Graupel and Hail Terminal Velocities: Does a “Supercritical” Reynolds Number Apply?

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(Manuscript received 1 March 2014, in final form 13 April 2014)

ABSTRACT

This study characterizes the terminal velocities of heavily rimed ice crystals and aggregates, graupel, and hail using a combination of recent drag coefficient and particle bulk density observations. Based on a non-dimensional Reynolds number (Re)-Best number (X) approach that applies to atmospheric temperatures and pressures where these particles develop and fall, the authors develop a relationship that spans a wide range of particle sizes. The Re–X relationship can be used to derive the terminal velocities of rimed particles for many applications. Earlier observations suggest that a “supercritical” Reynolds number is reached where the drag coefficient for large spherical ice—hail—drops precipitously and the terminal velocities increase rapidly. The authors draw on observations and model simulations for slightly roughened large ice particles that suggest that the critical Reynolds number is dampened and that the rapid increase in the terminal velocity of smooth spherical ice particles rarely occurs for natural hailstones.

1. Introduction

Hail produces considerable monetary damage in the United States and throughout many parts of the world, including Italy, South Africa, and Russia. Damage is mostly to crops and buildings [see Changnon (2009) and articles cited therein]. One primary source of hail information in the United States is the historical records of the crop–hail insurance industry, kept since 1948. The national annual values of insured crop–hail losses have shown ever-increasing amounts (2014 dollars), from $20 million in 1948 to $174 million in 1974, jumping to $358 million in 1980, approaching $550 million in the early 1990s, and with continuing increases since. In 2010, there were 468,000 claims for all types of hail damage filed in the United States. That number increased to 862,000 in 2012. Crop–hail losses for 1949–98, as measured by insurance data, averaged $575 million (2000 dollars) per year (Changnon and Hewings 2001). The intensity of hail at a point or over an area is a function of the frequency of hail, the size of the hailstones as a result of their fall speeds, their total cross-sectional area, and, of course, a function of the hail particle size distribution (their number concentration as a function of size) and the horizontal wind speed. A search of the literature reveals that there is a wide spread in estimates of graupel and hail terminal velocities as a function of their size (maximum dimension). The goal of our study is to improve these estimates, thereby leading to improved representations for use in climate models and hail damage predictions.

Accurate estimates of the terminal velocities \( V_t \) of graupel and hail are also important for improving the representation of precipitation development in weather forecast models. For example, using hail with a bulk density of 0.9 g cm\(^{-3}\) rather than graupel with a bulk density of 0.4 g cm\(^{-3}\) as the rimed ice species, with appropriate adjustments to the \( V_t \), a hail-producing squall-line simulation resulted in a much narrower convective line and slightly smaller stratiform region (Bryan and...
Comparing graupel and hail simulations with similar adjustments, Milbrandt and Morrison (2013) and van Weverberg et al. (2012) found that, because of the higher $V_t$ of this hail than graupel, the rate of precipitation fallout was larger than for graupel, and melting extended to the surface rather than not far from the melting layer. However, most schemes do not explicitly consider density but use a single $V_t$–$D$ relationship.

Terminal velocity depends on the drag coefficient $C_d$ and the particle mass $m$, which in turn depends on the bulk density of the particles $\rho_b$ (the mass of the particle divided by the volume of a sphere of the same maximum dimension $D$). For a particle at its equilibrium velocity at a given temperature $T$ and pressure $P$,

$$V_t = (2mg\rho_f C_d A)^{0.5} = \left[2(\pi/6)^{3/2}\rho_b g / \rho_f C_d A \right]^{0.5},$$

where $\rho_f$ is the density of air, $g$ is the gravitational acceleration constant, and $A$ is the cross-sectional area normal to the airflow. Note that $\rho_b$ actually considers two aspects: a reduction in density from that of a sphere due to a nonspherical shape (e.g., spherical versus conical graupel), and a reduction in density due to air pockets and voids inside of the particle. Defined as in (1), $\rho_b$ considers both effects.

Because $V_t \propto C_d$, accurate estimates of $V_t$ must be based on reliable $C_d$. For certain sizes of graupel and especially hail, however, there is a sudden drop and flattening of $C_d$ followed by an increase at larger sizes. This anomaly in $C_d$ may be best illustrated by the earliest measurements of particles simulating hailstones. To “at least furnish a rough idea of the order of magnitude of the terminal velocity actually occurring in nature,” Bilham and Relf (1937, hereafter BR37, p. 150) reported on the form of the relationship between terminal velocity and diameter “deduced from values of the $C_d$ obtained from observations on 4–14-cm spheres towed by airplanes” (see Table 1). They reported a rapid dropoff in $C_d$ for Reynolds numbers $< 300 000$, $Re < 400 000$ and a leveling off of $C_d$ for $Re > 4000$ (Fig. 1a).

The Reynolds number is given by

$$Re = V_t D / \nu,$$

where $\nu$ is the kinematic viscosity of air. Note that the actual data in the BR37 study were not reported, only the form of the relationship. The actual data used to derive the curve they show in their article were derived from a pioneering study by Millikan and Klein (1933), although this data source was not acknowledged in their article and took hunting to find.
With points taken from their Fig. 2 (and as shown in their Table 1) converted to appropriate units, \( V_t \) can be readily derived assuming the hail particles are solid ice spheres and falling at standard sea level conditions (Fig. 1b). Note that the BR37 definition of the \( C_d \) is one-half of the conventional definition, but we have adjusted their values upward by a factor of 2. Rather than showing a monotonic increase in \( V_t \) with size from 0 to above 15 cm and a constant \( C_d \) of 0.4, which is approximately what is usually assumed (dashed line, Fig. 1b), the resulting \( V_t \) show a rather large increase for sizes beginning at 4 cm and below 10 cm, associated with the decrease in \( C_d \). The resulting \( V_t \) is due to the trend of \( C_d \) with Re and the interplay of \( C_d \) and \( D \) and suggests that there may be an unexpected change in the \( V_t\text{-}D \) relationship. BR37 specifically note that “Over a certain range of diameters, depending on the densities of air and ice and the kinematic viscosity of air, three values of the terminal velocity would therefore appear possible.” The dip in the \( C_d\text{-}Re \) relationship above Re \( \sim 2 \times 10^5 \) has been referred to as a “supercritical Reynolds number” regime (Willis et al. 1964).

Following in the footsteps of Laurie (1960), the building industry has widely used the BR37 \( C_d\text{-}Re \) and/or the \( V_t\text{-}D \) relationships to assess and infer hail impact damage. Therefore, we need to ask: does this anomaly apply to real hailstones? Are there other unexpected changes in graupel and hail fall speeds that should be addressed? Can the values of \( C_d\text{-}Re \) based on smooth hail be applied to natural hailstones?
To answer these questions, this article uses a generalized, nondimensional Reynolds number–Best number ($X$) approach often used to derive $V_t$ that depend on characteristic properties of the particles and the local temperature and pressure (see, e.g., Heymsfield and Westbrook 2010). In what follows, we relate $C_d$ to Re and Re to $X$, so that for a given ice particle and environmental conditions, $X$ can be computed directly, Re can be estimated from $X$, and thus the fall speed can be derived directly.

In section 2, we present many of the observations of rimed crystals or aggregates, graupel, and hail drag coefficients and associated masses collected to date. Section 3 attempts to explain the observations and draw on theoretical models, resulting in the development of the nondimensional relationships for deriving the terminal velocities. The results are summarized and conclusions drawn in section 4.

A word on the nomenclature used in this article: Drawing on the American Meteorological Society Glossary of Meteorology (available online at http://glossary.ametsoc.org/wiki/Main_Page), hail is precipitation in the form of balls or irregular lumps of ice greater than 5 mm; small hail is hail less than 6.4 mm. Graupel are heavily rimed snow particles, often indistinguishable from very small soft hail, except for the size convention that these particles are less than 5 mm. Heavily rimed particles and aggregates are noted where applicable.

2. Observations of graupel and hail

This section presents many of the earlier $C_d$–Re observations and estimations from numerical simulations of the drag coefficients of rimed crystals and aggregates, graupel, and hail. The primary datasets from which we draw are summarized in Table 1.

According to (1), terminal velocity is proportional to particle mass. Particle mass is proportional to the particle bulk density, which is a highly variable and uncertain parameter. The graupel mass has a major effect on its fall speed, and there have been relatively few measurements of graupel $r_b$. As shown in Fig. 2, graupel masses and the associated $r_b$ average about 0.1 g m$^{-3}$. The $r_b$ values from the Knight and Heymsfield (1983) study (Fig. 2) are above the large end of the graupel size designation and are within the small end of the hail size range—small hail—although the $r_b$ values are relatively low. They derived the actual densities through volumetric measurements, thereby considering the ice-free volume inside the particle. Densities so derived were an average of 0.44 g cm$^{-3}$ for the actual particles and an average of 0.31 g cm$^{-3}$ for the corresponding values of $r_b$, or about 50% larger. Their $r_b$ values are higher than for most of the graupel studies to date and may suggest that the $r_b$ values for hail are higher than those for graupel.

When graupel are riming in relatively high–liquid water content regions and at subfreezing temperatures...
but close to the 0°C level, \( \rho_b \) values are probably higher than those in Fig. 2. Heymsfield and Pflaum (1985) measured the densities of graupel beginning on frozen drops with diameters of 0.3 and 0.6 mm and growing in a vertical wind tunnel with air temperatures from \(-3^\circ\)C to \(-15^\circ\)C and liquid water contents from 0.5 to 2.6 g cm\(^{-3}\). The relationship that they developed was directly proportional to the graupel density and the “impact velocity” of the cloud droplets on the graupel (which is approximately equal to the graupel terminal velocity) and inversely proportional to the surface temperature of the graupel. The density of the deposited rime at the warmest temperatures was about 0.6 and 0.25 g cm\(^{-3}\) for most temperatures and liquid water contents. Cober and List (1993) have also quantified the density of rime from laboratory measurements. Based on these experiments and the observations of Knight and Heymsfield (1983), it is reasonable to assume that, in convection with relatively high liquid water content and warmer cloud-base conditions than found in most of the collections used in Fig. 2 and most of the experiments reported in the Heymsfield and Pflaum (1985) study, graupel densities are closer to 0.3 g cm\(^{-3}\).

A curve fit to the graupel mass versus diameter data in Fig. 2, plotted as a line and listed in the figure, indicates that on average, the graupel density increases with size (exponent in the mass power law greater than 3). Assuming for simplicity that the graupel are approximately spherical rather than conical, one can derive an associated power-law density–diameter relationship for graupel:

\[
\rho = 0.18D^{0.33},
\]

where \( D \) is in centimeters and \( \rho \) is in grams per cubic centimeters. Note that diverse datasets are included in Fig. 2 and that the graupel density for one type of scenario (e.g., graupel developed from frozen drops in deep convection) may not conform to the results shown in Fig. 2.

The few measurements of \( \rho_b \) of hail suggest that they are often close to those of solid ice density. Prodi (1970) used an x-ray absorption technique to measure the internal density (e.g., cavities and hollows) of natural and artificial hailstones, obtaining values between 0.82 and 0.87 g cm\(^{-3}\). List et al. (1970) measured \( \rho_b \) of naturally occurring 2.54-4.82-cm-diameter hailstones to be approximately 0.9 g cm\(^{-3}\). By comparison, Knight and Heymsfield (1983) found \( \rho_b \) from 0.31 to 0.61 g cm\(^{-3}\) with an average of 0.44 g cm\(^{-3}\) for hail from 0.63 to 1.54 cm (see Fig. 2). These particles developed in a springtime Colorado convective storm with surface temperatures of \(+2^\circ\)C, implying that little melting had occurred and providing an indication of how much interior volume is free of ice.

No major sudden decreases have been found in the drag coefficients and the resulting terminal velocities of rimed crystals, rimed aggregates, and graupel particles. Variable parameters for \( V_t \) include the graupel diameter, shape (conical or spherical), fall orientation, and thus the cross-sectional area, mass, and associated bulk density. Figure 3 shows observations of \( C_d \) for particles identified as heavily rimed crystals, rimed
aggregates, graupel, and small hail are shown as a function of their derived Reynolds numbers (Locatelli and Hobbs 1974; Kajikawa 1975; Knight and Heymsfield 1983; Takahashi and Fukuta 1988; see Table 1 for identification of the various studies). With increasing Re or size, the $C_d$ decrease by almost an order of magnitude, signifying that all else being equal, $V_t$ would increase by about a factor of 3 rather than remaining constant.

Drawing on fluid dynamic tank studies and observations, Heymsfield and Westbrook (2010) developed an empirical relationship between $C_d$ and Re for graupel as a function of its area ratio $A_r$, defined as the ratio of the graupel cross-sectional area normal to the airflow relative to that of a circle with the same maximum diameter. This formulation predicts that $C_d$ decrease from about 4 to 0.7 with increasing Re over the typical range of typical graupel Re (Fig. 3). Their formulation yields $C_d'$ that are comparable to those derived from a more recent theoretical study (Wang and Kubicek 2013), where in Fig. 3a we plot both formulations assuming $A_r = 1$. Both the Heymsfield and Westbrook (2010) and Wang and Kubicek (2013) formulations give a relationship between $C_d$ and Re that agrees well with those derived from direct measurements (Fig. 3, from studies reported in Table 1). The main differences between the observations, those from tank experiments, and the theoretical $C_d(\text{Re})$ are differences in $C_d$ at the lower Re, possibly because of the graupel shape (spherical versus conical).

Observations of the $C_d$ for hailstone-size particles indicate that the particle’s external structure has a major effect on the resulting relationship between $C_d$ and Re. Observations of the $C_d$ for spherical, smooth ice are plotted in Fig. 4a. The rapid dropoff in $C_d$ with Re noted in the observations of BR37 (Fig. 4a, curve 1) has since been corroborated by Achenbach (1972; curve 2 and others). However, as the roughness of the ice sphere (hailstone) increases, the dip in $C_d$ with Re becomes increasingly flattened [cf. filled and open circles, labeled 11 and 12, from Achenbach (1974, hereafter A74) and curves 7 and 8 from List et al. (1973; Fig. 4b). As illustrated schematically in Figs. 4b and 5b, the amount of roughening is quantified by $d/D$, where $d$ is the diameter or height of the nodules on the surface of the hailstone (visualized as the reverse of the diameter of the dimples on a golf ball). In the A74 experiments, the rough surface was obtained by pasting glass spheres of diameter $d$ onto the surface or by abrading the surface with coarse emery paper. Indeed, for the more typical “spiky” giant hailstones and from theoretical considerations (curves 7 and 13 of Fig. 4b), the supercritical Reynolds number and the very low values of drag coefficients observed for smooth ice spheres are not observed.

Roughening damps out the supercritical Reynolds number observed for the smooth ice spheres. To show this effect more clearly, Figs. 5a and 5b plot $C_d$ versus Re for smooth spheres and lightly through very rough spheres, respectively. The Re where $C_d$ dips decreases with increasing roughening and is clearly damped out.

A question remains as to what happens to the $C_d$ of hail as it falls through the melting layer and partially melts. In an ingenious experiment, Willis et al. (1964) lofted ice spheres to subfreezing temperatures on balloons, and when the balloons popped, the spheres descended through the melting layer. A 5.1-cm slightly roughened ice sphere with a roughness parameter (ratio of the diameter of the roughened surface to the diameter of the sphere) less than 0.02 initially had a drag coefficient of 0.26 and Re of $1.3 \times 10^5$. After melting, $C_d$ increased to 0.56 and Re dropped by about 30%. For a 7-cm lightly roughened sphere with an initial $C_d$ of 0.24 and Re of about $1.6 \times 10^5$ and just below the critical Reynolds number, the drag coefficient remained constant during melting, presumably because the ice sphere diameter changed little during the melting process. Because of the effect of roughening on the fall speeds of the simulated hailstones, they concluded that the rapid increase in the terminal velocity observed for smooth ice spheres may only be “attained rather infrequently in nature” (Willis et al. 1964, p. 107).

In summary, graupel $\rho_b$ values increase with size or Re, and $C_d$ decreases with increasing Re or size in a systematic fashion that is reasonably well predicted from fluid tank (empirical) data and theoretical considerations. Hail of sizes 2 cm and above have densities close to those of solid ice. Experimental data indicate that there is a critical Reynolds number for smooth ice spheres, but this rapid decrease in the $C_d$ becomes more damped and the dip occurs at increasingly lower Re as the ice sphere becomes more roughened. Given this observation and the observations of Browning and Beimers (1967), whose data suggest that most hailstones are likely to be oblate and spiky, it can be concluded that only in occasional instances would a critical Reynolds number be reached by a naturally occurring hailstone.

3. Synthesis of results leading to the calculation of graupel and hail fall speeds

For calculation of terminal velocities, it is convenient to use the nondimensional Davies or Best number,

$$X = C_d \text{Re}^2,$$

where
and pressure. The objective of this section is to relate \( X \) to Re, so that for a given ice particle and environmental condition, \( X \) can be computed directly, Re can be estimated from \( X \), and thus the fall speed can be derived using (2).

Drawing on the rimed crystal, graupel, and small-hail datasets, and empirical and theoretical relationships identified in Table 1 and used in Fig. 3, Fig. 6 shows the relationship between the Best and Reynolds numbers for rimed through small hail particles. There is a monotonic increase in Re with \( X \) and no surprising deviations across the range of Re. The theoretical (Wang and Kubicek 2013) and the Heymsfield and Westbrook (2010) relationships agree quite closely except at the lower Re values, and both provide a reasonably good match with the observations. The Heymsfield and Westbrook (2010) data provide a reasonably good match to the data across the full range of approximately \( 1 < \text{Re} < 10^5 \).

The Reynolds number–Best number relationships for smooth and roughened spheres from the observations and for oblate spheroids based on theoretical considerations are compared in Fig. 7. The dotted straight lines in

\[
X = 2mD^2g/\left(\rho_f v^2A\right).
\]  

(5)
the two panels show the corresponding $C_d$. For smooth spheres, the discontinuity in the Re–$X$ relationship as $X$ increases above $10^{11}$ clearly reflects the abrupt decrease in $C_d$ that would be associated with a rapid increase in $V_t$ (Fig. 7a). This effect is appreciably muted or nonexistent for lightly to heavily roughened ice spheres and, where noted, occurs at much lower values of $X$ (Fig. 7b). A similar effect is noted from dimples on a golf ball (Choi et al. 2006), where the dimples cause local flow separation and trigger the shear-layer instability along the separating shear layer, resulting in the generation of large turbulence intensity. In any event, the theoretical

![Graph showing the relationship between drag coefficient and Reynolds number for spheres with increasing roughness as defined by $d/D$. The data are from BR37, A74, and Young and Browning (1967, hereafter YB67). The numbers shown in the lower left are the approximate diameter of the spheres (cm).](image)

**Fig. 5.** The relationship between drag coefficient and Reynolds numbers for spheres with increasing roughness as defined by $d/D$. The data are from BR37, A74, and Young and Browning (1967, hereafter YB67). The numbers shown in the lower left are the approximate diameter of the spheres (cm).

![Graph showing the Reynolds number–Best number relationship for rimed particles, graupel, and small hail based on observations of natural particles and from wind tunnel, theoretical, and fluid tank experiments.](image)

**Fig. 6.** Reynolds number–Best number relationship for rimed particles, graupel, and small hail based on observations of natural particles and from wind tunnel, theoretical, and fluid tank experiments.
Re–X curve in Fig. 7 falls considerably below the data for roughened spheres.

To prevent discontinuities in the fall speeds of graupel and hail for modeling studies and other applications, it is desirable to develop a continuous relationship across all values of the Best number. A power-law Re–X curve, fitted over different ranges of X with coefficient of fits of 0.95 and 0.99, respectively, are

$$\text{Re} = 0.106X^{0.693}, \quad X < 6.77 \times 10^4$$  \hspace{1cm} (6a)

and

$$\text{Re} = 0.55X^{0.545}, \quad X > 6.77 \times 10^4$$  \hspace{1cm} (6b)

The Re–X relationship developed here conforms well to the one developed by Knight and Heymsfield (1983) for small hail and hail of sizes 0.63–1.54 cm (Fig. 8). Because their relationship was developed for the actual particles both as they fell and then after soaking them in oil that fills the particle, it is probably applicable for both small hail as it falls through the melting level and following partial melting to fill void cavities. For rimed crystals and graupel, with sizes below those they considered, their relationship would overestimate Re, and for large hail at sizes above those they considered, it would underestimate Re.

We now apply the new Re–X relationship to derive graupel and hail V_t. For simplicity, we assume a pressure
level of 1000 hPa and temperature of 25°C. To illustrate the dependence of \( V_t \) on \( D \), two densities are assumed: 0.2 and 0.9 g cm\(^{-3}\). The results indicate that the logarithm of \( V_t \) is nearly a linear function of the logarithm of \( D \), indicating that they can be represented by the following power laws:

\[
V_t = 523D^{0.65} \quad \text{for a density of } 0.2 \text{ g m}^{-3}, \tag{7a}
\]

and

\[
V_t = 1207D^{0.64} \quad \text{for a density of } 0.9 \text{ g m}^{-3}, \tag{7b}
\]

where \( D \) is in centimeters and \( V_t \) is in centimeters per second. From (6), these relationships change with \( P \) by the ratio of \((1000/P)^{0.55}\).

It is also straightforward to estimate the effect of the particle density on \( V_t \). The density–diameter relationship developed for graupel and small hail in Fig. 2 [see (3)] is also applied in Fig. 9. The \( V_t-D \) relationship becomes

\[
V_t = 488D^{0.84}, \tag{8}
\]

thus, with a steeper slope comes an expected result. Note that this equation would only apply to particles that originate as rimed crystals.

Our \( V_t-D \) relationship, for the same particle properties, is quite similar to those of Milbrandt and Morrison (2013) for about the same bulk densities (Fig. 9). Their relationships are developed from a prognostic graupel density scheme that uses the Reynolds number–Best number approach of Mitchell and Heymsfield (2005) assuming that particles are spherical. Also shown is a fit to the terminal velocities derived from the Mitchell and Heymsfield (2005) representation for graupel, assuming solid ice spheres with an area ratio of 1.0. These conform nicely to our new relationship out to 0.1 cm and then diverge from it. Our new \( \text{Re}^r-X \) relationship, fitted across the full range of \( \text{Re}^r-X \) for rimed particles through hail, extends across a wide range of diameters and can be readily used with variable densities (e.g., see light blue solid curve; Fig. 9). Also shown in Fig. 9 are \( V_t-D \) relationships used in weather forecast modeling by Thompson et al. (2008) and Lim and Hong (2010). Although not intended to be used at such large diameters, those relationships do produce \( V_t \) that are only somewhat higher than those developed here. The range of diameters considered, although too large, is plotted because other modeling studies may apply them in this way.

As suggested by the experiments of Willis et al. (1964), melting will lead to a decrease in the graupel/hail diameter, more so for graupel than hail, with the net result being that \( X, \text{Re} \), and hence \( V_t \), will decrease. From those experiments with 5.1- and 7-cm hail, there is no evidence that there is an abrupt change in the form of the \( \text{Re}^r-X \) relationship. Soaking of graupel or hail with densities below those of solid ice (Knight and Heymsfield 1983)
may change the mass but not the diameter, and this increased mass could increase the terminal velocity.

4. Summary and conclusions

The goal of this study is to develop accurate expressions for the terminal velocities of rimed crystals, graupel, and hail over size ranges from several tenths of a millimeter to above 10 cm in diameter that can be used in cloud models or engineering-related applications and are general enough to be used for most atmospheric pressures and temperatures. Using observations of the masses and terminal velocities of these particles reported in the literature, we developed a nondimensional Reynolds number–Best number relationship that spans a broad range of Re and corresponding rimed crystal–graupel–hail sizes.

Necessary inputs into the development of this relationship are the particle masses or bulk densities and drag coefficients. For heavily rimed crystals or aggregates and graupel, \( \rho_b \) values are found to average about 0.1 g cm\(^{-3} \). In convection with relatively high liquid water contents and warmer cloud-base conditions than most of the data used in our study, graupel densities are likely to be closer to 0.3 g cm\(^{-3} \). The interior volume of graupel undergoing melting will fill with water, leading to densities of solid ice or above. Also, nonspherical graupel will become more spherical, with higher masses for a given size. The few observations of the \( \rho_b \) of hail are closer to those of solid ice, about 0.5–0.9 g cm\(^{-3} \), and possibly higher for low-density hail soaked with liquid water during a melting period. Also, because hail is often oblate and not spherical, most hail will have smaller masses for a given size, leading to lower terminal velocities. Detailed calculations of \( \rho_b \) using models with explicit consideration of the density of accreted water (e.g., Mansell et al. 2010; Milbrandt and Morrison 2013) are needed to further quantify particle densities under different scenarios.

Using rimed crystal and graupel mass and terminal velocity data, it is found that for increasing Re, \( C_d \) of heavily rimed crystals through graupel particles decrease by about an order of magnitude, from about 10 to 1. Drag coefficients developed recently based on theoretical treatments and laboratory tank data for graupel are somewhat lower than the observations. The \( C_d \) values of hailstones of about 0.4–0.45 are somewhat lower than the often-assumed value of about 0.5. The so-called hail “critical Reynolds number” observed experimentally and theoretically for smooth ice spheres above 10 cm in diameter is damped and occurs at increasingly smaller diameters as the particle surface becomes rougher. It can be concluded that only in occasional instances would a critical Reynolds number be reached by naturally occurring hailstones.

Acknowledgments. The authors thank Hugh Morrison and Jason Milbrandt for their helpful comments. We especially thank Meg Miller for her editorial assistance. This research was partially supported by NCAR.
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