are difficult to verify as we consider averaged conditions which comprise convective clouds at various stages of their lifetime, that is newly formed cumulonimbus, anvils and cirrus of largely different LWC. However, in view of the presence of cirrus the rather small values of LWC for high clouds is probably not unrealistic.

Whereas the prospects for verifying vertical profiles of LWC are slim, progress has been made recently towards observing vertical integrated LWC through microwave measurements from satellite. Unfortunately observational estimates presently available differ to a larger extent than the model estimates (Fig. 12) and therefore are of little value, but further progress in deriving LWC from microwave observations can be expected and will hopefully provide reliable estimates for verification of model results. At present we cannot be sure which one of the two model vertical integrated LWC (Fig. 12) is more correct. However, the more realistic vertical profile of LWC shown in Fig. 11 point to the larger values produced by the new scheme and it is worth noting that the larger values are also closer to the more recent of the two observational estimates.

5. CONCLUSIONS

We have discussed the present state of cumulus parametrization in the context of the various requirements in large scale modelling. In the past, research had concentrated predominantly on the foremost task of producing realistic fields of convective heating and considerable progress was made, mainly through diagnostic data studies. However, there is still uncertainty about various aspects of cumulus parametrization as for example the closure, the representation of cloud processes and in particular which parametrization approach (e.g. relaxation or mass flux approach) is the most appropriate for large scale modelling. Further progress in this field will depend largely on the availability of adequate observational data.

With the advance of pollution and climate issues other requirements in addition to that of producing fields of convective heating have become important in particular the specification of vertical transports by cumulus clouds and the representation of convective cloud fields. However, both aspects have received rather little

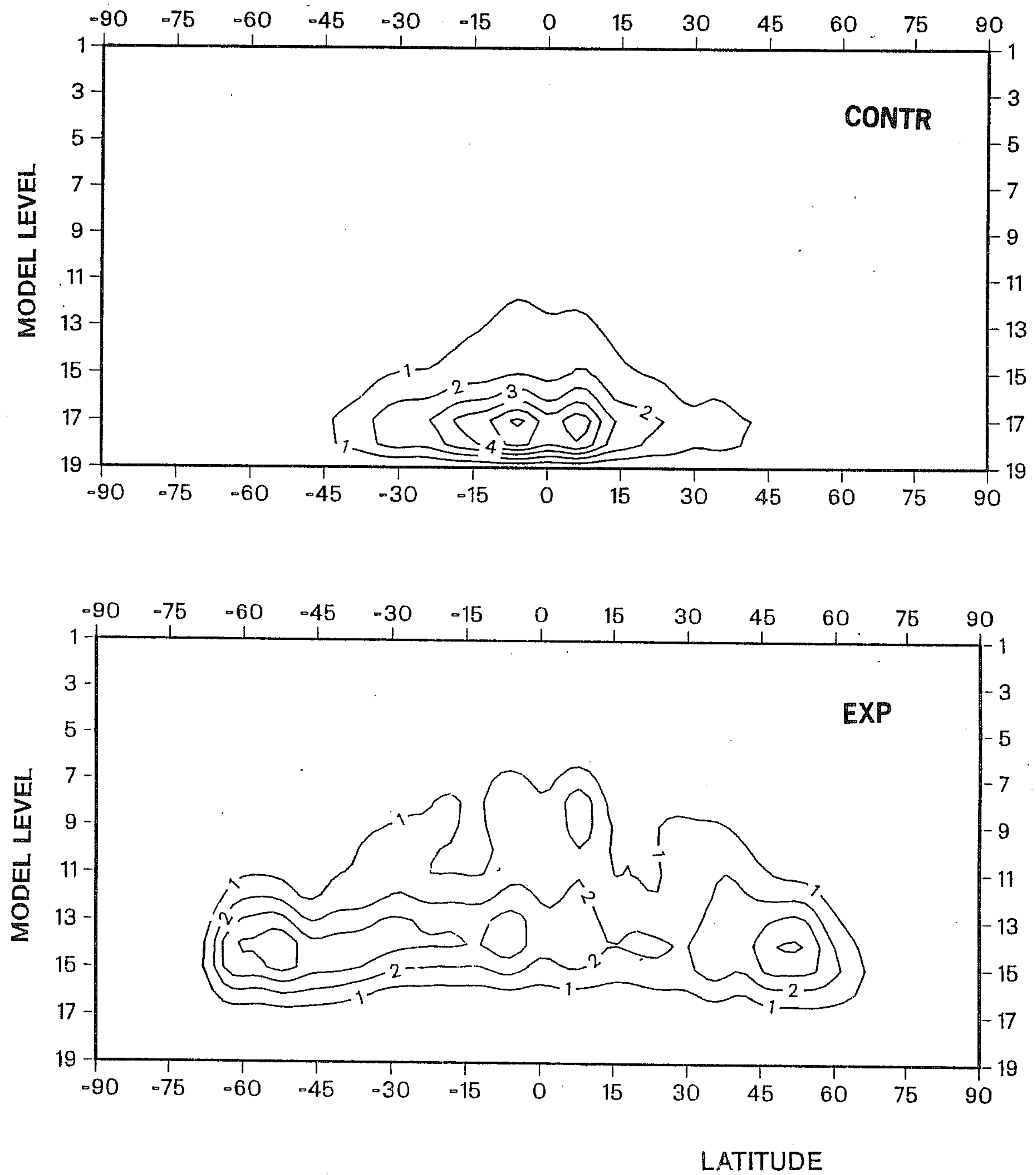

Fig. 10 10-day mean zonally averaged liquid cloud water content ($10^{-2} g/kg$) of cumulus cloud fields for T42 integrations from 16.4.85, 12Z.

Top: ECMWF operational scheme (CONTR)
Bottom: Predictive cloud scheme (EXP)

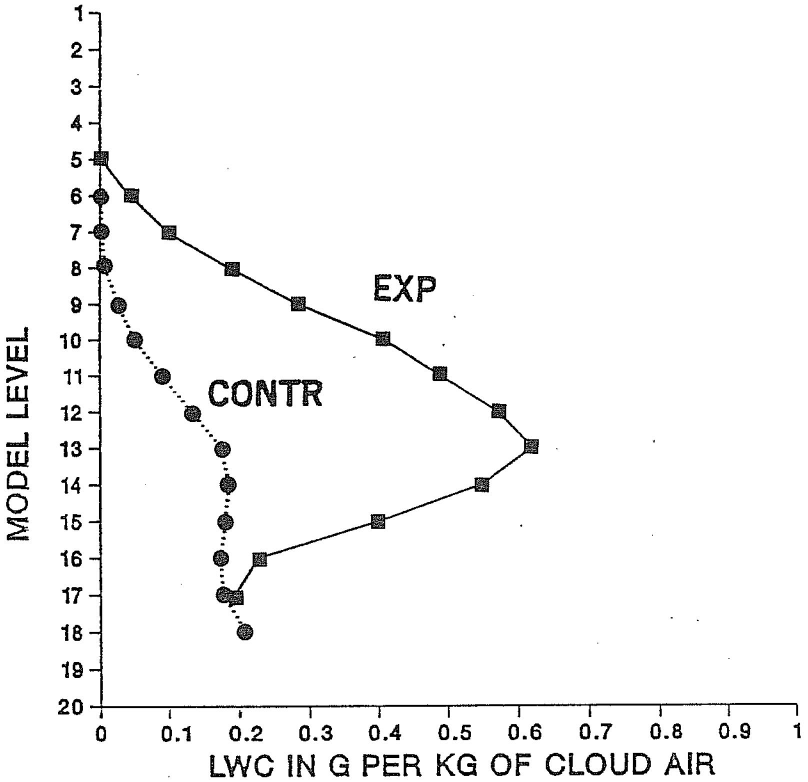

Fig. 11 10-day mean globally averaged liquid water content per cloud air for T42 integrations from 16.4.85, 12Z for ECMWF operational scheme (CONTR) and predictive cloud scheme (EXP)

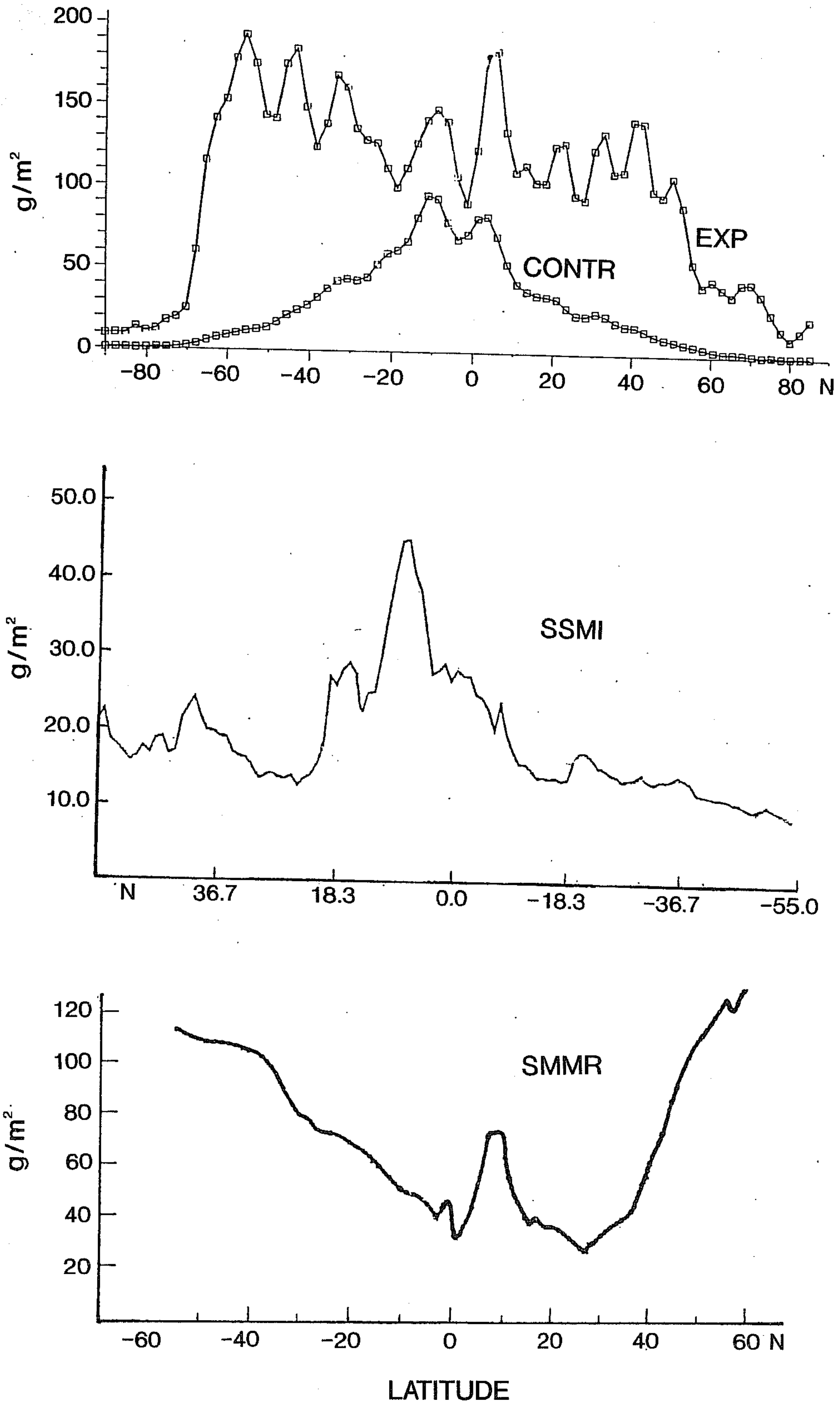

Fig. 12 Zonal averages of vertical integrated liquid cloud water content

Top:	10-day means for forecast with ECMWF operational scheme (CONTR) and predictive scheme (EXP)
Middle:	Measurements by SSMI over oceans (G. Rabeau and H. Le Treut, personal communication, from data provided by C. Gautier)
Bottom:	Measurements by SSMR over oceans (Njoku and Swanson, 1983)

attention until now and uncertainties are therefore particularly large. We have argued that parametrization is best carried out within the framework of the mass flux approach and we have presented results obtained with the ECMWF operational mass flux scheme. The results show that cumulus clouds transport, globally averaged, more than 10 $g\ m^{-2}\ s^{-1}$ from the boundary layer to higher levels which exceeds the contribution from the large scale flow but as model's values had been verified only for short periods of tropical convection we are still uncertain about the correct value. Clearly, there is a need for more observational data for a wide range of synoptic conditions.

Preliminary results presented for the new predictive cloud scheme indicate that a parametrization, where the generation of cumulus cloud fields is specified directly from the model convection scheme, indicate its superiority over a purely diagnostic approach as time evaluation and liquid water content appear more realistic. The predictive scheme provides a fully consistent treatment of cloud processes within large scale models but in order to develop and refine the scheme observational data are required for verifying the various aspects of the parametrization in particular cloud physics.

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