DESIGN AND TESTING OF A NEW SCHEME

FOR CONVECTION PARAMETERIZATION

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1. INTRODUCTION

The importance of cumulus parameterization for numerical weather prediction has long been recognized, and a number of different schemes have been proposed and tested in NWP models. After the completion of the GATE experiment, an excellent ensemble of data has been available, and several studies have investigated the performances of existing parameterizations from the "diagnostic" point of view. Among those, Lord (1982), and Krishnamurti et al. (1980, 1983) have made extensive comparisons between the radar estimated rainfall rates and the convective rainfall rates predicted by the Arakawa and Schubert (1974) scheme and several versions of Kuo's (1974) scheme. The apparent heat source Q_1 and moisture sink Q_2 due to cumulus convection have also been computed and compared to the observations.

As a result of these studies, the following "state of the art" can be assessed :

i) The prediction of the overall rainfall rate is satisfactorily accomplished by both schemes.

ii) The vertical distribution of the heating and drying effect is quite realistic,but suffers from a few systematic defects; for instance, the moisture sink is often overestimated in the lower troposphere.

iii) The imbalance between the large-scale and convective tendancies, measured for instance by the vertically integrated moisture tendancy, $\int_0^{p_s} \frac{\partial q}{\partial t} \frac{dp}{g}$, is not as well predicted as could be expected since it is the difference of two large and highly variable terms. However, some of the results are encouraging (Lord et al. 1982).

From the theoretical point of view, the contradiction between Kuo's and Arakawa and Schubert's approaches can be summarized in a few words. Whereas Kuo advocates a heating effect by mixing of warmer cloud air with the environment, the main heating in the Arakawa and Schubert scheme is caused by compensating subsidence. Many authors have performed observational studies of the mass budget of cumulus cloud clusters in the ITCZ during GATE, and the general result of theses studies supports Arakawa and Schubert's approach to the mass flux (see e.g. Johnson, 1980)

Another important development in cumulus parameterization studies is the appearance of several schemes for representing explicitly the effects of the cumulus on the momentum or the vorticity of the mean flow. Among those, Cho et al. (1979), Yanai (1982), and Esbensen et al. (1982), have proposed quite similar formulations. It must be noted that all these authors rely on the knowledge of the convective mass flux to formulate the solution of the parameterization problem for the dynamical terms.

As a conclusion,we feel that schemes based on the prediction of the convective mass flux have two major advantages :

i) They follow closely the observational knowledge of cumulus convection.

ii) They allow for further inclusion of the effects of clouds on the momentum or vorticity of the environmental flow.

Lindzen (1981) and Geleyn et al. (1982) have already proposed such schemes. Here we will describe another attempt in this direction, Bougeault (1984), with an interesting performance / simplicity ratio.

2. DESCRIPTION OF THE SCHEME.

The problem of cumulus parameterization is most simply formulated by use of the dry static energy s and the specific humidity q as dependant variables :

$$\frac{\partial s}{\partial t} = -\underline{V}.\nabla s - \omega\frac{\partial s}{\partial p} + \frac{L}{C_p}(C-E) + g\frac{\partial F_s}{\partial p} + Q_R \qquad (1)$$

$$\frac{\partial q}{\partial t} = -\underline{V}.\nabla q - \omega\frac{\partial q}{\partial p} - C + E + g\frac{\partial F_q}{\partial p} \qquad (2)$$

However, it is of advantage to use equations derived from 1 and 2, for the conservative variables $s_\ell = s-(L/C_p)q_\ell$, $q_w = q+q_\ell$:

$$\frac{\partial s_\ell}{\partial t} = -\underline{V}.\nabla s_\ell - \omega\frac{\partial s_\ell}{\partial p} + \frac{L}{C_p}R + g\frac{\partial F_{s_\ell}}{\partial p} + Q_R \qquad (3)$$

$$\frac{\partial q_w}{\partial t} = -\underline{V}.\nabla q_w - \omega\frac{\partial q_w}{\partial p} - R + g\frac{\partial F_{q_w}}{\partial p} \qquad (4)$$

where R is the instantaneous loss due to precipitations, and $F_s(p)$, $F_q(p)$, are the vertical subgrid-scale fluxes of s and q.

Thus, there are two different problems to overcome when modelling deep cumulus convection : First, how to model the rainfall rate; second, how to model the convective fluxes of energy and moisture. In keeping with the previous subsection, we want to relate these two effects to the convective mass flux ω^* . The rainfall rate can be expressed by assuming that , inside the clouds, there is a quasi-equilibrium between the precipitation and the vertical advection of heat and moisture :

$$R = -\omega^*\frac{\partial q_c}{\partial p} = \frac{C_p}{L}\omega^*\frac{\partial s_c}{\partial p} \qquad (5)$$

The most simple way to relate the fluxes to the convective mass flux is :

$$F_q = -\omega^*(q_c - q) + F_q^{dif}$$

$$F_s = -\omega^*(s_c - s) + F_s^{dif}, \qquad (6)$$

where F_q^{dif}, F_s^{dif} stand for that part of the sugrid-scale fluxes which is not related to the clouds.

Putting Eqs. 3, 4, 5, and 6 together, we obtain :

$$\frac{\partial s}{\partial t} = -\underline{V}.\nabla s - \omega \frac{\partial s}{\partial p} + \omega^* \frac{\partial s}{\partial p} - \frac{\partial \omega^*}{\partial p}(s_c - s) + g \frac{\partial F_s^{dif}}{\partial p} + Q_R \qquad (7)$$

$$\frac{\partial q}{\partial t} = -\underline{V}.\nabla q - \omega \frac{\partial q}{\partial p} + \omega^* \frac{\partial q}{\partial p} - \frac{\partial \omega^*}{\partial p}(q_c - q) + g \frac{\partial F_q^{dif}}{\partial p} \qquad (8)$$

However, this formulation proves to be very difficult to use because $\partial\omega^*/\partial p$ is highly variable. It is more efficient to replace $\partial\omega^*/\partial p$ by a constant in the vertical, K, which represents a bulk measure of the (inverse) time constant for the mixing of cloudy air with the environment. Furthermore, since we do not have , at this stage, a reliable scheme to compute F_q^{dif}, F_s^{dif}, we include them in the convection scheme and replace both $-\frac{\partial\omega^*}{\partial p}(q_c - q)$ and $g\frac{\partial}{\partial p}F_q^{dif}$ by $K(q_c - q)$.
Since we destroyed the exact, conservative form of the transport terms, we must ensure the conservation of the moist static energy. This gives an equation for K :

$$K = \left\{ F_h(p_B) - F_h(p_T) - \int_{p_T}^{p_B} \omega^* \frac{\partial h}{\partial p} \frac{dp}{g} \right\} \Big/ \int_{p_T}^{p_B} (h_c - h) \frac{dp}{g} \qquad (9)$$

Also, the rainfall rate must be modified in a constant way:

$$\int_{p_T}^{p_B} R \frac{dp}{g} = -\int_{p_T}^{p_B} \left[\omega^* \frac{\partial q}{\partial p} + K(q_c - q)\right] \frac{dp}{g} + F_q(p_B) - F_q(p_T) \qquad (10)$$

Next, the scheme must be closed by choosing an adequate expression for

$\omega^*(p)$. This quantity will be the measure of cloud activity, so it must be chosen very carefully. According to Arakawa and Schubert's theory, it must express some kind of equilibrium between the large-scale and cloud-scale processes. There are probably many ways to use this idea. Here we hypothesize that the vertical structure of $\omega^*(p)$ must be primarily determined by the vertical structure of the instability (hence by the thermodynamic profiles) whereas the magnitude of $\omega^*(p)$ must include some large-scale information (for instance the rate of moisture convergence in the column – the fuel for convection). More precisely, we write :

$$\omega^*(p) = \alpha (h_c - h)^{1/2} \qquad (11)$$

where h_c, h, are the moist static energies of the cloud and of the environment, and α is determined by equating the total moisture convergence and the moisture used to form clouds :

$$F_q(p_s) - \int_0^{p_s} \left(\underline{V} \cdot \nabla q + \omega \frac{\partial q}{\partial p}\right) \frac{dp}{g} = - \int_{p_T}^{p_B} \omega^* \frac{\partial q}{\partial p} \frac{dp}{g} \qquad (12)$$

This is another formulation of Kuo's initial idea that all the moisture available is used to feed the clouds; that is either to produce precipitations, or moisten the environment.

In summary, we propose the following expression for the heat source and moisture sink :

$$Q_1 = \omega^* \frac{\partial s}{\partial p} + K(s_c - s) \qquad (13)$$

$$Q_2 = -\omega^* \frac{\partial q}{\partial p} - K(q_c - q) \qquad (14)$$

where ω^* is computed by (11,12), and K by (9).

3. RESULTS OF DIAGNOSTIC COMPUTATIONS ON GATE.

Tests of the scheme have been performed with heat and moisture budget data-sets from the GATE experiment available at NCAR, processed by Dr. V. Ooyama (see Esbensen et al., 1982, for a presentation). The "observed" values of Q_1 and Q_2 can be seen in Figs. 1 and 2, taken from Bougeault (1984). The use of Eqs. 9 and 12 requires the knowledge of $F_h(p_b)$ and $F_q(p_b)$, the fluxes at the cloud base level. Here we replace the cloud base pressure with the surface level (which means only that the cloud-induced subsidence and detrainment effect extend down to the surface, a not very unrealistic assumption). $F_h(p_s)$ can be determined from the vertical integral of $Q_1-Q_R-Q_2$; however, this computation is subject to large errors, since Q_1 and Q_2 are measured independantly. Therefore we use only the time averaged value of this result, namely 146 W/m^2. This value is slightly larger than the direct measurements of this quantity, but has to be used in order to remain consistent with the data-set. The value of $F_q(p_s)$ was assigned as 130 W/m^2 in agreement with the previous remark.

Experiments have included different cloud profile determinations and various shape factors for $\omega^*(p)$. Although the results are not very sensitive to the way the cloud properties are obtained, the best agreement with the observations was obtained with the most simple method, where the cloud properties are those of a moist adiabatic ascent with some realistic value of the entrainment of environmental air (5. 10^{-4} $mbar^{-1}$, the same as the highest clouds in Arakawa and Schubert's scheme). Without entrainment, the clouds overshoot the tropopause by about 50 mbar, leading to an overestimation of the heating and drying at this level. With entrainment, the results are generally good, as can be seen from Figs. 3 and 4, where the time-height cross-section of the computed Q_1-Q_R and Q_2 can be compared to Figs. 1 and 2. Due to the use of the moisture convergence in the closure, the general shape and location of the heating and drying events is generally well reproduced. The main discrepancy lies in the under-estimation of the variability of Q_2 in the boundary layer. The scheme has a "climatological" behaviour that does not reproduce the large variations of moisture when convective events occur. We suspect, however, that this is a common defect to all parameterization scheme. As shown by Figs. 5 and 6, the averaged value of $Q_1 - Q_R$ and Q_2 during the 20 days of the Phase III of GATE is well captured by the scheme.

It is of interest to look at the mass flux – the main ingredient of the parameterization. This is compared to the large scale vertical velocity in Fig. 7. The magnitude of ω^* is slightly larger than ω, which is in good agreement with recent experimental work (Johnson, 1980). The vertical structure of ω^* is modelled after $(h_c - h)^{1/2}$ and has therefore only one maximum, whereas ω has two maxima. Several authors have tried to link the complicated structure of ω to the occurrence of different sizes of detraining clouds. However, no strong experimental evidence exists to support this point. Our assumption does not reproduce it in the mass flux. Nevertheless, as can be seen from Figs. 5 and 6, the predicted Q_1 and Q_2 do exhibit a double-maxima structure, presumably imposed by the gradients of s and q.

4. IMPLEMENTATION OF THE SCHEME IN A NWP MODEL.

The present study has shown that the effects of convection on the thermodynamic variables in the tropics may be parameterized by a fairly simple scheme, including a single cloud model, and a realistic prediction of the cloud mass flux. For the implementation of this scheme into a NWP model, the most immediate problem is posed by the interaction with the diffusion scheme. From our work on the diagnostic computations, it is clear that when convection is present, no existing diffusion scheme can work satisfactorily. Therefore, the most simple

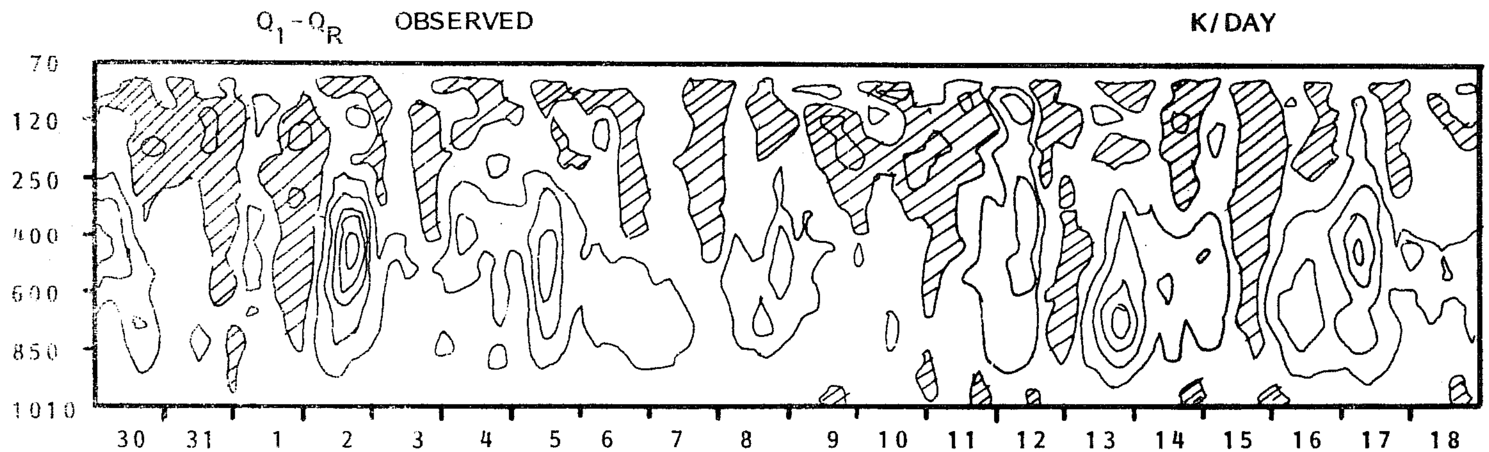

Fig. 1

Time-height cross-section of the observed apparent heat source. Time is in days, from 30. August to 18. September, 1974. The isolins interval is 5 K day^{-1}, and the dashed regions are negative values.

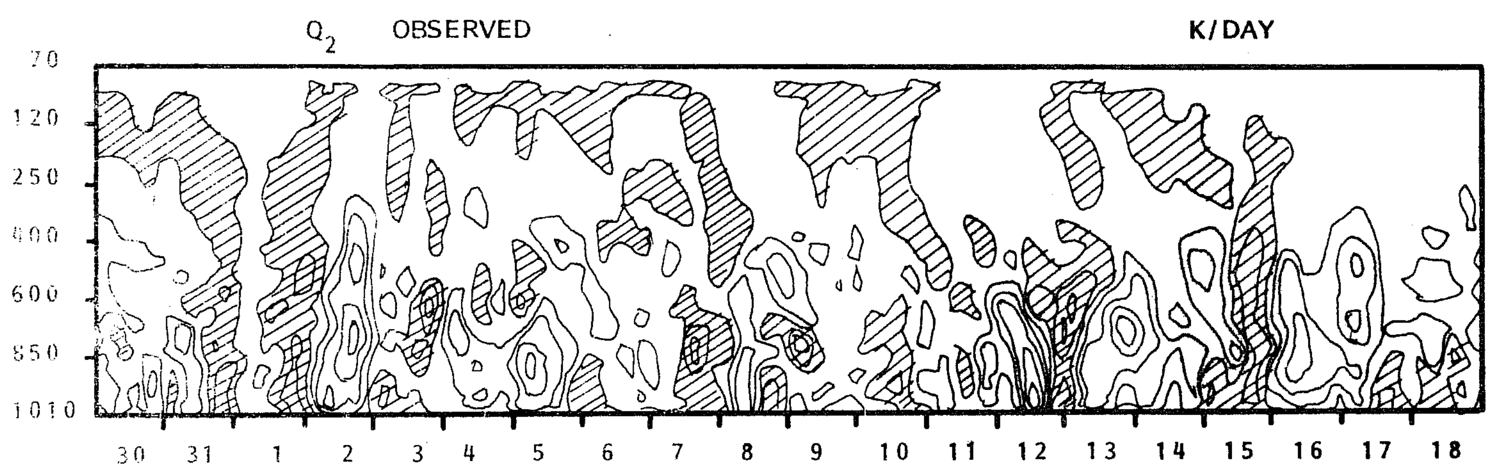

Fig. 2

Same as Fig.1, for the apparent moisture sink.

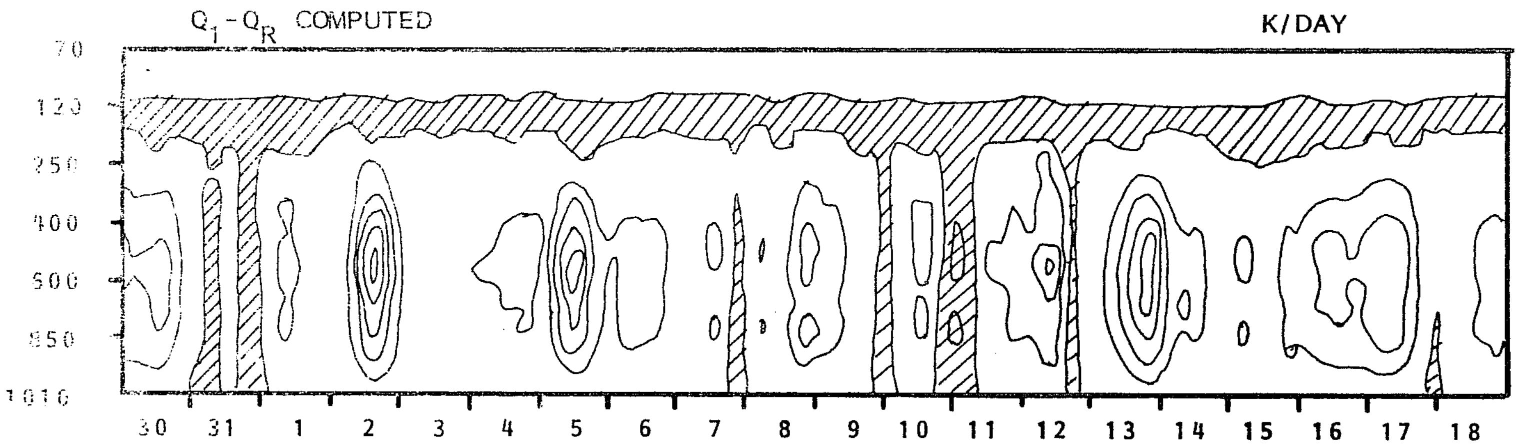

Fig. 3

Same as in Fig. 1 for the computed heat source.

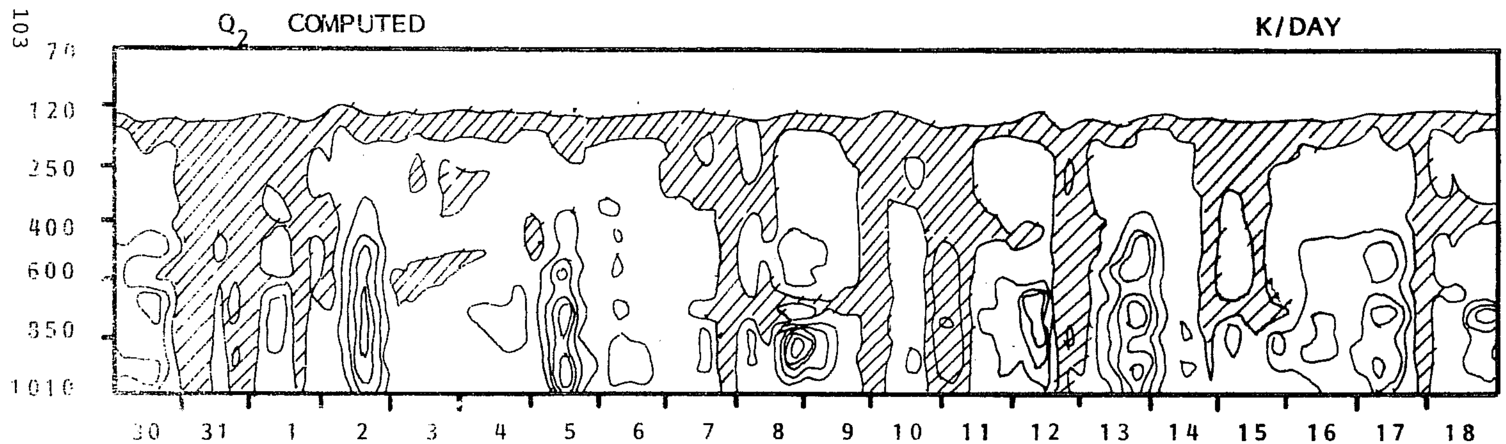

Fig. 4

Same as in Fig. 1, for the computed moisture sink.

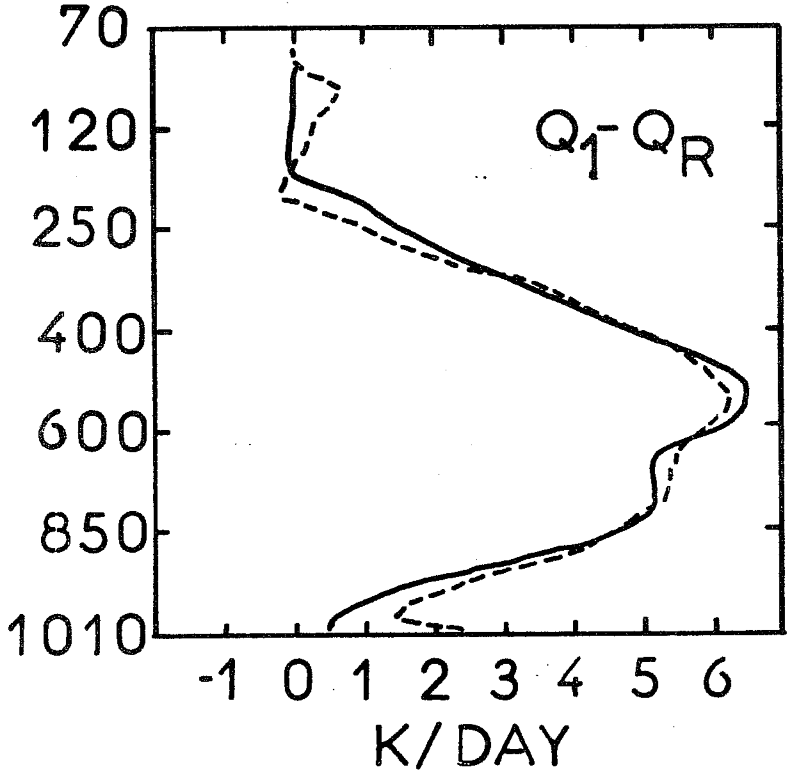

Fig. 5

Apparent heat source averaged over 20 days. Solid line : computed; dashed lined : observed.

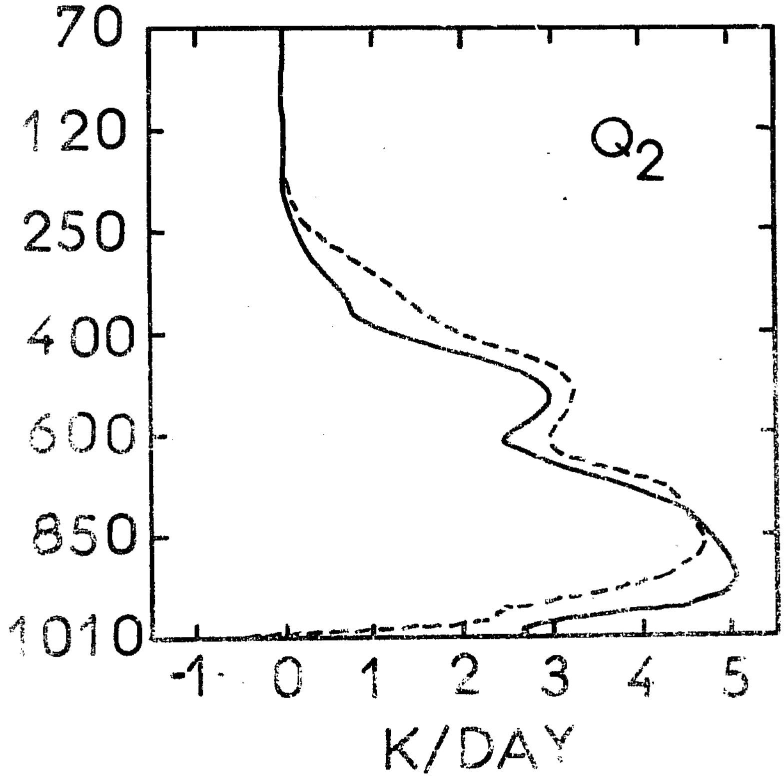

Fig. 6

Same as Fig. 5, for apparent moisture sink.

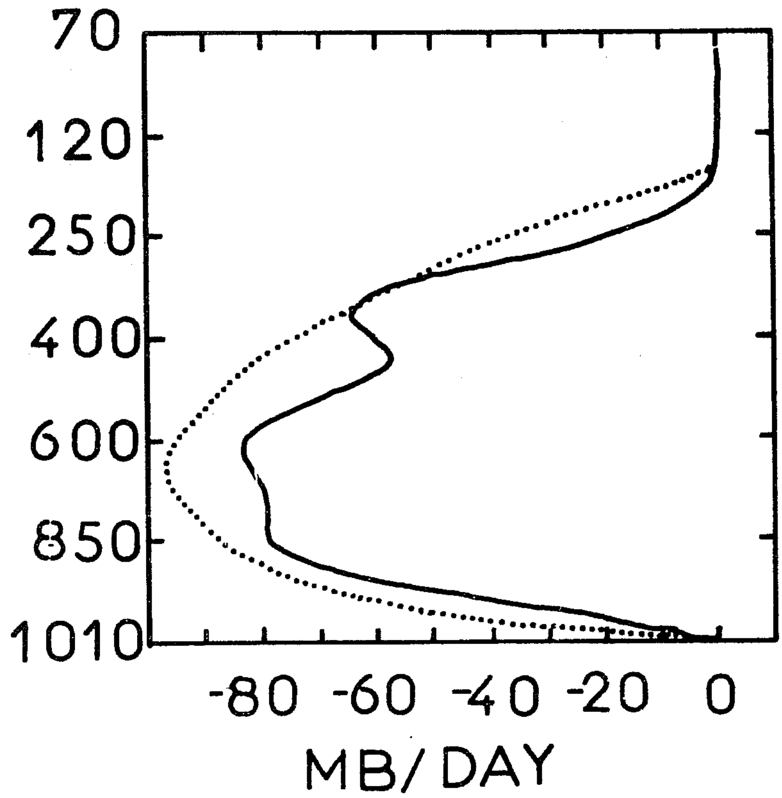

Fig. 7

Dotted line : convective mass flux, computed from Eqs. 11, 12. (20 day average). Solid line : Large-scale vertical velocity.

solution might be to turn off diffusion when convection is present at a grid point, as in the diagnostic study. The energy conservation is then assured by the presence of $F_h(p_b)$ in Eq. 9. However, this may cause other problems; for instance if dry instability is present in the column at the same time as moist instability, the diffusion scheme is necessary to damp the instability. Various solutions need to be investigated to solve this problem.

Another important point is related to the horizontal scale at which the scheme would be most effective. The good results obtained in the diagnostic study are clearly due to the good correlation between the rainfall and the moisture convergence existing already in the data. This is due to an optimal choice of the array size in the GATE experiment. For the NWP models, the question remains: Is there an optimal length scale to parameterize convection, instead of the rather arbitrary grid size? or should a convection scheme depend explicitely on the grid size of the model ? These questions have hardly been asked and certainly deserve investigation.

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