

STUDIES IN ARTIFICIAL RAIN : THEIR PROGRESS AND PROSPECTS

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Abstract

The progress made by studies of the phenomenon of rain is reviewed. Several techniques for modifying clouds so as to accelerate rain-drop precipitation are described.

Introduction

Ample evidence now exists that by suitable intervention, man may be able to induce rain artificially under favourable circumstances. The prospects raised by this possibility surely cannot be lost on any one. Chief among them is the prospect of the farmer's liberation from the caprice of natural weather. In addition, there is the prospect (to which developing nations most assuredly do not require conversion) that well-designed rainmaking could reduce the necessity of elaborate and costly irrigation networks. There seems to be no doubt, therefore, that studies in artificial stimulation of rain are very valuable indeed.

What, then, are the advances which such studies have made? What constitutes the phenomenon of rain? By what mechanism is natural rain formed? Can this mechanism be set off artificially, if so when and how? The branch of science which seeks answers to these and similar questions is called **cloud physics**. Cloud physics uses many of the methods of "conventional" physics. It has, however, an unmistakably interdisciplinary flavour about it, because it is also interwoven with other disciplines — notably, meteorology, chemistry and mathematics. This paper presents a brief review of the progress made in this relatively young discipline and of the prospects such progress raises. In a brief paper such as this, we have had to leave out much of the repertoire of experimental techniques employed in cloud physics. For the same reason, we have not rolled out the mathematical artillery of cloud physics. These shortcomings are corrected in the literature which is cited.

Condensation

When there is not enough water vapour in the atmosphere, rain cannot fall. Even so, the "rain problem" is scarcely one of adding water into the atmosphere. Natural processes, such as evaporation and diffusion achieve this remarkably well. Instead, the rain problem is one of wrenching water from the atmosphere. Here natural processes cannot be relied upon entirely, and an external "push" is often desirable. But for this strategy to be successful it must be based on detailed knowledge of the controlling factors at play.

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The initial process in the formation of rain is condensation. In this process liquid-water droplets are formed from water-vapour molecules, this being brought about primarily by adiabatic expansion of rising moist air. The process is governed by thermodynamic considerations and may be studied in terms of changes in the energy of a condensing vapour before and after condensation. Because atmospheric condensation occurs at nearly constant temperature and pressure, certain advantages exist in studying it using the Gibbs free energy, G . One such advantage is the fact that when the temperature and pressure are known to be constant, the conditions corresponding to equilibrium may be determined merely by searching for conditions which make G extremum. In this way one may investigate the various ways in which condensation may be accelerated. Condensation, it turns out, can be accelerated by the addition of various kinds of particles, including water droplets, to the condensing vapour. The added particles (called nucleators) then provide centres of condensation upon which water-vapour molecules attach themselves.

Not all nucleators accelerate condensation by the same amount. Some nucleators are better suited for this purpose than others. The efficiency of a nucleator may be measured in terms of the size of the droplets that will form around it under certain specified conditions (e.g. temperature and vapour-pressure). Kelvin (1870) and Gibbs (1928) were the first to show that for homogeneous condensation, in which water droplets are formed by the collection of water molecules around other water molecules, the radius, R , of the droplet so formed is given by

$$\ln \left(\frac{P}{P_0} \right) = \frac{2\sigma_{lv}}{nkTR} \quad (1)$$

Here T is the temperature, P the vapour pressure around the droplet, $\frac{P}{P_0}$ the vapour pressure over a plane liquid surface at the temperature T , k Boltzmann's constant, σ_{lv} the surface tension of water, and n the number of water molecules per unit volume of the droplet. Eq. (1) implies that smaller droplets require higher supersaturations (measured as the ratios $\frac{P}{P_0}$) and, when the actual ambient supersaturation is lower, will evaporate rather than grow. Since homogeneous condensation must necessarily start with small droplets, Eq. (1) explains why condensation may not occur for a long time even at high supersaturations.

One may get an idea of why spontaneous condensation occurs at all by regarding water vapour as a mixture of H_2O molecules and their complexes $(H_2O)_n$, $n \geq 2$ formed in response to the attractive dipole-dipole interactions between the water-vapour molecules (each of which is, as is well-known, a dipole) on another. Considerations based on Maxwell-Boltzmann statistics (according to which the number, N , of particles with energy G is related to the number, N_0 , of particles with energy G_0 by $N = N_0 \exp [(G_0 - G)/kT]$) show that water complexes form

about 1% of atmospheric water particles (Nikandrov 1965). However, these complexes are subject to thermal fluctuations, so that while their number remains more or less the same, the complexes themselves are not always, the same, the lifetime of any given complex being of the order of only 10^{-9} s. During their formation, complexes which are larger than about 4 water molecules acquire a property characteristic of liquid phase, namely, surface tension. Owing to surface tension, the equilibrium vapour pressure over the complex is greater than that over a planar surface of water (Eq.(1)). Consequently, only adequate supersaturation can prevent a complex from disintegrating in its normal lifetime. However, while it lasts, each complex is a *bona fide* condensation nucleus upon which single vapour molecules may collect. The efficiency of this type of condensation is nevertheless severely limited by the short lifetimes of the complexes. Efficient condensation must therefore be sought in processes other than homogeneous condensations — that is, in heterogeneous condensation.

Suppose, therefore, that water-vapour molecules condense on an ion — rather than on another water molecule or complex. Assume that the ion has charge q and that the permittivities of air (a) and water (w) are ϵ_a and ϵ_w , respectively. In this case the radius R of the water droplet formed by condensation can be shown (Fletcher 1969) to satisfy the following equation.

$$\ln \left(\frac{P}{P_0} \right) = \frac{2\sigma_{lv}}{nkTR} - \frac{q^2}{32\pi^2 nkTR^4} \left(\frac{1}{\epsilon_w} - \frac{1}{\epsilon_a} \right) \quad (2)$$

Comparing Eq. (2), one version of which was known to Thomson (1888), with Eq. (1), we see that everything else being the same, condensation upon ions is more efficient (i.e. requires lower supersaturations) than homogeneous condensation. In other words, an otherwise stable vapour may be made to condense by sprinkling it with ions. The effect of sprinkling the vapour with neutral particles can be shown to be the same as Eq.(1) (Fletcher 1969). Nucleation, or condensation, upon neutral particles thus requires just as high supersaturations as homogeneous condensation. It has the advantage, however, of lowering the free energy required by the onset of condensation. Furthermore, the detailed structure of the surface of the nucleating particle is also relevant. Cracks and crevices on the surface of the particle provide good condensation sites and, although the threshold for nucleation upon such surface irregularities depends in detail upon their geometry, it has been found always to be lower than the threshold for nucleation upon a plane or a convex surface (Turnbull 1950).

Another method of nucleation by foreign particles makes use of soluble particles. We recall Raoult's well-known law, according to which the vapour pressure over a solution with a mole fraction f_w of water is lower by the factor f_w than that over pure water. One way to increase R , therefore, is by sprinkling the vapour with soluble particles which readily disso-

live in the film of water that forms around them. In that case, the supersaturation which will support droplets of radius R is given by

$$\ln \left(\frac{P}{P_0} \right) = \frac{2\sigma_{lv}}{nkTR} + \ln f_w. \quad (3)$$

For the same value of R , this is lower (since $f_w < 1$) than the supersaturation required for homogeneous condensation (Eq.(1)). It is of course, even lower if the nucleating particles, beside being soluble, also contain ions.

The Growth of droplets

The preceding section has indicated the inadequacy of water-vapour molecules as condensation centres and has also suggested several ways in which the process of condensation may be accelerated by the addition of suitable nucleating particles. These ideas are sufficiently well supported by experiment. In this section we pass on to a consideration of how the water droplets, once formed, grow into larger drops which may eventually fall as rain. This happens in two ways. The droplets grow by diffusion and by coalescence.

Consider any one of the droplets formed by the initial process of condensation upon one nucleus or another. Assume that the droplet has radius R and is in environment of moist air which has n_0 water-vapour molecules per unit volume in regions close to the droplet and n_∞ water-vapour molecules per unit volume in regions far away from the droplet. Such a droplet will grow as water-vapour molecules diffuse into it and become part of it. The rate at which the mass M of the droplet increases as water-vapour molecules (each of mass m) diffuse through the surface of the droplet may be shown using Fick's well-known law of diffusion, to be given by

$$\frac{\partial M}{\partial t} = 4\pi R D m (n_\infty - n_0). \quad (4)$$

Thus, growth by diffusion, being proportional to R , accelerates as the droplet grows larger and larger, but it is less and less efficient for smaller and smaller droplets. (An enduring curse in cloud physics is that clouds must grow from small droplets and yet small droplets grow at an extremely slow rate.)

The second mechanism of droplet growth, coalescence, begins to be appreciable only after the droplet has (by another mechanism) grown large enough in diameter ($\approx 4 \times 10^{-5}$ m) for the frequency of collision between it and other droplets in the cloud to be considerable. In coalescence, the problem is primarily an aerodynamical one. At any moment, the droplets are envisioned to be falling through the viscous air under the action

of gravity towards the ground. Larger droplets will have greater fall velocities, v , as may be seen from Stokes' well-known law. At 20°C , $v \approx 1 \times 10^2 R^2 \text{ ms}^{-1}$ near sea-level. Thus larger droplets are expected to overtake smaller ones and occasionally to collide with them. Some of the collisions result in a merger, or coalescence. The rest do not. One of the problems that has engaged the minds of cloud physicists (Langmuir 1948, Sartor 1954; Pearcey and Hill 1957, Hocking 1959) and continues to do so, is one of determining the collection efficiency of a droplet — that is, the probability that collision of the droplet with another will result in coalescence. The calculations are complicated by many factors, including the fact that one must take into account the (turbulent) flow of air around the droplets. They show that the onset of coalescence requires that there be present initially some droplets greater than about $4 \times 10^{-5} \text{ m}$ in diameter. They also show, as one would intuitively expect, that the collection efficiency of any given droplet increases as the droplet grows larger, making the droplet capable of colliding and coalescing with virtually any other droplet in the cloud. All of this goes to show that a cloud in which few or no droplets are greater than about $4 \times 10^{-5} \text{ m}$ in diameter will be stable against coalescence and will be unlikely to lead to precipitation. This explains why clouds formed inland are more stable than clouds formed near the sea. The latter are formed from air masses in which giant salt nuclei are present while the former are formed from air masses in which few large aerosols are present. [Also see a survey of this subject by List (1974)].

How fast, it may be asked, does a droplet grow by the mechanism coalescence? In a cloud whose water content is $w (\approx 1 \times 10^{-3} \text{ kg m}^{-3})$, a droplet of mass M , radius R , terminal fall velocity v and collection efficiency e falling through an environment of smaller droplets each of radius R_s and fall velocity v_s will grow at the rate given by the following equation.

$$\frac{\partial M}{\partial t} = ew\pi(R + R_s)^2(v - v_s). \quad (5)$$

Eq. (5) may readily be verified by following the falling droplet as it mops up the smaller droplets in its path. As in growth by diffusion, Eq. (5) shows that small droplets grow more slowly than larger ones. However, in growth by coalescence larger droplets grow even faster than they do in growth by diffusion (compare Eqs. (4) and (5)). For this reason, once it starts, coalescence quickly dominates over diffusion. It remains to be pointed out, however, that in real clouds several complications enter to modify Eq. (5). Chief among these is the convective motion of the atmosphere which creates updraughts and downdraughts the effect of which is to modify Eq. (5). (Bowen 1950). In any case, when the droplets fall out of the cloud, they enter regions in which $w \approx 0$ and so cease to grow (Eq. (5)) and if by then they have not grown into sufficiently large drops they may in fact completely evaporate before reaching the ground, thus ending in a rainless dissipation of the cloud. Under suitable conditions, however, they reach the ground as rain.

Artificial Stimulation of Rain

The mechanisms of cloud-droplet growth discussed in the above section show that small droplets tend to stay that way and grow only with extreme reluctance. A cloud composed of small droplets is thus stable against precipitation. Attempts to induce the precipitation of clouds artificially must therefore reckon with this problem. They must seek ways in which cloud stability can somehow be upset. The techniques for achieving this fall into two broad categories: Those which are appropriate for warm clouds (0°C and above) and those which are appropriate for subfreezing clouds (below 0°C).

Stimulation of precipitation in warm clouds uses the principle that the addition of large hygroscopic particles (with diameters equal to or greater than the critical diameter required for coalescence), when properly made, will increase the number of large droplets in the cloud and trigger coalescence on a sufficiently large scale to end in rain. A sufficient concentration of salt (NaCl) particles released below the cloud base (and carried upwards through the cloud by updraughts) may therefore stimulate precipitation if the vertical extension of the cloud is several kilometres and its lifetime an hour or more. Davies (1954), then working in East Africa, launched balloons carrying finely powdered salt which was dispersed explosively at cloud base. He has reported that rain followed in 20-30 minutes. A second technique is to spray the cloud with fine water drops from suitably equipped aircraft (Fletcher 1969). Another method employs electrical effects: Ions are introduced from below and are transported by eddy diffusion (Vitta 1974) into the cloud where they become attached to cloud droplets. Electrostatic attraction then accelerates coalescence between oppositely charged drops and this may set off developments towards rain (Bradley and Semonin 1969).

The above and similar techniques of inducing precipitation are appropriate for warm clouds. They differ from those appropriate for subfreezing clouds. Here the principle utilized is the fact that subfreezing clouds become unstable when ice crystals are present in sufficiently large concentrations — about 1 crystal per litre — (Bergeron 1945). Techniques employing this principle seek to set off the formation of more and more ice crystals within the cloud until the stability of the cloud is upset. One way of achieving this is by adding solid CO_2 (which sublimates at -78°C). This chills the supercooled cloud droplets into tiny ice crystals, and may even produce spontaneous formation of ice nuclei directly from the water vapour within the cloud. The consequence of all of this is to upset the stability of the cloud. Other techniques disperse particles of silver iodide (AgI) or lead iodide (PbI_2) into the cloud (Vonnegut 1947). These iodides have crystal structures similar to that of ice; therefore ice readily nucleates upon them. The result of this is again to reduce the stability of the cloud and enhance the probability of precipitation.

In both of the above categories of methods for inducing precipitation, success depends on the proper choice of the type, amount and distribution of the reagent. It is believed that the optimum ratio of ice-forming nuclei

introduced into the cloud to the supercooled droplets in the cloud is about 1:1000 (Nikandrov 1965). With this ratio, the particles obtained after sublimation of the droplets on to the nuclei will have radii 10 times larger than the radii of the cloud droplets and will therefore readily grow by coalescence. With greater ratios, too many particles (all of them too small) will be formed after sublimation and the cloud will merely have been transformed from a water cloud to an ice-crystal cloud. With smaller ratios, not enough large particles will be formed to dissipate the cloud.

Conclusion

The preceding sections have reviewed briefly the progress made by cloud physics and have indicated the prospects raised by this progress on artificial rain. There is a possibility that we may have left the overly sanguine impression that the rain problem has been resolved. This is, however, far from true. One needs only to recall that it still rains when "it jolly well pleases" even in countries like the USA and the USSR which have carried out the bulk of the recent research in this field and which certainly have enough resources to make it rain when they please — if rainmaking were fully understood. Moreover, even when rainmaking is successful, there is need to ascertain that it would not have rained anyway. Satisfactory rejoinders to both of these demurs exist, of course. But in view of what has preceded in earlier sections, ending on these demurs seems to leave just the right flavour of the present state of the rain problem.

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