"SIDE-SKIM SEEDING" FOR CONVECTIVE CLOUD MODIFICATION*

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Abstract. Ice crystals growing by vapor diffusion at -10 C, primarily as short solid columns, fall faster than those developing dendritically at lower temperatures or those of long columnar shapes at warmer temperatures. To keep artificially induced crystals around -10 C as long as possible and thus cause them to grow and fall faster in order to enter the rapid riming growth regime, cumulus clouds should be seeded at the -10 C level just inside the cloud, rather than at the center, using liquid propane or other nucleant with little temperature dependence.

1. INTRODUCTION

Effective modification of convective clouds requires, first, knowledge of the clouds, seeding materials, seeding methods and microphysics-dynamics interactions in the clouds, and second, the selection and proper combination of these elements so as to maximize the desired effects of seeding. In this paper, we shall re-examine basic factors of cloud seeding in the light of our new finding about ice crystal fall behavior (Fukuta et al., 1979), and formulate a new seeding method which can avoid some previous difficulties. Possible applications of the new method will be discussed for cumuliform cloud modification for precipitation augmentation and hail suppression.

2. RE-EXAMINATION OF FACTORS INVOLVED IN CONVECTIVE CLOUD SEEDING

2.1 Purposes of convective cloud seedings

For precipitation augmentation seeding, maximization of precipitation is naturally the normal intent. Sometimes, in addition, transportation to a more desirable location may be required. Due to the relatively short life time of certain convective clouds, maximization of precipitation formation frequently demands rapid formation of precipitation after seeding. For other occasions where the atmosphere is conditionally unstable, the maximization may require fusing small clouds to induce a much larger cloud development.

Another common goal for seeding convective clouds is to suppress hail. Where hail occurrence is frequent, the total amount of precipitation is normally small. So, hail suppression operations should not lead to a reduction in the amount of precipitation. For these reasons, hail suppression operations should be aimed at the reduction of hail size with an increased number of hail embryos by proper seeding.

2.2 Ice nucleants and ice nucleation

Ice nucleants most frequently used at present are AgI and dry ice, especially the former. One drawback to AgI, apart from the recent quantum jump in price, is the strong temperature dependence in the number of active nuclei. Activity curves of AgI particles from various smoke generators are normally measured under coexistence of supercooled fog as a function of temperature (Garvey, 1975). When the temperature drops from -10 to -20 C, the number of active nuclei per gram of compound increases by approximately 10^3. This leads to a serious problem of depleting the available moisture at low temperatures if the number is adjusted for proper seeding at a warm temperature. As a result, ice crystals never grow to desirable sizes.

If a factor of 10^3 increase were assumed in the number of active nuclei as the temperature lowered from -10 to -20 C and if all the ice crystals formed were assumed to be the same size, the mass of each crystal would be smaller by a factor of 10^3 than that without the number increase. In the Stokes regime, this mass reduction corresponds to a fall velocity reduction by a factor of 10^2, since the fall velocity $v \propto r^2$, where r is the radius. Instead, if the number were adjusted for proper seeding at a high altitude, say at -20 C level, there would be hardly any ice crystals at the -10 C level, wasting the precious time available for ice crystal growth before the nuclei reach high altitude.

The second problem with AgI nuclei concerns the nucleation mechanisms. As Schaller and Fukuta (1979) have identified, the mechanisms of ice nucleation vary a great deal, depending on cloud conditions. Among now commonly accepted processes of heterogeneous ice nucleation, i.e., deposition, condensation-freezing, including immersion-freezing, and contact-freezing, the former two occur relatively quickly even at temperatures near the nucleation thresholds. On the contrary, contact-freezing is slow. Therefore, the values of ice nucleation shown by Garvey (1975) are overestimates to a large extent as far as contact-freezing nucleation is concerned, because developing natural clouds, the kind desired for seeding, do not allow much time for the nucleation mechanism to operate. On the other hand, the condensation-freezing mechanism does operate at warm temperatures without much time delay. However, it depends on the water supersaturations which the cloud process produces, and since the water supersaturation levels vary depending on the microphysics-dynamics interaction of cloud, the ice nucleation rate also varies.

The number of ice crystals generated by dry ice per gram of the compound is nearly independent

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of temperature at a level about $10^{12}g^{-1}$, a marked advantage over AgI nucleants. We believe this number of ice crystal produced per gram dry ice is well within the realm of operation, for reasons discussed below. Other than the well-known awkwardness of availability, storage and crushing as well as need for high flying airplanes, dry ice seeding tends to produce vertical curtains of ice crystal plumes. This, however, results in rapid upward movement of ice crystal plume due to heating by cloud parcel glaciation (Fukuta, 1973), and reduces the number of ice crystals formed at low altitudes as well as increases that at higher altitudes, although the problem is far less serious compared with that of AgI nucleants.

2.3 Growth and fall behaviors of ice crystals

To develop precipitation rapidly, fast growth of ice crystals is naturally desirable. The two basic kinds of ice crystal growth exist, i.e., one by vapor diffusion and the other by riming. After nucleation, ice crystals normally go through the diffusional growth regime with the fastest growth occurring at a temperature around -17 C, corresponding to plate form. The second peak of vapor diffusion growth occurs at around -6.5 C with columnar crystal shape (Fukuta, 1969; Fukuta et al., 1979). The growth rate of an ice crystal by vapor diffusion, disregarding effects due to fall, thermal and mass accommodation on its surface and supercooled fog existence under a given temperature, may be described as

$$\frac{dm}{dt} = 4\pi C(S_i - 1)\left[\frac{L_d^2}{KRT_\infty^2} + \frac{1}{\rho_{\infty,sat}D}\right]^{-1}, \qquad (1)$$

where m is the ice crystal mass, t the time, C the electrostatic capacitance of ice crystal, S_i the saturation ratio with respect to ice, L_d the latent heat of deposition per gram of water vapor, R the specific gas constant of water vapor, $\rho_{\infty,sat}$ the saturation water vapor density at the environmental temperature T_∞, and D the diffusivity of water vapor in air. If we can assume a spherical shape for the crystal,

$$\frac{dm}{dt} = 4\pi r^2 \rho_i \left(\frac{dr}{dt}\right), \qquad (2)$$

where ρ_i is the density of ice crystal. From Eqs. (1) and (2) with C = r, it is clear that $rdr \propto dt$. After integration, we have $r^2 \propto t$ or $r^3 \propto m \propto t^{1\frac{1}{2}}$.

On the other hand, ice crystal growth rate by riming mechanism is given as

$$\frac{dm}{dt} = \pi r^2 \bar{E} W_L v, \qquad (3)$$

where $\bar{E}$ is the average riming efficiency, W_L the liquid water content of cloud, and v the fall velocity of ice crystal. For a sphrical particle of graupel size, $v \propto r^{\frac{1}{2}}$ normally holds. Then,

$$r^{-\frac{1}{2}}\,dr \propto \bar{E}W_L dt.$$

After integration, we have

$$r^3 \propto m \propto (\bar{E}W_L t)^6. \qquad (4)$$

Although these estimations were carried out under highly simplified conditions, they show a drastic change in the growth rate of ice crystal, if the switch-over from vapor diffusion mechanism to riming occurs. Fig. 1 illustrates the diffusional growth regime where $r \propto t^{\frac{1}{2}}$ or $m \propto t^{1.5}$ and the riming growth regime where $r \propto t^2$, or $m \propto t^6$ in the zone where $v \propto r^{\frac{1}{2}}$.

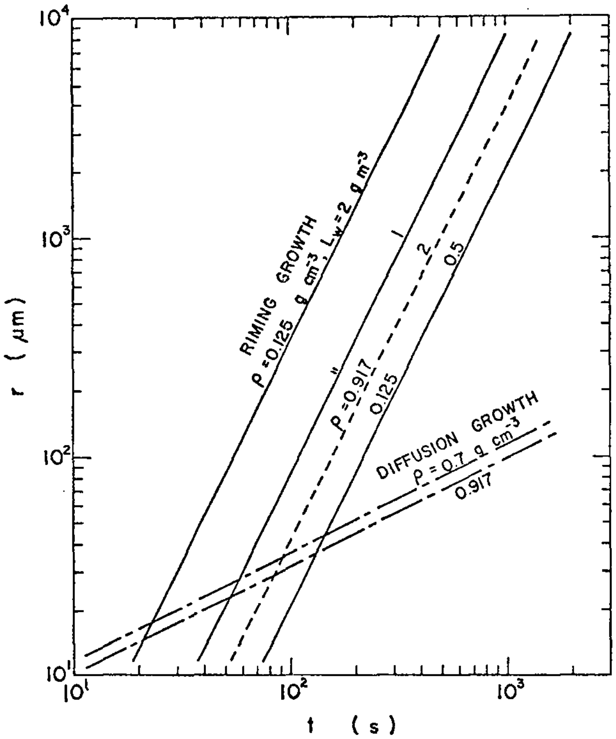

Fig. 1. *Relation between ice crystal radius r and time t for vapor diffusion and riming growths at 500 mb and -10 C. ρ is density of ice crystal and L_w is liquid water content of supercooled cloud. The riming efficiency is assumed to be unity.*

Under what conditions does this switch-over happen? Graupel fall fast compared with snow flakes, and fast-falling ice crystals are expected to enter into the riming regime more quickly than others. We recently discovered that ice crystals growing at -10 C develop fastest fall velocities although their mass growth rates are at a minimum. Fig. 2 shows development of fall velocities of ice crystals growing under different temperatures. Although the -10 C peak continues to increase linearly, the -15 C peak, corresponding to the diffusional maximum of mass growth, slows down rapidly apparently due to dendritic form development (Fig. 3).

Crystal habit changes from column to plate at -10 C as the temperature lowers, and the crystals at this temperature take a shape near spherical with high apparent density (Fukuta, 1969; Fukuta et al., 1979). Rapid development of precipitation is often required in convective cloud seeding, so -10 C is clearly the most advantageous temperature zone where rapidly growing and falling graupel can easily form.

2.4 Seeding modes, nuclei plume diffusion and cloud interactions

A few different methods of seeding are possible. Vertical sheet, horizontal and sometimes vertical line and point seedings have been employed in convective cloud seeding, in addition to broadcast seeding from the ground. As mentioned earlier, a vertically long ice crystal plume tends to develop a premature updraft due to heat generation by phase changes in the supercooled cloud. Different modes of seeding lead to different rates of plume diffusion. Ice nuclei and ice crystal diffusion from a point source is the fastest.

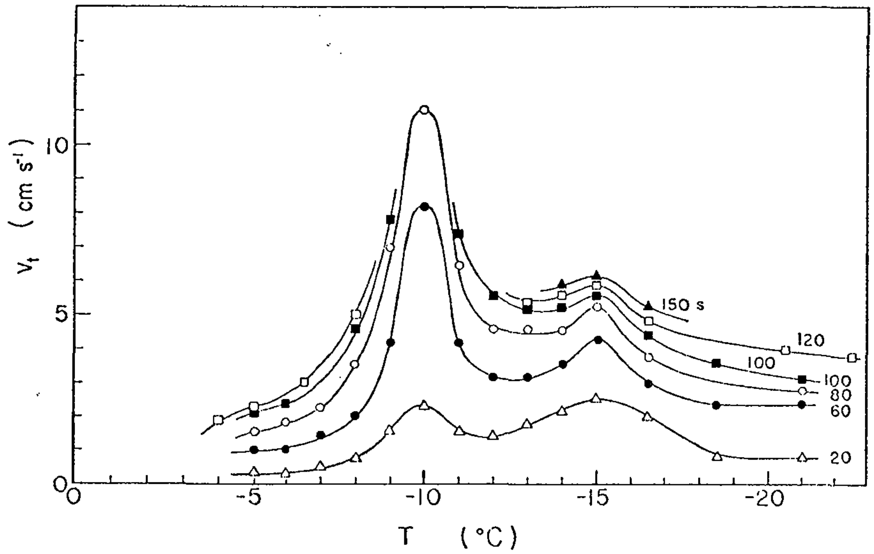

Fig. 2. Fall velocity of ice crystal v_t as a function of temperature T at different time intervals after onset of growth.

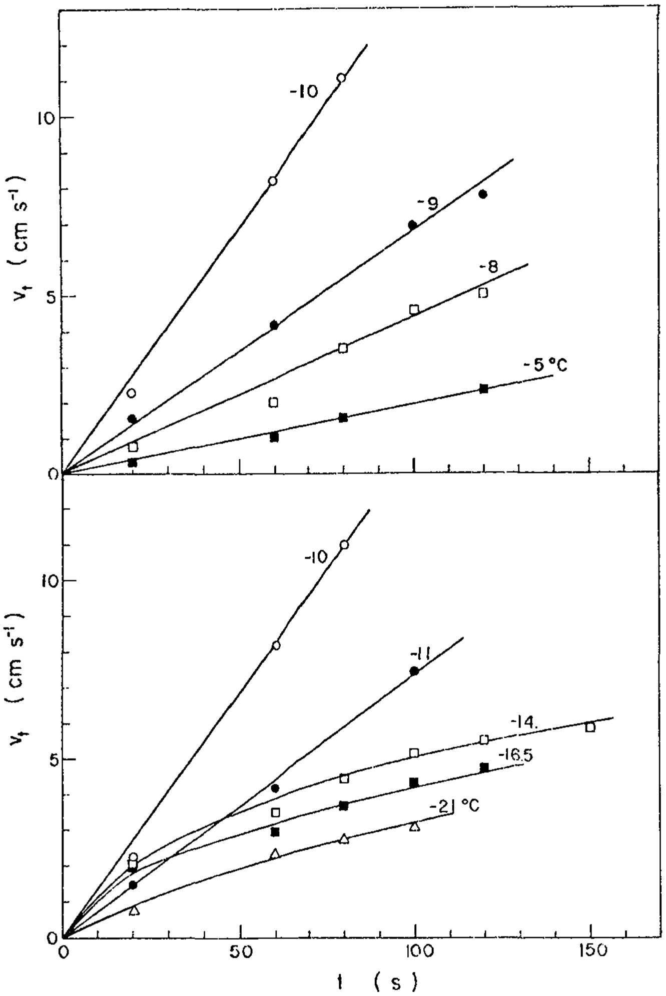

Fig. 3. Fall velocity of ice crystal v_t as a function of time t after seeding at different temperatures.

Additional buoyancy of cloud parcel due to glaciation depends on the total mass of ice crystals M which can be expressed as

$$M = \int_0^\infty n(r)m(r)dr,$$

where n(r) and m(r) are respectively the number and mass of ice crystals with radius r. Therefore, M can be increased in either of two ways, by increasing n or by increasing m. So-called "dynamic seeding" supplies a large amount of seeding material to increase n(r). This overdosage of nucleant, however, induces an overseeding effect, particularly at high altitudes, and does not necessarily produce the best result. Ice crystals thus formed or brought up to high altitudes are too small to fall and form precipitation within the available time period. By allowing sufficient time for molecular diffusion growth with the help of turbulent diffusion of the plume, m can be increased, rather than n, by securing sufficient moisture around growing ice crystals. In this regard, nucleants used should not increase activity at low temperatures.

This problem of n vs. m is also important in hail suppression seeding. Increasing n in the overseeding method of hail suppression, although difficult to achieve at warm temperatures (and if not achieved, the method does not work), is likely to reduce the amount of precipitation. A more desirable method is to increase m so that the artificially formed ice crystals compete with hail embryos, yet they are small enough to melt and not cause any damage on the ground. To achieve the desired effect of seeding, motions of cloud parcels including convection must be utilized carefully.

2.5 Seeding rate

Seeding rate is one of the most poorly defined quantities in cloud seeding and should be adjusted to achieve the best final result, not necessarily to produce dramatic intermediate reactions. For precipitation augmentation seeding, the rate may be estimated roughly from the following parameters; (a) the diffusion volume of ice nuclei plume within the available cloud life time, (b) the mass that ice crystals can attain under free growth during the cloud life time, (c) the liquid water content of the cloud parcel, and (d) the thermodynamic and dynamic status of clouds. Fall velocity consideration for the ice crystals formed is particularly important.

The seeding rate determination becomes complex when the active number of ice nuclei shows temperature dependency such as AgI nucleants. The disadvantage of temperature dependency comes in, so that optimization of the seeding rate has to be done within the restriction of the temperature dependent activity. Nevertheless, if an airborne seeding were carried out, the diffusing front of the ice crystal plume would receive sufficient moisture to generate a small number of falling ice crystals.

3. SIDE-SKIM SEEDING IN CONVECTIVE CLOUD MODIFICATION

The above discussions show that many of the previous problems in convective cloud seeding relate to increase in number instead of mass. Therefore, considering all factors involved in convective cloud seeding, we propose new methods of seeding for precipitation augmentation and hail suppression.

3.1 Cumuliform cloud modification for precipitation augmentation

Cumuliform clouds normally are quite tall, covering wide ranges of temperature. During the cloud growth stage, which is the best time for seeding, the convective motion has large scale rotations. Updraft velocity is often highest at the center of convective cell. The convective cell enlarges by entrainment along a cone with a semivertical angle of about 15°. In an active cell with a high liquid water content, which is often worth seeding, the central updraft is so fast that even ice crystals formed at warm temperatures pass quickly through the zone of columnar crystal habit and enter into the plate zone of low temperatures. Once ice crystals are carried to high altitudes, unless in hail clouds, they tend to become slow falling dendrites. This trend becomes stronger if more ice crystals form at high altitudes.

To avoid these problems, we propose "Side-Skim Seeding" of convective clouds for precipitation augmentation. Fig. 4 shows the principle of this seeding. At low level, the convective cell is assumed to be 4 km wide with the updraft velocity 5 m s^{-1} at its center and 0 at the sides. This motion has two components, a uniform vertical motion of 2.5 m s^{-1} and rotation with a tangential velocity of 2.5 m s^{-1}. The centers of rotation move upward at a vertical velocity of 2.5 m s^{-1}. The centers of cloud rotation are placed at -8 C level, slightly lower than the 6 km level.

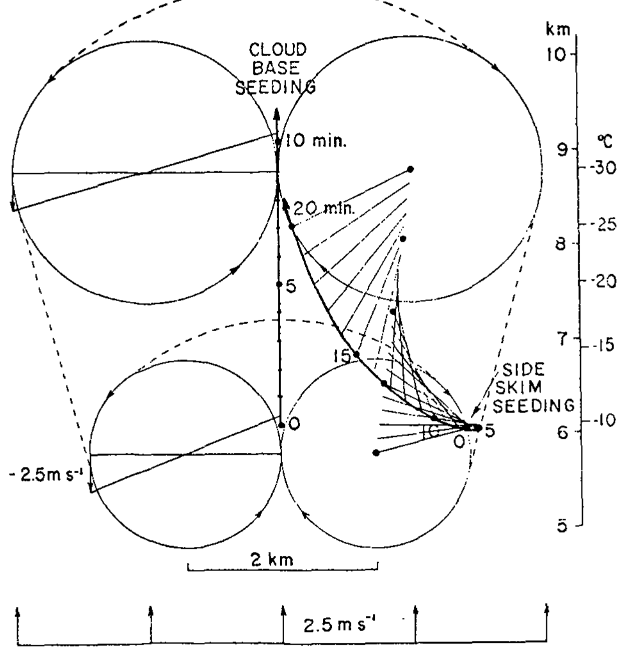

Fig. 4. "Side-Skim Seeding" concept of convective cloud modification. The updraft velocity of cloud is 5 m s^{-1} at the center and 0 at the sides. Trajectories of ice nuclei plume centers are shown for cloud base seeding as well as for Side-Skim Seeding.

Side-Skim Seeding assumes horizontal seeding at the -10 C level along the inside edge of the cloud with ice nuclei (or ice crystals) having little or no temperature dependence, such as liquid propane. In this manner, the seeding aircraft is unlikely to hit a strong updraft and can easily leave the cloud at any time. The center of the nuclei plume remains at the same altitude for about 10 minutes after seeding, and takes about 15 minutes to reach the -15 C level without the help of added buoyancy from seeding. Beyond this temperature, the tendency for dendritic growth becomes strong, if the riming process has not yet been achieved. During this 15 minute period, the ice crystal plume will spread in the eddy field and the ice crystals, in the form of graupel with a density of about 0.13 g cm^{-3}, will be about 2 mm in radius and fall at 1 m s^{-1} or more, if the cloud liquid water content is more than 0.5 g m^{-3}, because this is the temperature zone where ice crystals of the fastest fall velocity develop (Fukuta et al., 1979).

If the cloud center were seeded at the same altitude, the center of nuclei plume would take only 3 minutes to pass the -15 C level, even without the help of added buoyancy by seeding. Most of the ice crystals probably would start to develop dendritic forms, which do not enter readily into the riming regime of fast growth, and the crystals fall much more slowly than the graupel produced with the Side-Skim Seeding at -10 C.

The dynamic effect of Side-Skim Seeding is also expected to be better, due to wider coverage of cloud space by turbulent diffusion of ice crysals formed, utilizing the ample avilable time. Although slow at the beginning, uniform lifting over wider regions of the cloud will develop. This is more likely to bring a larger amount of moist air from below into the cloud and thereby enhance further cloud development.

3.2 Hail cloud modification

The rapid development of fast growing and fast falling graupel at -10 C may be utilized in hail suppression. When multicell storms are seeded by the Side-Skim Seeding procedure, the graupel formed should be efficient in reducing the liquid water avalable for hail growth in the clouds. In addition, a precipitation augmentation effect may be expected because the method avoids overseeding.

"Competing hail embryos" possibly may be introduced into supercell hail storms, by creating fast falling ice crystals in the -10 C zone, although the chance is slimmer compared with that in multicell storms. Side-Skim Seeding at around the -10 C level of small convective tower in front of the main updraft shaft of a supercell storm may possibly permit the fast falling ice crystals to enter the main updraft. Then they will be carried upward following the trajectory of the natural hail embryos as suggested by Browning and Ludlam (Mason, 1971, p. 360), provided that the embryos originated at around -10 C. A large number of hail embryos thus introduced should compete with natural ones for available moisture, thereby reducing hail size. Hail embryos are either frozen drops or snow pellets, and the latter formation should be easiest at around -10 C, provided that other necessary conditions are satisfied.

The effects of these new seeding methods for precipitation augmentation in convective clouds and for suppressing hail without reducing precipitation in multicell as well as supercell storms should be studied.

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