ICE MULTIPLICATION IN THE SIERRA NEVADA?--A REPLY

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INTRODUCTION

Is ice multiplication a prominent factor in orographic precipitation? Shaffer and Elliott (1976) have addressed this question by reanalyzing data from publications by P. V. Hobbs and colleagues for the San Juan Mountains and the Cascades (see references in Shaffer and Elliott, 1976) and data from Reinking (1973; 1975 a,b) for the Sierra Nevada. Shaffer and Elliott were kind to forward an advance copy of their manuscript with a request for comments. The comments here question the reanalysis and consequent conclusion in their paper regarding the possibility of ice particle multiplication in the Sierra Nevada. P. V. Hobbs will presumably present his own response to criticisms of his studies in the San Juan Mountains and the Cascades.

CLOUD TOPS, CRYSTAL HABITS, AND VERTICAL MOTION

The concepts of snow particle multiplication are open to question and should be subject to scrutiny from both fresh and renewed points of view. In a renewed effort to substantiate the physical significance of cloud top temperatures, Shaffer and Elliott (1976) postulate that natural ice crystal nucleation can account for concentrations of snow crystals observed during non-seeded snowfall in the Sierra Nevada. This hypothesis is reasonable. However, these investigators ignore some pertinent physical evidence. Also, on the basis of data replotted with some new and critical points that are totally arbitrary, they conclude, "We have shown that the theoretical number of ice nuclei formed at cloud top temperature generally agrees favorably with the number of ice particles observed in natural clouds in the San Juan Mountains. The limited data for the Sierra Nevada suggest the same conclusion."

First, note that Shaffer and Elliott use an approximate worldwide mean temperature spectrum for ice nucleation as their baseline for comparison, i.e., ice crystal concentration $N(\ell^{-1}) = 10^{-5}\exp(-0.6\ T)$ for T in degrees centigrade.* It is perhaps academic that this spectrum is empirical, not theoretical as they propound. Not so academic are the facts that (1) complexities of nucleation on background particles have precluded development of reference spectra that are truly theoretical and independent of empiricism, and (2) very sufficient evidence exists in the literature to show that the "average" spectrum can often be meaningless as a reference, especially in individual case studies. If "excessive" snow crystal concentrations do occur, they may well be due to greater than average nucleation on background particles, rather than to ice multiplication (Reinking, 1975 b; Mossop, 1963).

* Shaffer and Elliott (1976) are thanked for noting that the equation for the line spectrum presented in their Figure 3, from Reinking (1975 b), is in error. The factor of 10^{-5} in the equation should be 10^{-6}; the equation is presented correctly in Reinking (1973).

Assume for the sake of discussion that Shaffer and Elliott are correct in applying the mean spectrum for natural nucleation to the cited cases of Sierran snowfall. Specifically, S¢haffer and Elliott "postualte 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." The ice particle concentrations at any given level will indeed represent the particles nucleated in the vicinity of that level plus those accumulated there by mixing processes, and by settling from higher and colder levels. Therefore, when wind regimes permit, concentrations at a specific level below cloud top will presumably exceed those nucleated in situ, and numbers of crystals from levels of more prolific nucleation nearer cloud top will dominate. However, evidence in the form of snow crystal data presented by Reinking (1973) conclusively demonstrates that ice crystals at a given level in-cloud or at cloud base do not always include crystals from the higher and colder levels in prevailing clouds; high winds in upper cloud levels sometimes combined with limited spatial extent of the clouds, apparently can keep separate the trajectories of crystals nucleated in upper and lower parts of the cloud systems.

Shaffer and Elliott have reanalyzed data from the non-seeded Sierran snowstorm of 29 January 1973. This was a case with (a) cold cloud tops over the snow crystal sampling site ($T_{top} \lesssim -28°C$ in clouds above the 7,000-8,000 ft elevation, except during a sounding at 1804 PST when $T_{top} \simeq -16°C$), but (b) a distinct lack of fallout of the types of regular snow crystals representing the cold cloud tops (see Table 3, precipitation episodes numbers 24 and 25, Reinking, 1975 a). Shaffer and Elliott (1976) arbitrarily assume a cloud top temperature of -25°C over lower elevations upwind of the crystal sampling site. This assumption is hazardous. The actual cloud tops may have been much warmer or much colder; spatial and temporal variations of cloud tops in the Sierra are very substantial (Reinking, 1972). Total snow crystal concentrations for these episodes, from Reinking (1973, 1975 a) are arbitrarily plotted at -25°C in their Figure 4, and their conclusion for the Sierra Nevada is based on these points. The points could have been plotted at any other temperature between about -15 and -40°C with equal confidence, considering observed snow crystals and the natural cloud top variability.

Shaffer and Elliott have ignored the significance of the growth habits of the observed crystals, which provide the best physical information available. Snow crystals with growth habits representing cloud temperatures colder than -16 to -18°C were not found in significant numbers in precipitation at the sampling site. The only regular, colder region crystals observed were radiating assemblages of plates and dendrites, representing cloud temperatures near -20°C, which precipitated in concentrations of only 0.1/ℓ during one of the two non-seeded episodes within the storm. Snow crystals with growth habits representing cloud temperatures warmer than -16 to -18°C precipitated in concentrations exceeding the "average" spectrum for background nucleation, at corresponding temperatures, by one to four orders of magnitude (Figure 2, Reinking, 1975 b, reproduced as Figure 3 in Shaffer and Elliott. 1976).

The snow crystal work of Nakaya, Magono, Weickmann, Shaffer, Mason, Fukuta, and others shows that there is a positive correlation between temperature of initial crystal growth and habit (shape) of crystal growth (e.g., see Magono and Lee, 1966). Also, crystals grow with sufficient rapidity to develop recognizable habits within 1-3 minutes after nucleation, provided that cloud saturation is maintained; this is common knowledge based on experiments and quantitative theory of crystal growth rates. This factor ties the primary growth habit to temperatures near that at the level of nucleation; i.e., an imprecise but still restrictive correlation exists between temperature of nucleation and crystal habit.

The conclusion of Shaffer and Elliott, combined with the argument they present to support it and the existing physical evidence, requires that ice crystals nucleated at the cold temperatures near the surmised cloud top must settle or be transported thousands of feet down to warmer levels without growing sufficiently to develop recignizable habits. This phenomenon would be followed by crystal growth with development of the observed, relatively warm-region habits. This sequence does not appear to be possible. For example, the needlelike crystals (Group N, Figure 3, Shaffer and Elliott, 1976), which grow between -5 and -8°C, were observed in concentrations of 5.5/ℓ during the non-seeded storm. Note that this concentration is an average over a four and one-half hour sampling period. To account for these crystals, the necessary rapid transit mechanism would have had to carry the bits of ice, nucleated at the colder temperatures, in a very sustained downdraft at a rate well in excess of 2,000 ft/min (10 m/sec) over a vertical distance of 10,000 ft--from about 18,000 ft to about 8,000 ft. Convection is common in the Sierrian storms, but vertical motion of the required strength and persistence seems highly unlikely.

Also, a 2,000 ft/min rate of descent would still allow the ice particles 5 minutes to grow before reaching the needle regime; and the ice particles would have to pass through the dendrite regime without developing the dendrite habit. The dendrite regime is around -15°C where growth rate and development of habit are much faster than in the needle zone. Dendrites will grow to diameters of 200-400 μm in just 2-3 minutes.

Finally, if tiny ice particles were transported so rapidly, why were larger crystals from colder cloud top regimes not also transported and precipitated? The largest possible concentration of crystals with recognizable and irregular habits that could have represented regimes colder than about -18°C in the non-seeded storm totaled only 0.5 to 1.1/ℓ (Table 3, precipitation episodes 24 and 25, Reinking, 1975 a). In total, a rapid transit scheme to explain the high concentrations of snow crystals from the relatively warm levels is very difficult to accept.

CONCLUSION

Ice multiplication in the Sierra Nevada? Possible. Background nucleation well in excess of the worldwide "average" is also possible, since day-to-day variations in concentrations of ice nuclei active at a particular temperature may vary by several orders of magnitude (Mossop, 1963; Reinking, 1975 b).

The high concentrations of crystals observed in precipitation during the non-seeded storm of 29 January 1973 cannot be explained by nucleation at cloud top temperatures in quantities represented by the worldwide spectrum. This conclusion reached by Reinking (1973, 1975 b) still stands.

As for the seeded storms, the seeding itself certainly accounts for much of the significant concentrations observed. The simultaneous activity of significant background mechanisms cannot, however, be discounted, a priori.

Perhaps the most important problem facing purposeful weather modification is the explanation and prediction of concentrations of snow crystals in natural clouds. The initial need appears to be a project of sufficient scale to continuously monitor key physical factors that are now recognized. Our shortcomings to date have too frequently been in our piecemeal approach to monitoring even the parameters that we are capable of measuring. Many of the limiting factors have been practical rather than scientific. Some critical answers might be gained by pooling the resources of several research groups and intensively concentrating our efforts on selected volumes of the orogenic cloud systems.

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