THE EFFECT OF SILVER IODIDE SEEDING ON HAILSTONE SIZE DISTRIBUTIONS

JEAN DESSENS
Laboratoire d'Aérologie, Université de Toulouse, 65300 Campistrous, France

ROBERTO FRAILE
Laboratorio de Física de la Atmósfera, Universidad de León, 24071 León, Spain

Abstract. The hailpad data collected in the ANELFA operational area of southwestern France where hailstorms are extensively seeded from silver iodide ground generators show that hailstone size distributions are modified by the seeding. In the more heavily seeded hailfalls, the number of hailstones with diameters larger than 0.7 cm is decreased, while the number of small precipitation elements (melted or not) is increased; this results agrees with the physical hypothesis of the seeding process. As a consequence, the mean kinetic energy of the more seeded hailfalls is reduced by about 40%, which confirms a previous physical evaluation of the ANELFA project made with a lower number of hail seasons.

1. INTRODUCTION

The acceptance by the atmospheric community of the idea that hail prevention by cloud seeding could be efficient is a long process (World Meteorological Organization 1996, American Meteorological Society 1999). The reason is certainly that seeding effects are slight compared to natural fluctuations of hailfalls. However, during these past years several hail prevention projects have lead to significant results in Greece (Rudolph et al. 1994), Bulgaria (Simeonov 1996), the United States (Smith et al. 1997), France (Dessens 1998) and Argentina (Makitov 1999). In these projects, the number of experimental years has probably reached a level where the seeding effect overshoots the natural background, and it will be interesting to check if the significance of the results increases with the number of operational years.

The ANELFA hail prevention project which operates silver iodide ground generators in 15 departments of France has conducted three more seasons of hailstorm seeding since the last result analysis (Dessens, 1998), and the number of significant hailfalls recorded by the hailpad network has increased from 987 to 1323. It is then possible, not only to update the results already published, but also to go deeper into the physics of the seeding effect by computing the hailstone size distribution for different levels of seeding.

2. SUMMARY OF PREVIOUS RESULTS

The ANELFA field activities take place each year from April to October in the hail regions of southern France and in the Loire valley. The departmental ground generator networks, operated by volunteers (essentially farmers and wine growers) are ready to run on a mere warning after a hail risk forecast. In principle, the warning is given four hours in advance by the meteorological services, then transmitted to the emitting stations through a computerized telephone system. The generators emit their smoke from the burning of an acetone silver iodide solution and the ice forming particles scatter in the storm development areas. Emissions last until the end of the hail risk period, a warning having an average duration of about ten hours. The detailed characteristics of the generators and of the solution can be found in the yearly leaflets of the ANELFA (1953 to 1999).

About 20 years ago, the ANELFA first noted that the damage recorded by the hail insurers was weaker in the departments equipped with generators than in the surrounding regions (Dessens 1986). Around 1988, in order to check this observation with physical measurements, networks of hailpads were added (Dessens and Fraile 1994). After about ten years of operation of these networks, a sufficient number of hailfall observations was available to enable comparisons between the operation of the generators and the hail intensity (Dessens 1998). The correlations between the generator emission data and the measurements by the hailpads show that, in a statistically significant way, the number of hailstones bigger than 0.7 cm in a point hailfall is inversely proportional to the quantity of silver iodide scattered by the generators in the area where a storm develops about 80 minutes before the hailfall (Fig. 1). The area of storm development, for which the opposite correlation between seeding and hail is

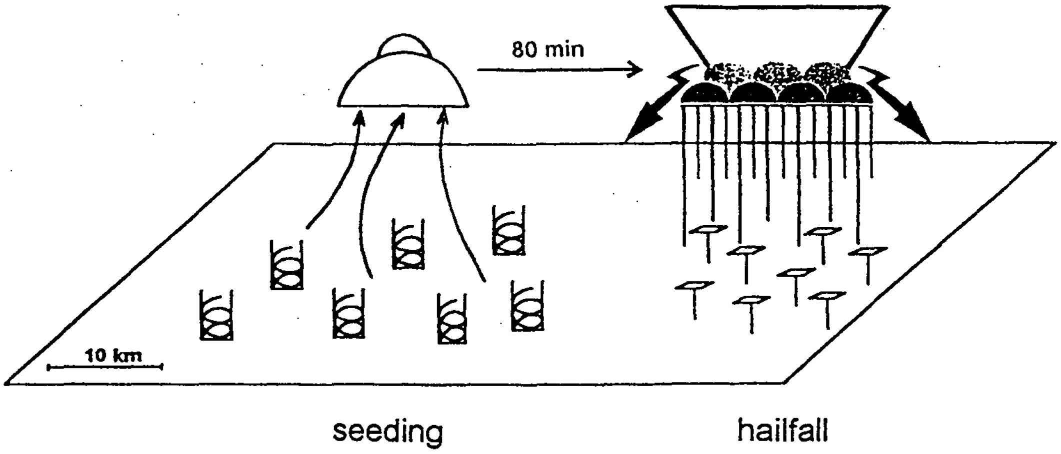

FIG. 1: Hailstorm seeding with silver iodide ground generators. In southwestern France, a decrease in the hailstone number is observed in hailfalls located at a distance corresponding to about 80 min of storm travel from seeded areas.

found to be maximum, is a circle having a diameter of about 26 km. When the storm propagation is not determined from radar data or hailfall time, it is evaluated from the wind at the 600-hPa level, assuming the storm motion propagates with a deviation of about 31° to the right and a speed reduction of about 18%.

A sound difference in the seeding effect is associated with differences in the daily mean amount of seeding. The seeding efficiency increases from 16 to 30% when the seeding increases from 23 to 39 g h^{-1} of silver iodide per 531 km^2. A maximum efficiency of 42% is found for the highly-seeded hailfalls (mean seeding of 50 g h^{-1}, corresponding to 11 generators per 1000 km^2).

3. HAILSTONE SIZE DISTRIBUTIONS FOR DIFFERENT SEEDING AMOUNTS

The results summarized above were relative to the total number of hailstones larger than 0.7 cm which are recorded on each hailpad. The hailpad data are much more pregnant with information, since the number of hailstones is determined in ranges of diameters increasing by 0.2 cm (or 0.4 cm above a 1.7 cm diameter). It is then possible to look for possible hailstone size distribution differences as a function of the amount of seeding delivered to hail cells.

Hailstone size distributions are of course very sensitive to different environmental parameters, mainly among the depth of the lower atmosphere in which hailstone melting occurs. If the classical exponential form:

$$N_D = N_0 \, e^{-\lambda D} \quad (1)$$

is used to represent the size distribution (Fraile et al. 1999), significant correlations are found between the altitude of the 0°C level, $h_{0°C}$, and both parameters N_0 and λ of the distribution (Dessens et al. 1996). It is then possible to compute a distribution normalized by $h_{0°C}$, but not by the other parameters (cloud condensation and ice forming nuclei, atmospheric stability index, environmental wind, etc.). As a consequence, it is difficult to draw conclusions about an effect of seeding on the hailstone size distribution by comparing daily distributions.

In order not to depend on the changing daily environmental conditions, a differential method similar to that developed for the evaluation of the mean intensity of hailfalls as a function of the seeding (Dessens 1998) is proposed. This method consists of computing two mean hailstone distributions for each hail day where these distributions are dependent on the hailfalls associated with below or above average seeding.

From 1988 to 1998, 900 hailfalls with hailstones larger than 1.0 cm were recorded on 108 seeded days. The size distribution of each hailfall is determined from the hailpad dents, and the amount of silver iodide, S_i, delivered per hour in a 531 km^2 circle relative to the storm's central position 80 min before hailfall time as determined by the generator station data. The number of documented hailfall positions reduces to 768 for the 66 days with a mean value of S_i greater than 0 (at least one hail cell was really seeded), and with at least two hailfalls observed. For these 768 hailfalls, 474 were seeded less than average ($S_i < S_m$), and 294 were seeded more than average. Table 1 gives the mean distributions for these two sub-samples of hailfalls.

TABLE 1. Mean hailstone numbers (m^{-2}) in different ranges for two samples of hailfalls. The same 66 hail days are represented in the two samples.

Range (cm)	474 hailfalls seeded less than average (5.6 g h^{-1})	294 hailfalls seeded more than average (46.3 g h^{-1})
0.5-0.7	1592	1640
0.7-0.9	636	627
0.9-1.1	291	245
1.1-1.3	129	98
1.3-1.5	57	39
1.5-1.7	26	17
1.7-2.1	21	15

The distributions are not very different, but large hailstones are less numerous in the more heavily seeded hailfalls. The Mann-Whitney U Test, applied in each range of diameters for the two sub-samples, indicates that the difference in the sample means is statistically significant at the 0.05 level in the 1.1-1.3 cm range.

The number of point hailfalls in each of the two sub-samples considered above are notably different due the fact that for days with low mean seeding, there are several unseeded hailfalls, and just a few with a small amount of seeding. As a consequence, there may be an unbalance in the computation of the exponential forms, more hailfalls of a same day being used in the first sub-sample than in the second one. This problem can be almost resolved by considering only the days for which the mean seeding exceeds a minimum level. Table 2 gives the distributions for the days with $S_m > 20$ g h^{-1}, and the Mann-Whitney U Test indicates that the difference in the sample means is now statistically significant in the 0.9-1.7 range. It is then possible to compute two different exponential forms for the less seeded hailfalls and for the more seeded ones. The computation is made without the first diameter class (0.5-0.7 cm) for which the number of hailstones is not determined with sufficient precision by the hailpad method, and without the classes above 1.5 cm for which the number of hailstones per hailpad is low. The results obtained with the number of hailstones in the 0.7-1.5 cm diameter range give the following exponential forms :

$$N_D = 89.660\ e^{-4.00\,D} \qquad (2)$$

for a mean seeding amount of 12.4 g h^{-1} per 531 km^2

$$N_D = 165.980\ e^{-4.92\,D} \qquad (3)$$

for a mean seeding amount of 59.3 g h^{-1} per 531 km^2.

TABLE 2. Same as Table 1, but for 32 hail days with important seeding.

Range (cm)	186 hailfalls seeded less than average (12.4 g h^{-1})	170 hailfalls seeded more than average (59.3 g h^{-1})
0.5-0.7	1485	1588
0.7-0.9	716	642
0.9-1.1	336	247
1.1-1.3	151	89
1.3-1.5	65	34
1.5-1.7	26	16
1.7-2.1	18	15

The number of hailfalls is nearly the same in the sub-samples, so that each hail day is about equally represented in the two distributions. Fig. 2 gives a graphical representation of these distributions.

4. COMPUTATION OF A SEEDING EFFICIENCY AND PHYSICAL IMPLICATION

The kinetic energy of a D diameter hailstone is:

$$e_c = 4.48 \times 10^{-2}\ D^4, \qquad (4)$$

with e_c in joule and D in cm (Dessens and Fraile 1994). The integration between D = 0 and D = ∞ of this expression combined with equation (1) gives the total kinetic energy of the hailfall:

$$E_c = 1.08\ N_0/\lambda^5. \qquad (5)$$

The distributions relative to the days with significant seeding give E_C = 94.7 J m^{-2} and E_C = 62.1 J m^{-2} for mean seeding amounts of respectively

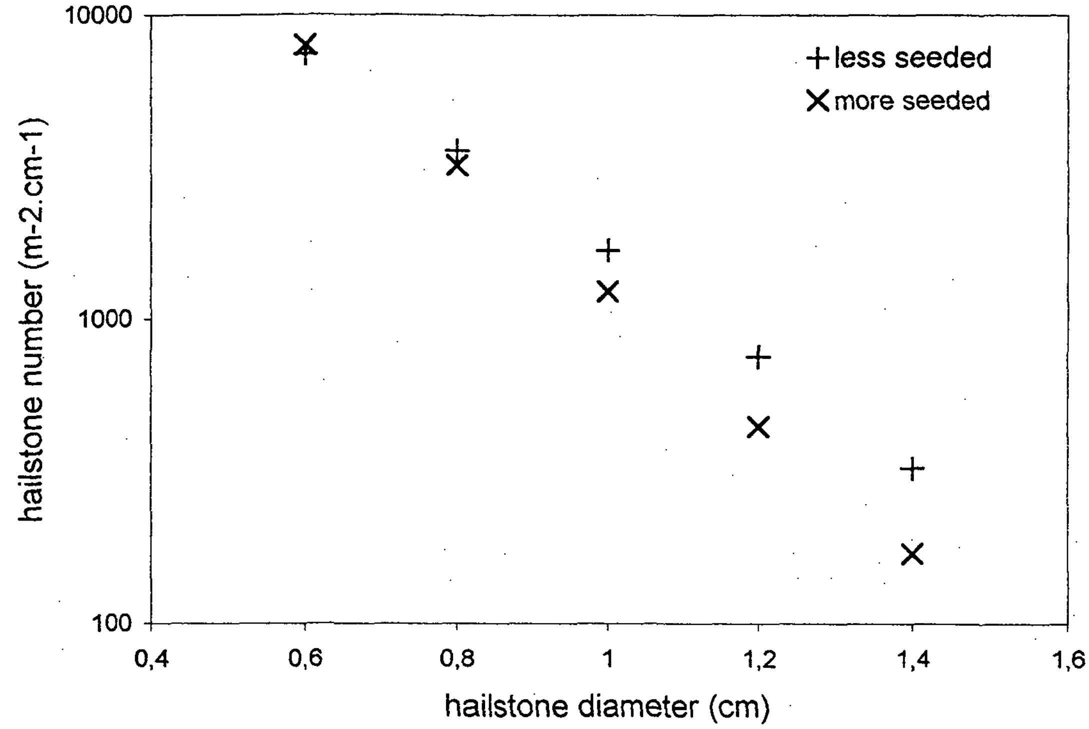

FIG. 2: Hailstone size distributions for the less seeded and the more seeded hailfalls of a sample of 32 hail days.

12.4 and 59.3 g h^{-1}. Assuming that the kinetic energy decrease is in linear relation with the seeding, the seeding efficiency is 40% for a seeding amount of 59.3 g h^{-1}. This result is comparable to that computed in a different manner for the 1988-1995 period (Dessens 1998).

It can be concluded from Eqs (2) and (3) that the seeding significantly reduces the number of hailstones larger than 0.7 cm, but increases the number of the smallest ones. In consequence, the total number of precipitation elements (melted or not) is increased, which agrees with the physical hypothesis of the seeding. The total number of hailstones can be computed by integration of Eq. (1) between D = 0 and D = ∞:

$$N_{TOT} = -N_0/\lambda \qquad (6)$$

For the days with significant seeding, the total number of hailstones corresponding to Eqs (2) and (3) is respectively 22.400 and 33.700, which corresponds to 50% more hailstones in the most seeded hailfalls. This result favourably compares with the fact that the seeding is responsible for roughly doubling the natural background in ice-forming nuclei (Dessens 1998), although evidently many physical processes do affect the comparison, such a ice crystal multiplication and hailstone melting.

5. CONCLUSION

Three more seasons of hailstorm seeding prevention with silver iodide ground generators in southwestern France have confirmed that hail severity is mitigated by seeding if the generators are running at least two hours before hailfall time, and in the area where hail cells are developing 80 min before hailfalls.

The analysis of the hailpad data made in this paper differs from the previously published analysis (Dessens 1998) since it determines the effect of the seeding on the hailstone size distribution. The distributions clearly show that the number of hailstones smaller than 0.5 cm is increased (most of these hailstones are virtual) for the more seeded hail cells, while the number of hailstones larger than 0.9 cm is decreased. In consequence, the kinetic energy of hailfalls, which mainly depends on the number of largest hailstones, is significantly decreased by the seeding. This reduction is of 40% for a mean seeding amount of 59 g h^{-1} per 531 km^2 (1 generator every 8.8 km), the result being significant at the 0.05 level.

In conclusion, there is increasing evidence that seeding hailstorms at the proper place and time has a favourable impact on the severity of hailfalls, but the differences between the hailstone size distributions of the more and less seeded hailfalls are slight, although statistically significant, and thus difficult to observe. However, these small differences are sufficient to induce beneficial effects on crops and other properties sensitive to hail.

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