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Cold downdrafts in cumulonimbus clouds

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ABSTRACT

The mechanism of maintenance of cold steady downdrafts in convective clouds is investigated in a numerical experiment using a one-dimensional steady state model of the updraft–downdraft interaction. It is established that usually the downdraft cannot be effectively chilled unless it is fed with small droplets from the updraft by at least two simultaneously acting mechanisms: entrainment of the updraft air and fallout of drizzle-size droplets through the inclined updraft–downdraft interface.

1. Introduction

The mechanism of cold, negatively buoyant downdrafts in cumulonimbus clouds is not a completely clear phenomenon. Byers and Braham (1949) in "The Thunderstorm" attributed it to the precipitation which initiates the downdraft by the drag and cools it by evaporation. Most of the numerical cloud models adopt this point of view, assuming, that in the presence of any liquid water, the air is saturated. However, Kamburova and Ludlam (1966) have proved that typical raindrops evaporate so slowly, that for reasonable rainfall intensity they can provide negative buoyancy only at very low downward velocities, or at very low hydrostatic stability of the ambient air. More recently Girard and List (1975) took this fact into account in a fairly sophisticated Cb model, showing that the rainfall can induce a cold downdraft but only of short duration. Thus the mechanism of quasisteady cold downdraft, which is an essential feature of squall lines or supercell storms, is still unclear. Some new ideas in treating this problem may be found in a paper by Betts and Dias (1979).

Haman (1973) suggested that the entrainment of air from the neighbouring updraft which is rich in small, fast evaporating droplets may explain this phenomenon. However, effect of entrainment of liquid water which chills the downdraft by evaporation is in this mechanism partly compensated by parallel entrainment of positive buoyancy and opposite vertical momentum. This suggests that there might be only a limited range of conditions under which such mechanism of chilling and maintaining the downdraft would work. A qualitative analysis performed by Haman (1973) confirmed this supposition, but a numerical experiment is necessary for more quantitative information. Performing such an experiment has been the primary goal of the present work.

It was found in the course of computations that the effect of entrainment from the neighbouring updraft, for realistic values of entrainment rates and stratifications, is less effective than had been formerly expected, particularly in the lower portions of the cloud. Search for another mechanism brought the authors to the hypothesis that if the updraft–downdraft interface is slanted, as is usually the case in quasisteady cumulonimbus clouds (see for instance Ludlam, 1963), the precipitation falling from the updraft may supply additional amount of fast evaporating water. It seems that the fraction of updraft's liquid water contained in droplets with diameter within the range 0.2–0.5 mm can be fairly effective in cooling the downdraft. This fraction may represent a considerable part of liquid water in the central

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parts of the updraft. Nevertheless yet another additional source of small droplets (breakup of raindrops?) might also contribute to this process.

The final conclusion is that driving a cold downdraft in Cb cloud down to the surface is a complex phenomenon resulting from simultaneous action of more than one mechanism.

2. The model

2.1. *Description*

The model used in the present paper consists of a one-dimensional, purely buoyant (no perturbation pressure forces) updraft and, also a one-dimensional, purely buoyant downdraft in a form of steady vertical or slanted jets with top-hat profiles of all variables, dependent only on the altitude. The updraft entrains the air from ambient environment, the downdraft from the updraft and eventually from the environment as well (Fig. 1). Liquid water content is divided into a small droplet fraction (SDF) which is treated as continuous medium moving with the air and evaporating instantly in an unsaturated atmosphere, and monodispersive rain, falling through the downdraft, interacting with small droplet fraction and water vapour by condensation–evaporation and continuous coalescence. The raindrops are assumed to fall with respect to air with terminal free fall velocities. Intensity of the rainfall is predetermined at the top of the downdraft. Entrainment into the updraft is assumed constant, for the downdraft it has been parameterized in various ways. For the updraft the initial conditions with respect to altitude (Cauchy type) are determined at the assumed cloud base, for the downdraft—at a certain predetermined level ("computational top"), at which the downdraft is assumed to have already a nonzero velocity. The computations are started from calculation of the vertical profiles of the updraft parameters, from the cloud base to the "computational top" of the downdraft. Initial conditions for the downdraft, consistent with the updraft properties, are then formulated and vertical profiles for the downdraft computed. Let us notice that in this way only the influence of the updraft upon the downdraft is taken into account. Justification for this procedure is partly of a technical nature. Consideration of mutual interaction between the drafts leads to a complex nonlinear boundary value problem for a large system of ordinary differential equations. A complete mathematical theory for such problem does not exist and a clear physical basis for its formulation is not available. On the other hand, results of calculations of certain range of runs with Cauchy type conditions in our simpler variant may give some idea about possible behaviour of more complex systems and some insight into the physics of the problem.

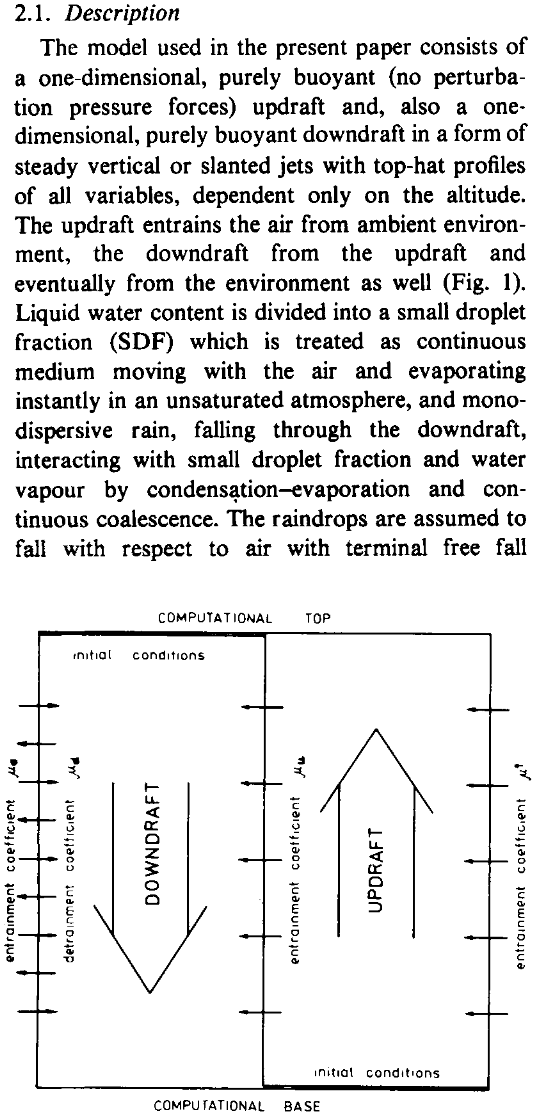

Fig. 1. Mass exchange and draft configuration in the model.

The authors are well aware of the limitations of one-dimensional modelling with respect to such a complex phenomenon as dynamics of cumulonimbus clouds. The aim of the model is thus not to give a realistic simulation of a steady cumulonimbus cloud, but rather to make a quantitative analysis of the physical processes taking place in such a cloud and to investigate bulk budgets of momentum, enthalpy and water which any cloud, no matter how complex, must fulfill. In other words, no natural cloud has such a simple structure as our model cloud, but results of the computations give certain reference data with which the real cloud data may be compared. This may help to detect physical inconsistencies of some hypotheses concerning the downdraft dynamics and to evaluate the possible importance of various physical processes participating in this phenomenon. Relatively small computer time requirements permit fast analysis of many variants of initial and external data and in this way provide answers for fairly sophisticated questions.

2.2. *Equations*

Equations for updraft and downdraft were carefully derived under the conceptual assumptions of the model from the conservation laws for total (humid and eventually wet air plus precipitation) fluxes of momentum, enthalpy, water substance and droplet number, as well as from classical laws of vapour diffusion, heat conduction and continuous coalescence with respect to evolution of a single droplet of the rain. A few extremely small terms were neglected for sake of computational economy. Derivation and simplifications of this system as physical analysis of the nature of various small terms usually neglected in one-dimensional models by other authors are given by Niewiadomski (1979). Let us take note that the form of the equations is independent on the angle of inclination of the drafts except for some particular parameterizations of entrainment.

Equations for the updraft are as follows:

Conservation of vertical momentum:

$$\frac{dw^{\uparrow}}{dz} = \left(\frac{\rho_e - \rho^{\uparrow}}{\rho^{\uparrow}} - V^{\uparrow}\right) \cdot \frac{g}{w^{\uparrow}} - \mu^{\uparrow} w^{\uparrow} \tag{1}$$

Conservation of enthalpy:

$$\frac{dT^{\uparrow}}{dz} = \frac{1}{\rho^{\uparrow} c_p} \frac{dp}{dz} + \mu^{\uparrow}(T_e - T^{\uparrow}) \quad \text{for } V^{\uparrow} = 0 \tag{2}$$

$$\left.\begin{aligned} \frac{dT^{\uparrow}}{dz} = {} & \left(c_p + V^{\uparrow} c_w + L^{\uparrow} \frac{\partial Q}{\partial T}\right)^{-1} \\ & \left[\left(\frac{1}{\rho^{\uparrow}} - L^{\uparrow} \frac{\partial Q}{\partial p}\right) \frac{dp}{dz} \right. \\ & + \mu^{\uparrow} c_p (T_e - T^{\uparrow}) \\ & \left. + \mu^{\uparrow}(L_e q_e - L^{\uparrow} q^{\uparrow})\right] \end{aligned}\right\} \text{for } V^{\uparrow} > 0 \tag{3}$$

Conservation of water substance:

$$\frac{d(q^{\uparrow} + V^{\uparrow})}{dz} = \mu^{\uparrow}(q_e - q^{\uparrow} - V^{\uparrow}) \tag{4}$$

The entrainment coefficient $\mu^{\uparrow}$ is assumed constant in the present computations. Detrainment coefficient for the updraft $\mu_d^{\uparrow}$ does not appear explicitly in the system, except in the equation for the cross-section area of the draft, which is not relevant in the present experiment, and being not interrelated with other equations is not included in the model.

Equations for the downdraft are as follows:

Conservation of momentum:

$$\frac{dw^{\downarrow}}{dz} = \left(\frac{\rho_e - \rho^{\downarrow}}{\rho^{\downarrow}} - V^{\downarrow} - \frac{Nm}{\rho^{\downarrow}}\right) \frac{g}{w^{\downarrow}} + \mu_u (w^{\uparrow} - w^{\downarrow}) - \mu_e w^{\downarrow} \tag{5}$$

Cross-section equation:

$$\frac{1}{S^{\downarrow}} \frac{dS^{\downarrow}}{dz} = \mu_u + \mu_e - \mu_d - \frac{1}{w^{\downarrow}} \frac{dw^{\downarrow}}{dz} - \frac{1}{(1 + V^{\downarrow})\rho^{\downarrow}} \frac{d[(1 + V^{\downarrow})\rho^{\downarrow}]}{dz} \tag{6}$$

Conservation of enthalpy:

$$\left.\begin{aligned} \frac{dT^{\downarrow}}{dz} = {} & \frac{1}{c_p}\left[\frac{1}{\rho^{\downarrow}} \frac{dp}{dz} \right. \\ & + \mu_u (c_p + V^{\uparrow} c_w)(T^{\uparrow} - T^{\downarrow}) \\ & + \frac{\beta}{w^{\downarrow}} V^{\uparrow} c_w (T^{\uparrow} - T^{\downarrow}) \\ & + \mu_e c_p (T_e - T^{\downarrow}) \\ & + \frac{L^{\downarrow} N(w^{\downarrow} - w_r)}{\rho^{\downarrow} w^{\downarrow}} (1 + q^{\downarrow}) \frac{dm}{dz} \\ & \left. - L^{\downarrow}\left(\mu_u + \frac{\beta}{w^{\downarrow}}\right) V^{\uparrow}\right] \end{aligned}\right\} \text{for } V^{\downarrow} = 0 \tag{7}$$

$$\left.\begin{aligned} \frac{dT^{\downarrow}}{dz} = {} & \left(c_p + V^{\downarrow} c_w + L^{\downarrow} \frac{\partial Q}{\partial T}\right)^{-1} \\ & \left\{\left(\frac{1}{\rho^{\downarrow}} - L \frac{\partial Q}{\partial p}\right) \frac{\partial p}{\partial z} \right. \\ & + \mu_e c_p (T_e - T^{\downarrow}) + \left[\mu_u (c_p \right. \\ & \left. + V^{\uparrow} c_w) + \frac{\beta}{w^{\downarrow}} V^{\uparrow} c_w \right] (T^{\uparrow} - T^{\downarrow}) \\ & + \mu_u (L^{\uparrow} q^{\uparrow} - L^{\downarrow} q^{\downarrow}) \\ & + \mu_e (L_e q_e - L^{\downarrow} q^{\downarrow}) \\ & \left. + \frac{L^{\downarrow} q^{\downarrow} N(w^{\downarrow} - w_r)}{\rho^{\downarrow} w^{\downarrow}} \frac{dm}{dz}\right\} \end{aligned}\right\} \text{for } V^{\downarrow} > 0 \tag{8}$$

Conservation of water substance:

$$\frac{d(q^{\uparrow} + V^{\uparrow})}{dz} = \mu_u(q^{\uparrow} + V^{\uparrow} - q^{\downarrow} - V^{\downarrow}) + \frac{\beta}{w^{\downarrow}} V^{\uparrow} + \mu_e(q_e - q^{\downarrow} - V^{\downarrow}) - \frac{N(w^{\downarrow} - w_r)}{\rho^{\downarrow} w^{\downarrow}} \frac{dm}{dz} \tag{9}$$

The term $\beta V^{\uparrow}/w^{\downarrow}$ in eqs. (7), (8) and (9) represents the inflow of water from the updraft, without exchange of air mass; its particular form is substantiated in Section 2.4.

Conservation of raindrops number:

$$SN(w^{\downarrow} - w_r) = \text{const} \tag{10}$$

This equation means that raindrops are not produced nor anihilated (except total evaporation, which in monodispersive rain happens simultaneously to all droplets) and that there is no lateral exchange of droplets with environment.

Enthalpy balance for a single droplet:

$$\frac{dT_r}{dz} = \frac{3w_r \rho^{\downarrow} V^{\downarrow} E(T^{\downarrow} - T_r)}{4r(w^{\downarrow} - w_r)\rho_w} + \frac{3B[\lambda(T^{\downarrow} - T_r) + \rho^{\downarrow} DL_r(q^{\downarrow} - Q_r)]}{r^2 c_w \rho_w (w^{\downarrow} - w_r)} \tag{11}$$

Mass balance for a single droplet:

$$\frac{dm}{dz} = [4\pi r B D \rho^{\downarrow}(q - Q_r) + \pi r^2 E w_r q^{\downarrow} V^{\downarrow}](w^{\downarrow} - w_r)^{-1} \tag{12}$$

For both, updraft and downdraft the following assumption is valid:

If $q + V \geqslant Q$ then $q = Q$

If $q + V < Q$ then $V = Q$

Diffusion and heat conduction coefficients, terminal free fall velocity and ventilation factor are given by the following expressions:

$$D = \rho_s D_s \sqrt{T/T_s} \tag{13}$$

$$\lambda = \lambda_s \sqrt{T/T_s} \tag{14}$$

$$w_r = w_{rs}\sqrt{\rho_s/r_s}\sqrt{r/\rho} \tag{15}$$

$$B = 1 + 0.22\sqrt{2rw_r/v_s} \tag{16}$$

Water vapour saturation specific humidity is given by the formula:

$$Q = (382/p)\exp[17.27(T - 273.15)/(T - 35.7)] \tag{17}$$

2.3. *Entrainment coefficients*

Parameterization of entrainment into the downdraft is a crucial problem in the present experiment. The following physical concepts were tried:

(i) $\mu_u = \text{const}, \quad \mu_e = \text{const}, \quad \mu_d = \text{const}$ (18)

(ii) Taylor hypothesis—lateral mass exchange proportional to the vertical velocity difference between the jet and environment and to the length of lateral perimeter at given height. This gives the following expressions for exchange coefficients:

$$\mu_u = \xi(w^{\downarrow} - w^{\uparrow})/(R^{\downarrow} w^{\downarrow}), \quad \mu_e = \eta/R^{\downarrow}, \quad \mu_d = \zeta/R^{\downarrow} \tag{19}$$

(iii) The rainfall induces the downdraft in the sense that the cross-section of the downdraft is identical to the cross-section of the rainfall shaft. The entrainment results from the fact that in the presence of horizontal wind velocity with respect to the source of rainfall, the streamlines of air are deflected under another angle than the trajectories of droplets (due to different vertical velocities—horizontal velocities of rain and air were assumed equal). Entrainment coefficients are given by the formula (Haman, 1973):

$$\mu_u = \mu_d = \frac{1}{\rho^{\downarrow}}\frac{d\rho^{\downarrow}}{dz} - \frac{\zeta U w_r}{R^{\downarrow}(w^{\downarrow} - w_r)}, \quad \mu_e = 0 \tag{20}$$

(iv) The rainfall induces the downdraft as in (iii) but the difference between streamlines of air and trajectories of droplets is induced not by presence of external wind but by horizontal convergence (divergence) caused by vertical acceleration. The mass exchange coefficients are then defined by means of the following expressions:

$$F = \frac{w_r}{w^{\downarrow} - w_r}\left(\frac{1}{\rho^{\downarrow}}\frac{d\rho^{\downarrow}}{dz} + \frac{1}{w^{\downarrow}}\frac{dw^{\downarrow}}{dz}\right)$$

$$\begin{aligned} &\mu_u = \xi F, \quad \mu_e = (1 - \xi)F, \quad \mu_d = 0 && \text{if } F \leqslant 0 \\ &\mu_u = \mu_e = 0, \quad \mu_d = -F && \text{if } F > 0 \end{aligned} \tag{21}$$

Profiles of several downdraft parameters obtained for entrainment coefficients given by formulas (18)–(21) with parameters ξ, η, ζ providing the same range of mean value of μ_u are presented in Fig. 2. In order to show influence of μ_d on S and N, and in this way on other downdraft parameters, in case (b) the formula (19) for μ_d was replaced by (27) which gives the same value of total entrainment coefficient $\mu^{\downarrow}$ as in case (a). Other input data for these calculations are the same as in Section 3.

As follows from Fig. 2 and other experiments performed by the authors, reasonably applied parameterizations of types (ii), (iii) and (iv) lead to nearly constant mass exchange coefficients over considerable portions of the downdraft. On the other hand, constant μ are very convenient in studying reaction of the model to the effects of entrainment. Thus parameterization (i) has finally been chosen.

2.4. *Additional water supply*

A series of experiments were performed under the assumption that entrainment of liquid water from the updraft to the downdraft is due only to the entrainment of air (with its enthalpy and vertical momentum—see runs with $\beta = 0$, i.e. Figs. 2–6). They indicated that this mechanism hardly can be responsible for driving cold downdrafts down to the ground or even to the cloud base. The following reasoning suggests, however, that there may be additional transport of fast evaporating small droplet fraction from the updraft without a simultaneous transport of opposite momentum and buoyancy, which would make this process more effective in driving a cold downdraft.

Let us suppose that the updraft is slanted and located above the downdraft. Since the cloud and precipitation droplets in the updraft have a certain gravitational sedimentation speed w_g, they will move across the updraft–downdraft interface (provided that the turbulence is unable to obscure this process too much). This creates the additional flux of fast evaporating water we are looking for. Its thermal effect can be estimated in one of the following ways. If the droplets are considered so small that they can be assumed to evaporate instantly in unsaturated air (as SDF in the model),

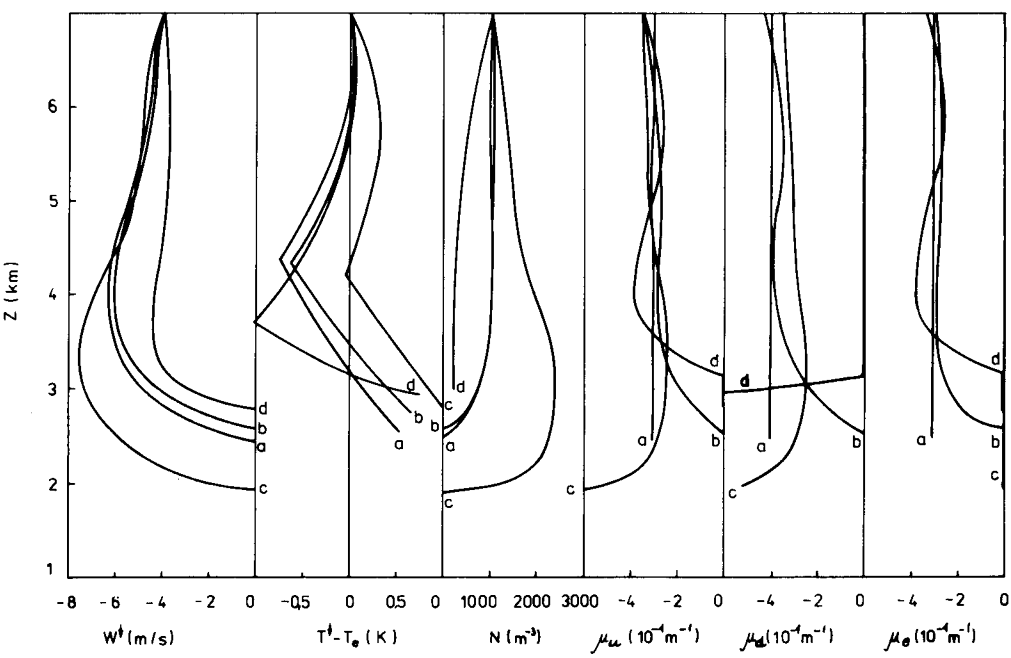

Fig. 2. Downdraft profiles for various parameterizations of entrainment—notice thick layers of nearly constant μ for all parameterizations, that substantiated use of constant μ in further experiments; $R = \sqrt{S}$; $\mu_u = -3 \cdot 10^{-4}$, $\mu_e = -3 \cdot 10^{-4}$, $\mu_d = -4 \cdot 10^{-4}$ (a); μ_d given by formula (27), μ_u, μ_e given by (19) with $\xi = -0.05$, $\eta = -0.75$ (b); μ_u, μ_d, μ_e given by (20) with $\zeta U = 2.4$ (c); μ_u, μ_e, μ_d given by (21) with $\xi = 0.5$ (d).

and keep the downdraft nearly saturated in a belt of width R, the effect of their transfer will be equivalent to adding to the term $\mu_u V^\uparrow$ in eqs. (7), (8) and (9) (with $\beta = 0$) a new one $\mu_g V^\uparrow$ defined by the following identity:

$$\begin{aligned} \mu_g V^\uparrow &= V_g^\uparrow w_g \operatorname{ctg}\alpha/(w^\downarrow R^\downarrow) \\ &= \gamma^\uparrow V^\uparrow w_g \operatorname{ctg}\alpha/(w^\downarrow R^\downarrow) \end{aligned} \tag{22}$$

where index "g" refers to the average properties of this part of $V^\uparrow$ which participates in the considered process and γ denotes V_g/V. If in contrary, the radii of droplets are considered to be so large that the assumption of instantaneous evaporation becomes too crude, their effect can be calculated as for rainfall, and introduced as an expression additive to the term $\mu_u V^\uparrow$ in eq. (9):

$$\begin{aligned} &N_r^\downarrow \cdot 4\pi BDr(q^\downarrow - Q_r)/w^\downarrow = \\ &\quad V_r^\downarrow \cdot 3BD(q^\downarrow - Q_r)(w^\downarrow r^2 \rho_w/\rho^\downarrow)^{-1} \end{aligned} \tag{23}$$

where $N_r^\downarrow$ and $V_r^\downarrow$ represent the number concentration and LWC of considered droplets with radius r in the downdraft.

Simple considerations of the kinematics of droplet motion close to the updraft–downdraft interface show that the concentration of droplets on both sides of the interface should be the same. Denoting by $V_r^\uparrow$ the LWC of considered droplets with radius r in the updraft and defining $\gamma_r = V_r/V$, we find that the expression:

$$\mu_r V^\uparrow = \gamma_r^\uparrow V^\uparrow \cdot 3BD(q^\downarrow - Q_r)(w^\downarrow r^2 \rho_w/\rho^\downarrow)^{-1} \tag{24}$$

should be an overestimate of (23). (Note that "r" refers now to the droplets in the updraft, so that the evaporating surface of droplets is overestimated by that at the beginning of evaporation.)

We notice that while (22) is too crude for an estimate of evaporation of large droplets, (24) is too crude for small ones. The first one depends on the size of the downdraft, the second one does not. Substituting for instance: $R^\downarrow = 1000$, $\gamma^\uparrow = 0.5$, $w^\downarrow = -5$, $\operatorname{ctg}\alpha = 1$, $w_g = 1$ (droplets about 0.2 mm in diameter) we find from (22) $-\mu_g = 1 \cdot 10^{-4}$. This is below the lower limit of μ_u which is significant for the downdraft maintenance (see Fig. 5). The same value $1 \cdot 10^{-4}$ we find for $-\mu_r$ in (24) substituting $\gamma_r^\uparrow = 0.5$, $w^\downarrow = -5$, $D = 2 \cdot 10^{-5}$, $B = 1$, $(q^\downarrow - Q_r) = 10^{-3}$, $\rho_w = 1000$, $\rho^\downarrow = 1$ and $r \approx 0.25$ mm. This means that with the accuracy for the particular choice of data in the above examples (which seems to be fairly reasonable), droplets with diameters smaller than 0.2 mm, or larger than 0.5 mm, would be hardly effective in maintaining cold downdrafts of reasonable size. Since the two estimates (22) and (24) intersect for droplet diameter somewhere about 0.4 mm, such droplets are probably optimal for downdraft cooling by the mechanism under consideration.

The essential feature of this mechanism is the increase of the entrainment coefficient for $V^\uparrow$ with respect to those for opposite buoyancy and momentum. It was parameterized in the model by adding to the term $\mu_u V^\uparrow$ in eqs. (7), (8) and (9) a new term of the form suggested by (22) and (24):

$$\mu^* V^\uparrow = (\beta/w^\downarrow) V^\uparrow \tag{25}$$

where β depends on the angle of downdraft inclination, downdraft size and shape, and droplet spectrum of the updraft liquid water content, and becomes small if this spectrum is strongly shifted towards large or very small droplets.

In our experiments β was assumed constant, which is a rather crude parameterization, but gives a possibility to estimate how effective the considered process can be.

3. The experiment and its results

The number of the various combinations of parameters which can be used in the present model is so great, that a certain reasonable key of experimentation is necessary. Of course any such key will leave a number of unanswered questions, which can be eventually considered in further experiments. In our case we decided to create a certain standard variant of updraft and downdraft and then study variations of output with respect to this standard when initial and external parameters are varied separately. The standard input data set is:

(i) *Environment*

Ambient air temperature (T_e) stratification is defined by the "stratification parameter" k:

$$k = (\gamma - \Gamma_w)/(\Gamma_d - \Gamma_w) \tag{26}$$

where $\gamma = -dT_e/dz$ and Γ_w, Γ_d mean wet and dry adiabatic temperature lapse rate.

In the "standard input data set" k increases linearly from the value 0.1 at $z = 1000$ m to 0.25

at z = 7000 m, relative humidity of ambient air is constant and equal 0.7 and initial values at z = 1000 m for T_e and p are 17.5 °C and 900 hPa.

(ii) *Entrainment coefficients*

$\mu^{\uparrow} = 0.0001\ \mathrm{m}^{-1}, \quad \mu_u = \mu_e = -0.0003\ \mathrm{m}^{-1}, \beta = 0$

In order to avoid changes in total downdraft entrainment coefficient $\mu^{\downarrow}$ which in direct form change only the S and N profiles (see Fig. 2), in all calculations:

$$\mu_d = \mu_u + \mu_e + 0.0002\ \mathrm{m}^{-1} \tag{27}$$

(iii) *Updraft*

Initial values for the updraft at z = 1000 m (cloud base) are as follows:

$w_0^{\uparrow} = 7$ m/s, $\quad T_0^{\uparrow} = 17$ °C, $\quad q_0^{\uparrow} = 0.014, \quad V_0^{\uparrow} = 0$

(iv) *Downdraft*

E = 0.6. Initial values of the downdraft parameters at z = 7000 m (computational top) are as follows:

$w_0^{\downarrow} = -4$ m/s, $\quad T_0^{\downarrow} = -20.77$ °C $= T_e$,
$V_0^{\downarrow} = 0.001, \quad N_0 = 1000\ \mathrm{m}^{-3}, \quad r_0 = 0.75$ mm,
$T_{r_0} = -20.77$ °C $= T_0^{\downarrow}$

The w, V and ΔT profiles for the "standard updraft" are given in Figs. 3 (case a) and 4 (case c) and for the "standard downdraft" for instance in Fig. 5 (case c). Profiles of N, w, and ΔT for the standard downdraft are given in Fig. 2 (case a).

Note that the data that are not individually explained in the figures are from the above "standard data set".

Four basic groups of experiments were performed (examples of some of them are shown in the figures), aimed at checking:

(1) the sensitivity of the model to variations of initial conditions at "computational top", which are rather arbitrarily formulated;
(2) sensitivity to variations of external stratification (Fig. 3);
(3) sensitivity to entrainment coefficients (Figs. 4–6) and
(4) sensitivity to the additional water supply (Figs. 7, 8).

The most important output parameter is the depth of penetration of cold downdraft, i.e. height at which the downdraft definitely becomes positively buoyant. It is usually closely related to the height at which the downdraft becomes unsaturated.

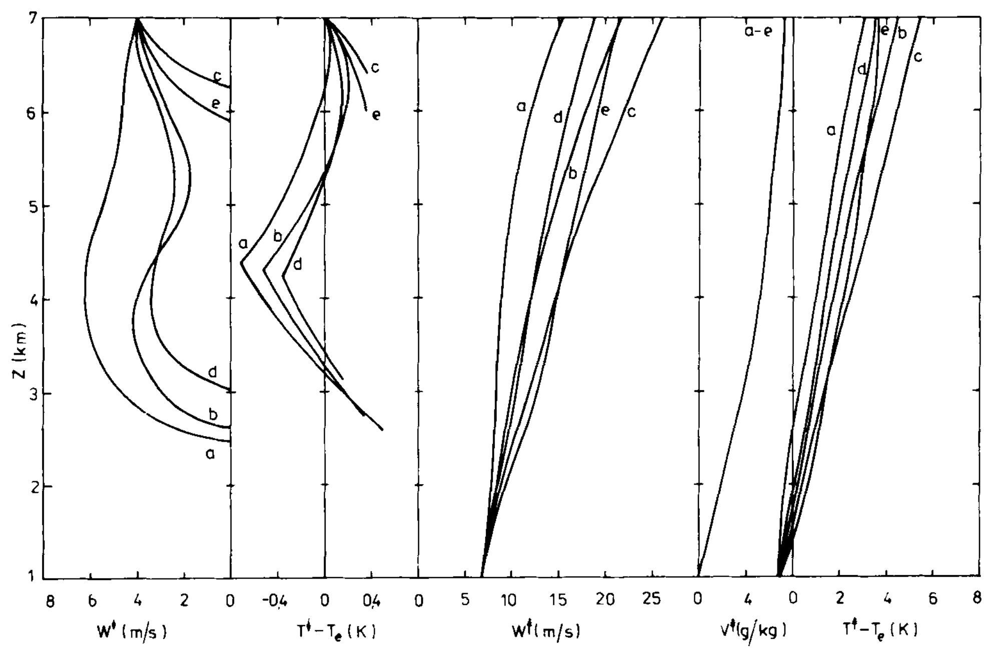

Fig. 3. Influence of environmental temperature profile (hydrostatic stability) on the downdraft profiles; k increases linearly from 0.1 to 0.25 (a), from 0.15 to 0.30 (b), from 0.20 to 0.35 (c), k = 0.175 (d), k decreases linearly from 0.25 to 0.1 (e).

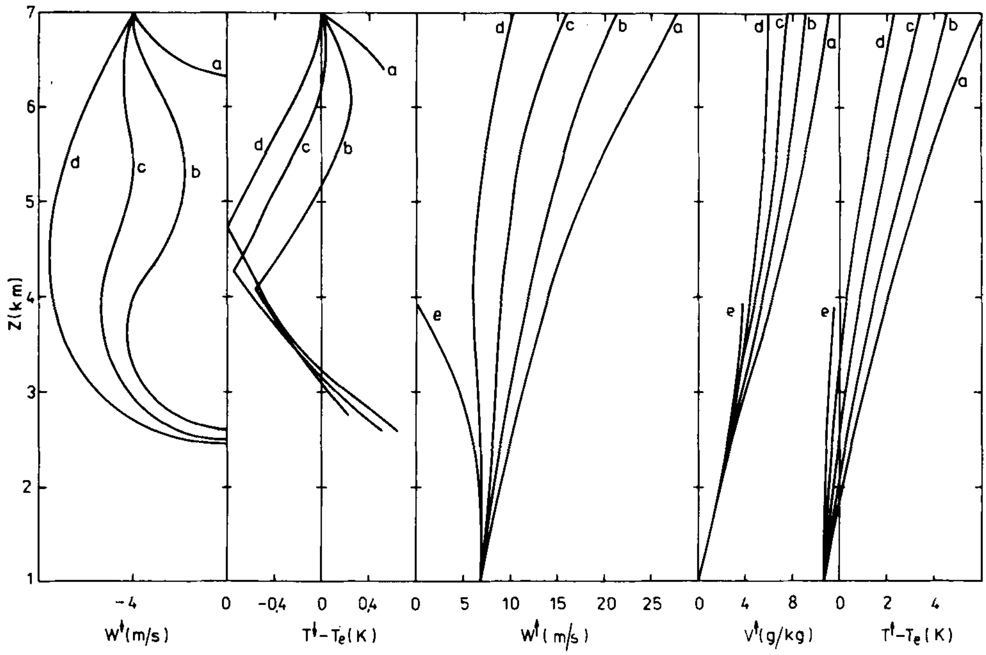

Fig. 4. Influence of entrainment into the updraft on the downdraft profile; $\mu^{\uparrow} = 0$ (a), $0.5 \cdot 10^{-4}$ (b), 10^{-4} (c), $1.5 \cdot 10^{-4}$ (d), $2 \cdot 10^{-4}$ (e).

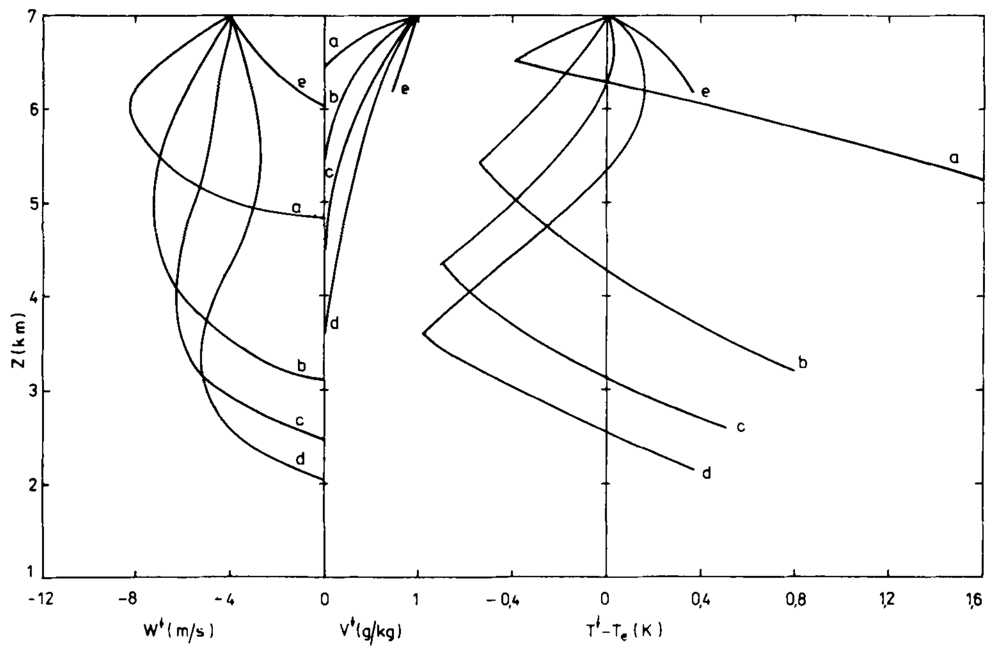

Fig. 5. Influence of the updraft–downdraft mass exchange on the downdraft profile; $\mu_u = 0$ (a), $-2 \cdot 10^{-4}$ (b), $-3 \cdot 10^{-4}$ (c), $-4 \cdot 10^{-4}$ (d), $-5 \cdot 10^{-4}$ (e).

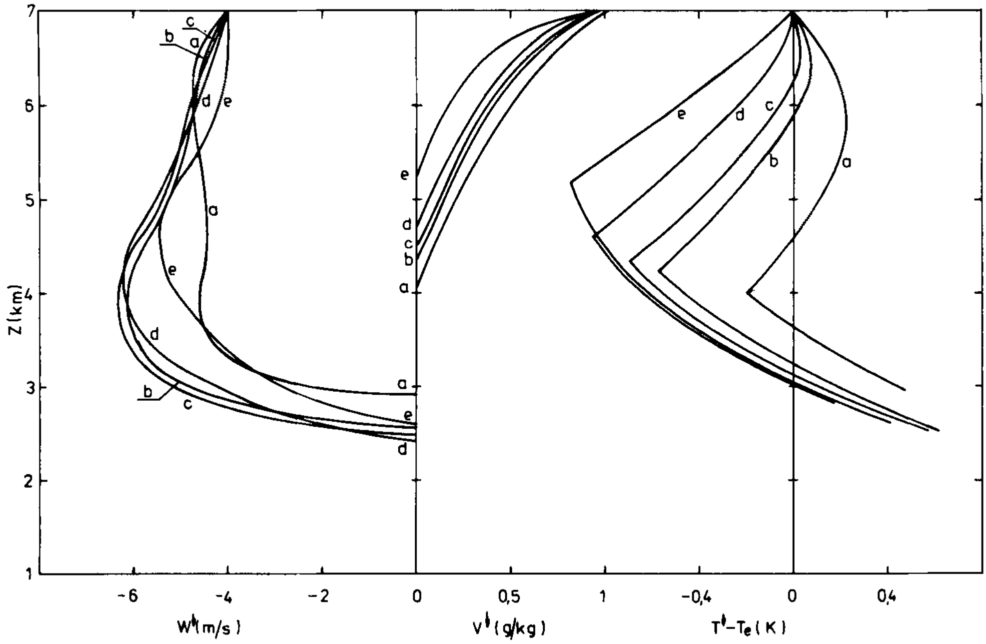

Fig. 6. Influence of ambient air entrainment into the downdraft on its profiles; $\mu_e = 0$ (a), $-2 \cdot 10^{-4}$ (b), $-3 \cdot 10^{-4}$ (c), $-5 \cdot 10^{-4}$ (d), -10^{-3} (e).

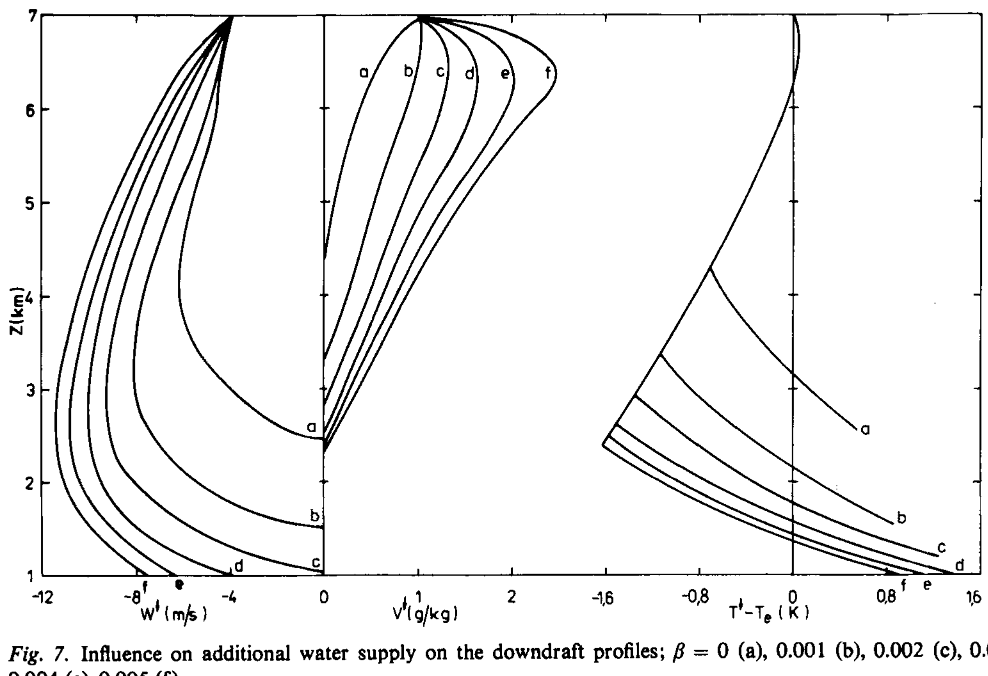

Fig. 7. Influence on additional water supply on the downdraft profiles; $\beta = 0$ (a), 0.001 (b), 0.002 (c), 0.003 (d), 0.004 (e), 0.005 (f).

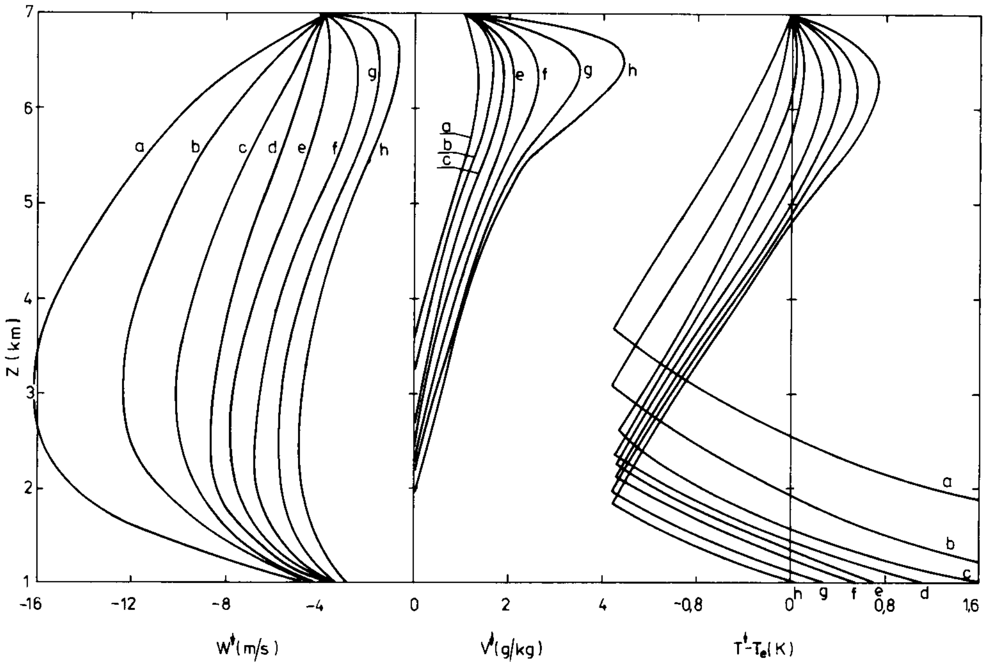

Fig. 8. Effect of simultaneous entrainment and additional water supply from the updraft on the downdraft profiles; $\beta = 0.003$; $\mu_u = \mu_e = -1 \cdot 10^{-4}$ (a), $-2 \cdot 10^{-4}$ (b), $-3 \cdot 10^{-4}$ (d), $-5 \cdot 10^{4}$ (e), $-7 \cdot 10^{-4}$ (f), -10^{-3} (g), $-1.5 \cdot 10^{-3}$ (h).

Decrease of vertical velocity to zero is a computational effect—computations were terminated for $w^{\downarrow} = -0.05$ m/s. Physically the drag and evaporation of rain will drive downdraft downwards at very low speed with buoyancy close to zero.

The main conclusions are:

If the initial velocity is consistent with the initial buoyancy and precipitation drag, the model of downdraft usually quickly "forgets" the conditions imposed at the "computational top". This is very important in view of many uncertainties concerning these conditions.

The downdrafts show a relatively high degree of "homeostasy" with respect to the variations of external stratification, particularly when the most deeply penetrating cold downdrafts are considered (see Fig. 3a, b, d). This follows from the fact that the changes in stratification are simultaneously favourable or unfavourable for both updraft and downdraft, so that their influence upon the downdraft can be opposed by the effects of buoyancy and momentum entrainment from the updraft. In certain cases of relatively low hydrostatic stability this latter may become overwhelming and kill the downdrafts nearly at the start (Fig. 3c, e).

Results of some other computations confirmed the conclusion derived qualitatively by Haman (1973) that low humidity is favourable for formation of cold downdrafts, though if too low it may prohibit development of the updraft. Fig. 4 shows that increased entrainment of ambient air into the updraft may increase the penetration depth of the downdrafts unless it is so large that the updraft cannot develop (Fig. 4e).

The model confirmed also that entrainment of air from the updraft is an essential factor in maintaining cold downdraft in the central parts of the cloud, and that there is certain, optimum in that respect value of entrainment coefficient (Fig. 5). Entrainment of dry environmental air appeared to be an important factor in improving the economy of downdraft chilling by evaporation of liquid water entrained from the updraft (Fig. 6) though by becoming too large may give an opposite effect (Fig. 6e). However, the computations have shown that the restraining effect of opposite buoyancy and momentum entrained from the updraft is greater than rough estimates made by Haman (1973) could suggest and with $\beta = 0$ no reasonable combinations of parameters checked in the present series of experiments permitted cold downdrafts to reach the cloud base.

A general conclusion which seems to follow from Figs. 3–6 is that moderate instability, moderate deficit of humidity and moderate entrainment of environmental air into the updraft and downdraft create optimal conditions for maintenance of quasi-steady cold downdrafts in central parts of the cloud.

Introduction of additional transport of fast evaporating water according to the idea presented in Section 2.4 improved the picture very much. Deeply penetrating downdrafts now developed easily as a result of cooperation between the "old" ($\beta = 0$) and "new" ($\beta > 0$) mechanism (Figs. 7, 8). However, fully satisfactory results (in the sense of a downdraft reaching the cloud base level) were obtained with $\beta \geqslant 0.003\ s^{-1}$ (Fig. 7c–f) which in view of estimates given in Section 2.4 seems to be unrealistically large. This suggests that one should search for yet other sources of fast evaporating water such as the collisional breakup of raindrops.

The computations confirmed the results of Hookings (1965) and Kamburova and Ludlam (1966) that precipitation (at least in the form of particles 1 mm dia. or more) cannot be responsible for the downdrafts with negative buoyancy, except maybe subcloud, adiabatic or even superadiabatic layer. The role of smaller droplets is unclear. Created eventually along the downdraft in collisions between larger droplets, they may perhaps become the additional source of water required by the present model. Investigation of this process would, however, require considerable changes in the model as well as much better empirical knowledge about the precipitation at higher levels of Cb clouds.

4. Conclusions

The set of computer runs presented in this paper, made with various artificial assumptions, cannot of course be directly interpreted in terms of real cumulonimbus cloud. They do not even give a full view of the properties of the model. However, cautious inter- and extrapolations between properly selected outputs of the model permit estimations of results expected for some other combinations of model parameters as well as estimations of some real cloud characteristics. Particularly, the authors suppose that the following conclusions can be presented at least in the form of a well-substantiated hypothesis.

Development of a cold downdraft, characteristic for the mature stage of quasipersistent Cb cloud, involves simultaneously a number of various mechanisms of chilling. Relative importance of these mechanisms may vary with altitude. At the beginning of the downdraft, evaporation of the small droplet fraction of the cloud into entraining dry environmental air (as suggested by Byers and Braham, 1949) is probably dominating. When this water has been exhausted, supply of the small droplet fraction from the updraft through entrainment process becomes the most important source of chilling. At lower levels effectiveness of this process is probably insufficient unless supported by gravitational sedimentation of drizzle-size droplets from the updraft.

In the subcloud adiabatic layer (if present), even evaporation of rainfall may become a sufficient agent of chilling and creating downward buoyancy (Kamburova and Ludlam, 1966). However, in the absence of such a layer the role of precipitation is negligible. Its importance may perhaps be increased by production of small droplet mist in collisions and breakup of larger droplets.

5. Appendix

Symbols used

B	ventilation factor [nondimensional]
c_p	specific heat of air at constant pressure [J/kg K]
c_w	specific heat of liquid water [J/kg K]
D	diffusion coefficient of water molecules in air [m^2/s]
E	coalescence efficiency for rain and small droplet fraction (SDF) [nondimensional]
g	gravity acceleration [m/s^2]
k	ambient air stratification parameter [nondimensional], see formula (26)
L	latent heat of water condensation [J/kg]
m	raindrop mass [kg]
N	number of raindrops in unit volume [m^{-3}]
p	pressure [Pa]
q	specific humidity [nondimensional]
Q	saturation specific humidity [nondimensional]
r	raindrop radius [m]

R radius or other linear scale of the downdraft or updraft [m]
S downdraft or updraft cross-section area [m^2]
T temperature [K]
U horizontal velocity [m/s]
V specific liquid water content of small droplet fraction (SDF) [nondimensional]
w vertical velocity ($w^\uparrow > 0$, $w^\downarrow < 0$) [m/s]
w_r free fall velocity of raindrops (positive) [m/s]
z vertical coordinate (positive upwards) [m]
α updraft–downdraft inclination angle [rad]
β additional water supply parameter (see section 2.4) [s^{-1}]
$\Delta T^\uparrow$ $= T^\uparrow - T_e$ [K]
$\Delta T^\downarrow$ $= T^\downarrow - T_e$ [K]
ρ air density [kg/m^3]
ρ^* $= (1 + V)\rho$ (SDF and air mixture density) [kg/m^3]
ρ_w liquid water density [kg/m^3]
$\mu^\downarrow$ $= [(\rho^* Sw)^{-1}\, d(\rho^* Sw + NSm(w - w_r))/dz]^\downarrow = \mu_u + \mu_e - \mu_d$ (entrainment coefficient for the downdraft) [m^{-1}]
μ_e partial entrainment coefficient (ambient air into downdraft [m^{-1}]
μ_u partial entrainment coefficient (updraft air into downdraft) [m^{-1}]
μ_d detrainment coefficient for the downdraft [m^{-1}]
$\mu^\uparrow$ $= [(\rho^* Sw)^{-1}\, d(\rho^* Sw)/dz]^\uparrow$ (entrainment coefficient for the updraft) [m^{-1}]
ν kinematic viscosity coefficient of air [m^2/s]
λ thermal conductivity coefficient of air [J/m s K]
ξ, η, ζ constants used in entrainment formulation in Section 2.3 [nondimensional]

Indices:

e ambient air
$\uparrow$ updraft
$\downarrow$ downdraft
w liquid water
r raindrops (or "in raindrop temperature")
s constant, reference value
0 initial value (at computational base for updraft, at computational top for downdraft)

Some other symbols are explained in text. All units are in SI if not otherwise stated.

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ХОЛОДНЫЕ НИСХОДЯЩИЕ ПОТОКИ В КУЧЕВО-ДОЖДЕВЫХ ОБЛАКАХ

Численные эксперименты, использующие одномерную, стационарную модель взаимодействия восходящего и нисходящего потока показали, что для достаточного охлаждения нисходящего потока необходимы по меньшей мере два способы его питания в мелкокапельную воду из восходящего потока: вовлечение воздуха и выпадание через наклоненную границу между восходящим и нисходящим потоком капель моросьных размеров.