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Energetics of Mixed Phase Cloud Particle Interactions

German Vidaurre and John Hallett*
Desert Research Institute, Reno, Nevada

1. Introduction

Data on cloud particle sizes and concentrations collected with airborne spectrometers during the last three decades is widely used for cloud parameterization and validation of remote sensing techniques. At the first stage of use of these probes the main efforts were concentrated on the study of the accuracy of sizing and counting of the cloud particles. Attempts to use airborne probes in ice and mixed phase clouds have raised a concern about the break up of ice particles due to impact with the probe housing and the effect on measurements. After collision with the probe surface, particles may break into a number of small pieces, which would generate multiple false counts, (Gardiner and Hallett 1985; Emery et al. 2004; Korolev and Isaac 2004).

Thus cloud particle break up may affect the calculations of the concentration, water content and radar reflectivity derived from the probe measurements. The break up behavior will depend on the ice particle habit and its impact kinetic energy. Knowledge regarding the ice break up during aircraft encounter provides basic scientific underpinning for prediction of the icing process itself, having implications for aircraft icing and instrumentation for collection and characterization of ice in the atmosphere, (Hallett and Isaac 2002); and also in cloud electrification resulting from ice crystal electrification following collision.

2. Instrumentation

The study of break up presented in this paper is based on the analysis of 1) images observed using the replicator, and 2) video recorded images with the Cloudscope.

Samples of ice crystals from convective clouds over Central Pacific (Kwajex project) and over Florida (Camex project), in the range from 0.3 mm to 2.5 mm, were video-recorded following impact on the optical flat of a cloudscope mounted on the NASA-DC8 aircraft, air speed about 200 m/s for a volume sample about 85 ℓ / s. Samples from continental clouds in Oklahoma, in the size range from 5 µm to 320 µm, were collected in formvar solution by continuous replicator mounted on the UND Citation aircraft, volume swept out by slot 1.3 ℓ / s at an average aircraft speed of 130 m/s.

The cloudscope records particles as they approach and impact on the probe window using a video recorder attached to a long working distance microscope located behind the window (Meyers and Hallett 1999). A surface heater, which can be manually controlled for deicing, corrects crystal impact accumulation problems and allows use of the instrument in regions where ice particles are present in high concentrations. Twenty segments of 40 seconds duration of cloudscope data were hand analyzed from digitized segments of the movie. The surface area of crystals and any fragments were measured.

3. Results and Analysis

i. Examples of ice particle break up during encounter with the Replicator

Figure 1 shows a 300 x 400 µm image of an ice cloud particle measured by the replicator. Cloud particles collected were in the size range from 5 µm to 320 µm. In some cases, fractures and fragments can be easily observed and counted. In many cases, the break up is excessive and the ice particle breaks up into a high number of small pieces.

Figure 1 shows how the break up may yield regions with few fractures and regions with hundreds of small fragments. Also note how the fractures are parallel to the crystal axis in many cases. Fracture distribution results from the crystal orientation at the moment of impact; the area of the crystal first impacting on the surface will fracture in many small pieces providing some cushioning for the rest of the crystal and as a result the other sides will fracture into a few relatively bigger fragments.

ii. Examples of ice particle break up during encounter with the Cloudscope

Figure 2 shows images of particles from convective clouds in Central Pacific video recorded following impact on the flat surface of the cloudscope during the Kwajex project. Larger particles than the ones observed with the

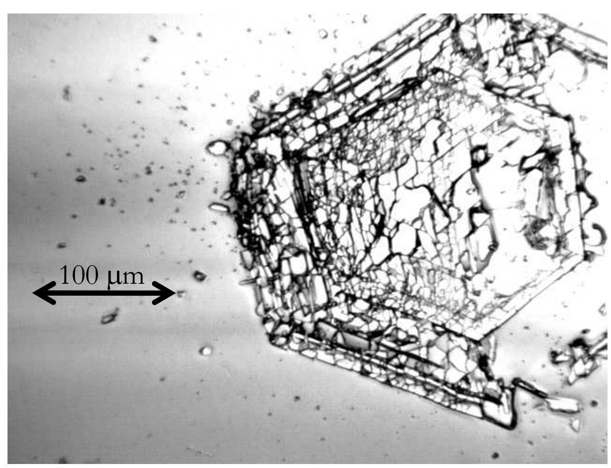

Figure 1: 300 x 400 µm still images showing broken ice crystals collected in formvar solution by continuous replicator from continental clouds in Oklahoma in the size range from 5 µm to 320 µm, showing multiple fractures. Note ice fractures are parallel to crystal axis in many areas and the fracture density is not homogeneous

Corresponding author address: John Hallett, Desert Research Institute, Reno, NV 89512; e-mail: hallett@dri.edu

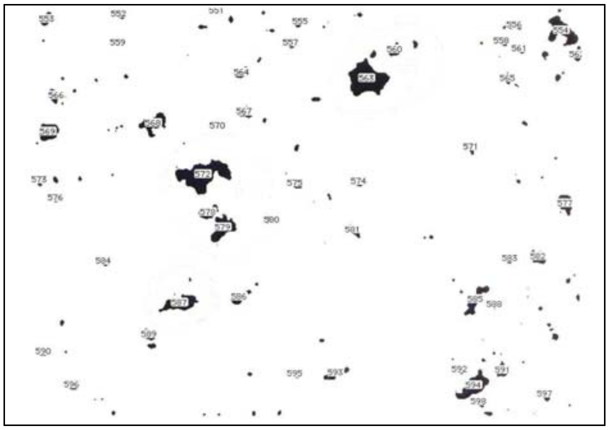

Figure 2: 24 x 18 mm digital image of broken ice crystals video-recorded following impact on the optical flat of a cloudscope from convective clouds in Central Pacific during the Kwajex project. Observed particles vary in size from 0.3 mm up to 2.5 mm.

replicator were collected by the 24 x 18 mm window. However the resolution is lower and it is not possible to observe fractures in the crystal or to identify individual small fragments of a cluster when they remained very close to each other.

iii. Correlation between number of fragments and particle size

The expected number of fragments correlated to particle size is shown in Figure 3. a) Shows small ice particles collected on formvar solution by the airborne replicator and b) shows larger particles video recorded when impacting on the optical flat surface of the Cloudscope. The variability related to the average number of fragments, up to 70% in many cases, was qualitatively related to ice crystal habit and crystal orientation during impact with the film or optical flat surface.

iv. Broken to unbroken ratio

Several hundreds of unbroken ice particles, mostly small crystals, were also measured to get the broken to unbroken particle ratio, which varies from 0.2 to 0.95 for particles smaller than 80 μm diameter. The variability of this ratio is attributed to ice habit and also to the orientation that the crystal takes at the moment of impact. As the size of the particles increases, the ratio becomes closer to 1, indicating that almost 100% of the bigger particles are broken during impact. A few unbroken crystals as large as 1mm were replicated.

4. Energetics of Mixed Phase Cloud Particle Interactions

As the particle approaches the probe, it crosses streamlines into slower moving air and kinetic energy is lost.

Numerical simulations of ice particle trajectories of different densities and effective radii around a cylinder were conducted following Langmuir (1944); Ranz and Wong (1952) algorithm and with the aid of empirical relationships to describe the drag coefficient C_D and Reynolds number. The simulations gave estimations of

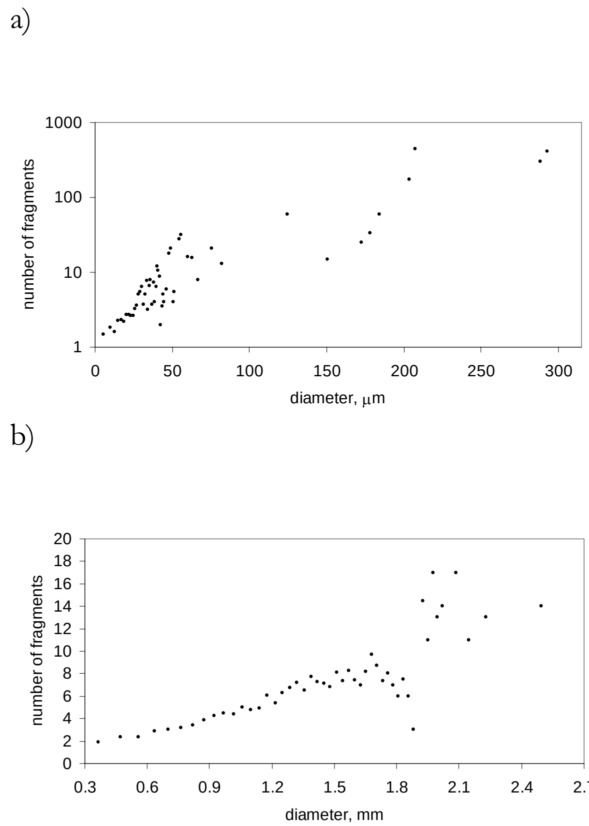

Figure 3: Average number of fragments vs. size for ice particles a) collected in formvar solution by continuous replicator from continental clouds in Oklahoma in the size range from 5 μm to 320 μm; with an average speed of 130 m/s flying on the UND Citation aircraft, and b) video-recorded following impact on the optical flat of a cloudscope from convective clouds in Central Pacific (Kwajex) and Florida (Camex) in the range from 0.3 mm to 2.5 mm; with an average speed of 200 m/s flying on the NASA DC-8 aircraft.

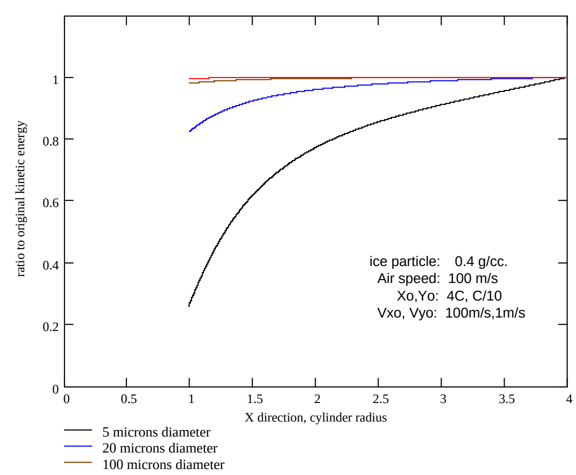

Figure 4: Kinetic energy profile as different size particles and density 0.4 g/cc approach a 4 mm diameter sensor.

the velocity and kinetic energy losses as the particle approaches the sensor device.

Figure 4 shows the kinetic energy profile for spherical ice particles of different diameter and density 0.4 g/cc moving in the negative X direction toward a 4 mm diameter sensor. Small particles lose most of their kinetic energy before impact. At the moment of impact, the 5 μm particle diameter retains about 1/4 of its original kinetic energy, meanwhile the 20 μm particle diameter retains about 4/5 and the other two particles, 100 μm and 400 μm, retain almost all of their kinetic energy. The fraction of kinetic energy remaining for break up is therefore highly sensitive to the size and shape of the sensor and size, density, and drag coefficient of the ice particle. This fact is important when considering that probes characterize ice habits by particle size and shape and do not consider their density, which may vary from about 0.02 g/cc up to 0.92 g/cc, (Hallett and Isaac 2002).

The detail of the physical processes of the impact determines how the kinetic energy is distributed:

i. Converted to thermal energy through viscous dissipation of deforming liquid or displacing air on impact.

ii. Part retained by bouncing particles

When a drop impacts on a surface, it may remain adhered to the surface, may splash, or may bounce back to the air around the sensor, (Hallett and Christensen 1984). It is assumed in this paper that ice particles, behaving similarly to drops, may a) bounce away with little or no fracture at all, b) remain on the instrument surface and melt or sublime, or c) break up into many fragments, some remaining on the surface and some bouncing away. However, the impaction and break up processes for ice is much more complex than for drops. The nature of these processes depends on particle size and density, ice habit, selected orientation as the crystal approaches the sensor, and impacting velocity.

iii. The creation of new surfaces during break up

A measure of the available energy for break up is the ratio of the kinetic to surface energy of the crystal, L, which represents a measure of the maximum possible surface area increase resulting from the impact. Hallett and Christensen (1984) show that drops with L larger than 7, will splash during the encounter. Recognizing that ice may behave differently with respect to water droplets during break up, and with a constant ice surface energy, σ_i = 0.12 J/m^2, the same criterion was applied to ice crystals. The actual value depends on the detail of impaction process.

Figure 5 shows the kinetic to surface energy ratio for ice particles, with assumed density 0.46 g/cc, at different impacting velocities. The assumed ice break up criterion is plotted. Ice particles larger than 10 μm and traveling at 100 m/s with respect to the probe, retain more than ¼ of their kinetic energy, impact at speeds greater than 50 m/s (L = 7) and approach break up. At higher speeds such as 200 m/s (cloudscope) or 130 m/s (replicator) impaction

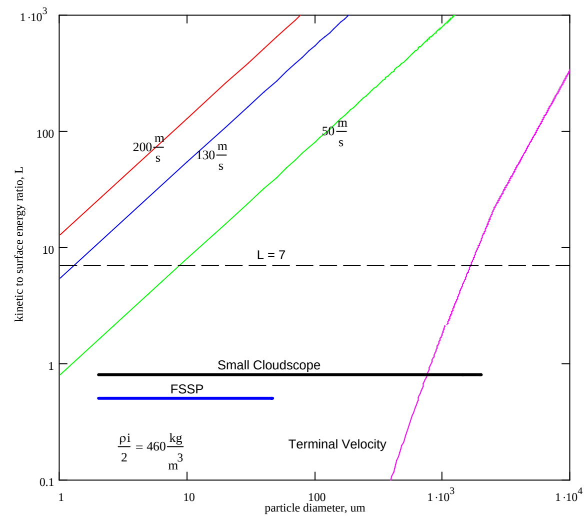

Figure 5: Kinetic to surface energy ratio, L, for ice particles with an effective density ρ = 0.46 g/cc, at different air speeds and terminal velocity. Small cloudscope and FSSP size range also plotted.

yields L ratios significantly grater than 7. Break up of crystals larger than 10 μm (and smaller particles with larger density) may influence the small cloudscope and FSSP observations as Figure 5 shows. Table 1 shows the kinetic to surface energy ratio for plates (20 μm diameter and 1 μm thickness) and spherical (20 μm diameter) ice cloud particles that may be measured by the FSSP (airflow guiding cylinder wall thickness ~4mm) at 200 m/s and 130 m/s. Thus 20 μm spherical particles impact with enough velocity to approach break up, as do particles with density as low as 0.05 g/cc. 1 μm thick plates collected at high speed (200 m/s) will also break up meanwhile plates collected at lower speed (130 m/s) may not break up during the impact. Thicker plates have higher effective density and most likely break up during impact. The kinetic to surface energy ratio for particles falling at terminal velocity are also plotted on Figure 5. At this impacting velocity the FSSP should not be affected by break up of particles smaller than 0.9 mm diameter, neither should the small cloudscope.

Table 1: Kinetic to surface energy ratio L for plates and spheres of 20 μm diameter as they impact with the edge of the FSSP airflow guiding cylinder wall thickness 4mm.

Ice particle shape	Aircraft speed	Impact speed	KE/SE ratio
Plate	200 m/s	102 m/s	19
(0.9 g/cc - 1 μm thick.)	130 m/s	58 m/s	6
Sphere	200 m/s	194 m/s	470
(0.9 g/cc)	130 m/s	125 m/s	195
Sphere	200 m/s	186 m/s	192
(0.4 g/cc)	130 m/s	120 m/s	80
Sphere	200 m/s	123 m/s	10
(0.05 g/cc)	130 m/s	111 m/s	9

Ice particles with larger density have a larger kinetic to surface energy ratio; they are more susceptible to break up during the impact. At 130 m/s, regardless of their density according to this calculation, most of the ice particles larger than 10 μm break up during impact with the FSSP or cloudscope probes. Smaller particles (3 to 10 μm) with large density most likely will break up during impact with the sensor.

The break up process is also of importance when considering interactions of graupel falling at terminal velocity with droplets and ice particles such as snow flakes. 100 μm particles have enough relative kinetic energy to break up or splash as falling graupel particles larger than 0.9 mm ($V_T > 4$ m/s) collect them. The break up of ice particles during ice/ice and ice/water interactions of this nature may play an important role in electrification.

Calculations show that all of the kinetic energy of crystals impacting at 200 m/s is converted to surface energy of cracks (from top to bottom of plate) distributed either homogeneously along the crystal in assumed hexagonal fragments of size 60 nm, or concentrated in about 0.8% of the area when the hexagonal fragments are as small as 0.45 nm (the size of the ice lattice structure).

iv. Phase change during impact.

The impact kinetic energy of the crystal may also be converted as result of phase change during impact. A crystal impacting at 200 m/s has enough kinetic energy to melt 6% or evaporate 1% of its mass.

5. Conclusions

Insights of the origin of small ice particles observed during collection by aircraft instruments show that they may not only be a product of nucleation but also originate from the impacts on the instrument surface. Further, these conclusions can be also applied to ice-ice interactions, with smaller range of impact velocity during precipitation.

The break up of ice particles during sampling may occur due to the mechanical impact of particles with the film surface on the replicator, optical flat of the cloudscope or with probe parts upstream of the sample area, and from interaction between particles around the probe housing. The average number of fragments resulting from the impact depends on the particle diameter, ice habit, and orientation during impact.

The kinetic to surface energy ratio, used as break up criterion, indicates that ice crystals larger than a few microns may break up during the impact with the instrument surface. Before impact, crystals lose between 2% to 70% of the kinetic energy as they approach the probe; then break up, resulting in low and high-density fracture regions, melt and evaporation may account for the remaining kinetic energy loss. When a crystal impacts on the sensor, all three processes described may occur. The replica of an ice crystal on Figure 1 shows regions broken in few relatively big fragments, regions broken in many small fragments and regions where optical methods failed to identify fragments or fractures present in the crystal. The conversion of kinetic energy to surface energy as result of the impact was estimated by measurements of the crystal visible fracture area, less than 1% on average over the whole crystal. However, the observed range is significantly wider; some parts of the crystals showed few or no fragments at all, meanwhile in other parts break up is so severe that it is impossible to measure by optical examination the length of the fractures. Size of shattered fragments varies from place to place suggesting a localization of stress following impact on collection. A problem remains in estimating internal defects not readily visible, related to viscous energy losses on impact into the formvar and in displacing air on impact.

Break up is also of importance when larger falling particles interact with smaller falling particles. When the size ratio of the particles is at least 1 to 10, there is sufficient kinetic energy for break up to take place. Small hail or graupel particles, reaching up to several centimeters in size, densities anywhere from 0.2 to 0.92 g/cc, and terminal velocity larger than 4 m/s, may interact with small ice crystals creating the conditions adequate for break up processes and other processes to take place, as crystal electrification.

6. References

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7. Acknowledgement

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