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SHORT CONTRIBUTION

On the mechanisms of downdraft maintenance in cumulonimbus clouds

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ABSTRACT

The mechanisms of maintenance of cold steady downdraft in convective clouds have been investigated in numerical experiments using a one-dimensional steady-state model of the updraft–downdraft interaction. It was found that evaporation of cloud water entrained from the updraft in the presence of dry air entrained from the environment may in certain circumstances provide cooling sufficient for development and persistence of a quasisteady downdraft in the middle part of a cumulonimbus cloud. This effect may be essentially enhanced if the equivalent-potential temperature, θ_e, has a distinct minimum in the middle troposphere.

1. Introduction

For many years, the dynamics of downdrafts in convective clouds in general, and in quasisteady cumulonimbus particularly, has been a very intriguing problem. Early work like that of Byers and Braham (1949) attributed development of a downdraft to the load and evaporation of precipitation. However, Hookings (1965) and Kamburova and Ludlam (1966) showed that big droplets that prevail in showers evaporate so slowly, that resultant cooling is insufficient to maintain fast downdrafts, except in the case of very low static stability or intense rainfall rate. Others, for instance, Clark and List (1971), Das (1964) and Srivastava (1967) found that heavy rainfall can induce strong but only very short-lived downdraft.

Haman (1973) suggested another possible mechanism of maintaining a quasisteady downdraft in cumulonimbus clouds: a turbulent exchange of air between the updraft and downdraft. In this way, the updraft, usually rich in small droplets, supplies the downdraft with rapidly evaporating water which can cool it effectively enough to prevent the excessive compression heating during the descent and maintain negative buoyancy. However, the updraft also supplies the downdraft with upward-directed momentum and positive buoyancy which have the opposite effect. Thus, only a certain limited range of exchange rates leading to optimal effects can be expected.

The qualitative considerations of Haman (1973) have been verified in numerical experiments made by Haman and Niewiadomski (1980). Their results strongly suggested that even for the optimal choice of model parameters, the downdrafts terminate well above the typical cloud base. The depth of penetration of the downdraft increases, however, if the updraft and the downdraft are slanted and have such a configuration that the drizzle-size fraction of the updraft water content can fall into the downdraft, supplying it with fast evaporating water but not with opposite momentum and buoyancy. Such a configuration seems to be present in many observed convective clouds. However, the numerical results suggest that with realistic estimates of intensity of this additional water supply, the downdrafts still terminate too fast. Haman and Niewiadomski suggested that one should search for still another source of fast evaporating water (e.g., mist forming as a by-product of collisions and breakup of raindrops).

The aim of the present paper is to show that the reason that Haman and Niewiadomski (1980) did not obtain a realistic downdraft was due mainly to the way of how they conducted their numerical experiment, and that in certain conditions the initial idea of Haman (1973) may work.

First, we shall show that optimal (in the sense of providing the deepest possible downdrafts) values of entrainments rates given by Haman and Niewiadomski (1980) are incorrect, i.e., that with other conditions unchanged, certain different combinations of those rates lead to deeper and stronger downdraft.

Second, we shall show that we can obtain more intensive downdrafts when they develop in an environment in which the equivalent-potential temperature has its minimum within the convection layer. Haman and Niewiadomski (1980) assumed height-independent stratification of relative humidity. This resulted in lack of a minimum of equivalent-potential temperature in the ambient air stratification, which is characteristic for quasisteady thunderstorms.

Third, we shall show that the downdrafts develop especially well when the entrainment of ambient air is allowed in large rates but through a relatively shallow layer around the minimum of equivalent-potential temperature. This corresponds well to observational evidence known for a long time (see, e.g., Desai and Mal (1938); Normand (1946); Newton (1950); Foote and Fankhauser (1973); Fankhauser (1976); Lemon (1976); Barnes (1976); Ogura and Liou (1980)) that regions with the most intensive downdrafts are associated with low θ_e values.

2. The numerical experiments

The experiments were conducted with the same model as Haman and Niewiadomski (1980) used (we shall refer to it as HN80) and all model details can be found there. Schematically, the model consists of a one-dimensional updraft and downdraft as shown in Fig. 1. The equations used

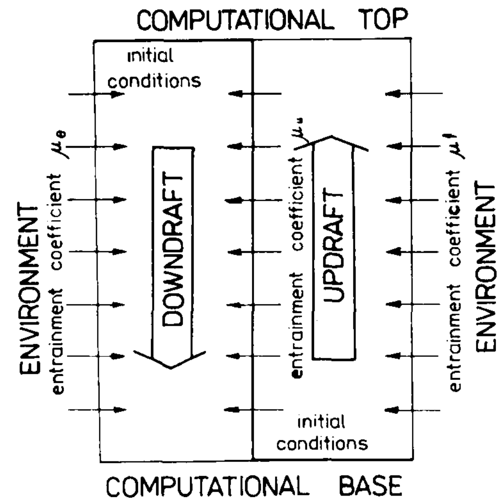

Fig. 1. Draft configuration and entrainment directions in the model.

are typical for one-dimensional entraining buoyant jets: the anelastic, nonbuoyant pressure forces are neglected. The entrainment coefficient μ is defined as

$$\mu = \frac{1}{M}\frac{\mathrm{d}M}{\mathrm{d}z},$$

where M is the mass flux in the updraft (downdraft) and z, the vertical coordinate. $\mu^{\downarrow}$ for the downdraft is assumed to be the sum of μ_u the entrainment from updraft and μ_e the entrainment from the environment.

The experiments were conducted by varying the parameters of the model around the so-called "standard set" of the values used in HN80 (see HN80 for more details).

The most important output parameter is the depth of penetration of a cold downdraft (here it is determined conventionally by the height at which the downdraft velocity becomes less than 1 m/s).

In HN80, it was suggested that the optimal values of the entrainment coefficients are $\mu_u = -0.0004$, $\mu_e = -0.0003$ and $\mu_u = -0.0003$, $\mu_e = -0.0004$. Outside this optimum, the depth of downdraft penetration seems reduced either by overdrying (too great μ_e), insufficient cooling due to evaporation (too small μ_e), insufficient supply of small droplet fraction (too small μ_u) or too large entrainment of opposite vertical momentum

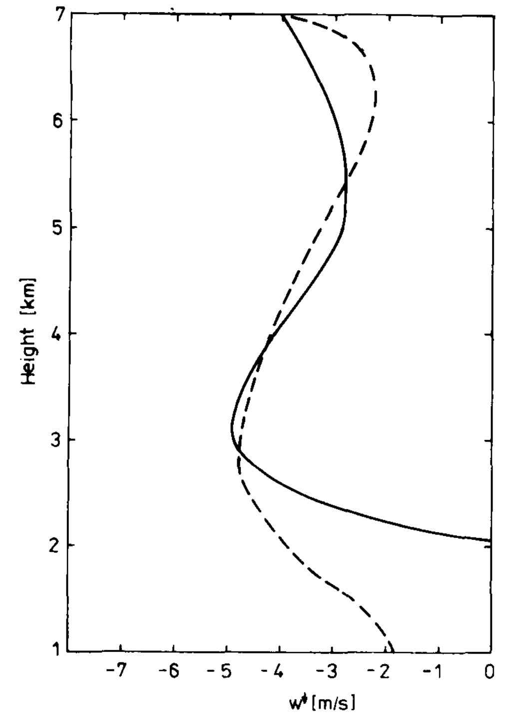

Fig. 2. Downdraft profiles for entrainment coefficients $\mu_u = -0.0004$, $\mu_e = -0.0003$, solid line; $\mu_u = -0.0007$, $\mu_e = -0.0009$, dashed line. Profile of equivalent-potential temperature in the environment without distinct minimum as shown in Fig. 3a.

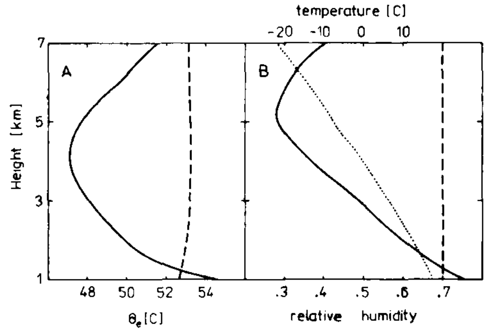

Fig. 3. (a) Profile of equivalent-potential temperature θ_e in the environment. (b) Profile of relative humidity and temperature (dotted line) in the environment. Solid line: profiles used in this work; dashed line: profiles used in Haman and Niewiadomski (1980).

(too great μ_u). However, the experiments now conducted for a wider range of entrainment coefficients showed another much deeper penetrating downdraft (e.g., $\mu_u = -0.0007$, $\mu_e = -0.0009$) (Fig. 2). This results from the common action of relatively large entrainments of both ambient and updraft air which produces enough negative buoyancy to overcome high entrainment of opposite momentum. This was not detected by HN80 because of the strategy of their experiments—to vary each of the model parameters separately.

In HN80, the downdrafts developed in an environment with equivalent-potential temperature θ_e increasing slightly with height. In our further experiments, we shall change the relative humidity profile in order to obtain the minimum of equivalent-potential temperature in the middle part of the convective layer (Fig. 3). As was mentioned earlier, such a minimum of equivalent-potential temperature in the ambient air stratification is characteristic for quasisteady thunderstorms.

Fig. 4 shows the influence of different shapes of equivalent-potential temperature profiles on a downdraft velocity. The new modified profile with a minimum near 500 mb leads to more intensive development of a downdraft. The downdraft descends to the cloud base with fairly great velocity, whereas the downdraft that develops in an environment without a minimum of equivalent-potential temperature still terminates before reaching the cloud base.

It should be noted that nearly identical or even in some parts more intensive downdrafts are obtained if entrainment of ambient air is allowed only in a relatively shallow layer close to the level of minimal equivalent-potential temperature θ_e. As already noted, this seems to have observational support. Results of simulation of this effect in our model are shown in Fig. 5. Unrealistic increases of velocity close to the top and the bottom of the entrainment layer are artifacts of the discontinuous distribution of entrainment coefficient μ_e which is assumed nonzero within the entrainment layer and zero outside it.

In HN80, the supply of drizzle-size droplets falling gravitationally from the updraft was an important factor in driving deeply penetrating downdrafts, though an unrealistically high intensity of this process was necessary to get satisfactory results. It is worth noting that with our assumption about entrainment and stratification,

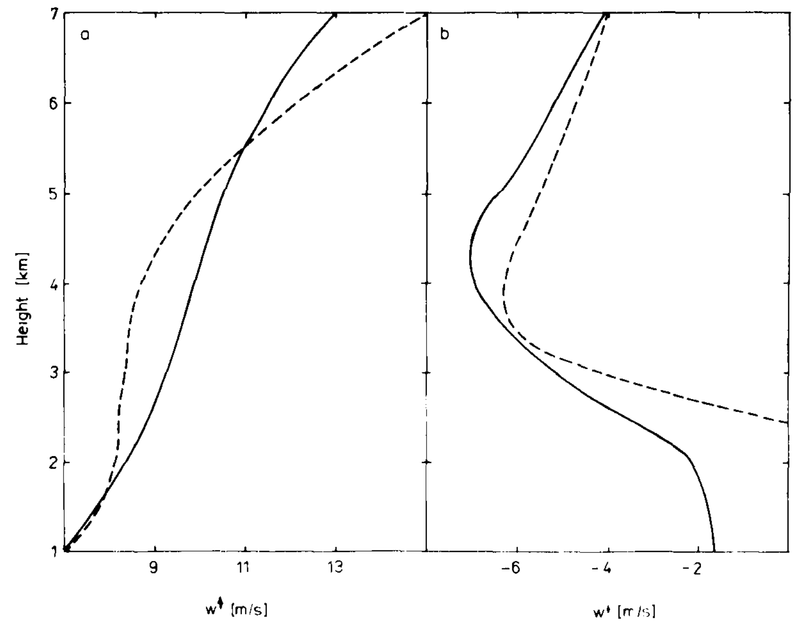

Fig. 4. Influence of different shapes of equivalent-potential temperature profiles on updraft and downdraft velocity. θ_e profile without distinct minimum, dashed line; θ_e profile with distinct minimum, solid line. (a) Updraft velocity profile. (b) Downdraft velocity profiles: $\mu_u = -0.0003$, $\mu_e = -0.0003$.

its importance becomes much smaller, though this effect still considerably increases the depth of penetration even if introduced with smaller (and thus more realistic) intensity than in HN80.

The above results suggest that joint entrainment of environmental and updraft air into the downdraft, with possible support of gravitational sedimentation of drizzle-size fraction of the updraft droplets, may sufficiently explain formation and persistence of quasi-steady downdraft in the middle part of cumulonimbus clouds without the need to introduce other factors.

Applicability of one-dimensional models to the investigations of the dynamical problems in clouds may be questioned on the grounds that nonbuoyant pressure effects which are absent in one-dimensional models may sometimes have a decisive rôle in the dynamics of convective clouds and particularly for downdraft formation.

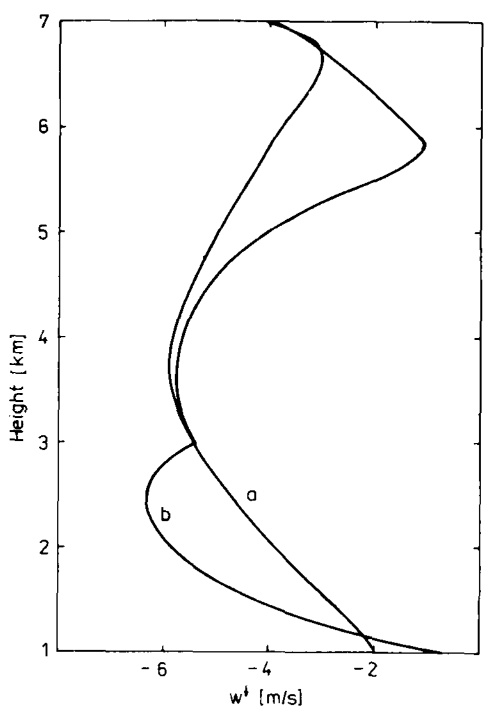

Fig. 5. Influence of the position and depth of the ambient air entrainment layer on downdraft velocity. $\mu_u = -0.0007$, $\mu_e = -0.001$. Entrainment layer: (a) 7000–1000 m, (b) 5800–3000 m.

Accepting in principle this point of view, we should notice that nonbuoyant effects are not likely to overcome high positive buoyancy which must develop rapidly in fast and relatively dry downdrafts. Thus, the thermodynamics, which is fairly well reflected in one-dimensional models, remains the main key to the puzzle of quasisteady downdrafts in cumulonimbus clouds.

3. Conclusions

The numerical experiments described above show that the formation and maintenance of deep quasisteady downdrafts in the conditionally unstable middle part of a cumulonimbus cloud may result from simultaneous entrainment of cloudy air from the updraft and dry air from the environment. The presence of a distinct minimum of equivalent-potential temperature in this layer seems to be an essential factor for this mechanism to work. Other effects like gravitational sedimentation of drizzle-size droplets may play a considerable but only secondary rôle in this process.

4. Acknowledgements

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