Melting and Shedding of Graupel and Hail. Part II: Sensitivity Study

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ABSTRACT

A sensitivity study on the melting and shedding behavior of individual graupel and hail is presented utilizing the detailed microphysical model presented in Part I. The influence of particle density and size, atmospheric temperature profile, relative humidity profile, liquid water content, shedding parameterization, and heat transfer rates are investigated. The results show that the melting of graupel and the melting and shedding behavior of hailstones are significantly affected by the initial particle density and size, temperature profile, and relative humidity.

When graupel and hail are grown in a Doppler-derived three-dimensional wind field, the results show that the melting and shedding behavior of the graupel and hail are relatively insensitive to changes as large as 25% in the heat transfer coefficient or to the differences between the Rasmussen et al. and the Chong and Chen shedding parameterizations.

1. Introduction

In Part I of this study (Rasmussen and Heymsfield, 1987a) we presented a detailed model of the melting and shedding of individual graupel and hail. In this paper we present a sensitivity study utilizing this model. Specifically, we examine the influence of 1) initial particle density, 2) initial particle size, 3) atmospheric temperature profile, 4) relative humidity profile, 5) liquid water content, 6) shedding parameterization, and 7) heat transfer rates on the melting and shedding behavior of graupel and hailstones. This will be done for hailstones and graupel falling in both still air and in a three-dimensional (3-D) Doppler-derived wind field. In both cases, the atmospheric sounding is based on the 1 August severe storm day during the Cooperative Convective Precipitation Experiment (CCOPE) (Knight, 1982). Feedback effects of melting and shedding hydrometeors on their environment are not considered in this study.

2. Hail and graupel falling through still air

The atmospheric temperature and relative humidity profiles used are shown in Fig. 1. Note that the ground is at 0.8 km MSL (920 mb). The 0°C level is at 5.2 km (525 mb), and is based on pseudoadiabatic ascent of an air parcel from cloud base at 2.85 km. The surface temperature and relative humidity were obtained from

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measurements in the gust front during the 1 August 1981 severe storm near Miles City, Montana. Assuming this profile, we release hailstones and graupel at the 0°C level and let them fall through still air to the ground. As they fall they melt and, if conditions are right, may also shed liquid water drops.

a. Initial density

Figure 2 illustrates the evolution of melting hailstones with initial densities of 0.91 and 0.45 g cm⁻³. The layout of this figure and of the eight following will be the same. The first four plots will always be height (km) versus 1) diameter of ice (upper left), 2) axis ratio (upper right), 3) terminal velocity (just below the diameter of ice plot), and 4) number of 1-mm drops shed per km (just below the axis ratio plot). Below these four plots there will be two or four plots of various other parameters. Except for Figs. 3 and 4, the upper left plot of diameter of ice versus height will present the evolution with height of 0.5, 1.0, 2.0 and 3.0-cm diameter initialized hailstones, while the remaining plots in a particular figure will only consider a 2-cm diameter initialized hailstone.

Returning to Fig. 2, we note from the plot of the diameter of ice that a 1.0-cm diameter hailstone of density 0.91 g cm⁻³ reaches the ground as a 0.2-cm diameter ice particle, while the same sized hailstone with initial density 0.45 g cm⁻³ completely melts ~1.3 km above the ground. Similarly, a 2.0-cm hailstone of density 0.91 g cm⁻³ reaches the ground as a 1.5-cm diameter particle, while the 0.45 g cm⁻³ particle melts down to a 0.7-cm diameter particle at the ground. These results show the strong sensitivity of the final
hailstone size at the ground to the initial hailstone density assumed.

Figure 2e presents the mean density of 2.0-cm diameter hailstones with initial densities of 0.45 and 0.91 g cm$^{-3}$. The rapid increase in mean density with decreasing altitude for the 0.45 g cm$^{-3}$ particle is due to the soaking of the particle's meltwater. The 0.91 g cm$^{-3}$ density hailstone does not soak meltwater, but rather accumulates it on its surface. This behavior causes its axis ratio to decrease as a water torus builds up around its equator (Fig. 2b), and its terminal velocity to decrease (Fig. 2c). Once an unstable amount of meltwater accumulates on its surface, shedding of water drops can begin (Fig. 2d). For this example, shedding does not start until 2.3 km below the 0°C level.

The 0.45 g cm$^{-3}$ density hailstone behaves in a similar fashion after it has completely soaked its meltwater. During the soaking process, however, the terminal velocity increases (Fig. 2c) due to the reduced cross section. The formation of a water torus (Fig. 2b) and shedding (Fig. 2d) occur at lower levels due to the soaking process, but ultimately results in smaller axis ratios and larger rates of shedding than the 0.91 g cm$^{-3}$ particle because of the rapid melting of the low-density ice core towards the end of melting.

b. Initial size

To examine in more detail the sensitivity of melting to initial size, consider Fig. 3, which presents initial diameters of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 cm and a density of 0.91 g cm$^{-3}$. Figure 4 presents the same sizes for a density of 0.45 g cm$^{-3}$. Figures 3a and 4a show that whether or not a particle can survive as ice to the ground is strongly sensitive to its initial size. For instance, Fig. 3a shows that a 0.5-cm particle melts completely in ~2 km, while a 1-cm particle survives the 5.2 km fall to the ground. This strong dependence upon initial diameter reflects the cubic relation of diameter to the particle's total mass.

Also note from Figs. 3a and 4a that the shape of the diameter of ice versus height curves vary from one particle to another. This is due to the particles entering the various heat transfer regimes described in Part I, Table 1. For instance, Fig. 4a (0.45 g cm$^{-3}$) shows that a 1.5-cm diameter particle has a distinct slowdown in the rate of decrease of ice diameter near 0.9-cm diameter. This reflects the buildup of a water torus on the particle at this stage of melting which inhibits heat transfer at these Reynolds numbers due to the lack of internal circulation in the meltwater (Part I, Table 1, Eq. 3). We note that a 1.0-cm particle is in this weak heat transfer regime as well, allowing it to survive almost 3.0 km before it melts (Fig. 4a). The 0.5-cm particle, on the other hand, shows a rapid decrease in the ice core diameter. This particle is in the heat transfer regime in which the ice core is embedded in a spheroid of water which rapidly circulates, increasing the heat transfer [Part I, Table 1, Eq. (2)]. Particles larger than 2.5-cm diameter experience efficient heat transfer because most of the meltwater is shed (Part I, Table 1, Eqs. 4 and 5).

Figure 3e presents the overall diameter of 0.91 g cm$^{-3}$ density particles as a function of height. During the beginning of the particle’s fall its diameter remains the same (except for the small change in bulk density) because the liquid water on the particle’s surface has not begun to shed. The sudden decrease in overall diameter in Fig. 3e is related to the onset of shedding for each particle. We note from Figs. 3e and 3d that the 1.5-cm diameter particle falls the shortest distance before it starts to shed. Figure 4d shows that this is also true for the 0.45 g cm$^{-3}$ density hailstone. This behavior derives from the fact that larger particles require more water to accumulate on their surface before shedding occurs (see Part I, Fig. 1). The increase in falling distance before shedding onset for a 1.0-cm particle is due to the slower heat transfer for particles of this size (see Part I, Table 1). In Fig. 4e we also note that the overall
diameter decreased initially due to the soaking of meltwater. After the meltwater has completely soaked into the low-density ice core, the overall diameter remains constant for a short period during which the particle melts sufficient water for an unstable torus to form. Once shedding occurs, the overall diameter decreases again until a stable drop size is reached (we assumed 8-mm diameter to be the largest stable drop size).
Figure 3c presents the terminal velocity of these particles as a function of height for an initial density of 0.91 g cm$^{-3}$. Note that the terminal velocity decreases nearly linearly with height for all the particles. The 0.5-cm diameter increases its terminal velocity initially due to the transition from a rough to a smooth particle. The change in slope of each curve is due to the onset of shedding. Figure 4c presents a similar figure for the same sized particles with an initial density of 0.45 g cm$^{-3}$. In contrast to the 0.91 g cm$^{-3}$ density particles, terminal velocity increases initially for most of the particles (except the largest). This increase in terminal velocity is due to the soaking, and consequent reduction in the cross section of the particles (reduced drag). The larger particles change cross sections so slowly that they initially experience a reduction in terminal velocity due to the air density effect. The rapid decrease in terminal velocity at midlevels in Fig. 4c occurs when the meltwater has completely soaked, and a water torus is allowed to form (except for the two largest particles). Note that the terminal velocities all tend towards the terminal velocity of a stable 8-mm diameter drop.
Fig. 4. As in Fig. 3, except the initial ice density is equal to 0.45 g cm$^{-3}$, and plots (g) and (h) of mean density of particle (g cm$^{-3}$) and mass of ice (g) have been added.
Figure 3b presents the change in axis ratio for particles with 0.91 g cm$^{-3}$ density, while Fig. 4b shows the axis ratio change for particles with a density of 0.45 g cm$^{-3}$. Note that the axis ratio starts to decrease immediately for the 0.91 g cm$^{-3}$ particles, with the rate of decrease nearly constant for a particular sized particle. Also note that the slope becomes steeper for the larger hailstones. Because of their rapid fall and large size, these larger hailstones are not able to accumulate sufficient water about their equator to cause a large change in axis ratio (most of the water is shed).

In contrast to the 0.91 g cm$^{-3}$ particles, the axis ratio does not decrease immediately upon melting for 0.45 g cm$^{-3}$ density particles (Fig. 4b). Instead, the particles first soak their meltwater, as shown in Fig. 4g, until they are completely soaked, after which a rapid decrease in axis ratio occurs. For instance, a 1.5-cm diameter particle falls ~2.5 km before it melts enough water to completely soak the particle, after which the axis ratio rapidly reaches its equilibrium value within 1 km of fall due to the rapid formation of a water torus.

Figures 3d, f and 4d, f present the shedding behavior of these particles. In Fig. 3d we note that, as mentioned earlier, the 1.5-cm diameter particle sheds water after falling the shortest distance (density = 0.91 g cm$^{-3}$). The rate of shedding, however, is highest for the 3.5-cm diameter particle. This results in the 3.5-cm diameter particle shedding the most mass overall (Fig. 3f).

Figure 4d shows behavior similar to that shown in Fig. 3d, except that particles larger than 3.0 cm diameter are not shedding since these larger particles are still soaking up the meltwater by the time they reach the ground (Fig. 4g), and thus do not accumulate any liquid water on their surface. Figure 4f shows that a 2.0-cm diameter particle sheds the most cumulative mass because of this behavior.

c. Atmospheric temperature profile

The sensitivity to temperature profile was investigated by modifying the surface air temperature of 24°C by ±5°C, resulting in the temperature profiles shown in Fig. 5e. Figure 5 presents results for particles of initial density 0.91 g cm$^{-3}$, while Fig. 6 presents results for initial density 0.45 g cm$^{-3}$. These figures show that the temperature profile significantly affects the melting and shedding behavior of these particles, especially those with low density. For instance, a 2-cm diameter hailstone of density 0.91 g cm$^{-3}$ can change its final diameter by ±20% (Fig. 5a), while a 0.45 density hailstone can change its final diameter by ±50% (Fig. 6a) compared to the standard temperature profile.

The height at which shedding starts is also sensitive to the temperature profile, as shown in Figs. 5d and 6d.

d. Relative humidity profile

Relative humidity effects were investigated by using the temperature profile in Fig. 1 with relative humidities of 1) 50% and 2) 100%. Figure 7 presents results for initial particle densities of 0.91 g cm$^{-3}$, while Fig. 8 presents results for initial particle densities of 0.45 g cm$^{-3}$. These results show that the melting and shedding behaviors of hailstones and graupel are very sensitive to relative humidity, especially the lower-density particles. As an example, Fig. 8a shows that a 2-cm diameter hailstone of density 0.45 g cm$^{-3}$ melts down to a 1.2-cm diameter particle while experiencing a relative humidity of 50%, while it melts completely for a relative humidity of 100%. Thus, evaporative cooling is shown to significantly slow down the melting process.

The height at which shedding starts is also very sensitive to the relative humidity profile, as shown in Figs. 7d and 8d.

e. Liquid water content

The sensitivity of melting and shedding to liquid water content is presented in Fig. 9 for liquid water contents of 0.0, 2.0 and 4.0 g m$^{-3}$, assuming hailstones with initial densities of 0.91 g cm$^{-3}$. This figure shows that the melting behavior of hailstones and graupel is relatively insensitive to liquid water content despite the fact that we assume all the heat content of the collected liquid water is added to the hailstone before it sheds. This behavior was also observed by Gvlesian and Kartsvadze (1968) in their experiments on melting hailstones. They found that liquid water contents less than 10 g m$^{-3}$ had minimal effects upon the melting rates of their hailstones. Note that the runs in Fig. 9 had no updrafts. The effect of the sensible heat term, however, becomes more important when considering larger hailstones. The 5-mm diameter particle actually melts more slowly while collecting liquid because it has grown large enough to enter the slow heat transfer regime [see Part I, Table 1, Eq. (3)].

The shedding behavior, however, is clearly sensitive to liquid water content, as shown in Fig. 9d. This sensitivity is obviously a result of a hailstone's ability to store only a limited amount of the collected cloud water on its surface. Results for hailstones of initial density 0.45 g cm$^{-3}$ are similar.

f. Shedding parameterization

Figure 10 presents the results of sensitivity runs using two different shedding parameterizations for particles with 0.45 g cm$^{-3}$ initial density. Also shown is a heat transfer parameterization (parameterization 3) to be discussed in the next section. Parameterization 1 is the current shedding parameterization presented in Part I of this study. Parameterization 2 is based on the study by Chong and Chen (1974) which theoretically investigated the stability of water shells on an inner ice core. In Part I, Fig. 2, we presented the results of this study. From this figure we note that Chong and Chen allow shedding to occur for much smaller sizes of ice core than we do. Above an ice mass of ~0.35 g, they assume that all water is shed, while the current parameteriza-
Fig. 5. Melting and shedding behavior of spherical ice particles with initial ice density of 0.91 g cm$^{-3}$ falling through the temperature profiles shown in Fig. 5c, and the humidity profile in Fig. 1, with updrafts/downdrafts and liquid water content set to zero. Plot (a) presents the evolution of diameter of the ice core with height for initial particle diameters of 0.5, 1.0, 2.0, and 3.0 cm. Plots (b)–(d) present the evolution with height of several particle characteristics for a 2-cm initial diameter particle. Plot (f) presents the evolution with time of a 2-cm initial sized particle.

...tion based on experimental data predicts a water coating for all ice core sizes. Gvelesiani and Kartsivadze (1968) also found that part of the meltwater was retained on the surface of their hailstones suspended in free fall. Thus, these two parameterizations represent the two extreme cases of nearly all water being shed versus large amounts of liquid water being retained. For an ensemble of shedding hydrometeors, collection of shed water may deplete the concentration of shed drops (Rasmussen and Heymsfield, 1987b), and thus results in lower concentrations than predicted by this study.
We note from this figure that the final ice core size (Fig. 10a) is relatively insensitive to the parameterization used, while the terminal velocity and shedding behavior are markedly affected by choice of scheme. The terminal velocity after soaking of the ice core (Fig. 10c) does not decrease as rapidly for the Chong and Chen scheme as predicted by the current parameterization due to the nearly complete shedding of any meltwater. The current parameterization allows more meltwater to accumulate in a torus around the equator of the particle, causing the particle to fall more slowly (increased cross section). The particle shedding with the Chong and Chen (1974) parameterization in Fig. 10c hits the ground at a speed 50% faster than the current parameterization predicts.

Figure 10d shows that shedding occurs at a higher level with the Chong and Chen parameterization than the current parameterization predicts because the Chong and Chen parameterization requires much less water mass to build up before shedding occurs. The
cumulative amount of mass shed, however, is comparable in magnitude because nearly the same amount is melted by the time the two particles hit the ground (Fig. 10a) with the only difference between particles being the relatively small mass of water coating retained on the ice core in the current parameterization. Thus, the main effect of Chong and Chen's parameterization is to change the distribution of shedding with height, but not the absolute amount of mass shed.

**g. Heat transfer parameterization**

In Part I, Table 1, we present heat transfer equations for melting graupel and hailstones. In the Reynolds number range between $6 \times 10^3$ and $2 \times 10^4$, we set
the heat transfer coefficient, $\chi$, equal to 0.76 (as found experimentally by Macklin, 1963, and Rasmussen et al., 1984). Many modelers, however, have used a value of $\chi$ equal to 0.60 in this Reynolds number range, following Ranz and Marshall (1952). In order to investigate the sensitivity of melting to the value of this coefficient, we present in Fig. 10 parameterization 3, which sets $\chi = 0.60$, rather than $\chi = 0.76$ as for parameterization 1; all other aspects are unchanged. We note from Fig. 10a that using Ranz and Marshall heat transfer coefficient for this Reynolds number range results in less mass melted for particles greater than 1 cm (smaller particles have Reynolds numbers less than 6000, and thus are not affected by this change). The difference, however, is not large. For instance, a 2-cm particle of initial density 0.45 melts down to a 0.75-cm diameter ice particle at the ground using $\chi = 0.76$, while setting $\chi = 0.60$ results in a 0.85-cm particle at
the ground. Figures 10b–10f show the corresponding small changes in axis ratio of the particle, terminal velocity, number of 1 mm drops shed per km, mean density, and the time spent in the melting region before hitting the ground.

3. Hail and graupel melting in a 3-D Doppler-derived wind field

In the previous section we presented results on the melting and shedding of hail and graupel falling
through still air. In natural clouds, however, the air is far from calm. In this section we present results of melting and shedding calculations in a 3-D Doppler-derived wind field for the 1 August 1981 severe storm observed during CCOPE. A discussion of this wind field is presented by Tuttle et al. (1988), and Rasmussen and Heymsfield (1987b).

In the following, we use the same procedure for in-
initializing particles as Rasmussen and Heymsfield (1987b). This involves initializing 1-mm drops between altitudes of 3–7 km (MSL) throughout the main updraft region of the storm. Drops were initialized every 500 m in the X, Y and Z directions, and allowed to freeze, grow, melt (using the microphysical model in Part I), and move in the wind field until they hit the ground. This results in nearly 5400 particle trajectories. We also assume the same thermodynamic structure in this wind field as Rasmussen and Heymsfield. In downdrafts, we assume the temperature and relative humidity profile shown in Fig. 1. For updrafts, we assume the temperature profile shown in Fig. 11, based upon pseudo-adiabatic ascent of a parcel. The downdraft temperature profile is also shown in Fig. 11 for comparison. Relative humidity in updrafts is assumed to be 100%. Below cloud base the environmental sounding is used. Liquid water content is assumed to be adiabatic in updrafts greater than 10 m s\(^{-1}\), linearly decreasing to zero at zero updraft. Below \(-25^\circ\text{C}\) we linearly deplete the liquid water to zero at \(-40^\circ\text{C}\).

In the following, we first present frequency plots of the melting and shedding behavior of these particles as they fall from the 0°C level (∼5.0 km) to the ground (0.8 km). We then present tables showing the deviation of this run from runs using 1) the Chong and Chen (1974) shedding criteria, and 2) the Ranz and Marshall (1952) formulation of the heat transfer coefficient.

a. Melting and shedding in a 3-D wind field

The results of the melting and shedding behavior of the hailstones grown in the 3-D wind field are shown in Figs. 12 and 13 in the form of frequency plots. The height of each bar indicates the relative frequency of the parameter in the horizontal interval of the bar. The format of these figures is such that each horizontal row of figures represents the frequency of the indicated parameter at 5.0, 3.0 and 0.8 km MSL, respectively. For instance, Figs. 12a, b, c represent the frequency of the diameter of ice at 5.0, 3.0 and 0.8 km MSL. Also indicated on each figure is the mean and standard deviation.

We note from Fig. 12a that the size distribution of hailstones (initialized uniformly in space as 1-mm drops) is essentially exponential at 5 km MSL, with sizes up to 5 cm diameter. This result shows that the probability of a 1-mm drop growing into a hailstone in this wind field decreases exponentially with increasing final diameter. For instance, a 1-mm drop randomly initialized in the updraft regions of this storm has only a 1 in 1000 chance to grow into a hailstone larger than 4 cm in diameter.

Figures 12b and 12c show the evolution of the hail spectra with height. We note that the general exponential character of the size distribution is maintained, but the slope becomes significantly flatter at lower elevations. This is attributed to the faster melting of smaller particles, as shown in Figs. 3 and 4.

Figures 12d, e, f show the mean density of the hailstones as they fall from the 0°C level (∼5.0 km) to the ground (0.8 km). Note that the mean density increases from a mean of 0.84 g cm\(^{-3}\) at 5 km to 0.98 to 0.8 km, reflecting the soaking process of the hailstones.

In Figs. 12g, h, i, we present the number of 1-mm drops shed per kilometer. The standard deviations in Figs. 12g and 12i were too large to provide meaningful information. We note that a few particles shed nearly 10 000 1-mm drops km\(^{-1}\) as they fell. At each height, ∼20% of the 5400 particles are shedding. On average, each particle sheds ∼500 drops km\(^{-1}\) of fall, which results in one drop shed every 2 m of fall for each particle. The shedding of drops by melting hail is thus seen to be an abundant source of raindrops and possible new hailstone embryos.

Figures 13a, b, c show the cumulative amount of water mass shed between 5.0 and 0.8 km. We note that some particles shed 30 g of water during their fall to the ground. Most particles, however, shed between 0 and 5 g of water.

The updraft experienced by the particles is shown in Figs. 13d, e, f. At 5 km, a mean updraft of 2.2 m s\(^{-1}\) is experienced, while at 3.0 km (just above the cloud base at 2.85 km), a mean updraft of 1.12 m s\(^{-1}\) is felt. Below cloud base the updraft rapidly falls to zero (Rasmussen and Heymsfield, 1987b).

Correlating with updraft, the liquid water content (Fig. 13g, h, i) experienced by the particles falls from a mean value of 0.685 g m\(^{-2}\) at 5 km, to 0.067 at just above cloud base. (The liquid water content of shed particles is not considered.)
Fig. 12. Frequency plots (derived from the 5,400 particles grown in the 3-D wind field) of ice diameter (cm) (top row), mean density (g cm$^{-3}$) (middle row) and number of 1 mm drops shed per km (bottom row) at 5.0 (a, d, g), 3.0 (b, e, h), and 0.8 km (c, f, i) MSL. Also given is the mean and standard deviation at each altitude.

The above discussion of Figs. 12 and 13 reveals some of the basic melting and shedding behaviors of the 5400 hailstones initialized as 1-mm drops. The melting behavior of specific sizes of hailstones, however, is not easily apparent from these figures. In Fig. 14 we have plotted the mean variation of ice diameter with height for particles with initial diameters between 0.5 to 0.75, 1.25 to 1.5, 2.0 to 2.25, and 3.0 to 3.25 cm as dashed lines. Also indicated on these plots is the range of one standard deviation about the mean value at specific
levels. For comparison, we have also plotted calculations of ice diameter with height assuming still air and the temperature and humidity profiles given in Fig. 1. Each solid line represents an individual particle initialized with the same ice density (Fig. 15) and bulk density (Fig. 16) as the average value of the particles in the indicated size range at 5.2 km.

We note from Fig. 14 that particles greater than 1 cm in the 3-D wind field melted, on average, slightly faster than the particles falling through still air. This behavior is due to the particles in the wind field falling through regions which are, on average, warmer, moister, and have higher updrafts than the conditions assumed for the still air runs (see Figs. 5–8).
results suggest that estimates of the mean melting behavior of hailstones in free fall can be made with a 1-D model as long as the vertical profiles of temperature, humidity, and updrafts are all taken into account.

b. 3-D sensitivity tests

Sensitivity tests were run in order to check various parameterizations of microphysics. Specifically, tests of the

1) Chong and Chen (1974) shedding criteria, and
2) the Ranz and Marshall (1952) formulation of the heat transfer coefficient

were made. The results of these tests are given in Tables 1 and 2 in the form of the mean and standard deviation of the differences of the normal run in the previous section, to runs made with the above two parameterizations. The differences are calculated by comparing the trajectories of particles initialized at the same location. Table 1 presents the mean differences calculated by the normal run minus the run with the Chong and Chen parameterization. Positive differences are thus correlated with larger values in the normal run than the Chong and Chen run. Examination of frequency plots of these differences reveals that they are normally distributed, and that the mode of the distribution is close to zero, except for the terminal velocity distribution. In Table 1, for instance, the terminal velocity difference has a mean of $-55 \text{ cm s}^{-1}$ at 3 km, suggesting that the hailstones which were melting and shedding with the Chong and Chen parameterization fall on the average faster than the current parameterization. The positive times at 3.0 and 0.8 km reflect this behavior, as well. As shown in Fig. 10d, this occurs because the Chong and Chen parameterization sheds nearly all meltwater on its surface, thus reducing the particle's drag. The reduction in terminal velocity by reduced drag is partially compensated for by the loss of mass from shedding. Despite the different fall speeds, the Y (north–south) horizontal position of the particles on the ground (0.8 km) has a mean near zero, normally distributed. The $X$ (east–west) position on the ground also has a mean near zero, but skewed slightly towards negative values, suggesting a slight shift in $X$ position.

The remarkable result from these runs, however, is the centering of the mean of the distribution near zero (with a normal distribution) for most of the distributions. This is remarkable because these two shedding parameterizations represent two extreme behaviors (nearly all shed vs large amounts retained). Thus, effects of turbulence, wind shear, and particle collisions on shedding are not expected to have major effects upon the mean melting behavior of an ensemble of particles.

The same type of delta calculations were also performed for the Ranz and Marshall (1952) heat transfer coefficient calculations. The results of these calculations are shown in Table 2. In this case very little variation is observed, suggesting that changing the heat transfer coefficient by $\pm 25\%$ will have very little effect upon the average behavior of these particles in real 3-D wind fields.

4. Discussion

In the following we will discuss some of the implications of the above results.

a. Initial hail density

In both previous sections, we showed the strong sensitivity of melting and shedding behavior of hailstones and graupel to the ice density assumed. Previous methods of measuring hail density using hail collections from the ground obtained densities which were generally between 0.88 and 0.917 g cm$^{-3}$ (Vittori and di Caporiacco, 1959; Macklin et al., 1960; Mossop and Kidder, 1961). We feel, however, that the measurement of hailstone density from hailstones collected at the ground may often lead to higher densities than actually occur aloft because of the soaking of meltwater into the hailstone's lower-density interior (Kidder and Carte, 1964; Prodi, 1970; Prodi et al., 1984). The storage of collected hailstones at subzero temperatures will freeze any soaked meltwater, and certainly lead to higher densities than it had before melting. Thus, the com-
monly assumed hailstone density of 0.88–0.91 g cm⁻³ as determined by ground measurements may significantly overestimate the hail density before melting. The recent study of graupel and hail density by Knight and Heymsfield (1983) in which hail and graupel were collected during subfreezing ground temperatures, suggest that hailstones up to 1.6-cm diameter can have densities in the range of 0.31 to 0.61 g cm⁻³, significantly less than 0.89 g cm⁻³. Liquid water contents for the clouds in which their hail formed may have been lower than those typical for summertime storms, however. These results suggest that when modeling the melting and shedding of hailstones, careful attention should be given to the assumed hailstone and graupel density before melting. For instance, graupel and hail rime growth could be modeled using the density parameterization of Pflaum and Pruppacher (1979), as modified by Heymsfield and Pflaum (1985), and Rasmussen and Heymsfield (1985). This parameterization was used in the present study, and resulted in much lower hail densities (see Fig. 15) than the commonly used values of 0.88–0.91 g cm⁻³. Collections of hailstones and graupel in cloud should also be made in order to resolve this issue.

The density of graupel and hail assumed before melting is also important because of the implications for hail suppression. For example, a 2-cm diameter hailstone with density 0.91 g cm⁻³ hits the ground in eastern Montana as a 1.5-cm diameter hailstone with a terminal velocity of 12 m s⁻¹, while the same sized hailstone of 0.45 g cm⁻³ density, before melting, reaches the ground as a 0.8-cm diameter particle with a terminal velocity of only 9 m s⁻¹ (see Fig. 2). Thus, significantly less damage at the ground will result from the lower-density hailstones for the same initial overall diameter. Previous studies have shown that the occurrence of high-density hailstones is associated with hailstones growing near the wet–dry growth transition, allowing most of the accreted liquid water to freeze with a high density (Dennis and Musil, 1973; Rasmussen and Heymsfield, 1987b). This type of growth for a given storm depends critically on the liquid water encountered by the growing hailstone (Pflaum and Pruppacher, 1979; Rasmussen and Heymsfield, 1987b; Tuttle et al., 1988) and may to some extent be prevented if the overall liquid water content is reduced.

b. Temperature profile

The melting and shedding behavior of hailstones was shown to be fairly sensitive to the atmospheric temperature profile assumed. For instance, the melting behavior was shown to be different in storms in which the hail falls predominantly through warm updrafts, as in the 1 August storm, or predominately through cooler downdrafts, where not only the temperature, but also the relative humidity is lower.

c. Depth of the atmospheric layer warmer than a wetbulb temperature of 0°C

The present results also show the strong dependence of melting upon the depth of the layer of air warmer than 0°C (warm bulb). For instance, Fig. 4 shows that...
Table 1. Mean and standard deviation of the difference between the normal run minus the Chong and Chen shedding parameterization at 5.0, 3.0 and 0.8 km.

<table>
<thead>
<tr>
<th>Delta</th>
<th>5 km</th>
<th></th>
<th>3 km</th>
<th></th>
<th>0.8 km</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ice (cm)</td>
<td>0.038</td>
<td>0.280</td>
<td>0.057</td>
<td>0.319</td>
<td>0.039</td>
<td>0.0343</td>
</tr>
<tr>
<td>1 mm drops shed per km</td>
<td>2.496</td>
<td>575.9</td>
<td>77.7</td>
<td>428.7</td>
<td>169.5</td>
<td>168.5</td>
</tr>
<tr>
<td>Cumulative mass shed (g)</td>
<td>-0.042</td>
<td>1.057</td>
<td>0.061</td>
<td>1.638</td>
<td>0.299</td>
<td>2.480</td>
</tr>
<tr>
<td>Terminal velocity (cm s⁻¹)</td>
<td>-18.43</td>
<td>263.9</td>
<td>-54.7</td>
<td>240.9</td>
<td>-21.1</td>
<td>184.1</td>
</tr>
<tr>
<td>Time (min)</td>
<td>-0.171</td>
<td>1.65</td>
<td>0.009</td>
<td>1.717</td>
<td>0.141</td>
<td>1.862</td>
</tr>
<tr>
<td>Updraft velocity (m s⁻¹)</td>
<td>0.096</td>
<td>1.799</td>
<td>0.046</td>
<td>1.063</td>
<td>0.001</td>
<td>0.033</td>
</tr>
<tr>
<td>Liquid water content (g m⁻³)</td>
<td>0.016</td>
<td>0.390</td>
<td>0.002</td>
<td>0.057</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>X position (km)</td>
<td>0.414</td>
<td>1.408</td>
<td>-0.476</td>
<td>2.149</td>
<td>-0.555</td>
<td>2.328</td>
</tr>
<tr>
<td>Y position (km)</td>
<td>-0.008</td>
<td>0.911</td>
<td>0.037</td>
<td>0.780</td>
<td>0.096</td>
<td>1.003</td>
</tr>
</tbody>
</table>

A 1.5-cm diameter hailstone with initial density of 0.45 g cm⁻³ completely melts in eastern Montana where the ground is at 0.8 km MSL. If this storm was in northeast Colorado, with the ground at 1.6 km MSL, the same hailstone would reach the ground as a 0.5-cm diameter hailstone. This strong dependence upon the depth of the warm layer occurs because of the rapid change in hailstone diameter towards the latter stages of melting. The hailstone sizes most strongly affected depends upon the depth of the layer. For the current situation, hailstones between 1 and 2 cm diameter are most sensitive.

d. Relative humidity

One of the most important results of this study is the strong sensitivity of the melting and shedding behavior of hail to relative humidity. Rasmussen and Pruppacher (1982) showed that the onset of melting depends only upon the temperature and relative humidity. For example, particles falling through air of 50% relative humidity will not start to melt until the air temperature reaches 4°C. Thus, regions of low relative humidity will delay the onset of melting to lower altitudes.

If we assume 50% relative humidity in the present 1 August case, the effective layer of warm air is reduced because of this effect by 16%, from 4.4 to 3.7 km. Thus, not only do particles falling through low relative humidity regions have reduced heat transfer due to evaporative cooling competing with the convective heating, they also fall through a smaller layer of warm air.

e. Liquid water content (LWC)

The effect of LWC on melting was shown to be minimal for LWC less than 4 g m⁻³, which is typically the maximum found in most convective storms. The effect on shedding, however, was strong. If the shedding occurs in sufficiently strong updrafts, creation of new hailstone embryos may occur (Rasmussen and Heymsfield, 1987b). Otherwise, the efficient conversion of cloud drops to raindrops occurs.

f. Melting and shedding in the 3-D wind field

The 3-D results show that for this particular storm, mean behaviors during the melting and shedding of hailstones grown in the wind field are not significantly affected by changes in shedding parameterization and heat transfer rates. This suggests that this hailstorm had the ability to grow hailstones to large sizes independent of small changes in the physics of growth,

Table 2. Mean and standard deviation of the difference between the normal model run minus the Ranz and Marshall ventilation coefficient runs, at 5.0, 3.0 and 0.8 km.

<table>
<thead>
<tr>
<th>Delta</th>
<th>5 km</th>
<th></th>
<th>3 km</th>
<th></th>
<th>0.8 km</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ice (cm)</td>
<td>-0.005</td>
<td>0.021</td>
<td>-0.005</td>
<td>0.021</td>
<td>-0.003</td>
<td>0.053</td>
</tr>
<tr>
<td>1 mm drops shed km⁻¹</td>
<td>0.086</td>
<td>44.5</td>
<td>1.911</td>
<td>29.3</td>
<td>-4.56</td>
<td>636.2</td>
</tr>
<tr>
<td>Cumulative mass shed (g)</td>
<td>-0.001</td>
<td>0.031</td>
<td>0.0</td>
<td>0.045</td>
<td>-0.003</td>
<td>0.088</td>
</tr>
<tr>
<td>Terminal velocity (cm s⁻¹)</td>
<td>2.822</td>
<td>24.96</td>
<td>-5.02</td>
<td>28.9</td>
<td>-0.622</td>
<td>10.82</td>
</tr>
<tr>
<td>Time (min)</td>
<td>-0.026</td>
<td>0.066</td>
<td>-0.027</td>
<td>0.082</td>
<td>-0.018</td>
<td>0.062</td>
</tr>
<tr>
<td>Updraft velocity (m s⁻¹)</td>
<td>0.008</td>
<td>0.083</td>
<td>0.004</td>
<td>0.071</td>
<td>0.0</td>
<td>0.020</td>
</tr>
<tr>
<td>Liquid water content (g m⁻³)</td>
<td>0.002</td>
<td>0.019</td>
<td>0.0</td>
<td>0.009</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>X position (km)</td>
<td>-0.023</td>
<td>0.065</td>
<td>-0.027</td>
<td>0.070</td>
<td>-0.035</td>
<td>0.082</td>
</tr>
<tr>
<td>Y position (km)</td>
<td>-0.001</td>
<td>0.221</td>
<td>-0.005</td>
<td>0.030</td>
<td>-0.002</td>
<td>0.032</td>
</tr>
</tbody>
</table>
melting, and shedding. As shown by Tuttle et al. (1988) the main limitation to hail size in this storm was the amount of liquid water encountered by the particle along its trajectory.

Comparison of the mean 3-D behaviors of melting and shedding with runs assuming no horizontal advection showed that the 3-D runs compared favorably with the runs assuming no horizontal advection as long as the correct temperature, humidity, and updraft profiles were used. This allows for a simple method to obtain reasonable estimates of melting effects in complicated situations, as long as good estimates of the above three parameters are available.

5. Conclusions

Sensitivity studies were conducted on the melting and shedding of hailstones and graupel assuming that the particles fall through either 1) still air or 2) a 3-D Doppler-derived wind field. These studies revealed that the melting and shedding behavior of graupel and hailstones is significantly affected by 1) the initial hydrometeor density, 2) initial size, 3) temperature profile, and 4) relative humidity.

The mean melting and shedding behavior of graupel and hail in a three-dimensional wind field was shown to be relatively insensitive to 1) 25% changes in the heat transfer coefficient and 2) the differences between the Rasmussen et al. (1984) and the Chong and Chen (1974) shedding parameterization.

These results indicate that models which include melting and shedding of hail and graupel should pay careful attention to the hail density assumed, and to the temperature, humidity, and updraft profiles through which the hail is falling, in order to produce accurate results.

The feedback between melting hydrometeors and their environment was not explicitly treated in this study. Such feedback needs to be addressed in the future.

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REFERENCES


