Reply

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Schaefer and Vonnegut (1986) correctly point out that the description of seeding methodology in Huggins and Rodi (1985) lacked some of the details necessary to completely evaluate the dry ice seeding procedures used in the experiment we described. One of our original references (Bureau of Reclamation, 1983) does describe the design of the experiment much more fully, including the seeding agent and seeding procedures. Also, Stith (1984) made calculations of dry ice effectiveness in clouds seeded as part of the Sierra Cooperative Pilot Project (SCPP), where similar methods and dry ice seeding rates were used. Depending on the type of instrument used to determine ice crystal concentration, Stith computed dry ice efficiencies ranging from 9.8×10^{11}–1.5×10^{13} crystals per gram of sublimated dry ice.

Specifically, during the experiment on 19 January 1983 (Huggins and Rodi, 1985), cylindrically shaped dry ice pellets were dispensed from the bottom of the seeding aircraft using an auger-type mechanism. The pellets were formed by an extruding process, had a consistent diameter of 1.5 cm, but varied in length from 1.5–2.5 cm. The most common pellet was about 1.5 cm in length and had a mass of about 3.5 g (density of 1.4 g cm^{-3}).

A week prior to the seeding experiment on 19 January, some dry ice drop tests were performed. Pellets were dropped from eight evenly spaced altitudes varying from 300–2400 m above the ground. The time of fall was measured at each altitude and the resultant average fallspeed estimate was 20 m s^{-1} (± 1 m s^{-1}). Pellets were observed to hit the ground or a lake surface from each altitude, although very few were observed from the 2400 m drop. As Stith (1984) reported, pellets were collected and sized after fall. For a fall of 1500 m, which required about 76 s, the pellets collected were about 50% of their original size. For a 3.5 g pellet this would correspond to a sublimation rate of 2.3×10^{-2} g s^{-1}. This is in reasonable agreement with the calculations of Holroyd et al. (1978) who used an empirical relationship from Eadie and Mee (1963). The equation predicted a sublimation rate of 2.3×10^{-2} g s^{-1} for a pellet whose original mass was 3.5 g in an environmental temperature of $-5°C$.

Seeding on 19 January occurred from $-13°C$ (3018 m MSL). The distance to the 0°C level was about 1820 m. The tests described herein indicate that pellets would have reached the freezing level after about 91 s, and about 60% of the original pellet mass would have sublimated. Huggins and Rodi (1985) quoted a seeding rate of 100–200 g km^{-1}. This was based on a hopper dispensing rate of 468–936 g min^{-1} at an aircraft airspeed of 78 m s^{-1}. The variability in the hopper rate was due to pellet size variation, some pellet aggregation and nonuniformity in the rate at which pellets were fed into the auger mechanism.

Huggins and Rodi (1985) made no estimates of the efficiency of the dry ice seeding on the 19 January experiment and attempt no detailed analysis here. A simple calculation is, however, provided as an example. Using a specific dispensing rate of 544 g min^{-1} and assuming 60% of the dry ice mass sublimated in falling from $-13°C$ to 0°C, the effective seeding rate for a 1 km wide cloud would be 70 g km^{-1}. Using data (PMS 1DC probe) found in Huggins and Rodi (1985) for seeded cell 1, the mean particle concentration in the seeding plume was about 350 l^{-1} at 2.5 min after seeding. Assuming the plume was vertically uniform, the cloud volume affected was about 1.8 km deep, 1 km long and 450 m wide. Liquid water probe data suggested the cloud was at least 1 km wide, so ice crystals had not filled the entire cloud volume. Dry ice efficiency is then estimated by multiplying volume by concentration and dividing by sublimated mass of dry ice. This example gives a value of 4×10^{12} crystals g^{-1} of CO_2. This agrees well with the value of 10^{12}–10^{13} crystals g^{-1} reported by Lawson and Rodi (1986) for clouds in Montana seeded using similar methodology to that of SCPP.

As Schaefer and Vonnegut point out, crystal production can be a function of pellet terminal velocity. Eadie and Mee (1963) showed a sharp drop in crystals produced at temperatures warmer than about −8°C by fast falling (~16 m s^{-1}) pellets. Morrison et al. (1984) also show that dry ice effectiveness is temperature dependent, with values ranging from 2.2×10^{11} crystals g^{-1} at −2°C to 8.9×10^{12} at −20°C. The example just given is therefore probably an overestimate since all concentration measurements in Huggins and Rodi (1985) were taken at about −8.5°C. Uncertainty in estimates of cloud volume or sublimated mass of CO_2 could increase or decrease the sample calculation by at least 50%.

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