A Physical Evaluation of a Hail Suppression Project with Silver Iodide Ground Burners in Southwestern France

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ABSTRACT

The large-scale hail prevention program operated by the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques in southwestern France combines the seeding of hail clouds by a network of silver iodide ground generators with a survey of hailfalls by a network of hailpads. Using the joint data from the two networks, a physical method has been developed to measure the change in hailfall severity in the seeded hailstorms. The method associates the number of hailstones larger than 0.7 cm in a point hailfall at the ground (the ''hailstone number'') to the amount of seeding material released in the area where the storm was developing just before hailstone growth. The fundamental but not proven hypothesis employed is that a simple negative correlation should exist between the two parameters. During the years 1988–95, 630 point hailfalls were recorded on 53 hail days with seeding. The method indicates that the hailstone number is basically responsive to the amount of seeding material released 80 min before the time of the point hailfall in a 13-km radius area centered on the place where the storm was developing. The decrease in the hailstone number is in linear relation with the seeding amount—the more heavily seeded hailfalls decrease by 42%. The results are based on significant but weak correlations that have to be strengthened with a larger sample of hailfalls. However, they agree with former evaluations by insurance data of the same hail prevention program. The method gives a model that can be used to arrange the generator networks according to the movement of the storms.

1. Introduction

Hail prevention is the subject of endless debate in weather modification. While the scientists responsible for operational programs have reported successful results of hailstorm seeding from aircraft (Rudolph et al. 1994; Smith et al. 1997), from rockets (Mesinger and Mesinger 1992; Simeonov 1996), and from the ground (Dessens 1986b), none of the three national or international research projects aimed at evaluating the scores of the different seeding methods have succeeded in proving that any of the methods reduce the losses therefrom (Schmid 1967; Knight et al. 1979; Federer et al. 1986). Except for the Greek National Hail Suppression Program (Rudolph et al. 1994), the operational programs referenced above were nonrandomized, and their results were evaluated from crop–hail insurance data, two techniques rejected by a recent meeting of experts aimed at reviewing the present status of hail suppression [World Meteorological Organization (WMO) 1996]. The WMO's recommendation that physical parameters be used for evaluation instead of crop–hail insurance data is not debatable. The problem of randomization is more complex. Even after a long period of experimentation in a large area, a very small number of ''hail days'' invariably contribute a large fraction of the hail amount for the whole period, and these days may be unevenly distributed in the seeded and nonseeded samples. One possibility is that hailstorm seeding does prevent some hail, but its efficiency was not demonstrated through the randomized research projects. Another possibility is that suppression was not effective at all. What is missing in this debate is an evaluation method that may be duplicated anywhere in the world. It is the purpose of this paper to propose such a method for ground seeding operations.

The large-scale hailstorm seeding project with silver iodide ground generators monitored in France by the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA) has produced some promising results (Dessens 1986b). A study based on insurance data has revealed a 41% decrease of the damage in the operational area, which is attributed to the seeding. A similar result, a 45% decrease, has just come out of an aircraft seeding program in North Dakota (Smith et al. 1997), but in both situations the parameter used for the demonstration is the loss-to-risk ratio, that is, not a physical parameter. In 1987, the ANELFA decided to set up a permanent network for measuring hailfall on the ground in the seeded area, with the hope that

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this network could be used not only for climatological studies but also for checking the effectiveness of seeding on hailfall severity. This hailpad network, however, does not extend much beyond the generator network, and thus it is not possible to compare hailfalls in seeded and nonseeded areas but only in areas seeded more or less than average. From a determination of the differential efficiency, it was anticipated that an absolute efficiency may also be computed.

After an 8-yr period of simultaneous operation of the ground generator and hailpad networks, an efficiency control method has been devised. Since the generators are arranged in such a way that storms that might strike a vulnerable crop area are seeded before their arrival in the area, a logical control of the experiment then consists in comparing the hailfall intensity with the amount of seeding material released in the area where the storm was during the initial stage of the precipitation formation process (the ‘‘development area’’). This method yields results that appear to confirm the beneficial effect of the seeding previously determined from the insurance data and gives an accurate determination of the most efficient geographical disposition of the generators. The method could be easily replicated in other weather modification experiments based on cloud seeding from the ground, including rain stimulation.

2. Method for the control of hail prevention by ground seeding

Hail prevention with silver iodide ground generators is based on the release of artificial ice nuclei where and when convective clouds are developing. Several experiments in the field have shown that atmospheric turbulence and convection can transport the ice nuclei from near the ground through the boundary layer to the level where ice nucleation occurs (Super et al. 1975; Robitaille et al. 1986; Martner et al. 1992). The concept is simply that a storm cell developing above a surface layer with a relatively higher concentration of (silver iodide) nuclei will produce less severe hail than a storm cell developing above a surface layer with a relatively lower concentration. If this hypothesis is tested on a single day, it may lead to positive results (more seeding/less hail) if all the hail-producing cells are of similar intensity, and very positive apparent results if the strongest cells are developing above low seed concentration areas. It may also lead to nonsignificant or even negative results if the strongest cells are developing above high concentration areas and if the seeding effect is insufficient to reduce their severity below that of the other cells. However, if the control is applied to a great number of hail days, then the true correlation between seeding and hail should be revealed because the strongest cells will be randomly distributed over the generator network area. The method requires a normalization of the seeding and hail data in order to constitute a single sample of hailfalls with all the hail days.

a. Hail data

A hailfall at a given point—a point hailfall (Morgan 1988)—of a hailpad network having its stations distributed throughout a given area can be characterized by many different parameters, such as the total number of hailstones, the number of hailstones in different hailstone diameter classes, the maximum diameter, the total mass or kinetic energy of hailstones, etc. According to Changnon (1971), the degree of loss to crops can be properly estimated using one or two hailfall parameters: the frequency of hailstones with diameters greater than 0.25 in. (0.64 cm) and the energy imparted by the total point hailfall. Kinetic energy is often used in hail studies (Schmid and Waldvogel 1990; Schiesser 1990), so it was considered as the characterizing parameter in the early stages of this study. However, a reviewer noticed a problem of data normality with this parameter due to 12 point hailfalls with very large hailstones. The ‘‘hail number,’’ the number of hailstones with diameters greater than or equal to 0.7 cm, is thus used in this paper as the characterizing hail parameter. This parameter has the following advantages. Hailstones larger than 0.7 cm are accurately counted on the pads, while the smaller ones are not (Dessens and Fraile 1994); the parameter is not computed with a hypothetical hailstone fall velocity as it is for the energy; and it is in linear relation with the percent crop loss (Changnon 1971). The way in which the seeding may reduce the hailstone number will be discussed in section 6.

For a ‘‘hail day’’ (a day having one or more point hailfalls), each point hailfall is then characterized by the total number of hailstones with diameters greater than or equal to 0.7 cm, N_i, and the mean hailstone number for the day is

$$N_m = \sum_{i=1}^{i=n} N_i/n,$$

where n is the number of point hailfalls occurring that day.

For each point hailfall on a given hail day, a differential hailstone number is defined as follows:

$$\Delta N_i = N_i - N_m. \tag{1}$$

The mean value of ΔN_i for a hail day is 0.

b. Seeding data

A seeding amount, S_i, can be associated with each point hailfall. From the movement of the storm cell, it is possible to estimate the location where the storm developed before producing the observed hail and then to estimate the mass of silver iodide released in an area centered on this location during a given time, S_i. The size of the seeding area and the ‘‘displacement time’’ used for computing S_i values will be taken as constant for all the point hailfalls.

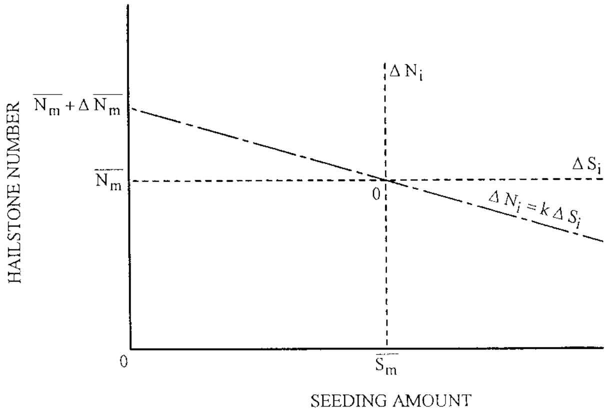

FIG. 1. Sketch of the computation of the seeding efficiency. The correlation between the seeding and the hailstone number is given by the regression line between ΔS_i and ΔN_i.

In the same way as for the hailstone number, a mean seeding amount is computed per hail day:

$$S_m = \sum_{i=1}^{i=n} S_i/n,$$

which gives for each point hailfall the following seeding, relative to the daily mean seeding:

$$\Delta S_i = S_i - S_m. \qquad (2)$$

Here, $\Delta S_i > 0$ corresponds to a seeding greater than average and $\Delta S_i < 0$ corresponds to a seeding less than average. The mean value of ΔS_i for a hail day is 0.

c. Correlation between hail and seeding data

The correlation between ΔS_i and ΔN_i can be computed for a day, for all the days, or for groups of days arranged according to meteorological situations. As each group contains an integer number of days, the regression line of ΔS_i with respect to ΔN_i has a point of intersection (0, 0) and a slope, k (Fig. 1, dashed axes). The slope characterizes the correlation between seeding deviation and hail deviation. The level of significance of the correlation is expressed by the correlation coefficient and the number of data pairs [see, e.g., Eq. (622b) in Essenwanger 1986]. A significant negative (positive) correlation will indicate that greater-than-average seeded areas have received less (more) hail than the less-than-average seeded areas.

The correlation is relative to the mean value of the daily mean seeding amounts for the group of days considered, $\overline{S_m}$, and to the mean value of the daily mean hailstone numbers for this same group, $\overline{N_m}$. The regression line indicates that, without seeding, the hailstone number would have been $\overline{N_m} + \Delta\overline{N_m}$ (Fig. 1, continuous axes). The negative of mean relative change in the mean hailstone number gives the hail suppression seeding efficiency E for a seeding amount, $\overline{S_m}$:

$$E(\%) = -100 \times \frac{\Delta\overline{N_m}}{\overline{N_m} + \Delta\overline{N_m}} = -100 \times \frac{k\overline{S_m}}{\overline{N_m} + k\overline{S_m}}. \qquad (3)$$

3. Application of the method to the ANELFA project

A detailed description of the ANELFA project has been given by Dessens (1986b). In 1995, the Aquitaine seeding network consisted of 467 seeding stations covering about 40 000 km^2 (Fig. 2). The type of generator used is the acetone vortex burner with a swirl nozzle (Monarch NS, 0.65°–30°) supplied with a 1% solution of AgI-0.5 NaI in acetone at a pressure of 1.8 atm; the solution flow rate is 1.07 L h^{-1}, giving a silver iodide output of 8.6 g h^{-1}. The generators run continuously during hail warnings, and the exact time of proper burning is recorded by the operators. Measurements in a cloud mixing chamber show that the AgI-0.5 NaI solution burning produces 0.8×10^{14} ice nuclei per gram of silver iodide, active at -15°C, and 3.0×10^{14} at -18°C (Dessens 1986b). However, it is quite possible that these standard cloud mixing chamber measurements may underestimate the activity of AgI-0.5 NaI in clouds (Blumenstein et al. 1987; DeMott 1988).

The hailpad network, the material, the calibration, and the data processing are described in Dessens and Fraile (1994). In 1995, the network consisted of 817 hailpad stations; all the generator stations are equipped with a hailpad, and extra hailpads are located in surrounding areas, both inside and outside the seeding network (Fig. 2). Immediately after a hailfall, the individual in charge of a hailpad station writes the date, approximate time of beginning, and duration of the point hailfall on the back of the pad.

During the 1988–95 hail seasons, the hailpad stations recorded 1562 point hailfalls in the 12 southwestern departments. Only the 987 hailpads hit by at least one hailstone of 1-cm diameter or more were processed; all hailstones larger than 0.7 cm being counted on these pads. This simplification was decided because the crop damages due to hailstones smaller than 1 cm are generally light (except for fruit), but the intention is to process the remaining 575 hailpads with an automatic system. Out of the 987 hailpads now processed, 630 correspond to 74 days with seeding, where the seeding was not necessarily extended to the whole area. The other 357 hailpads correspond to 101 days without seeding. Low severity hail situation, missed forecast, forecast not followed by seeding in case of flash-flood warning, or, finally, missed transmission of the warning were among the reasons for the absence of seeding.

The seeding and hail data were processed using two interconnected programs. The seeding program analyzes data on generator stations: geographical coordinates, periods of burning, malfunctions, etc. It allows computation of the mass of silver iodide released at any time

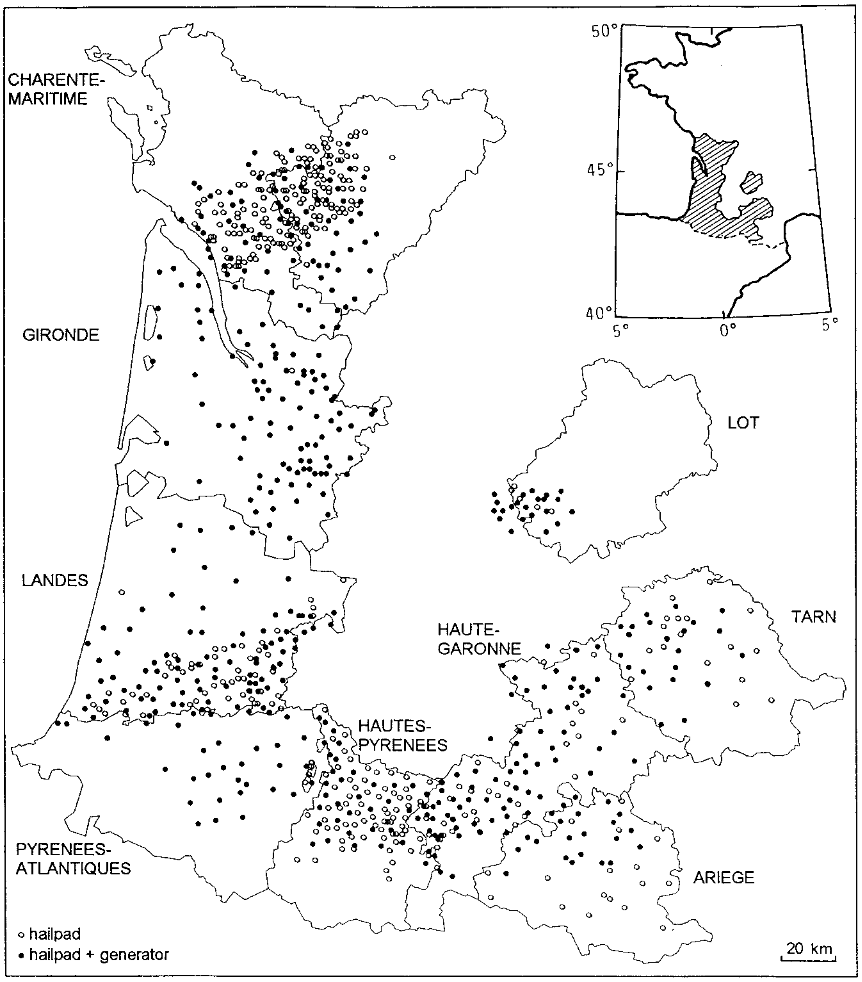

FIG. 2. Map of the hailpad and seeding stations of the ANELFA network in southwestern France in 1995.

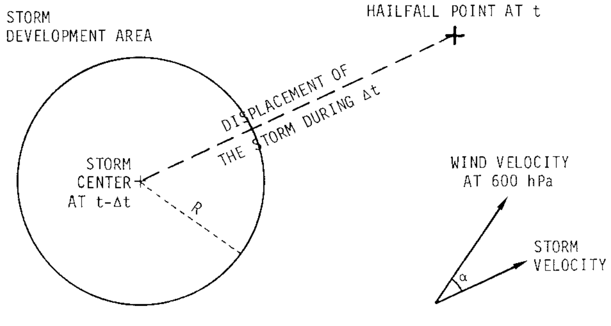

FIG. 3. Conceptual scheme of the method. The point hailfall at time *t* is taken to be associated with the amount of seeding material released in a circular development area of radius *R* centered on the place where was the storm at $t - \Delta t$. The displacement time Δt (the interval of time) is between the seeding and the hailfall. The storm velocity vector is computed from the wind at the 600-hPa level, assuming for the storm motion a propagation deviation α and a speed reduction.

in any specified circular area. The circle is defined by its geographical coordinates and radius. The hail data are contained in a spreadsheet, each line documenting a point hailfall with the following information: geographical coordinates, time, duration of the hailfall, number of hailstones in 2-mm classes of diameter (4 mm for hailstones larger than 17 mm), integrated mass, and energy. The dataset also includes some meteorological parameters of the day measured by the sounding made at Bordeaux at 1200 UTC: altitude of the 0°C temperature level, wind direction, and velocity at the 600-hPa level, and maximum tropospheric wind velocity. A connection established with the seeding program allows inclusion in the hail data of the seeding amount in any area located around the hail point.

The problem is to know the displacement time interval Δt necessary for the production of a point hailfall at time *t*, and the location of the storm at time $t - \Delta t$ (Fig. 3). Once the storm center has been fixed, it is necessary to determine the development area for which the seeding amount is computed. Three parameters, 1) direction of storm propagation, 2) displacement distance, and 3) radius of the development area, were first fixed according to physical considerations. The method then used to refine the three parameters consists in looking for the better correlation between hailstone number and seeding amount by moving the development area around its hypothetical position.

a. Storm propagation

Several radar studies have shown that small cumulonimbus echoes move approximately with the mean wind in the midtroposphere (between about 3 and 6 km), while large echoes (from more intense storms) tend to move more slowly and by as much as 30° to the right (Ludlam 1980; Browning 1985). In southwestern France, direction and velocity of storm propagation have been compared to direction and velocity of the mean wind from 1 to 12 km. The mean angular deviation of typical major hailstorms was found to be 28° to the right of the wind, with only one case of perceptible deviation to the left (Dessens 1986a). The mean storm velocity was 15 m s^{-1}, compared to the mean wind velocity of 21 m s^{-1}. A refined study has been made with a sample of 34 hail days for which the direction of the storm propagation was determined by the hailstreak orientation and with a subsample of 22 hail days for which the velocity of the storm was determined from the time progression of the point hailfalls. Instead of a computation of the mean tropospheric wind, the correlations between the storm and wind parameters at each kilometer between 1 and 10 km were examined. The results indicate that the storm propagation is strongly correlated with the wind at 4 km (600-hPa level). On average, storms move 31° to the right of the wind at this level and at a speed 18% lower than the wind velocity.

Many of the 987 point hailfalls measured from 1988 to 1995 were not generated by ‘‘intense’’ hail cells, and the propagation of these cells probably did not obey the same deviations from the environmental wind. However, as a first step, it was considered that the displacement of the storms was 31° to the right of the wind direction at the 600-hPa level at a velocity 18% lower than the wind velocity at this level. Using these initial estimates, better values were estimated for the direction and velocity, which give stronger correlations between the seeding amount and the hailstone number.

b. Time interval between seeding and hailfall

Numerical simulations of hailstorms give an estimation of the characteristic time interval from the development of the hail cell above the boundary layer to the fall of the hailstones at the ground. As an example, the simulation of an Alberta hailstorm with a two-dimensional, time-dependent cloud model where the precipitating ice field is discretized into 20 logarithmically spaced size categories (Farley 1987) shows that the maximum precipitation reaches the ground 60–80 min after the initial growth stage of the simulated convection. In another simulation made with this model, a hailstorm in North Dakota is shown to produce hail at the ground about 75 min after the convection is forced with perturbations in temperature and humidity at low levels (Farley et al. 1996).

Various simulations with other models also give time intervals of approximately the same length. Robinson and Srivastava (1982) found growth times ranging from 40 to 60 min for large hailstones. Foote (1984) gives a time of 28 min for the growth of a hail embryo of 0.2-cm diameter into a hailstone of 1.7 cm, which again gives a total time of about 1 h with the added time of transfer of the air parcel from the ground to a height of 6 km. The time duration between the release of silver iodide nuclei from the ground generators and the fall of the hailstones related to this seeding is not strictly a constant parameter. However, it was assumed that, on average, this time interval was a good first estimate of $\Delta t = 60$ min for the whole sample of point hailfalls; then better correlations were sought with other values of Δt.

c. Development area

The last parameter that has to be defined in order to compute the seeding amount is the radius R of the seeding area related to the hail cell that will produce the observed point hailfall. If the available nuclei are those directly produced by the generators, as suggested by Soulage and Admirat (1968), then the surface area is of the same order of magnitude as the area of the storm activity zone. In numerical simulations, the model domain is usually 30 km wide, which also seems to be a reasonable value for the present purpose. Since the software deals with circular areas, an area limited by a 15-km-radius circle centered on the hailstorm center was first considered; then, as for the other parameters, better correlations were sought with other values of R.

In summary, the sample of 630 measured point hailfalls will be used as follows.

1) Computation of ΔN_i from Eq. (1).
2) Determination of the location of the storm for each point hailfall 1 h before the hailfall by considering the storm to have propagated 31° to the right of the wind at the 600-hPa level and at a velocity 18% lower than this wind. Evidently, these precise numbers do not give an account of their physical accuracy, and they are only mean values used for an evaluation of the storm propagation.
3) Computation of ΔS_i from Eq. (2) by considering a 15-km-radius circle centered on the storm location 1 h before the point hailfall. The seeding amount that is computed with the program relates to the generators running at the time $t - 1$ h. For example, if five generators have been running in the circle, the

corresponding seeding amount is 5 × 8.6 = 43 g h^{-1}.

4) Computation of the correlation between ΔN_i and ΔS_i for the total sample of point hailfalls or for groups of hail days arranged according to different conditions.
5) Computation of the seeding efficiency from Eq. (3).

4. Results

a. *Correlation before adjustment of the development area*

The correlations between ΔN_i and ΔS_i are first examined for the seeded days with the parameters fixed above ($\Delta t = 60$ min, $\alpha = 31°$, and $R = 15$ km). They are computed after removing from the sample the 12 days for which there is only one recorded point hailfall and the 9 days for which $S_m = 0$ (some seeding occurred on the network but not in the development areas relative to the recorded hailfalls). The linear regression for the 565 remaining point hailfalls gives a slope parameter, $k = -3.63 \pm 1.69$, and correlation coefficient, $r = -0.090$. This weak negative correlation is statistically significant at the 0.05–0.02 level when the data are subjected to a single-tailed Student's t-test.

b. *Adjustment of the development area*

The effect of varying the three parameters Δt, α, and R discussed in the previous section is shown in Fig. 4. The upper curve shows that the correlation coefficient is maximum for $\Delta t = 80$ min, which is higher than the preliminary hypothetical value of 60 min. This means that either hailfalls take more than 1 h to brew or that storms move faster than supposed. The middle graph of Fig. 4 indicates that the correlation is indeed maximum for $\alpha = 31°$, and the lower graph shows that the effect of parameter R is less pronounced than the effect of the other two parameters. The correlation does not decrease rapidly for small values of R; this is probably because the generator stations located in the middle part of the development area are those that have the biggest weight in the correlation. The correlation coefficient is maximum for $R = 13$ km. The small oscillations of the correlation coefficient around this value are probably due to the rounded values of the geographical coordinates of the seeding stations, which is a problem that will be addressed in the next software evolution.

Figure 4 shows that the correlations fall rapidly below the 0.05 level of significance when the values of the parameters are removed from their peak values. In particular, there is no correlation between the hailstone number and the seeding amount in the area centered on the hailfall point ($\Delta t = 0$ min), which suggests that, in general, the generators are not protecting themselves against hail.

If the correlation coefficient r is then recomputed with the optimum values of the three parameters ($\Delta t = 80$ min, $\alpha = 31°$, $R = 13$ km), the value of r is higher than the previous one ($r = -0.125$ instead of $r = -0.090$). In consequence, this set of parameters was retained for the rest of the study. There are exactly 541

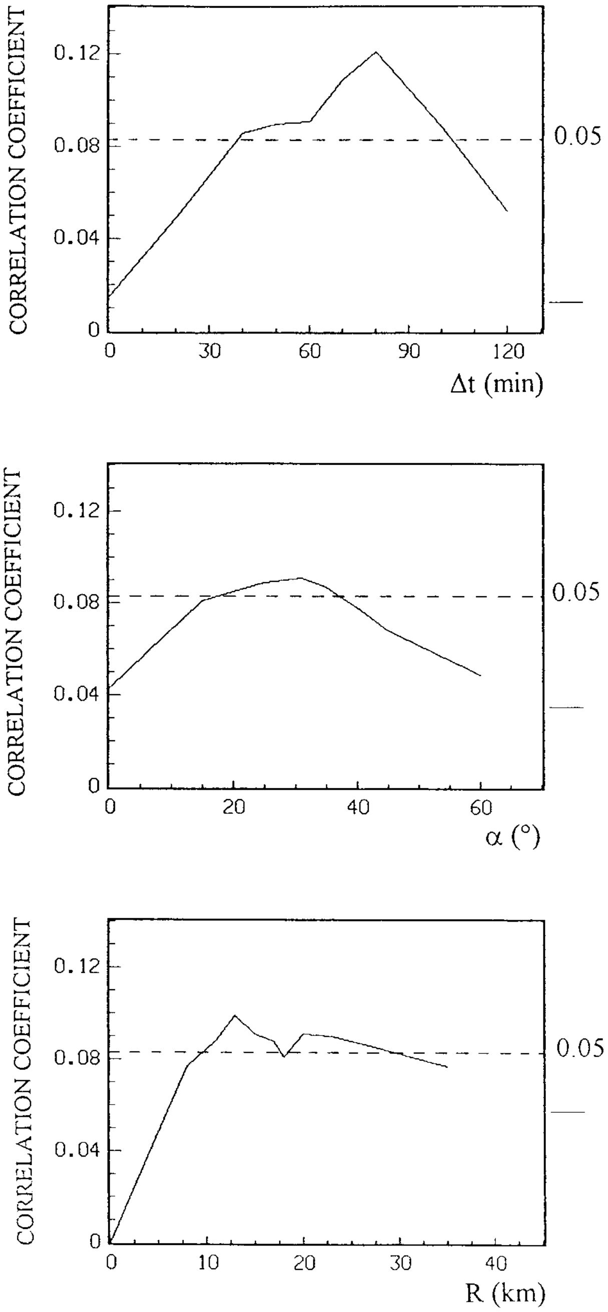

FIG. 4. Effect of varying the displacement time Δt, the propagation deviation α, and the development area radius R on the correlation between seeding amount and hailstone number. The dashed lines denote the 0.05 level of significance. (Top panel) Varying Δt with $\alpha = 31°$ and $R = 15$ km; (middle panel) varying α with $\Delta t = 60$ min and $R = 15$ km; (bottom panel) varying R with $\alpha = 31°$ and $\Delta t = 60$ min.

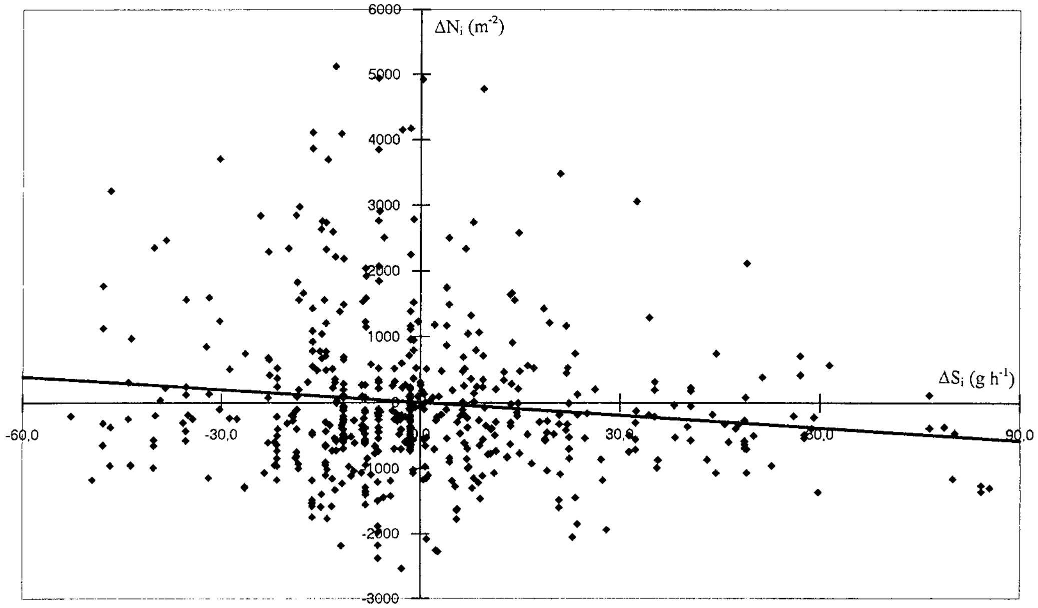

FIG. 5. Illustration of the correlation between the seeding amount and the hailstone number for seeded hail days. As an example, the upper point refers to a point hailfall having 5119 m^{-2} hailstones more than the mean hailstone number of the day and seeded with 12.9 g h^{-1} of silver iodide less than the mean seeding amount of the day.

point hailfalls relative to days with $S_m \neq 0$ when this new set of parameters is used. Figure 5 is an illustration of the correlation between the seeding amount and the hailstone number for these hailfalls. In spite of the large scattering of the points, the negative correlation appears to be due to the severe hailfalls that are concentrated on the left side of the figure (less-than-average seeded hailfalls) and to the small number of overenergetic hailfalls on the right side (greater-than-average seeded hailfalls). The mean values of S_m and N_m are, respectively, 23.2 g h^{-1} of silver iodide per 531 km^2 and 1105 m^{-2}, and the slope parameter of the correlation, $k = -6.44 \pm 2.21$, suggests that the mean seeding has led to a 15.6% decrease in the mean hailstone number. The significance level as computed from the chi-squared test, which does not strictly apply in this analysis (see section 5a), is better than 0.01.

c. Results for different classes of seeded hail days

It is to be expected that the seeding efficiency would be better in some meteorological situations than in others. To explore this possibility, the correlation between the seeding amount and the hailstone number was computed for groups of days arranged according to environmental parameters. Among the parameters that are relevant for a hail day at the scale of the project area, we have selected the wind velocity and direction at midlevel, the altitude of the 0°C level, the recorded diameter of the largest hailstones, and the mean amount of seeding. Table 1 gives the results for each of these parameters for similar size subsamples relative, respectively, to low and high values of the parameters. For all the parameters but the wind direction, a significant correlation is obtained with each subsample, and the computed efficiency seems more in relation with the mean seeding amount than with the parameter stratification. For the wind direction, the correlation is not significant for α values lower than 210°—most cases being relative to southerly winds. On the other hand, its level of significance is much better than 0.01 for α values higher than 210°—most cases being relative to westerly winds. Figure 6 gives the illustration of the correlation between seeding and hail in this favorable westerly situation, and the beneficial effect becomes visually more apparent.

The efficiency of hail prevention then appears to be better in westerly situations than in southerly ones. Since these westerly situations often correspond to cold fronts coming from the Atlantic Ocean, the result supports the hypothesis that ground seeding is more efficient under cold front situations (Dessens 1986b), which is a result observed in other similar projects (Atlas 1977). Why ground seeding is less efficient by southerly situations is not clear. A hypothetical but attractive explanation could be that in these situations, which are often associated with Saharan dust outbreaks (Dessens and van Dinh 1990), the desert dust could be a detrimental factor for the seeding effectiveness, as recently observed in Israel (Levin et al. 1996; Rosenfeld and Nirel 1996).

The mean amount of seeding in the hailed area can also be considered as an environmental parameter since it may contribute to the background in ice-forming nuclei. Table 1 gives the correlation results for low and high seeded days. The correlation is found to be significant only for the highly seeded days, and the seeding

TABLE 1. Correlation between the seeding amount and the hailstone number for all days and for days grouped together according to different environmental parameters. Here, V_{600} and α are, respectively, the velocity and the direction of the wind at the 600-hPa level, $h_{0°C}$ is the altitude of the 0°C temperature level, D_{max} is the hailstone maximum diameter observed on a hailpad, and S_m is the mean seeding amount per 531 km².

Parameter	Number of cases	Mean seeding amount (g h^{-1})	Mean hailstone number (m^{-2})	Correlation coefficient r	Significance level	Hail change (%)
All days	541	23.2	1105	-0.125	0.01	-15.6
$V_{600} < 13$ m s^{-1}	289	28.8	1251	-0.125	0.05	-18.5
$V_{600} > 13$ m s^{-1}	252	16.7	936	-0.126	0.05	-11.8
$\alpha < 210°$	290	19.4	1243	-0.055	ns*	
$\alpha > 210°$	251	27.5	945	-0.218	0.01	-34.3
$h_{0°C} < 3.5$ km	278	25.0	1424	-0.122	0.05	-15.2
$h_{0°C} > 3.5$ km	263	21.3	767	-0.140	0.02	-17.0
$D_{max} < 30$ mm	283	29.3	1021	-0.115	0.05	-18.3
$D_{max} > 30$ mm	258	16.5	1196	-0.135	0.05	-11.7
$S_m < 20$ g h^{-1}	294	10.1	1123	-0.091	ns*	
$S_m > 20$ g h^{-1}	247	38.7	1083	-0.163	0.01	-30.3
$\alpha > 210°$	146	40.1	1038	-0.220	0.01	-44.8
$S_m > 20$ g h^{-1}	”	”	”	”	”	”

* Not significant.

efficiency per seeding amount is larger for this sample of days than for the total hailfall sample. The correlations for the two samples show that when the seeding increases from 23.2 to 38.7 g h^{-1}, the efficiency increases from 15.6% to 30.3%. It is possible to complete the graph giving the efficiency as a function of the seeding (Fig. 7) by an appropriate selection of the seeded hail days. The correlations used to plot the points in Fig. 7 are all significant at levels better than 0.05. Although these correlations are not independent (except for 1 and 5, the samples have days in common), the graph suggests that the mean hailstone number is in linear relation with the seeding amount, as assumed in section 2 when computing the correlation between ΔS_i and ΔN_i. A maximum efficiency of 41.6% is found for the higher seeded hailfalls ($\overline{S_m} = 50.1$ g h^{-1}, corresponding to 11.0 generators per 1000 km²).

It is finally interesting to combine the most favorable situations and to compute the mean seeding efficiency that is obtained in these conditions. The last line of Table 1 gives, for example, the correlation parameters for a group of days with a wind direction higher than 210° at the 600-hPa level and with a mean seeding amount larger than 20 g h^{-1}. The decrease in hailstone number, significant at the 0.01 level, reaches 44.8% for a seeding amount of 40.1 g h^{-1} of silver iodide per 531 km².

All the correlations computed above are relative to hailpads pitted by at least one hailstone larger than 1 cm. When the other hailpads are processed, it will be interesting to check if their N_i values will be preferentially associated to low S_i values.

5. Possible flaws in the analysis

The correlations between seeding amount and hailstone number are blurred by the high spatial variability of the hail phenomenon. Even in the most favorable meteorological conditions, the correlation coefficient between the seeding amount and the hailstone number just reaches about 0.2, and the significant statistical level is obtained only because the sample of hailfalls is large. With such weak correlations, a critical examination of the data is necessary, and it mainly raises two problems.

a. *Independence of the units*

This problem is typical in meteorology in that it is rare that two successive events are completely independent. In hail studies, if the units are single hailstorms or single days, the assumption of independence is never completely satisfied because single storms and even single hail days may be associated to a same meteorological situation. In the case of data from single hailpads, the independence is unlikely if the hailpad network has a mesh lower than the length scale of a hailfall. The mean distance between two hailpads of the ANELFA network is 7 km, which, when compared to the mean structure of a hailfall (Changnon 1977), prevents the hailpad data from being overly redundant. However, there are several much denser clumps of hailpads in the network, and there is no exact way of determining what the dependence might be. An estimate of the independence of the units is given by computing the correlation coefficients between ΔN_i on adjacent observations, where the observations are chronologically ordered. For the 541 point hailfalls, the correlation coefficient between ΔN_i and ΔN_{i+1} is -0.03, which is statistically nonsignificant. We may, however, conclude that this problem of independence may lead to some overestimation of the significance of the correlation between seeding and hail.

b. *A possible bias*

The reviewers have suggested two possibilities of introduction of a bias in the correlation analysis. The first

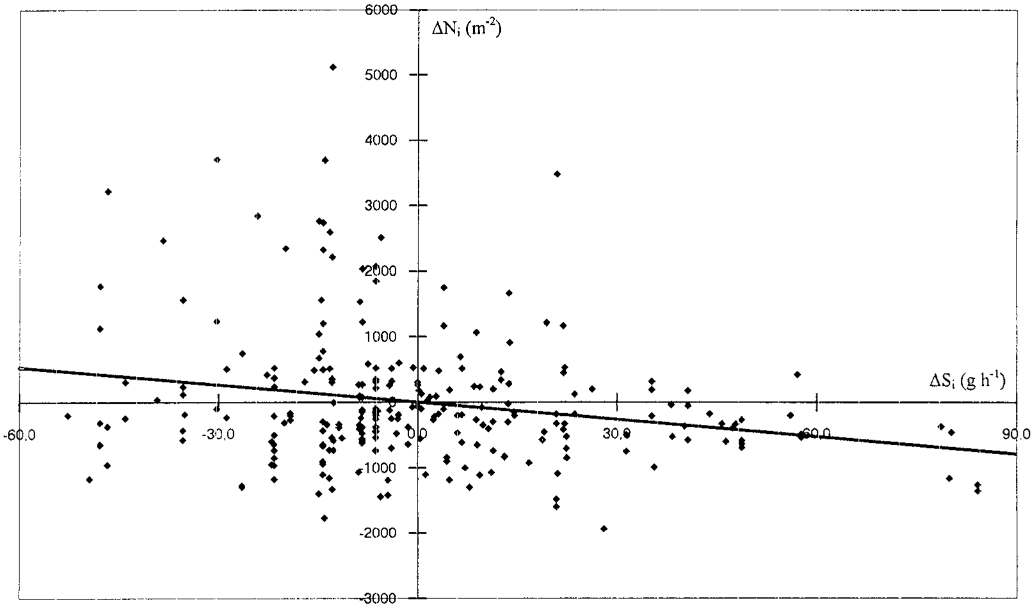

FIG. 6. Same as Fig. 5 but for hail days with wind direction at the 600-hPa level greater than 210°.

one concerns the criteria used for operating the seeding generators. The generators are switched on when hail is forecast by the French meteorological services. The seeding starts 3 h before the forecast hail period and ends with the forecasted end of this period. The forecast is made at the departmental scale, so that not all the departments of the ANELFA networks are necessarily operating during a hail warning. Since the sample of data constitutes all the point hailfalls relative to days with at least some seeding in the network, hailfalls in seeded areas are, in some circumstances, compared to hailfalls in nonseeded areas where the risk was considered as lower by the forecast. It then appears that the risk of a bias introduced by an effective forecast is not in favor of the negative correlation found between seeding and hail.

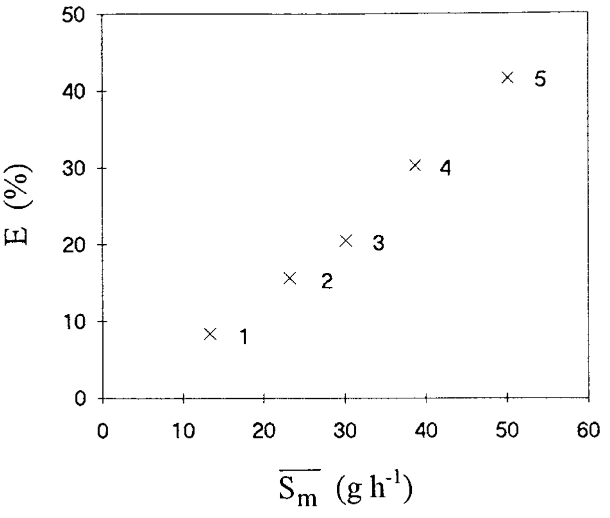

FIG. 7. Relationship between the seeding amount and a seeding efficiency defined as the reduction of the number of hailstones larger than 0.7 cm. Point 1 is relative to days with $S_m < 30$ g h^{-1} (381 point hailfalls), point 2 is relative to days with $S_m > 0$ g h^{-1} (541 point hailfalls), point 3 is relative to days with $S_m > 10$ g h^{-1} (389 point hailfalls), point 4 is relative to days with $S_m > 20$ g h^{-1} (247 point hailfalls), and point 5 is relative to days with $S_m > 40$ g h^{-1} (119 point hailfalls).

The second possibility of bias in the analysis concerns the relative positions of the generators and of the hailfalls. The geographical distribution of yearly frequencies of severe hailfalls in southwestern France (Dessens 1986a) shows an increase of the risk from the Atlantic coast line and the Spanish border to the center of the region, that is, from nonseeded areas to seeded areas. When looking for a bias, then, it appears that hail might be more severe as one goes inside the most seeded areas, which again may lead to a positive correlation between seeding and hail, not to a negative one as observed.

Other biases in the analysis are evidently possible but are not explored in this paper.

A control test may be made with the 357 point hailfalls that occurred on 101 days without any seeding, so as to ensure that the correlation observed between the seeding and the hailstone number is not artificially produced by the disposition of the generator networks or by another condition. To this end, all generators were considered to be running on the days without warning, and the correlation between the hailstone number and this ‘‘virtual'' seeding was computed in the same way as for the days with seeding and with the same parameters as before ($\Delta t = 80$ min, $\alpha = 31$, $R = 13$ km). The sample decreases to 312 point hailfalls for the days with more than 1 point hailfall and to 300 for the days

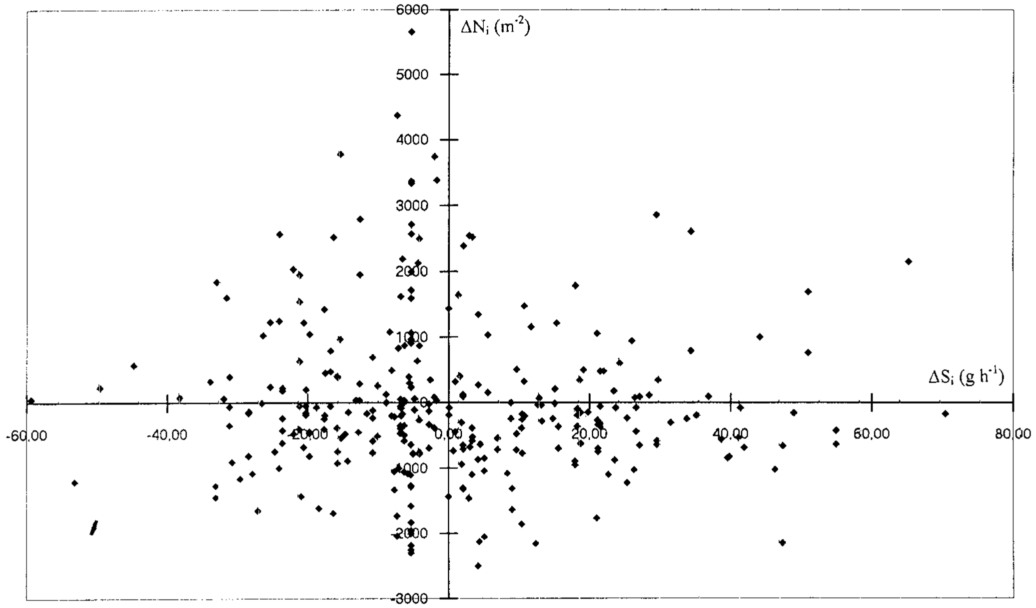

FIG. 8. Same as Fig. 5 but for hail days without seeding. The *x* axis gives an estimate of the amount of seeding that would have occurred if the generators have been burning (virtual seeding), assuming that the operators followed standard procedures.

with a virtual seeding different from 0. The values of $\overline{S_m}$ and $\overline{N_m}$ are, respectively, 26.6 g h^{-1} (virtual) and 1209 m^{-2}. The correlation coefficient is found to be -0.049, which is far from being significant, since a coefficient value of 0.113 would be necessary for a 0.05 significance level with a population of 300 point hailfalls. Figure 8 gives ΔN_i as a function of ΔS_i for the virtually seeded hailfalls. In contrast to Fig. 5, there is no difference in the distribution of ΔN_i in the left and right sides of the graph. When only the days with $S_m > 20$ g h^{-1} are considered (those for which the correlation is significant in case of real seeding), the correlation coefficient falls to 0.018 for a sample of 198 virtually seeded point hailfalls.

6. Summary and discussion

The physical evaluation of a hail suppression project with silver iodide ground generators proposed in this paper is based on a day-by-day computation of the correlation between the hailfall and the seeding and on the cumulative evaluation of this correlation for a large set of hail days. The results obtained from ANELFA data for the years 1988–95 are as follows.

1) For a set of 630 point hailfalls that occurred on 53 seeded days, there is a significant negative correlation between the number of hailstones larger than 0.7 cm in a point hailfall and the mass of silver iodide released in the area where the storm developed before producing this hailfall.

2) Varying successively the three parameters that determine the development area around its theoretical position shows that the best response of the seeding is observed when the seeded area is taken as a 13-km-radius circle centered on the location of the storm 80 min before the hailfall. The negative correlation between seeding and hail, significant at the 0.01 level, suggests that a 15.6% decrease in hailstone number is obtained with a seeding amount of 23.2 g h^{-1} of silver iodide per 531 km^2. Such an amount of seeding corresponds to five generators per 1000 km^2. When the development area is removed from the above position, the correlation decreases and rapidly becomes nonsignificant, which supports the physical plausibility of the results.

3) Cutting the hailfalls sample in two parts according to daily environmental parameters shows that the seeding effect is not sensitive to the wind speed at the 600-hPa level, to the altitude of the 0°C level, or to the diameter of the largest hailstones. By contrast, there is a marked difference in the seeding effect according to the wind direction at the 600-hPa level, confirming that frontal hailstorms are more responsive to ground seeding than hailstorms developing in southerly air masses. There is also a sound difference in the seeding effect according to the daily mean amount of seeding.

A discussion of these results raises two main questions: are the low correlation coefficients found between the seeding and the hailstone number really significant, and is the observed seeding effect consistent with physical and numerical models of hailstorms? Concerning the first question, there is certainly a problem with the independence of the units used for computing the correlation since the hailfall sample consists of point hailfalls associated to same hailstorms, or to same hail days, or at least to a same meteorological region. The significance of the correlation then may be overestimated, but the problem will be attenuated in a few years with a larger sample of hailfalls. The possibility of a bias in the data analysis also exists, although it has not been revealed for the moment. In fact, the analysis method, when applied to a set of point hailfalls that occurred on days without seeding, does not give any significant correlation between the number of generators located in the development areas (but not burning) and the hailstone number.

Concerning the second point, the seeding process followed by the ANELFA is in agreement with the most recent conceptual models for hail suppression. The World Meteorological Organization (1996) has favored three concepts relevant to the modification of hailstorms by cloud seeding that are based on glaciogenic effects: beneficial competition, early rain out, and trajectory lowering. A fourth concept, dynamic seeding, probably needs much more seeding material than that released from ground generators. The first three concepts require a necessary treatment of young developing convective cells rather than mature cells and strong updrafts. The validity of an early treatment is suggested by experimental results (Waldvogel et al. 1987) as well as by numerical results (Farley et al. 1996). The ANELFA seeding process is mainly a preventive one applied several hours before hailfalls. However, it is necessary to check if the low amount of seeding released by the generators is compatible with the results observed. A seeding amount of 23.2 g h^{-1} of silver iodide per 531 km^2 generates about 3.5 ice nuclei L^{-1} at $-15°C$ in 1 h in a 1-km height boundary layer. This is the order of magnitude of natural ice-forming nuclei concentrations in the region of the project (Dessens 1986a), so the seeding is then responsible for roughly doubling the natural background. The extra hailstone embryos then compete for the available supercooled water, which results in the formation of numerous hailstones, many of which melt before reaching the ground. The modeling of such a doubling of the ice-forming nuclei concentration in the boundary layer has not yet been done, and it would be interesting to look for its effect on the number of hailstones falling to the ground.

The main physical weakness of the method is that the seeding amount used to compute the correlation between seeding and hail is the instantaneous production of silver iodide nuclei in the development area and not the number of ice nuclei really available in the boundary layer. From the generators to the upcurrents there is a horizontal transport of the nuclei that has not yet been considered. One can imagine the possibibility of using a model of plume dispersion coupled with the method developed in this study, but the space and time variabilities of the surface winds in the project area are too important to allow it at this early stage of the research. However, in the future, it might be the necessary condition for finding stronger correlations between seeding and hail.

To conclude, the small negative correlation coefficient value between differential seeding amount and differential hailstone number for individual hailfalls is probably the weak signal of hail suppression within the high natural variability. The seeding efficiency computed with this method is only the part due to the direct seeding from the generators located beneath the storm. To this part should be added an indeterminate part relative to the silver iodide nuclei scattered from the surrounding generators during the hours preceding the storm development. A practical lesson of the present study is that the protection of hailed areas requires generators running not only in these areas but also at great distances in the direction from where the storms are coming. In the most severe situations, storms are traveling at 60 km h^{-1}, and the generators must be placed at around 80 km from the areas to be protected. This is a very restricting condition in the field.

The confidence in the method proposed above will grow with the increase of the negative correlation between seeding and point hailfalls, which could be obtained by a better localization of the storm development area, for example, with a storm propagation survey by radar and by improvement of the seeding itself. On the second point, a step has been made by ANELFA in 1996 by replacing the AgI-0.5 NaI aerosols with $AgI_{0.8}\,Cl_{0.2}$ 0.5 NaCl aerosols (Finnegan et al. 1994), which produce about 100% more ice-forming nuclei active at $-10°C$ (ANELFA 1996). For now, the method already gives ANELFA the first physical indication of a beneficial seeding effect as well as information on the appropriate disposal of the generator networks according to the movement of the storms. It is hoped that these results, together with those obtained by new techniques, like the tracking of chaff fibers in convective clouds by dual-circular-polarization radar (Martner et al. 1992), or by recent developments in numerical simulation of cloud seeding, may contribute to a better knowledge of the science of hail suppression.

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