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CURRENT PROBLEMS IN RESEARCH

How Does a Raindrop Grow?

Precipitation in natural clouds may develop from ice crystals or from large hygroscopic aerosols.

Roscoe R. Braham, Jr.

The formation and growth of natural raindrops, and the possibility that man can exercise some degree of control over their formation, is one of the most fascinating developments of modern meteorology. So great is the present interest in the subject that a considerable number of meteorologists, chemists, and physicists have turned their research efforts toward this goal. Although control of the weather still appears to be a long way off, the intensive research in cloud physics of the past few years has given considerable insight into the processes of formation of natural precipitation. Thus, it has only been within the past few years that anything approaching a satisfactory answer to the question of raindrop growth has been available.

To understand how a raindrop grows, we must first consider how clouds and cloud droplets are formed. Most clouds are made up of small droplets of water which form through condensation of water vapor upon atmospheric aerosols as the air parcels containing these small particles move upward in the atmosphere (see Fig. 1*A*). In the case of very high clouds (for example, cirrus), the small droplets quickly freeze so that the cloud is composed of very small ice crystals. Since the atmospheric pressure decreases with height, and since the capacity of air for holding water vapor decreases with decreasing temperature, it follows that upward-moving air parcels will undergo adiabatic expansion and cooling, with a consequent increase in relative humidity.

Under most conditions in the lower atmosphere, lifting to the extent of a few thousand feet will bring air to saturation; further lifting and cooling would produce a condition of supersaturation, except for the fact that the atmosphere always contains copious numbers of solid particles which serve as nuclei for inducing the formation of the liquid phase at very low values of supersaturation—of the order of less than 0.5 percent. This remarkable efficiency of atmospheric condensation nuclei is attributable to the fact that many of them are hygroscopic—probably small particles of sea salt and sulfate-bearing compounds. As soon as a sufficient number of these nuclei have been activated to absorb the water vapor as fast as it is made available by the rising air parcel, the supersaturation begins to wane, and no additional nuclei are activated.

The mechanism of droplet growth is largely Fickian diffusion of vapor toward the droplet in response to a difference in vapor pressure between the droplet and its environment. It is the nature of such growth that the rate of change of size of a growing droplet is inversely proportional to its radius. Therefore, other things being equal, the small droplets grow faster than the large ones, and the entire system tends to reach a uniform or "average" size. Thus, in a cloud which is not developing precipitation, the number of droplets per cubic centimeter is determined by (i) the speed of the updraft, which fixes the rate at which water is made available to the cloud, and (ii) the amount and nature of the particulates within the air, or, in other words, the relative numbers of "favorable" and "unfavorable" nuclei. The average final size is determined by the amount of lifting (condensation) following the initial activation (for this determines the mass of water condensed per unit volume in the updraft), by the number of droplets upon which the condensation occurs, and, to a minor extent, by the age of the individual cloud parcels.

Since upward motions within the atmosphere vary by orders of magnitude from one meteorological situation to another, and even from one cloud to another on a given day, and since the amount and nature of atmospheric particulates vary considerably, depending upon the previous history of the air, it is natural to expect considerable variation in the cloud-droplet spectra within various clouds. This is exactly what is found (*1*). A typical distribution curve for cloud droplets is shown in Fig. 2. In general, nonprecipitating convective clouds are characterized by large numbers of fairly small droplets, the breadth of the distribution depending upon cloud size.

The data for nonprecipitating stratus clouds are rather scarce, except for a series of measurements by Diem (*2*). Such clouds appear to be characterized by relatively fewer droplets of a wide size range.

Formation of Rain through Ice Crystals

The only essential difference between a cloud droplet and a raindrop is one of size. Whereas cloud droplets range in radius up to 20 or 30 microns, raindrops are of the order of a few millimeters in

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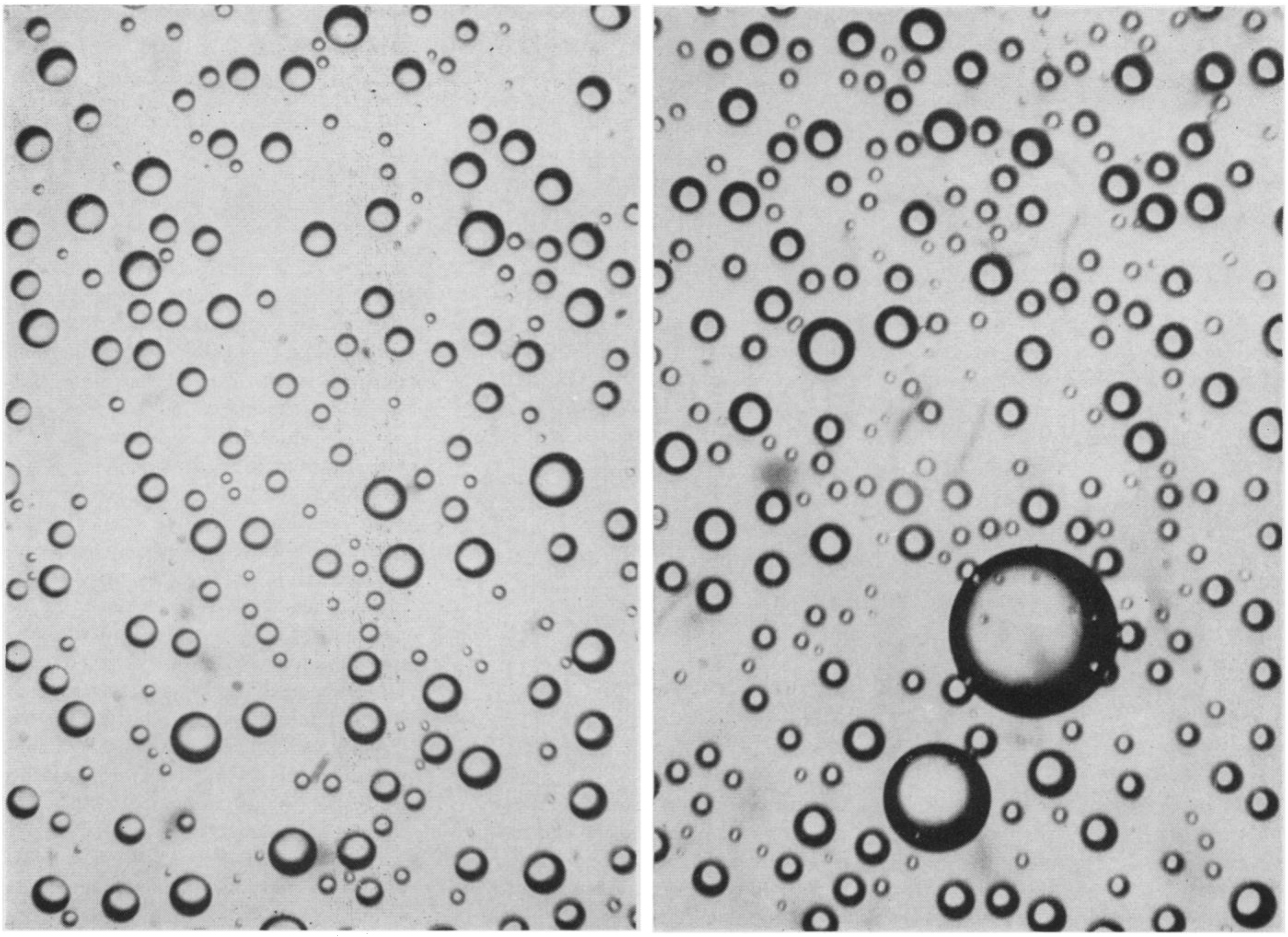

Fig. 1A (left). Typical microphotograph of cloud droplets collected in a nonprecipitating cloud. Fig. 1B (right). Microphotograph of two incipient precipitation particles in a collection of cloud droplets. Cloud droplets in actual clouds are not as close together as is suggested by these photographs. These droplets were obtained by exposing oil-coated slides to the slipstream as an airplane flew through the clouds.

radius. In mass, an average raindrop is about 10^6 times as large as an average cloud droplet. In the early 1930's it was thought that raindrops resulted from continued condensation upon cloud droplets until they were large enough to fall as rain. Now we know that this is not the case. Somehow nature selects only a very few of the droplets for continued growth. Occasionally the cloud physicist, sampling a nonprecipitating cloud, is fortunate enough to find one of these favored droplets. An example of such a droplet is shown in Fig. 1*B*. Aside from the two large droplets, this droplet system is remarkedly similar to that in Fig. 1*A*. We must now tackle the problem of why a particular droplet is favored for growth over thousands of others.

This problem, concerned with the overcoming of the colloid-like stability of natural clouds, has long been recognized as one of great importance. In 1911, the German chemist Wegener called attention to the fact that the saturation vapor pressure over ice was less than that over a subcooled liquid water surface at the same temperature (*3*). Because of this difference, small ice crystals in the presence of subcooled water droplets will grow at the expense of the droplets, the droplets evaporating as the crystals grow by sublimation. In 1933, Bergeron, a Swedish meteorologist, noted that subcooled water clouds were very common in nature and, aware of the inherent stability of a condensing system of water droplets, suggested that all rain had its origin in the melting of snowflakes (*4*). This idea, further developed by the German meteorologist Findeisen, has since become known as the Bergeron-Findeisen, or ice-crystal, theory of precipitation formation.

According to this theory, the atmosphere contains a limited number of special particles which are capable of inducing the nucleation of ice directly from the vapor by means of sublimation. These particles are called "sublimation nuclei." It was supposed that no significant amounts of rain could fall from a cloud until the top of the cloud reached a level where these nuclei could become effective. Once ice crystals were formed within a subcooled cloud, they would continue to grow because their environment, saturated with respect to water, would be supersaturated with respect to ice. It was thought that the end product of this process would be a group of snow flakes which would melt as they fell through the "freezing" level and continue to the ground as rain. In the event that temperatures at the ground were below freezing, the particles would arrive as snow instead of rain.

Ice Nuclei

Although subsequent research has shown that ice crystals are not the only route of precipitation formation, the importance of ice and snow as weather phenomena has prompted a moderate amount of inquiry into the number and nature of ice-forming nuclei, the manner in which they work, and the structure of the ice particles which grow from them. Additional work along these lines is sorely needed.

Apparently there are two kinds of ice nuclei in the atmosphere—those which induce freezing of the liquid phase and those which induce the direct formation of crystals from vapor. Thus far researchers have not devised a suitable method for distinguishing between them, and it is customary to consider them collectively as ice nuclei. Measurements of natural ice nuclei are usually made by cooling a known volume of air, introducing water vapor to form a cloud, and counting the number of ice crystals which appear at various subfreezing temperatures. These measurements show that nuclei effective at temperatures higher than about $-10°C$ are scarce, rarely exceeding 10 per cubic meter. The number of effective nuclei increases with decreasing temperature, reaching values of about 10^4 per cubic meter at $-25°C$. Some investigators find a marked increase in the number of nuclei as the air temperature falls below $-25°C$ and attribute this to the fact that the threshold temperatures of many kinds of terrestrial dusts, presumed to be important in the formation of ice, are in this temperature range (*5*).

As a consequence of the scarcity of effective ice nuclei, clouds reaching upward beyond the freezing level undergo extensive undercooling. In general, however, measurements made inside clouds reveal more snow than would be expected from the laboratory counts of ice nuclei. Whether this is due to poor counting techniques or to some unidentified process operating within the clouds is not clearly known.

Laboratory studies show that the mean freezing temperatures of water droplets are related directly to the size of the droplets (*6*). In the mean, a raindrop of 1-millimeter radius will freeze at a temperature of about $-15°C$, whereas small cloud droplets freeze at much lower temperatures—for example, a droplet of 5-micron radius, on the average, will freeze at about $-35°C$. The freezing temperature apparently depends upon the droplet volume—the larger the droplet the greater the probability that it will contain one of the few nuclei effective at a comparatively warm temperature.

The homogeneous freezing temperature for water is approximately $-40°C$. When a cloud rises to heights where these temperatures prevail, or whenever a cloud first forms at these temperatures, the droplets quickly freeze. Such clouds are known as cirrus and probably are very important sources of ice nuclei for atmospheric precipitation processes.

The role of the occasional droplet which freezes at a warm temperature (from $-10°$ to $-20°C$) is not understood, but in all probability it is an important one. Research now under way at the University of Chicago suggests that such particles form the first few large particles for precipitation growth in convective clouds. It is thought that the differences between nuclei counts and flight observations of snow may be reconciled on the basis of this hypothesis.

Unexplainable Observations

From the time of the meetings of The International Union of Geodesy and Geophysics in Lisbon in 1933, at which Bergeron presented his paper, until the early years of World War II, the ice-crystal theory of rain production remained unchallenged. It was commonly observed that cloud tops usually extended well above the 0°C isotherm before rain was observed at the cloud bases. Unfortunately, knowledge about nucleation and crystal growth was inadequate to test the theory in terms of the amount of time required, and the character of the clouds necessary, for the production of rain by this mechanism. Textbook authors and scientists of the period apparently were convinced that the question of rain production was largely settled. Unfortunately, nature didn't read the textbooks.

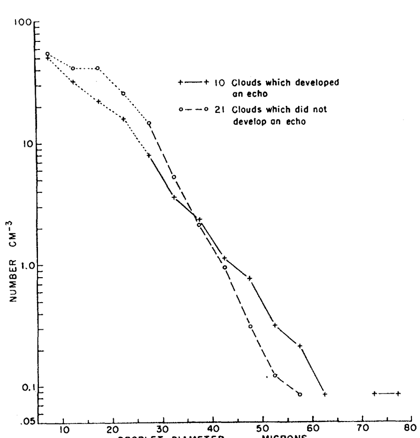

Fig. 2. Typical cloud droplet size distribution. This particular distribution represents collection made in rapidly building cumulus clouds. Note that clouds which precipitate (develop radar echoes) contain slightly fewer small droplets and slightly more large droplets than the nonprecipitation clouds.

During the war years, weather observers were sent throughout the world in a stepped-up program of weather observing. For the first time there was a vast increase in the number of trained weather observers, and large numbers of airplanes were available to carry the observers in, around, and over the clouds. From the tropical regions came reports that rain was occasionally observed from clouds whose tops were wholly warmer than freezing—in other words, in clouds where it was impossible for ice nuclei to have formed.

At the same time, important developments were taking place in another area. Early in the war the engineers developing radar for the detection of ships, and planes were disturbed to find that, under certain conditions, clouds would return significant amounts of radar energy—in fact, radars at the shorter wavelengths were largely useless for surveillance purposes because of weather return. Troublesome as this was for the radar designers, it proved to be fortunate indeed for the meteorologist. For the first time it was possible to examine the interior of a cloud without the necessity of flying into it. Immediately following the war, the Thunderstorm Project was organized by the U.S. Weather Bureau, the Air Force, the Navy, and the National Advisory Committee for Aeronautics, with Horace Byers (University of Chicago) as its director (*7*). Radar studies on convective clouds, carried out by that project in 1946 and 1947, proved conclusively that many clouds develop rain without the involvement of ice crystals. Extensive subsequent research has now demonstrated that rain from "warm" clouds is very common, particularly in the tropical regions (*8*).

Project Cirrus

Another postwar event of major importance in meteorology took place in the Schenectady laboratories of the General Electric Company. There Irving Langmuir and Vincent Schaefer were engaged in military research concerning the effects of weather phenomena on aircraft flight. This work led inevitably to studies of cloud formation and of ice-crystal formation in the atmosphere. There, in November 1946, Schaefer performed the first experiments designed to test the Bergeron-Findeisen theory of precipitation. It was shown that subcooled clouds could be turned into systems of small ice crystals, either by reducing the temperature below $-40°C$ or through the introduction of suitable ice nuclei. Schaefer showed beyond a shadow of doubt that subcooled stratus clouds could be caused to snow-out through seeding with Dry Ice. The Dry Ice caused the formation of many ice crystals by virtue of cooling some of the air to below $-40°C$. In the same laboratory, Vonnegut found silver iodide smokes to be very effective as sublimation nuclei at temperatures as high as $-4°C$.

Thus, within the space of a single year, it had been shown that the ice-crystal mechanism was capable of creating precipitation in subcooled clouds, while at the same time it was found that precipitation in some natural clouds occurred under circumstances such as to preclude the involvement of ice.

Rain without Ice Crystals

Just as some of the atmospheric dust particles have special properties that cause the formation of ice crystals, others of them are hygroscopic. These are called "giant condensation nuclei." Because of their large sizes they behave differently from the other hygroscopic nuclei in two important ways: (i) Because of their larger mass, their ultimate size as solution droplets in vapor-pressure equilibrium with their environment will be much larger than that of the other, smaller, condensation nuclei; and (ii) the rate at which they approach their equilibrium size is much slower than that of the smaller nuclei. Measurements of atmospheric nuclei and calculations based upon these measurements suggest that the nuclei which account for the overwhelming majority of cloud droplets have masses of the order of 10^{-13} to 10^{-17} moles, if they are composed of NaCl. These correspond to dry sizes (for masses assumed to be spherical) of the order of 0.8- to 0.04-micron radius. A series of computations by Howell (*9*) showed that these particles would grow into cloud droplets of sizes up to about 10-micron radius after 1000 seconds and that thereafter growth of the droplets would tend to stabilize, the final radius being between 10 and 15 microns. The exact final sizes depend upon initial conditions and the updraft speed.

Atmospheric particulate counts made since the time of Howell's work, however, show that the atmosphere contains a limited number of hygroscopic particles ranging in size up to 10 microns in radius (dry size). Extensive measurements reported by Lodge (*10*) and by Byers, Sievers, and Tufts (*11*) show that air over the Caribbean and over the humid eastern part of the United States may contain up to 10^3 chloride particles of greater than 5-micron radius (dry size) per cubic meter. Similarly, large numbers of giant sulfate particles are found in the same regions. The exact size to which a NaCl particle of 5-micron radius will grow in 1000 seconds, if it is rising in an air parcel with an average number of the smaller aerosols, is unknown, although approximate calculations suggest a size of about 25-micron radius. However, the drops formed upon the large nuclei will continue to grow by condensation, reaching appreciably larger sizes after the other droplets have stopped growing. (At 99.99 percent relative humidity, the equilibrium radius for this droplet would be about 50 microns; however, over 5000 seconds would be required for growth to this size through condensation alone.) Thus, in air containing natural hygroscopic aerosols in a wide range of sizes, there is a built-in mechanism whereby, given sufficient time, the cloud-droplet distribution can be broadened sufficiently to overcome the colloidal stability of the droplet system.

Growth by Collision and Coalescence

As we now understand the physics of clouds, there are two ways in which incipient precipitation particles can be formed in cloudy air—namely, through the formation of ice crystals on sublimation nuclei and through the formation of solution droplets on giant condensation nuclei. The effect of either of these is to broaden the size spectrum of the cloud particles. Once this has been accomplished, another factor comes into play to permit further growth of the large particles.

The falling speed of particles is a direct function of particle size. Every particle within a cloud is falling relative to its environment. Even the smallest cloud droplet is falling with respect to the air about it. However, the falling speed of cloud particles, droplets, and small crystals is so low that it is more than compensated for by the upward motions of the air within the clouds. However, when some of the particles grow to be significantly larger than the rest, they will fall through the cloud and collide with some of the slower-moving particles. Some of these collisions will be elastic, but a certain fraction of the intercepted droplets will aggregate with the larger particle and cause its further growth. Both the relative approach speed and the collision efficiency increases with increasing differences in size between the collecting and collected particles. Once an incipient precipitation particle reaches a size sufficiently larger than the bulk of the cloud droplets to permit collision with them, its further growth is assured. Only when it falls through the base of the cloud, or when the cloud evaporates from around it (as through mixing with dry outside air), will the growth of the particle be interrupted.

How large must an incipient precipitation particle be before it will grow appreciably through collision and coalescence? Studies made by Houghton and others (*12*) suggest that once a droplet has attained a size of 30 to 50 microns in radius, growth by collision and coalescence will be much faster than growth by condensation. By the time a droplet reaches a radius of 100 microns, growth by coalescence is very rapid and condensation may be entirely neglected.

The ultimate size to which a droplet can grow by coalescence within a cloud

Table 1. Approximate fall distances and times required for growth of drops of initial 25-micron radius in a uniform cloud composed of droplets of 10-micron radius.

Drop radius (μ)	Water content: 1 g/m³		Water content: 3 g/m³	
	Fall distance (ft)	Fall time (min)	Fall distance (ft)	Fall time (min)
25	0	0	0	0
50	500	24	200	8
100 (Drizzle)	1640	40	540	13
250 (Rain)	4400	48	1470	16
500	8300	55	2700	18

depends largely upon the liquid water content of the cloud and the depth of cloud through which the droplet falls. Since the terminal speed and collision efficiency of a droplet are essentially functions only of its size, it is possible to compute the distance through which a droplet of any given size must fall, within a cloud of specified cloud water content, to grow to any larger size. Table 1, adapted from some early work by Langmuir, gives this distance for clouds of water content 1 and 3 grams per cubic meter, respectively. The larger values apply to isolated cores within convective clouds. Stratus clouds average considerably below 1 gram per cubic meter. It is immediately obvious that rain is unlikely to fall from stratified decks of less than about 5000 feet in thickness. Rain can form in convective clouds of much less depth, however, both because of the greater average water content and because the updraft, which is always much stronger in cumulus clouds than in stratus, may hold the growing drop within the cloud for a considerable period of time.

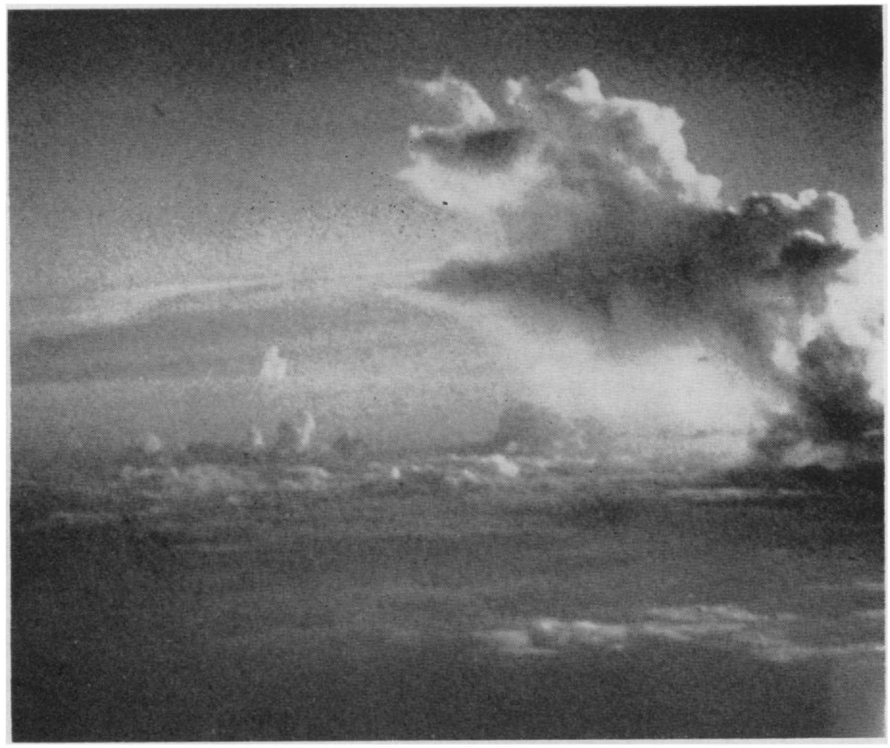

Fig. 3. Small cumulus cloud of the trade-wind region which has developed rain through the all-water mechanism. Temperature of the cloud top, about 10°C. By raining, such a cloud destroys itself.

Collision with smaller particles is also important in the growth of precipitation through the ice-crystal mechanism. Once an ice crystal has reached a size of about 100 microns in radius, its falling speed relative to the cloud droplets will be sufficient to cause it to collide with them. The results of these collisions depend upon several factors, of which the most important are the height at which the collision takes place (and consequent temperature and pressure), the relative sizes of the colliding particles, and the number of collisions per unit time. At temperatures lower than about −10°C to −15°C in typical mid-latitude cumulus clouds, ice particles smaller than about 2 millimeters in radius will be able to dissipate the latent heat of fusion of the colliding droplets, and the ice particle will grow into a snow pellet. Snow pellets are white, opaque agglomerates of frozen droplets and ice crystals, often giving the appearance of a closely packed bunch of grapes. When such a particle falls into lower regions, where the temperature is higher than about −10°C, it will be unable to dissipate the latent heat of fusion of all the intercepted water, and the result will be partial freezing into a clear ice structure, with the excess water streaming off the rear side. Such a particle has been termed a "wet hailstone." The larger the particle initially, and the greater the water content of the cloud, the lower the temperature at which the snow pellet begins to collect clear ice and to become wet. Should a particle, in falling through a large cumulus cloud, find itself in a succession of areas of differing water content, such that it alternately becomes wet and dry, a true hailstone of the concentric-layered type may form.

After falling into regions where the temperature of the cloud droplets is higher than freezing, the colliding droplets will carry heat to the wet snow pellet and hasten its melting.

Snow pellets, both dry and partially melted, reach the ground in mid-latitudes rather frequently in the spring and fall months. They are usually associated with thunderstorms and other convective-cloud weather.

In stratified clouds the common forms of solid precipitation are relatively large single crystals of ice and clusters of small ice crystals, either of which is commonly known as snow. Extensive research by Nakaya and his associates has shown that the crystal form of snow is largely determined by the temperature and degree of supersaturation of the air in which the crystals grow (*13*). The endless variety of detail in crystals apparently is due to the continuous fluctuation of vapor densities in the microvolumes through which they fall.

Clumping of snow crystals into large aggregates occurs only at temperatures between 0°C and −5°C. Research by Hosler and others suggests that ice particles are coated with a liquid film which materially assists adhesion in this temperature range. At temperatures lower than −5°C, very little clumping occurs. However, the maximum rate of growth of individual snowflakes will occur at temperatures of about −15°C, because the difference between saturation over ice and over water reaches a maximum value at approximately this temperature.

Ice Crystals versus Solution Droplets

Following the publication of the Bergeron-Findeisen hypothesis, the theory that all significant amounts of rain involved the prior formation of snowflakes in the subcooled regions of the clouds was accepted. During and immediately after World War II it was found that many clouds, particularly in tropical regions, developed rain long before the tops had grown to heights where ice could have been involved. At the present time several research groups are busily engaged in detailed studies of the microphysics of clouds in an effort to determine the relative importance of these two mechanisms of precipitation development. Far from being a purely academic question, the matter assumes importance in relation to attempts to induce precipitation in clouds which

Fig. 4. Towering cumulus cloud forming over mountains in Arizona. Cloud base, near 5°C; cloud top, near −15°C. In spite of their large size, such clouds seldom contain precipitation. Precipitation first forms when the top of the cloud reaches a temperature of about −20°C. [E. L. Harrington]

would not have precipitated naturally, and in attempts to otherwise modify the behavior of clouds. Studies by the Cloud Physics Laboratory at the University of Chicago have shown that virtually every cumulus cloud in the tropics develops rain by the all-water process (*14*). Most of the cumulus clouds of the trade-wind regions (Fig. 3) produce measurable amounts of rain by virtue of the large hygroscopic particles. Riehl has shown, however, that most of the rain in the tropics occurs in connection with organized convection which extends well above the freezing level. In all probability, these clouds also first develop rain through the all-water process; however, it is also a virtual certainty that these same clouds subsequently develop snow pellets in their upper regions. The fraction of the total rain at the ground that results from the snow pellets is unknown.

Battan has shown that most of the summer thunderstorms in Ohio first develop rain in a manner best explained by the all-water mechanism (*15*). Here again, measurements made from airplanes flown through the storms show that snow pellets are a very common form of precipitation in the upper reaches of these clouds. As yet the data are not adequate for determination of the relative roles of the two mechanisms.

Arizona is the only other region in which extensive measurements have been made of randomly selected cumulus clouds (*16*) (Fig. 4). These measurements show that initial precipitation develops at temperatures lower than 0°C but not so low as to rule out the all-water mechanism. Flight observations in these clouds show that snow pellets are invariably observed about the same time that precipitation echoes first show up on the radars.

The only detailed flight examination of mid-latitude cyclonic disturbances made to date was carried out by Cunningham (*17*). It was his observation, on a limited number of flights in the New England states during the winter months, that most of the precipitation at the ground had its origin in snow aloft.

Summary

On the basis of presently available data, combined with present-day knowledge of the physics and chemistry of cloud particle development, it is possible to make the following generalizations about the mode of precipitation in natural clouds.

1) The all-water mechanism begins to operate as soon as a parcel of cloud air is formed and continues to operate throughout the life of the cloud. The ice-crystal mechanism, on the other hand, can begin to operate only after the top of the cloud has reached levels where ice nuclei can be effective (about −15°C). Some clouds never reach this height; any precipitation from them must be through the all-water mechanism. In cold climates and at high levels in the atmosphere, the cloud bases may be very close to this critical temperature. In the tropics, approximately 25,000 feet separate the bases of low clouds from the natural ice level.

2) The number of large hygroscopic nuclei in maritime air over tropical oceans is entirely adequate to rain-out any cloud with a base below about 10,000 feet, provided the cloud duration and cloud depth is sufficient for the precipitation process to operate. Extensive trajectories over land will decrease the

number of sea-salt particles, both because of sedimentation and removal in rain. Measurements show an order-of-magnitude decrease in the number of large particles as maritime air moves from the Gulf of Mexico to the vicinity of St. Louis, during the summer months. Measurements in Arizona and New Mexico show even smaller chloride concentrations, presumably because of the long overland trajectories required in reaching these areas. The maritime particles lost in overland trajectories apparently are more than replaced by particles of land origin. The latter are usually of mixed composition and are less favorable for the formation of outsized solution droplets.

3) Ice nuclei, required for the formation of ice crystals and for droplet freezing, are rather rare at temperatures higher than about $-10°C$. This, of course, accounts for the fact that natural clouds undergo extensive undercooling. Because of the scarcity of suitable nuclei, precipitation through the ice phase usually is not found in clouds warmer than about $-15°$ to $-20°C$. Natural cirrus clouds might provide ice nuclei for precipitation at somewhat higher temperatures, but this possibility has not been extensively studied.

4) Precipitation in tropical clouds invariably first develops through the all-water mechanism; points discussed in paragraphs 1, 2, and 3 above all work toward this end. Tropical clouds which reach to heights above about 25,000 feet also develop precipitation through snow pellets.

The data for mid-latitude clouds are conflicting. Some measurements suggest that summer clouds in the central United States and in the semiarid Southwest develop rain largely through the all-water process; existing theories support such a suggestion. However, flight measurements indicate that there is considerably more ice and snow in the clouds than can be accounted for by present theory; as a consequence, one must be careful in ruling out the ice mechanism in these areas. It appears to me, however, that the ice particles in these clouds are best accounted for through the hypothesis of freezing of drops which have grown to fairly large size through diffusion of vapor. Thus, the ice would be only incidental to the precipitation development.

Winter clouds in the central United States and almost all of the clouds of northern United States and Canada appear to precipitate largely through the ice-crystal mechanism. The relatively cold cloud bases and the continental sources of air masses in these regions appear to retard the warm-rain mechanism to the point where the ice mechanism dominates. But here again, a great deal of research must be completed before a firm conclusion can be drawn (*18*).

References and Notes

1. L. J. Battan and C. H. Reitan, "Droplet-size measurements in convective clouds," in *Artificial Stimulation of Rain* (Pergamon, New York, 1957), pp. 184–191; B. J. Mason, *The Physics of Clouds* (Oxford Univ. Press, New York, 1957).
2. M. Diem, *Meteorol. Rundschau* 1, 261 (1948).
3. A. Wegener, *Thermodynamik der Atmosphare* (Barth, Leipzig, 1911).
4. T. Bergeron, "On the physics of clouds and precipitation," *Proc. Intern. Union of Geodesy and Geophys. 5th Assembly, Lisbon* (1935), pt. 2, pp. 156–178.
5. V. Schaefer, "The Occurrence of Ice-Crystal Nuclei in the Free Atmosphere," *Project Cirrus, Gen. Elec. Co. Occasional Rept. No. 20* (1950).
6. E. K. Bigg, *Proc. Phys. Soc. (London)* 66B, 688 (1953).
7. H. R. Byers and R. R. Braham, Jr., *The Thunderstorm* (Government Printing Office, Washington, D.C., 1949).
8. H. R. Byers and R. K. Hall, *J. Meteorol.* 12, 176 (1955).
9. W. E. Howell, *ibid.* 6, 134 (1949).
10. J. P. Lodge, *ibid.* 12, 493 (1955).
11. H. R. Byers, J. R. Sievers, B. J. Tufts, "Distribution in the atmosphere of certain particles capable of serving as condensation nuclei," in *Artificial Stimulation of Rain* (Pergamon, New York, 1957), pp. 47–72.
12. H. G. Houghton, *J. Meteorol.* 7, 363 (1950).
13. U. Nakaya, *Snow Crystals* (Harvard Univ. Press, Cambridge, 1954).
14. R. R. Braham, Jr., *Geofis. pura e appl.* 35, 126 (1956).
15. L. J. Battan, *J. Meteorol.* 10, 311 (1953).
16. R. R. Braham, Jr., *ibid.* 15, 75 (1958).
17. R. M. Cunningham, "The Distribution and Growth of Hydrometeors around a Deep Cyclone," *Mass. Inst. Technol. Weather Radar Tech. Rept. No. 18* (1952).

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Science and Public Policy

Recent actions by the Federal Government in helping science and technology help the nation are surveyed.

James R. Killian, Jr.

Those of you who planned this joint meeting of Phi Beta Kappa–Sigma Xi had a happy inspiration. You reduced the number of scheduled annual speeches by one—an act of the purest sort of humanism not easily come by—and you exemplified Laertes' observation that "a double blessing is a double grace." By joining forces tonight you doubly bless the theme of this AAAS meeting and endow with grace your proclamation that man and his world are one and that science and humanism are complementary, each dependent upon the other.

You also have placed the speaker you didn't cancel in a position of double responsibility, if not double jeopardy. That I had the temerity to accept your invitation bespeaks my sense of privilege in speaking on this occasion.

To relate my remarks to the theme of this AAAS meeting, I wish to discuss some of the ways in which the affairs of men and the affairs of science interact in the area of public policy-making. This is a subject very much in vogue today. It is a topic of conferences, and universities appropriately are beginning to establish special programs dealing with science and public policy. My approach, however, is not academic; I come to you fresh from the firing line, where I have been engaged day in and day out in marshaling scientific advice for the Federal Government. I report to you on this experience—on the work of the Office of the Special Assistant to the President for Science and Technology and of the President's Science Advisory Committee. Until November a year ago, this office never existed in its present form in the

Dr. Killian is Special Assistant to the President for Science and Technology. This article is adapted from an address delivered 30 Dec. 1958 before the 125th annual meeting of the American Association for the Advancement of Science, in Washington, D.C.