

AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF AIR POLLUTION ON THE INITIATION OF RAIN

By Ross Gunn and B. B. Phillips

U. S. Weather Bureau

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ABSTRACT

Measurements in a giant expansion chamber show that the size of newly formed cloud droplets depends critically upon the cleanliness of the processed air. Droplets formed in ordinary air are small, but droplets large enough to precipitate are immediately formed by condensation whenever the condensation-nuclei density is sufficiently reduced. The product of mean drop mass and the activated nuclei density approximates the available free water per unit volume. Cloud droplets formed from polluted surface air are usually too small to precipitate, but large droplets formed overhead by condensation in sufficiently clean air may fall through the polluted cloud and initiate rain through association processes. Since the activated nuclei density is normally observed to decrease with increasing altitude, the probability of generating droplets sufficiently large to initiate rain increases as the vertical development of a cloud system increases. The population densities of large cloud droplets normally observed near the tops of precipitating clouds may be explained in terms of an overlying parcel of cooled air that is initially relatively free of nuclei.

Since pollution is swept out of the atmosphere by diffusion onto cloud droplets, and by droplet movement, it is suggested that periods of general cloudiness and precipitation reduce the original nuclei density and permit the subsequently formed droplets to grow still larger, thus increasing the probability of appreciable precipitation. The rain producing cycle is, therefore, equipped with a feed-back or regenerative mechanism which normally proceeds, in a given mass of air, until the air is appreciably desiccated.

Condensation nuclei as well as water vapor normally accumulate simultaneously in fair weather. The presence of nuclei may delay the initiation of precipitation until sufficient vertical instability can be established to lift or cool the relatively clean overlying layers. The precipitation cycle may then be re-established. The investigation shows that rain may be formed directly from the vapor in clean air, without the production of clouds.

1. Introduction

It is now well established that rain may be precipitated from clouds that are everywhere above the freezing temperature. Such rain is known to be formed by larger cloud droplets falling relative to smaller ones and growing at their expense by successive association and capture. Although such a process is quantitatively satisfactory once the precipitation cycle is fully established, there have been serious difficulties in understanding just how the process gets started. A cloud consisting of nearly uniform small droplets is essentially stable and will not precipitate unless it is subject to appreciable electrostatic fields [1]. However, since such electric fields are never produced except by precipitation falling somewhere in the vicinity, the rain-initiating mechanisms in warm clouds have remained obscure. Perhaps most cloud physicists agree that for a cloud to precipitate by the association of the cloud droplets, a basic requirement is that moderately large numbers of droplets of radius 15 to 50 μ be continually generated *well above the base of the cloud* [9]. Droplets of this size are not commonly produced when surface air is cooled. It has been suggested that droplets of large size are produced by the condensation and absorption of water vapor by giant salt nuclei which are

always present in the atmosphere. Salt nuclei doubtless contribute to the initial instability of the cloud, but their known population density is so small (much less than 1 salt particle per cubic centimeter) that there is doubt as to their importance in the rain-generating regime.

Many measurements are available which show that atmospheric pollution consisting in part of large numbers of condensation nuclei exists throughout the atmosphere, and that their population density is highly variable. There are data suggesting that such generalized atmospheric pollution has been steadily increasing [8]. It is important to understand what effect such increased pollution would have on the rain-initiating and -producing cycle. In particular, it would be valuable to know whether the systematic increase of atmospheric pollution during the last half century has a physical relation to marginal areas of serious drought and concomitant floods.

To secure fundamental information on these matters, a series of tests in the U. S. Weather Bureau's giant cloud chamber has been conducted, and it was found that the abundance of condensation nuclei profoundly influences the character of the rain-initiating processes. Hundreds of clouds artificially produced in

the chamber have shown that normal expansions of ordinary saturated air usually produce a dense cloud of droplets having approximate radii of $7\ \mu$ or less. Such clouds are quite stable, persist in the cloud chamber for times exceeding a half hour, and ultimately evaporate as the chamber recovers from the initial cooling of the processed air. It is also observed that if the expansion rate is much less than that typically produced in nature, so that relatively few of the available nuclei are activated, some of the droplets can grow to radii of something like $15\ \mu$.

In striking contrast to the above results, it is found that the behavior of clouds formed by the expansion of air that has been carefully freed of pollution and of condensation nuclei behaves in a radically different manner. The cloud droplets so formed are notably larger than those formed from ordinary air, and the cloud largely disappears by precipitation rather than evaporation. In fact, we have successfully produced a mist-like rain by expanding well cleaned and saturated

air in our 60-ft cloud chamber. This is impossible when ordinary air is used. These observations are consistent with experimental data reported by Wilson [10] nearly 60 years ago, but their significance and application to meteorological problems were not appreciated.

It is known that the number of condensation nuclei in the lower atmosphere is highly variable, is a maximum near cities and decreases, in general, with increasing altitude [4; 5]. Because the air is known to be relatively much cleaner at rain-forming levels than at the surface, it seemed worthwhile to examine cloud production and droplet formation in air that is systematically cleaned by physical processes analogous to those taking place in nature. Accordingly, we have studied the stability of clouds in a large expansion chamber under controlled conditions wherein the expansion rates were all roughly the same. The only factor that has been permitted to vary over a large range is the cleanliness of the air and the resulting numbers of activated condensation nuclei suspended

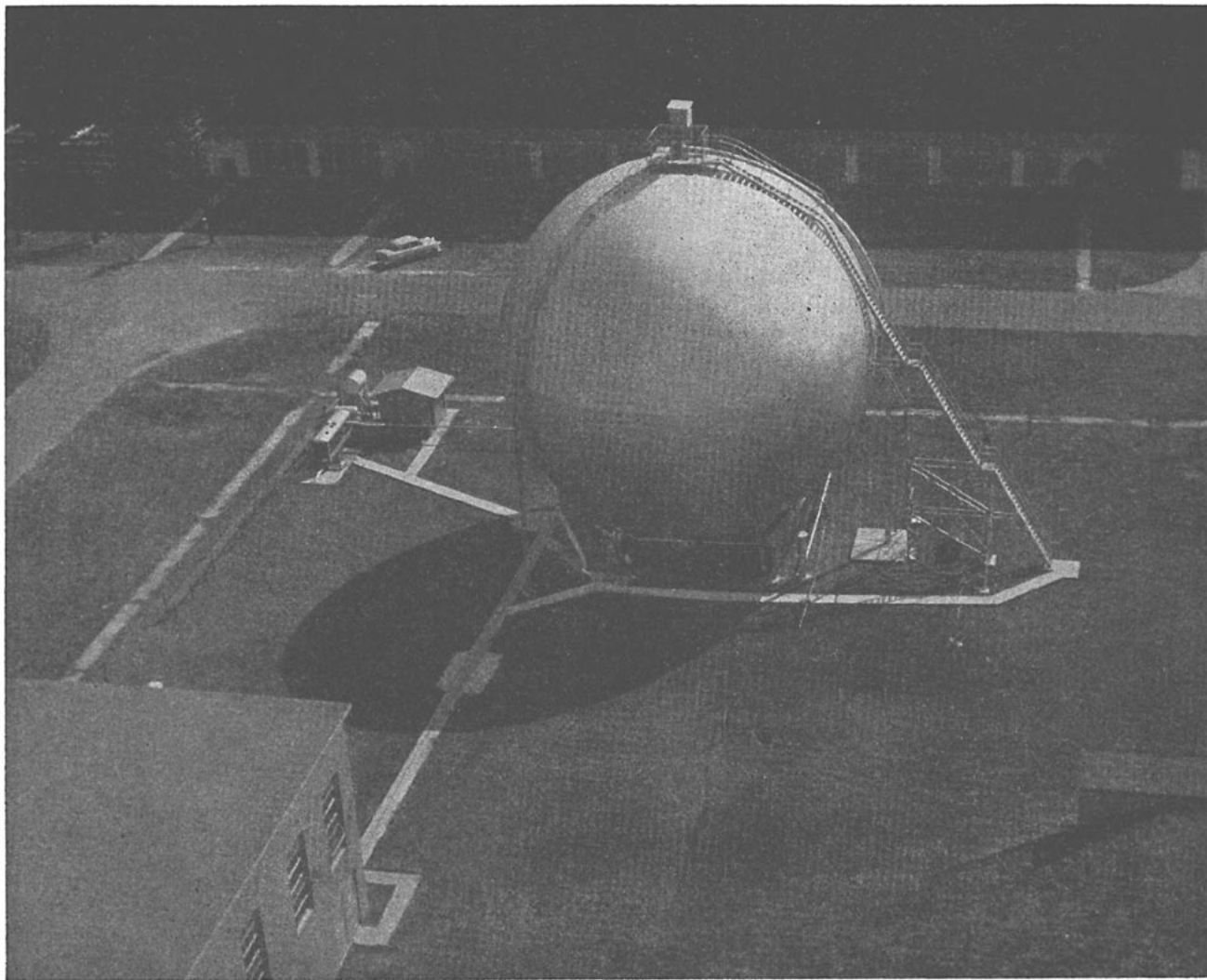


FIG. 1. Cloud chamber. Volume: $3000\ \text{m}^3$. Compressors at left. Main laboratory in left foreground. Access to chamber is through air lock and valve adjacent to triangular walkway. Small laboratory is located under sphere.

therein. We turn now to a description of the experimental arrangements.

2. Experimental procedures

The present experiments were carried out in a 60-ft spherical cloud chamber shown in fig. 1. A close-up of the entrance to the chamber is shown in fig. 2. The chamber was usually compressed to a gauge pressure of some 3 to 5 lb/in², the air saturated with water vapor, and clouds formed by a subsequent controlled expansion. The air introduced into the chamber from the compressor was washed by a pressure-type water spray during its passage through the ducts into the cloud chamber. This washing spray introduces electrified nuclei, and these were always allowed to discharge for at least 12 hr before a cloud was formed by expansion. A rotary displacement type of compressor was used throughout the experiment. It is so constructed as to introduce a minimum of oil, smoke and vaporized matter into the compressed air. Measurements showed that nearly a month is required for most

of the air pollution in typical air to settle out in the chamber by gravitational means, but this could be shortened to about 3 days by the use of electrostatic precipitators [6]. Such electrostatic devices were installed in the cloud chamber, and they greatly expedited the precipitation of the normal pollution particles. Numerous examinations were made of the cloud formations resulting from expansions of successively cleaner air.

The experimental cloud chamber stands only a few miles from the coast of the Gulf of Mexico, with no sources of pollution between. Southerly winds blowing off the Gulf, therefore, offered the most uniform source of air; throughout the experiment, air was introduced into the sphere only when such winds existed. Accordingly, the ordinary air that was employed is relatively pure ocean air; but, of course, it still contains salt and large numbers of other condensation nuclei. Measurements have shown that normal expansion of such saturated surface air from the Gulf activates large numbers of condensation nuclei, and these share the

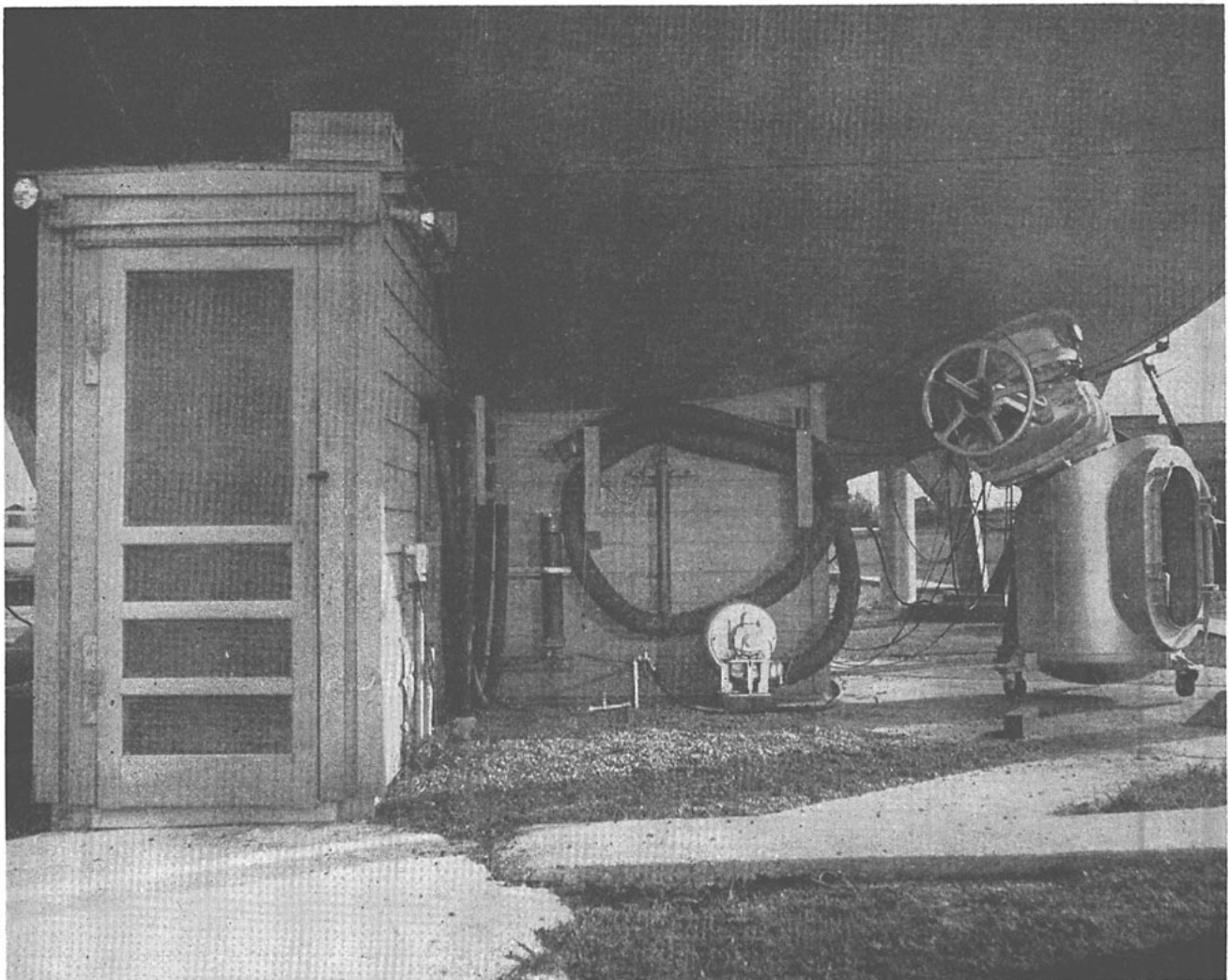


FIG. 2. Entrance to expansion chamber through air lock and to small laboratory under chamber.

moisture available from the expansion. Dense clouds, consisting of 2000 to 5000 droplets per cubic centimeter, of small cloud particles are usually generated.

In general, the air in the chamber was completely saturated prior to expansion. Accordingly, the free water content is determined accurately from the initial and final temperature and from an appropriate correction for the pressure reduction that accompanied the expansion. However, if the air happens to be unsaturated initially, the temperature and pressure associated with the initial appearance of the cloud must be utilized. The temperature within the sphere was determined by the use of thermocouples mounted some meters away from the walls. In addition, a light beam, located at the top of the sphere, was focused on a photocell mounted at the bottom. This arrangement permitted one to determine the amount of light scattered by the cloud, which in turn could be used as a rough check of the nuclei density calculated by more direct methods. Similarly, a pressure-sensitive element provides a current proportional to the pressure. The thermocouple, photocell, and pressure-element currents were automatically plotted on a multi-point recorder in the laboratory, furnishing a permanent record of the time of appearance and density of the cloud, and of its instantaneous temperature.

A standard procedure for all the expansions was adopted, to simplify the comparison of the properties and characteristics of the various clouds. The sphere was ventilated with fresh Gulf air for several hours prior to each compression by means of a high-volume blower. After air is introduced into the chamber by

the compressor, it is cleaned by an electrostatic precipitator unit consisting of four high-voltage insulated electrodes, each 40 ft long, suspended inside the sphere. A 20,000-volt D. C. power supply was connected to this electrode system throughout each clean-up period prior to the generation of the cloud. All electrode radii were sufficiently large so that no corona discharge was produced. The high voltage was always cut off some hours prior to the actual cloud formation.

In order that the measurements would bear directly on rain-production problems, the majority of the expansions were made from an initial pressure of approximately 3 lb/in² gauge, to atmospheric pressure in 3 min. All expansion rates approximated the values given by fig. 3, unless specifically stated otherwise. The expansion rates were selected to be typical of the lifting imposed on air parcels during rapid cumulus development.

The size distributions of the produced cloud droplets were determined by capturing droplet samples on magnesium-oxide coated slides which were exposed at intervals to a constant-velocity cloud stream drawn from the main body of the cloud chamber. By means of a simple mechanical device, successive slides could be exposed during and after the period of cloud formation. The median droplet radius $\bar{R}$ was calculated from the distribution data provided by the magnesium-oxide slide according to the relation

$$\bar{R} = \left(\frac{\sum_1^k nR^3}{\sum_1^k n} \right)^{\frac{1}{3}}, \quad (1)$$

where n is the number of droplets within a given range

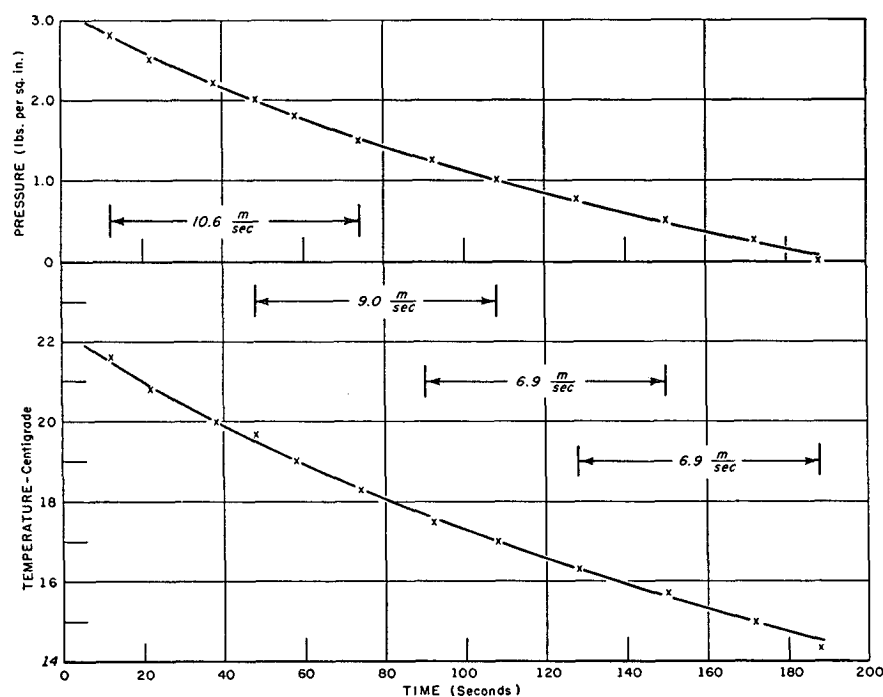


FIG. 3. Dependence of temperature and pressure upon time for adopted standard expansion. Cloud forms immediately on beginning of expansion. Equivalent rates of lift in atmosphere are also indicated.

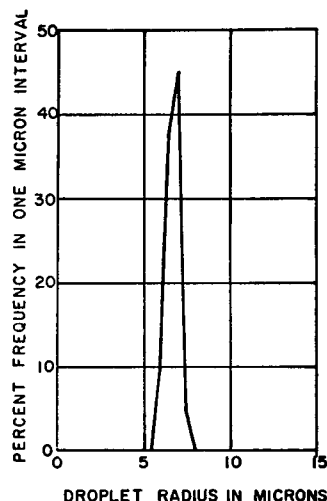


FIG. 4. Uncleaned Air. Droplet size-distribution at completion of expansion. Median radius: 7.02×10^{-4} cm. Liquid water content: 3.74×10^{-6} g/cm³. Activated nuclei density: 2500 cm⁻³.

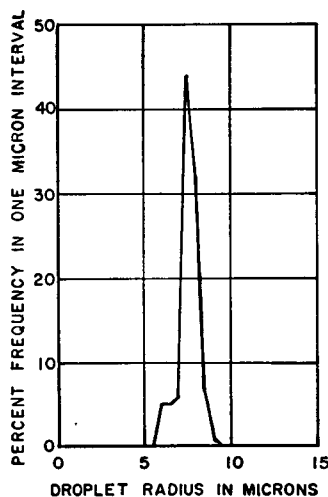


FIG. 5. Air electrostatically cleaned 16 hr. Droplet size-distribution at completion of expansion. Median radius: 8.15×10^{-4} cm. Liquid water content: 3.5×10^{-6} g/cm³. Activated nuclei density: 1500 cm⁻³.

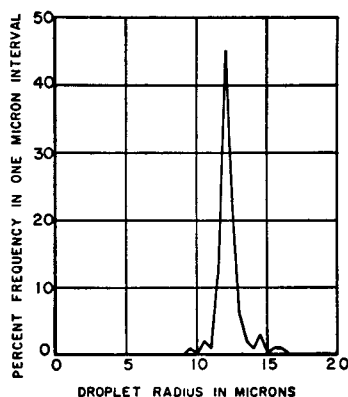


FIG. 6. Air electrostatically cleaned 32 hr. Droplet size-distribution at completion of expansion. Median radius: 12.4×10^{-4} cm. Liquid water content: 3.8×10^{-6} g/cm³. Activated nuclei density: 400 cm⁻³.

of drop radius R . The liquid water content of the cloud was determined from the initial and final temperatures and pressures through reference to saturated vapor-density tables, together with an appropriate correction for the change in volume due to the expansion. The activated nuclei density given in table 1 was then determined as the ratio of the liquid water content and the mean droplet mass. Table 1 shows clearly that the droplet size increases as the air is made successively cleaner. The effective nuclei density clearly decreases from some 2600 activated nuclei per cubic centimeter within ordinary uncleaned air to less than 10 cm⁻³ for air treated by the precipitator for 64 hr. This reduction in nuclei density is accompanied by more than a 40-fold increase in the droplet masses.

Experience has shown that the best method for specifying the number of condensation nuclei and their effective radius in a sample of polluted air is to measure the ratio of the positive and negative light ion conductivities. For example, a series of conductivity measurements made in the cloud chamber showed that the suspended pollution in ordinary air frequently so modifies the ionic equilibrium that the positive and negative electrical conductivities approach equality [6]. On the other hand, as the pollution decreases, the value of negative conductivity increases relatively more than does the positive conductivity. Thus, in air free of suspended particles, it is found that the ratio of the negative to positive conductivities approaches 1.4. This ratio follows from the fact that ions are always produced in pairs, and the negative ion mobility in clean air is 40 per cent greater than the mobility of the positive ion. An analytical expression for the dependence of the number of suspended nuclei and their radius upon the ratio of the conductivities has recently been worked out by Gunn [2]. In view of the above, a column has been included in table 1 giving the measured ratio of the negative light ion conductivity to that of the positive ion at a time just prior to the formation of the cloud by expansion.

3. The measurements

Droplet distributions determined under a number of different conditions of cloud formation are plotted in figs. 4, 5, 6, and 7.

TABLE 1. Summary of results.

Cleaning time (hours)	Liquid water released by expansion (g/cm ³)	Mean drop radius (microns)	Calculated droplet density (cm ⁻³)	Approximate ratio of negative to positive ion conductivity
0	3.74×10^{-6}	7.0	2580	1.04
16	3.50×10^{-6}	8.1	1550	1.10
21	3.96×10^{-6}	8.7	1430	1.12
27	3.52×10^{-6}	11.2	580	1.22
32	3.80×10^{-6}	12.4	380	1.25
41	3.65×10^{-6}	16.0	200	1.30
64	2.67×10^{-6}	55.0	10	1.40

Electrostatic precipitator not operated (fig. 4). — Air from the Gulf was saturated, introduced into the cloud chamber, and subsequently allowed to stand overnight. No special effort was made to clean the air, and the distribution of droplets immediately after completion of the expansions is shown in fig. 4. The median droplet radius was 7.02μ , and the original number of activated nuclei, as inferred from the estimated

liquid water content of $3.7 \times 10^{-6} \text{ g/cm}^3$, was 2580 nuclei/cm^3 .

Electrostatic precipitator operated 16 hr (fig. 5). — In this test, conditions were maintained exactly as in the foregoing, except that the electrostatic precipitators were operated for a total of 16 hr. The high voltage applied to the precipitators was removed some hours before the expansion and the formation of the cloud.

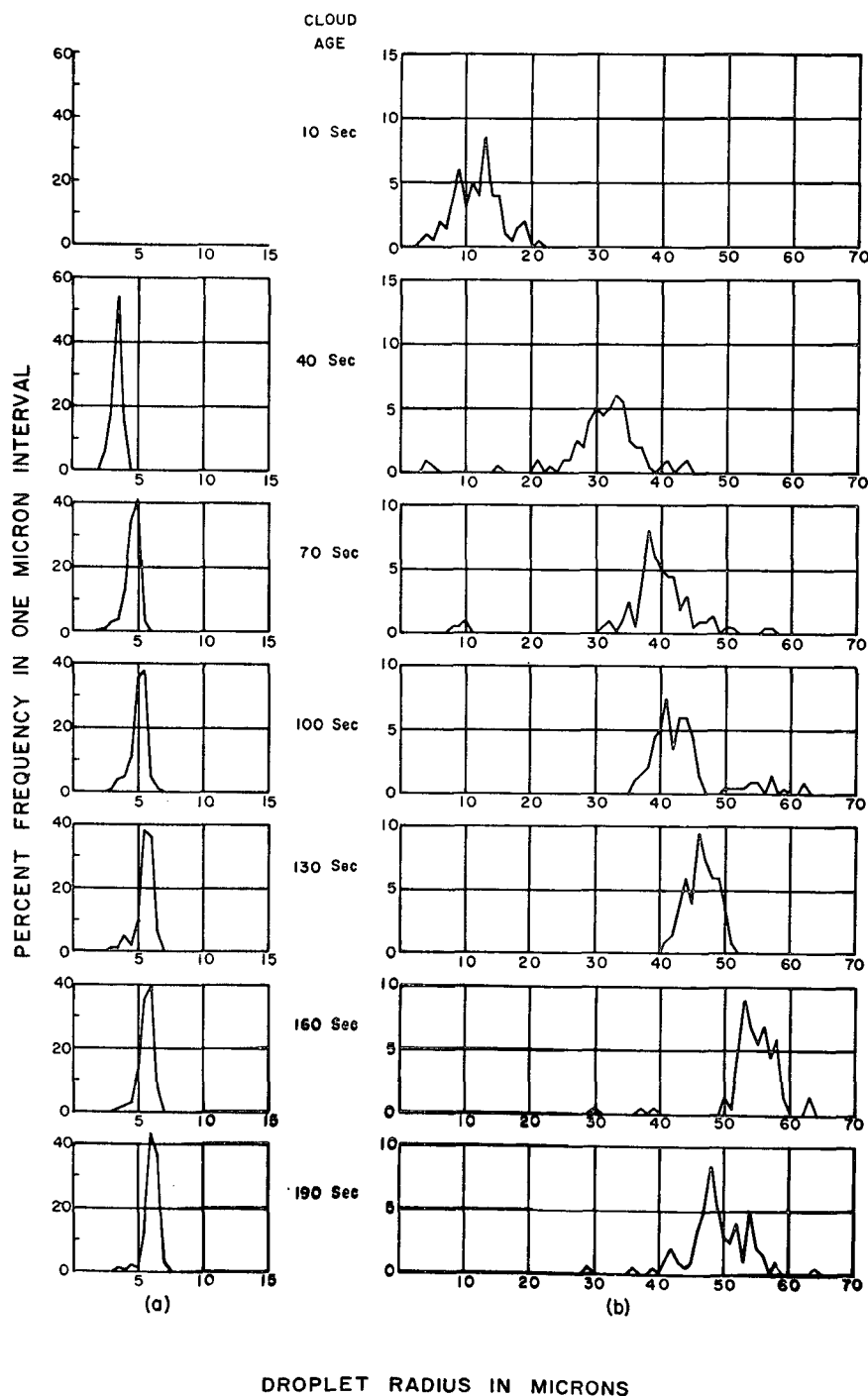


FIG. 7. Left: uncleaned Gulf air; droplet size-distributions during expansion; cloud age is time from beginning of expansion which continued for 180 sec; liquid water content: $4.3 \times 10^{-6} \text{ g/cm}^3$; activated nuclei density: 4500 cm^{-3} . Right: air electrostatically cleaned 64 hr; droplet size-distributions at indicated ages; liquid water content: $2.7 \times 10^{-6} \text{ g/cm}^3$; activated nuclei density less than 10 cm^{-3} .

The median droplet radius in this case was measured as 8.15μ , which leads to an estimated 1550 nuclei/cm^3 for the estimated free water content of $3.50 \times 10^{-6} \text{ g/cm}^3$.

Electrostatic precipitator operated 32 hr (fig. 6). — In this test, conditions were the same as before, except the electrostatic precipitators were operated for 32 hr. The droplet size-distribution here is noticeably different from those above, and the median drop radius was 12.4μ . The estimated free water content was $3.80 \times 10^{-6} \text{ g/cm}^3$, and therefore the activated nuclei density was 380 nuclei/cm^3 .

All of the above determinations were made in washed Gulf air that had stood in the chamber for many hours prior to the formation of the cloud. They show a marked increase in droplet radius as the pollution and condensation nuclei are progressively removed.

Electrostatic precipitator operated 64 hr (fig. 7). — To verify the interpretation of the above experiments, a further test was carried out. The electrostatic clean-up apparatus was operated this time for a total of 64 hr. Parallel measurements of electrical conductivity ratios, such as those indicated by table 1, showed that the air in the chamber finally was relatively free of pollution and condensation nuclei. In this expansion of carefully cleaned air, cloud-droplet distributions were determined at successive times beginning 10 sec after the first formation of the cloud. The observed distributions as a function of the cloud age are shown in the right part of fig. 7. It will be noticed that the droplets systematically grow by condensation right up to the end of the expansion, which terminated at 180 sec. The distribution shows no evidence of growth by association, and the growth must be attributed to condensation. The distribution at 190 sec, which occurred 10 sec after completion of the expansion, suggests droplet fall-out and evaporation. The median final radius of the droplets was found to be 55μ , from which it was estimated that there were less than ten active nuclei particles per cubic centimeter.

The foregoing expansion and droplet-growth analysis may be directly compared with the analysis shown in the left part of fig. 7, wherein conditions were exactly as above, but the air was ordinary Gulf air introduced into the cloud chamber and allowed to stand overnight. The electrostatic precipitators were not operated. The left part of fig. 7 shows how the droplets grew with increasing age. It may be noted that the final median radius was only 6μ , instead of 55μ as with the clean air. The estimated nuclei density in this case was 3900 nuclei/cm^3 . The striking differences between the two parts of fig. 7 emphasizes the probable importance of air pollution in the production of ordinary rain.

As a final test, an expansion was produced in well cleaned air, initially at 6.0 lb/in^2 , that was reduced to

atmospheric pressure in 90 sec. Such an expansion rate would approximate the expansion existing in rapidly developing cumulonimbus clouds. A very sparse cloud resulted from this expansion, but the mean droplet radius was in excess of 150μ . Such a radius was consistent with available liquid water and the estimated number of activated condensation nuclei.

4. Significance of the measurements

Observations from aircraft and meteorological radar equipment leave no doubt that rain can, and often does, form in cumulus clouds at temperatures warmer than 0°C , where ice cannot play any part in the mechanisms. There is substantial evidence for believing that coalescence of the droplets take place, and that precipitation from such warm clouds, and even from supercooled clouds deficient in sublimation nuclei, results from the association of relatively large cloud droplets falling systematically through great clouds of smaller ones. Fair-weather cumulus clouds contain few droplets larger than $15\text{-}\mu$ radius, and it is well known that fair-weather cumulus clouds do not precipitate through droplet growth by gravitational action and therefore remain stable for long periods. We have shown that electric fields can precipitate such clouds, but such fields normally are not generated until precipitation is well advanced [1]. Many data, like those discussed by Weickman [9], show that inside *precipitating clouds* there are invariably moderate numbers of large cloud droplets. The origin of these larger cloud droplets has been obscure, but the above measurements suggest that they may be produced by direct condensation under favorable conditions.

The measurements suggest that the fractional number of condensation nuclei activated depends only on the degree of supersaturation of water vapor when a cloud is first formed, and thus is related to the rate at which the air parcel is lifted. Once the nuclei are activated, subsequent changes in their environment do not modify their numbers. This conclusion is consistent with the view already expressed by Howell [3], that the activation of additional nuclei requires a supersaturation greater than that encountered when the cloud was first formed, and the statement of Junge [4] that "only those nuclei which require the lowest supersaturation are active in the actual atmosphere." By employing our observed data and the well known laws governing thermal and vapor diffusion, it is possible to calculate that the supersaturation existing at the mid-point of a standard expansion is less than 0.2 per cent when $350 \text{ activated nuclei/cm}^3$ are present. Accordingly, there was little likelihood of new condensation nuclei becoming activated during the period of droplet growth. Thus, the number of activated nuclei first produced by an expansion remains constant during further periods of droplet growth, precipitation

or evaporation. This conclusion is well supported by all of the present observations.

It may be noticed that the liquid water released in all expansions was approximately the same, but the mean size of the droplets increased with increasing cleanliness. Conservation of mass requires that the size of cloud droplets formed at above freezing temperatures be determined only by the available free water content and the number of active nuclei in the parcel of air from which the cloud is formed. So long as inappreciable numbers of ice-forming nuclei are present in a cloud, there is no reason to suppose that this conclusion is not similarly applicable to super-cooled clouds. Accordingly, the mean droplet size established in a parcel of air by cooling may be quantitatively determined once the initial and final vapor densities, together with the nuclei density, are fully specified.

The principal results of the foregoing investigation are summarized in the figures and in table 1. A critical examination of table 1 shows very clearly that an expansion of saturated clean air produced droplets that are many times more massive than those produced by the expansion of a similar sample of ordinary Gulf air. The cleaning time and the ratio of the negative to the positive ion conductivity, both, measure the number of nuclei per unit volume that may be activated and their mean radius. These quantities are therefore included in table 1. The measurements imply that the condensation-nuclei density in ordinary air has a profound influence on the rain-initiating cycle of many natural clouds. It is fully recognized that conditions within the cloud chamber do not reproduce in detail all of the mechanisms simultaneously occurring within a natural precipitating cloud. However, the fundamental requirements of available water vapor, condensation nuclei, and decreasing temperature induced by expansion were carefully preserved in the experiments, and turbulence, extraneous droplets from super-incumbent layers, and entrainment were excluded.

The differences in temperature induced in a cloud by mixing or cooling may be several degrees, and the resulting free water available to form cloud droplets is frequently sufficiently great to produce droplets from 25 to 100 μ in radius, *provided* the activated condensation-nuclei density is of the order of 100 or less. Accordingly, it is concluded that a fundamental requirement for the production of precipitation from natural clouds, generated from ordinary air, is a considerable volume of cooled, clean, nearly saturated air immediately above, which is relatively free of condensation nuclei. The critical nuclei densities in the clean overlying layers may range from 100 to 1 nuclei/cm³ or even less.

The source of the clean air is of no importance. Indeed, it may occasionally be rising low-level air

through which small droplets have fallen or remain suspended for a time such that the condensation nuclei have an opportunity to diffuse onto them. It is possible for such a cloud-filtering action to remove nearly all of the condensation nuclei and thus yield clean air.

Probably every careful weather observer has noted precipitation falling from phantom clouds overhead and has wondered how it could have possibly been produced. Precipitation of this character has been artificially produced in the large cloud chamber, under the conditions outlined above, wherein the droplet sizes were sufficiently large to be felt as distinct droplets on one's upturned face. One may, therefore, suggest that natural precipitation is sometimes formed not by the normal association processes, but by direct condensation on the relatively few nuclei present in the clean air at high condensation levels. If such condensation takes place and produces large droplets, it is certain to play a part in the initiation of rain.

In spite of the marked pollution normally existing in the lower atmosphere, large volumes of relatively clean air exist at higher levels [5]. Therefore, one is led to suggest that cloud droplets produced from air at high levels will tend to stimulate precipitation, whereas clouds produced by the vertical transport of surface air are more likely to produce stable clouds. It is probably significant that the rain-inducing clouds containing large droplets will, in general, be produced at levels well above the stable cloud level. Accordingly, the larger droplets can fall through the cloud of much smaller particles and thereby sweep their free water content to the earth in the form of rain.

It seems important to point out that the generation of clouds and falling precipitation always act to purge the atmosphere of its pollution [7; 10], and a continuing regime of cloudiness and rain removes the nuclei to such an extent that rainfall becomes progressively easier. In this way, the rain continues until the air is finally desiccated and a period of clear weather initiated. On the other hand, nuclei and other pollution are transferred to the atmosphere during clear weather, and their density normally increases steadily with the accumulating water vapor re-evaporated from the ocean and the land. The instability induced in an air mass by the accumulation of water vapor cannot at first induce precipitation, because of the large nuclei content at low levels; but as the air mass becomes more unstable, development to clean air levels become possible, and the environmental conditions necessary to establish a new precipitation cycle is established. Such mechanisms emphasize the regenerative character of precipitation processes.

5. Conclusion

Investigation of the factors that control the characteristics of clouds shows very clearly that the size of

cloud droplets produced by given expansions depends critically upon the numbers of condensation nuclei in the air. Expansions of clean air normally produce, by simple condensation, droplets sufficiently large to play a vital part in the initiation of precipitation. The measurements show that condensation is adequate to describe the observed occurrence of large cloud droplets near the top of precipitating clouds. The requirement is, simply, that the available liquid-water content be divided between the activated condensation nuclei in such a way as to provide the droplet of assigned size.

The foregoing criterion for the initiation of precipitation from typical warm clouds is consistent with our experiments. Hundreds of artificial clouds have been produced under a variety of conditions that generally reproduce the production of clouds in the free atmosphere. When these clouds are formed from ordinary air, it is entirely clear that no large droplets have ever fallen to the bottom of the chamber and the clouds, in general, re-evaporate during their return to thermal equilibrium. In marked contrast to the above, an expansion of saturated clean air in the cloud chamber always produces droplets that are large enough to precipitate. We regularly produce mist or light rain by such expansions, whereas this is quite impossible with ordinary air.

The application of these measured results to meteorological processes may only be suggested, but it is believed that the presence of large numbers of contaminating particles in the lower atmosphere acts to generate clouds that do not precipitate but persist in the atmosphere until they re-evaporate. Thus, cloudiness rather than rainfall is characteristic of saturated and highly polluted air masses. On the other hand, moderate numbers of droplets larger than $40\ \mu$ in radius may be generated to promote appreciable rates of precipitation if only relatively few condensation centers are activated.

The reported series of measurements seem to imply that the precipitation cycle is regenerative. That is to say, a precipitating regime tends to cause more precipitation because of the removal of the condensation nuclei. On the other hand, if the air has been dried out by a rain-producing cycle, new nuclei are progressively transferred into the relatively clean atmosphere and accumulate along with the progressive increase in water-vapor content. The water vapor contributes to the mechanical instability of the lower layers, but the large nuclei content simultaneously discourages the formation of clouds that are capable of precipitation. Thus, large-scale convective activity is inhibited and rain production delayed until gross mechanical instability is finally established. It is yet too early to draw a final conclusion on this matter; but as further data become available, it should be possible to test quite fully the reality of this inference.

Our experiments were designed to be consistent with the fundamental principle that extraneous and subsidiary processes must be eliminated in order that the underlying behavior of nature under specific conditions can be clearly formulated and fully understood. We are of the opinion that an understanding of the basic mechanics of precipitation processes can best be developed by bringing these processes into the laboratory, where physical conditions are fully known or can be controlled and measured. The results outlined above would have been long delayed if it had been necessary for the processes to be studied and developed against the background of complex variations commonly observed in the free atmosphere. The physical processes summarized above are believed to superimpose on the ever-present complexities of the free atmosphere and to determine the trend of events during the initiation of precipitation from natural clouds.

A number of readers will have little confidence in the controlled experimental approach to the study of precipitation mechanics and will deny the applicability of our results. These readers may consider the above results as a working hypothesis to be tested and compared with the same processes in nature. Such a comparison is ultimately possible.

The above investigation, and the possible consequences as outlined above, emphasize the importance of preserving a clean atmosphere throughout the Earth for all time.

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