The Problem of Artificial Control of Rainfall on the Globe[1].

I. General Effects of Ice-Nuclei in Clouds.

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Abstract:

Different kinds and degrees of *colloidal* and *thermodynamical instability* of diverse systems of cloud-particles, partly leading to release of precipitation, are discussed, aiming at estimating the possible effect of "seeding" clouds artificially with ice-nuclei. — A low ratio ν of supercooled cloud-droplets versus ice-crystals ($\nu \leq 1$) would ensure very rapid glaciation of the cloud, but no precipitation release and no substantial improvement of visibility within it: *overseeding*. High values of ν ($> 10^6$) would lead to the formation of big, though very sparse precipitation elements, but not noticeably improve visibility within the cloud: *underseeding*. Favourable values of ν seem to lie around 10^3. — Cases of successful artificial seeding may be explained by natural seeding indirectly caused by the artificial one: *double release*. — Lastly, an inventory of the actual tropospherical clouds and cloud systems indicates that the main possibility for causing considerable artificial rainfall might be found within certain kinds of orographic cloud systems, to be treated in a following article.

Since ALFRED WEGENER's first suggestion in 1911[2], concerning the rapid growth of ice-crystals in supercooled water-clouds, those investigators who have advanced and studied the hypothesis of the release of ordinary precipitation from clouds by ice-nuclei[3] certainly all have felt that artificial rain from supercooled clouds would in principle be possible, provided efficient natural ice-nuclei were *not* omni-present, and that one could easily produce artificial ones in a sufficient number, i.e. to the order of magnitude of billions or trillions (10^{12} to 10^{18}). In fact, for every artificial rain-drop desired one would in principle need *one* ice-nucleus; and an ordinary Cumulonimbus certainly produces the just-mentioned enormous number of rain-drops during its life-time. — It was not, however, until I. LANGMUIR and V. SCHAEFER[4] at Schenectady, a few years ago, began "seeding" clouds with solid carbon-dioxide (and thereby cooled moist air below the critical temperature —35° C, where ice-nuclei seem to form spontaneously) that Meteorology got a practicable method of artificially introducing any desired amount of ice-nuclei into the free atmosphere. SCHAEFER 1948 estimates the number of ice-nuclei produced, under favorable circumstances, by a single dry-ice pellet of pea-size, during its fall through moist air, to about 10^{16}, before it is evaporated.

On the *one* hand the ice-nucleus theory of the release of ordinary precipitation has been generally accepted for higher latitudes by meteorologists. On the *other* hand some of the seeding experiments of LANGMUIR and collaborators, and others[1], seem most decidedly to have caused those characteristic changes of supercooled clouds which accompany the release of precipitation from such clouds. It is, therefore, justifiable to say that to-day both theory and experiment show artificial release of precipitation to be possible. The experi-

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[1] Based on a lecture delivered Aug. 25, 1948 at the Meeting of the U.G.G.I. at Oslo, and on a manuscript Report, dated April 24, 1947 (see References).

[2] ALFRED WEGENER, Thermodynamik der Atmosphäre, Verlag J. A. Barth, Leipzig 1911.

[3] T. BERGERON (1928, 1935), W. FINDEISEN (1938) and others.

[4] Cfr list of References.

[1] e. g. E. BRUN and L. DÉMON 1947; E. B. KRAUS and P. SQUIRES 1947.

ments have then also been repeated in many places, and much publicity, and perhaps too much optimism, has been bestowed on this activity. At the UGGI-conference in August 1948, however, Dr FR. REICHELDERFER stated that, out of a great number of cases of cloud-seeding in the U.S. which had been followed by precipitation from the cloud in question, none had occurred without precipitation from similar clouds within 30 miles[1]. This statement was also, at that occasion, in principle supported by Dr H. BYERS.

The general discussion of this question seems, however, to a certain extent, to have gone astray, as the opinions on it range between "no artificial release proved" and "world-wide rain control possible". The question we now have to investigate is, in reality, no longer whether precipitation can be released artificially, but rather whether such a release can produce an *appreciable amount of rainfall*, and *when* and *where* this could be done. To arrive at any conclusions regarding this problem we ought then to take an inventory of the different kinds of rain-producing clouds on the globe as to their properties in this respect and their relative frequencies. — Before proceeding to this work, though, we need to make certain statements and to define some fundamental concepts within this field.

1. Thin stratiform clouds, i.e. clouds of small vertical extent (e. g. < 100 m), occurring within a more or less stably stratified and quasi-laminar current, formed quite recently and at temperatures not much lower than $-5°$C (Stcu, Acu), will in general mainly consist of minute water-droplets ($1\,\mu < r < 10\,\mu$) of rather uniform size. In these cases, also, the electrostatic field in the cloud will be weak, the electric charge of the droplets, if any, will be unipolar (and their temperature will be uniform, cfr below). Thus, there will be little probability for coalescence (collision and fusion) of droplets from kinematic or electrodynamic reasons within such stratiform clouds as defined above, and the cloud-mass will be rather *colloidally stable*. — Any growth of some slightly colder or bigger (surface tension effect) droplets by condensation, at the cost of or in comparison with the other droplets, will be counteracted by the latent heat of condensation, and also by convective and radiative heat exchange. These factors should generally check any such growth of selected droplets, provided the difference in temperature or radius has not already become considerable thanks to other influences, and if the cloud elements are not too small ($r > 10^{-6}$ cm). The cloud-mass will then also be *thermodynamically stable*. — As a term comprising both these states (and equivalent to the earlier, and often misused, term "colloidal stability") we shall use the expression *physical stability of a cloud-mass*. Any new-formed and rather thin stratiform clouds would then be termed "physically stable" as long as they remain pure water-clouds. — According to FINDEISEN 1932, HAGEMANN 1936, HOUGHTON and RADFORD 1938, and others, however, even newly formed fog contains droplets of widely different sizes (e. g. $2\,\mu < r < 30\,\mu$). In fact, fog and Stratus rarely show typical coronae etc. (whereas these are frequent and often brilliant in thin Altocumuli, cfr 8 b). From these statements we infer that neither fog, nor clouds forming near the surface of the earth, in general possess real physical stability, but that their state will approach the one treated in 2.

2. Within old stratiform clouds of considerable thickness, but still not reaching the natural ice-nucleus level (cfr 6 b), differences of droplet-size may have had time to get established, by coalescence, by different "time-of-rise" due to turbulence etc. (I. LANGMUIR 1944, 1948), or by other agents, though weak, and by ensuing differences of fall velocity. The further growth of the biggest droplets, especially by coalescence, but possibly also by direct condensation, may then no longer remain negligible: the cloud-mass becomes (*slightly*) *colloidally unstable*.

According to FINDEISEN 1939 a, in pure water-clouds, collisions caused by different fall-velocities v (due to different size of droplets) will be the only important agent for growth of very small droplets. From his formula [12], l. c., p. 367, one can calculate the vertical distance z required for an isolated

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[1] Cfr R. COONS and collaborators 1948 a, b. — With *stratiform* clouds the effects of seeding were none or insignificant. Trace of precipitation reached the ground in 4 cases of 38, and then only from Stratus with a base 600—1 200 m above the ground. — With *cumuliform* clouds the most obvious effect of seeding was even the dissipation of (part of) the clouds, without precipitation.

droplet of size r' to grow by collisions to a size r'' when falling through a cloud of n_1 droplets/cm^3, having a uniform size r_1. — Assuming $r' = 20\mu$, $r'' = 50\mu$, $r_1 = 10\mu$, and $n_1 = 400$, we get $z = 80$ m. Even in this extreme case, corresponding to the improbably high water content of 1.7 g/m^3 in a Stratus (and since only few drops would start their fall at the very top of it), a cloud layer of about 100 m depth would, by this process, mainly deliver droplets of a size $r'' < 50\mu$. — Moreover, **Findeisen** mentions experiments showing that for droplets with $r > 10\mu$ the speed of coagulation in reality is less than the one calculated from his formula [12]; and the bigger the droplets, the smaller this speed. These results are corroborated by the experience that droplets with $r > 100\mu$ rarely fall out of any pure water-clouds, at least in temperate and polar regions, in day-time. — As an explanation of the above facts it is tempting to assume that the hydrodynamic repulsion, studied by V. **Bjerknes**, between bodies moving with different velocities through a medium (cfr V. **Bjerknes** and collaborators 1933, p. 247, and T. **Bergeron**, 1935, p. 161), gains a supreme influence for values of r and v (or Δv) exceeding certain limits, presumably the limits of validity of **Stokes**' law (roughly $r = 100\mu$ and $v = 0.8$ m/s).

3. Within cumuliform clouds both condensation and turbulence will occasionally be intense, and the vertical extent of the cloud-mass will be much greater than in the cases 1—2. If, now, the fall of the biggest initial droplets is nearly balanced, for a long time, by a suitably distributed updraft, this state will correspond to a much prolonged "path of fall" (Fallstrecke) within the cloud; the growth by collision (and also to some extent by direct condensation), shown in **Findeisens** diagram (1939 a, p. 368), may then attain extraordinary values. Even before the cloud-mass reaches the natural ice-nucleus level, therefore, the factors mentioned in case 2 may now cause a *marked colloidal instability* of the cloud-mass. This instability, together with the thermodynamic instability discussed in 4, reaching appreciable values in case of intense convection, may explain the fact that such clouds, in tropical regions, sometimes give showers although their tops still, seemingly or manifestly, are pure water-clouds and even may not reach the 0°-isotherm; cfr **Kotsch** 1947, **Haggard** 1948. See also footnote, p. 40.

In higher latitudes both the vertical extent of convective clouds, and their intensity of condensation and of turbulence, is on an average smaller. Moreover, in these regions, the cloud tops will reach the — 10°-isotherm by the time the above-mentioned factors could achieve appreciable precipitation release, and the efficient release by ice-nuclei (cfr 6 b) will then dominate the process. In many cases, it is true, weak trails of precipitation can be detected underneath real summer-Cumuli even at our latitudes at midday or in the afternoon. The release will then only be of the slow or inefficient type (cfr 5), though. The droplet-radius will keep $< 10^{-2}$ cm, and the trails will almost invariably evaporate before reaching the ground over low-land, owing to the rather high condensation level, the considerable humidity deficit — and in some cases also thanks to the updraft — below the cloud; cfr the table showing the time of evaporation, for droplets of different sizes, given by **Findeisen** (1939 b, p. 457). Not until near sunset, or at night, when the Cumuli transform into Stratocumuli vesperalis, the lower strata cool down, and the updraft ceases, may these trails reach the low-land in appreciable amount (cfr also 4 below).

It should also be borne in mind that there are as yet no systematic observations as to the rain intensity of those tropical convective clouds which keep below the natural ice-nucleus level as compared with those that reach it and have their tops transformed into ice-cloud. It is very probable that the latter cloud-type, the real Cumulonimbus, just as in our climates, on an average renders much more precipitation. The report of L. B. **Leopold** and M. N. **Halstead** 1948 is of interest in this connection. Their Test Cloud No. 1 at last surpassed the 0°C-level, and from then on it rendered about 80 % of its total precipitation (about 25 mm in the maximum zone; l. c., p. 528). Cfr also the hypothesis of a "double release" treated in 11 below. — Anyhow, the burden of proof regarding this problem remains with the adherents of opposing theories.

4. At night, and in the shadowed parts of cumuliform clouds even in day-time, the outermost droplets of the cloud-mass are

cooled by outgoing radiation more than those in its interior; condensation will then increase on these droplets, especially if the cooler droplets mingle with the warmer ones thanks to turbulence: the cloud-mass will then become *slightly thermodynamically unstable*. Already in 1877 O. REYNOLDS ascribed the ordinary release of precipitation to this very effect. — SV. PETTERSSEN (1940) has pointed out (l. c., p. 45—46) that very small temperature differences ΔT, ranging from 0.01° C for $T = +25$° C to 0.12° for $T = -20$°, suffice to render a difference in saturation pressure equal to the maximum value of $E_w - E_i$ (cfr 6 b and 7). Droplets of different temperature can also be brought very close together without any radiation cooling, by turbulence alone, and it is reasonable to assume that this effect will operate intensely within Cumuli, even in day-time. — This thermodynamic instability, however, is in reality counteracted in two ways: firstly by the heat of condensation (cfr 2), and secondly by the obvious fact that the temperature differences ΔT will only be efficient between droplets at very short mutual distances Δa. The smaller Δa, however, the greater will the equalization of ΔT be, thanks to radiation and conduction of heat between the droplets; i.e. ΔT will rapidly decrease with Δa, and, under ordinary conditions, the cloud-mass may then gradually regain thermodynamic stability.

5. In extratropical regions, all the processes 2—4 described above, implying coalescence or individual growth of droplets, will generally only lead to a slight or easily suppressed physical instability within a cloud-mass. Therefore, they are only slowly and weakly contributing to the precipitation release within the cloud. The drop-size and intensity of the precipitation released will be so small that it cannot reach the ground unless with the very low cloud-base of Stratus or fog, and it has then mostly the character of *drizzle* ($r < 250\ \mu$). These kinds of precipitation releases, therefore, shall be termed *slow* or *inefficient;* cfr also 12.

6. *The only systems of cloud elements, i.e. cloud-masses, which possess intrinsic and irrepressible thermodynamic instability are those where water coexists in all three phases.*

(a) With temperatures above 0° C this case will occur within or underneath a cloud from which snow is falling but is as yet not entirely melted, i.e. down to the +2°- or +3°-isotherm of the air itself. Within this layer the air will be markedly supersaturated with respect to the melting snow of 0° C temperature; therefore, condensation will be intense on the snowflakes, particularly above the general condensation level (the cloud base), and their latent heat of fusion will compensate the heat of condensation as long as they are not entirely melted. Thus, the water content of the precipitation may be considerably increased within the layer mentioned, cfr 4. It must be borne in mind, though:

(1) that this effect involves that real precipitation from the cloud already has been started by some other agents, and

(2) that the effect disappears soon after the melting of the last snowflakes, thanks to several cooperating factors, partly mentioned above.

This process is then only operating within a layer of, say, $\leqq$ 500 m vertical thickness and under quite special conditions.

(b) With temperatures below 0°C unstable systems are formed by clouds containing both supercooled cloud droplets and ice-crystals of any sizes, because $E_w > E_i$ for $T < 0$°C; cfr BERGERON 1928, p. 29, and 1935, p. 164.

How the ice-nuclei or ice-crystals form, or are introduced, within supercooled water-clouds, has still not been satisfactorily proved. Experience shows, however, that in the atmosphere they generally appear, at a temperature of ca — 10° C, in such a number, and/or with such an efficiency, that the thermodynamical instability in question leads to a very rapid *glaciation* of the cloud and an efficient release of precipitation from it. These observations, mostly made with Cumulus-clouds, do not preclude the possibility that some ice-nuclei exist also at higher temperatures (perhaps even above 0° C). Their number and/or efficiency, though, may then be so small that their effect remains insignificant and undetectable in natural clouds (cfr below p. 36, and SHEPPARD 1947, p. 492), until, at lower temperatures, the effect starts increasing at such a pace that it becomes manifest from a rather well-defined threshold-value T_i of the temperature, and downward.

It is also plausible that the ice-nucleus effect is a function of time. Within the towering Cumuli, then, the tops generally would have had time to reach, say, the — 10°C-level before the effect becomes manifest, although it started an appreciable but clandestine work within the cloud already, for instance, at the — 5°C-level. Within cloud sheets forming by the slow processes of condensation, on the other hand, the time factor will probably allow release of precipitation even from clouds that only reach that lower level (about — 5°C). — The possible order of magnitude of this time-factor will be discussed at a later occasion. It may be mentioned here, though, that the time of partial resp. complete glaciation of a supercooled water-cloud increases with the ratio ν (see 7) and with the original droplet-size. The latter fact was already stated by FINDEISEN in 1939 (l. c., p. 460).

Whichever is the nature of the ice-nuclei, and the cause of their appearance and of their nuclear effect, enough theoretical and empirical evidence has now accumulated to show that they form an agent of precipitation release which cannot be suppressed by any of the checking factors mentioned in 1—4, because they provoke intrinsic thermodynamic instability within certain cloud-masses, and as they are not melted or destroyed by the sublimation which takes place on them. — Whichever is the varying level at which their effect of releasing precipitation becomes manifest we shall call it the *natural ice-nucleus level*. The position of this level, within different clouds, will probably be defined by the above-mentioned threshold-value T_i and by the time factor τ_i.

7. The process of natural ice-nucleus precipitation release hinted in 6 b must have an optimum effect at certain values of temperature, size and number of droplets, ratio ν between specific number of droplets n_w and of efficient ice-nuclei n_i, and, last but not least, the efficiency of the latter. All other conditions being the same, temperatures around — 12°C, where $E_w - E_i$ is a maximum, must be the most favorable for the diffusion transport of water vapor from droplets to crystals, and the speed of this transport should be roughly proportional to $E_w - E_i$. Increasing efficiency of the ice-nuclei can in itself only favour the release. Decreasing size of droplets will increase the vapor pressure at their surface and also favour the process.

(a) When the ratio ν is exceedingly great (e.g. 10^9, with 10^9 droplets and 1 crystal in 1 m^3) each crystal may grow at a maximum speed, and it may attain a considerable size. The total number of precipitating elements (rain-drops when melted) will be very small, though. Thus, the change effected within the cloud itself, as to water content, visibility etc., will be slow and generally unconspicuous. A cloud sheet of 1000 m vertical thickness would then in total only render 1000 elements per m^2, or 10 per dm^2, of its base surface, until the stock of nuclei was reproduced or renewed from outside; the bulk of these few precipitation elements — spread over minutes, if not over hours, cfr (c) below — would certainly evaporate at a rather short distance below the cloud base (cfr the remark on evaporation in 12). See also footnote, p. 40.

(b) On the other hand, if the ratio ν were 1 (e.g. $n_w = 1000$ elements/$cm^3 = n_i$), and all these ice-nuclei were of equal efficiency, then in a very short time the crystals would have "consumed" all the droplets by the diffusion transport of water vapour. If we then neglect the water contents of the original ice-nuclei, this would only mean, however, that the 1000 droplets/cm^3 would have transformed into just as many ice-crystals of the same weight as the droplets. (We then also neglect the effect of the release of heat of fusion on the state in the cloud.) Assuming the original droplets to have $r = 6\,\mu$, which corresponds to a water content of the cloud of about 1 g/m^3, and a fall velocity $v = 0.45$ cm/s, or 16 m/h, at normal pressure (provided $v = 1.26 \cdot 10^6 \cdot r^2$), the end result would be an ice-cloud of the same geometric properties and values of ν, and *no release of precipitation at all*. If this great number of ice-nuclei were artificially seeded into the cloud, we should then denote it as entirely *overseeded* from the view-point of artificial precipitation release.

(c) Thus, the optimum ratio ν_0 must lie somewhere between 1 and ∞, and further investigations, based on mathematical and experimental methods and on measurements in natural clouds, may throw some light on this problem. A reasonable figure for ν_0 in precipitating clouds might be of the order 10^3, because then the final diameter of the growing ice-crystals will be 10 times that of the original droplets if we neglect all other releasing factors and any further general condensation within the cloud-mass; and at the same time their specific number n_i will be considerable. Under the above assumption ($n_w = 1000$, $n_i = 1$, and $r_w = 6\,\mu$) r_i would become 63 μ, which would cause great differences of fall velocities (0.45 and 44 cm/s); these would in turn start coalescence at a large scale in the cloud. A rough calculation (BERGERON 1935) showed that under these assumptions, at — 10° C, half the water amount of the droplets would sublimate on the crystals in about 5 min. In 1939 FINDEISEN arrived to similar results, l. c., p. 459—460. — The improved treatment of this problem, hinted on p. 36, indicates 6 min. as a preliminary value for the time of complete glaciation τ_i of the above "model cloud." These figures agree rather well with the times observed in nature at these temperatures for the transformation of a Cu-top into a fibrous Cunb-top. This does not prove, though, that $\nu = 1000$ is either the ordinary ratio in nature, or the optimum ratio ν_0, but it may serve to indicate that, probably, very much cannot be gained as to precipitation by seeding clouds with artificial ice-nuclei above the (— 5° C- or) — 10° C-isotherm since, within these strata, Nature itself seems to perform the seeding and precipitation release in a most efficient manner. — The thing to be aimed at, artificially, must be *the introduction of suitably numerous and sufficiently effective ice-nuclei into cloud strata surpassing the 0° C- but not the (— 5° C- or) — 10° C-isotherm.*

Fig. 1. Orographic, physically stable cloud-cap, formed on the volcano, Soembing, Wonosobo, Java. — Photo VISSER, 26. II. 1924.

8 (a). Clouds of the kind shown in fig. 1, orographically formed individual cloud-caps of about 1—5 km horisontal and 0.1—0.5 km vertical extent, however intense the condensation may be within them, contain only wet fog — or, at the utmost, very fine drizzle — because they are too thin vertically, and their cloud droplets are too short-lived. Each individual droplet forms within the windward part of the stationary cloud-mass, rushes through it in less than 10 min., and is dissolved at its leeward end before any of the inefficient factors of precipitation release have had enough time to cause an appreciable effect. In all the cases where the cloud-cap lies entirely below the natural ice-nucleus level (in the case of fig. 1 the whole cloud lies even below the 0° C-isotherm), then, the cloud-mass will remain physically stable and will deposite little or no precipitation on the ground enveloped in the cloud. This statement is confirmed by the fact that the cloud-cap is symmetric with respect to the obstacle causing it; then, also, no Föhn-effect will occur on the lee-side of the obstacle.

(b). What has here been said concerning stationary clouds enveloping an obstacle must also hold in applicable parts for all clouds occurring in stationary (orographic) waves of the size and kind treated here, even if their base lies many km above any mountain top, as is the case with most of the orographic and frontal Acu lenticularis. An excellent proof of their constitution (minute water-drops of almost equal size) and physical stability is in this case often rendered by the brilliant diffraction phenomena (coronae, gloriae, irisation etc.) displayed by their thinner parts.

(c). Whenever any of the clouds discussed above surpass the ice-nucleus level, on the other hand, they will soon become physically unstable, which in case (a) leads to appreciable precipitation on the mountain and an asymmetric cloud-cap. In case (b) the precipitation will be visible as marked *virga*, evaporating before reaching the ground, and the diffraction phenomena will disappear: the Acu transform (partly) into Cicu.

(d) Synoptic experience shows that a similar unstable state is reached already by aid of the slow release factors alone, if the horizontal extent downstream of the orographic cloud is increased to, say, 10—50 km (and the thickness possibly to 1 km or more). Such *orographic cloud systems* may then render even abundant precipitation, though mainly of the drizzling type ($r < 250\,\mu$); cfr the rain-fall in Hawaii as described by SELLING and WALLÉN (see SELLING 1948, especially l. c., p. 65). — As to artificial seeding of Hawaiian clouds, the observations of LEOPOLD and HALSTEAD 1948 (l. c., p. 531) hint that it is ineffective when the cloud thickness is only about 1300 m, but that it may become effective when the thickness attains 2000 m.

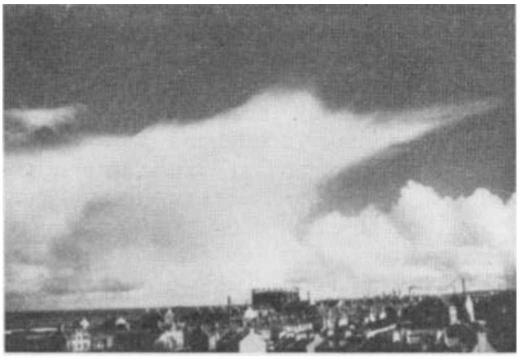


Fig. 2. Cumulonimbus (left) with a snow-shower, and Cumuli (right), demonstrating the typical difference in outward appearance between ice-clouds and water-clouds. — Photo C. A. CLARKE, Aberdeen, 18. IV. 1921.

9. Good samples of convective clouds are shown in fig. 2. The Cu to the right are still typical water-clouds with a clear-cut and cauliflower-shaped surface; they are either not reaching the ice-nucleus level or as yet not showing the outward signs of any glaciation or precipitation release. Within these clouds there would not occur any appreciable precipitation release, even if the drops had opportunity to exist for a considerable time, as long as the clouds did not reach the ice-nucleus level (e.g. if spreading out as *Acu cugen* below an inversion near the 0° C-isotherm). — The cloud in the middle and left part of fig. 2 reaches much higher; its top has the fibrous structure produced by efficient precipitation release within it. In fact, a shower is seen to fall from the cloud base, and so low were the 0° C- and + 3° C-isotherms on this spring day (18th April) that most of the cloud and precipitation could get glaciated, once the release was started.

10. The mechanism of the artificial ice-nucleus seeding by a CO$_2$-pellet falling through a supercooled cloud is represented tentatively in fig. 3 by the schematic pictures A—C, with a successive reduction of scale of representation, but in principle with the same symbols. Assuming the temperature of the falling pellet to be — 80° C, a film of air with a temperature below the critical — 35° C must form around it and spread a little in its "wake". Inside the isotherm of — 35° C, therefore, ice-nuclei will form spontaneously, according to theory and well-established experiments (cfr CWILONG 1945, SHEPPARD 1947). Once formed, these *ephemeral nuclei* will subsist as long as $T < 0°$ C and $e \geqq E_i$, and they will even grow rapidly into simple ice crystals when $e > E_i$, and into skeletons if $e \gg E_i$; cfr A. WEGENER 1911, p. 89. — Concerning *permanent ice-nuclei*, of silver iodide, see B. VONNEGUT 1947.

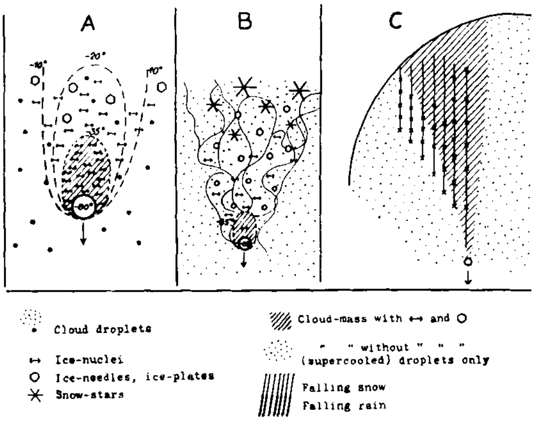


Fig. 3. The principle of artificial ice-nucleus seeding by CO$_2$-pellets, and ensuing growth of ice-crystals.

Fig. 4 illustrates how a Cu with supercooled top is artificially seeded by CO$_2$-pellets from an air-plane. Just as in fig. 3 the ice-nuclei and ensuing snow-crystals are assumed to spread conically in the wake of each pellet (in the same way as a smoke

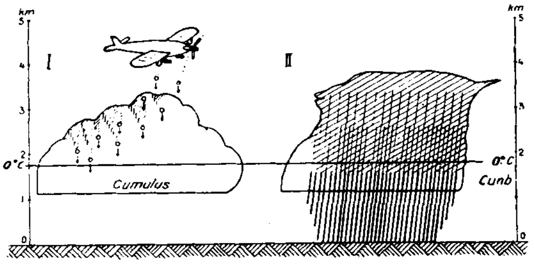
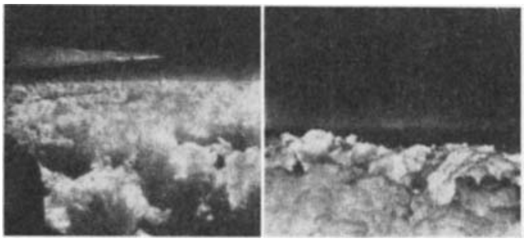


Fig. 4. I. Cumulus seeded from an air-plane. II. Cumulus transformed into Cumulonimbus. — Legenda see fig. 3.

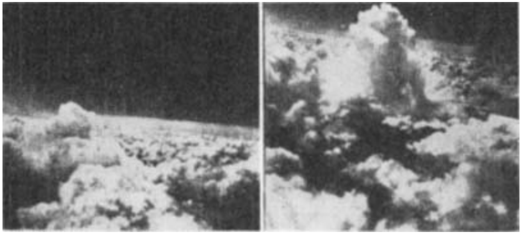
column) thanks to the intense turbulence within a Cumulus. Only in this manner can even a limited number of CO_2-pellets induce a complete seeding of the cloud below the path of the air-plane.

11. It remains to explain, though, how the narrow path seeded artificially across a Cumulus-top can later on lead to a complete glaciation of the whole of its upper part and to the transformation of a whole Cu into a Cunb. To explain such cases, if the evidence concerning them is reliable, we shall postulate a *double release* which may act both (a) at the natural, and (b) at the artificial, seeding of supercooled clouds. The first, relatively small number of ice-nuclei, (a) formed within, (b) or introduced into, the cloud, will cause a certain amount of water to crystallize by sublimation. The heat of fusion then set free will raise the temperature of this part of the cloud and give it an additional updraft, provided the temperature lapse-rate, just above the cloud, already beforehand was nearly moist-adiabatic; thereby it reaches a lower temperature at which the natural ice-nuclei, (1) will be omnipresent, and much more numerous and/or effective, (2) or will form for the first time in sufficient number etc.

The much quoted experiment in Australia, by **Kraus** and **Squires** 1947, see fig. 5, is perhaps the only properly controlled case which seemingly contradicts the findings of **Coons** and coll. 1948 b, mentioned in the footnote on p. 33. In the Australian case precipitation came solely from the two seeded Cumuli, out of many hundreds observed from the airplane, during a whole day. This case may belong to the above category, with a double release, since the vertical temperature gradient was favourable, and since the seeded Cu shot up very markedly and high above the level of the others — possibly thanks to heat of fusion (l. c., p. 494) — at first without showing much glaciation (subfigs 3—4) and no Radar echo. Not until 16 min. after the seeding, when spreading at the 12 km level (subfig. 5), such an echo began; a little later the "anvil" got the typical ice-cloud aspect (subfig. 6), and a shower went down from the cloud.



1. Inland cloud types before seeding. 2. General situation loking east over the Pacfic



3. Nine minutes after the release of "dry ice". 4. Thirteen minutes after the release of "dry ice".

5. The small anvil which formed after about twenty minutes. 6. The fully developed anvil.

Fig. 5. Artificial seeding of a Cumulus at Lithgow, near Sydney, Australia, on 5. II. 1947. — From **Kraus** and **Squires** 1947.

12. It is here the proper place to emphasize one main reason why the results of artificial seeding of Cu clouds, as to precipitation induced, must be difficult to control, both by Radar and by rain gauges at the ground. Drops of sizes up to $r = 10^{-2}$ cm will evaporate completely already 100—200 m, or less, below the cloud base, even if numerous (see **Findeisen** 1939 b, p. 458), and have no chance of reaching the ground. Greater drops may fall a considerable distance, but they are certainly not numerous in the cases considered, and the vertical extent of the region with maximum drop size will be relatively small. Consequently, the Radar echo intensity, varying roughly as r_w^6 and as the total number of drops, will be faint. — To get a deep column filled with sufficiently big drops, a "joint and continual attack" from above of a very great number of big drops is necessary. The first lot of drops will penetrate the underlying dry atmosphere and moisten it in evaporating, at least to a great extent. To get the rain properly down

to the ground, the favorable conditions thus created must be followed immediately by a continued invasion of droplets from the cloud. This latter stage, though, will probably be missing in many (or most) of the cases with artificial seeding by solid CO_2, because of the limited number of artificial ice-nuclei produced, if this process is not supplemented by a second, natural seeding and release[1].

*

We may now proceed to discuss and estimate the possible success of artificial seeding within the main types of clouds and cloud systems existing in nature.

I. The natural evolution of convective cloud formed within a deep layer of more or less unstable air is shown very schematically in fig. 6. Three main cases can be distinguished.

(1) With insufficient statical instability or start of convection, the cloud may never surpass the stage *Cu humilis* (a in fig. 6). Over land in the summer half of the year, the clouds will then, almost at all latitudes, be warmer than 0°C and thus be artificially unreleasable. During the winter half of the year, *Cu hum* may surpass the 0° C-isotherm, but they will then mainly form over sea or along the coast, and their release will not be important to Man.

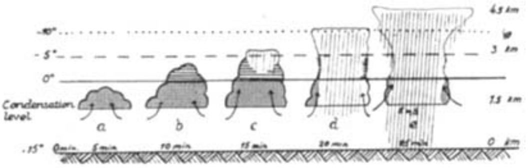


Fig. 6. Natural evolution of convective clouds in unstable air (schematic vertical section).

(2) The Cu may grow into *Cu congestus* (b in fig. 6), but they will then, even in summer and over land, in temperate latitudes, rapidly reach the natural ice-nucleus level and transform into true *Cunb* (6 c = Cunb calvus, 6 d, e = Cunb capillatus). Artificial release has then no real mission to fulfil, in good agreement with the findings of COONS and coll. 1948 b.

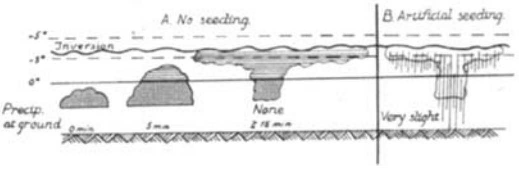


Fig. 7. Evolution of convective cloud below an inversion (schematic vertical section).

(3) As to the *Cu congestus* in subtropical and tropical regions, cfr discussion in 3 above. These cases are not represented in fig. 6.

The natural evolution of convective cloud with an inversion at a medium level leads to the well-known *Acu cugen*, shown schematically in fig. 7 A, characterized by lack of precipitation release, at least in temperate latitudes, in day-time. As shown by fig. 7 B, though, artificial release would presumably not produce much real rain, because the bulk of the cloud is too thin, its base is too high, and condensation has ceased.

II. A frontal cloud system may be regarded as a huge and extended Cunb-cloud the axis of which forms an angle of a few degrees with the horizontal instead of about 90°. The fully developed upslide cloud system already contains the complete mechanism of natural precipitation release. Only when such a cloud system is just forming, or in systems formed entirely within Tropical air, this mechanism may still lack or work slowly. In any case the rain intensity from these cloud systems is much less than from a Cunb. Consequently, an artificial seeding, perhaps effective in the initial stage, would have to be continued over a long time and great space to be of any real use, and would then probably be uneconomic or impracticable.

III. The clouds formed by the slow or weak agents of condensation: fog, St, Stcu, and Acu due to radiation, turbulence, advection etc., belong decidedly to the category treated in 1—2; and strata just above the 0° C-isotherm may remain releasable but unreleased for a considerable time if left alone — apart from sparse grains of snow (or drops), cfr 7 (a). The low intensity of condensation, however, implies that, even by artificial seeding, no intense and/or continued precipitation could be extracted from them. Generally, the only amount of water which could be brought down to the ground from such clouds is the one already condensed

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[1] In a paper which could not be considered until this article was already in print, I. LANGMUIR (1948) treats the release of precipitation by a "chain reaction" which may be started even in "warm clouds" by seeding with big water-drops only. The possible reaction of this theory on the problems in 3, 7(a), 11—12, and on the conclusions I—IV below, will be duly heeded in a following article.

beforehand. If k is the amount of condensed water within the cloud in g/m^3 (generally of the order 1 g/m^3), then the maximum amount of releasable precipitation would be k mm per 1000 m thickness of cloud, i.e. of the order of 1 mm. Therefore, even artificial release would, at best, give appreciable but not abundant precipitation at the ground, mainly as drizzle and only from the cloud species named *opacus*, cfr fig. 8, but not from the species named *translucidus*.

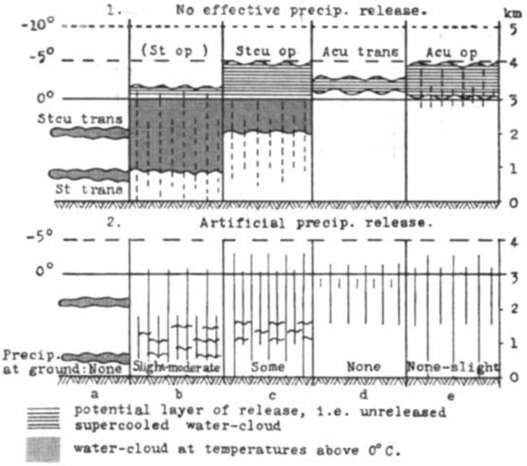

Fig. 8. Different kinds of stratiform clouds (schematic vertical section).

There is, however, an effect of the artificial ice-nuclei on this kind of cloud which may prove useful for aviation and other purposes: the precipitation release, though weak, tends to dissipate stratiform clouds, as shown at an experiment conducted by LANGMUIR and reproduced here (from V. SCHAEFER) as fig. 9.

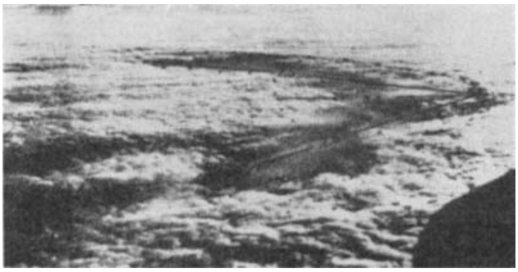

Fig. 9. L-shaped gap produced in a Stratocumulus-deck by artificial seeding with CO$_2$-pellets. — From V. SCHAEFER 1948.

It follows from 7, however, that the ratio v is a very important factor also in this case. A too great value, e.g. 10^6, might imply a day to clear the air within the area seeded, whereas with $v = 1$ the effect would be almost instantaneous, if working at all (as will be shown in a later article). In the latter case, however, the seeding would transform the water-cloud (or water-fog) into an ice-cloud (or ice-fog) with the same size and specific number of elements, i. e. the same opacity; such "overseeding" must then also be avoided. —This effect has also another aspect, apparently not heeded hitherto, which, in the long run, may considerably diminish or even nullify its usefulness. If the artificial precipitation mainly evaporates before reaching the ground, as shown in fig. 8 c—e (lower row), and made plausible by the reasoning in 12, this means that water has been transferred from above the 0° C-isotherm, where it is releasable, to below this isotherm, where it is unreleasable. Ensuing condensation effects, acting without lifting of the air (radiation etc.), may then reproduce the Stratus etc. at this new and lower level — where it no longer can be artificially dissipated and/or brought down to the earth as precipitation.

We may on the other hand assume that a certain region, like a coastal or mountain area, with a prevailing wind direction, is often invaded by fog and Stratus, impeding traffic and decreasing the hours of sunshine. In this case artificial seeding might dissipate, to a certain degree, the persistent cloud-deck in the manner just discussed. At the same time the lowering of the moist layer in the atmosphere would do no harm because the prevailing wind would continually bring it into another region with an entirely different regime, e.g. to a hot continent, where convective processes reign. — In summer, the Scandinavian mountain range, the Scandes, offers an example of such a region, especially in the area between 63° and 65° N lat., see fig. 10. A considerable part of the "fog" shown on this map is produced by stratiform clouds forming over the adjacent cool ocean, or favoured by the stable stratification over it, and brought in, or produced, over the mountains by the prevailing W wind at this season. Provided that these clouds (just) surpass the 0° C-isotherm, they might, to some extent, be dissipated by the method outlined above, and the sunshine hours might be increased. The lowering of the moist layer, accompanying the dissipation, would have no unfavourable effect on the climate leeward (i.e. to the E) of this region because, in summer, the combined dynamic and continental heating of the W current, flowing downwards and inland, would in any case bring fair weather or showers there.

IV. The discussion in I—III can be summarized by stating that any seeding, natural or artificial, mostly will be of little direct use for supplying water to the earth's surface, especially at low levels, if there is no condensation by systematic lifting going on within the clouds, even when they are releasable but not released. Having shown, on the other hand, that the convective and frontal clouds, on an average, cancel from the list of such clouds, the main remaining possibility for systematically causing abundant artificial rain must consist in seeding cloud-masses produced by a stationary and slanting upward motion, sufficiently strong, and surpassing the 0° C-isotherm, but not the —5° C- (or — 10° C-) isotherm. These conditions are, as a rule, only realized within very special orographic cloud systems, to be treated in a following article.

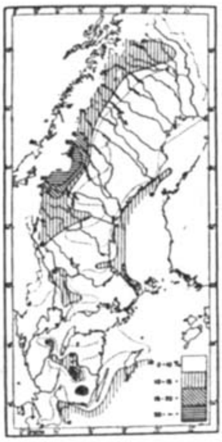

Fig. 10. Average fog distribution in summer (June—August) in Sweden. — From A. Ångström 1946.

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