On the Radar-Measured Increase in Precipitation Within Ten Minutes Following Seeding

JOANNE SIMPSON

Experimental Meteorology Lab., ESSA, Coral Gables, Fla.

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It will be shown using measurements, a numerical cumulus model, and physical reasoning that the radar-measured precipitation from a seeded cloud will increase markedly (relative to an unseeded cloud) within 10 min following seeding.

First it is important to bring out that the University of Miami 10-cm radar sees a layer ranging in height from 2000–9500 ft when the subject cloud is 55 n mi from the radar (Fig. 1, after Senn and Courtright, 1968) which was the mean distance of the seeded clouds in the experiment. The beam is thus centered at an elevation of ~5750 ft above ground at the cloud's range.

The reasoning in this note is illustrated schematically in Fig. 2. The case of cloud 6 on 16 May 1968 will be used in this illustration since it is completely documented by measurements, calculations and numerical modeling (Simpson and Woodley, 1969). The control cloud does not grow above the seeding level of 6 km (above cloud base). The top of the seeded cloud has reached 10.3 km after 10 min following seeding. The calculation to be presented will show that precipitation particles from level L in the seeded cloud will reach the radar beam center B in 10 min. The level L is 1 km above level l, the top of the unseeded cloud. Thus, in 10 min following seeding the radar will observe precipi-

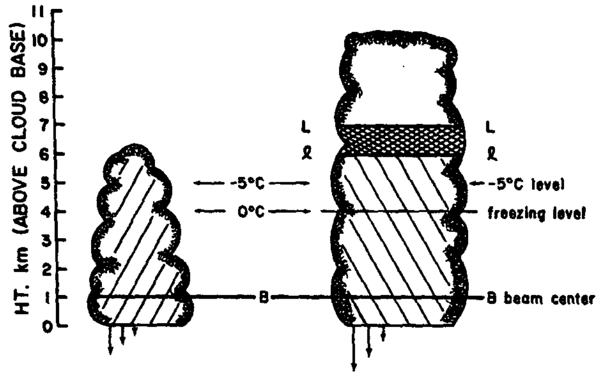

FIG. 2. Schematic illustration of the calculations for seeded (right) and control (left) clouds for a period 10 min after seeding.

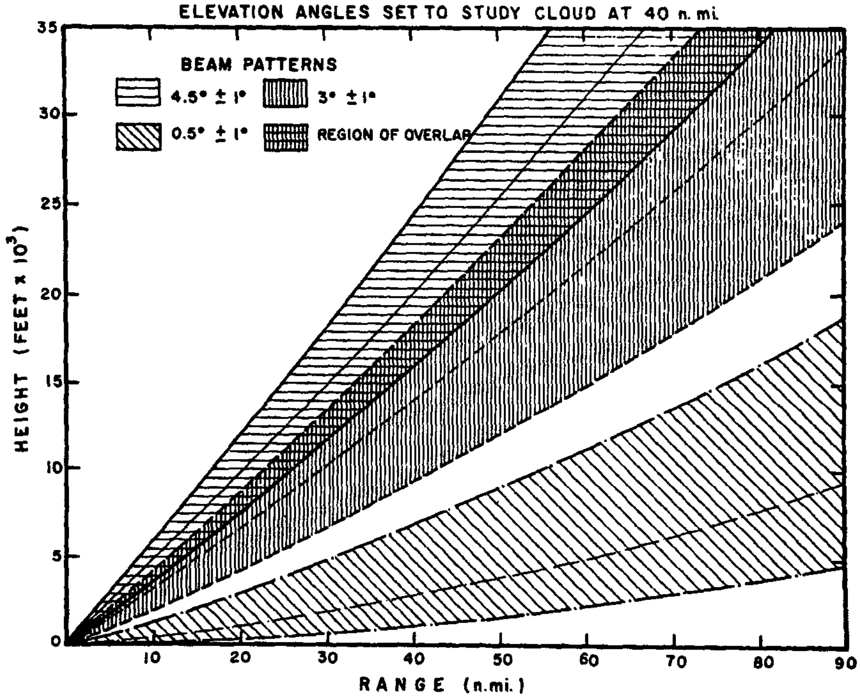

FIG. 1. 10-cm half-power beam widths at various tilts for a typical echo at 40 n mi (after Senn and Courtright, 1968).

TABLE 1. Velocity and fall time of precipitation.

Height interval above base (km)	Drop diameter (mm)	V_T (m sec^{-1})	$0.7V_{T1}$ (m sec^{-1})	$V+4$ (m sec^{-1})	Δt (sec)
7–6	1.2	6.59	4.61	8.61	116
6–5	1.5	6.94	4.86	8.86	113
5–4	1.9	7.42	5.19	9.19	109
4–3	2.3	7.78	7.78	11.78	85
3–2	2.7	8.07	8.07	12.07	83
2–B	3.1	8.22	8.22	12.22	82
					588 sec$<$10 min

tation from the layer *l-L* in the seeded cloud, which is above cloud top in the unseeded cloud and hence contributing no precipitation.

The cloud tower rises from *l* to *L* in 2–3 min following seeding, simultaneously dropping out an amount of precipitation calculated by our numerical model (Simpson and Wiggert, 1969). We will first show that precipitation originating at *L* can easily penetrate down to level *B* within 10 min. We have measurements of the volume median drop size of the precipitation at two levels[1], 5 km and cloud base. We assume a cloud water content of 0.8 gm m^{-3} in the cloud body, a conservative value. With this and a simple continuous collection equation we derive column 1 of Table 1, the volume median precipitation diameter as a function of height, as the particles fall through the cloud growing by coalescence. To calculate the terminal velocity of water drops we use

$$V_T = -130D^{\frac{1}{2}}\left(\frac{\rho_0}{\rho_z}\right)^{\frac{1}{2}}, \tag{1}$$

after Kessler (1965), where ρ_0 is taken as 1.2×10^{-3} gm cm^{-3}. The droplet diameter D is in meters and V_T in meters per second. This equation gives smaller values than Mason (1957) and hence is conservative. For ice particles we use the observation of Braham (1964) that the terminal velocity is 0.7 times that of water drops of equal mass. We neglect the small density difference he found between ice and water and we use the similarity of our ice formvar replicas to Braham's to apply the same ratio for our ice terminal velocity.

Finally, to complete Table 1 we assume a downdraft of 4 m sec^{-1} bringing the precipitation particles down. Aircraft measurements[2] in this cloud at about the 6-km level showed a downdraft of 4–5 m sec^{-1}. Generally, these downdrafts may be expected to increase downward (Malkus, 1955). Therefore, this is a conservative value. Byers and Braham (1949) found considerably larger downdrafts prevailing through a sizable portion of a typical mature thunderstorm. The total time required for a precipitation particle starting at 7 km to reach level *B* is just under 10 min.

We will next show that the amount of precipitation contributed to the radar measurement from the layer *L-l* in 10 min is large enough to account for the average measured rainfall difference between seeded and control clouds in the interval 0–10 min (Woodley, 1970). The latter amount is about 25 acre-ft or about 18% of the total average difference between seeded and control clouds of 140 acre-ft.

The EMB 68 numerical model gives a total fallout from the rising tower as 4.92 gm of water per kg of total mass for the unseeded tower and 8.72 gm kg^{-1} for the seeded tower for the case of this 16 May cloud. The layer *L-l* contributes 1.47 gm kg^{-1} or 39% of the difference between the seeded and unseeded fallouts. A simple cloud physics calculation in progress considers the growth of the fallout from the tower as it descends through the cloud body and the droplets grow by coalescence. This calculation shows that the final difference between radar-measured seeded and control rainfall is readily accounted for. Here we will only consider the 1.47 gm kg^{-1} contributed by layer *L-l*. Taking the measured volume of the tower and multiplying by the appropriate density, we get 7.2×10^9 gm of precipitation starting its descent between level *L* and level *l*. The drops have the sequence of diameters shown in Table 1 so that the mass increment in each layer is proportional to the ratio of diameters cubed. With this, we find that if half the precipitation in the layer *L-l* is caught in the downdraft we produce 109 acre-ft of rainfall at cloud base. If only 15% of the fallout in layer *L-l* is caught in the downdraft and carried to cloud base, we get the 25 acre-ft measured difference between average seeded and average control cloud in the interval 0–10 minutes following seeding.[3]

In conclusion, we note that none of this reasoning depends on an invigorated downdraft in the seeded relative to the control cloud. If the downdraft in the seeded cloud is enhanced relative to the control cloud, we would expect a faster response and a bigger response in seeded vs control rainfall soon after seeding. There is reason to expect the downdraft would be enhanced in the seeded cloud concomitantly with its updraft. Seeding has been shown to increase the updraft throughout the cloud body in a very few minutes. In laboratory plumes an accelerated updraft at the core is accompanied by accelerated downdrafts at the outer edges.

Finally, the important point to emphasize is that pyrotechnic seeding fills the whole supercooled depth of the cloud with silver iodide and hence rapidly freezes

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[1] Values for higher levels have been taken from the numerical model. Its drop size predictions have checked very well with observations whenever direct checks have been possible.

[2] The downdrafts were calculated by Mr. R. Sheets (personal communication), using the radar altimeter and the aircraft attitude, power setting, etc., to calculate its sinking speed.

[3] This 16 May cloud produced a total of 850 acre-ft in the first 40 min after seeding, compared to only 26 acre-ft in a comparable period by a control cloud. Hence, the first 10 min after seeding can readily contribute 13% of the difference according to this calculation.

all the cloud existing above −5C. We have shown that the precipitation contained in a layer 2 km deep above −5C reaches the center of the radar beam within 10 min after seeding.

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