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A model of the downdraft from convective clouds

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सार — वाष्पन शीतलन प्रक्रिया को अधोमुखी गति के लिए जिम्मेदार मानते हुए संवाही मेघों से उत्पन्न अधोप्रवाह् के निदर्श प्रस्तावित किये गये । उचित प्राचलीकरण द्वारा घर्षण तथा तरल जलांश के प्रभावों के योगदान पर भी ध्यान दिया गया है तथा सभी उपरि-स्तरों से अंशदान के द्रव्यमान भारित माध्य के रूप में किसी भी स्तर पर अधोप्रवाह् के वेग तथा तापमान को संगणित किया गया है ।

ABSTRACT. A model of the downdraft from convective clouds has been proposed assuming evaporative cooling as the mechanism responsible for the downward motion. Effects of friction and liquid water content have also been taken into account through suitable parameterization and velocity and temperature of the downdraft at any level have been computed as the mass-weighted mean of contributions from all upper levels.

1. Introduction

Over most of the stations in India, arrival of cool moist air normally accompanied by strong surface wind and increase in pressure often precedes the arrival of convective cloud and associated rain. This phenomena is called "squall" when speed and duration of the surface wind exceed prescribed limits (13 mps and 1 minute respectively) and constitutes one of the hazards to aviation. Squalls originate inside the cloud as a downward moving current of cool air and upon reaching ground spreads horizontally sometimes moving ahead of the cloud by as much as 30 km.

Many hypotheses have been presented to explain the origin of the downdraft and most of these consider one or the other of the microphysical processes going on inside the cloud as the cause of the initiation of the downdraft. Most favoured amongst these hypotheses is the one put forward by Byers and Braham (1949) in which downdraft is produced by precipitation loading. Recently Mukherjee and Mukhopadhyay (1983) have explored the possibility of melting of hailstones and resultant absorption of latent heat contributing significantly to the genesis of downdraft. In the present model, it is assumed that entrained parcel at any level is potentially cooler than cloud and hence experiences a downward motion initially. As it descends it is warmed adiabatically and cooled diabatically by evaporation of liquid water present inside the cloud. Since the adiabatic warming is at a constant rate, it is the rate, at which evaporation and diabatic cooling occur, that determines whether the parcel continues to move downwards or reverses its motion and finally becomces a part of the updraft.

2. Model equations

The vertical acceleration experienced by a parcel of air of unit mass entrained into the cloud can be expressed as :

$$\frac{dW}{dt} = gB - C_D\, W^2/R \tag{1}$$

where the buoyancy factor B is given by

$$B = [\triangle T^* - \triangle T^*(\mathrm{LWC})]/T^*$$

In the above equation C_D, R and T^* are the drag coefficient, radius of the descending current and virtual temperature of the environment respectively. In deriving the above equation, it was assumed that the environment is in hydrostatic equilibrium and there is no discontinuity in pressure across the cloud. The effect of liquid water on buoyancy is further parameterized in the form

$$\triangle T^*(\mathrm{LWC}) = \mathrm{LWC}\,.\,T^*.\,(V - W)/(V + W)$$

where V is the mean terminal velocity of liquid drops (taken as 5 mps) and LWC is the liquid water content expressed in gm/gm. In the initial stages of the downdraft liquid water exerts a downward force while in later stages the downdraft experiences a drag similar to the liquid water loading of the updraft.

As the parcel entrained at level Z moves vertically by a distance Z, the buoyancy factor due to virtual temperature difference assumes the form

$$T_e^*\,(Z + \triangle Z)/T^*\,(Z + \triangle Z) - 1 = [(T_e\,(Z) - g\triangle Z/c_p - L\triangle q_e/c_p)\;(1 + 0.6\;q_e\;(Z + \triangle Z)]/[(T_e\,(Z) - \gamma(Z)\,\triangle Z)\;(1 + 0.6\,q\,(Z + \triangle Z))] - 1 \tag{2}$$

where $\triangle q_e$ is the amount of moisture acquired by the entrained parcel between levels Z and $Z+\triangle Z$ and $\gamma(Z)$ is the environmental lapse rate. Neglecting the effects of moisture on density we can simplify Eqn. (2) to the form

$$B = (-g\triangle Z/c_p+\gamma(Z)\ \triangle Z-L\triangle q_e/c_p)\ /T(Z+\triangle Z) \tag{3}$$

It is evident from the above expression that any entrained parcel displaced upward will experience a downward acceleration as $\triangle q_e$ is positive for an unsaturated parcel. For a downward displacement, the entrained parcel experiences upward or downward displacement depending on whether the adiabatic warming $(g/c_p-\gamma(Z))\triangle Z$ with respect to the environment exceeds or not the cooling. $L\ \triangle q_e/c_p$ due to moisture acquisition during the descent. If the environmental lapse rate is assumed to be 5.8°C/km, then the relative warming due to adiabatic descent is 4°C/km and to offset this the parcel must acquire moisture at a rate faster than 1.6 g/kg for each kilometre of descent. This critical limit for the minimum rate of moisture acquisition puts a upper bound on the level from which downdrafts can originate. Since the downward moving current is not expected to be supersaturated to any great extent, downdraft will not exist at levels where the vertical gradient of saturation mixing ratio is less than the critical limit. The effect of moisture is to increase the critical limit further as parcel temperature should be lower so as to offset the positive buoyancy effect of lighter water vapour.

The amount of moisture acquired by the parcel during its transit through a layer depends on time taken by the parcel to traverse the layer, relative humidity of the parcel, liquid water content of the layer and microphysical properties of the cloud such as droplet size distribution, phase of the liquid water etc. Thus the rate of moisture acquisition of the parcel not only varies with height but also with the life cycle of the cloud. In the present model, it is assumed that the downdraft starts at the mature stage of the cloud when raindrops have already formed and started transporting liquid water content to the lower levels. Thus the formation of raindrop and hail inside the cloud is related to the formation of downdraft though not directly responsible for it.

The downdraft velocity at any level within the cloud is the resultant of velocities of parcels entrained at different levels and can be expressed as

$$V(Z)= \int_{Z}^{Z_T} M(Z')\,V(Z,Z')\,dZ' \Big/ \int_{Z}^{Z_T} M(Z')\,dZ', \tag{4}$$

$$(Z_T \geqslant Z \geqslant Z_C)$$

where $V(Z, Z')$ is the velocity at a level Z of parcel entrained at level Z'. The downdraft velocity at the ground can be computed by assuming that moisture acquisition within the subcloud layer is not significant. This assumption is valid when either the LCL is close to the ground as in northeast India or when intensity of precipitation is small as in northwest India during premonsoon season. The downward velocity according to the present model depends on heights Z_T and Z_C of the top and the base of the cloud and on the thermodynamic structure of the atmosphere but not on the mass flux entering the base of the cloud, *i.e.*, the cloud size.

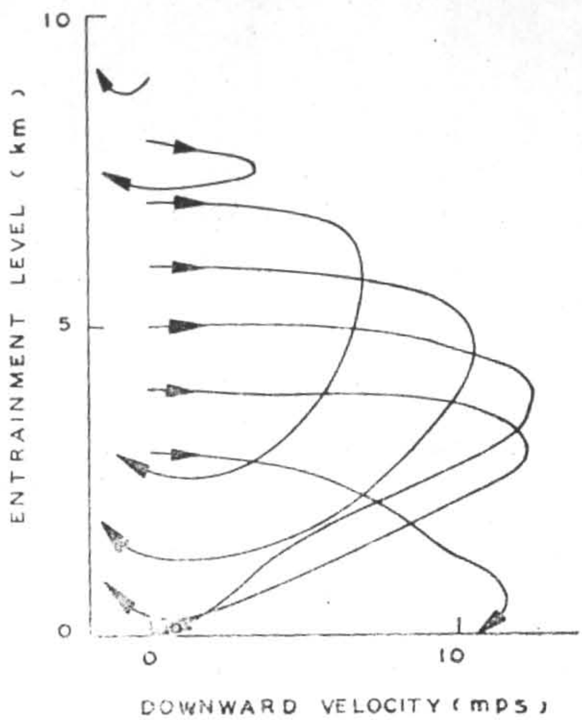

Fig. 1. Motion of individual parcels entrained into cloud at different levels

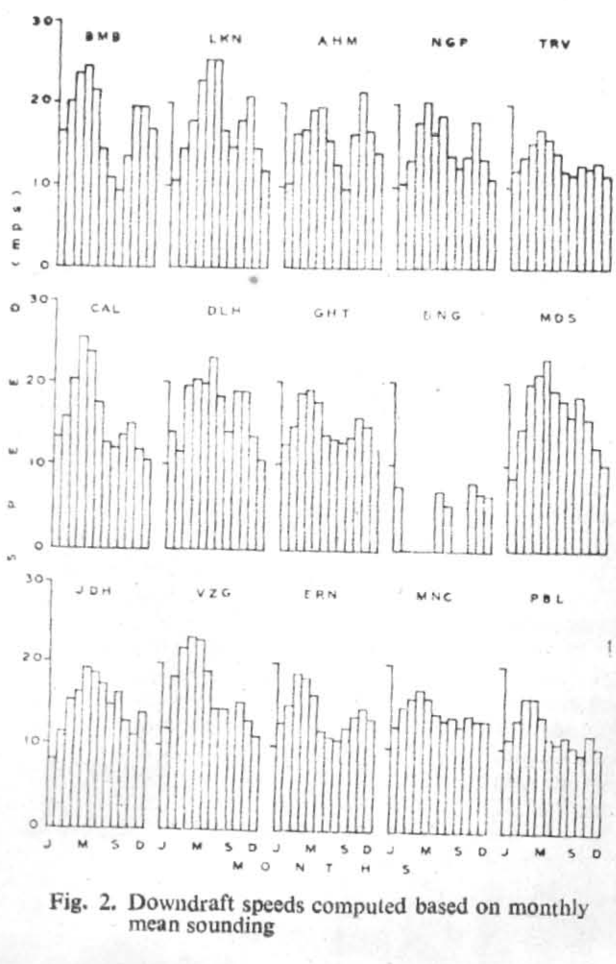

Fig. 2. Downdraft speeds computed based on monthly mean sounding

3. Difference equations and computations

From numerical computation of the downdraft velocity and other thermodynamic variables Eqn. (1) is approximated by the difference equation

$$W(J+1)^2 = (W(J)^2 (1-\alpha\triangle Z) + F(J))/(1+\alpha\triangle Z) \quad (5)$$

where,

$$\alpha = .94/R$$

$$F(J) = 2g\triangle Z\,(\triangle T^*(J+\tfrac{1}{2})/T^*(J+\tfrac{1}{2}) + \triangle T(J+\tfrac{1}{2}))$$

$$\triangle T^*(J+\tfrac{1}{2}) = T_e^*(J+\tfrac{1}{2}) - T^*(J+\tfrac{1}{2})$$

$$\triangle T(J+\tfrac{1}{2}) = \text{LWC}(J+\tfrac{1}{2})\,(5-W(J))/(5+W(J))$$

The level $J+\frac{1}{2}$ refers to the middle of the layer bounded by levels J and $J+1$. The virtual temperature of the descending parcel has been approximated by the difference equation

$$T_e^*(J+\tfrac{1}{2}) = (T_e(J) + 0.5\,(g\triangle Z - L\triangle q_e)/c_p) \times \times (1 + 0.6\,(q_e(J) - 0.5\triangle q_e)) \quad (6)$$

where,

$$\triangle q_e = K.\ \text{LWC}(J+\tfrac{1}{2})\ .R_H\ .\triangle Z/W(J+\tfrac{1}{2})$$

The value of the constant of proportionality K has been determined aposteriori from a series of numerical experiments and the value 5×10^{-2} m^3/s is found to be most suitable. For computational purpose, the top of the cloud was allowed to attain a maximum height of 15 km agl and the intervening atmosphere was divided into equal layers of 500 metres depth. The layer in which the bottom of the cloud appeared was further subdivided into two layers, one below the cloud bottom level and the other above it. The coupled set of Eqns. (5) and (6) are solved by using a iterative procedure and temperature and moisture at the middle and velocity at the bottom of the layer are determined. This procedure is continued till ground level is reached. Using Eqn. (4) the mean downdraft velocity at any level is now computed. The liquid water content (LWC) and the fractional entrainment rate $M(Z)/M(Z_B)$, where $M(Z_B)$ is the mass flux at the bottom of the cloud, were computed following the procedure laid down by Arakawa Schubert (1974).

4. Result

Downdraft velocities at the ground and other levels inside the cloud were computed by using the above model equations. In Fig. 1 actual trajectories of parcels entrained at different heights have been presented. It is seen that parcels entrained at higher levels sometimes descends by 3 km or more before becoming a part of the updraft. This is a consequence of the fact that extremely dry air at upper levels initially acquire moisture at a faster rate and thus gain in downward momentum. Once the relative humidity of the entrained parcel increases subsequent moisture acquisition rate may fall below the critical value and further descent is inhibited. Thus, the moisture acquisition rate, though initially dependent on the relative humidity of the environment at the entraining level, is finally dominated by the availability of the liquid water content inside the cloud.

The downdraft velocities obtained from the model by using monthly averages (51-70) of climate temp. as environmental temperature distribution are presented in Fig. 2. While computing the above velocities it was assumed that clouds have uniform top at 15 km

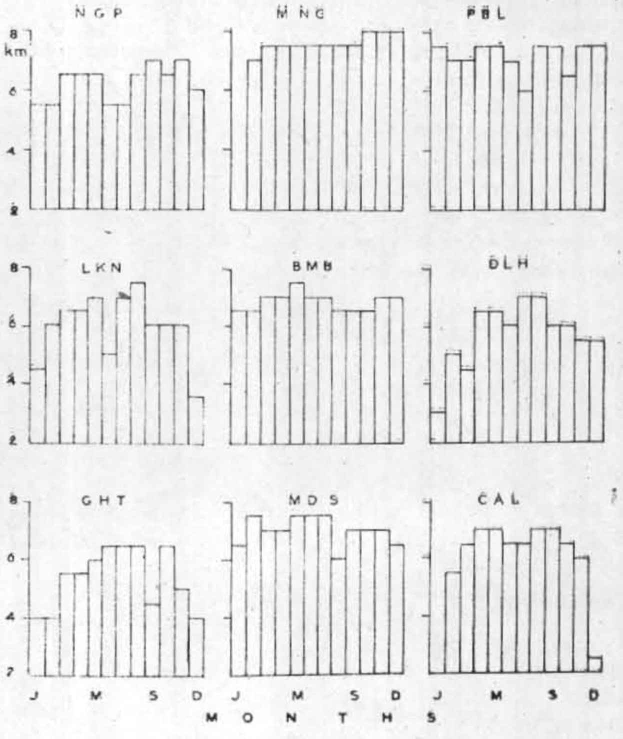

Fig. 3. Monthly variation in the height of the top of downdraft

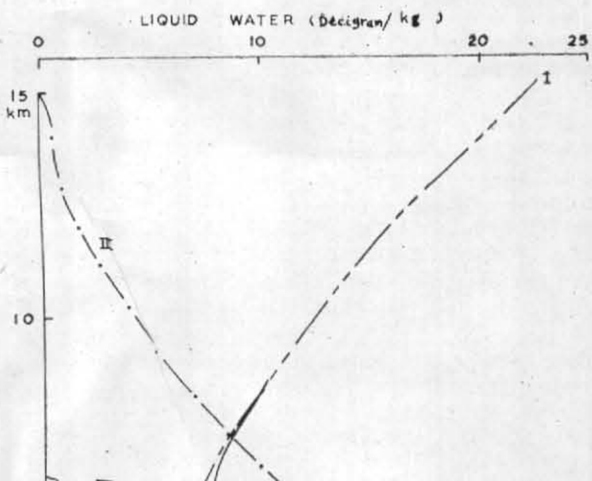

Fig. 4. Vertical variation in dry static energy (I), moist static energy (II), liquid water content (III) and downdraft velocity (IV) for vertical sounding of 12 GMT on 12 April 1983 at Dum Dum

and uniform fractional entrainment rate of 1 % per kilometre. However, computations with cloud tops at 12 km and 9 km and with corresponding fractional entrainment rates showed no significant difference in the downdraft velocity. This result indicates that downdraft velocity is nearly independent of cloud height and primarily depends on the thermodynamic structure of the environment. This is an advantage of using the present model for day-to-day forecasting of squall speed as the actual cloud top height over a station need not be predicted.

The present model was tested with actual radiosonde data of 12 GMT at Dum Dum on 12 April 1983. On that day, widespread convective activity was reported around Calcutta with a tornado forming about 30 km to the east of Dum Dum airport. From the hourly observations of surface temperature and humidity at Dum Dum airport the moist static energy of the mixed layer was calculated and the same was used to compute values of thermodynamic variables inside the cloud. In Fig.4, results of this computation are presented.

5. Conclusions

From computations based on the above model, the following conclusions are arrived at :

(1) The highest level from which an entrained parcel can reach ground has an upper limit depending on the environmental lapse rate. However, the height below which downdraft actually exists in a cloud is lower than this cut-off limit and depends weakly on the moisture acquisition rate. In Fig. 3, variations in the height of downdraft in different months of the year is depicted.

(2) It is found that downdraft velocity at the ground is significantly smaller during the monsoon months — a fact well supported by actual observations.

(3) The speed of the downdraft reaching ground depends on the thermodynamic structure of the environment and not on the height of the cloud top. Hence, under suitable atmospheric conditions even a cloud of moderate depth (top reaching 6 km) may give rise to strong downdraft inside the cloud and squall at ground.

(4) Over island stations under maritime influence, the highest level where downdraft can be detected inside a cloud does not vary appreciably with season. The same feature is also noticed for coastal stations but not for inland stations. In the mean over the year, the above level is higher (7 km) over island and coastal stations than over inland stations (6 km). There is no apparent correlation between the strength of the downdraft and the highest level where it can be detected.

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