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Distribution of Graupel and Hail With Size

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ABSTRACT—Observations have been made on the size and concentration of graupel and hail occurring in untreated convective cloud systems over the High Plains of the United States. From these data, an average graupel and hail distribution has been generated. The comparison of this size spectrum with data from other studies, along with the implications to hail detection and hail suppression, is also discussed.

1. INTRODUCTION

The significance of hailstone sizes and concentrations occurring within convective clouds is a point of some speculation in the study of hail detection. Information about hailstone size is usually presented in terms of frequency of occurrence over seasonal periods of time and thus is of no use in real-time hail detection or in such activities as aviation, cloud seeding for hail suppression, and others.

During recent years, the Atmospheric Research Group of the University of Wyoming has conducted several flights near cloud base within the organized updrafts of severe hailstorms; in addition, numerous penetrations of vigorous cumulus congestus clouds have been made. Encounters with graupel and hail (often inadvertent) have occurred, especially while flying in the updrafts of large thunderstorms beneath the overhang [1] and in the vicinity of high radar reflectivity gradients that border the weak echo region. Observations of the monodispersity of hail encountered near the updrafts is a subject of another paper (Auer and Marwitz 1972). The purpose of this note is to report on the observed relationships between graupel or hail diameters and their respective concentrations. Since similar laws have been given as approximations to the size spectra of particles in both rain (Marshall and Palmer 1948) and snow (Gunn and Marshall 1955, 1958), it seems reasonable to generate such a relationship for hail.

2. PROCEDURES

During the summer seasons 1968–70, convective cloud systems were selected for study in the Alberta Hail Studies and in the northeastern Colorado Joint Hail Research Project. Often during routine flights within the updraft area, hail would be encountered by the aircraft when entering or exiting the updraft area. From the aircraft cockpit, hail can be seen up to several tens of meters ahead of the aircraft position. The onboard meteorologist can then ready himself for hailstone size estimates. Hailstone concentrations were estimated by counting the number of stones impacting on a known surface area (e.g., cockpit windshield) in a given time increment and recording the true airspeed of the aircraft. From this crude but effective technique, airborne hail size distribution could be generated by knowing the number and size of the hailstones contained in a volume swept out by the aircraft.

Following many of the airborne encounters with hail, mobile ground units were vectored into the same hailshaft according to procedures outlined by Auer and Marwitz (1969). Thus, complementary size distribution from hailfall around the cloud base updraft (i.e., just following the passage of "scud" cloud) could be obtained by these ground observers by sizing the hailstones impacting on a unit surface area in some increment of time.

The High Plains area surrounding Laramie, Wyo., is ideally suited for observing graupel and hail distributions at the surface because of the frequency of graupel or hail showers similar to those described in other elevated terrain by Battan and Wilson (1969). When airborne observations were not available, concentration data could still be collected at the surface by simply sizing and counting the graupel or hail particles impacting on a given area in a known increment of time.[2] Of course, this method requires information concerning the terminal fall velocity of the solid hydrometeor so that the volume from which the graupel or hail fell may be computed. Surface observations of terminal fall velocity for such hydrometeors have been systematically conducted. This terminal fall velocity was determined directly with a stopwatch by timing the hydrometeor as it fell a known vertical distance, usually 1–2 m. After the hydrometeor landed on black velvet, its characteristic dimension was determined by micrometer measurement. Figure 1 shows the observed relationship between the diameter of spherical and conical graupel or hail and the corresponding measured terminal fall velocity. Other previously published derived and observed terminal fall velocity data have been included in figure 1 for comparative purposes and as an extension of the range of data. Information from figure 1 was used in determining the size spectrum for any hail observed at the surface.

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[1] Overhang refers to the radar echo located above the updraft.

[2] Concentration $C=N/Avt$ where N is the number of particles falling at terminal velocity, v, upon an area, A, in time increment, t.

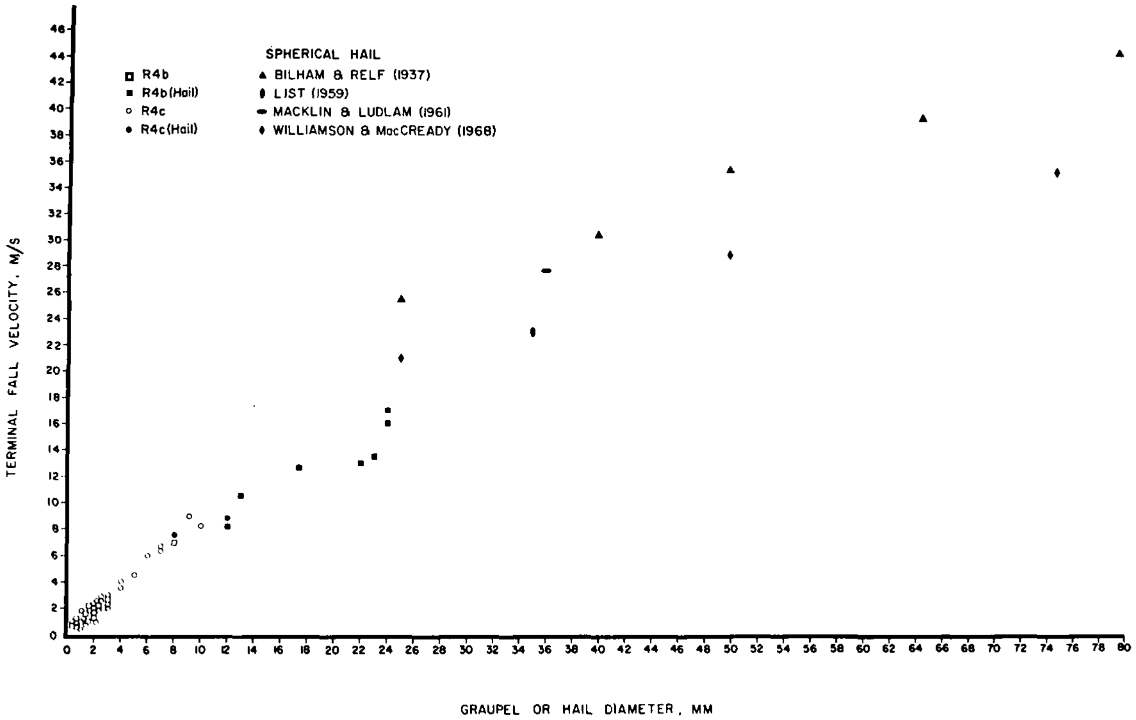

FIGURE 1.—Observed relationship between terminal fall velocity and diameter of spherical (R4b) and conical (R4c) graupel and hail. The hydrometeor identification code is taken from Magono and Lee (1966). All observations were made at a ground elevation of 7,000 ft MSL; other referenced fall velocity data were reduced to 7,000 ft MSL for comparison.

The average vertical fall distance for hail from the airborne encounter to the surface was 1.5 km (maximum 2.0 km); for hailstone diameters>1 cm, the effects of melting (Mason 1956, Ludlam 1958) are inconsequential. For example, according to those authors, a 1-cm hailstone is reduced by melting only to 0.9 cm when falling 5.0 km below the freezing level. No attempt was made, therefore, to consider the effect of melting on the hailstones observed at the ground.

To enable us to expand the range of the size distribution data for graupel found within convective clouds, aircraft penetrations of isolated vigorous cumulus congestus clouds (uncontaminated by cirrus) were also made. Typically, individual clouds chosen for penetration and graupel sampling possess cloud-top temperatures colder than −5°C but warmer than −12°C. Graupel sizes and concentrations are determined by exposing a single aluminum foil impactor for a known time outside the aircraft; calibration data for the impactor was given by MacCready and Williamson (1969). Graupel data obtained by this method were generally limited to diameters of 6 mm or less.

3. RESULTS

A total of 161 observations of graupel and hail concentrations were made from 69 convective clouds. Concentration values from all convective cloud systems were averaged over 1-mm diameter increments and plotted as the histogram shown in figure 2; in addition, the least-squares technique was employed to generate a best-fit equation from all observed graupel and hail concentration values. Figure 2 shows the average graupel and hail size distribution found in the clouds in this study. From the best-fit equation in figure 2, we see that the graupel and hail concentrations vary approximately as the cube of their diameter.

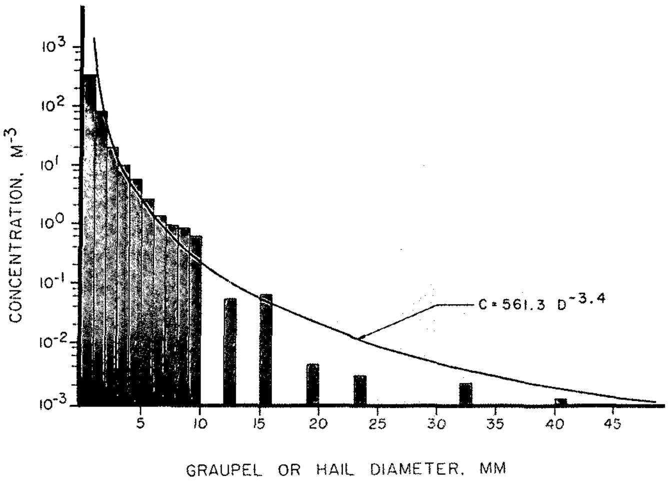

FIGURE 2.—The average graupel and hail size distribution observed from convective cloud systems over the High Plains.

Hail size distributions reported or derived from hailfall data (i.e., hail size upon an area or for a known duration) of other researchers are shown in figure 3. In general, those distributions agree with the data presented herein. Because sufficient documentation of large size hail (diameter

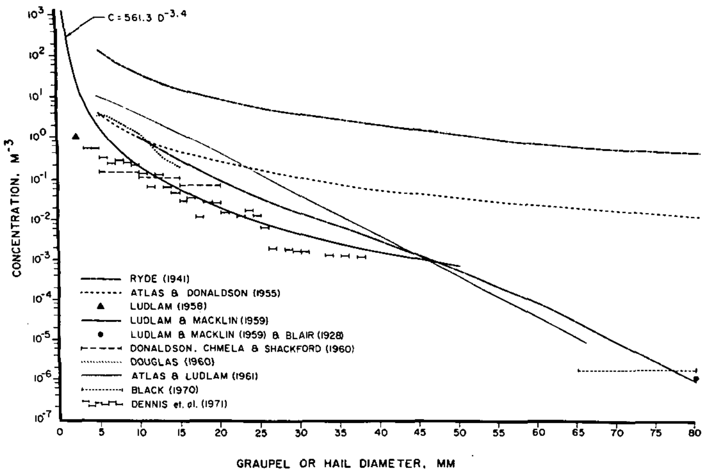

FIGURE 3.—A collection and comparison of other observed or derived hail size distributions. The distribution from this study is presented as the best-fit equation shown in figure 2 (Ryde 1941 data from Ludlam and Macklin 1959).

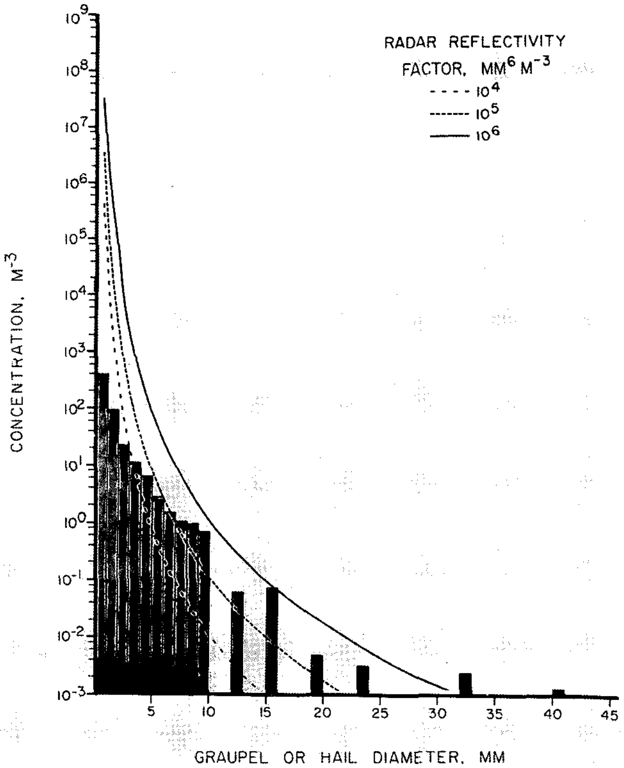

FIGURE 4.—A comparison of calculated radar reflectivity factors (assuming spherical, electromagnetically "wet" particles) with the observed graupel and hail size distribution shown in figure 2.

greater than 30 mm) is sparse and does not always allow for concentration data to be derived, the existing, limited comparative data may only suggest some relative shape of the hail size distribution beyond the range of the observations of this study.

It is noteworthy that in this study graupel was occasionally found in cumulus congestus clouds with tops colder than $-5°C$ but was always found in clouds with tops colder than $-8°C$ but warmer than $-12°C$.

4. IMPLICATIONS

If the growth assumptions concerning the spherical shape and electromagnetically "wet" surface of hail are allowed, estimates of the radar reflectivity factor, Z, may be made from the observed graupel and hail distributions presented herein.[3] Figure 4 shows the radar reflectivity factors of 10^4, 10^5, and 10^6 $\mathrm{mm^6 \cdot m^{-3}}$ plotted as a function of hydrometeor diameter and concentration; the observed graupel and hail size spectrum is again shown from figure 2 for comparison. One can see from figure 4 that the observed graupel or hail concentration exceeds the concentration for $Z=10^4$ $\mathrm{mm^6 \cdot m^{-3}}$ at a hydrometeor diameter greater than 4 mm; similarly, the observed concentration exceeds the concentration for $Z=10^5$ and 10^6 $\mathrm{mm^6 \cdot m^{-3}}$ at hydrometeor diameters of 8 and 35 mm, respectively. Thus, it is suggested here that radar reflectivity factors exceeding 10^5 $\mathrm{mm^6 \cdot m^{-3}}$ could be indicative of the presence of graupel or hail (within the framework of the assumptions mentioned above) of diameters greater than 8 mm; likewise, radar reflectivity factors exceeding 10^6 $\mathrm{mm^6 \cdot m^{-3}}$ might be interpreted as an indication of the presence of hail exceeding 35 mm in diameter.

These suggested relationships of radar reflectivity factors to the presence of hail in thunderstorms have been studied by several investigators. Donaldson (1961) and Wilk (1961) found that hail is often associated with a reflectivity factor aloft of $Z>10^5$ $\mathrm{mm^6 \cdot m^{-3}}$ for 3-cm wavelength radar. Geotis (1961) provided comparative data for 10-cm wavelength radar and found that height variations of radar reflectivity do not furnish a unique indication of hail, but that hail is indicated by low-altitude radar reflectivity exceeding 5×10^5 $\mathrm{mm^6 \cdot m^{-3}}$. Ward et al. (1965), utilizing 10-cm wavelength WSR–57 radar data, indicate that storm reflectivity at low levels or aloft is an index of the occurrence and size of hail. They found that hail occurred occasionally with radar reflectivity factors as low as 10^4 $\mathrm{mm^6 \cdot m^{-3}}$; in these cases, however, hail is usually not larger than 6 mm in diameter. Furthermore, Ward et al. (1965) state that for Oklahoma storms hail is associated with those radar echoes with a radar reflectivity factor of 10^6 $\mathrm{mm^6 \cdot m^{-3}}$; and most radar echoes with $Z \geq 10^5$ probably contain some significant hail. These suggestions appear to be confirmed by the size distributions presented in figure 4.

Inadequate understanding of the overall hail process severely hampers development of a realistic hail suppression theory. Hail size distribution in the untreated hailstorm, for example, is unknown. The hail size spectral data contained in this report may shed some light on this topic. Some current thinking (e.g., Iribarne and de Pena 1962; Sulakvelidze et al. 1967) concerning hail suppression entails bringing about a reduction in the ambient concentration of large hailstones by inducing competitive growth of additional hail embryos through massive seeding. These authors suggest that such a seeding concept

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[3] Radar reflectivity factor $Z=\sum_i C_i d_i^6$ ($\mathrm{mm^6 \cdot m^{-3}}$) where C and d are the concentration and diameter, respectively, for a size interval i.

for steady-state conditions obeys the relationship $r_s = r_b (C_b/C_s)^{1/3}$ between the hail concentrations, C, and radii, r (the subscripts b and s refer to background and seeded states, respectively). The fact that the background hail concentrations, at least for the storms shown in figure 2 and possibly those of Dennis et al. (1971) in figure 3, vary approximately as the cube of the hail diameter may be of some encouragement to the proponents of this concept of hail suppression.

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REFERENCES

Atlas, David, and Donaldson, Ralph J., "The Feasibility of the Identification of Hail and Severe Storms," *Air Force Surveys in Geophysics*, No. 65, U.S. Air Force Cambridge Research Center, Cambridge, Mass., **1955**, pp. 91–100.

Atlas, David, and Ludlam, F. H., "Multi-Wavelength Radar Reflectivity of Hailstorms," *Quarterly Journal of the Royal Meteorological Society*, Vol. 87, No. 374, London, England, Oct. **1961**, pp. 523–534.

Auer, August H., Jr., and Marwitz, John D., "Comments on 'The Collection and Analysis of Freshly Fallen Hailstones,'" *Journal of Applied Meteorology*, Vol. 8, No. 2, Apr. **1969**, pp. 303–304.

Auer, August H., Jr., and Marwitz, John D., "Hail Encountered in the Vicinity of Thunderstorm Updrafts," *Journal of Applied Meteorology*, Vol. 11, No. 3, June **1972** (In press).

Battan, Louis J., and Wilson, David S., " 'Hail' on a Mountain in Arizona," *Journal of Applied Meteorology*, Vol. 8, No. 4, Aug. **1969**, pp. 592–595.

Bilham, E. G., and Relf, E. F., "The Dynamics of Large Hailstones," *Quarterly Journal of the Royal Meteorological Society*, Vol. 63, No. 269, London, England, Apr. **1937**, pp. 149–160.

Black, D. E., Managing Editor, *The Coffeyville Journal*, Coffeyville, Kans., **1970** (personal communication).

Blair, Thomas A., "Hailstones of Great Size at Potter, Nebr.," *Monthly Weather Review*, Vol. 56, No. 8, Aug. **1928**, p. 313.

Dennis, A. S., Smith, P. L., Jr., Peterson, G. A. P., and McNeil, R. D., "Hailstone Size Distributions and Equivalent Radar Reflectivity Factors Computed From Hailstone Momentum Records," *Journal of Applied Meteorology*, Vol. 10, No. 1, Feb. **1971**, pp. 79–85.

Donaldson, Ralph J., Jr., "Radar Reflectivity Profiles in Thunderstorms," *Journal of Meteorology*, Vol. 18, No. 3, June **1961**, pp. 292–305.

Donaldson, Ralph J., Jr., Chmela, Albert C., and Shackford, Charles Reeve, "Some Behavior Patterns of New England Hailstorms," *Geophysical Monograph* No. 5, American Geophysical Union, Washington, D.C., **1960**, pp. 354–368.

Douglas, R. H., "Size Distributions, Ice Contents and Radar Reflectivities of Hail in Alberta," *Nubila*, Vol. 3, No. 1, Verona, Italy, **1960**, pp. 5–11.

Geotis, Spiros G., "Some Radar Measurements of Hail," *Proceedings of the Ninth Weather Radar Conference, Kansas City, Missouri, October 23-26, 1961*, American Meteorological Society, Boston, Mass., **1961**, pp. 133–138.

Gunn, K. L. S., and Marshall, J. S., "The Effect of Wind Shear on Falling Precipitation," *Journal of Meteorology*, Vol. 12, No. 4, Aug. **1955**, pp. 339–349.

Gunn, K. L. S., and Marshall, J. S., "The Distribution With Size of Aggregate Snowflakes," *Journal of Meteorology*, Vol. 15, No. 5, Oct. **1958**, pp. 452–461.

Iribarne, Julio V., and de Pena, Rosa G., "The Influence of Particle Concentration on the Evolution of Hailstones," *Nubila*, Vol. 5, No. 1, Verona, Italy, **1962**, pp. 7–30.

List, R., "Remarks Concerning the Aerodynamics of Hailstones," *Journal of Applied Mathematics and Physics*, Vol. 10, No. 2, Zeitschrift für Angewandte Mathematik und Physik, Basel, Switzerland, **1959**, pp. 143–159.

Ludlam, Frank Henry, "The Hail Problem," *Nubila*, Vol. 1, No. 1, Verona, Italy, **1958**, pp. 12–96.

Ludlam, Frank Henry, and Macklin, W. C., "Some Aspects of a Severe Storm in S.E. England," *Nubila*, Vol. 2, No. 1, Verona, Italy, **1959**, pp. 38–50.

MacCready, P. B., Jr., and Williamson, R. E., Meteorology Research, Inc., Altadena, Calif., April **1969** (personal communication).

Macklin, W. C., and Ludlam, Frank Henry, "The Fallspeeds of Hailstones," *Quarterly Journal of the Royal Meteorological Society*, Vol. 87, No. 371, London, England, Jan. **1961**, pp. 72–81.

Magono, Choji, and Lee, Chung Woo, "Meteorological Classification of Natural Snow Crystals," *Journal of the Faculty of Science*, Ser. 7 (Geophysics), Vol. 2, No. 4, Hokkaido University, Sapporo, Japan, Nov. **1966**, pp. 321–335.

Marshall, John Stewart, and Palmer, W. McK., "The Distribution of Raindrops With Size," *Journal of Meteorology*, Vol. 5, No.4, Aug. **1948**, pp. 165–166.

Mason, Basil John, "On the Melting of Hailstones," *Quarterly Journal of the Royal Meteorological Society*, Vol. 82, No. 352, London, England, Apr. **1956**, pp. 209–216.

Sulakvelidze, G. K., Bibilashvili, N. Sh., and Lapcheva, V. F., *Formation of Precipitation and Modification of Hail Processes*, Israel Program for Scientific Translations, Jerusalem, **1967**, 208 pp. (translation of Obrazovanie Osadkov i Vozdeĭstvie na Gradovye Protsessy, Gidrometeoizdat, Leningrad, U.S.S.R., 1965, 264 pp.).

Ward, Neil B., Wilk, Kenneth E., and Herrman, William C., "WSR-57 Reflectivity Measurements and Hail Observations," *National Severe Storms Laboratory Report* No. 24, U.S. Weather Bureau, Environmental Science Services Administration, Norman, Okla., Aug. **1965**, pp. 1–8.

Wilk, Kenneth E., "Radar Reflectivity Observations of Illinois Thunderstorms," *Proceedings of the Ninth Weather Radar Conference, Kansas City, Missouri, October 23-26, 1961*, American Meteorological Society, Boston, Mass., **1961**, pp. 127–132.

Williamson, R. E., and MacCready, P. B., Jr., "Aircraft Probing of Hailstorms," *Final Report*, Contract No. 5-2-67, Meteorology Research, Inc., Altadena, Calif., **1968**, 37 pp.

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