NOTES AND CORRESPONDENCE

Possible High Ice Particle Production during Graupel–Graupel Collisions

TSUTOMU TAKAHASHI, YOSHIHIRO NAGAO,* AND YUZURU KUSHIYAMA

Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

5 August 1993 and 24 May 1995

ABSTRACT

In a cold room collisions of two ice spheres having different growth modes were studied to examine ice production. The production of ice particles through this process was high, with a maximum rate more than 800 per collision at −16°C. This ice particle production mechanism is different from the Hallett–Mossop ice multiplication process and may help to explain the high concentrations of ice crystals observed in maritime winter cumuli.

1. Introduction

One of the unsolved problems in cloud physics is that a much higher concentration of ice crystals is observed in some clouds than would be expected by ice nucleation (Koenig 1963; Braham 1964; Hobbs and Rangno 1985). Based on new indications from aircraft observations (Mossop et al. 1968, 1970, 1972), Hallett and Mossop (1974) conducted laboratory work and demonstrated that secondary ice particles can be produced during riming at temperatures between −3°C and −8°C, when clouds include drops larger than 25 μm in diameter. They suggested that ice particles would be produced through this process at the rate of one per 200 large-drop collisions to the riming surface.

Although there are many observations over Florida and Australia (Hallett et al. 1978; Keller and Sax 1981; Mossop 1985) that seem to support the Hallett–Mossop ice multiplication process, Hobbs and Rangno (1985, 1990) found it difficult to use this mechanism to explain their observations of a high rate of ice crystal production in winter maritime cumuli near the Washington state coast. They suggested that another, higher-rate, ice multiplication process must have been operative.

Videosonde ascents in tropical cumulonimbus clouds have sometimes showed very high ice crystal concentrations on the order of 1 cm^{-3}, frequently accompanied by graupel (Takahashi and Kuhara 1993). Takahashi (1993) also noted very high ice crystal concentrations in winter maritime cumulus clouds that developed over the Japan Sea. He used an aircraft equipped with a new, video particle counter that can monitor ice particles over a wide size range from 20 μm to 6 mm in diameter. Very high ice crystal production was observed in cloud regions where both large and small graupel, but not medium-sized graupel, were present. Takahashi hypothesized that these ice crystals were generated by collisions between graupel in a weak updraft region where large graupel fell from upper levels while small graupel were forming at lower levels. The expected low cloud water content due to the weak updraft in this region could lead to depositional growth for small graupel and to riming growth for large graupel. The surfaces of small graupel thus would be brittle, while the large graupel would have solid surfaces (Macklin 1961). When the two sizes of graupel collided, ice branches on the small graupel might be broken, producing many ice crystals. After observing ice crystal collisions on a fixed plate, Vardiman (1978) also suggested that ice fragmentation may also be important to ice particle production.

The purpose of this laboratory experiment was to examine the possibility of ice crystal production during graupel–graupel collisions.

2. Experimental apparatus

Graupel of different size were simulated by varying the rate of rotation of the ice sphere. Two sets of rotating rods were installed in a cold box. Graupel were simulated by rotating ice spheres (Figs. 1 and 2). A quickly rotating ice sphere was assumed to correspond to large graupel, while a slowly rotating ice sphere was

---

* Current affiliation: Hitachi Electric Company, Ibaraki, Japan.

Corresponding author address: Dr. Tsutomu Takahashi, Dept. of Earth and Planetary Sciences, Kyushu University, Faculty of Science 33, 812 Hakozaki, Fukuoka, Japan.

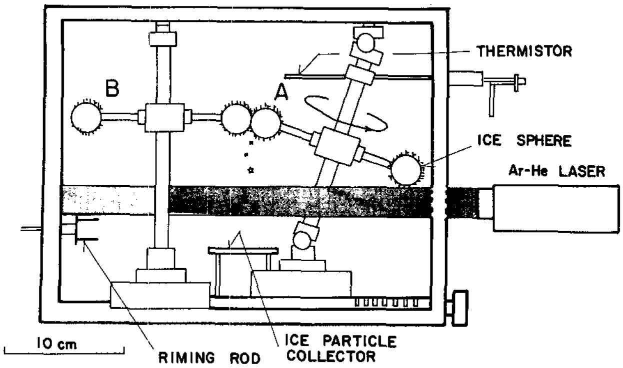

FIG. 1. Experimental apparatus: (A) ice spheres (right) were set up to rotate at a tangential speed of 4 m s^{-1}, while (B) ice spheres (left) were stationary. The ejected ice particles were collected on a plate at the bottom of the chamber. A thermistor for temperature measurement was installed at the top. Cloud droplets were supplied through the tube from the center of the right wall. During the actual experiment, all parts except ice spheres exposed to the cloud droplets were cleaned by ethylene glycol for frost prevention.

assumed to correspond to small graupel. In this experiment, one ice sphere was kept stationary to form a single, depositionally grown ice surface. Each 1.8-cm diameter ice sphere was formed by first inserting a brass rod halfway into a spherical metal cavity that could be separated in half. Water was directed in the metal sphere through a small hole in the metal surface and was slowly frozen. The ice sphere was then separated from the metal cavity after slight melting of the ice sphere, and the brass rod with the ice sphere on the tip was screwed into the main rotating rod.

Two sets of rotating rods were set up in an aluminium box with dimensions of 30 cm × 24 cm × 24 cm. The front side of the box had a polyethylene window so that the inside operation could be viewed. The interior of the cold box could be cooled down to −30°C inside the cold room. One of the rotating rods (on the right in Fig. 1) could be moved horizontally by turning a screw. Before the experiment the inner surfaces of the box were cleaned with ethylene glycol to prevent frost growth on the surface.

The cloud droplets were supplied by a centrifugal drop producer that was positioned outside the cold room. The liquid water content of the cloud droplets was estimated by the rate at which rime ice collected on the miniature rotating probes. A similar technique was used during earlier studies of riming electrification (Takahashi 1978). The modal diameter of the cloud droplets was 12 μm with sharp size distribution (standard deviation 2.5 μm). The collision efficiency of the ice sphere was estimated to be 0.15 for droplets of 12-μm diameter at a rotation speed of 4 m s^{-1} (Ranz and Wong 1952). The drop producer was thus adjusted to keep the cloud water content at a relatively high 2 g m^{-3}. The cloud water content necessary to achieve the same riming rate for 4-mm diameter graupel is 0.3 g m^{-3}, which is within the range of Hokuriku winter clouds [1.0 g m^{-3} in developing stage and 0.2 g m^{-3} in mature stage, Murakami et al. (1994)]. A thermistor was used to monitor the temperature in the upper portion of the chamber, and an argon–helium laser beam was used to monitor ice crystal ejection.

The experimental procedures were as follows.

(a) The ice spheres were positioned on the rotating arms.

(b) Cloud droplets were supplied to the chamber from outside the cold room.

(c) In order to make interpretation of mechanisms simpler, a set of two extremely different ice surfaces were prepared: a depositionally grown ice surface and an ice surface grown mostly through riming. One of the rotating arms (on the left in Fig. 1) was kept stationary so that it could grow solely by depositional growth, while the other (on the right) was made to rotate at a tangential speed of 4 m s^{-1}. This rotation speed corresponds to the terminal velocity of lump graupel of about 4-mm diameter when its density is 0.3–0.4 g cm^{-3} (Maruyama 1968; Locatelli and Hobbs 1974). At this rotation speed the critical cloud water content at which the riming growth rate exceeds the deposition growth rate is estimated to be around 0.1 g m^{-3} considering the low collision efficiency of the ice sphere due to its large size. The riming growth rate, therefore, overwhelms the diffusional growth rate for the rotating ice sphere.

(d) After continuing ice sphere rotation as described in (c) for 15 min, the rotating arm was moved toward the stationary ice sphere and positioned so as to collide. When multiple collisions resulted, data were averaged by collision number.

(e) Following the collision, the resulting ice particles were checked optically by laser. Ice crystals were collected on a 9 cm × 6 cm plastic plate placed beneath the collision area. The ice crystals collected on the plate were allowed to grow for another 10 min and then were counted under a magnifying glass (×25). When the ice sphere were not collided, only one or two ice crystals were counted during these processes. Also, only a few ice crystals were ejected during collisions in which both ice spheres were kept stationary in the cloud and were made to grow by deposition. The present experiments were first conducted using relatively strong collisions to produce a much greater number of ice particles than those found in the control experiments.

The relationship between the number of ice particles collected and the total number of ice particles ejected was examined by placing several plastic plates to cover the entire bottom area of the chamber. The total number of ice particles ejected turned out to be roughly four times the number collected on the main plate positioned beneath the colliding ice spheres.

An additional experiment was conducted to study how the number of ejected ice particles changed as col-

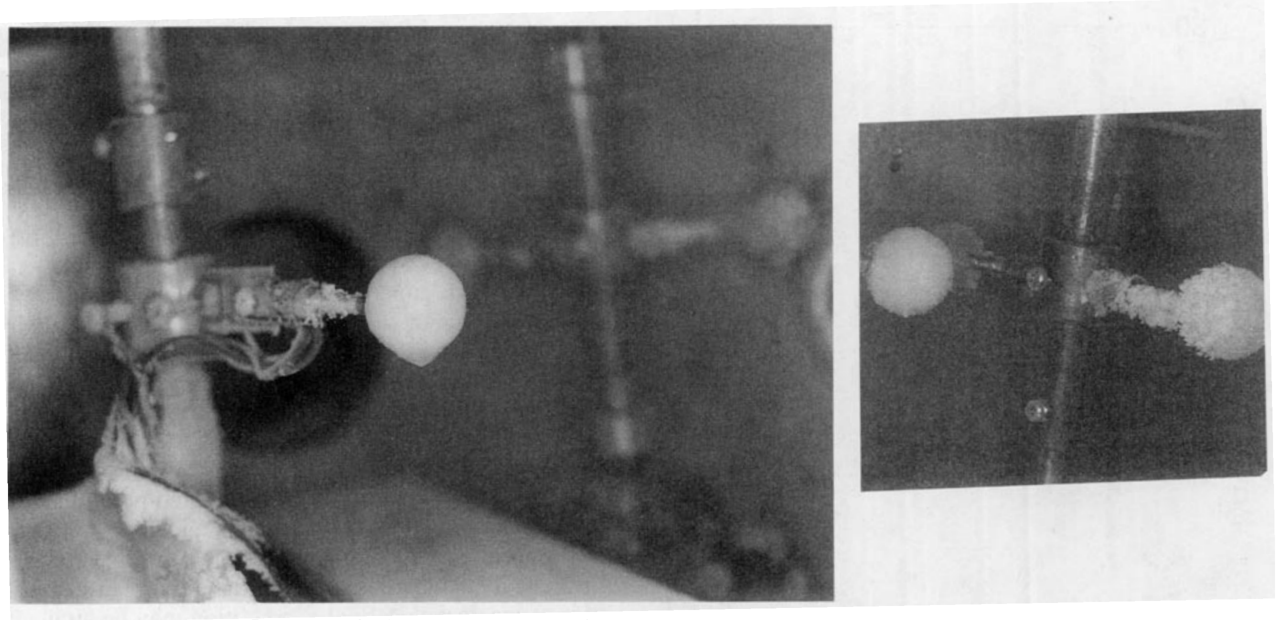

Fig. 2. Ice spheres in the chamber. Ice particle collecting plate is seen at the bottom of left picture. (Left) Stationary ice sphere after depositional growth. (Right) Rotating rimed ice sphere (far right).

lision forces increased. The middle part of the brass rod on the main rotating arm was replaced by a thin phospher–bronze plate (Fig. 3) so that the wide face of the plate was parallel to the rotating axis. Four strain gauges, two at each face of the plate, were attached to monitor the force of the ice sphere collisions.

3. Results

The experiment was first conducted in the cold chamber at various temperatures and with collision forces on the order of 500 dyn. Although the data exhibited considerable scattering, as shown in Fig. 4, there is an indication that the highest rate of ejection of ice particles, up to around 800 per collision, occurred at around −16°C.

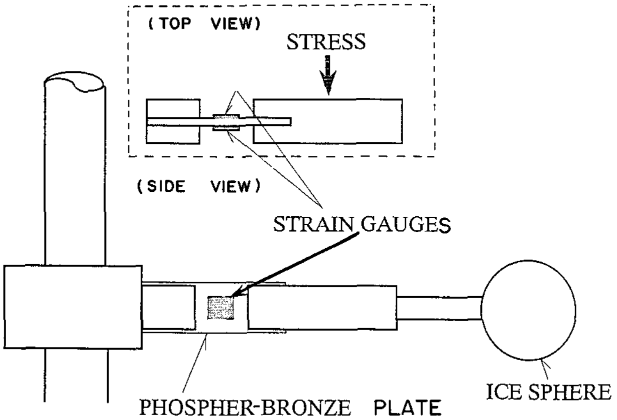

Fig. 3. Strain gauge attached to a phospher–bronze plate at the middle of the rotating arm.

The collision force was then reduced incrementally to 20 dyn while maintaining a chamber temperature between −13°C and −18°C. Although data scattered

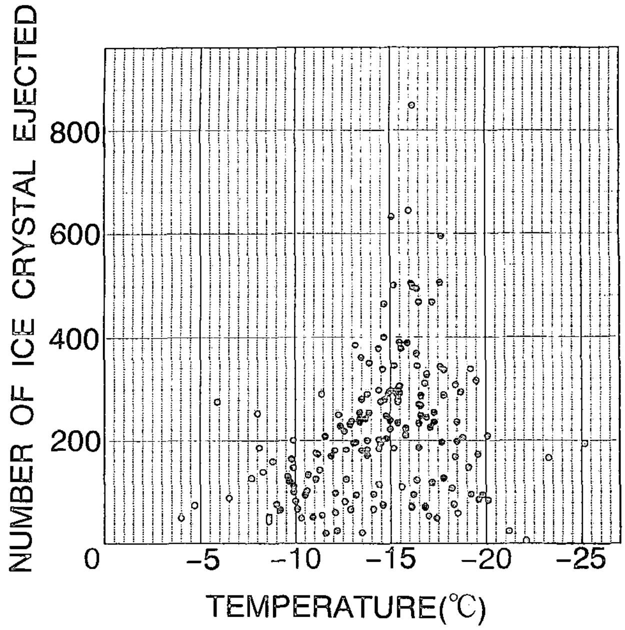

Fig. 4. Total number of ejected ice particles as a function of chamber temperature. The number of ice crystals collected by the main plate was simply multiplied by 4. The total number is therefore approximate. Cases of various collision forces were all included. Collision force was on the order of 500 dyn.

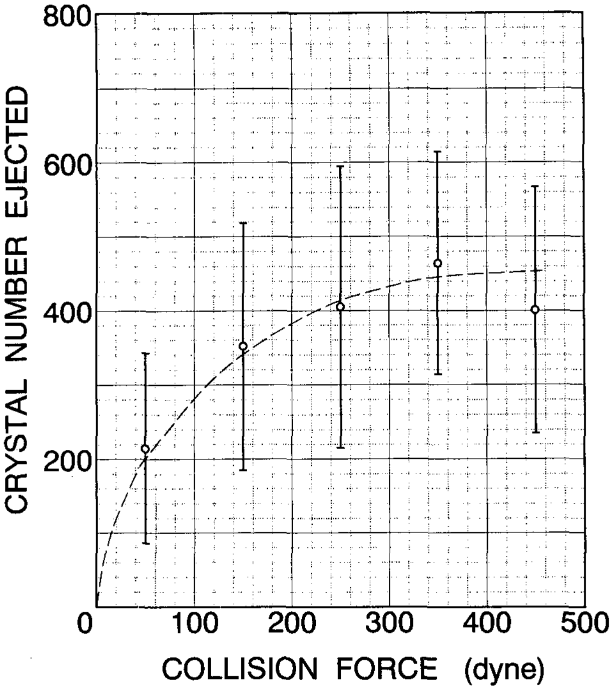

FIG. 5. Total ejected ice particle numbers vs collision force. Thick marks represent standard deviations of the measurements, and the thin dashed line is the smoothed value. Data was grouped in 100-dyn range for analysis.

widely, there is a tendency for the rate of particle ejection to increase with increasing collision force (Fig. 5). However the rate of particle production was less sensitive to incremental changes in collision force when collision force was high. Next, temperature and collision force were fixed, while the duration of cloud drop supply was changed. Here, the rate of ice particle ejection was found to increase with drop supply duration (Fig. 6). Finally, temperature and cloud drop supply duration were fixed, while the rotation rate of the rimed ice sphere was changed. Generally, ice particle production increased roughly exponentially with rotation speed (data not shown).

4. Discussion

Experiments showed maximum ice particle ejection to occur at −16°C. Since this temperature is close to that found during periods of maximum ice crystal growth (Mason 1953), ice branches grown by deposition may contribute primarily to this ice particle ejection. Data, however, scattered more than was expected from different values in collision forces. This scatter in the data was probably due to variability in the character of each of the rimed surface collided in each experiment because of uneven riming on the rotating ice sphere (see Fig. 2). Experiments showed higher total ice particle production to be associated with longer cloud drop supply (Fig. 6), harder-rimed surface, and stronger collision force (Fig. 5). It is suggested that breaking of depositionally grown ice branches on the stationary ice sphere is the primary cause of the ice particle ejection.

Rangno and Hobbs (1991) found it difficult to use the Hallett–Mossop ice multiplication process to explain their observations of maritime winter cumuli off the Washington coast. They suggested the possible existence of high supersaturation in the cloud and subsequent enhancement of ice nucleation. However, their observations of high ice particle concentrations were obtained during the dissipating stage of the cloud, not during the developing stage when high supersaturation is expected.

Our laboratory results support Takahashi's (1993) hypothesis that ice crystals are generated by collisions between large and small graupel. Our work suggests the importance of collisions between graupel having different growth modes in the production of large quantities of ice particles. Such a condition may be attained in weak updraft regions where large graupel fall from upper levels while small graupel are forming below. Weak updrafts of this nature in combination with low cloud water content can occur in the dissipating stage of clouds, where the observations by Rangno and Hobbs were obtained.

We first apply our results to the Hokuriku winter cumuli (Takahashi 1993). Production (P) of ice particles in unit volume and time t will be

$$P = \pi(R + r)^2(V - v)ENn\alpha t,$$

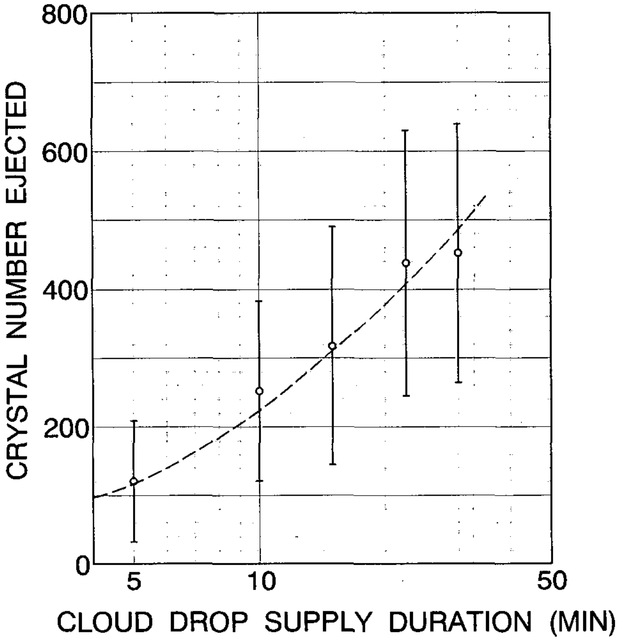

FIG. 6. Total ejected ice particle numbers vs time duration of cloud droplet supply. Others are as in Fig. 5.

where n, v, N, V, R, and α are number concentration and fall velocity of small graupel, number concentration, fall velocity, radius of large graupel, and ejected ice particle number per collision. Typical values for small graupel (0.25 mm in radius) will be $n = 3\ \mathrm{L}^{-1}$ and $v = 1\ \mathrm{m\ s}^{-1}$. For large graupel ($R = 2$ mm), $N = 1\ \mathrm{L}^{-1}$ and $V = 4\ \mathrm{m\ s}^{-1}$. Since collision force will be about 10 dyn, α is estimated as 60 per collision on average (Fig. 5). If we take t as 10 min, which Hobbs and Rangno (1990) stated to be the critical time needed to observe high ice crystal number, and collision efficiency E as unity, P will be about $4000\ \mathrm{L}^{-1}$. Since observed ice particle number concentration is around $50\ \mathrm{L}^{-1}$, the present experiment may be sufficient to explain the observation.

When we next apply this result to Washington coast winter cumuli where graupel are of a much smaller size (Hobbs and Rangno 1990), P is reduced to $50\ \mathrm{L}^{-1}$ by assuming $R = 1$ mm, $N = 1\ \mathrm{L}^{-1}$, $n = 3\ \mathrm{L}^{-1}$, $V = 2.5\ \mathrm{m\ s}^{-1}$, $v = 1.0\ \mathrm{m\ s}^{-1}$. We used upper values as found in the table by Hobbs and Rangno (1990). The P value will be further reduced due to the warmer cloud temperature, as Hobbs and Rangno observed. However, we may need to consider the effect of size on ice growth rate. Since ice growth rate per unit surface area on the ice sphere depends on the ice sphere size, 15 min of growth time for 1.8-cm-diameter stationary ice sphere will correspond to 0.3 min for 2-mm falling graupel. Ice growth time for small graupel may be too short to grow enough brittle ice branches on the surface. Figure 6 indicates an increase of ice particle ejection with longer depositional growth time. If we can simply increase depositionally growth time 10 times, the number of ejected ice particles according to Fig. 6 will increase by one order of magnitude, which is on the order of ice crystal concentration observed by Hobbs and Rangno (1990).

5. Conclusions

Laboratory work has demonstrated that a large number of ice particles can be ejected during collisions of ice spheres having different growth modes such as riming and deposition. The maximum production rate was observed at a temperature of −16°C. This ice production process could be operative in the weak updraft regions of maritime winter cumuli, where cloud water content is low enough that large graupel grow through the riming process while small graupel grow by deposition.

Although the present experiment could show the possible importance of ice particle ejection phenomena during graupel–graupel collision, more detailed experiments should be conducted to investigate the ice particle ejection rates with respect to different ice sphere sizes, different collision modes, and different cloud drop size distributions. Experiments in a wind tunnel are strongly recommended in order to better simulate natural clouds.

Acknowledgments. This research was supported by the Ministry of Education, Science and Culture of Japan. The study was conducted as part of the World Climate Research Programme in Japan. Dr. W. Johnson (NCAR) kindly read this paper and gave valuable suggestions for revision.

REFERENCES

Braham, R. R., Jr., 1964: What is the role of ice in summer rain showers? *J. Atmos. Sci.,* **21,** 640–645.

Hallett, J., and S. C. Mossop, 1974: Production of secondary particles during the riming process, *Nature,* **49,** 26–28.

——, R. I. Sax, D. Lamb, and A. S. R. Murty, 1978: Aircraft measurements of ice in Florida cumuli. *Quart. J. Roy. Meteor. Soc.,* **104,** 631–651.

Hobbs, P. V., and A. L. Rangno, 1985: Ice particle concentrations in clouds. *J. Atmos. Sci.,* **42,** 2523–2549.

——, and ——, 1990: Rapid development of high ice particle concentrations in small polar maritime cumuliform clouds. *J. Atmos. Sci.,* **47,** 2710–2722.

Keller, V. W., and R. I. Sax, 1981: Microphysical development of a pulsating cumulus tower: A case study. *Quart. J. Roy. Meteor. Soc.,* **107,** 679–697.

Koenig, L. R., 1963: The glaciating behavior of small cumulonimbus clouds. *J. Atmos. Sci.,* **20,** 29–47.

Locatelli, J. D., and P. V. Hobbs, 1974: Fall speeds and masses of solid precipitation particles. *J. Geophys. Res.,* **79,** 2185–2197.

Macklin, W. C., 1961: The density and structure of ice formed by accretion. *Quart. J. Roy. Meteor. Soc.,* **88,** 30–50.

Maruyama, H., 1968: On conical graupel and its density. *Pap. Meteor. Geophys.,* **19,** 101–108.

Mason, B. J., 1953: The growth of ice crystals in supercooled water cloud. *Quart. J. Roy. Meteor. Soc.,* **79,** 104–111.

Mossop, S. C., 1985: The microphysical properties of supercooled cumulus clouds in which an ice particle multiplication process operated. *Quart. J. Roy. Meteor. Soc.,* **111,** 183–198.

——, R. E. Ruskin, and K. J. Hefferman, 1968: Glaciation of a cumulus at approximately −4°C. *J. Atmos. Sci.,* **25,** 889–899.

——, A. Ono, and E. R. Wishart, 1970: Ice particles in maritime clouds near Tasmania. *Quart. J. Roy. Meteor. Soc.,* **96,** 487–508.

——, R. E. Cottis, and B. M. Bartlett, 1972: Ice crystal concentrations in cumulus and stratocumulus clouds. *Quart. J. Roy. Meteor. Soc.,* **98,** 105–123.

Murakami, M., T. Matsuo, H. Mizuno, and Y. Yamada, 1994: Mesoscale and microscale structures of snow clouds over the Sea of Japan. Part 1: Evolution of microphysical structures in short-lived convective snow clouds. *J. Meteor. Soc. Japan,* **72,** 671–694.

Rangno, A. L., and P. V. Hobbs, 1991: Ice particle concentrations and precipitation development in small polar maritime cumuliform clouds. *Quart. J. Roy. Meteor. Soc.,* **117,** 207–241.

Ranz, W. E., and J. B. Wong, 1952: Impaction of dust and smoke particles. *Ind. Eng. Chem.,* **44,** 1371–1381.

Takahashi, T., 1978: Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.,* **35,** 1536–1548.

——, 1993: High ice crystal production in winter cumuli over the Japan Sea. *Geophys. Res. Lett.,* **20,** 451–454.

——, and K. Kuhara, 1993: Precipitation mechanisms of cumulonimbus clouds at Pohnpei, Micronesia. *J. Meteor. Soc. Japan,* **71,** 21–31.

Vardiman, L., 1978: The generation of secondary ice particles in clouds by crystal-crystal collision. *J. Atmos. Sci.,* **35,** 2168–2180.