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Dynamics of Thunderstorms

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PART II—ORIGIN OF DOWNDRAFTS IN A THUNDERSTORM AND THE CIRCULATION IN A FULL-FLEDGED THUNDERSTORM CELL

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ABSTRACT. The present explanation for downdraft in Airmass Thunderstorm does not account why all Cumulonimbus clouds do not culminate in a full-fledged thunderstorm. An alternative explanation is offered based on the development of instability within the cloud as a result of the sudden congelation of the supercooled layer.

1. *Introduction.*

In an earlier paper [1], the authors deduced purely on theoretical grounds, a stage in the development of the Cumulonimbus cloud, when the cloud with its fully grown anvil, could maintain itself without any further growth or decay for hours together. It was shown therein that though the cloud reaches a stage, when it does not grow further, the vertical currents do not cease or decrease in magnitude. Hence a thundercloud will not break into a thundersquall unless some other mechanism comes into operation. In this paper it is proposed to discuss this mechanism which brings about such a breakdown of the Airmass Cumulonimbus cloud into a full-fledged thunderstorm and the circulation resulting thereby.

2. *Present Ideas Regarding the Breakdown of Airmass cumulonimbus cloud into a full-fledged Thunderstorm.*

Meteorologists are generally agreed that before an Airmass Cumulonimbus cloud can culminate into a thunderstorm, it is essential that a local concentrated cooling must develop at a high level inside the cloud. According to Humphreys [2] such a condition is produced in an Airmass Cumulonimbus after a stage is reached when as a result of abundant condensation induced by the convectional cooling, rain is formed at a considerable altitude, where, of course, the air is quite cold, in fact so cold that often hail is produced. Now this cold rain or rain and hail, as it falls and as long as it falls, chills the air from the level of its formation all the way to the earth, partly as a result of its initial low temperature and partly because of the evaporation that takes place during its fall. Hence, this continuously chilled column of air, partly because of the frictional drag of the rain, but mainly because of the increase, due to this chilling, of its own density, immediately and necessarily, becomes a concentrated and vigorous return branch of the vertical circulation. From rough computation Humphreys finds that chilling the air with cold rain is very small and hence evaporational cooling accounts for much of the greater portion of the cooling.

That the process outlined above by Humphreys [2] cannot be the primary cause for initiating the downdraft in the cloud is evident from the following reasons :—

(1) In the life history of all Cumulonimbus clouds at some stage or the other, the vertical currents inside the cloud either completely cease or are not strong enough to hold the rain or cold rain drops any more in the air. The process suggested by Humphreys for initiating the downdraft will therefore come into operation and as such one should expect that all Airmass Cumulonimbus clouds must at a certain stage culminate into thunderstorm. Experience, however, at least in the tropics shows that this is not always so, and that there are good many cases, when a Cumulonimbus cloud after having existed for hours without any further growth, dissipates without culminating into a full-fledged thunderstorm.

(2) The mechanism suggested by Humphreys will be equally operative in the case of all thick clouds from which rain is falling and the environment is not nearly saturated. Yet we know that clouds other than Cumulonimbus do not cause downdrafts.

(3) The presence of rain drops or hail and raindrops is essential for the maintenance of the downdraft. As such the cloud cannot evaporate in the zone of the downdraft. That

such is not always the case is evident from the report of thunderstorm cloud at Kano,[3] which looked like an inverted crater.

(4) Every Cumulonimbus cloud from which rain is falling should be associated with downdraft and squall on the basis of the above mechanism, which is however not the case, since there are any number of cases of thunderstorms in the tropics associated with heavy rain but not associated with squall.

(5) According to Humphreys a considerable portion of the rain that leaves the thundercloud evaporates before it reaches the ground and the temperature decrease of the atmosphere in a thunderstorm is largely due to this evaporational cooling. He further states that even in the case of a heat thunderstorm around which the air is the same in every direction, the absolute humidity increases with the onset of the rain. If the downdraft is not associated with an increase in the absolute humidity, one can reasonably assume that the water vapour content of the downdraft has not increased due to evaporation from falling rain. In fact severe squalls have occurred in which vapour pressure of the atmosphere actually decreased with the onset of the downdraft. (See Table I.).

TABLE I.

Station—Jodhpur.

Date and time of occurrence of squall.	Vapour pressure before the squall.	Vapour pressure during the squall.	Vapour pressure after the squall.
17-5-44 1715 I.S.T.	22.1 mb.	18.1 mb.	19.7 mb.
28-6-44 1245 I.S.T.	36.8 mb.	32.5 mb.	27.9 mb.
5-10-44 1700 I.S.T.	31.2 mb.	20.1 mb.	23.1 mb.

Byers[4] and collaborators on the basis of the data from the Thunderstorm Project Observations in Florida put forward a description of thunderstorm structure and circulation, according to which the downdraft results primarily from the presence of falling rain in an area of former updraft where the lapse rate of temperature has been modified considerably from the moist adiabatic by the process of entrainment and turbulent mixing. The action of the rain in starting the downdraft is to force air downwards 2000 or 3000 feet when according to the thermodynamics of entrainment, it becomes more dense than the environment and strikes the ground as a downdraft. It was pointed out by Kaplan[5] also that rain is capable of dragging air downwards. As the velocity imparted to the surrounding air by the falling rain drops cannot be large, it is doubtful if with that velocity, the air can move through 2000 to 3000 feet in a short time such as half to one hour.

Also from the account of Byers[4] and collaborators a thundercloud which looks as a single body, 'is most often composed of several regions of convective action' which are termed cells. In such a case, it is not clear how a cell in the central part of the cloud where the downdraft is most intense can entrain the unsaturated air of the environment.

3. *Suggested Physical Process for Initiating the Downdraft in a Cumulonimbus.*

It is well known that although Cumulonimbus clouds consist of ice crystals above the freezing level in some cases, yet in the majority of cases they consist of supercooled water drops. Bergeron has, on the basis of Kohler's results inferred that in an adiabatically ascending air mass in which the droplets would be expected to be considerably disturbed and to have a large size, the region of supercooled water drops would not extend above the level of −10°C or −20°C. Or in other words the Cumulonimbus clouds would consist of ice crystals only above the level of −10°C or −20°C.

If for some reason such a layer of supercooled water drops gets suddenly disturbed and stirred up, sudden congelation of these supercooled water drops would result and as a consequence, heat would be liberated raising the temperature of that layer. On account of this heating, the layer of air aloft will now be potentially colder than the layer below which initially contained supercooled drops, resulting in a turbulent motion similar to the one observed in an unstable layer of fluid. As this occurs very near the freezing level, the turbulence will carry some of the ice crystals to levels where the temperature is higher than 0°C. These ice crystals will melt consuming the heat from the environment and thus cooling it suddenly. Such a cooling will be local, concentrated and decided and will act as a trigger for the downdraft.

To illustrate the above, let us consider that the rising airmass has temperature of 30°C at 1000 mb. level and a mixing ratio of 20 gm/kg. (See Fig.1) The ascent of the parcel will be along the dry adiabat upto 920 mb. and along the saturated adiabat upto 490 mb. where its temperature would be 0°C. At this stage the air has 12 gm/kg. as liquid water and 8 gm/kg as water vapour. If further air motion is such that the cloud consists of water drops in a supercooled state upto -10° C or -20°C the ascent will be along the saturated adiabat through 0°C at 490 mb., whereas if the freezing started immediately at the 0°C, the path will be along the 0°C isotherm upto 450 mb. and along the saturated adiabat through 0° C at 450 mb. later. It will be seen that the result of the freezing of the liquid water is to make the air follow a path $3\frac{1}{2}$°C warmer than the one in the supercooled stage.

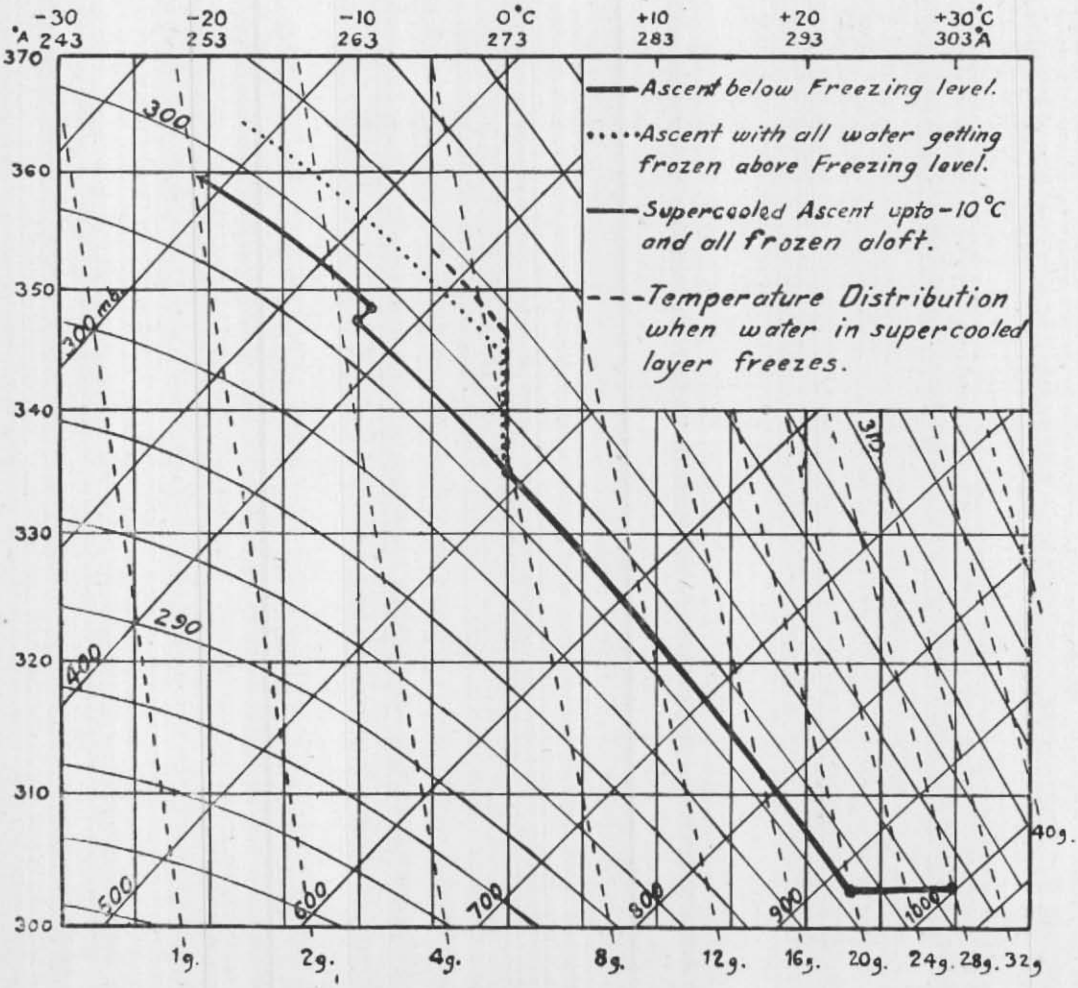

Fig. 1.

The above computation has been made using the equation (10) on page 60 of Brunt's Physical and Dynamical Meteorology (1941 Edition) reproduced below:—

$$\log (p-e)_1 - \frac{59\cdot71}{(p-e)_1} = \log (p-e)_0 - \frac{52.39}{(p-e)_0} - 1.846\, z$$

The subscripts 0 and 1 respectively refer to the initial and final stages, p and e are the total pressure and partial pressure of water vapour respectively and z the total water content (in all the three phases) per gm. of the dry air. Apriori it can be seen that the above result could have been derived to a first degree of approximation in a simpler manner. The twelve gm. of liquid water (contained in 1 kg. of dry air) will give out $12 \times 80 = 960$ calories of heat. About 250 calories will be required for raising 1 kg. of dry air and its total water content of 20 gm. through 1°C; hence the rise in temperature would be about 4°C., whereas by the more rigorous computation it would be $3\frac{1}{2}$°C.

Consider the path when the water drops do not freeze at 0°C but remain in a supercooled state. As we know supercooled drops are in a metastable state and the forces of crystallisation become stronger as the temperature decreases below 0°C. As mentioned before when the air rises by this path the supercooled drops occur upto −10°C or −20°C and aloft the cloud mainly consists of ice crystals. For further discussion let us assume as an ideal case that all supercooled water carried upwards across the −10°C level freezes rapidly in a shallow layer. Owing to the freezing of the supercooled water, the path will not be a continuation of the saturated adiabat followed below the −10°C level, but a warmer adiabat (how much warmer will depend upon the amount of supercooled water). If the air was carrying all the water vapour content it had initially at the −10°C level, there should be 5 gm. of water vapour and 15 gm. of supercooled liquid water per kilogram of dry air.

There are, however, reasons to think that all the water vapour at the base of the convection is not carried right upto the top. The vertical velocity in a cumulonimbus cloud increases with height upto a certain level and thereafter decreases. The two portions may be referred to as the accelerated part and the decelerated part. In the accelerated part there is airflow from the sides as confirmed by Stommel[6]. In the decelerated part air will flow out to the side. The air flowing out will not be able to carry the liquid water content as the flow becomes horizontal and there is no vertical component to support the liquid drops. It, therefore, follows that the level of maximum vertical velocity becomes the level of accumulation of water drops or ice crystals and that in the decelerated part the liquid or solid content will accumulate in the lower levels and decreases with height. This view is supported by the observation that above a certain level (*i.e.* the necked - in portion of the Cumulonimbus cloud), the denseness of the cloud decreases with height. It will be shown later that the temperature at the level where accumulation of the liquid/solid contents occurs is of considerable importance in the mechanism of the origin of downdrafts. Assuming that 3 gm (per kg. of dry air) of supercooled water drops are carried across the -10°C level, the saturated adiabat followed above −10°C after freezing will be 1°C warmer than if the freezing had not occurred. This path is also shown in Fig. 1.

Now consider the temperature distribution when the layer of supercooled water drops (between 0 and -10°C) gets disturbed for some reason resulting in congelation of the supercooled water drops. Latent heat will be liberated by the freezing and the air layer will be warmed. The increase in temperature can be computed from the amount of supercooled water in the layer.

At the base of supercooled layer (at 0°C level) the saturation mixing ratio is 8 gm/kg leaving 12 gm/kg, as liquid water. At the top, the saturation mixing ratio and supercooled liquid water are respectively 5 gm/kg. and 15 gm/kg. This is on the assumption that all the initial water vapour content is carried into this layer in some form or other, which will definitely hold when the 0°C to -10°C coincides with region of maximum vertical velocity. The average supercooled water content is then 13.5 gm/kg. In addition, account has to be taken of the liquid water content 'filtered' out (on account of the decreasing vertical velocity upwards) into this layer from the air crossing the —10°C level. To evaluate this, the total mass flux that has occurred across the −10°C level should be known. We can, however, assume that the supercooled water content between 0°C and −10°C levels is not less than 13.5 gm/kg. The rise in temperature, if 13.5 gm/kg. of supercooled water freeze, is about 4.5°C. If there had been considerable accumulation of water drops between 0°C and -10°C levels the rise in temperature will be considerably greater than 4.5°C. An approximate temperature distribution after the congelation of supercooled layer is shown in Fig. 1.

The temperature distribution shown in Fig. 1, after the supercooled water drops have frozen, is unstable at the interface between the supercooled layer and the ice layer aloft. Considerable turbulence will, therefore, develop in the two layers. As this turbulence zone is very near 0°C level, some ice crystals are likely to be carried by turbulence to levels below, which are warmer than 0°C. The ice crystals will melt drawing the heat of fusion from the environment and thereby cooling the environment.

It is evident that the degree of cooling will depend upon the amount of ice crystals. But since the lowest temperature to which any layer at a temperature higher than 0°C can be cooled by the melting of ice is 0°C, the possible amount of cooling will be greater, as the ice crystals are carried further below the 0°C level. This will depend upon the degree of turbulence—the greater the turbulence the greater will be the descent of ice crystals. Both the amount of ice crystals and the intensity of turbulence will be maximum if the zone of supercooled water drops is the level of accumulation. The cooling so produced will act as a trigger for the downdraft. This descending air will follow a saturated adiabat on account of the water drops it carries and will thus be colder than the surrounding column of air at all levels right upto the base of the cloud, for the lapse rate in the cloud air is greater than saturated adiabatic. As the down rushing air is moving in an energy producing medium it will get accelerated in its descent from the 0°C level right upto the cloud base. If below the cloud, the vapour pressure of the environment is less than the vapour pressure of the downrushing air futher cooling of the downdraft on account of the evaporation of water drops into the environment will take place and this will further increase the acceleration of the downrushing air. Judging, however, from the fact that severe squalls do occur even with high humidities below the cloud it would appear that this effect cannot be of major importance. In the examples given in Table I the vapour pressures before the squalls were much larger than those during the squalls. Considering the vapour pressure values recorded before and during squalls as representative of the environment and the downdraft, it is obvious that no cooling through evaporation was possible in these cases.

In the above treatment the supercooled layer and the ice layer have been treated as if separated by a rigid boundary for convenience of computation. In nature the transition may be gradual; but the general validity of the arguments made out above will not be affected.

It is very likely that all the water in the supercooled layer (0°C to —10°C) does not freeze at once but only gradually. The value of 13.5 gm/kg. used in the calculations above is an underestimate of the total water content in that layer; for as shown by Harrison[7] the amount of liquid water at the level of accumulation may be as much as 50 gm kg. If this is so, the rise in temperature estimated above will correspond to the congelation of only a part of the supercooled water.

The main features of the mechanism are as follows:—

If the 0 to—10°C zone is the level of accumulation of "Condensation products" in the cloud, the ice crystals formed as a result of congelation at this level are carried below suddenly in sufficient number by turbulence that develops with the sudden freezing of the supercooled drops in layers 0 to — 10° C. This fall of ice crystals into regions warmer than the freezing point is responsible for the cooling of the air which initiates the downdraft. This is to some extent confirmed by the report of Byers and collaborators who found "that downdrafts of a magnitude great enough to be detected by the aircraft first occur near 15000 feet", near about the freezing level.

On the basis of the process outlined above one would expect that,

(i) Cumulonimbus clouds with only ice crystals above the freezing level will not culminate into a thunderstorm.

(ii) Cumulonimbus clouds with supercooled water drops above the freezing level will culminate into a thunderstorm only if the level of accumulation of water in liquid and solid phase coincides with the levels of supercooling so that the amount of liquid water (per kg. of dry air) contained in supercooled layers is greater than the amount in the layers above having only the solid phase.

(iii) In clouds other than Cumulonimbus, the zone of accumulation is far below this freezing level for the above mechanism to operate and hence no downdraft develops.

(iv) As the presence of rain drops or hail is not essential for the initiation of downdraft, the thunderstorm cloud will develop a crater in the zone of downdraft, if the amount of water content in the downdraft is not enough to keep the humidity 100% and a hole will develop at the base of the cloud which will look like an inverted crater as the one observed at Kano [3].

(v) As the process is independent of evaporational cooling, it is possible to have a squall associated with a thunderstorm in which the environment has a higher water content than the downdraft itself.

4. *Circulation in the Thundercell*

It is well-known from the experiments carried out in the laboratory that if in a thin layer of fluid, instability is produced, the unstable layer of fluid breaks down in the form of polygonal cells. The instability can be produced either by cooling the top or by heating the bottom. Whereas, in the case of liquids, whatever be the way the instability is produced, the motion is an ascending one at the centre of the cell and descending one at the edges, it is, however, not always so in the case of air. It has been found that when the instability is produced in the air layer by heating it from below, the motion is an ascending one in the centre as long as (i) the layer of fluid is shallow and (ii) the excess of the temperature of the bottom over the top of the chamber in deep layers is only a little above the marginal value required for any circulation to occur. When, however, the instability is produced either by cooling the top or when the excess of temperature at the bottom over the top in deep layers is great, the motion is a descending one in the centre of the cell and ascending one at the edges.

It is also possible to produce cells with decending centres even in the case of liquids as has been shown by the experiment performed by A. Graham [8] described below :—

"Hot water was poured into a cigarette tin to a depth of about 1 cm. When the disturbance had died away, a little cold milk was carefully poured into the water. The cold milk sank to the bottom forming a white layer with clear water above. When the free surface of water was cooled by blowing upon it, a number of round holes appeared in the milk layer, demonstrating the descending column."

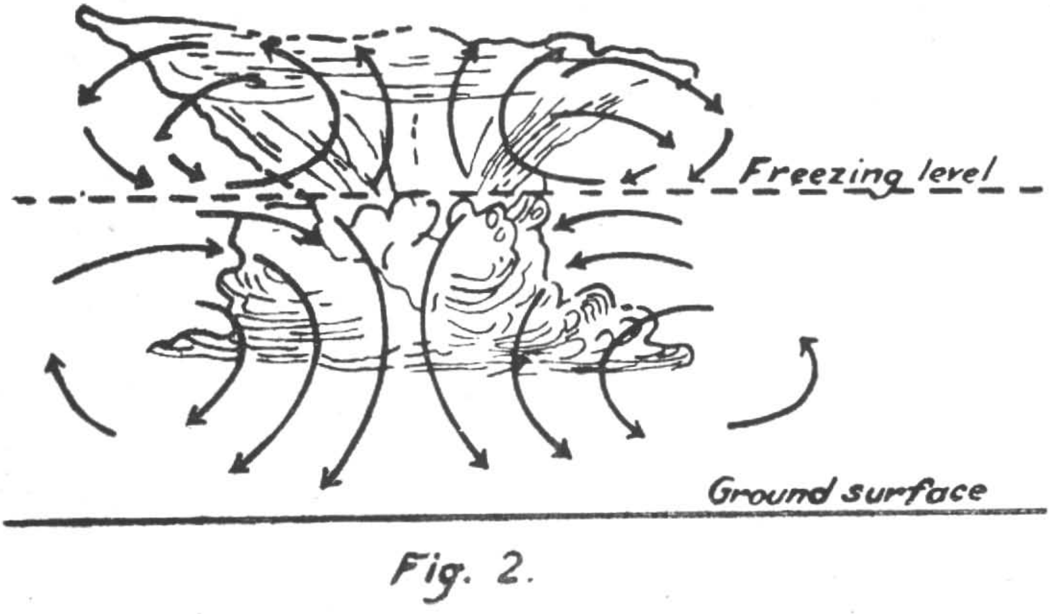

Fig. 2.

The experiment of A. Graham is of great importance as it shows that when instability develops suddenly at the boundary between two fluids of different densities the cells produced are those with descending current in the centre and ascending one at the periphery.

The local concentrated cooling which results in a cumulonimbus cell near the freezing level as a result of the process outlined before is similar to the cooling produced at the boundary between the two fluids of different densities and hence, as in the experiments of Graham, such an instability will result in setting up cells with descending centres. This descending current is the main downdraft. The resulting circulation from analogy is given in Figure 2. This diagram does not take into account any general translatory motion superposed on the thunderstorm system.

That such a circulation does exist in a Cumulonimbus when the same has culminated into a thunderstorm, has been shown by the thunderstorm project observations of Byers and his collaborators[4].

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