21 October 1960, Volume 132, Number 3434 SCIENCE

CURRENT PROBLEMS IN RESEARCH

New Developments in Hail Research

Artificial production of hailstones leads to advances in the understanding of their natural formation.

Roland List

Men have long been curious about the natural phenomenon of hail, and it is therefore not surprising to find that hailstones have become the object of intensive study among scientists during the last century (*1*). What is astonishing is, rather, the variety of observational material collected and the conclusions derived from it. As a result of wars on the continent of Europe, however, a large part of this knowledge has been lost, and although leading centers of research have been built up in England and the United States, their traditions do not go back so far. A perusal of the scant statements about hail formation in the standard work *The Physics of Clouds* (*2*) makes this situation quite clear.

Where observational material was lacking there was all the more imaginative speculation about the way in which hail is formed. The first major hail theory in mathematical form was given by Schumann in 1938 (*3*). Although it has not been borne out in every detail, it contains most of the assumptions necessary for a procedure of this kind. Subsequent work has pointed out very little that is new in this respect. On the contrary, further development has tended to be trivial, degenerating into mere exercises in calculation based on apparently reasonable assumptions. The effects and countereffects that have been calculated have led to a series of propositions and counter-propositions, all of them the work of the same researchers, who can continually invoke them to demonstrate the correctness of this or that point of view.

It is consoling that nature has allowed unforeseen and surprising discoveries to be made, which result in the more or less complete collapse of these proud intellectual constructions.

Research Methods of the Hail Research Station in Davos

It was, in fact, dissatisfaction with the whole development of hail research that led to a fundamentally new approach to all the problems on an experimental, physical basis. Existing publications were duly taken note of but not used as a foundation—a procedure which turned out to be fully justified.

The aim of research at Weissfluhjoch is to clarify understanding of the atmospheric conditions that lead to the formation and growth of hailstones. There can be no question, because of the extraordinary risks involved, of measuring by airplane the unknown parameters in an actual storm cloud with hail: the air temperature, the air pressure, the free-water content in the form of drops, the magnitude spectrum and supercooling of the particles, the icing nuclei spectrum, the speed of up-currents, and the speed of hailstones relative to their environment. Therefore, other methods have had to be sought.

To design sounding devices that will penetrate hail clouds presents equal difficulties, and there is no guarantee that these devices will rise through the most dangerous cloud zones. But of the conditions that prevail there, we do in fact have evidence: the hailstones themselves represent nothing less than the product of these conditions, and the largest hailstones bear witness to the strongest icing conditions.

This means that it is useful to investigate the structure and build-up of natural hailstones. What has been learned from such an investigation is presented in the next section. But when we look at the results, we see that we lack both the experience and the intuition to interpret the various signs and symptoms. We need still to make such experiments as will give us the knowledge upon which to base our interpretation. The apparatus that achieves an imitation of the icing process under atmospheric or even more extreme conditions is the Swiss hail tunnel. On the one hand, experiments that can be conducted in this wind tunnel with variable climate give us information about the relation between atmospheric conditions and the resultant ice deposit, and thus also provide the foundations for a modern, physical hail theory based not merely on reasonable but on correct assumptions. The significance of this is discussed in subsequent sections. On the other hand, these experiments offer the key to an interpretation of the way in which actual, collected hailstones have been built up. From the data ob-

The author is head of the hail section at the Swiss Federal Snow and Avalanche Research Institute, Weissfluhjoch-Davos, Switzerland.

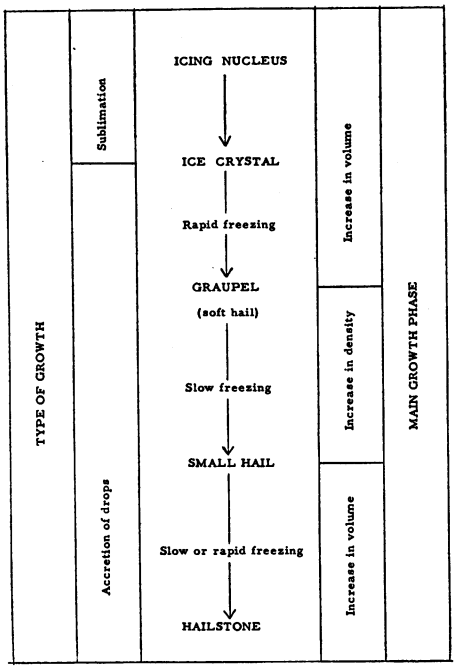


Fig. 1. Characteristics of the growth of hailstones.

tained by this method it should be possible to extrapolate from the physical space surrounding individual ice particles to meteorological space. However, we have deliberately limited ourselves to the physical space of hail formation, for an understanding of the processes here is essential for a meteorological hail theory that is also physically correct and that takes account of the processes in nature.

Origin and Build-up of Hailstones

The location of the research institute at 2665 meters above sea level affords a unique opportunity for direct observation of all phases in the formation of hail and for investigation of the ice particles peculiar to each phase. Of particular interest are those cases where two or more stages in the formation of hailstones and of the particles from which they originate can be observed together. The results of all these observations are given in Fig. 1 and show the development from an ice-forming nucleus into an ice crystal, then into a soft hail particle, then into "small hail," and finally into a hailstone. There is an important difference to be noted between an increase in volume and an increase in density without increase in volume. This means that two growth phases can be spatially superimposed, so that the open ice framework of a graupel (soft hail particle) can be filled up at a later point in time with slowly freezing water, which may even remain partly liquid. This produces a small hail particle, about which more specific details are given below. Subsequent interpretation of hailstone structures is, of course, complicated by this filling up of loose ice zones. There are, however, certain unmistakable signs which in many cases permit clear identification of two such superimposed growth phases.

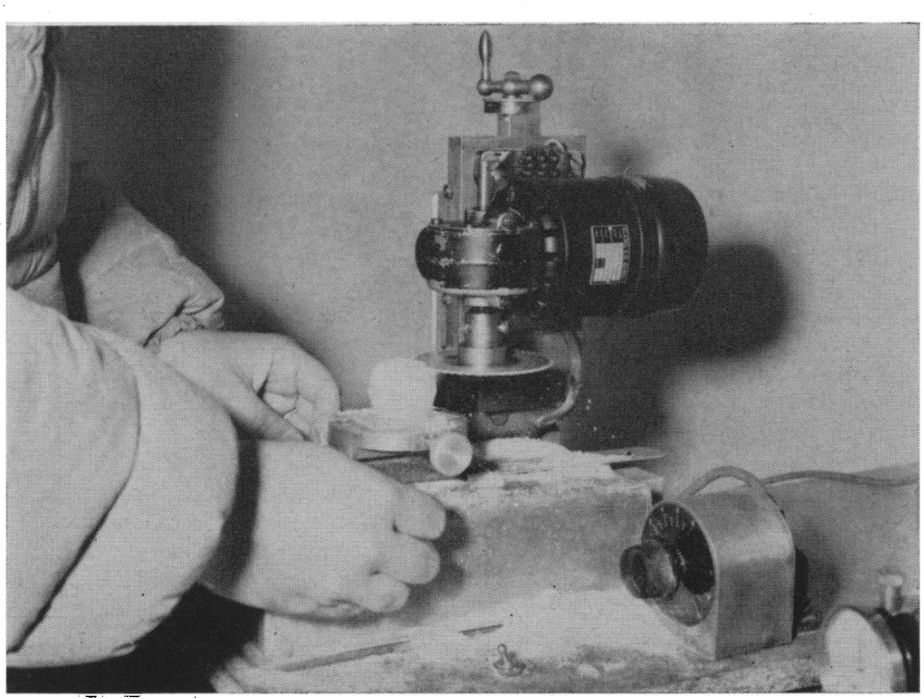


Fig. 2. Thin section saw.

At this point it should also be remarked that various research workers are of the opinion that the formation of hailstones starts from drops of water. Indeed, there are sometimes in individual hailstones indications to support this point of view. In the majority of hailstones, however, graupels can quite clearly be recognized as the originating particles, and they can contain an ice crystal which in 50 percent of all cases can be identified—a crystal of dendritic form (*4*). There is no reason, therefore, to modify the scheme shown in Fig. 1.

Characteristics of Hailstones

Published works often give drawings and photographs of hailstones together with sizes, and sometimes also details about weight. But we find that figures are wanting as soon as we inquire about density. The earliest more or less reliable values for density were those obtained by me (*5*), while measurements were also made later by Vittori (*6*). These measurements, however, were not made on freshly fallen hailstones but on hailstones that had been kept before and during measurement at a temperature below 0°C. This fact is of decisive importance, as was established only later (*7*), because the hailstones *normally* contain liquid water and thus exhibit a density greater than that of ice.

It is also important to indicate and classify the *forms* of hailstones, since their form is responsible, in the first place, for their aerodynamic behavior when falling and, in the second place, should permit conclusions to be drawn retrospectively about the conditions in which they originated. For it can in fact be clearly shown that the form of a hailstone represents a consequence of these conditions (*8*). But as different growth phases can succeed one another in the development of these ice particles, it is necessary to learn all the different forms through which a hailstone passes during its growth. For this purpose mere external observation of the hailstone is no longer adequate; cross sections must be prepared in order to gain a picture of the inner structure.

Here the methods devised by M. de Quervain (*9*) for research on snow proved to be invaluable. By means of a special circular saw (Fig. 2), ice sections 0.2 millimeter or more thick

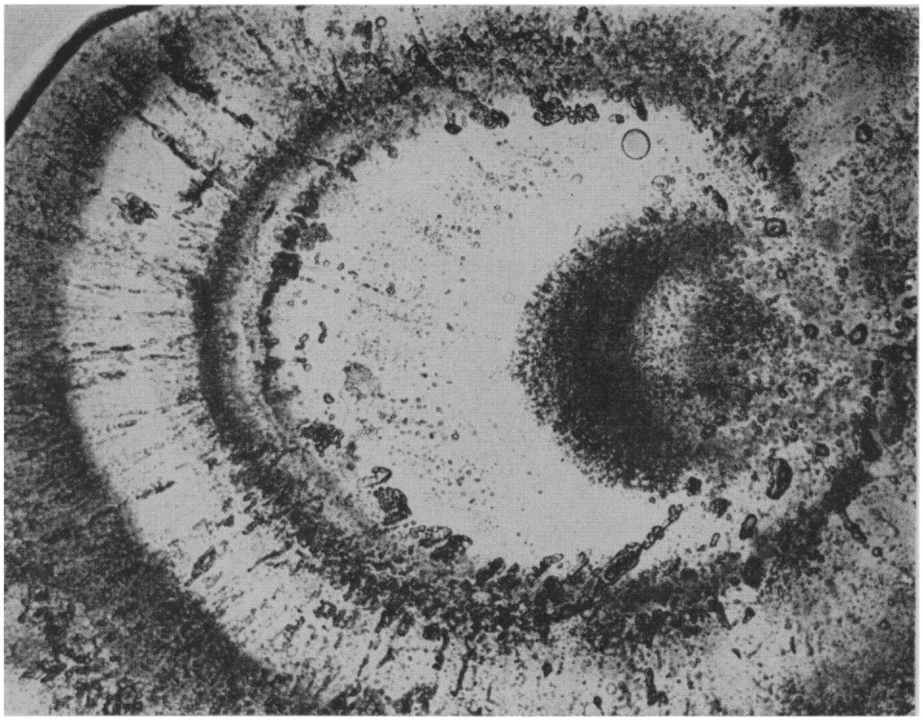


Fig. 3. Thin section of hailstone No. K 57.15, with translucent light (real length of the figure, 3.1 cm).

are cut out of the hailstones. A variety of such thin sections can be prepared from any given hailstone. When light penetrates these sections, the arrangement of the air pockets becomes visible, and from these the form at different stages of growth may be inferred wherever the air bubbles are arranged in onionskin-like layers. From the symmetry of the sections it is also possible to recognize the oldest part of the hailstone (see Fig. 3). Similar results are obtained from observing the crystal structure of the ice; for this, polarized light has to be used. Figure 4 shows one such arrangement of individual ice crystals. Figures 3 and 4 both show the same thin section. Further details about hailstone structures can be found in the references at the end of this article (*4, 5, 10, 11*).

Aerodynamics of Hailstones

In every hail theory, assumptions must be made about the relative speed of hailstones in relation to their immediate environment. The obvious step was, of course, to idealize hailstones as spheres and to use the values obtained in the field of aerodynamics. Some 25 years elapsed, nevertheless, before such data were used to calculate the speeds of fall of spherical ice particles. Bilham and Relf (*12*) then repeated the experiments on the coefficients of air resistance for spheres, because the existing experimental data seemed to them to be too strongly affected by the turbulence in the wind tunnels that had been employed. Did they believe, perhaps, that in a storm cloud with hail, particularly laminary conditions would prevail? Despite a wide variety of contradictions, the calculations established by their work—calculations regarding the dependence of the speed of fall on the air density and the transition from laminary to turbulent flow resistance at the critical Reynolds number—were all adopted without exception. It is understandable that Schumann (*3*) should have based his work on these calculations, since in 1938 the knowledge gained from boundary-layer theory was still neither far developed nor well known: but it is surely surprising that modern work should still rely without hesitation on these results.

The great fallacy was to have idealized hailstones as smooth spheres and then to have attributed to them the flow characteristics of such spheres. This procedure is not permissible since hailstones can be idealized as at best *rough* spheres. Flow is then turbulent at a much lower Reynolds number, and higher coefficients of air resistance result (also different heat-exchange values). Above all, calculations concerning the "aerodynamically conditioned" maximal diameter of hailstones are invalidated, since these are based on the shift in the separation point of the air stream along the sphere at the critical Reynolds number.

But even with small ice particles we are dealing with the supracritical zone.

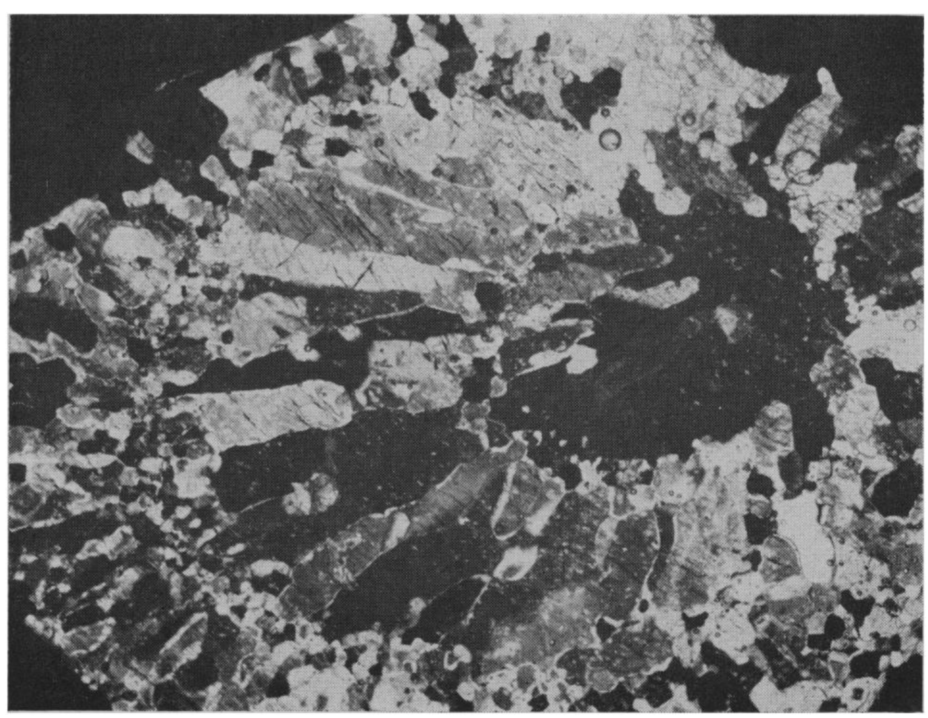


Fig. 4. Thin section of hailstone No. K 57.15, with polarized light (real length of the figure, 3.10 cm).

For this reason, therefore, it is necessary to measure the coefficient of air resistance on natural hailstones. The main forms in particular—for example, triaxial ellipsoids compressed along the shortest axis—have been measured. Figure 5 indicates the values obtained for hailstone No. K57.24 (weight, 24.3 grams; specific weight, 0.908 gram per cubic centimeter; ratio of main axes, 1.0: 0.79: 0.44). It may be mentioned here that a system of axes was in each case drawn through the hailstones, such that axis l_1 coincided with the largest diameter and axis l_3, with the smallest diameter of the ice particle. Measurements were made only of lines lying in the main planes. Fig. 5 shows the coefficients of air resistance C_w (where $W = C_w \cdot \delta \cdot v^2 \cdot F/2$), the projection plane of the hailstone against the air current F, and the appropriate speed of fall v thus obtained. Since not every direction of fall is stable, however, further experiments were carried out in a water tank, and these showed that these types of hailstone fall parallel with the smallest axis. If we represent the coefficients of resistance as a function of the Reynolds number, then we obtain zones of the kind indicated in Fig. 6. Unfortunately, the wind tunnel being used was not adequate for obtaining higher values of Re, so the figures are exact (that is, experimentally substantiated) only for hailstones with a maximum diameter of 6 centimeters. On the basis of Fig. 6, if we use values for C_w corresponding to the hailstone form, we obtain data for the speed of fall as shown in Fig. 7. As a basis of comparison the curve (No. 1)

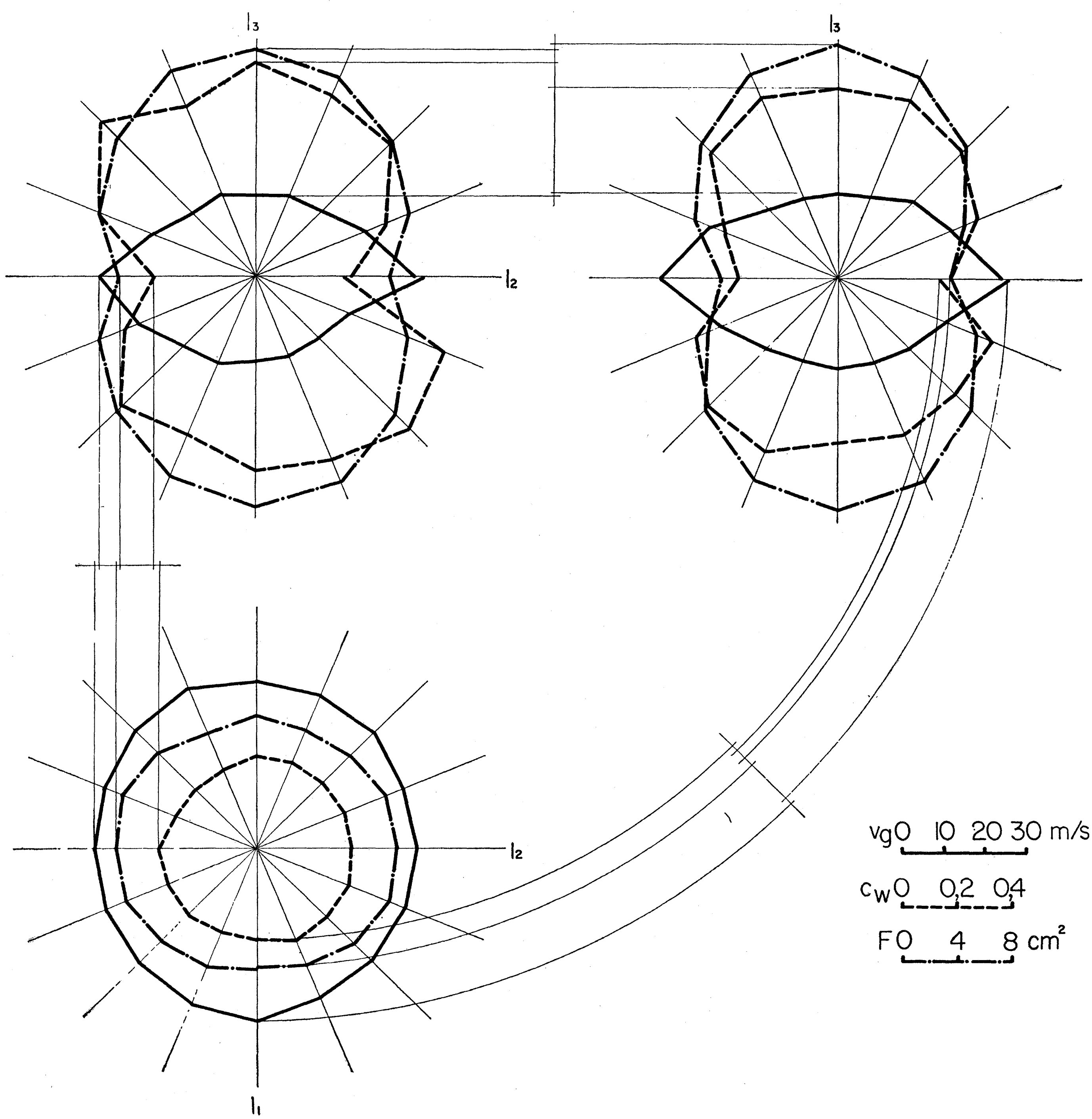


Fig. 5. Drag coefficient C_w, projection plane F, of hailstone No. K 47.24 in the direction of fall, and terminal velocity v in air, as a function of the position of free fall. Longest axes, l_3; shortest axes, l_1; medium axes, l_2.

which is valid for smooth spheres has also been entered and may be regarded as an extreme limiting condition.

From all these statements it follows that, in terms of aerodynamics, natural conditions turn out to be much more favorable for the formation of large and heavy hailstones than deductions based on theoretical considerations would lead one to suppose.

The Experimental Wind Tunnel

All practical work hitherto has treated hailstones as temporally stationary particles. As soon, however, as we want to examine their temporal behavior in a cloud with supercooled water—that is, in conditions where they can grow—we must create artificial atmospheric conditions of the kind that could occur in a storm cloud. This was accomplished by means of the hail tunnel, which is essentially nothing more than a wind tunnel having a closed circuit and an adjustable climate. Its construction is shown diagrammatically in Fig. 8. The actual section used for experiments is a measuring place in which the test object is either suspended or "floated" (where this is possible). To indicate the main features of the tunnel's performance the following figures may be given (*15*): temperature range, + 30° to − 65°C; maximum temperature change in either direction in 1 minute, ± 25°C, provided that the air speed amounts to 10 meters per second; maximum air speed, 80 miles per hour; free-water content of the air, up to 30 grams per cubic meter (that is, values considerably greater than are to be expected in a storm cloud); variation in the diameter of the drops, 1 to 100 microns. The water can be supercooled according to need down to − 35°C without its becoming frozen; spectra of the ice-forming nuclei are available.

The conditions described can be not only produced but also satisfactorily measured and regulated—as a rule an even more complicated undertaking. The reason for this is that supercooled drops of water moving with the stream of air freeze as soon as they encounter obstacles, whether these are measuring instruments or other objects. An impression of the construction of the plant may be gained from Figs. 9 and 10. Figure 9 shows the actual control unit, from which all apparatus is operated and all measurements and recordings are carried out. In addition, the test object itself, the artificial hailstone, can be observed in its growth from the same place (the measuring place appears on the left in Fig. 9) through a Plexiglas window. Figure 10 shows an ascending section of the wind tunnel below the measuring place, where the water is injected (at rear). On the right of the tunnel stands the refrigerating compressor.

Results Obtained So Far from the Hail Tunnel

The value of this plant will be determined by the extent of the new knowledge which can be gained from it with regard to hail formation. It already promises well, to judge from the first experiment, which has brought to light an apparently somewhat strange

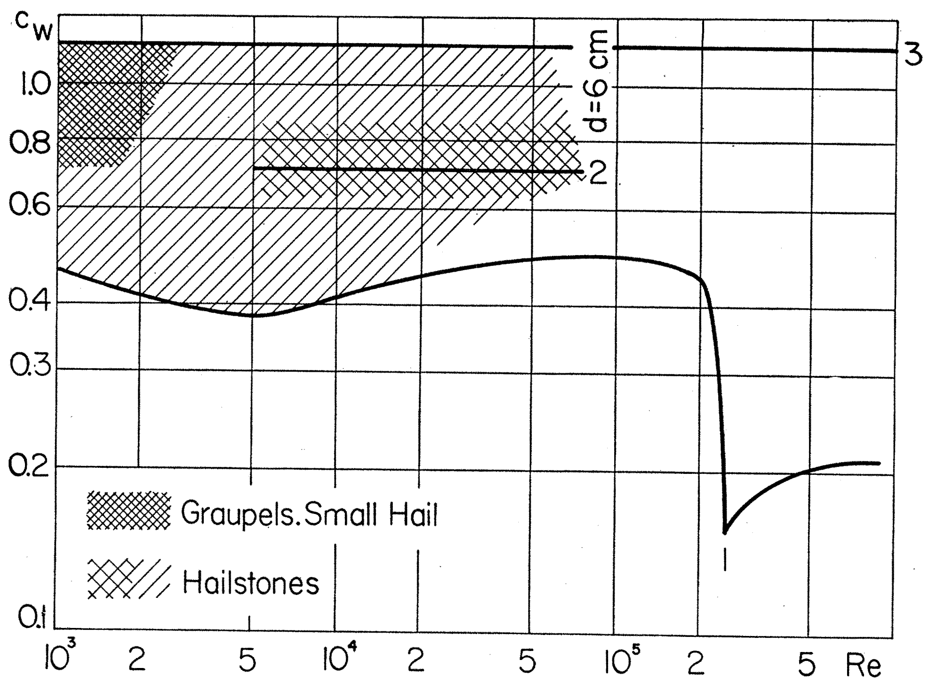


Fig. 6. Drag coefficient of graupels and hailstones as a function of the Reynolds number *Re*. Curve 1, values for smooth spheres; curve 2, values for ellipsoidal hailstones; curve 3, the drag coefficient for plates, giving an upper limit.

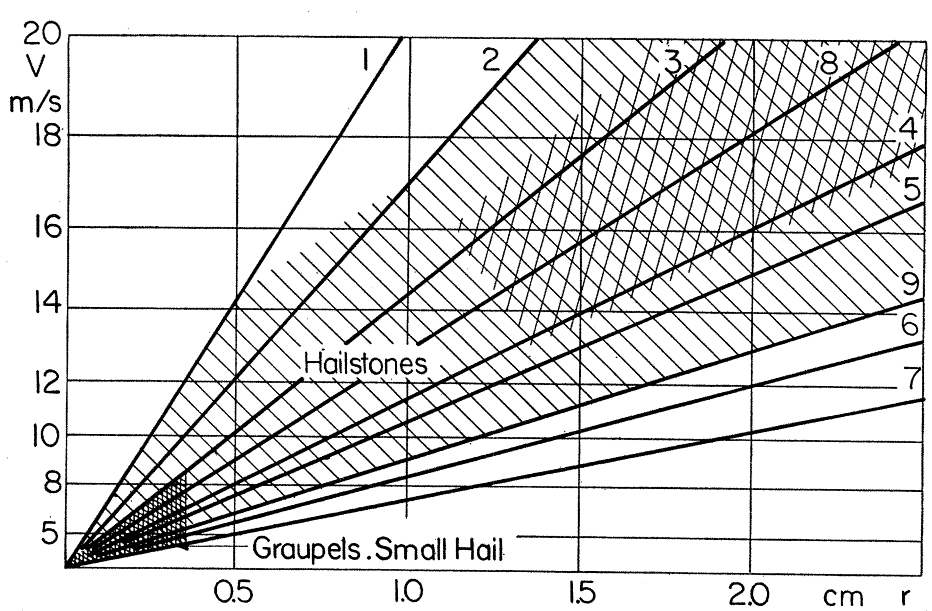


Fig. 7. Fall velocity of hailstones of different shapes: (1) sphere, density $\delta = 0.8$ g/cm^3, $C_w = 0.5$; (2) sphere, $\delta = 0.8$ g/cm^3, $C_w = 0.7$; (3) sphere, $\delta = 0.8$ g/cm^3, $C_w = 1.0$; (4) sphere, $\delta = 0.5$ g/cm^3, $C_w = 1.0$; (5) cone, angle 90°, $\delta = 0.8$ g/cm^3, $C_w = 0.8$; (6) cone, angle 90°, $\delta = 0.5$ g/cm^3, $C_w = 0.8$; (7) cone, angle 70°, $\delta = 0.5$ g/cm^3, $C_w = 1.0$; (8) triaxial ellipsoid, $\delta = 0.8$ g/cm^3, $C_w = 0.7$; (9) triaxial ellipsoid, $\delta = 0.8$ g/cm^3, $C_w = 1.4$.

phenomenon: the growth of conglomerations of ice and water, which may be referred to conveniently as "ice-water mixtures."

What these ice-water mixtures are and how they grow can best be explained by telling the story of their discovery. If a spherical obstacle becomes covered with ice, then a quite definite ice deposit can be brought about, according to the icing conditions (temperature, air speed, free-water content, and so on). Thus, in one experiment a plate-shaped structure was formed with a diameter of approximately 20 centimeters and thickness of between 2 and 4 centimeters. The original diameter of the sphere was 8 millimeters. Since it could be seen that the surface of this growing ice structure was wet, the liquid film on the surface was dried by freezing before the plate of ice was taken out of the tunnel. When we came to remove it, it appeared that our hands were perhaps getting wetter than might normally have been expected, but no conclusions were drawn from this. Afterwards the test object was stored on a table in a cold laboratory at −10°C. Half an hour later it was found that the space between the curved undersurface of the ice plate and the table was filled up with ice. The only thing which could have been responsible for this was water built into the ice, which had subsequently worked its way out through capillary systems. This fact contradicts all the assumptions made in the past, from Schumann (*3*) to Ludlam (*13*), who have asserted that only as much water can be gathered by accretion onto a growing hailstone as can freeze. Of necessity, it was supposed, all superfluous water was removed from it by the air stream. This was assumed in contradiction to nature, although no trace of water returned back into the air stream could ever be observed in hundreds of experiments on spheres of diameter up to 2.5 centimeters, speeds up to 80 miles per hour, and water content up to 20 grams per cubic meter (*14*).

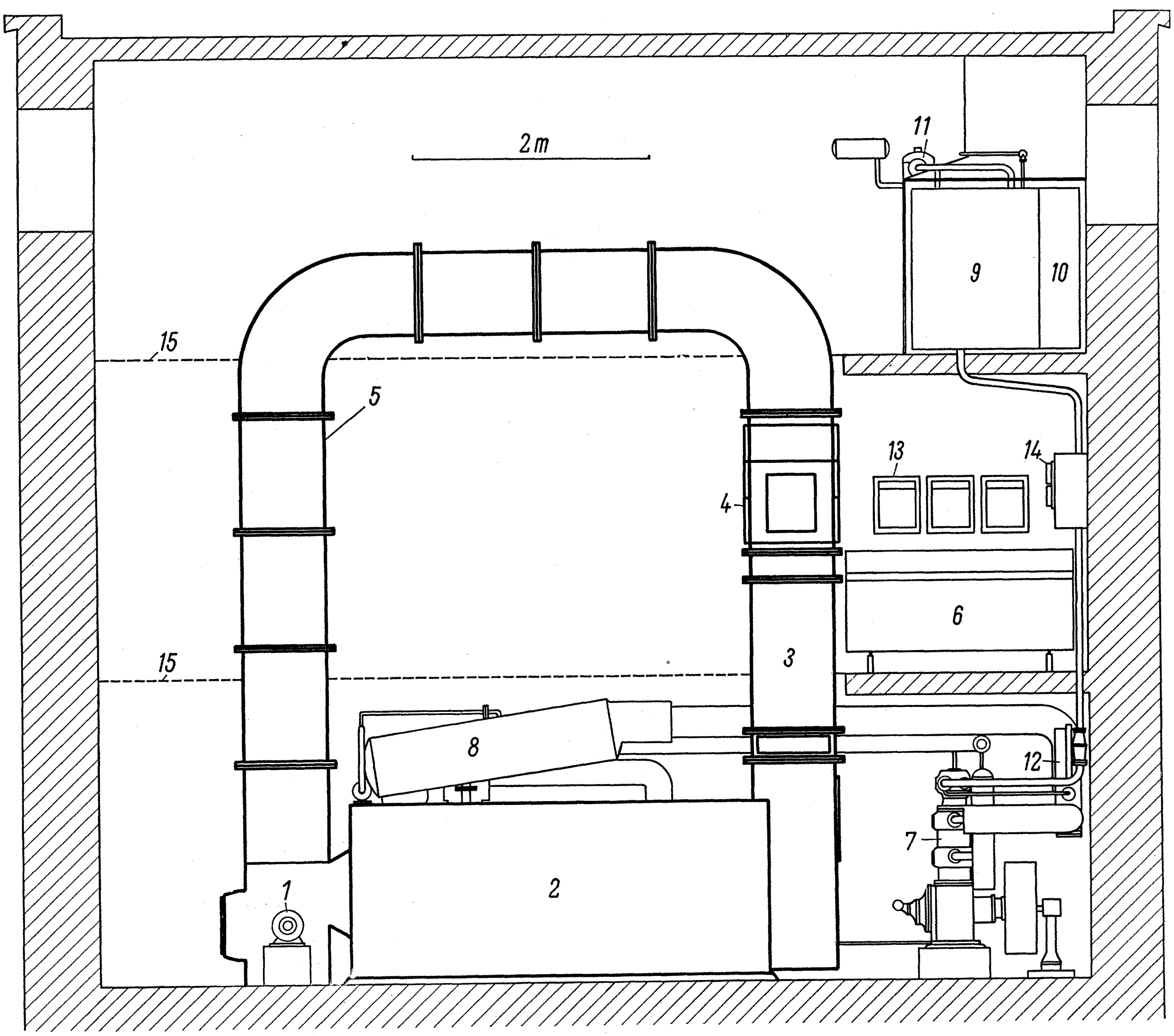
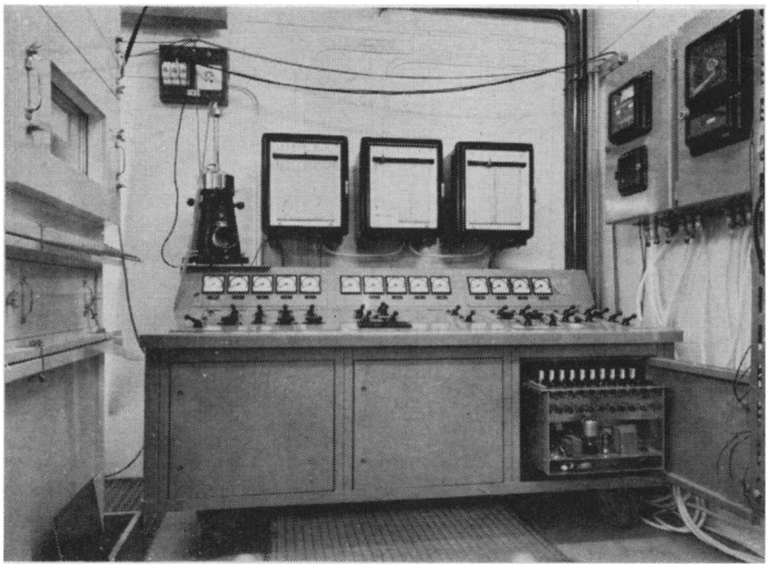


Fig. 8. The Swiss hail tunnel. (1) Blower; (2) section with refrigerating, heating, and filtering elements; (3) drop injection; (4) measuring place; (5) section for bringing the circulation back to the blower; (6) control panel; (7) refrigerating compressor; (8) liquid separator; (9) ammonia condenser; (10) alcohol-water cooler for cooling the refrigerating compressor; (11) oil separator; (12) motor valve; (13) compensating recorders; (14) regulating system for temperature; (15) floors.



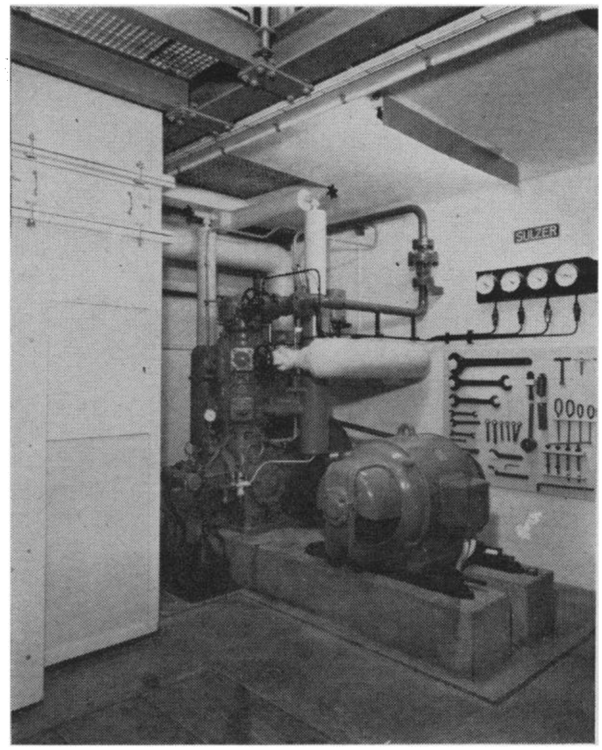


Fig. 9 (top). The measuring section of the tunnel, the control panel, the compensating recorders, and the regulating systems. Fig. 10 (right). The refrigerating compressor.

This example shows again that one's concern must always be with the actual way in which nature behaves rather than with the rationality of human ideas.

The conditions leading to the formation of such ice-water mixtures signify that the total amount of cold administered to the icing object (directly by heat conduction, indirectly by exchange of material as well as by the deposited supercooled water) is not sufficient to freeze all the water that is accreted.

A number of considerations indicate that only one structure is possible where there is steady accretion of water: an ice framework resembling a sponge whose holes are filled with water. And according to the ratio between the cold added and the heat of fusion of all water deposited, the ice walls become thicker or the capillary systems with their water become smaller in extent. By contrast with the superimposition of two growth phases, mentioned above, where a loose ice framework subsequently became filled with water, there is here a parallel growth of ice and water together. It is even possible to show that in fact the water skin grows against the air stream and that subsequent stabilization takes place as an ice framework grows after it. A more extensive series of experiments was made in this connection, during which water was obtained either calorimetrically or by means of a centrifuge. The ice structure of an ice-water mixture formed under the given conditions appears, as indicated in Fig. 11, after the water has been removed. What has so far been learned from this procdure can be summarized as follows. (i) Where hailstones grow in a supercooled cloud it can be shown that normally liquid water is incorporated in the ice particle. (ii) The proportion of liquid water in a single growth phase depends on the total heat exchange with the environment. The proportion increases with increasing values for temperature, free water content, air speed, and the diameter of the icing particle (*14*).

At the same time one should ask

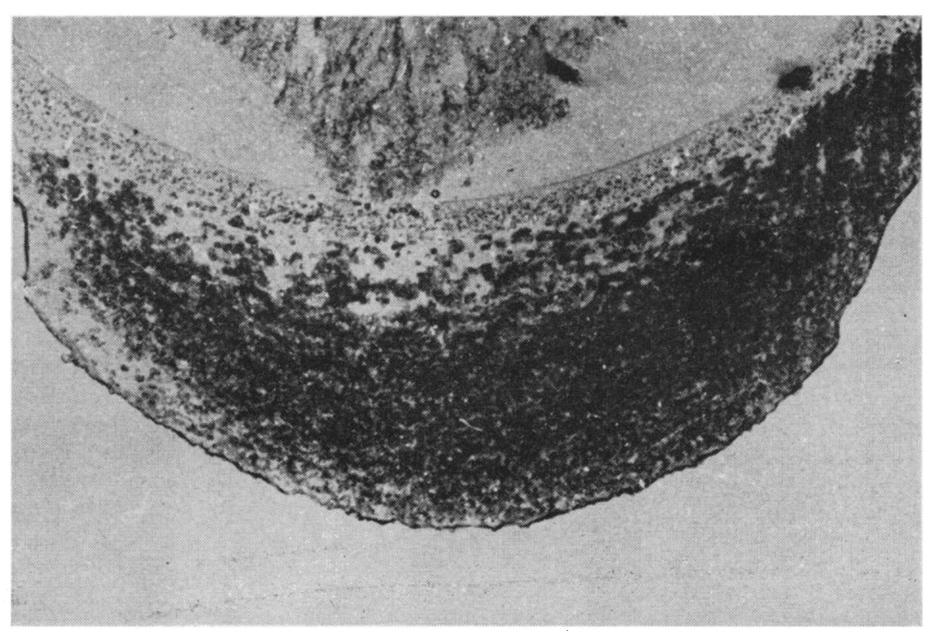


Fig. 11. Ice framework of an ice-water mixture, grown on an initial ice sphere with a diameter of 2.0 cm. Growing conditions: air temperature, —30°C; air velocity, 24 m/sec; free-water content, 8.1 g/cm^3; resulting water content, 19 percent of the total deposit.

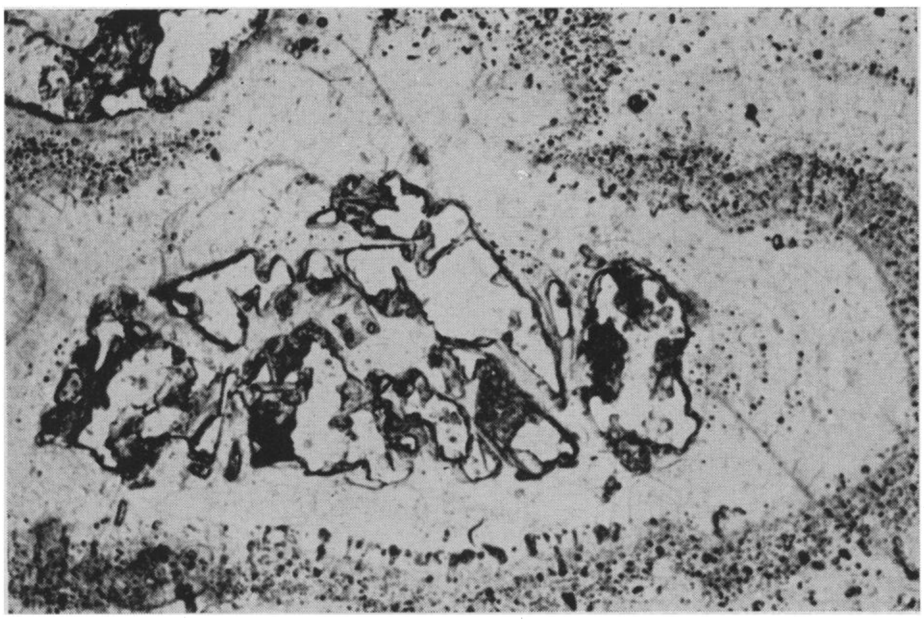


Fig. 12. Hailstone No. K 59.2. Diameter of the cavity, 15 mm; height of the cavity, 5 mm.

whether such watery hailstones are actually observed in nature. For the present the answer is in the negative, for the simple reason that such hailstones had not been expected, and the necessary apparatus for establishing their existence has never been available. Moreover, water which slowly runs out of a hailstone is considered to result from melting. There are, however, indications in the reports of collectors on the mechanical behavior of hailstones that suggest ice-water mixtures. It has been reported possible, after a hailfall, to break apart hailstones which could also split on hitting the ground, as they often do because of low mechanical cohesion. But when similar unbroken hailstones had been kept in a deep freeze, it was quite impossible to break them any longer by hand. This change may clearly be attributed to a solidification of the liquid water present in the capillary systems.

Also found are hailstones with large caverns in them which, it may be concluded, were originally zones formed almost exclusively by liquid water. At a stage subsequent to this formation the water flowed out, and structures resulted of the kind shown in Fig. 12. Virtually identical caverns can also be produced artificially in the growth of ice-water mixtures. Hailstones and artificial ice structures can at the same time exhibit ice crystallites, rather like stalactites, inside such caverns.

In the next few years, however, still greater efforts will have to be made in order to establish definitively, by calorimetric methods or by means of a centrifuge, exactly how much water natural hailstones can contain.

Conclusions

A central problem in every physical hail theory has hitherto been that of calculating the time required for the formation of a hailstone. It was generally felt that in certain circumstances the growth, for example, of an ice particle of 4-centimeter diameter would have to take place (in an extreme case) within 10 to 15 minutes; this was confirmed by radar observations, but no actual values of this order could be got by calculation. The effective relationships, which have been described above, make it possible to show that the ice growth occurs much more quickly than had been supposed under the old assumptions. The factors which help to bring this about are: (i) considerably larger increments of growth, since the water deposited on a hailstone in liquid form contributes progressively to the enlargement of the particle; (ii) an increase in the amount of the deposits as a result of the hailstone's having most frequently, according to observations, the form of a flat ellipsoid (the product of the plane of projection against the air stream and the speed of fall is improved, and this allows more drops of water to be caught); (iii) the hailstones remain longer in zones of heavy ice deposit as a result of a reduced speed of fall, due either to more favorable shape or to greater surface unevenness of the hailstones.

At the same time, we should clearly recognize that all too many points still remain obscure and that these new effects, even if they can be to some extent formulated mathematically, in no wise present an adequate basis for a new, reliable, physical hail theory. For years to come experiments and tests will have to be made, designed to shed light on all aspects of the growth of hailstones. To what extent electrical forces play a part cannot now be said; they are by no means unimportant, however, for under certain icing conditions in our wind tunnel we were able to observe lightning discharges from the icing particle to the environment (*16*).

References and Notes

1. Waller and Harting, *Album der Natur* (ed. 2, 1853), p. 33; W. Trabert, *Meteorol. Z.* **10**, 433 (1899).
2. B. J. Mason, *The Physics of Clouds* (Oxford Univ. Press, London, 1957).
3. T. E. W. Schumann, *Quart. J. Roy. Meteorol. Soc.* **64**, 3 (1938).
4. R. List, *Z. angew. Math. u. Phys.* **9**, 180 (1958).
5. ———, *ibid.* **9**, 217 (1958).
6. O. Vittori and G. di Caporiacco, *Nubila* **2**, 51 (1959).
7. R. List, *Helv. Phys. Acta* **32**, 293 (1959).
8. ———, *Z. angew. Math. u. Phys.* **10**, 143 (1959).
9. M. de Quervain, *Verhandl. schweiz. naturforsch. Ges. 114th* (1950).
10. R. List and M. de Quervain, *Z. angew. Math. u. Phys.* **4**, 3 (1953).
11. R. List, "Growth and structure of graupels and hailstones," in *Physics of Precipitation* (Waverly Press, Baltimore, Md., 1960).
12. E. G. Bilham and E. F. Relf, *Quart. J. Roy. Meteorol. Soc.* **63**, 149 (1937).
13. F. H. Ludlam, *Nubila* **1**, 12 (1958).
14. R. List, *Z. angew. Math. u. Phys.* **11**, 273 (1960).
15. ———, *ibid.* **10**, 381 (1959); "Design and operation of the Swiss hail tunnel," in *Physics of Precipitation* (Waverly Press, Baltimore, Md., 1960).

16. The work described here was carried out as part of the research program of the Swiss Committee for Hail Research and Hail Defense. Grants were also made available by the Swiss National Foundation.