Reply

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Finnegan and Pitter (1991), hereafter referred to as FP, correctly point out some errors we made in describing the seeding material used in an orographic cloud (Deshler and Reynolds 1990, hereafter referred to as DR). We were careless in describing both the combustion process and the nucleating aerosol produced in the combustion of the AgI NH_4I NH_4ClO_4 acetone solution used for seeding. This is true both in DR and in Deshler et al. (1990) where seeding effects from an experiment on 18 December 1986 are described, four days prior to the experiment described by DR, which used the same seeding material and procedure. In keeping with the results of DeMott et al. (1983) the nucleating agent used in DR and in Deshler et al. should have been stated as AgI–AgCl rather than as AgI NH_4I NH_4ClO_4. It is important to reiterate that it is this AgI–AgCl aerosol that provides the improved ice nucleating properties at the warmer temperatures as FP point out.

We do, however, take issue with FP concerning the mechanism for production of the regions of enhanced ice crystal concentration (ICC), which were observed 60–90 min after seeding. Based on the width of the regions of increased ICC, DR calculate a dispersion rate of 1.3 m s^{-1} for the seeding material, directly comparable with other similar measurements (Hill 1980). To suggest that these regions of high ICC have occurred naturally requires an explanation of why the effect would be limited to such a local region. In particular, there is no reason to expect natural ice nuclei to be confined to such a small region. Ice multiplication, on the other hand, may occur in a small region of cloud where the conditions are appropriate. There were many instances during the Sierra Cooperative Pilot Project (SCPP) when ice multiplication processes were measured (an example is given by Deshler et al. 1990); however, in all cases the width of the region of high ICC implied dispersion rates of more than 4 m s^{-1}, assuming the ice crystals originated at the location of seeding. This dispersion rate is much higher than has been measured during this or other seeding experiments. In addition at 60 min after seeding on 22 December 1986 the ice crystal habits, cloud-droplet sizes, and temperatures were not appropriate for a Hallett and Mossop (1974) ice multiplication mechanism, the type most commonly observed during the SCPP. Based on the 2D-C images collected 60–90 min after seeding on 22 December 1986, the regions of increased ICC were composed of small plates and rimed particles, whereas the surrounding ice crystal regions were dominated by larger dendritic crystals, singly and in aggregates. Needles, which may be expected from a Hallett–Mossop ice multiplication mechanism, were not observed. Given the coexistence of the regions of increased ice nuclei and ice crystal concentration, and that the widths of the regions of increased ICC are comparable to other measurements of seeded plumes (Deshler et al. 1990; Hill 1980), the most straightforward conclusion is that the increases in ICC are a direct result of seeding.

It is a more difficult matter to identify the primary or for that matter the multiple nucleating mechanisms that may have occurred during the experiment described by DR. We agree with FP that during the first 5 to 12 min after seeding there is no indication of seeding effects. These observations are consistent with contact nucleation as the nucleating mechanism, since only 1 l^{-1} of ice crystals should be observed after 10 min from seeding in a cloud of 100 cm^{-3} of 5-μm cloud drops (Slinn 1971), assuming dispersion rates for the seeding material of 1 m s^{-1} horizontally and 0.1 m s^{-1} vertically. (The 40 l^{-1} of ice crystals calculated by DR was based on these same dispersion rates, but assuming that 80% of the ice nuclei had activated without regard to the details or timing of the mechanism.) After 60 min, however, a seeding effect is apparent and the

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increases in ICC attributable to seeding may be 10–20 l^{-1}. An estimate of the ICC expected due to contact nucleation at this point is only 5 l^{-1}, and in fact may be even lower since for this calculation a droplet concentration of 100 cm^{-3} was assumed, whereas the droplet concentration in the cloud after 60 min was 10–15 cm^{-3}. As FP observe, the small particles observed coincident with the ice nucleus regions here probably nucleated, or at least began growing, only within the previous 5–15 min, so this lower droplet concentration may be more appropriate for calculation of the ice nucleus scavenging rate. This lowers the ICC resulting from contact nucleation to less than 1 l^{-1}, much less than the ICC observed. Thus, we believe there are substantial reasons to doubt that the AgI–AgCl ice nuclei used here functions only by contact nucleation in the field. This is different than the conclusions reached by DeMott et al. (1983) based on laboratory measurements.

We can only speculate concerning the nucleation mechanism for these ice crystals. Perhaps a turret of rising air coincident with the ice nuclei plume created enough water supersaturation to allow the AgI–AgCl to act as condensation freezing nuclei; or perhaps there were embryonic crystals nucleated shortly after seeding due to forced condensation freezing (Finnegan and Pitter 1987), which only lately had experienced enough ice supersaturation to begin growing. The field measurements are not detailed enough to determine the exact conditions and rates of ice crystal nucleation within the seeded plume and thus determine the mechanism of ice crystal nucleation. We do feel, however, that these measurements combined with those of Deshler et al. (1990) are enough to suggest that these regions of enhanced ICC were generated by seeding and that more than one nucleating mechanism was operating in these cases. It remains for future experiments to better document the exact nucleating processes occurring.

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