EFFECT OF THE TEMPERATURE SPECTRUM OF ACTIVE ICE NUCLEI ON TARGETING OF SEEDED OROGRAPHIC PRECIPITATION*

N. Fukuta

Denver Research Institute, University of Denver
Denver, Colorado 80210

1. INTRODUCTION

Seeding a supercooled cloud or cloud system with ice forming nuclei marks the start of ice phase weather modification. The characteristics of ice nuclei not only can be controlled within the existing technology, but they also largely affect the results of seeding. Weather modification research programs in general aim at determining conditions for maximizing the physical effect, although factors such as ecological and economical problems have to be simultaneously considered. Whereas, in actual operations, optimization of the physical seeding effect will be pursued in consideration with the overall circumstances.

Weather modification for the purpose of precipitation augmentation relies on the possibility of enhancing the mechanism of precipitation formation by proper seeding, and of targeting the precipitation to the desired area. It is, however, always accompanied by the possibility of an opposite effect, i.e., reducing the precipitation by improper seeding such as by overseeding. Therefore, it is clear that a blindly planned statistical experiment does not accomplish the objective of the program. Identification of all the physical factors which strongly influence achievement of the desired seeding result must be carried out first. Only when one succeeds at this task can the statistical method be employed for proving the seeding concept. Concerning ice nuclei characteristics, this paper discusses a highly sensitive factor for targeting the seeded precipitation and a way to avoid the difficulty. This factor is important in winter orographic cloud modification, particularly when sizable convective cells are embedded in the clouds.

2. TEMPERATURE SPECTRUM OF ACTIVE ICE NUCLEI AND TARGETING THE SEEDED PRECIPITATION

The task of carrying out winter orographic seeding can be considered as targeting the seeded precipitation to the desired area, normally the mountain slope. The targeting has to be accurate, partly because the available moisture for the additional precipitation by seeding diminishes on the leeward side of the mountain. The formation of the additional precipitation by seeding for the targeting involves primarily two physical processes, i.e., nucleation and growth of hydrometeors. Before commencing to the targeting problem of seeded precipitation, we shall first discuss a

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"forgotten seeding window" by reexamining the capability of non-AgI nucleants and the warm temperature peak of ice crystal growth rate.

a. <u>The Peak of Ice Crystal Growth Rate at -6^{o}C</u>

As we have experimentally determined (Fukuta, 1969), and as has been recently substantiated by Ryan et al (1974), the growth rate of freely falling ice crystals in supercooled fog has two maxima, one appearing at around -6^{o}C and the other at about -16^{o}C. In order to utilize the peak of the growth rate at the warm temperature for precipitation augmentation, the ice crystals have to be in the cloud environment in reasonably high number as well as in large size (Fukuta, 1974). For this to happen at around -6^{o}C, ice nucleation must take place at temperatures considerably higher than -6^{o}C so as to acquire the desirable size.

Figure 1 shows ice nucleation behavior of AgI recently obtained in our laboratory for freely suspended smoke particles, using a special ice thermal diffusion chamber. The temperature and particularly the supersaturation were accurately controlled in the chamber. As one can see in the figure, there are two main areas of ice nucleation, one at warm temperatures and above water saturation, and the other at colder temperatures and below water saturation. The former is believed to be the zone for condensation-freezing nucleation and the latter that for deposition nucleation. Although it is possible to nucleate ice on AgI particles at a temperature as high as -4^{o}C, the water supersaturation required for this to happen generally does not occur in nature. In orographic clouds, the ascending rate of air mass is not as large as that in some convective clouds, and with the existing level of cloud condensation nuclei (CCN), the supersaturation with respect to water, being of the order of 0.5%, cannot reach high enough values to nucleate ice in sufficient numbers. By the time a reasonable number of ice nucleation is finally achieved in the rising cloud air, the temperature is lowered well below the -6^{o}C level. Thus, it seems that the -6^{o}C peak of the ice crystal growth rate has never been adequately utilized in AgI seeding in the orographic clouds.

In view of the fact that AgI nuclei do not make efficient use of the temperature zone above -10^{o}C, if one employs other kinds of ice nucleants active in the range of 0 to -5^{o}C, and if such nucleants satisfy seeding agent requirements, it may be possible to utilize this forgotten temperature zone and to obtain additional precipitation. Figure 2 shows the ice nucleation behavior of metaldehyde smoke recently determined in our laboratory. The condensation-freezing nucleation zone of metaldehyde above water saturation extends to warmer temperatures. As the author has frequently pointed out, metaldehyde is a remarkable self-promoting contact nuclei (Fukuta, 1972). Its contact nucleation rate is about 10^3 times greater than that of AgI when compared under identical conditions. The high threshold temperature of ice nucleation as well as the rapid contact nucleation, the latter being independent of water supersaturation as long as supercooled droplets exist, make metaldehyde the only heteorgeneous ice nucleant usable for this purpose.

As far as homogeneous ice nucleants, or coolants, are concerned, dry ice, liquid CO_2, liquid propane and liquid nitrogen (or air) can generate approximately 10^{12} ice crystals per gram at temperatures up to almost 0^{o}C.

The ease of remote generator control, low cost, and safety in ecology, make the use of coolants, liquid propane in particular, attractive for seeding of clouds warmer than $-10^{o}C$ although the generator has to be operated in the cloud where the temperature is below $0^{o}C$. At the beginning or near the end of the cold season, there should be this marginal temperature condition with cloud temperatures near $0^{o}C$, and in which the clouds, being warm, frequently contain a substantial amount of liquid water.

b. Precipitation Targeting

As we have discussed above, targeting must be carried out as accurately as possible for orographic seeding, and nucleation and growth of ice crystals in the diffusing ice nuclei smoke are the prime physical factors one has to adjust in harmony with the existing orographic cloud conditions. However, the existing dynamic and microphysical conditions of the orographic cloud air present a problem of inherent "diffuseness" when the targeting is considered. In other words, the situation there is similar to what happens when one tries to adjust the "head," and the "tail" bulges out, while if the "tail" is adjusted to the situation, the "head" sticks out. The situation is characteristic to the chosen animal--in the present case, it is the nucleant chosen--, and the discussion we give below will concern the way to ease the problem by selecting different nucleants.

Suppose we have a cloud air mass into which an ice nuclei smoke of total active particle number per gram

$$N = f(T,C,), \tag{1}$$

is dispersed, where T and S are the temperature and the supersaturation with respect to ice. For simplicity, we assume that all the nucleated particles not only grow to the same size but deplete the liquid water completely in the air mass, and that they continue to fall. In addition, we take the Lagrangean view, i.e., the observer rides on the moving air mass, and all the induced perturbations are ignored. Assumptions are also made that ice particles are spherical, only the cloud liquid water is converted into ice* and the condensed water content remains unchanged throughout the process in question. Although these assumptions are crude, use of them may be justified by the relative nature of discussions here.

Then, the liquid water content (LWC) distributed to each particle must equal the mass of an ice particle

$$\frac{(LWC)}{n} = \frac{4}{3}\Pi\rho_i r^3, \tag{2}$$

when n is the number of active ice nuclei in a unit volume of cloud air, and ρ_i and r are the density and the radius of ice particles, respectively.

The terminal velocity of particles whose sizes fall in the range of r = 100 μm - 2.5 mm, obeys the following relation

$$w \propto r^{\frac{1}{2}}. \tag{3}$$

* Strictly speaking, this is not true (Fukuta, 1972).

By the time the ice particles reach the ground they cover a distance of

$$z = wt, \tag{4}$$

where t is the time. Then, during the same fall period, the particles will be carried by the wind in the horizontal direction by

$$x = ut, \tag{5}$$

where u is the horizontal component of the wind velocity.

Eliminate t from Eqs. (4) and (5) by holding u = const, results

$$x \propto w^{-1}. \tag{6}$$

Inserting Eq. (2) under the condition (LWC) = const, the relation (3) into (6), and using $n \propto N$, one obtains

$$x \propto N^{1/6}. \tag{7}$$

In targeting the seeded orographic precipitation, change of x in Eq. (7) by uncontrollable factors should be minimal. Then, N should be as insensitive as possible to the environmental variables such as S and T. As we have frequently pointed out (Fukuta, 1972), the ice nucleability of AgI smoke from acetone generators, which are efficient and economical, is highly temperature dependent, disregarding its supersaturation dependency for the time being. Whereas, one of the common features of organic nucleants, which are economical and biodegradable, is the flat activity spectrum with respect to temperature.

Our orographic laminar flow cloud model (Plooster and Fukuta, 1975) showed in its computer experiment of seeding that the strong temperature dependency of the activity of AgI smoke dispersed in a cloud with a typical vertical temperature variation, would lead to the "head and tail" effect. When the active nuclei concentration at high altitude and low temperature was adequate, that at the low altitude and high temperature was too small, and vice versa. On the other hand, an organic nucleant (1,5 dihydroxynaphthalene) with a flatter activity spectrum of nuclei with temperature, resulted in a larger maximum amount of precipitation when the seeding rate was varied to optimize the total precipitation.

The California orographic clouds often carry active convective cells, and this convective action enhances the "head and tail" effect making the targeting problem more awkward for the ice nuclei smoke with strongly temperature dependent activity. If the active nuclei concentration is adjusted to the optimum level for targeting in the laminar flow part of the cloud and if the nuclei activity spectrum is highly temperature-dependent like AgI, then when convective cloud towers develop from the low lying laminar flow region and gather up the nuclei existing there, a large number of ice nuclei will be activated in the towers. This makes the fall pattern of ice crystals from the convective clouds quite different from the rest of the cloud, and they will be carried away into the forbidden lee side. Thus, failure of targeting of moisture from convective towers results. If this problem of the convective part were anticipated and the nuclei concentration were adjusted to the convective tower situation, the active nuclei concentration in the laminar part would drop so low that the moisture there would not be properly utilized. If the organic nucleant with flatter activity spectrum vs temperature were used instead, the number of ice crystals in the convective towers would not drastically increase so that the targeting situation remains relatively unchanged.

If this temperature change due to the convective activity is from -10 to -15°C, the ratio between the increased number of active AgI nuclei and that of 1,5-dihydroxynaphthalene (Plooster and Fukuta, 1975) is about 15. Inserting this number in the relation (7), we obtain the ratio of horizontal transfer distance of ice crystal during the fall for AgI and the dihydroxnaphthalene to be 1.6. If the temperature change happens from -10 to -20°C, the number ratio becomes 160 and the distance ratio of 2.3 results.

Thus, the high temperature dependency of activity of seeding material adds an inherent problem for targeting the seeded orographic precipitation and when convective towers develop out of the laminar orographic cloud, this targeting problem becomes worse resulting in a lower level of maximum precipitation in the desired area. One way to cope with this problem is to use nucleant with flatter activity spectrum with temperature, and organic nucleants generally have such a characteristic.

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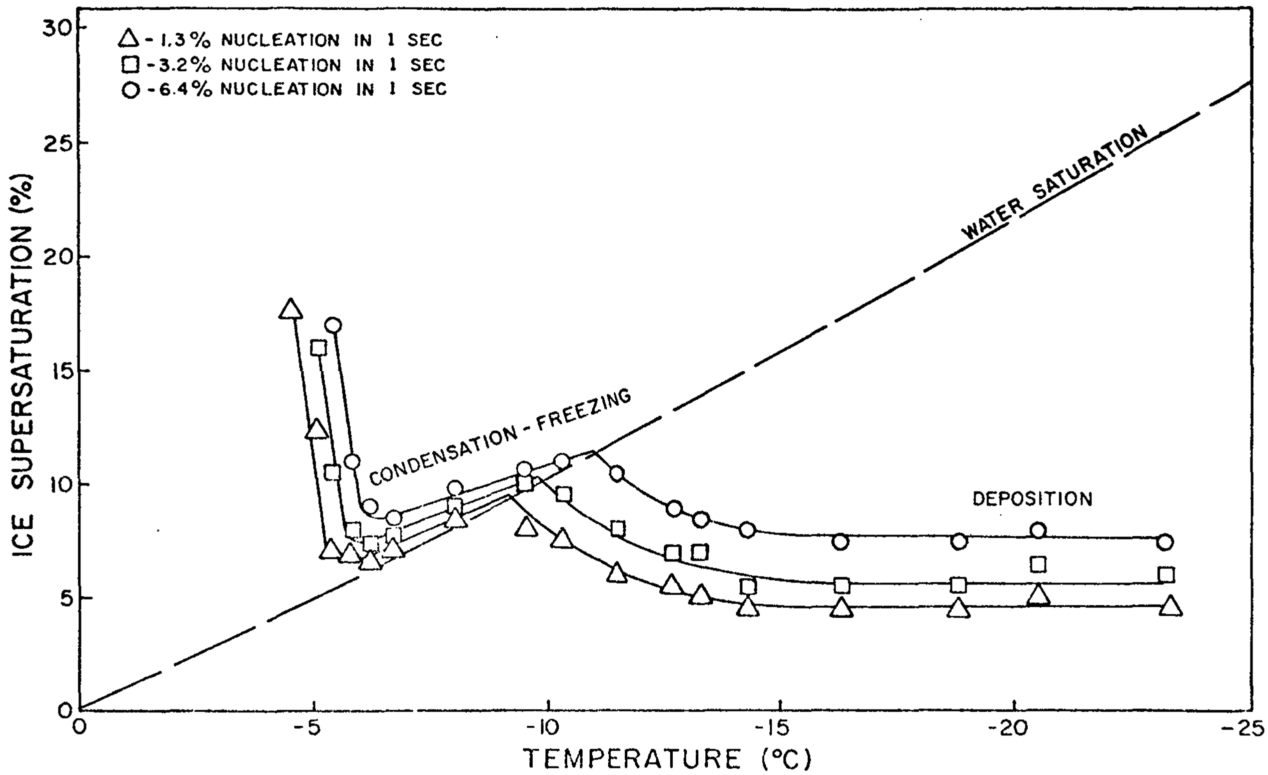

Fig. 1. Ice nucleation by AgI smoke particles as a function of supercooling and supersaturation

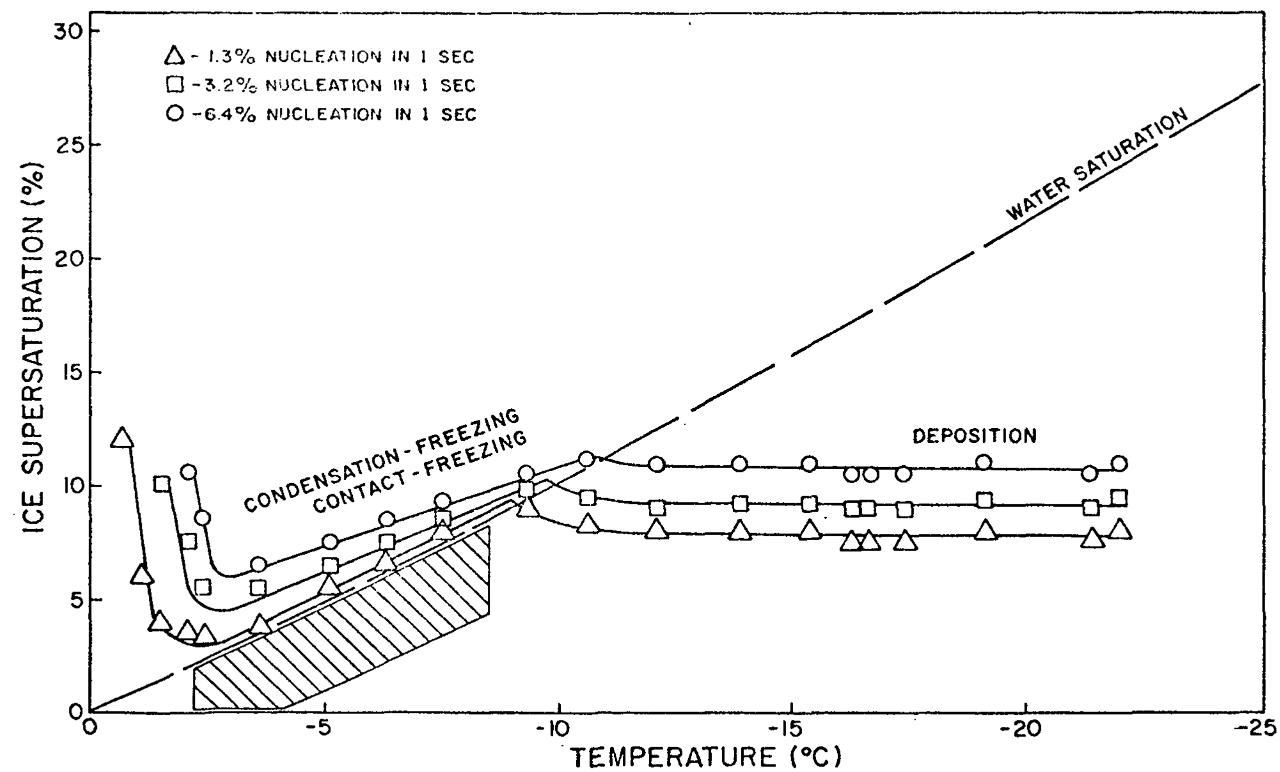

Fig. 2. Ice nucleation by metaldehyde smoke particles as a function of supercooling and supersaturation