IS ICE MULTIPLICATION A PROMINENT FACTOR IN OROGRAPHIC PRECIPITATION?

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1. INTRODUCTION

Cloud top tempeature is considered to be the crucial factor for the production of nuclei which may be distributed in significant concentrations throughout the vertical extent of the cloud by convective and turbulent mixing. The nuclei production curve for silver iodide shows the number of effective nuclei per gram increasing exponentially with decreasing temperature at first, with a lesser rate of increase at colder temperatures. The average number of natural nuclei increases exponentially with decreasing temperature. Since the coldest cloud temperature normally occurs at cloud top, the number of nuclei produced naturally or artifically at or near the cloud top temperature far overshadow the number of nuclei produced at lower and warmer temperatures. The high concentrations of ice crystals produced near cloud top are distributed throughout the cloud via settling and mixing.

Observational evidence of the control of cloud top temperature on the effectiveness of cloud seeding to augment precipitation has been presented by several investigators: Grant and Mielke (1967); Rhea et al. (1969); Smith (1970); and Elliott et al. (1971). More recently Grant and Elliott (1974) presented evidence showing a cloud seeding temperature window within which seeding effects on precipitation are positive. Seeding with cloud top temperatures colder than the cold side window boundary (critical temperature) showed a decrease in precipitation that was attributed to overseeding due to competition for available water. Seeding with cloud top temperatures warmer than the warm side window boundary showed either no effect or a decrease. A decrease in the warmer cloud top temperature range has been suggested to be the result of natural ice multiplication which results in overseeding, again due to competition.

Ice particle concentrations have been compared to several variables:

- -- theoretical activated nuclei concentrations at cloud top temperature
- -- measured nuclei concentrations at cloud top temperature
- -- theoretical activated nuclei concentration at sampling level temperature
- -- measured nuclei concentratations at specific temperature
- -- typical crystal habit formation temperature

We postulate that ice particle concentrations at any level in a given not-seeded cloud will reflect the theoretical number of natural nuclei produced at the temperature of the cloud top, unless the cloud is being seeded naturally from above, or ice multiplication is occurring. In the seeded case the number of ice particles will be greater than this postulated level. This pertains to the first comparison in the above list. As will be shown on the basis of experimental data presented for the San Juan and the Sierra Nevada Mountains, the first is indeed the most appropriate comparison. When this type of comparison is employed, the evidence favoring abundant ice multiplication almost vanishes.

2. ICE MULTIPLICATION ON THE COLORADO RIVER BASIN PILOT PROJECT?

The ice multiplication process has been suggested (Hobbs, et al., 1975) as playing a prominent factor in the cloud physics processes of clouds over the San Juan Mountains of the Colorado River Basin Pilot Project. Although this may be true, the conclusion appears to result from comparing ice particle concentrations to the air temperature at which they were collected rather than to cloud top temperature.

Ice particle concentrations were measured in seeded and not seeded clouds on a series of aircraft flights by the Cloud Physics Group of the University of Washington from February 17 to March 30, 1974. Analysis and interpretation of these measurements have been reported in a University Research Report (Hobbs, et al., 1975) and summarized by Hobbs (1975a) at a weather modification conference:

> "The natural background concentrations of ice particles in clouds over the San Juan Mountains can vary by several orders of magnitude. However, the concentrations are generally quite high and are often several orders of magnitude greater than the ice nucleus concentrations at -20°C (see Figure 3.4). We attribute these differences to ice multiplication.
>
> "The concentrations of ice particles in clouds on the 'seeded days' are within the range of variability of the natural background con-concentrations on the 'control days'. However, on two 'seeded days', out of the four which were studied, increases in ice particle concentrations attributable to artificial seeding were detected. On both of these days the atmosphere was unstable."

The ice particle concentrations are described as "best estimates" based on measurements from the continuous formvar particle sampler, metal foil impactor, and the automatic optical ice particle counter. In their Figures 3.4, 3.8, 3.11, and 3.13 Hobbs, et al (1975) plotted these against the corresponding air temperature at the level of sampling. We have replotted these data onto one figure, Figure 1. They note (page 54) "....that the background concentrations of ice particles in clouds over the San Juan Mountains can vary over several orders of magnitude at the same sampling temperature" and admit that "these variations are no doubt due in part to varying cloud top temperatures". Analysis results are based on the former which is surprising, because cloud top temperatures apparently were used in Hobbs' (1975b) earlier work.

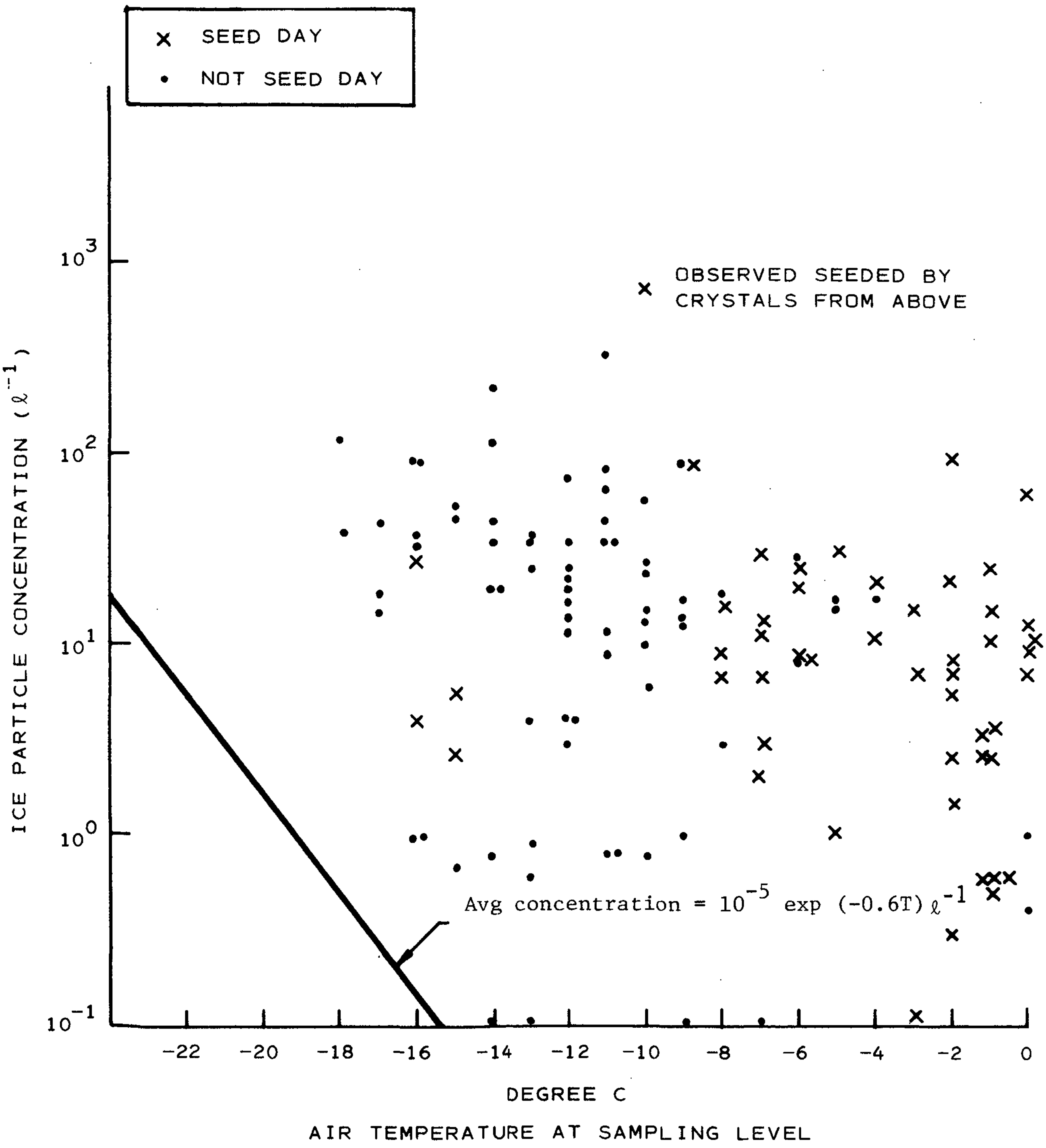

Fig. 1 Ice particle concentrations in seeded and unseeded clouds of the Colorado River Basin Pilot Project. Selected cases during February and March 1974.

On our assumption that ice particle concentrations in a given cloud reflect the theoretical number of nuclei produced at the temperature of cloud top, we have plotted data against cloud top temperature. Dates, time, and flight track information for not-seeded days, not presented in the report by Hobbs et al (1975), were provided by Dr. Radke of the University of Washington Cloud Physics group. This permitted ice particle concentrations for seeded and not-seeded days (three of these were non-experimental days) to be plotted against rawinsonde estimated cloud top temperature in Figure 2. The estimated cloud top temperature was either the rawinsonde determined cloud top temperature or that top temperature corrected for lifting, depending upon the position of the aircraft. A simplified airflow model was developed for determining the lifted cloud top temperatures (Elliott and Court, 1973).

Basically, the 9000 foot contour was employed as the division line for selecting a lifted or unlifted cloud top temperature. Also shown on Figures 1 and 2 is the average number of ice forming nuclei in the atmosphere determined from $N = 10^{-5} \exp(-0.6T)\,\ell^{-1}$, where T is the temperature in degrees centigrade (Mason, 1968).

Data plotted for a seed day at -30°C are for March 18, 1974. The operational criteria, at this time, were a 500 mb temperature of -23°C or warmer which was met. Hobbs et al. (1975, p 63) reported that nuclei were entering cloud base only along the southern boundary of the target area. Since sampling further downwind could not be accomplished due to FAA flight restrictions, we conclude that the AgI nuclei could not have altered the concentration observed and that these data represent not-seeded concentrations.

Data plotted at -17°C are for a seed day, February 19, 1974. The highest concentration was noted by Hobbs et al. (1975) as being from a cloud being seeded by ice crystals from above. In their diffusion studies on this date they found no nuclei from the generators and concluded that nuclei were not entering the cloud. This suggests that the remaining concentrations on February 19, 1974 were also due to natural seeding from the higher cloud. Hence, the not-seed concentrations for March 2, 1974 are circled as they represent concentrations on the only other day measurements were made when a cloud deck lay above the main cloud deck. The higher than expected concentrations at the estimated cloud top temperature of the lower cloud deck may be a result of natural seeding from above. In fact, for a short period during the course of the Colorado River Basin Pilot Project the operational criterion of cloud top temperature was applied to the highest observed clouds including cirrus.

If our assumption about the circled concentrations is correct, the sharp division between the not-seed cases and seeded cases by the average number of ice forming nuclei is most remarkable. It would also mean that there was no observation of particles in not-seeded (natural or by AgI) clouds with cloud top temperatures warmer than -26°C. The rejection of our assumption about the circled concentrations would make them the only ones that could be considered candidates for the ice multiplication process.

The observation by Hobbs et al. (1975, p 81) that background "concentrations are generally quite high and are often several orders of magnitude

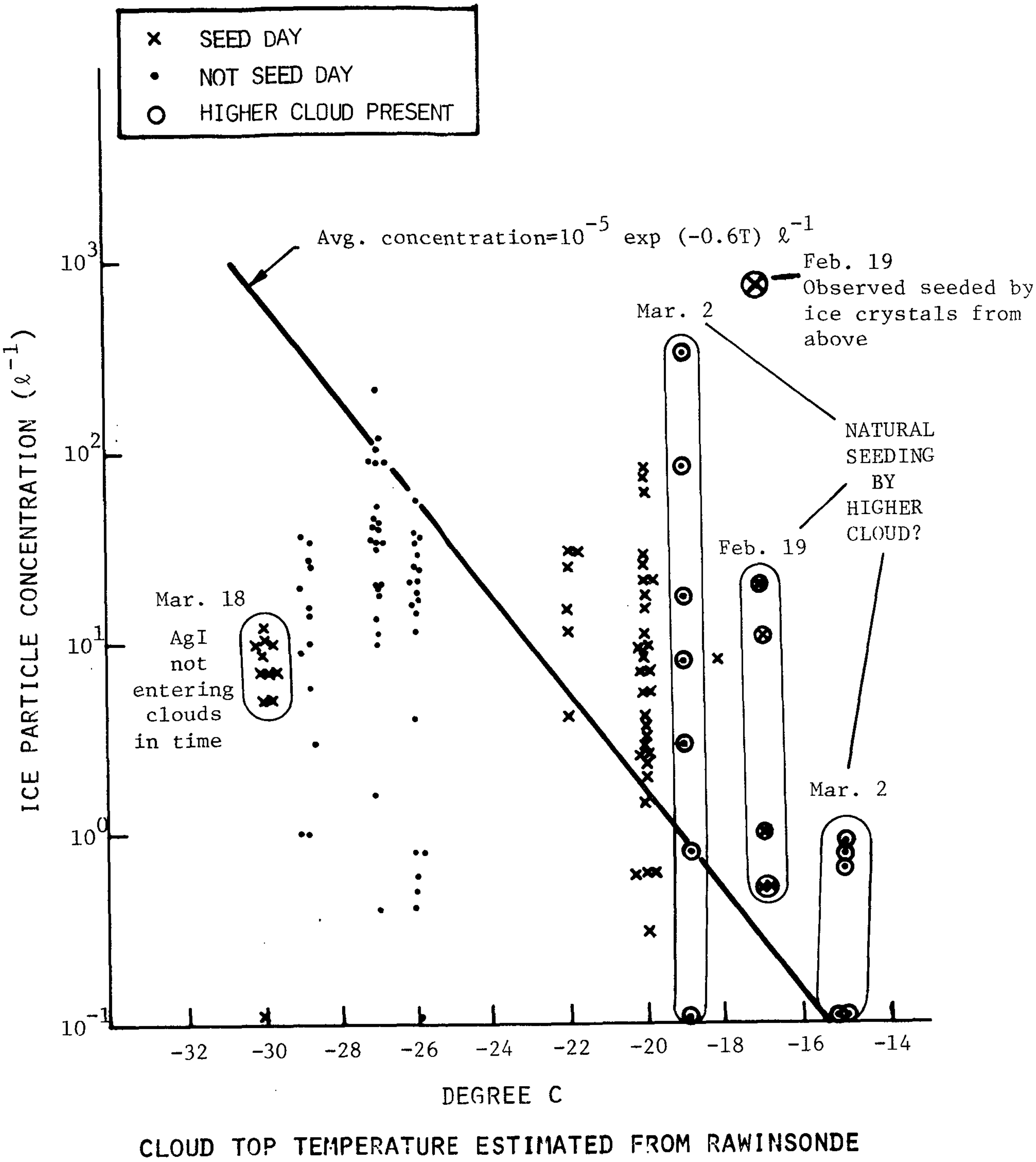

Fig. 2. Ice particle concentrations in seeded and unseeded clouds of the Colorado River Basin Pilot Project. Selected cases during February and March 1974. Concentrations are the same as those plotted in Figure 1.

greater than the ice nucleus concentration at -20°C" is not surprising because of the cold cloud top temperatures (-26 or less) on most of the background days when ice particle concentrations were obtained. The design (Grant et al., 1974) of the Colorado River Basin Pilot Project had specified that seeding was not to be conducted with cloud top temperatures colder than -26°C. It was believed that at colder temperatures concentrations of natural ice nuclei are nearly always sufficient for natural nucleation.

Our argument is not that the ice multiplication process cannot occur in the project area, but rather that there is lack of evidence to indicate that it does and especially to the extent interpreted by Hobbs et al. (1975).

3. ICE MULTIPLICATION IN THE SIERRA NEVADA?

Project CENSARE (CENtral SierrA REsearch) was designed to study snow formation processes and the corresponding potential for precipitation enhancement by cloud seeding. The target area for the project consisted of the upper portions of the Mokelumne and Stanislaus River watersheds on the windward slope of the central Sierra Nevada of California. Radiosondes were released from Tamarack (2109 m) within the target area and Jackson (522 m) approximately 65 km west-southwest of Tamarack.

During the course of Project CENSARE samples of snow crystals were collected at Tamarack during eight seeded storms and one not seeded storm. The samples were analyzed by comparing concentrations with crystal habit formation temperature. The analysis was reported by Reinking (1975a) and our Figure 3 is a reproduction of his Figure 2. It is pointed out that the line in this figure does not correspond to the formula given for it (10^{-5} should be 10^{-6}). He notes that

> "The concentrations of habits forming at warmer temperatures (needles and sheaths, N; columns, C; plates, P1A; branched planar crystals, P1B) are significantly greater than expected from 'normal' activation of background nuclei. The seeding material was active at least at tempeatures of -5°C and colder; seeding certainly contributed crystals to at least some of the cases. However, ice crystal multiplication or naturally enhanced nucleation may have contributed a portion of the observed crystals in any of the cases. Note from Figure 2 (our Figure 3) that some of the concentrations representing the <u>unseeded data equal or exceed many of those for the seeded cases, and are greater than the 'mean' background by one to four orders of magnitude</u>." (Emphasis is ours.)

We question this interpretation of the data. Table 1 lists the date and time crystals were collected, Jackson rawinsonde release time, cloud top temperature, plotting temperature, and the total number of particles other than fragments, and fragments. Sample 1 was the seeded periods and Sample 2 the not-seeded. Sampling periods were obtained from a report by Reinking (1973, p 77) and total number of particles and fragments were obtained from Table 18 of the same report (pp 111-112) which listed concentrations by crystal habit group. The concentrations may be found in

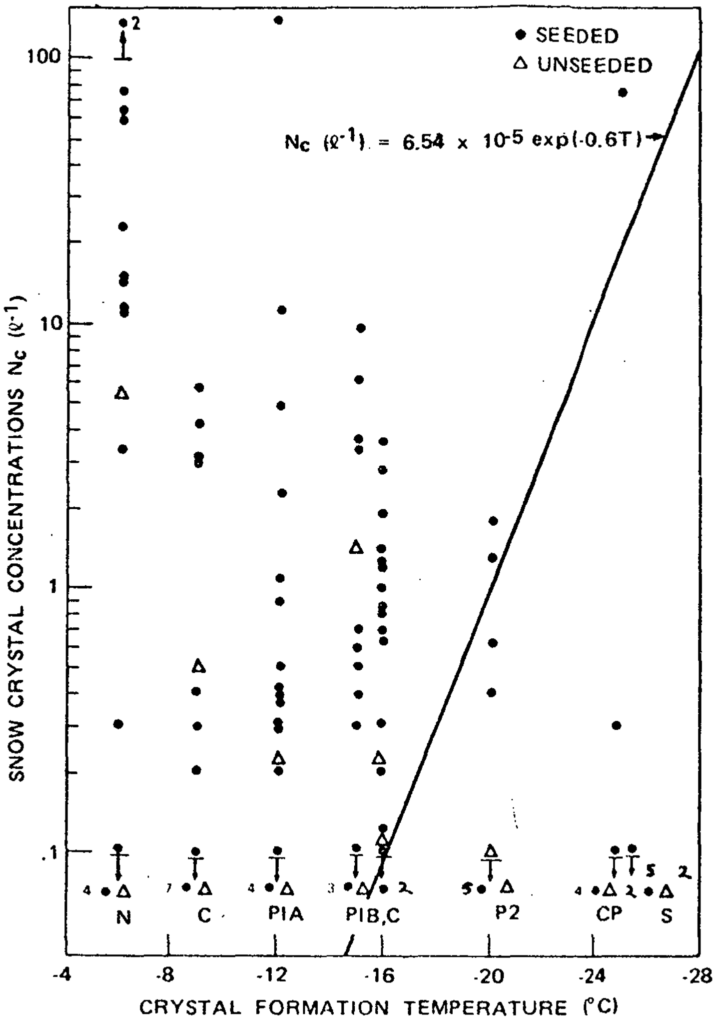

Fig. 3 Concentrations of snow crystals in the various habit groups observed in CENSARE target area. Arrows indicate cases with more than 100/ℓ or fewer than 0.1/ℓ. A dot indicates data from a seeded case ; an △ indicates data from untreated cases. Multiple cases are indicated by a subscripted number beside a dot or an △ The line is the natural ice nucleus spectrum often presumed to represent the worldwide mean.

a more recent article (Reinking, 1975b, p 748). Fragments are his listing for the PIC group which he attributed to multiplication breakup. Jackson sounding times and rawinsonde estimated cloud top temperature were provided by Don Griffith[1], Assistant Director of Atmospheric Water Resources Research, Fresno State College Foundation, during Project CENSARE.

Sounding data for Jackson rather than Tamarack have been used from a consideration of the time and distance required for nucleation, growth and fallout at the Tamarack sampling site. It was noted by Reinking (1975a, p 89) "corresponding distances from points of nucleation to fallout ranged from 33 to 110 km and averaged 65 km, according to calculations accounting for winds at all levels, crystal mean sizes, unrimed and rimed crystal fallspeeds, and zero vertical motion". Soundings were not taken at Jackson during the single not-seeded storm. Soundings taken at Tamarack during this not-seeded storm were provided by Dr. Reinking for our analysis. In Table 1 we have listed the temperature where the relative humidity (going up the sounding) dropped below 80%, an approximation of the cloud top temperature. The cloud top temperature may have been warmer at the Jackson site and for comparison with the seeded concentrations we have plotted them at -25°C on Figure 4. Seeded concentrations were plotted on Figure 4 for periods soundings were available as noted in Table 1. The number of fragments are noted for each case.

It may be noted in Table 1 that ice particle concentrations are greater than background during all but two of the seeded storms. These two storms had the coldest cloud tops of the seeded sample. The concentration of ice particles is indeed expected to be greater than background when seeding is effective. It may be noted that the number of fragments generally constitute a small fraction of the number of other particles.

1 Present affiliation is with North American Weather Consultants.

Table 1 CENSARE snow crystal collection periods, Jackson rawinsonde cloud top temperature and total number of particles excluding fragments, and fragments.

Sample 1	Date	Crystal Sampling Time	Jackson Sounding Time	Jackson Cloud Top Temp.	Plotting Temp.	Total Particles Excluding Fragments	Fragments	Oakland Time	Oakland Cloud Top Temp.
	1971:								
3	Dec 28	1900-2300	2159	-49	-49	21.8	-	1600	-24
	1972:								
6	Jan 25	0930-1030	1006	- 8	- 8	1.3	1.0		
7	Jan 25	1130-1230	1243	- 4	- 6	16.7	.7		
8	Jan 25	1300-1830	1550	- 5	- 5	14.6	.8		
10	Jan 27	0830-1200	0958	-17	-17	6.4	2.8		
11	Jan 27	1300-1700	1248	- 3		10.2	3.5		
12	Mar 22	0630-1030	0702	-12	- 7.5	16.4	.1		
13	Mar 22	1200-1300	1009	- 3		5.8	1.4		
14	Mar 22	1300-1400	1316	-19	-19	66.4	-		
15	Mar 22	1430-1630				3.0	.8		
16	Apr 5	1100-1200	0950	-27	-28.5	1.1	.1		
17	Apr 5	1330-1430	1558	-30	-28.5	2.8	1.2		
18	Apr 5	1500-1700	2152	- 6	-30	17.4	.2	1600	-21
19	Apr 11	0900-1200	0958	- 4	- 4	78.4	1.2		
20			0355	-23					
	Apr 12	0630-1200	0955	-14	-14	28.8	.7		
21	Apr 12	1200-1630	1255	- 9	-12.5	157.7	.3		
			1552	-16					
22	Apr 12	1700-1800				73.5	1.9		
23	Apr 12	2100-2200	2152	-10	-10	513.0	0		
Sample 2	1973:		Tamarack						
				80% RH					
			1011	-39					
			1313	-32					
1	Jan 29	1000-1530	1502	-28	-25	2.1	1.0		
2	Jan 29	1530-2000	1804	-16	-25	7.1	.2		
			2159	-29					

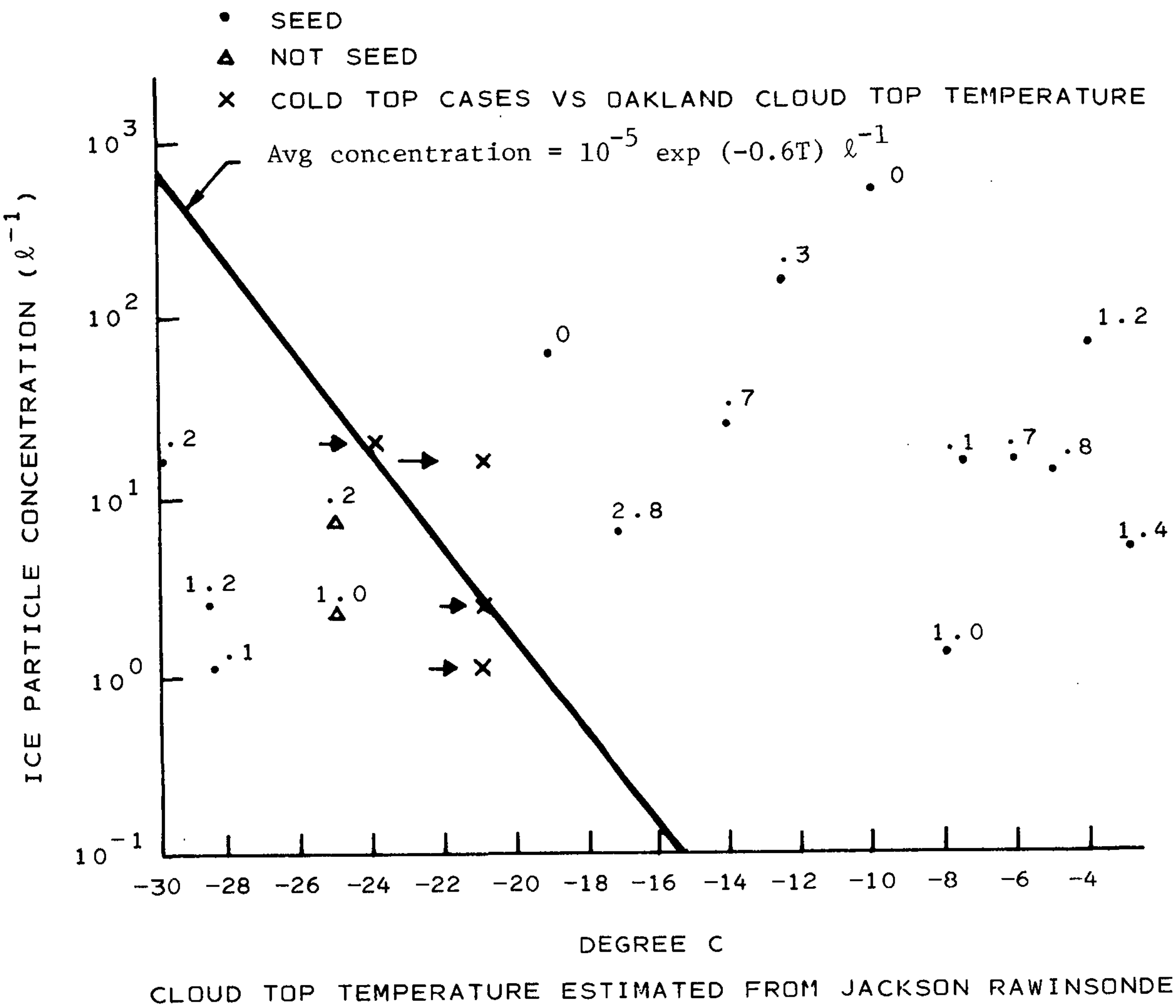

Fig. 4 CENSARE ice particle concentrations vs cloud top temperature.

We interpret Figure 4 as presenting strong evidence that seeding increased the particle concentration on all seeded storms except perhaps the two coldest ones. Also, analyzed in this manner, we find no evidence of multiplication during the not-seeded storm. The low concentrations indicated for the two cold cloud top storms we believe is a result of using the cloud top temperature determined from the Jackson sounding instead of a cloud top temperature further upwind. In regard to observing few crystals in the colder crystal habit formation temperature range during seeding, Reinking (1975a, p 89) notes that "crystals were therefore too far upwind and/or too far above the seeding generators to allow for nucleation from seeding with corresponding fallout in the target area. Most of the crystals of these types could have fallen out farther downwind, or they could have blown entirely over the mountain barrier and sublimed". We argue that this may occur in the natural case as well. If the concentrations for the two coldest storms are plotted versus the Oakland cloud top temperature (provided by Don Griffith), they appear as the X's in Fig. 4.

Although the ice multiplication process may be a factor in some storm systems over the central Sierra Nevada, analysis of ice particle concentrations versus cloud top temperature does not indicate it to be a factor in the one not-seeded storm sampled.

4. ICE MULTIPLICATION IN THE CASCADES?

In an article by Hobbs (1975b) ice multiplication is suggested as the cause of the frequent observation of high ice particle concentrations over the Cascade Mountains of Washington. Cloud formations for a detailed case study, January 31, 1972, are described by Hobbs (1975c, p 822) as follows: "During the period 1130 to 1300 PST the cloud formation over the Cascade Mountains consisted of extensive layered stratus and stratocumulus with bases near 0.9 km on the western slopes to 2 km over the mountains. The tops of these clouds were reported at 2.6 to 2.9 km. A second distinct layer of altocumulus had its base at 3 km and was approximately 0.6 km thick. A thin cirrus layer near 6 km was also observed. During the period 1300 to 1600 the two cloud layers with cirrus overhead persisted; however, some changes in cloud structure were evident. The lower deck became more cumuliform, as evidenced by the ground and airborne observations, and complete glaciation of the upper layer was observed at times from the aircraft". Plotting the temperature data for 1600 January 31, 1972 in Hobbs' Figure 2 (Hobbs, 1975c, p 820) on a pseudo-adiabatic diagram we obtain a temperature of -30°C for the 6 km level. The number of ice forming nuclei at this temperature determined from the formula for the average number given in Section 2 is 657 ℓ^{-1}. If the temperature of the cirrus layer was actually 0.5°C warmer, the number of ice forming nuclei, determined from the formula for the average, would approximate the 450 ℓ^{-1} of ice particles measured (Hobbs and Radke, 1975, Table 1, p 812). The suggestion here is that natural seeding may have been occurring from the higher cirrus layer. Dr. Radke has said, however, that considerable effort was expended on the Cascade Project to determine if natural seeding from above could account for the high ice particle concentrations observed and that, except for a few cases, they were unable to do so. He believed that had crystals been falling from the cirrus layer in the above case that they would have been observed. Is it not possible that we do not yet fully understand all of the details of the microphysical interactions between cloud layers?

Cirrus seeding of a lower cloud layer has been reported by Braham (1969), and Braham and Spyers-Duran (1967) observed that some crystals from cirrus survived falls through clear air up to 5 km. Burrows and Robertson (1969, p 1340) in their analysis of data collected in the Cascades infer ice multiplication although they note that the high ratio of concentrations of ice crystals to freezing nuclei could possibly be explained by natural seeding. We quote the following from their article:

> "At least one other possible explanation of this high ratio should be added to the multiplication process. That is the effect of higher level (colder) clouds on seeding the lower level ones. In the higher clouds, all nuclei effective at temperatures warmer than, say, -30C, will form ice particles. If the particles fall into a lower cloud whose top temperature is -20C, all (assuming no particles are lost due to evaporation) these crystals will be included

in the ice crystal concentration, but the number of nuclei will be assumed to be only those effective at -20C or warmer. Those nuclei effective between -20 and -30C will not be included because of the choice of cloud top temperature. Hence, more crystals than nuclei are indicated. In all the cases presented here, the vapor densities with respect to ice were calculated for each sounding, the results indicating the possibility of higher clouds, usually in the -30C region."

A greater understanding of the ice multiplication process and microphysical interactions between cloud layers is needed. This is needed for a better definition of seeding potential in an area, and also for providing inputs for operational and evaluation procedures. We agree with Dr. Radke that "...all of the circumstances behind 'high ice crystal concentrations' should receive priority attention...".

5. CONCLUSIONS

Although ice multiplication may be a prominent factor in the cloud physics processes in some clouds, we do not find supporting evidence that it is a prominent factor in orographic clouds of the San Juan Mountains of Colorado and the Sierra Nevada of California. We have shown that the theoretical number of ice nuclei formed at cloud top temperature agreed favorably with the number of ice particles observed in the few natural clouds sampled in the San Juan Mountains. The limited data for the Sierra Nevada suggests the same conclusion. In three cases higher concentrations than expected at the cloud top temperature were attributed to natural seeding from a higher cloud layer.

Interpretations from analysis comparing ice particle concentrations to cloud top temperature are opposite to the interpretations from analyses comparing ice particle concentrations to sampling level temperature or crystal habit formation temperature.

We conclude that the interpreatation of ice particle concentration data is dependent on the analysis technique employed and that cloud top temperature remains the most useful tool available in the interpretation of these data.

This analysis has been completed as a portion of our on-going basic analysis of the Colorado River Basin Pilot Project under contract with the U.S. Department of the Interior, Bureau of Reclamation, Division of Atmospheric Water Resources Management.

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