Radar Observations of Ice Spheres in Free Fall[1]

J. T. WILLIS, K. A. BROWNING AND D. ATLAS

Air Force Cambridge Research Laboratories

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ABSTRACT

Simultaneous measurements of the radar cross section and fallspeed of 5 cm (and larger) ice spheres falling in free air have been obtained using a high-precision tracking radar operating at a wavelength of 5.47 cm. While they were dry, the spheres fell with supercritical Reynolds numbers and drag coefficients of only 0.24 to 0.30. These coefficients are much smaller than those normally attributed to hailstones under any conditions. The surface of one sphere, 5.1 cm in diameter, became wet during its fall. This was accompanied by a 5 db decrease in its normalized radar cross section and a twofold increase in its drag coefficient. The implications of these observations are discussed.

1. Introduction

Experiments by Atlas *et al.* (1961) and theoretical work by Herman and Battan (1961a) show that the radar cross section of large hail (diameter > wavelength) changes appreciably when it acquires even a thin coating of water. In particular Atlas *et al.* showed that an 0.01 cm water coat reduced cross sections by about 10 and 6 db at wavelengths of 3.3 and 4.7 cm, respectively. Whether or not such effects would occur with hail in nature was open to conjecture since it was uncertain whether or not a sufficiently thick water coat could be sustained during free fall. Consequently an experiment was designed to measure the radar cross section of simulated large spherical hail as it melted in free fall. As part of this experiment, the fallspeed of the ice spheres was also measured, and this led to the detection of a striking decrease in fallspeed of one sphere as it became wet. Thus, we shall discuss both radar cross section and fallspeed.

2. The experiment

The experiment was conducted at the Gulf Missile Test Range, Eglin Air Force Base, Fla., during June 1962. The principal radar was an AN/FPS-16. This is a powerful high precision monopulse tracking radar which operates at 5.47-cm wavelength.[2] Polar coordinates of target position were recorded at intervals of one tenth second on magnetic tape for later processing with a digital computer, programmed to produce rectangular coordinates and their time derivatives at one second intervals. The tracking ability of the radar and the smoothing in the computation were such that the velocity information was rendered accurate to within ± 0.5 m sec^{-1}.

The intensity of the signal returned from the target was recorded continuously, using the automatic gain control (AGC) voltage required to maintain the echo power at a fixed level. The AGC voltage scale was calibrated using a secondary standard signal generator and precision attenuators, the known signal being coupled to the waveguide input at the antenna. Such a calibration was carried out at least twice daily to give an uncertainty of less than ± 0.5 db in the measurement of the power incident at the antenna. Absolute radar cross-sections were computed to an accuracy of ± 2 db by comparing the power returned from the target with that returned from either a standard 6-in rigid metal sphere or a 2-m metallized mylar sphere, at least two of which were released and tracked daily.

Well-formed ice spheres were cast and then stored at temperatures from -30 to -50C, during which time they acquired frost coats of from 0.01 to 0.02 cm thick. Just before each one was used it was weighed to the nearest 0.5 g and its diameter measured to the nearest 0.1 cm. Each ice sphere was then carried aloft, one at a time, within a small styrofoam carrier borne by a standard radiosonde balloon. A small timing mechanism on the carrier was set to release the sphere at an altitude of around 20,000 ft, about 8000 ft above the level of the 0C wet-bulb temperature. Whereas some of the spheres were between -30 and -50C at the beginning of their ascent, others were permitted to warm somewhat before release in the hope that they might reach ambient temperature during their 20 min ascent to 20,000 ft.

Because of the finite radar cross section of the carrier and release mechanism, the radar was found to track the carrier rather than the ice sphere when small spheres

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[1] A preliminary version of this paper is listed in the references.

[2] 3 and 10 cm radars were used as well but tracking errors precluded the use of their data.

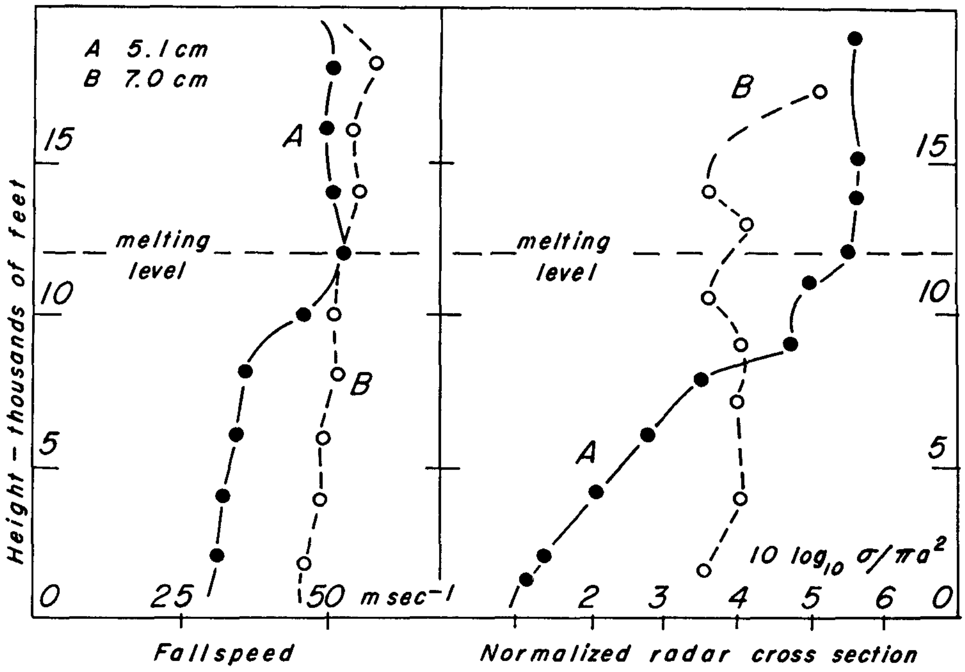

FIG. 1. Variation of fallspeed and normalized radar cross section during the descent of ice spheres A and B.

were used. For this reason the experiment was restricted to ice spheres with diameters in excess of 5 cm.

3. The results

Fig. 1 shows the variation of fallspeed and normalized radar cross section[3] during the descent of a sphere 5.1 cm in diameter (Sphere A) and of one 7.0 cm in diameter (Sphere B). Whereas Sphere B is typical of the behavior of the other 4 spheres, the behavior of Sphere A was rather different. At first it descended at about 50 m sec^{-1} and had a normalized radar cross section of 5.5db. These values were preserved without major fluctuation during its descent through the first 8000 ft but then, as the sphere descended below the 0C wet-bulb level at 12,000 ft, both its fallspeed and radar cross section decreased significantly. At the end of the reliable radar track of Sphere A, at an altitude of about 1000 ft, its fallspeed had decreased by nearly 20 m sec^{-1} and its radar cross section by about 5 db. On the other hand, Sphere B showed no such marked decrease, either in fallspeed or in radar cross section.

4. Discussion

4.1 Radar cross section. The initial value of the normalized radar cross section of Sphere A whilst above the 0C wet-bulb level (at 12,000 ft) is within 2 db of the appropriate theoretical value computed by Herman and Battan (1961a) for an all-ice sphere: the subsequent decrease of about 5 db as it descended below this level is about half that to be expected during a transition from an all-ice sphere to one of all-water, and compares well with the 4.7-cm radar measurements of Atlas *et al.* (1961) for virtually unventilated ice spheres. Evidently, therefore, the wetting of large hailstones in free fall may produce a significant decrease in their radar cross section, at least at a wavelength of 5.47 cm.

The diameter to wavelength ratio of Sphere A was 0.93. According to experimental data (at 3.2 cm wavelength) on stationary melting ice spheres obtained by Harper (see Atlas and Glover, 1963; Fig. 8), the decrease in radar cross section accompanying the complete wetting of a sphere of this size is about 10 db. That the decrease observed in free fall was only half this is perhaps partly due to the fact that the thickness of the water film which can be maintained about a freely falling ice sphere is less than the 0.01-cm film observed by Atlas *et al.* (1961) for stationary spheres. However, there is really no good basis for a quantitative comparison between our observed decrease in radar cross section at 5.47 cm and, either that observed by Harper at 3.2 cm or, for that matter, that computed by Herman and Battan (1961b) at 3.21, 4.57 and 10 cm. This is because the absolute value of the radar cross section for a given thickness of water film is a rather sensitive function of the wavelength, even though the positions of the maxima and minima are only a function of the diameter to wavelength ratio. For this reason there is at present no means of deducing the thickness of the water coat surrounding Sphere A during its descent, short of ex-

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[3] The normalized radar cross section is the ratio of the measured radar cross section to the geometrical cross section of the target.

tending Herman and Battan's computations to 5.47-cm wavelength.

The persistence of the radar cross section of Sphere B close to the all-ice value indicates that its surface remained substantially dry throughout its fall. Unpublished laboratory measurements by Ludlam and Atlas have shown that surface melting occurs only after practically the whole ice sphere has warmed to 0C. It therefore seems likely that Sphere B, as well as most of the other spheres, never reached this temperature. In any future experiments designed to study surface wetting effects, greater care must be exercised in adjusting the initial temperature of the ice spheres so that there will be a greater likelihood of them approaching the ambient temperature at the programmed release level than there was during the series of releases reported here.

We have considered only spheres larger than 5 cm, and at a wavelength of 5.47 cm. For this reason we should like to see further measurements of this kind for smaller ice spheres and for other wavelengths. It is especially important to determine the wetting effect at longer wavelengths such as 10 cm where the theoretical data of Herman and Battan (1961b) indicate that the wetting of a 5-cm ice sphere would give an *increase* in its normalized radar cross section. Obviously, such opposing effects must be confirmed experimentally if we are to correctly interpret hailstorm reflectivity profiles at various wavelengths.

4.2 Fallspeeds. The major decrease in the fallspeed of Sphere A, from 50 m sec^{-1} to 35 m sec^{-1}, occurred within a height interval of 4000 ft just below the 0C wet-bulb temperature level. That it accompanied the initial wetting of the hailstone surface is confirmed by the concomitant reduction in radar cross section. Since all the measurements were made with the ice spheres falling in cloud-free air, we assume that no significant part of the decrease in fallspeed was due to vertical air motions. Therefore, this decrease must have been produced by a decrease in size by melting, an increase in air density, or an increase in the aerodynamic drag. Now, any decrease in size by melting would have been negligible, since the sphere took only 30 sec to traverse the entire height interval within which the major decrease in fallspeed occurred. Furthermore, the change in air density over this height interval was sufficient to produce only a 6 per cent decrease in fallspeed. Evidently, therefore, the observed decrease in fallspeed must have been due predominantly to an appreciable increase in drag as Sphere A started to melt.

At first Sphere A had a drag coefficient C_D of 0.26 and a Reynolds number Re of 1.3×10^5: after melting it had a C_D of 0.56 and a Re of 9.8×10^4. This large increase in drag is interpreted as being due to a transition of the boundary layer flow from turbulent to laminar at the critical Reynolds number. [This well-known phenomenon was first explained by Prandtl (1914), and his interpretation has since been supported by a great deal of theoretical and experimental evidence; see, e.g., Goldstein (1938), Shapiro (1953), Clauser (1954) and Schlichting (1955).] Fig. 2 (from Hoerner, 1958) shows that for smooth spheres in a relatively non-turbulent air stream the critical Reynolds number is about 2×10^5, somewhat higher than the Reynolds number of Sphere A. However, according to Bicknell (1962), the critical value for rough spheres is lower than that for smooth spheres. Unfortunately, Bicknell's results were obtained over only a limited range of roughness parameters[4] and so we shall consider instead the rather similar but more extensive results obtained by Hoerner (1958) for circular cylinders (Fig. 3). Evidently a body behaves as though smooth when its roughness parameter k is less than about 0.0004. On the other hand, when k exceeds 0.02 there can be only a slight change in drag at the critical Reynolds number. However, for roughness parameters between these two values ($0.004<k<0.02$), it appears that roughness effectively triggers a transition of the flow in the boundary layer from laminar to turbulent at a lower Reynolds number than is required for smooth bodies. Just before Sphere A melted it probably had a roughness parameter between 0.002 and 0.004 mainly owing to the frost coat acquired during storage. Therefore, its Reynolds number of 1.3×10^5 at this time is likely to have been supercritical, thereby accounting for its low drag and high terminal fallspeed. As confirmed by the decrease in reflectivity, this frost coat subsequently melted. Its Reynolds number and drag coefficient then changed to values characteristic of laminar boundary layer flow about a smooth sphere at subcritical Reynolds numbers ($\mathrm{Re}=9.8\times10^4$, $C_D=0.56$). Consequently, we can be fairly confident that the decrease in fallspeed observed as Sphere A fell below the melting level was due to a transition of the boundary layer flow from turbulent to laminar which accompanied the melting of the frost coat.

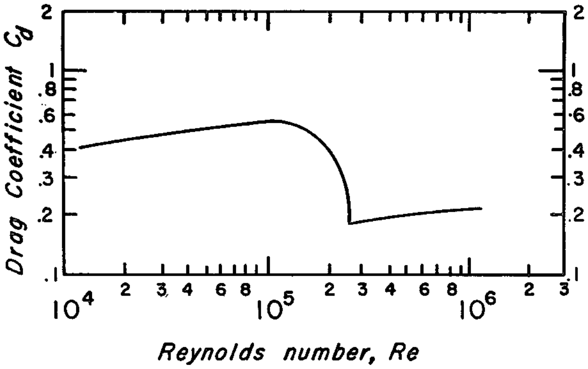

FIG. 2. Variation of drag coefficient of smooth spheres with Reynolds number (from Hoerner, 1958).

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[4] The roughness parameter, k, is the ratio of the mean diameter of the roughness elements to the diameter or characteristic length of the sphere or body under consideration.

Throughout their descent Sphere B and the other 4 spheres maintained the high radar cross sections to be expected of dry ice spheres. Therefore, the absence of any marked decrease in fallspeed during their descent was probably due not only to their larger size (5.8-to 9.8-cm diameter) but perhaps also to the retention of the rough frost coat.

The drag coefficient for Sphere B remained close to 0.24, while that for the other spheres was between 0.25 and 0.30. Along with the value of 0.26 for A before it started to melt, all these drag coefficients are considerably below those obtained for freely falling 5-cm ice spheres by Macklin and Ludlam (1961). It appears that their spheres were behaving as though smooth, even before they started to melt. This probably explains why they also observed no change in drag to accompany melting.

5. Fallspeed of hailstones

Until now we have been considering only simulated hailstones. The question remains as to whether or not our results are applicable to natural hailstones.

Bilham and Relf (1937) computed curves of the terminal fallspeed of smooth spheres as a function of diameter, and hence inferred the possibility of two stable terminal fallspeeds over a small range of rather large hail. They pointed out that a smooth hailstone could acquire the higher fallspeed only as a result of an increase in the Reynolds number owing to a perturbation in the external flow. They reasoned that the required perturbation could be produced only by discontinuities in the updraft velocity which are far sharper than those likely to be encountered even in hailstorms. Bilham and Relf therefore concluded that the higher terminal fallspeed could never be attained.

In the present paper we have presented experimental evidence to support the opposite view; namely that a large (5 cm) hailstone with a rough surface can attain the higher terminal fallspeed. It is able to do this, not by virtue of discontinuities in the updraft velocity, but rather because of turbulence induced within the boundary layer by surface roughness. Whether or not this view is valid depends largely on the value of the roughness parameter for rime accretions. However, it seems quite reasonable that this should fall within the required range, $0.0004<k<0.02$, since, on a 5 cm hailstone, this corresponds to roughness elements of between 20 μ and 1 mm. On the other hand, a hailstone of this size is unlikely to grow with its surface dry (and rough) except near the −40C level and in the presence of small cloud water concentrations (Browning, Ludlam and Macklin, 1963; Fig. 4), so that perhaps, after all, the higher terminal fallspeeds may be attained only rather infrequently in nature.

It is apparent from Fig. 3 that the decrease in fallspeed which accompanies the melting of a rough surface can be large only in the case of large hailstones with Reynolds numbers in the vicinity of 10^5. It is also apparent that there can still be a perceptible effect for suitably rough hailstones with diameters as small as 2 cm (Re about 4×10^4). Moreover, for growing hailstones (whose surface temperature can be as much as 40C above that in their environment) a decrease in fallspeed may even accompany the melting of these small hailstones when their initial roughness parameter is quite small. This is because the critical Reynolds number depends upon the direction and rate of heat transfer between the general flow and the hailstone surface (Lin, 1959). According to Lees (1947) and Liepman and Fila (1947), a 20C temperature excess at the surface of a sphere will give rise to a twofold decrease in the critical Reynolds number.

So far we have discussed only spherical hailstones, whereas it is well known that natural hailstones are usually otherwise. Thus, for example, Weickmann (1953) reports that from 100 years of records, 42 per cent of the hail which was observed was ellipsoidal, 22 per

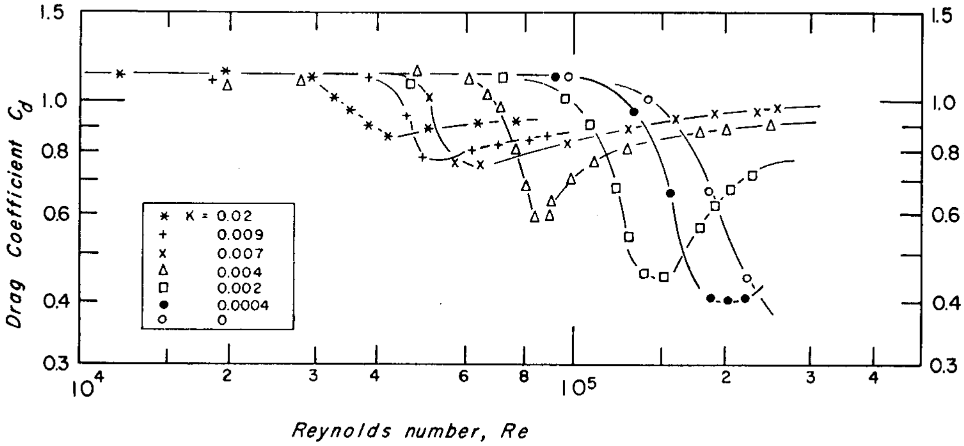

FIG. 3. Variation of drag coefficient with Reynolds number for circular cylinders with different roughness parameters, k, (from Hoerner, 1958).

cent conical, 22 per cent irregular, and only 20 per cent nearly spherical. Regrettably, little is known about the drag of quasi-spherical objects. However, the effect of shape on the drag for cylinders of various non-circular cross sections has been investigated extensively by Delany and Sorensen (1953). They show that transitions of the boundary layer flow from turbulent to laminar may still occur, together with a large increase in drag coefficient.

Throughout this section, we have been considering the way in which the terminal fallspeed of a hailstone may be increased by virtue of turbulence induced within the boundary layer by roughness (and temperature gradients). This same effect might also be produced by turbulence in the general flow itself. This has been treated by Dryden (1956) and also by Hoerner (1938), who shows that turbulence in the general flow may cause the critical Reynolds number to decrease by as much as a factor of 2, provided the turbulence is on the scale of the hailstone. Grimminger (1933) believed that there was insufficient small-scale turbulence in the atmosphere to have any effect. However, Dr. W. C. Macklin (personal communication) now suspects that the turbulent wakes from nearby hailstones might be important in this respect.

6. Multi-layered structure of hailstones

Multi-layered hailstones can be grown within a pulsating updraft which repeatedly carries them upwards and allows them to descend again. However, recent studies by Cunningham (1960) and Browning and Ludlam (1962) have shown that they may be grown within a persistent and rather steady unicellular updraft. Although multilayered hailstones might possibly be produced by virtue of rapid recycling within a steady updraft, Browning, Ludlam and Macklin (1963) have shown that such recycling is not necessary to their formation. They visualize that most of their growth is acquired during a single slow ascent within the updraft while their surface temperature is persistently at or just below 0C. Small fluctuations in cloud-water concentration can then cause transitions between wet and dry growth, giving rise to alternately clear and cloudy layers of ice. However, as Browning *et al.* (1963) point out, if the updraft profile is not just right, then the occurrence of transitions implies unduly large variations in the concentration of cloud-water if the updraft is steady. Therefore, because of the prevalence of multilayered structures, they inferred the possible existence of a stable feedback mechanism favoring fluctuations between the wet and dry growth regimes.

A mechanism of this kind is suggested by Macklin (1963), since hailstones tend to grow spherically when their surfaces are dry but become oblate when they grow wet. This causes their drag to increase and their fallspeed to decrease, thereby decreasing the rate of collection of supercooled water and favoring a return to dry growth provided they remain within a reasonably strong updraft. However, once hailstones have become oblate they generally remain so even if they resume dry growth, so that this mechanism is unlikely to give rise to further growth transitions. A somewhat similar mechanism for promoting fluctuations between wet and dry growth is suggested by the present study. It is as follows: a hailstone growing dry will have a more or less rough surface; they may be associated with a turbulent boundary layer and hence a low drag, high fallspeed and high accretion rate. If, because of this high rate of accretion, the hail surface becomes wet (and smooth), the flow in the boundary layer may change from turbulent to laminar. The concomitant increase in drag and decrease in fallspeed may then slow down the accretion rate sufficiently for the hail surface to become dry and rough once more. This in turn may make the drag increase again, perhaps repeating the cycle of events. Fluctuations in this fashion between wet and dry growth would give rise to the observed alternate layers of clear and cloudy ice, even with hailstones growing within updrafts which are steady and not of optimum intensity.

In the original version of this paper (Willis *et al.* 1963) we considered this as a plausible explanation of the layered structure of hailstones. However, at that time we had omitted consideration of another important factor. This is the fact that the onset of turbulence within the boundary layer will be associated with an increase in the heat transfer as well as a decrease in drag. According to Macklin (personal communication) the increased rate of liberation of heat at the surface of a hailstone accompanying the onset of turbulence in the boundary layer may be more than compensated by the increase in the rate at which this is lost to the environment. If this is true then the stable feedback mechanism suggested above will not operate, and the question of the origin of the multilayered structure of hailstones will remain open. In any case it seems rather unlikely that this mechanism will operate for hailstones smaller than about 2 cm in diameter (for which the drag cannot fluctuate appreciably).

7. Conclusions

While we must admit that we have presented insufficient data to make any bold assertions, we believe that we have given fairly convincing evidence to suggest that:

1) the wetting of large hailstones in *free fall* may account for a significant decrease in their radar cross section at 5.47-cm wavelength, and

2) large hailstones may have a drag coefficient as low as 0.24 to 0.3 when they are dry provided they are sufficiently rough, but will acquire a drag coefficient about twice as great when their surface becomes wet (and smooth).

Whether or not the low drag coefficient is in fact ever attained in nature depends on whether or not sufficiently large hailstones ever grow sufficiently rough. To answer this it will be necessary to determine:

1) the roughness parameters of riming hailstones under various circumstances, and

2) the dependence of the critical Reynolds number for *spheres* upon the surface roughness (to see if hailstones smaller than 5 cm can attain the higher terminal fallspeed).

Wind tunnel experiments are now under way to investigate this second factor.

REFERENCES

Atlas, D., and K. M. Glover, 1963: Back-scatter by dielectric spheres with and without metal caps. *Electromagnetic scattering*, New York, Pergamon Press, 210–236.

Atlas, D., W. G. Harper, F. H. Ludlam and W. C. Macklin, 1961: Radar scatter by large hail. *Quart. J. R. meteor. Soc.*, **86**, 468–482.

Bicknell, J., 1962: Report of wind tunnel tests on the aerodynamic drag of spheres with roughness and distortion. pp. 41–47 of *Balloon, high-altitude, fast-rising*, Final report of the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., Contract No. DA36-039Sc84944.

Bilham, E. G., and E. F. Relf, 1937: The dynamics of large hailstones. *Quart. J. R. meteor. Soc.*, **63**, 149–162.

Browning, K. A., and F. H. Ludlam, 1962: Airflow in convective storms. *Quart. J. R. meteor. Soc.*, **88**, 117–135.

——, —— and W. C. Macklin, 1962: The density and structure of hailstones. *Quart J. R. meteor. Soc.*, **89**, 75–84.

Clauser, F. H., 1954: Turbulent boundary layers in adverse pressure gradients. *J. aero. Sci.*, **21**, 91.

Cunningham, R. M., 1960: Hailstorm structure viewed from 32,000 ft. *Geophys. Monogr. No. 5*, Washington, Amer. Geophys. Union, 325–332.

Delany, N. K., and N. E. Sorensen, 1953: Low speed drag of cylinders of various shapes, NACA T. N. 3038 (Ames Aeronautical Laboratory), 88 pp.

Dryden, H. L., 1956: *Hydrodynamics*. New York, Dover Publications, 634 pp.

Goldstein, S., 1938: *Modern developments in fluid mechanics*. Vol. I and II, Oxford, The Clarendon Press, 702 pp.

Grimminger, G., 1933: The upward speed of an air current necessary to sustain a hailstone. *Mon. Wea. Rev.*, **61**, 198–200.

Herman, B. M., and L. J. Battan, 1961a: Calculations of Mie backscattering of microwaves from ice spheres. *Quart. J. R. meteor Soc.*, **87**, 223–230.

—— and ——, 1961b: Calculations of Mie backscattering from melting ice spheres. *J. Meteor.*, **18**, 468–478.

Hoerner, S., 1938: Tests of spheres with reference to Reynolds numbers turbulence and surface roughness. NACA T. M. No. 777, 32 pp.

——, 1958: *Fluid dynamic drag*. New York, published by the author, 203 pp.

Lees, L., 1947: *The stability of the laminar boundary layer in a compressible fluid*. NACA Report No. 876, 331–377.

Liepman, J., and R. Fila, 1947: *Investigations of effects of surface temperature and single roughness elements on boundary layer transitions*. NACA Report No. 890, 587–598.

Lin, C. C., 1959: *Turbulent flows and heat transfer in high speed aerodynamics and jet propulsion*. Vol. V, Princeton, The Princeton Press, 549 pp.

Macklin, W. C., 1963: Heat transfer from hailstones. *Quart. J. R. meteor. Soc.*, **89**, 360–369.,

Macklin, W. C., and F. H. Ludlam, 1961: The fallspeeds of hailstones. *Quart. J. R. meteor. Soc.*, **87**, 72–81.

Prandtl, L., 1914: Über den Luftwiderstand von Kugeln. *Goettinger Nachr.*, 177–182.

Schlichting, H., 1955: *Boundary layer theory*. New York, McGraw Hill, 535 pp.

Shapiro, A. H., 1953: *The dynamics and thermodynamics of compressible fluid flow*. New York, Ronald Press, 647 pp.

Weickmann, H., 1953: Observational data on the formation of precipitation in cumulonimbus clouds. *Thunderstorm electricity*, Chicago, The University of Chicago Press, 66–138.

Willis, J. T., K. A. Browning and D. Atlas: Radar observations of melting ice spheres during free fall. *Proc. Tenth. Wea. Radar Conf.*, Boston, Amer. Meteor. Soc., 151–156.