Cumulonimbus

New Ideas on Hail-, Thunder- and Tropical Storms

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1. The transformation of cumulus into cumulonimbus

The striking change which occurs in the tops of cumulus during the release of a shower and the transformation into cumulonimbus is one which is familiar to all air-minded people. The hard, clear outlines of the bulging cumulus towers become softened, and the craggy details on their sides are smoothed away until the towers gain a lustrous sheen and fibrous texture characteristic of ice clouds. Often this transformation is seen to begin in the cloud tops some minutes before the first shower streaks appear below the cloud base, and such observations were the inspiration of the splendid theory of shower release proposed by Bergeron in 1933 and strongly supported and developed by Findeisen.

According to the Bergeron-Findeisen theory the processes of condensation and collision (followed by coalescence) within a cloud containing only droplets are so inefficient in the production of raindrops that the cloud can be said to be "colloidally stable". When, however, a cumulus reaches above the 0° C. level and its droplets become supercooled, this stability is disturbed if a few ice crystals are formed. A rapid preferential condensation occurs on the crystals, and within a minute or two they become large enough to settle quickly through and collide with the supercooled droplets. Thereafter the crystals grow mainly by collecting droplets, which become frozen upon their surfaces, and at an accelerating rate as the crystalline masses—embryo hailstones—become larger and fall faster. Thus within a few minutes of the appearance of the crystals in supercooled cumulus a shower of hailstones is produced, which may melt into raindrops before reaching the ground. The shower is produced so quickly that one can speak of its sudden *release*.

Frequently cumulus tops reach levels where the temperature is as low as —10° C. or even —20° C., but no shower is released and no traces of ice crystals can be seen in the cloud tops. The theory therefore focussed attention on the phenomenon of supercooling and crystal formation in clouds. It was concluded that special solid nuclei are necessary for the formation of ice crystals, and that in the atmosphere the nuclei which are active at temperatures down to —20° C. are very rare, and sometimes altogether absent. On these occasions showers could not form even in towering cumulus whose tops were strongly supercooled.

Throughout the last war, and indeed up to the time of his disappearance in Prague in 1945, Findeisen studied the properties of ice nuclei and sought for very efficient artificial nuclei which could be used to remedy natural deficiencies and hence to provoke shower release. His experimental researches were made on laboratory clouds produced, in order best to simulate the properties of natural clouds, in closed and carefully insulated chambers. He was therefore denied the later success of the American physicist Schaefer, who in 1946 accidentally discovered the marvellous crystal-nucleating effect of dry ice when he placed a lump of it in a supercooled cloud held in an *open* box.

2. Shower release in the tropics

During and after the war documented evidence accumulated which showed that in tropical climates showers are frequently released from cumulus whose tops do not reach the 0° C. level. It is impossible that the Bergeron-Findeisen process can be responsible, and consequently increased attention was paid to the growth of raindrops by the coalescence of cloud droplets, notably by Bowen in Australia. It was established that, partly in consequence of the great variation in the sizes of condensation nuclei, cloud droplets soon after their formation have a range of sizes, a small proportion being three or four times larger than the great majority. These outsize droplets grow by settling amongst and colliding with the remainder, and at an accelerating rate which can bring them, in a moderately dense cloud, to the size of raindrops within about 20 minutes.

According to the present simple models of cumulus structure, these clouds are composed of a succession of buoyant "bubbles", or thermals, which are about a kilometre across, and which rise at a speed of a few m/sec. from the cloud base to the summits (Ludlam and Scorer, 1953). During their rise they mix with the surrounding air; this mixing has no pronounced effect within the cloud mass, but has a disastrous effect upon the buoyancy of a thermal which rises into clear air, for the mixing is then accompanied by an evaporation of the cloud droplets and a strong chilling. Consequently the cloud thermals which emerge from the main cloud mass to form the summit towers rarely rise more than a few thousand feet before they are brought to rest and dissolved. Cloud droplets can therefore be regarded as carried through the cumulus by its thermals: the droplets are formed at the cloud base and rapidly evaporated into clear air surrounding the summits. If the droplets spend as long as 20 minutes within the cloud then the thermals reaching the summit levels may contain raindrops grown by droplet coalescence; these are too large to suffer evaporation during the ensuing dissolution, and instead fall back into the cloud mass and later emerge from the base as a shower. On the other hand, if individual thermals pass from the cloud base to its summits in considerably less than 20 minutes, the cloud droplets can never achieve the size of raindrops; all are evaporated at the top and sides of the cloud, and no shower forms.

This brief account is greatly over-simplified, but it does fairly indicate that in the formation of showers by the coalescence of cloud droplets the vital matter is the time spent by cloud droplets within the cloud. This is in great contrast to the vital parameters suggested by the Bergeron-Findeisen theory: the temperature of the cloud tops and the presence or absence of ice nuclei active at that temperature.

In a moderately vigorous cumulus, whose thermals rise at about 2 m/sec., the coalescence process may result in shower formation if the cloud tops are some 2400 m (2 m/sec.×20 min.) above the cloud base, and therefore probably some 3 or 4 km above the ground. In the tropics, where the 0° C. level is about 4 km. above the ground, showers are therefore to be expected from some clouds whose tops do not reach this level. On the other hand in temperate latitudes, where the 0° C. level is lower, and when the cumulus are more vigorous, showers cannot form in this way unless the clouds become so large that their tops are supercooled and liable to infection with ice crystals. In these circumstances, then, either the coalescence or the Bergeron-Findeisen process might be responsible for shower release.

3. Shower release in temperate regions

In recent years observational studies made in America and in Europe have provided evidence that very frequently the release of showers in these regions is accomplished by the coalescence process even in large clouds with strongly supercooled tops. In particular, recent work in Sweden, where the clear air is a great help to acute visual observation, has shown that on particular days showers form only in clouds whose tops surpass a rather well-defined level, whose height above the ground and temperature vary considerably from occasion to occasion (Ludlam and Saunders, 1956). When the tops barely attain this level faint radar echoes from incipient showers can be received from the cloud towers, which in dissolving show traces only, often evanescent, of the transformation into a fibrous texture. These cloud towers are said to become "fibrillated", and the critical summit level at which the transformation first occurs is called the "fibrillation level".

The streaky texture of fibrillated cloud is due simply to the presence of large particles falling in trails, and does not indicate certainly whether these particles are raindrops, snowflakes, or hailstones. The observational evidence suggests that frequently they are predominantly raindrops grown by the coalescence process, for the thickness of the cloud in which they are first produced varies according to the upward speed of the cloud thermals. If this speed is high—say 5 m/sec.—then no fibrillation or shower formation occurs unless the cloud thickness exceeds about 5 km (the summit-level temperature may then be below —20° C.). On the other hand in relatively weak clouds, whose thermales rise at speeds of only 1 to 2 m/sec., showers form in clouds which are only about 2 km. thick, and whose summit-level temperatures are barely below 0° C. The relation between the thermal speeds and the cloud thickness required for shower formation is in reasonable accord with what is known of the rate at which coalescence proceeds. It is therefore inferred that even when cumulus tops are strongly supercooled, it is frequently the coalescence process which is responsible for shower formation.

4. The development of shower clouds. Glaciation

When the summits of growing cumulus reach several hundred metres above the fibrillation level, shower formation is efficiently begun: the radar echoes usually strengthen steadily and spread down towards the ground, and within several minutes large volumes of the cloud tops acquire a persistent fibrous texture, and are said to have become "glaciated". Flight observations and indirect evidence suggest that at the end of this period those parts of the cloud lying above the 0° C. level do indeed contain high concentrations of ice- and snow-crystals.

It is most remarkable that this infection with many crystals often appears to follow the shower release, rather than to precede it. It has been observed to occur even when the cloud tops were restricted to levels where the minimum temperature has been about —5° C. It is difficult to imagine that these crystals are formed on special ice nuclei, active in great numbers once a shower has been released. It is much more probable that during the shower formation some process of crystal multiplication is set into operation, perhaps in ways first discovered by Findeisen himself and recognised by him to have great potential importance in cumulonimbus. He found that small splinters are broken from the fragile arms of snow crystals during their fluttering fall, and that some similar process of splinter formation seems to occur at a great rate during the growth of small hail by the sweeping up of supercooled droplets. This latter process is clearly likely to begin if a few of the large raindrops, grown by coalescence of cloud droplets, should freeze in the supercooled cloud tops, and continue their growth as small hailstones. During a period of several minutes splinter crystals left in the wake of the hailstones can grow into feathery snow-crystals and these may produce fresh crystals by the first-mentioned process. The stirring motions within the cloud thermals efficiently distribute the crystals over the whole cloud above the 0° C. level, below which they melt. The details of the ways in which the ice phase develops extensively throughout the cloud tops need intensive study, but observations leave no doubt that in general they are very effective once shower formation has begun.

Conditions within the maturing shower cloud therefore become much more complicated. Above the 0° C. level there is at first a large amount of supercooled water in the form of cloud droplets and raindrops, some of which may freeze and become hail; later there is a predominating proportion of ice and snow crystals, and small hail. Below the 0° C. level there are at first only cloud droplets, but soon raindrops, melting ice- and snow-crystals, and hailstones arrive from above.

Rising thermals are actively mixed with their surroundings, and those which ascend through the maturing shower cloud therefore become infected with many ice crystals as they pass above the 0° C. level. Subsequently there are collisions between these snow crystals and the supercooled droplets and small raindrops carried up in the thermal, and the freezing of this water liberates latent heat which by warming the thermal adds substantially to its buoyancy.

Consequently after the thorough glaciation of the cloud tops, new towers are often seen to rise with speeds two or three times greater than that of their predecessors, and the shower cloud rapidly builds to much greater heights, often being checked only at the tropopause, where the towers become flattened and spread out into the familiar expanding anvil cloud. The evaporation which occurs at the edges of anvil clouds is strikingly less effective than that which so harshly restrains the growth of cumulus towers, partly because the clear air is often nearly saturated with respect to ice, but not with respect to liquid water, and partly also because the anvil cloud often has a higher excess temperature and concentration of cloud water than the tops of ordinary cumulus. Evaporation wastes away cumulus tops, so that the clouds taper upwards, whereas after glaciation has occurred and anvil formation has begun the cloud accumulates at the top, and often eventually grows into a very massive cumulonimbus extending over a hundred km or more.

5. The three phases of cumulonimbus evolution

According to the ideas outlined above we can distinguish three phases in the evolution of cumulonimbus clouds:

Phase I. *Cumulus of less than the critical size for shower formation:* the clouds contain no rain, hail, or snow. In very unstable atmospheres, when the upward speeds of thermals are high, these clouds may be very tall, with strongly supercooled tops.

Phase II. *Immature shower clouds.* Raindrops form near the cloud summits, and a shower develops: if the summits are supercooled then hail may form by the freezing of some raindrops, and processes of ice crystal multiplication are set into operation. In this phase, however, the cloud is composed mainly of liquid water: there are very few ice crystals, although there may be some hailstones.

Phase III. *Mature cumulonimbus:* anvil clouds. The cloud tops, above the 0° C. level, contain a high proportion of ice, in the form of ice- and snow-crystals, and small hailstones. The typical cloud is many times bigger than clouds in the other growth phases.

When the atmosphere is very stable above the level which cumulus summits must attain before shower formation begins, then Phase III clouds are not noticeably taller than Phase II clouds. Commonly, however, the shower formation level is in the middle troposphere and the upper troposphere is marginally unstable. The transition from Phase II to Phase III is then accompanied by a surge upwards in the level of the cloud summits, leading to the development of a few anvil clouds whose tops are about twice as high as the general level of the tops of the biggest cumuliform clouds.

6. The growth of large hail

Large hailstones are grown when a strong updraught sustains a few stones for several minutes in a region rich in supercooled cloud droplets or raindrops. These conditions are fulfilled only in warm, very unstable atmospheres, and only in Phase II clouds. The cloud thermals then have very great rising speeds, and showers form only in very tall clouds whose tops are strongly supercooled and contain high concentrations of liquid water.

After the transition to Phase III conditions become unfavourable for the growth of large stones: there are far too many ice particles competing for the diminished supply of supercooled water. There may nevertheless be many small hailstones, some of which may simply be raindrops lifted above the 0° C. level by rapidly rising thermals and subsequently frozen after collisions with ice crystals.

7. The generation of thunderstorm electricity

According to a recent theory due to Reynolds of New Mexico, the most effective process of charge generation and separation in cumulonimbus is the collision of hailstones and ice crystals. It is too early to say whether this theory will prove more satisfactory than previous ones, or indeed if the generation of thunderstorm electricity is predominantly due to one process alone. Nevertheless Reynolds' theory has attractive features, and it is desirable to test and develop it. An important implication is that electrical activity is to be expected in Phase III and not in Phase II clouds, which may contain large hailstones but only insignificant numbers of ice crystals. The association of anvil clouds with thunderstorms is of course well known, and there is an equally close association between thunderstorms and the fall of large hail. It is interesting that for the first time these two phenomena are regarded as unlikely to be produced within the same kind of cloud, but rather are characteristic of clouds in two distinct phases of cumulonimbus evolution. Towering cumulus grow preferentially near the flanks of mature cumulonimbus, probably over the micro-cold-fronts which herald the cool down-draughts spreading out of the precipitation areas, and thus the Phase II clouds in which large hail may be grown commonly develop at the very edge of extensive Phase III clouds, so that their distinction is not an easy task.

8. The formation of tornadoes and tropical cyclones

A tropical cyclone can be regarded as a great system of cumulonimbus, which are arranged in spiral bands about the storm centre in patterns which recall the spiral nebulae. There have been many attempts to explain how cumulonimbus, which ordinarily occur randomly scattered over a large area, can become organised into such a system. A stumbling-block has been the difficulty of explaining an initial fall of surface pressure in a restricted locality, which is required to establish a cyclonic wind circulation. Once such a circulation about a low pressure centre has begun, it becomes less difficult to account for a continued deepening and the development of hurricane winds. An unusually intense cumulonimbus has been proposed as a starting-mechanism, but studies with a dense network of observing stations, necessarily conducted overland, have shown that the most pronounced feature of the pressure-change beneath developing cumulonimbus is the pressure *rise* associated with the cool downdraught in the region of heavy rain. Consequently the idea that the tropical cyclone forms as an intense cumulonimbus has been rejected.

In my opinion this hypothesis deserves fresh examination. The observational studies made overland may not be representative of cumulonimbus behaviour over the ocean: trocipal cyclones do not form overland, but only over the ocean. To a good approximation the barometric pressure varies with height according to the hydrostatic equation, and a low surface pressure implies relatively warm air in the column above. Since cumulus clouds are composed of buoyant air, warmer than the surrounding air, one might expect a fall of surface pressure beneath individual clouds. Available evidence suggests that such a fall is detectable beneath large clouds, but that it amounts only to about 0.1 mb., negligible in a problem where a mechanism for producing a fall of at least several mb. is sought. That the pressure fall beneath a cumulus should be so small is not surprising, for experience shows that the cloud thermals have temperature-excesses of only about 1° C., and, moreover, that only a relatively small part of a cumulus is at any moment composed of buoyant thermals, the remainder consisting of slowly sinking and dissolving residues of earlier thermals which have been mixed with clear air, and which are now *cooler* than the environment. The situation is quite different, however, during the transition of cumulonimbus from Phase II to Phase III, with the production of an expanding anvil cloud. In a very unstable atmosphere an anvil cloud may occupy the whole upper half of the troposphere, between the pressure levels of the 0° C. level (say 500 mb.) and of the tropopause (say 200 mb.), and, in consequence of the release of latent heat of freezing and the now negligible evaporation during mixing with the surroundings, the entire mass of the anvil may be several centigrade degrees warmer than its environment. Under these circumstances application of the hydrostatic equation suggests that beneath such a massive cloud a pressure fall of several mb. could occur.

However, during the period while the transition from Phase II to Phase III is occurring, heavy precipitation is initiating a downdraught in the lower parts of the cloud. The downdraught is sustained by a *chilling* due to the partial evaporation of rain and hail, and beneath the downdraught column there is a rise of pressure, which swamps any fall which might be due to the growing anvil and produces a small *anticyclone* in the rain area. Only if wind shear tilts the cumulonimbus, so that the anvil projects on one side beyond the rain area, might we look for traces of surface pressure fall. It is interesting that such depressions are shown beside downdraught anticyclones on detailed micro-analyses recently produced in America (Fujita, 1955). Similarly, tornado funnels have been located inside *tornado cyclones* of radius about 10 miles and depth a few mb. Conceivably these phenomena are associated with expanding anvil clouds and represent the formation-stage of tropical revolving storms. Overland, however, the precipitation and downdraughts drench and chill the ground and thus interfere with the continuation of convection in one locality. Over the ocean, on the contrary, the inexhaustible heat resources of the sea are available to warm the downdraught air, which therefore cannot interfere with the convection (Bergeron, 1954). Moreover, a large part of the pressure rise below the downdraught column is due to chilling of air below the level of the cloud base; over the ocean the cloud base may be only two or three hundred metres above the sea, so that the downdraught anticyclone may be relatively weak and easily destroyed by convection. In these circumstances a microcyclone beneath an expanding anvil cloud can be imagined to continue its development into a tropical cyclone of hurricane intensity.

9. Investigation of cumulonimbus
The work of voluntary observers

It will be apparent from the skeletal outline of ideas in the previous paragraphs that there is both incentive and need for more intensive studies of cumulonimbus. These clouds are too large to be surveyed from one observing point, yet too small to be represented on the network of observations routinely made for weather forecasting. Their study demands special networks of observers over areas tens of miles across, supplemented if possible by radar and aircraft observations. Work of this kind will be conducted in England during the summer of 1957 jointly by the Meteorological Office and Imperial College. During the months of June and July it is hoped that a small army of volunteers living within about 100 mi. of our radar station base will report accurately the location and time of falls of hail and of lightning strokes. On stormy days the area will be surveyed continuously by radar and occasionally by aircraft reconnaissance, and it is hoped in this way to determine the growth phase of the individual clouds which are responsible for falls of large hail and lightning discharges to the ground. Related studies will be made, including the examination of favoured cumulonimbus breeding-sites and the processes whereby the clouds often become organised into isolated groups or belts. For this purpose the routine synoptic observations will be supplemented by observations made at official establishments and by private individuals. Information is also needed about the conditions inside cumulonimbus, especially concerning the rising speeds of thermals and the form of precipitation, and it is expected that valuable data of this kind will be obtained from pilots who make soaring flights from the several sailplane clubs which are situated in England. Other cloud flights will be made by aircraft of the Meteorological Research Flight, during which samples will be obtained of the condensation nuclei used in cloud formation, of the spectrum of droplet sizes near the cloud bases, and of the crystal-content and temperature of cumulonimbus anvils.

The investigations thus cover a range of phenomena whose scale varies from the microscopic to the synoptic. Voluntary observers will play an essential part. They will be unpaid, but will have the satisfication of knowing that their efforts will make a substantial contribution to our understanding of cumulonimbus, perhaps the most impressive of weather phenomena.

References

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