What does the regularity which such changes often show imply concerning historical determinism as opposed to human liberty?

If it is the wise archeologist who now restricts his formulations to the development and persistence of civilizations, cultures, technologies, arts, and lesser matters, it must also be the very dull archeologist who could be unconcerned with the implications of these for some of the perennial problems of Western man.

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CURRENT PROBLEMS IN RESEARCH

Cloud Physics

Not all questions about nucleation, growth, and precipitation of water particles are yet answered.

Henry G. Houghton

Cloud physics is concerned with the condensation and precipitation processes of the atmosphere. In scale, the phenomena studied range from the nucleation of the more ordered phases of water substance and the growth of particles by water-vapor diffusion to the dynamics of the atmospheric processes that lead to the formation of clouds. Although not a new field, cloud physics was given a substantial stimulus in 1946 by the discovery, by Langmuir and Schaefer, of means for the artificial nucleation of ice in supercooled water clouds. In a short article it is not possible to cover all aspects of what has become an active field of research. An effort will be made to point up some of the more recent developments and certain of the intriguing but as yet unanswered questions. The subject of the artificial stimulation of rainfall will be touched on only incidentally, because an adequate treatment of this still-controversial topic would require an article in itself.

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Homogeneous Nucleation

A central problem of cloud physics is the nucleation of a new phase—of water from water vapor or of ice from the liquid or the vapor. The theory of homogeneous nucleation in which the new phase appears without the intervention of any foreign substance has been developed by Volmer and Weber (*1*) and has been expanded upon by others. According to this theory, the appearance of an embryo of, say, water from the vapor is considered to result from the chance aggregation of molecules. If the surface free energy of the embryo is less than the energy released when the molecules aggregate (latent heat), the embryo will persist and become a nucleus; otherwise it will be disrupted into its molecules. The rate of increase of the surface energy is proportional to the radius, while the rate of release of latent energy is proportional to the square of the radius. Hence, there is a critical radius above which the embryo will persist, and this is given by an equation developed by Kelvin (*2*).

$$r_c = \frac{2M\sigma}{\rho RT \ln p/p_\infty}$$

where r_c is the critical radius, M is the molecular weight of the liquid, σ is the specific surface energy of the interface, ρ is the density of the liquid, R is the universal gas constant, p is the pressure of the vapor, and p_∞ is the equilibrium vapor pressure over a plane surface at the absolute temperature T. Thus, homogeneous nucleation is a probabilistic phenomenon and may be said to occur when the probability of the chance aggregation of molecular aggregates large enough to persist becomes arbitrarily large. From Kelvin's equation and the statistics of molecular aggregation, it is possible, in principle, to predict the conditions under which homogeneous nucleation will occur. Unfortunately, inadequate knowledge of certain physical constants, notably the specific surface free energy of molecular aggregates, to which the equation is very sensitive, preclude definitive quantitative answers. Theory plus experiment suggest that the homogeneous nucleation of the liquid from the vapor occurs only at six- to eightfold supersaturations and that the homogeneous nucleation of ice from the liquid takes place at about −40°C. It appears that it is energetically easier for ice to be nucleated from the vapor via

the liquid phase than directly from the vapor.

From direct observation it is known that condensation occurs in the atmosphere at extremely small supersaturations, and hence it does not seem that homogeneous nucleation of the liquid is involved in the natural condensation process. However, supercooled clouds are occasionally observed at temperatures close to $-40°C$; this and other evidence suggests that the homogeneous nucleation of ice is a factor in the atmosphere. It is of interest here to note that the pellets of solid CO_2 used for cloud seeding apparently form ice seeds by the homogeneous nucleation of the liquid from the vapor, followed by the homogeneous nucleation of ice in these liquid droplets. In this way a pellet of dry ice 1 cm in diameter may lead to the formation of on the order of 10^{12} ice crystals.

Condensation on Foreign Nuclei

Nucleation of a new phase of water in the atmosphere occurs more commonly on foreign nuclei. The nuclei of condensation have been studied for many years, since the pioneering work of Aitken (*3*) and of Wilson (*4*). In accordance with the scheme of Junge (*5*), condensation nuclei may be classed in order of increasing size as Aitken nuclei, large nuclei, and giant nuclei. Aitken nuclei have radii of between 5×10^{-7} and 2×10^{-5} cm and are probably formed by condensation or by chemical reactions from gaseous substances. The concentration of Aitken nuclei varies from about 100 per cubic centimeter over the oceans to as many as several million per cubic centimeter in strongly polluted air. Their composition is not known, but it is suspected that many are hygroscopic products of combustion.

A large fraction of the Aitken nuclei carry an elementary electric charge, presumably as a result of collisions with small ions. Ions act as condensation nuclei only at about fourfold supersaturations, and hence the electric charge on the Aitken nuclei is of minor importance in the condensation process.

Large nuclei have radii ranging from 2×10^{-5} to 10^{-4} cm. According to Junge (*6*), the soluble component of large nuclei is principally ammonium sulphate. Many of the large nuclei consist of insoluble material coated with this hygroscopic salt. The concentration of large nuclei is of the order of from tens to hundreds per cubic centimeter. The giant nuclei are believed to be composed of sea salts, and their concentration may reach 10 per cubic centimeter near the surface of the sea. Their concentration in continental areas is much smaller near the surface but appears to increase with elevation, as compared with a decrease with height over the sea such that the concentrations over land and sea are much the same at a height of a few kilometers.

The mechanism by which ocean salts are introduced into the atmosphere has been the subject of recent research. Earlier it had been thought that spray from breaking waves was the only source of atmospheric salt particles, but it was difficult to reconcile the apparent worldwide rate of production with the restricted areas of the ocean covered by breaking waves at any one time. Recent studies by Woodcock, Blanchard *et al.* (*7*) and by Moore and Mason (*8*) have shown that the bursting of bubbles at the sea surface is an effective means for the injection of drops of sea water into the air.

Droplets are formed in two ways when a bubble bursts; the upper water film shatters into drops and is followed by a vertically ejected jet, which breaks into larger drops. For bubbles a few millimeters in diameter, the drops from the jet are so large that they fall back to the surface, and only those formed by the rupture of the film remain air-borne. The drops formed from the jets of much smaller bubbles are, however, small enough and numerous enough to be an important source of salt particles. Large bubbles are probably produced mainly by breaking waves. A very much larger number of small bubbles form not only in breaking waves but, as shown by Blanchard, also from the air carried into the oceans by precipitation particles and perhaps in other ways. There is also preliminary evidence that electric charge separation occurs during the bubble-bursting phenomenon. Although the concentration of salt nuclei in the atmosphere is relatively small, these giant nuclei may be of dominant importance in the formation of rain in certain types of clouds.

The size, composition, and concentration of condensation nuclei is only one aspect of the much larger and little-studied subject of atmospheric chemistry. There are many types of particulate matter in the atmosphere that do not usually serve as condensation nuclei, and there are many gaseous components. The equilibrium between the various gaseous, liquid, and solid substances would form the basis for many interesting studies. There is evidence of numerous photochemical reactions in the lower atmosphere. Natural rainfall brings many of these air-borne chemicals to the surface. A simple computation reveals that a square kilometer of the earth may receive on the order of 10 metric tons of soluble substances in the course of a year. Thus, there may be considerable truth in the old saying that snow is the poor man's fertilizer.

The number of nuclei that actively participate in natural condensation is often a small fraction of the total. The largest and most hygroscopic nuclei are activated first, and the total number participating depends primarily on the rate of cooling of the air at the condensation level and thus, in the case of clouds, largely on the updraft velocity. Typically, all of the giant nuclei and most of the large nuclei but few of the Aitken nuclei will be involved. In cumulus clouds the droplet concentration is of the order of a few hundred per cubic centimeter of air, while fogs, in which the condensation rate is much slower, have only a few tens of drops per cubic centimeter. Once the cloud drops are formed they grow by the diffusion of water vapor at supersaturations that rarely exceed a few tenths of 1 percent. The limit to the size they attain is set by the water vapor available for condensation, and, because of the large concentration of drops, they rarely grow by condensation to have a radius much in excess of 5×10^{-3} cm.

The range of drop sizes present in a small volume of cloud has an important bearing on the release of precipitation by one of the processes discussed below. The initial range of sizes is determined in part by the size range of the nuclei, but the condensation process tends to narrow the size range (when measured in terms of drop radii). The observed size range of drops in a small volume of cloud is often markedly greater than would be predicted if the drops grew by condensation under uniform conditions. It has been suggested that the initial rate of condensation will be different in different regions of the cloud and that subsequent turbulent mixing will bring drops of varied history into a given cloud volume. It is also probable that collisions between droplets help to broaden the size distribution. The expansion of moist air in a laboratory cloud chamber leads to the formation of drops of much more uniform size than is typi-

cal of natural clouds; this supports the idea that the broadening is a result of larger-scale processes. Further clarification of this matter is certainly needed.

The Ice Phase

Attention has been centered on the nucleation of the ice phase in the atmosphere since 1935, when Bergeron (*9*) proposed his now-classical theory of the formation of precipitation through the appearance of ice crystals in a cloud of supercooled water drops. By virtue of the lower equilibrium vapor pressure over ice than over water at temperatures below 0°C, the ice crystals grow rapidly by vapor diffusion at the ultimate expense of the liquid cloud drops. Subsequent observational and theoretical studies have established the importance of this mechanism. The crucial question is how and under what conditions the ice crystals appear in the supercooled cloud. As already noted, it seems that the homogeneous nucleation of ice in water occurs at a temperature of about −40°C. Observation reveals that ice crystals actually appear in most cases at temperatures from about −10° to −25°C. Further, the operation of the ice-crystal precipitation mechanism demands that the concentration of ice crystals be small compared to that of the cloud drops so that the ice crystals can grow large enough to fall as precipitation; homogeneous nucleation would tend to convert the water cloud to an ice cloud of the same particle size and concentration. It is clear that some type of heterogeneous nucleation (involving foreign nuclei) is operative.

Wegener (*10*) postulated the presence of sublimation nuclei, by analogy with condensation nuclei, which would promote the formation of ice directly from the vapor. This concept seemed to explain the observations and was widely accepted. It was speculated that natural sublimation nuclei were composed of substances having a crystalline structure similar to that of ice. Subsequently a number of laboratory investigations have been carried out with the purpose of studying the way in which ice is nucleated. A number of different approaches have been used. These have included small expansion chambers of the Wilson type, in which rapid but controlled expansions can be produced; larger chambers in which the expansion rate is slower; diffusion cloud chambers; static cold chambers in which supercooled clouds are formed; and chilled surfaces arranged so that the temperature and vapor pressure may be carefully controlled over extended periods. The results, although somewhat varied, show that in the great majority of cases ice crystals appear only when water saturation is attained. In only a few instances have ice crystals been observed when the vapor pressure is below water saturation but is supersaturated with respect to ice. These results have been interpreted as showing that the ice phase is attained only through the liquid phase. The occasional appearance of ice below water saturation is attributed to condensation on hygroscopic mixed nuclei or on microporous nuclei below water saturation. These conclusions are supported by the knowledge that the interfacial free energy between a solid particle and supercooled water is less than that at the solid-vapor interface. The nuclei responsible for the appearance of ice particles are properly called freezing nuclei if they nucleate ice from the liquid. Because of uncertainties about the process involved, some meteorologists prefer to use the term *ice-forming nuclei* or simply *ice nuclei.*

The concentration of ice particles that appear in natural surface air increases rapidly as the temperature is decreased. Typically, one crystal per cubic meter (about the limit of detectability) may appear at temperatures of from −10° to −15°C. At about −20°C there may be ten crystals per liter, and at −30°C a very large number, approaching 1000 per cubic centimeter, may be observed. At any given temperature the concentration of ice crystals is found to vary by several orders of magnitude from one day to another. Computations of the rate at which ice crystals must form to explain the observed precipitation rates lead to a requirement for concentrations of the order of 100 per liter. This would appear to require temperatures of the order of −20° to −25°C, but observations show that snow often forms at much higher temperatures. It has been suggested that ice crystals may provide additional seed crystals by shedding tiny splinters as they fall. Such a process has been demonstrated in the laboratory, though it is difficult to imagine that the more solid forms of snow crystals, such as unbranched plates and columns, could participate in this process.

The cloud chamber experiments discussed above do not reveal the nature of the natural ice nuclei but only the temperatures and vapor pressures at which the cloud chambers nucleate ice. Because of the minute size of the nuclei, their composition has been studied principally by adding nuclei of known composition to cloud chambers or to purified water drops. Much of this work was stimulated by the discovery by Vonnegut (*11*) that silver iodide crystals were effective as ice nuclei at temperatures lower than about −5°C. Vonnegut chose silver iodide on the basis of the close quantitative agreement between the crystal lattice dimensions of silver iodide and of ice. Subsequently the activity of a large number of chemicals, natural soils, and dusts has been studied.

The results have been diverse and often confusing. Most investigators agree on the activity of AgI, PbI_2, $HgCl_2$, CuS, CuI, and I_2. It also seems clear that many clay (silicate) minerals are effective as ice nuclei. A wide variety of other substances, some soluble in water, have been reported to be effective by some investigators and ineffective by others. It is suspected that some of the disagreement has resulted from contamination of the materials, either as obtained or during the experiments. Bigg (*12*) found that the freezing temperature of water drops was raised by the addition of small amounts of HI, in distinction to the depression of the freezing point caused by most soluble inorganic substances. Isono (*13*) has suggested that the ice-nucleating effect of $AgNO_3$ or of other soluble substances is due to the salt acting first as a condensation nucleus, followed by freezing after condensation has led to the appropriate dilution. The insoluble ice nuclei, such as AgI, PbI_2, CuS, and kaolinite, have lattice parameters that are reasonably close to those of ice. It has been postulated that ice crystals may form on such host crystals by oriented overgrowth, sometimes called epitaxy. It is expected that continuing research will confirm this mechanism.

Current knowledge thus suggests that there may be three distinguishable types of ice nuclei. These are the insoluble crystalline substances on which ice may form by oriented overgrowth, certain soluble substances which act in an unknown way in the liquid at suitable concentrations, and insoluble particles that act when immersed in the liquid. Of the substances studied in the laboratory, the clay minerals are most likely to be present in the atmosphere in suitable concentrations. This has been partly confirmed by Kumai (*14*) and by Isono (*15*), who used the electron microscope

and electron diffraction to identify the nuclei of natural snow crystals. The great majority contained soil particles, and Isono was able to identify 15 of 20 as clay particles. Mason and Maybank (*16*) have found nine natural silicates and a number of other minerals active as ice nuclei at temperatures between −5° and −17°C. They also found that about half of these substances became active at significantly higher temperatures when they had served as nuclei once and the ice had been evaporated at temperatures somewhat below 0°C. This preactivation may serve to explain the formation of ice crystals in the atmosphere at temperatures higher than the initial activation temperatures of natural particles.

Bowen (*17*) claims to have shown that there are certain calendar dates on which the total rainfall over a long period of years and in all parts of the world is significantly greater than on adjacent dates. He ascribes this to ice nuclei injected during meteoric showers and arriving in the lower atmosphere about 30 days later. Mason and Maybank (*16*) found one sample of powdered stony meteorite that served as ice nuclei at −17°C, but there is still no adequate evidence to support Bowen's interesting hypothesis. One of the most difficult points to explain is the remarkably constant time of 30 ± 1 days for the particles to reach the cloud level from the outer atmosphere.

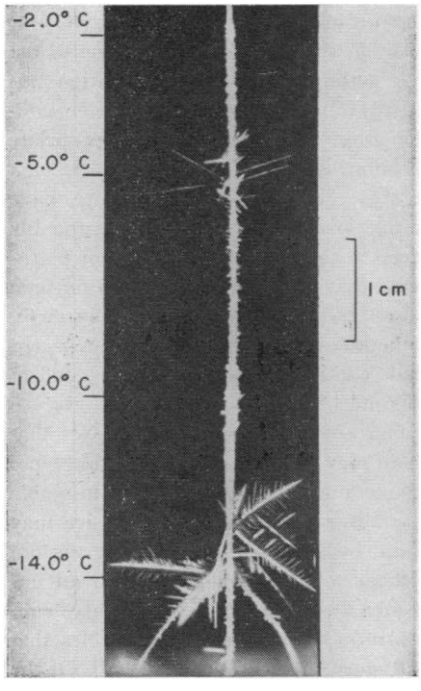

Fig. 1. Ice crystals grown in a diffusion cloud chamber in which the temperature varies with height, as indicated on the scale at left. Note the needles at −5°C and the dendritic crystals at −14°C. [Photograph furnished through the courtesy of B. J. Mason (*18*)]

Growth of Ice Crystals

Once ice is nucleated in the atmosphere it grows by diffusion of the vapor and by the accretion of supercooled cloud drops. The former process leads to the formation of a variety of crystal forms, while the latter tends to produce irregular masses. The beauty and complexity of form of snow crystals has attracted the attention of artists for many years. Ice crystals may be broadly classified into hexagonal plates, stellar crystals, columns, needles, spatial dendrites, capped columns, and irregular particles. Within each classification there exist many varieties, and it has been said that no two crystals are exactly alike. All of these crystals are formed in a temperature range of about 50°C and with vapor pressures between ice and water saturation. No other substance exhibits such a wide variety of crystal forms within such a narrow range of ambient conditions.

Experimentation has made it clear that temperature plays the dominant role in determining the crystal habit, the degree of supersaturation with respect to ice being of secondary importance. As the temperature is reduced, the general habit changes from plate to column to plate to column. Needles are formed in a narrow temperature range around −5°C; dendritic forms, around −15°C. The transition from one form to another is very sharp, one or two degrees often being sufficient to cause a change of form. One is struck by the fact that the precedent form has no effect; plates may be caused to form on the end of needles, or dendrites to sprout from plates, simply by properly changing the temperature. Supersaturation over ice governs the rate of growth, and there are limiting supersaturations below which a particular form will not occur, but even changes of several hundred percent make no major differences in the crystal form. Photographs taken by Mason (*18*) in a diffusion cloud chamber (Figs. 1 and 2) graphically illustrate this remarkable property of ice crystals. On the other hand the presence of traces of organic vapors (even the low vapor pressure of the silicones) produce marked changes in crystal habit. No satisfactory explanation has been found for this great

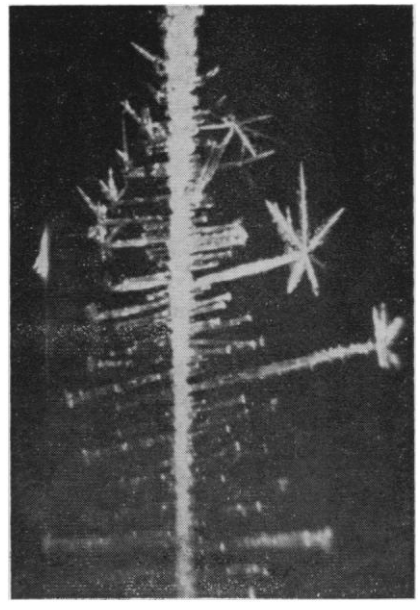

Fig. 2. Needles which were grown at about −5°C in the diffusion cloud chamber developed stellar crystals on their ends when transferred to a temperature of about −15°C. [Photograph furnished through the courtesy of B. J. Mason]

sensitivity of crystal habit to temperature. It is believed that the changes observed must be due to alterations in the surface structure and properties of the crystal faces, but no real clues have yet come to light.

Precipitation Mechanisms

Cloud is the precursor of rain, and it was once thought that raindrops formed through continuation of the process of cloud condensation. It has already been noted above that the limit to the size attained by cloud drops is set by the total vapor available and the concentration of the drops. It is often argued that the limit is set by the time required for growth to raindrop size by condensation, but this overlooks the fact that ice crystals have larger masses than cloud drops because of their lower concentration. In any event the mass of a typical raindrop is about one million times that of an average cloud drop, and it is abundantly clear that processes other than condensation on cloud drops are involved in the formation of rain. Two processes are known which, in combination or separately, seem to be capable of explaining the release of rain and snow from clouds. One of these is the ice-crystal process which is attributed to Bergeron (*9*), although Wegener (*10*) presented the basic idea much earlier.

This process envisages the appearance of a number of ice crystals in a supercooled water cloud either by nucleation or by the intrusion of crystals from a higher level in the atmosphere. The ice crystals will grow at the ultimate expense of the cloud drops, and, if the concentration of the ice crystals is several orders of magnitude smaller than that of the cloud drops, the former may attain a size sufficient to fall as precipitation particles.

The second precipitation mechanism is the accretion or collision process, which was first seriously proposed by Houghton (*19*), although others had previously discussed the possibility and rejected it as contrary to experience. This process is based on the relative velocities of fall and of the consequent collisions to be expected in a cloud of drops of nonuniform size. The ice-crystal process is operative only in supercooled clouds and is most effective at a temperature of about −15°C. The accretion process operates at any temperature, although there are differences depending on whether the particles are liquid or solid. The rate at which precipitation elements can form and grow by accretion depends on the initial range of particle sizes (particularly on the size of the largest drops), on the concentration of drops, and on the sizes of the collecting and collected drops.

It is necessary to examine each precipitation mechanism quantitatively to ascertain that it is capable of forming precipitation particles of commonly observed size under the conditions that obtain in the atmosphere. Ice crystals in a supercooled water cloud grow by diffusion, and the basic equation for this process is well known. The difficulties result from the complex shapes of the ice crystals and from the effect of the fall of the crystals through the atmosphere. Substitution of simple shapes, such as a circular disc or an ellipsoid of revolution, as suggested by Houghton (*20*), gives results that compare favorably with such experimental data as have been obtained. Some empirical data for spheres are available on the effect of the velocity of fall on the growth rate. These are of doubtful applicability to ice crystals, but nothing better is available. It is not likely that computations of growth rates of ice crystals made on the basis of these approximations are in error by more than a factor of two.

The accretion process seems disarmingly simple on first sight. Through

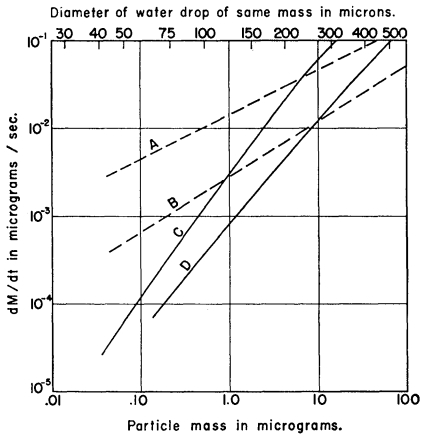

Fig. 3. Rate of growth of precipitation particles by diffusion on ice crystals (dashed lines) and by accretion of liquid drops (solid lines) versus mass of the particle. (*A*) Stellar crystal at water saturation at −15°C; (*B*) hexagonal plate at water saturation at −5°C; (*C, D*) growth by accretion of liquid droplets in two clouds of different observed drop-size distribution.

knowledge of the velocity of fall of the drops and their concentration, the growth rate of the largest drop by collision with the smaller ones is easily computed if it is assumed that all of the drops follow linear, parallel paths. It was soon realized that the aerodynamics of the process would cause the trajectories of the small drops to be diverted from those of the larger drops and that the "catch" would be less than that predicted by the simple linear motions. This problem was solved numerically for all cases in which the small drop could be assumed to be a mass point; such solutions apply when the collecting drop is much larger than the collected drops. The collection efficiencies, defined as the ratio of the actual number of collisions to the number predicted from linear trajectories, were found to range between 0.5 and 0.9 under typical conditions.

When the collected and collecting drops are both small and of about the same size, as would be the initial situation in a cloud, the aerodynamics are more complex, since the changing flow pattern around the pair of drops must be considered. No analytic solution has been obtained, but it is observed that the overtaking drop is diverted towards the wake of the smaller drop, and that this results in collection efficiencies greater than unity. It has also been observed that two small droplets on a collision course usually do not coalesce but only undergo an elastic collision. This behavior, which is poorly understood, is profoundly modified by the presence of a vertically oriented electric field, as shown by Sartor (*21*). This has led to suggestions that the electric field that appears in most pronounced form in a thunderstorm may be an important cause for the release of precipitation, rather than simply an effect. In any event the effect of the electric field and presumably of droplet charge on the coalescence process shows that electrification processes in clouds must be included in any complete study of the precipitation mechanism. Space does not permit a discussion of the current status of knowledge on atmospheric electricity in this article.

In spite of the uncertainties touched on above, it is possible to gain an important insight into natural precipitation processes from the approximate computations that can now be made. Examples of such computations are presented in Fig. 3. This shows the rate of growth of ice crystals by diffusion and of liquid drops by accretion as a function of the mass of the growing particle. When the particles are small, the rate of growth of the ice crystals is much greater than growth by accretion. For larger particles the reverse is true. The two mechanisms are equally effective at a particle mass corresponding roughly to drizzle drops. Clearly, the most efficient precipitation process would be one that started with growth of ice crystals, followed by growth by accretion. As will be seen later, nature often appears to follow just this pattern.

Natural Precipitation Processes

Clouds may be classified into two broad types, which will here be called convective and stratiform. Convective clouds are formed by rising bubbles and columns of warm air; this process results in the various forms of cumulus clouds, from the small fair-weather variety to the thundercloud. Stratiform or layer clouds result from large-scale lifting processes that may extend over several thousand square miles. They are usually associated with the migratory storms or low-pressure areas of middle latitudes. The stratified form reflects the moisture stratification that is almost always found in the atmosphere except when it is violently stirred by penetrative convection. convective clouds that produce precipitation are characteristically of large vertical extent, have a small horizontal cross section, and have a life of the order of an hour. Stratiform

clouds are typically of great horizontal extent, are relatively thin, and have lifetimes of the order of days. One of the most important differences is that the vertical air velocities in convective clouds are of the order of meters per second, while such velocities are only of the order of centimeters per second in stratiform clouds. This is not only a difference of two orders of magnitude; it spans the range of falling speeds of cloud particles and precipitation elements. In convective clouds only the large precipitation particles can fall with respect to the ground; all others will be carried up by the vertical air currents. This means that the precipitation process must start in the lower part of the cloud; otherwise the particles would be discharged from the cloud top before they reached a size sufficient to survive descent outside the cloud. On the other hand the gentle updrafts in the stratiform cloud are barely sufficient to sustain the cloud particles. In this case the precipitation process must begin in the upper part of the cloud or clouds.

Much interest has centered around the question of whether the ice crystal or the accretion mechanism is dominant in convective clouds. In low latitudes there is now ample evidence of rain falling from clouds all parts of which are warmer than 0°C. This shows that the accretion process acting alone can produce rain. It is in these regions over the tropical oceans that sizable numbers of large sea-salt nuclei have been observed, and the large cloud drops formed on them favor the accretion process. In middle latitudes the situation is not so clear. In most cases a convective cloud deep enough to produce rain extends above the 0°C level, thus making the ice phase possible. As noted above, the precipitation process begins in the lower and hence warmer part of the cloud, and ice is not likely to be involved unless the cloud base is very high and cold. This has been largely confirmed by radar observations of the first echo in convective clouds in the Midwest and also over England. In the majority of cases the first echo appears at a level where the temperature is near or above 0°C. It would not be expected that ice would appear at temperatures warmer than −10° to −15°C.

As the growing particles are carried higher, they will freeze, but it is believed that even then they grow mainly by accretion because of the high drop concentrations typical of convective clouds. Accretion under these conditions forms graupel or, in extreme cases, hail. Actually the accretion process is favored by the formation of graupel because its bulk density is much less than unity (0.125 has been measured) and therefore the capture cross section is increased. Thus, the present impression is that the accretion mechanism is the dominant one in convective clouds. That this is not always so is indicated by the appearance of convective snow showers in the winter. This makes it clear that under certain conditions the ice-crystal mechanism can operate in convective clouds.

Many more observations in the free atmosphere will be required to really clarify the details of convective precipitation. A cumulus cloud may appear to be a relatively simple phenomenon, but we have much to learn about its dynamics as well as about the distribution of ice and water particles before we can speak with confidence about the way in which precipitation is released. Radar has proven to be a valuable tool, but there is no substitute for properly instrumented aircraft, and very few have been available for meteorological research.

Substantial amounts of precipitation seldom fall from a single layer of stratiform cloud. There are commonly several layers of cloud separated by cloud-free air. The upper layers are often composed of ice crystals, and there may be both supercooled and warm water clouds at lower levels. It should be emphasized that there is no standard arrangement of such clouds and that, in a single storm, there are marked differences from one region to another. It is believed that the precipitation forms as ice crystals, which grow by the diffusion of water vapor. Growth is enhanced if the crystals fall through a supercooled layer, and they may accrete a number of drops, but not to the extent of forming graupel. If the surface temperature is near or below 0°C, the crystals reach the surface as snow. Individual snow crystals seldom attain a mass greater than that of a drizzle drop. Even casual examination will show that individual crystals seldom reach the ground; instead, the "snow flakes" are commonly aggregates of many individual crystals. This is a type of accretion about which we know very little, but it is clearly of considerable importance. It was thought that such aggregation was most probable near 0°C when it was believed that the crystals must be wet in order to stick. Some recent experiments, by Hosler *et al.* (*22*), with ice spheres has shown that they will stick at temperatures as low as −40°C if the atmosphere is saturated with respect to water and as low as −25°C at ice saturation. The mechanism is not understood, although it has been suggested that there is a film of liquid on the ice surface even at quite low temperatures. Here again is evidence that we need to know much more about the surface properties of ice.

If the temperature at the ground is above 0°C, the snow which is formed aloft will melt and reach the surface as rain. In order to explain raindrops of the observed size, it is necessary to assume that considerable aggregation of the ice crystals occurs before they melt. Often a low, warm cloud is present in which these melted aggregates can grow further by accretion before they reach the ground. The dominant mechanism in stratiform precipitation appears to be the ice-crystal process, but accretion in the form of crystal aggregation or accretional growth in lower warm clouds must be invoked to explain the observed size of the precipitation particles reaching the ground. Convective elements are often imbedded in predominantly stratiform systems. These may appear at relatively high levels, releasing streamers of snow which may grow further at lower levels by some of the processes already mentioned. As in the case of convective precipitation, we possess only a skeleton knowledge of stratiform precipitation processes. Here again radar and instrumented aircraft are the most promising research tools.

Conclusions

One can be quite confident that the ultimate success of methods for the artificial release and control of precipitation will depend on the acquisition of much more complete basic knowledge of the ways in which nature produces rain and snow. Present attempts at rain-making are often uncomfortably close to shooting in the dark. This is not to say that nothing has been learned from or accomplished by these efforts, but simply that the effective control of any mechanism demands much more complete information than is now available on natural precipitation.

It is hoped that this brief article will give the reader some insight into the current knowledge and unsolved problems of cloud physics. The solutions will

require the application of a variety of scientific disciplines, and it is hoped that scientists other than meteorologists will be encouraged to tackle some of the challenging problems. There is need for both laboratory and field research. The tools that have been applied are in many instances inadequate. This applies particularly to the difficult problem of measuring cloud-physics parameters from aircraft. Not only is the subject of cloud physics an interesting scientific study but it bears directly on the increasingly pressing problem of the fresh-water supply of the world.

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Alvin Seale, Naturalist and Ichthyologist

Alvin Seale, adventurer, explorer, field naturalist, ichthyologist and aquarium expert, soldier of fortune, and one of the last of David Starr Jordan's personal disciples, died recently at his home in Corallitos, California, aged 87 years and 20 days.

This Indiana Quaker farm boy rode his bicycle across the country to enter Stanford in 1892. He was an outstanding zoology student and in the usual course of events should have graduated in 1896. But he was an unusual student, and his field trips often caused great gaps in classroom work. In 1896 Jordan selected Seale and Norman B. Scofield to go to the mouth of the Mackenzie River, British America, to see if there were salmon there. This was Seale's first trip to Alaska, Point Barrow, and the Arctic Ocean. His unpublished narrative of this trip is very interesting. Another year he collected sea birds on the Alaskan coast for the British Museum. Then he and his roommate joined the gold rush to the Klondike. His companion "struck it rich," but Seale was too busy studying animals in the wild to bother with panning gold. In his diary he says, "an exciting year."

He went back to Stanford in the fall of 1899, only to leave for Honolulu when appointed field naturalist for the Bishop Museum. In 1900 he made the first zoological survey of Guam, returning via Manila, Hong Kong, China, and Japan. From then until September 1903 he collected all over Polynesia. He explored the Society Islands, the Tuamotu Archipelago, and the Marquesas, Gambier, Austral, Cook, and Samoan islands. He visited, in turn, New Zealand, Australia, the New Hebrides, and the Solomon Islands, returning to Australia several times. These South Sea years were filled with many rare experiences. Just a few of them were related in his privately printed book, *Quest for the Golden Cloak.*

He returned again to Stanford in the fall of 1904 and graduated the following May, 13 years after matriculating. During those 13 years he had come to know more about Polynesia and about its fishes and fisheries than anyone else in the United States and had published a creditable number of important papers.

His next adventure stemmed from his being sent by Jordan to the Texas coast to collect cyprinodonts and carry them to Honolulu to combat the mosquito pest. One of them, *Gambusia patruelis,* was an eager destroyer of mosquito larvae. During the next two decades it was distributed to warm countries all round the globe and was of great help in fighting the mosquito plague.

In 1906 Seale was put in charge of the Anna Alexander Expedition to Alaska. Bears, moose, bighorn sheep, and other mammals were collected for the Alexander Museum of Vertebrate Zoology at the University of California.

In February 1907 President Theodore Roosevelt appointed Alvin Seale fishery expert for the Philippine Government. The next 10 years were spent in this attractive and stimulating position with the Philippine Bureau of Science. Some of the important things accomplished were the following: collecting, studying, and publishing on the little-known fishes of the islands, emphasizing those of economic importance; publishing the first study of the very important bangos fishpond industry; publishing the first study of the valuable pearl and pearl-shell industry, mapping the pearl oyster beds, and drawing up laws to regulate the industry; publishing the first studies of the island sponges, mapping the sponge reefs, and developing a profitable sponge industry; developing a pearl-button industry through studies of shells suitable for the purpose, and drawing up laws to regulate the industry; demonstrating the feasibility of canning the high-quality sardines so plentiful in the Philippines; publishing upon the wealth of other marine shells and developing methods of utilizing them commercially; publishing studies upon sea cucumbers and the trepang industry; publishing upon other marine resources and suggesting how to utilize them; and publishing on the fishes of Hong Kong and of Borneo. Seale brought carp from China and introduced them to the rivers of Mindanao; he brought black bass from the United States and planted them at Baguio, northern Luzon, at an altitude of 5000 feet; he brought mosquito fish from Honolulu to Manila and planted them in various parts of the Philippines;