ARTIFICIAL STIMULATION OF PRECIPITATION

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From the earliest times man has sought to modify the conditions of the environment in which his activities are conducted, so that they become more congenial than those provided by nature. He has succeeded in adding to his comfort by protecting himself, by artificial means, against the elements, and of conditioning the air for greater personal comfort or to meet particular requirements in a variety of industrial and commercial projects. In cold climates he has been able to simulate tropical conditions in confined areas, for the cultivation of plants which thrive only in such an environment. He has found ways of protecting valuable crops against frost and, in another sphere of activity, has been able to remove fog from aerodromes to add to his safety in air travel. By the storage of water for agricultural, domestic and industrial use he has been able to secure for himself, his property and his food supply, some measure of insurance against the withering effects of drought.

These are but a few examples of the ways in which man has succeeded in changing the natural conditions within small areas. Untiringly he has sought to find methods for larger scale modifications, directed mainly towards the artificial production of rain and to the suppression of destructive storms. There has never been any dearth of ideas in this fertile field for the imagination and, as Dr. W. J. Humphreys puts it, the growing and marketing of rain-making schemes is a never-failing drought crop. However, it is only within recent years that methods which suggest the practical possibility of achieving effectual large scale weather modification have been developed. It is my intention to tell you something about these activities which were initiated in the Research Laboratory of the General Electric Corporation and which have aroused considerable public and scientific interest.

Before referring to this work of Dr. Langmuir and his associates, I should like to give you a brief outline of the theories which have been developed to account for cloud formation and for the precipitation which occurs naturally and, at times, in abundance.

The atmosphere which surrounds the earth consists of a mixture of gases one of which is water vapour. The proportion of water vapour varies considerably. It is increased by evaporation from the earth's water surfaces and is decreased by precipitation in the liquid or solid form. This involves a change of state and it has been proved beyond reasonable doubt that condensation of vapour into liquid droplets can take place only in the presence of suitable nuclei. The interior of a small droplet is under hydrostatic pressure, owing to the effects of surface tension, which produces, in its environs, an excess of vapour pressure over that above a plane surface of water. This excess of vapour pressure is inversely proportional to the radius of the drop, and in the absence of nuclei of appreciable dimensions it would have to be extremely high for a drop to form and the degree of supersaturation exceed greatly any value ever observed in the atmosphere.

Numerous samples of air have been examined and these have shown that nuclei are always present in the atmosphere. Their number varies considerably and is greatest over cities where as many as 4,000,000 per c.c. have been found. Over the oceans the average figure is about 1,000 per c.c.

When humid air is cooled below its saturation point condensation occurs on the nuclei, and cloud particles form. The cooling required for condensation may occur as a result of loss of heat by radiation, or by contact with a colder surface, or, possibly, by mixing of air masses having different temperatures, or by dynamic cooling in ascending currents of air. Dynamic cooling is by far the most important of all these processes and the only one of practical significance in the ultimate development of precipitation.

For a long time it was thought that once the formation of cloud particles had taken place continued cooling would promote the growth of droplets to a size at which they would be able to fall from the cloud as rain. This explanation, however, does not meet all the observed facts, and it was finally realised that some form of release was required before precipitation could be started. It was, for example, observed that clouds, although very deep and persistent, often fail to produce precipitation and that it seemed to be necessary for part of the cloud to consist of ice crystals before appreciable precipitation could occur.

In the light of these observations let us again consider the process of condensation on the nuclei in the atmosphere. Some of these nuclei are non-hygroscopic and consist of particles raised as dust from the earth's surface or of the insoluble products of combustion. Others are hygroscopic and their main source of origin is still debatable. It seems likely that the majority originate from sea spray and are carried into the atmosphere by the wind. Some probably consist of particles of sulphuric acid formed from the absorption of water by the sulphur dioxide from coal gas, and some probably consist of nitrous acid formed by the combination of oxygen, nitrogen and water vapour of the atmosphere in lightning discharges, or by ionisation due to cosmic radiation.

It is very probable that only the hygroscopic nuclei, most of which have a diameter between 10^{-6} and 10^{-5} cms. in a dry environment, play any part in the process of condensation of water vapour into cloud particles. Examination of rain water has failed to disclose the presence of any solid particles and the possibility of condensation on atmospheric ions has to be discounted as it would require about 400 per cent. supersaturation for the process to be initiated. Such a high degree of supersaturation has never been observed in the atmosphere.

The vapour pressure over a droplet forming round a hygroscopic nucleus is increased owing to the small radius of curvature and diminished by the dissolved hygroscopic material contained in the droplet. Except in the case of very small nuclei the latter is of greater significance than the former and the particles may begin to grow in relative humidities as low as 70 per cent. This explains the deterioration of visibility which often occurs with increasing relative humidity. Condensation commences on the larger and more hygroscopic nuclei but, if these are few, or the rate of fall of temperature rapid, the diffusion of water vapour to the environs of the developing droplets may not take place rapidly enough for the distribution of relative humidity to be uniform. The result is that condensation on the smaller nuclei will take place in those parts where a higher relative humidity temporarily obtains.

Although the droplets may begin to grow at comparatively low relative humidities, the effect of the hygroscopic nuclei on vapour pressure rapidly diminishes as the solution becomes increasingly dilute and their growth to cloud droplet size will not continue until a measure of supersaturation has been attained. In the case of the very small hygroscopic nuclei having a diameter of 10^{-6} cms. this degree of supersaturation may be as much as 20 per cent., falling away very rapidly with increase in size to only 1 per cent. for nuclei with a diameter of 10^{-5} cms. Once the droplet has attained a diameter of 10^{-4} cms., or about the size of the smallest droplets in clouds, the effects on vapour pressure of curvature and the dissolved hygroscopic material in the droplet become negligible and the cloud droplets are in equilibrium in an atmosphere of 100 per cent. saturation.

Prof. H. G. Houghton has derived an expression to determine the growth of droplets which shows that the droplets, with time, tend to acquire a uniform size as condensation continues, even though their existence began on nuclei of different sizes. As an example, Prof. Houghton shows that droplets initiated on nuclei 2×10^{-5} cms. and 2×10^{-4} cms. in diameter reach diameters of 1×10^{-3} and 1.02×10^{-3} cms. respectively at about the same time. The size of the droplets is limited by their number and the amount of water vapour available, but even if there were only one droplet per cubic centimeter the maximum size would be of the order of 2×10^{-2} cms., which is about the minimum size that can be classified as a raindrop.

At this stage I should like to refer to some important investigations made by Köhler at the Haldde Observatory in Norway. This observatory is often within cloud and Köhler devised a way of measuring the size of cloud particles and he collected quantities of cloud water. He assumed that the hygroscopic nuclei were all derived from sea spray and he examined the cloud water he collected for chlorine content, which he found amounted to 3.6 mg. per litre. Numerous measurements of the chlorine content of rain water have been made in many parts of the world and almost all have shown a chlorine concentration similar to that found in cloud water by Köhler. It should be remembered that rain may collect impurities in its fall through the air, but the similarity in chlorine concentration between rain water and cloud water strongly suggests that raindrops develop not by continued condensation but by coalescence of the cloud droplets.

The evidence therefore indicates very strongly that drops of sufficiently large dimensions to form raindrops cannot grow from the continued condensation of water vapour and that the coalescence of a number of cloud particles, or some other process, is an essential feature of raindrop formation.

Later on I shall discuss possible methods by which cloud particles coalesce to form raindrops, but, before doing so, I want to tell you of a very important fact about cloud particles at temperatures below the freezing point. It is well known that water can exist in all three phases (gaseous, liquid and solid) at sub-freezing temperatures, but it is perhaps rather astonishing that in the atmosphere it is not until temperatures below -40°C are attained that clouds are composed entirely of ice crystals. In a recent letter to Nature an account is given of experimental work carried out at the Clarendon Laboratory at Oxford. In these laboratory experiments with outdoor air it was found that above -32°C, condensation occurred almost entirely in the form of water droplets and that ice crystals, if present, did not exceed 1 per c.c. Between temperatures of -32°C and -35°C clouds usually contained ice crystals in numbers up to 20 per c.c., or about 2 per cent. of the water particles present, and no noticeable increase occurred on further cooling to temperatures between -35°C and -40°C. Below -42°C however, clouds were composed mainly, if not entirely, of ice crystals.

In atmospheric clouds the existence of supercooled water droplets is of common occurrence and is responsible for the hazard of ice accretion on aircraft. The possibility of ice crystals being introduced into regions where clouds consisted of supercooled water droplets suggested to Bergeron, a Norwegian Meteorologist, an explanation for the growth of raindrops.

The Bergeron-Findeisen theory of rain formation is based on the fact that the vapour pressure over ice is lower than that over supercooled water at the same temperature. At —10°C, for example, the saturation vapour pressure over ice is 2.62 millibars and 2.87 over water. If ice crystals are introduced into supercooled cloud they enter an atmosphere saturated with respect to water but supersaturated with respect to ice, and the ice crystals will, therefore, grow at the expense of the water droplets. At the temperature of —10°C quoted, this supersaturation will be about 10 per cent. and the change from supercooled water droplets to ice crystals will take place rapidly. Assuming the introduction of one ice crystal for every 8 water droplets, Bergeron estimated that the change would occur in 10 to 20 minutes. The large ice crystals formed would fall more rapidly than the water droplets and therefore continue to grow by collision with the latter. In this way, Bergeron considered that growth to the size of raindrops took place, and made the pronouncement that "almost every real raindrop and all snowflakes originate round an ice crystal."

How do these ice crystals become available? Bergeron suggests that nuclei of suitable shape for crystallisation may be acquired by some of the water droplets and 1 ice crystal per c.c., as found in the experiments at the Clarendon Laboratory at temperatures above —32°C, may be sufficient. Another possibility is that ice crystals forming in the lower temperatures at a higher altitude drift downwards.

The Bergeron-Findeisen theory of precipitation has been generally accepted and it is undoubtedly true that most rain originates from clouds which extend above the freezing level in the atmosphere. It provides the release mechanism referred to earlier, as a requirement for precipitation, and it explains the sudden commencement of rain which often occurs from deep and persistent clouds. It cannot, however, account for the development of all rain as there are many well substantiated accounts of the occurrence of heavy rain, particularly within the tropics, from clouds whose tops are at a temperature well above freezing.

In presenting his theory that the fundamental cause of rain is due to the coexistence of ice and water particles, Bergeron discusses other possible ways in which the coagulation of cloud particles might take place. He considers that electric charges are too small to be significant and that the capillary and hygroscopic forces, although important in the growth of nuclei, are insignificant in their subsequent development and the effect about a billion times too slow in promoting growth from cloud particles to rain drops. Turbulence, he says, might cause collisions between cloud particles and lead to their coalescence. Dr. Langmuir of the General Electric Corporation, has suggested another process which I shall come to presently.

Against this background of the theories which have been evolved to account for the process of precipitation, I want now to tell you something about the researches carried out by Dr. Langmuir and his associates of the General Electric Corporation.

These researches developed from a study of ice accretion on aircraft flying in clouds at temperatures below freezing and by what Langmuir called "serendipity," or the art of profiting from unexpected occurrences, grew to embrace the basic problems of cloud physics and practical methods of stimulating precipitation artificially.

Experiments connected with the study of aircraft icing were conducted on the summit of Mount Washington and there Dr. Langmuir and his assistant Mr. Schaefer became aware of the astonishing fact, already mentioned, that at temperatures as low as —20°C there were normally no ice crystals present in clouds or, if there were any at all their number was quite insignificant. Suddenly, however, the supercooled cloud might be transformed into a snowstorm and they observed that many snowstorms occurred in clouds, no part of which was at a temperature lower than —5°C. These observations indicated that the development of snow crystals was not a matter of temperature alone and that in the atmosphere there sometimes exist nuclei on which snow crystals are able to develop.

Mr. Schaefer undertook laboratory experiments to investigate this problem. He acquired a cold box of about 4 cubic feet capacity, which could be cooled to —25°C. He lined the sides and base of this box with black velvet and used an intense beam of light to illuminate the interior of the box from above. By breathing into the box he found that it became filled with a cloud of supercooled water droplets and that if any ice crystals were present they became visible in the beam of light.

Mr. Schaefer tried to induce the formation of ice crystals by dusting a wide variety of powders into the box, but without success except for a very small number of ice crystals which were seen to form at the lowest temperatures.

In July 1946, he introduced a needle, suspended on a thread and cooled in liquid air, and swung it once across the top of the cloud. Immediately an intense blue haze developed in the path of the needle and within a few seconds myriads of ice crystals were seen to develop along this path and in 10 to 20 seconds had spread throughout the box.

Subsequent experiments by Schaefer showed that a cloud of supercooled water droplets spontaneously changed to a cloud of ice crystals when any portion was cooled below a threshold temperature of $-38.9°C$. At a higher temperature only a few ice crystals formed. Further experiment also showed that if only 1 c.c. of air were cooled below this temperature the ice crystals, spontaneously produced, reached the prodigious number of 1.6×10^{10}.

The low temperature to which it was necessary to cool a small volume of saturated air suggested to Schaefer the use of solid carbon dioxide (dry ice) as the cooling agent, and he found that a single minute fragment left behind a track of ice crystals when dropped into the cloud in the cold box.

Langmuir made some calculations and came to the conclusion that the diameter of the ice nuclei formed was about 10^{-6} cm. and that a single pellet of dry ice, dropped through a cloud at $-20°C$, would produce about 10^{16} ice nuclei. If each of these grew into a snowflake weighing 10^{-5} grams the total weight of snow would amount to 100,000 tons or the equivalent of the amount of liquid water contained in 100 cubic kilometres of cloud. He came to the conclusion that if dry ice were released into supercooled clouds the limiting factor would be the rate at which the nuclei could be distributed and not the number of nuclei which the release of dry ice will produce.

When a cloud of supercooled water droplets is converted to ice crystals there is an associated rise in temperature due to two causes. The first of these is the release of the latent heat of fusion due to the phase change from water to ice. The second is due to the fact that the vapour pressure over ice is lower than that over water and therefore the water vapour content will be reduced releasing the heat of sublimation. At $-20°C$ these effects will be to raise the temperature more than 0.5°C and in this way produce vertical accelerations which will lead to turbulence and bring about spreading of the regions affected by the ice nuclei seeding.

Langmuir concluded that the complete nucleation of supercooled stratiform clouds could be effected in about 30 minutes by seeding along lines about a mile or two apart.

The first experiment in seeding supercooled clouds in the atmosphere with dry ice was made on 13th November, 1946, by Mr. Schaefer. In this experiment three pounds of fragmented dry ice were scattered from an aircraft at an altitude of 14,000 feet and a temperature of $-20°C$. A sheet of snow developed suddenly below the cloud and within five minutes the whole cloud was converted to snow, which fell about 2,000 feet before evaporating.

A number of other cloud-seeding experiments were subsequently carried out and Dr. Langmuir, as one of the conclusions submitted with the first quarterly report on this project, wrote:

> "It seems probable that if dry ice is dropped over incipient thunderstorms as soon as the tops reach the freezing level, the development of the storm may be profoundly modified. The storms should be less severe, but will last longer and hail should be avoided."

At about the time that the first seeding of cloud was carried out by releasing dry ice from an aircraft, Dr. Vonnegut, another of Dr. Langmuir's assistants, found that very fine particles of silver iodide serve as effective ice nuclei at temperatures below $-5°C$. He selected this substance for an experiment because he had found after examining X-ray crystallographic data of many substances, that silver iodide had almost exactly the same crystalline form as ice.

Simply by rubbing the head of a safety match on a silver coin and striking the match in an iodine vapour sufficient nuclei of silver iodide could be produced to create 100,000,000 ice crystals in the cold box used by Schaefer in his original experiments.

Vonnegut developed generators for creating smokes of minute particles of silver iodide, by means of which it is possible to produce as many as 10^{13} particles per second, each about 10^{-6} cms. in diameter. In these generators silver iodide is vaporized in a flame and the vapour cooled suddenly by means of a jet of air blown over the top of the flame.

Although silver iodide particles provide effective nuclei only at temperatures below $-5°C$, they possess the advantage of being persistent and remain in the atmosphere at temperatures above freezing and are thus available to produce their effects when they come into the presence of supercooled water droplets at a sufficiently low temperature. Langmuir has suggested that, with the use of generators on the ground introducing silver iodide nuclei into vast quantities of air, it might be possible considerably to alter the climate over large parts of the earth.

When a cloud of supercooled water droplets is seeded with sublimation nuclei a number of changes take place which can now be visualised. Firstly, very large numbers of ice crystals begin to grow round the nuclei provided in an atmosphere supersaturated with respect to ice. Soon the air will no longer be saturated with respect to water and the supercooled water droplets will begin to evaporate, thus providing a further source of water vapour to promote the growth of the ice crystals. While this process is taking place latent heat of fusion is being released and atmospheric turbulence created, which causes the wider distribution of the ice crystals. Eventually the ice crystals may reach a size at which their rate of fall exceeds that of the vertical currents supporting them and they will sink to lower levels growing, not only by sublimation, but by collision with cloud particles. If the lower portions of the cloud are at temperatures above freezing the ice crystals will begin to melt, but continue to grow by collision with the cloud particles, through which they fall, eventually leaving the cloud as drops of rain.

Following the cloud-seeding with dry ice, carried out by Schaefer, numerous experiments have since been conducted in many parts of the world, including Hawaii, where some rather remarkable results were obtained after seeding cumulus clouds, at temperatures well above freezing, with rather large quantities of dry ice. The processes just described could not have occurred but the proof that heavy rain was produced by dry ice seeding is excellent. By what process could this have developed? Langmuir, with characteristic ingenuity, produced an explanation and in doing so evolved a theory for the production of rain from cumulus cloud by a chain reaction.

Explaining the Hawaiian experiment Langmuir suggests that a film of ice would collect on the falling dry ice and that, on melting, water drops of large dimensions would be introduced into the cloud. As these drops continued to fall they would grow by collision with cloud particles until eventually they reached the maximum size at which drops can exist, which is about 0.5 cms. Any further growth would lead to the drops breaking up and the fragments may be carried up with the vertical currents. If the rising drops are of larger dimensions than the cloud particles, and therefore move with a different upward velocity, they will grow by collision until their weight could not longer be sustained by the updraught. At this stage they would begin to fall and continue to grow until fragmentation again took place on attainment of the maximum size. If the second fragmentation occurred at an altitude at least as high as the first fragmentation, the process is capable of continued repetition and a chain reaction in which the number of drops increase in a geometric progression will have been set up. As soon as the ascending currents in the cloud diminish, and this will occur with an increasing number of falling drops, the process of drop multiplication will come to an end and they will fall from the base of the cloud.

Langmuir establishes the conditions necessary to start a chain reaction, such as that described above. Briefly stated, the essential requirements are an updraught of at least 5 m.p.h., a high liquid water content in the clouds (about 0.1 inch of liquid water) and rather large cloud particles.

These conditions are exactly those to be expected in cumulus clouds in a warm moist climate and the theory suggests that precipitation may be started in such clouds by the simple expedient of introducing a small quantity of water into the cloud in order that drops of large size may be available to set going a chain reaction. For this purpose one large drop may be sufficient.

Experiments based on the chain reaction principle are now being carried out and it is possible that seeding cumulus clouds with water may prove an effective way of stimulating precipitation. Here in South Africa an extension of the same basic principle is being tried and in place of water a solution of calcium chloride in water is being employed with the object of increasing the rate of growth of drops. The effect of the calcium chloride is to lower the vapour pressure over the drops with the result that their growth will take place, not only by collision, but, by condensation of water vapour. By using a calcium chloride solution the quantity required would be smaller than that of water to produce the same effects and it is thought that the chain reaction may perhaps be initiated in less critical conditions.

Before concluding this paper I should like to tell you something of the results of the practical experiments which, as I have said, have been carried out in many parts of the world.

Published reports are now available of experiments conducted in the United States, Canada, Australia and South Africa. In this country I have been associated with experimental work being carried out as a joint project known as operation ASPIC by the Council for Scientific and Industrial Research, the Meteorological Office and the South African Air Force.

As a general conclusion there can be no doubt that the nucleation of clouds at sub-freezing temperatures does bring about a profound modification in the cloud structure and visual observation shows that ice crystals do develop rapidly and in large numbers in the region of supercooled water droplets, in clouds which have been seeded.

In considering the practical results it is convenient to deal with seeding experiments carried out on stratiform or layer clouds separately from those carried out on cumulus type clouds in which the vertical development is the dominating feature of their structure.

In experiments on stratus cloud, carried out by the General Electric Corporation, it was shown that by discharging only 12 lbs. of dry ice it was possible to remove the supercooled droplets from an area of cloud no less than 50 square miles in extent. The practical value of being able to achieve this result to eliminate the danger of ice accretion on aircraft may be considerable.

In regard to the stimulation of rain from stratiform cloud, a report published in the Bulletin of the American Met. Society in May 1948, gives the preliminary results of 38 operations on stratiform cloud. An analysis of these results shows that there was no case of rain being produced by artificial means unless precipitation was occurring naturally within 30 miles of the seeded area.

In the case of cumulus cloud the results have been more encouraging and in some cases have been spectacular, but in assessing the results from clouds of this type there is the crucial difficulty of separating the natural effects from those artificially induced.

An interesting report, in which the artificial effects have been statistically evaluated, is that prepared by Irving P. Krick, for the Arizona Weather Research Foundation, on seeding experiments in the Phoenix area during the summer of 1948. In all, 27 cloud-seeding flights were made using dry ice or silver iodide, including three occasions when both these nucleating agents were used. Krick, from previous records, made an estimate of natural rainfall incident to each weather type in which seeding was carried out and derived a computed mean rainfall for six day periods which would have only a 5 per cent. chance of being exceeded had more abundant data been available. He came to the conclusion that only three basic weather types, determined by a consideration of atmospheric flow patterns, were favourable for artificial stimulation of precipitation and the results of his analysis of three six-day periods in which four or more seeding operations were conducted is striking. For these three six-day periods he assessed the probability of the natural occurrence of the precipitation actually measured as 8 per cent., 4 per cent. and less than 1 per cent. respectively. On 66 per cent. of all flights he considered that good rains were started as a result of seeding operations.

In Australia, 38 experiments, mainly on cumulus clouds, had been carried out up to August, 1948, and in the majority of cases the top of the cloud was observed to change from water droplets to ice particles and rain was seen to fall from the cloud base within 10 to 25 minutes, while similar clouds in the vicinity showed no such effects.

Here in South Africa experiments have been carried out in the neighbourhood of Johannesburg and radar records used for assessing the results. Thirty-six clouds were seeded with dry ice and a summary of the results shows that on only 4 occasions radar echoes, corresponding to the seeding positions could not be traced, while on 8 occasions the echoes were doubtful owing to the existence of permanent echoes on the radar screen in proximity to the seeded clouds.

One of the objects of the experiments conducted in the Union was to investigate the contention that the sudden creation of large numbers of sublimation nuclei in incipient thunderstorms may considerably modify the subsequent development by:—

(*a*) inducing precipitation at an earlier stage
(*b*) extending the area affected by the precipitation
(*c*) reducing the intensity and prolonging the duration of the precipitation.

In examining the results in relation to these contentions it seemed to be the case that the release of dry ice had the effect of inducing precipitation at an earlier stage in the cloud development. With one possible exception there was, however, no evidence to indicate an extension of the area affected by the precipitation, and it was not possible to adduce any evidence in regard to the effect of the nucleation on its intensity. In South Africa, where rainfall occurs over large areas in the form of localised showers, short in duration and often intense, there are very great potentialities in any system of weather control in which the area affected and the intensity of the precipitation may be modified. There are obvious applications in the elimination of hailstorms apart from such long term possibilities as that of furthering soil conservation.

In some of the seeding experiments with dry ice the cloud tops have been observed to change to ice crystals and within a short time the whole cloud structure has been seen to break down and disappear. This is not an uncommon feature and has been referred to in a number of the available reports. A striking example occurred in the Transvaal in February 1948, when a bank of cumulus cloud with numerous towering heads changed to an ovoid shaped mass with a smooth upper surface, apparently consisting of ice crystals and devoid of convective heads. No rain occurred and in three hours the entire cloud had dissipated. These observations suggest a possible application of a cloud nucleation technique as a method of terminating precipitation during periods of excessive rains.

From the widely divergent results which appear to follow cloud-seeding experiments, it is clear that there is much to be learnt in the technique of nucleation. A potent danger in stimulating precipitation artificially seems to be that of over-seeding. It would appear to be a requirement that the ice nuclei should be very much less numerous than the supercooled water droplets which they are to replace. Langmuir has shown however, that there is a prodigious concentration of nuclei forming spontaneously in saturated air which has been cooled below −38.9°C, and he has quoted a figure of the order of 10^{10} per cubic centimetre. This is, probably, millions of times the concentration most desirable and the success of results is likely therefore to depend on the rapidity with which the ice crystal nuclei can be distributed through a large volume of the supercooled cloud. The development of too numerous ice crystals in convective clouds is not a feature which is singular to those occasions when nuclei are artificially created, and it is thought that this does occur not infrequently in nature. Observations of convective cloud on summer afternoons in the Transvaal show that ice crystals sometimes form readily and are present in much larger numbers than is usual, and that it is on these occasions that, although all the signs are most propitious, showers seldom result.

It may well be that silver iodide particles, released below the cloud base, so that they are carried up with the vertical currents, and are thus well distributed by the time they reach the region of supercooled water droplets, may sometimes prove more effective than dry ice which results in such high concentrations of nuclei, instantaneous in action and capable of development and persistence only in sub-freezing temperatures. Recent research in the laboratory of the General Electric Corporation has shown that ice crystals do not form immediately on all the silver iodide particles present and that in the cold box experiments ice crystals forming on silver iodide nuclei precipitated for as long as one hour after these nuclei were first introduced. The report of this research suggests that the presence of silver iodide nuclei might be regarded as merely greatly increasing the probability of the formation of ice and it appears that this, rather than the sudden creation of ice crystals in astronomical numbers in a small volume, might be the more effective agent in stimulating precipitation artificially, in some conditions.

It is perhaps premature to speculate on the economic possibilities of weather control, or of artificial stimulation of precipitation, as one of its aspects.

The activities, about which I have told you, have assisted materially in elucidating some of the problems of cloud physics. There is much, however, which is still in the realm of speculation and the basic problem, to which research must continue to be directed, is that of gaining a clear understanding of the processes which result in the occurrence of natural precipitation.

If, or when, this is achieved, it may well be that the knowledge which has already been gained may be applied with predictable results in stimulating precipitation from clouds, not in a state for its spontaneous development, or of creating conditions to terminate precipitation during periods of excessive rainfall or, perhaps, to suppress destructive storms.

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The PRESIDENT had introduced Mr. King, an officer of the Government Metereological Department, stating that the Association much appreciated his coming to Durban from Pretoria at short notice to read the paper.

The author had indicated the use of dry ice and silver iodide, which both induced precipitation but in a different way. He had also mentioned rainwater as containing 3.6 milligrammes per litre of sodium chloride, and he would like to know if this applied in continental countries far from the sea. He would like to know, further, how the electricity in thunderstorms was formed, and what its action was as far as rain was concerned.

Mr. KING said that when saturated air is cooled below −39°C., ice crystals form spontaneously in prodigious numbers, and it is around these crystals that growth by sublimation takes place. On account of the similarity in structure between crystals of ice and those of silver iodide, particles of the latter also act as effective nuclei for ice crystal development.

The chemical analysis of rain-water samples, collected in different parts of the world, including samples from places near the middle of large continents, showed the concentration of chlorides to be remarkably constant.

Over the sea the number of condensation nuclei is relatively small, averaging about 1,000 per c.c.; over large cities much higher concentrations, one as high as 4,000,000 per c.c., have been found. Most metereologists believe that the major source of origin of condensation nuclei is sea-spray carried into the atmosphere by the wind. Sir George Simpson, however, considers that most of these nuclei consist of nitrous acid which may be formed by the electrical discharge in lightning flashes. Whatever their origin, examination of numerous samples of air has not disclosed a shortage of nuclei for the condensation of water droplets.

It was not thought that thunderstorm electricity played any part in precipitation release. As far as the growth of water droplets by collision is concerned, the electric charges on cloud particles are considered to be much too small to have an appreciable effect.

Mr. PALAIRET wished to know the height of the clouds experimented on, their kind and their temperature. Also, he desired information as to the frequency of suitable conditions for precipitation in this country. Many believed that, especially during a drought, there were often occasions when humidity approached preicpitation point, but owing to the limited evaporation this point was not quite reached. He thought that probably explained droughts, and also why, at the end of one, clouds were seen to pile up long before rain eventually fell. When it then came, it was usually a flood, and also usually over one of our bigger cities where there were correct conditions. Over the bigger towns, where gardens were watered and much fuel burnt, the moist air rising provided the required conditions. He asked if there were any chance that water conservation and irrigation schemes might spread evaporation over the countryside, sufficient to raise the humidity that extra degree or part of a degree which would induce precipitation.

Dr. DODDS said that since minute particles of sodium chloride form an important part in the occurrence of condensation, and they could be expected to occur in greater concentration nearer the sea, he wished to know whether tests had been made in districts where there were large salt lakes at a high altitude. Somewhere near the Great Salt Lake in Utah might provide every required condition, with salt forming a large proportion of nuclei.

Mr. King had mentioned that silver iodide crystals somewhat resembled ice crystals in form, and thus could be used as nuclei for ice formation. The crystallised form of pure sugar was not unlike that of ice or silver iodide, and he would like to know if sugar crystals had ever been used as nuclei.

Mr. KING replied that in the Transvaal the majority of experiments had been carried out on cumulus clouds which are distinguishable from cumulonimbus clouds by the absence of ice crystals at their tops. Parts of the cumulonimbus where ice crystals are present lack the clear-cut outline of cumulus cloud. In most cases cumulus clouds extended into regions where temperatures were well below freezing, without any ice crystal formation taking place. Observation showed that in a few cases ice crystal formation did not occur until a very high level was reached, and then took place with the sudden formation of very numerous crystals. By artificial means the aim is to promote the formation of ice crystals—to convert a cumulus to a cumulonimbus—at an earlier stage in the development of the cloud than that at which this might occur naturally, if at all.

The freezing level in the atmosphere varies considerably, but the average height in the Transvaal in summer would be about 15,000 feet above sea-level, while cumulonimbus clouds generally reached an altitude of 35,000 feet or more.

The cumuliform cloud seems to provide the best material for experiments, but the frequency of occurrence of suitable conditions was difficult to state. He thought that in the Transvaal the number of occasions on which artificial stimulation could be carried out with advantage was fairly high. It is not infrequently that clouds develop, and precipitation would appear to be imminent, but does not occur spontaneously.

Experience in the Transvaal seems to confirm the belief that after a period of drought thunder-showers appear to occur less readily than under similar conditions following thunderstorms on the preceding day. If it is the case that the first thunderstorms, following a period of drought, tend to break over large towns, the explanation might possibly be associated with the higher concentration of nuclei found over such areas.

Whether or not precipitation occurs is only partly dependent on the water vapour available. There are numerous other factors which must be taken into account, and there is no simple relationship for thunderstorm prediction in terms of humidity.

He was unable to say whether experiments had been carried out with sugar crystals as possible sublimation nuclei.

Dr. DODDS said this subject had not been discussed before at our Congresses. It was of great importance to everybody, and not least to the sugarcane industry, which exists here at the lower limit of rainfall for this crop. It was of great interest to hear of world-wide developments arising from the primary researches in the artificial promotion of rainfall. It might be that a new phase in human history was beginning and that belore long the problem of producing rain artificially would be solved.