A SENSITIVITY TEST FOR HAIL PREVENTION ASSESSMENT WITH HAILPAD MEASUREMENTS

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Abstract

The evaluation of the French hail prevention project with silver iodide ground generators is based on daily correlations between the running time of the generators and the intensity of point hailfalls as indicated by hailstone number determined with hailpads. A normalization of these two parameters by their daily mean values allows the aggregation of hail days, and the setting-up of larger data samples for a statistical examination in which the random nature of hail becomes less important. In this paper, the evaluation is made from the 1948 point hailfalls recorded in an area of 16,000 km² of the Midi-Pyrénées region during 17 hail seasons. A cumulative method of correlation between the seeding and hailfall data shows that only the major hail days, with at least 15 point hailfalls measured in a hailpad network of 7 km mesh, may enable the detection of a seeding effect from a ground generator network of 10 km mesh. With this observation, the correlation between the seeding and hailfall data for 438 hailfalls on 18 major hail days indicates a beneficial effect of the seeding on 15 days, with a hail decrease of 40% for the correctly seeded events. This ratio amounts to 50% when the hailfall kinetic energy is considered instead of the hailstone number.

1. Introduction

The French hail prevention program of the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA) has been operated continuously since 1952 without any change in its principle (Dessens 1953), which consists of the preventive seeding of the developing hailstorms with ice-forming silver iodide nuclei released from ground generator networks. For many years, the seeding effects were evaluated from cloud physics measurements and hail insurance statistics (Dessens 1986). In 1988, hailpad networks were added to the generator networks, and after 8 years of combined exploitation, correlations were detected between the amount of seeding delivered to the hailstorms and the severity of the hailfalls (Dessens 1998). A second data set, obtained a few years later, allowed to refine the first results and to improve the efficiency control by performing a geographical partition in the data processing (Dessens et al. 2003).

This paper presents an updating of the results in the most documented area of the project with three more years of experimental data. A slight change in the correlation computations is also introduced in the normalization of the data by their daily mean values. The results are summarized on graphs giving the cumulated effect of the seeding day after day. Such a cumulative method, which is motivated by the variability of the hail phenomenon, was successfully used with the double mass curves of the hail insurance loss-to-risk ratios (Dessens 1986). In this paper, it will allow the determination of the minimum number of daily point hailfall measurements necessary to the detection of a possible seeding effect.

2. Method used for the evaluation of a seeding effect

The data available to determine a seeding effect of the ground generator emission on hailfalls are the following:

- The starting time and duration of each generator emission, for days with a hail warning correctly transmitted to the operators (details available in Dessens 1998). In 2004, 698 generator stations were deployed in 15 local networks in the main hailed regions of France. The total area covered by the operation is 55,000 km². From April to October, each year, there are some 20 warning days per local network, a typical event lasting around 10 hours. One generator burns 8.6 g of silver iodide per hour and produces 2.0 x 10^{11} s^{-1} ice-forming nuclei active at -15°C.

- The characteristics of each point hailfall recorded on the 1104 hailpad stations (in 2004) installed in the same areas. Each emitting station is also a measuring station, and extra hailpads are located in areas immediately surrounding the target areas. The observers note the exact time of each hailfall. All the hailpad stations are located close to where the observers live, and in each local network a technician is in charge of the pad collection the day after the hailstorm. The hailpad sensor is a 0.1 m² extruded polystyrene plate (Dessens et al. 2001) and an image analysis system gives the hailstone numbers in 0.2 cm diameter classes from 0.5 to 1.7 cm, and in 0.4 cm classes above 1.7 cm.

The difficulty, if not the impossibility, of measuring a seeding effect by comparison of hailfalls from seeded or unseeded days is well known in weather modification, even for a randomized experiment. For this reason, a specific method has been developed by the ANELFA (Dessens 1998). The method consists in comparing the hailfall intensity to the amount of seeding material released in the area where the storm was located during its development stage. The comparison is made on a day-by-day basis, after a normalization of the data by their daily average. This normalization allows the aggregation of individual days together and then the increase of the data sample. The application of the method to the 1988-1995 hail prevention campaigns has shown that the number of hailstones larger than 0.7 cm in a point hailfall is basically responsive to the amount of silver iodide released during the 3 hours before the hailfall time in a circle of radius R = 13 km centered on the location of the developing cell 80 min before this time (the "development area"). The data collected over 6 more seasons have confirmed these parameters (Dessens 2003).

Based on these results, the whole data sample of the 1988-2004 period is examined in the next two sections of this paper, with a new illustration of the results.

3. Sensitivity of the method in the Midi-Pyrénées region

Four geographical areas of France are now equipped with generator and hailpad networks, the most homogeneous and best documented of these areas being the Midi-Pyrénées region (Fig. 1). In this region, an average of 152 generators and 283 hailpads covered an area of approximately 16,000 km² during the 17 hail seasons of the 1988-2004 period.

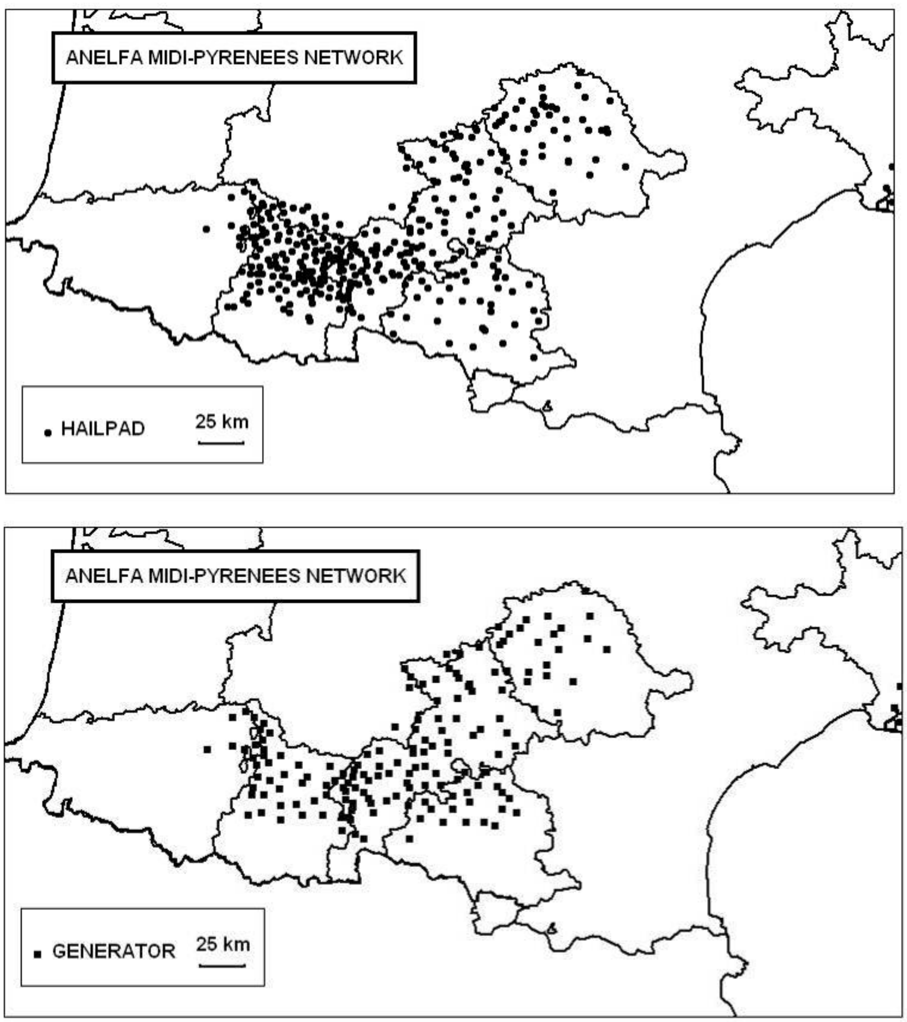

Fig. 1. Maps of the hailpad and seeding stations in the Midi-Pyrénées region in 2004.

The seeding and hail data considered in this paper are those already used in the first physical evaluation of the project (Dessens 1998):

i, measured point hailfall on a given day,
n, number of point hailfalls for the day,
N_i, total number of hailstones larger than 0.7 cm at this point,
N_m, mean value of N_i for the day,
$\Delta N_i = N_i - N_m$,
S_i, amount (in g) of silver iodide released in the development area during the 3 hours preceding the hailfall time,
S_m, mean value of S_i for the day,
$\Delta S_i = S_i - S_m$.

On a given day, the variations in the S_i values essentially depend on the relative positions of the point hailfalls and of the generator stations, since all the generators of a local network run simultaneously (except in the cases when an operator is unavailable or when there is a technical failure)

The determination of the development area is described in Dessens (1998), but a slight correction has been introduced in Dessens (2003). The center of the circle is now computed by considering a mean value of 27° for the deviation of the storm to the right of the wind direction at the 600 hPa level, instead of 31° before. The storm velocity is still estimated to be 18% lower than the wind velocity at the same level. The other two parameters for the localization of the development area are unchanged: ΔT = 80 min, R =13 km.

In this paper, the estimate of the seeding effect is based on the correlations between $\Delta S_i/S_m$ and $\Delta N_i/N_m$, instead of ΔS_i and ΔN_i before. The aim of this normalization will be explained in section 5a. The physical principle of the method remains that, if there is a beneficial effect of the seeding, the hail cells which have developed over dense parts of the generator network will produce hailfalls of lesser intensity. For a visual display of the seeding effect, the cumulative deviations of the parameters are also graphically represented.

The total sample examined here amounts to 1948 point hailfalls distributed over 425 days. The number of hailfalls per day varies from 1 to 43, with more than half of the occurrences being relative to days with only one or two hailfalls (minor hail days).Out of these 425 days, there were only 82 days with 860 hailfalls for which a hail warning was followed by at least some seeding (S_m >0), and for which at least two hailfalls were measured (n>= 2). This difference is explained by the forecasting rules which specify that warnings are issued only in severe situations. The distribution of the 82 hail days according to the number of hailpads per day is given in Fig. 2 which shows, for example, that 55 hailfalls occurred on days when only 2 or 3 hailpads were impacted.

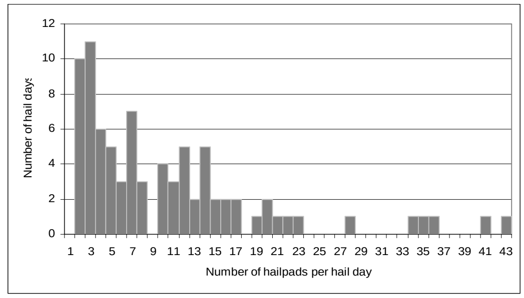

Fig. 2. Distribution of 860 hailfalls measured during 82 days with seeding.

The coefficient of the linear correlation between the independent 860 data pairs ($\Delta S_i/S_m$, $\Delta N_i/N_m$) of the 82 seeded days is r = -0.105, which corresponds to the 0.01 significance level. The graph in Fig. 2 is drawn with the cumulative values of $\Delta N_i/N_m$ as a function of the cumulative values of $\Delta S_i/S_m$. The right part of the graph is for the 323 hailfalls seeded more than average, and the left part for the 537 ones seeded less than average. On the right part of the graph, when the normalized number of hailstones is below the daily average (beneficial seeding effect), the curve goes down. On this graph, the hailfalls have been ordered chronologically (day, hour) from the point of coordinates (0, 0). On the whole, the right curve is observed to go down, and does not seem likely to return to the x axis in the future. This means that, on a daily average, more seeding corresponds to less hail. The left part of the graph gives a nearly reversed image, since at the end of each day, the cumulative values of the parameters are exactly opposite.

A careful examination of Fig. 3 indicates that the slope of the curves is higher for the heavily hailed years, suggesting a better efficiency of the seeding during major hail days. This observation is confirmed when the day-by-day correlations are considered, but the explanation is probably that the seeding response is only visible when many hailfalls are recorded. For the days with only a few hailfalls measured, the correlation is masked by the natural random distribution of hailfall severity. This effect is highlighted in Fig. 4, which is a rearrangement of Fig. 3 once the days have been ordered by increasing number of impacted hailpads from n = 2 to n = 43. The oscillations of the curve around the x axis show that no seeding effect can be clearly discerned if n is lower than 12 to 14, which corresponds to the point where the curve intersects with the x axis for the last time. The effect is even better visualized in Fig. 5 where the cumulated daily values of ΔN_i for $\Delta S_i > 0$ are plotted as a function of n, the seeding amount not being taken into account. The curve for the less-seeded-than-average hailfalls is not reproduced, since it is exactly symmetrical to the one for the positive ΔS_i. Obviously, no seeding effect can be systematically observed for the days with less than 14 or 15 recorded hailfalls. This observation is quantitatively confirmed by the values of the correlation coefficients: r = -0.04 for the 422 hailfalls for days with 2 to 14 hailpads, and r = -0.16 for the 438 remaining hailfalls.

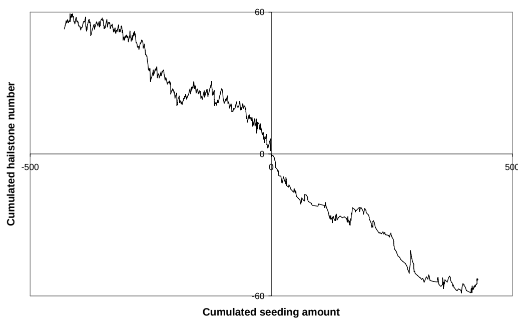

Fig. 3. Cumulated values of $\Delta N_i/N_m$ as a function of the cumulated values of $\Delta S_i / S_m$ for 323 hailfalls seeded more than average (right part), and for 537 hailfalls seeded less than average (left part). The days are chronologically ordered.

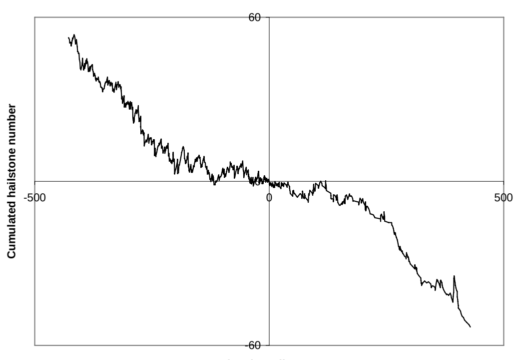

Fig. 4. Same as Fig. 3 but with days ordered by increasing number of impacted hailpads.

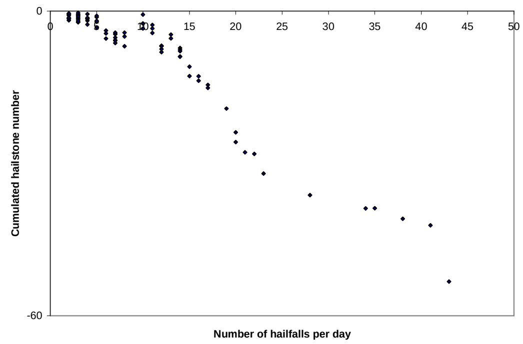

Fig. 5. Daily cumulated values of $\Delta N_i/N_m$ for 323 hailfalls seeded more than average. The cumulated values are plotted at the end of each day. The hailfalls are relative to 82 days ordered by increasing number of impacted hailpads.

Results for 18 major hail days

For the quantitative determination of a seeding effect, the sample is then reduced to the 438 hailfalls recorded on the 18 days with at least 15 recorded hailfalls. These few days are evidently the major hail days for which the hail prevention system has been developed, and luckily the control method is adapted to these events. The graph in Fig. 6 gives the curve relative to the 156 hailfalls seeded more than average, each point being computed at the end of a new day. As in Fig. 5, it is not useful to reproduce the curve for the 282 less-seeded-than-average hailfalls. The days are ordered chronologically.

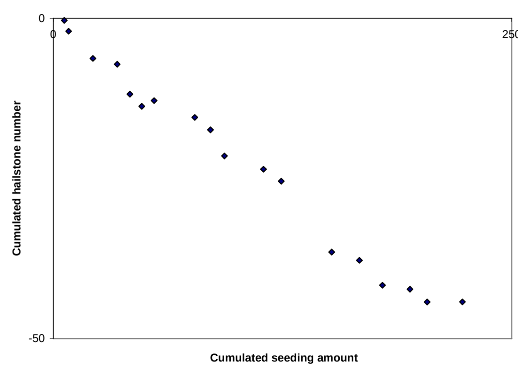

Fig. 6. Cumulated values of $\Delta N_i/N_m$ as a function of the cumulated values of $\Delta S_i/S_m$ for 156 hailfalls seeded more than average and relative to 18 major hail days. The cumulated values are plotted at the end of each day, and the days are chronologically ordered.

The graph in Fig. 6 shows a rather regular decrease of the hailstone cumulated number as a function of the seeding surplus. Among the 18 days, 15 well contribute to the appearance of a beneficial seeding effect, 2 days are neutral, and only one day gives the impression that the seeding has increased the hailfall severity. The daily values of S_m, N_m, and of the correlations between $\Delta S_i / S_m$ and $\Delta N_i / N_m$ are given in Table 1. All but one day have negative r values, but a significant level is reached only for the day with most impacted hailpads. For each day, the correlation in parentheses is also computed with all the hailfalls until this date (and including it). A statistically significant correlation is observed from day N° 11 at the 0.05 level, or from day N° 13 at the 0.01 level. The last days of the series reduce a little the coefficient r, which nevertheless remains at the 0.01 level.

Table 2 summarizes the seeding and hail data for the major-day hailfalls. The N values given in Table 2 allow the computation of a mean seeding effect. The hailfalls seeded less than average have received a small amount of seeding and, if we suppose a linear response to the seeding, their mean hailstone number is slightly lower than it would have been without any seeding. The hailstone number N for S = 0 can be computed with the equation:

$$(N - 1514)/17.7 = (N-1315)/57.2 \quad (1)$$

which gives N = 1603. The seeding efficiency based on the reduction in the number of hailstones is then:

$$[1- (955/1603)] \times 100 = 40.4\%. \quad (2)$$

Table 1. Number of recorded hailfalls (n), mean seeding amount (S_m, g/3h) and mean haistone number (N_m, m^{-2}) for major-day hailfalls. The correlation coefficient (r) between the normalized values of S_i and N_i is given by day, and, in parentheses, for all the days together until that day.

Day	Date	n	S_m	N_m	r
1	17/05/90	22	130	1007	-0.04 (-0.04)
2	13/08/90	17	191	296	-0.27 (-0.11)
3	27/09/92	28	20	2077	-0.29 (-0.20)
4	05/07/93	16	20	641	-0.12 (-0.14)
5	16/05/94	20	72	803	-0.27 (-0.15)
6	18/06/94	20	98	1392	-0.26 (-0.16)
7	31/07/94	16	101	1318	-0.10 (-0.15)
8	02/07/95	34	46	1510	-0.06 (-0.13)
9	17/05/97	15	12	1144	-0.14 (-0.13)
10	01/07/98	19	48	934	-0.21 (-0.13)
11	02/07/98	36	56	2158	-0.15 (-0.14)
12	26/09/98	15	7	1091	-0.17 (-0.14)
13	29/04/99	43	33	1479	-0.46 (-0.19)
14	18/05/99	41	91	1216	-0.11 (-0.17)
15	02/06/99	23	17	1661	-0.31 (-0.18)
16	13/05/00	17	5	1174	-0.10 (-0.17)
17	01/06/03	21	33	843	-0.20 (-0.17)
18	28/08/03	35	56	1317	+0.05 (-0.16)

Table 2. Mean seeding amount, hailstone number and kinetic energy for major-day hailfalls seeded respectively more and less than average.

Parameter	All hailfalls	Hailfalls seeded more than average	Hailfalls seeded less than average
Number of hailfalls	438	156	282
Mean seeding, g/3h	57.2	128.5	17.7
Mean hailstone number, m^{-2}	1315	955	1514
Mean kinetic energy, $J.m^{-2}$	99.3	63.6	119.0

4. Discussion

The results presented in this paper reinforce those already given in Dessens (1998), because they are relative to a larger sample of major hail days in a more homogeneous region. They also suggest a few points not discussed before, among which:

a. Normalization of the data

The normalization by S_m and N_m has initially been adopted because it gives better values for the correlation between seeding and hailfall intensity. For example, with the normalization, the correlation coefficient increases from -0.082 to -0.105 for the 860 hailfalls of the total sample, and from -0.139 to -0.162 for the 438 major-day hailfalls. The normalization, however, does not deeply change the analysis, as shown in Fig. 7, where the graph of Fig. 6 is redrawn with the non-normalized data. The curve progression in Fig. 6 is simply more regular than that of Fig. 7.

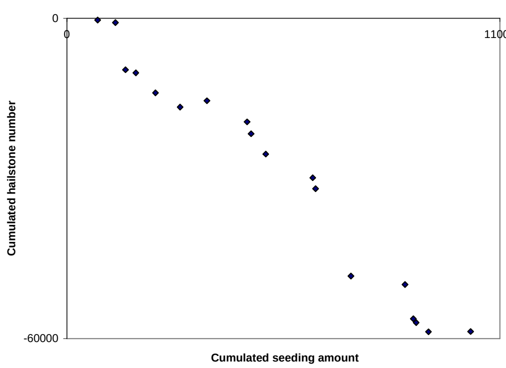

Fig. 7. Same as Fig. 6 but with cumulated values of ΔN_i (in m^{-2}) as a function of the cumulated values of ΔS_i (in g/3h).

b. Statistical significance of the evaluation

The coefficient of the correlation between the paired values ($\Delta S_i / S_m$, $\Delta N_i / N_m$) gives an estimation of the seeding effect significance level. A paired t-test can also be applied to the daily differences between the mean value of $\Delta Ni / N_m$ when $\Delta S_i > 0$, and the mean value when $\Delta S_i < 0$. For the 82 hail day sample, the averaged difference is -0.196, its standard deviation is 0.946, and the 95% confidence interval is 0.205, which means that the null hypothesis cannot be strictly rejected. For the 18 hail day sample, the averaged difference is -0.468, the standard deviation is 0.359, and the 99.9% confidence interval is 0.278; the null hypothesis is rejected. Unlike the correlation computation, the t-test results are the same with or without the normalization.

c. Virtual seeding

The Midi-Pyrénées sample also contains 921 hailfalls recorded on 173 days without any seeding and with at least 2 impacted hailpads. A sort of placebo method consists in computing the seeding amount for these hailfalls as if the generators had been running. A graph like that of Fig. 3 for these hailfalls (not reproduced here) does not show any seeding effect. If the same process is repeated for the 11 days with at least 15 impacted hailpads, a hail decrease tendency is nevertheless observed (not significant at the 0.05 level). In the future, a few more major hail days without seeding will possibly confirm some persistent effect already observed with silver iodide (Bigg and Turton 1988).

d. *Direct correlation between S_m and N_m*

The significant measured effect of the seeding on the number of hailstones makes it possible to observe a direct correlation between S_m and N_m. For the 18 seeded major hail days listed in Table 1, the correlation coefficient is r = -0.38, which is not far from the significant level. The correlation, however, is mainly driven by day N° 2. On that day, the 0°C isotherm was at an altitude of 4 km, the maximum value for the sample. The reduction of the hailstone number is probably due to the combined effect of the melting and the seeding. This observation illustrates the interest of a differential method correlating the parameters on a daily basis.

e. Evaluation based on the kinetic energy

Instead of the hailstone number, the total kinetic energy of a hailfall is often used as a measure of its severity. This parameter was not used in the former evaluations of the ANELFA project with the hailpad data because of a problem of data normality due to the small number of hailfalls with very large hailstones (Dessens 1998), but the problem has decreased now that a larger data sample is available. When the evaluation for the major-day hailfalls is made with this parameter, the hail decrease computed as in Section 4 for the hailstone number amounts to 50.2%, the result being significant at the .01 level.

6. Conclusion

A sensitivity test for the control of hail prevention by silver iodide ground seeding has been conducted in one of the most hailed regions of France. In this region (Midi-Pyrénées), there is a generator station releasing silver iodide nuclei on days with a hail forecast each 10 km, and a hailpad station each 7 km. These distances are comparable to the dimensions of hail cells. With this geographical disposition, the correlations between the amount of silver iodide presumably delivered to a developing hail cell, and the intensity of the subsequent hailfall show that, probably due to the random nature of hail, no seeding effect can be properly detected if less than about 15 hailfalls have been measured. It is not sure that this number can be reduced by an increase of the hailpad density, because such an increase may introduce redundant measurements and then reduce the independence of the data.

With this restriction in the hailfall sample, the differential method of control of the ANELFA hail prevention project for 18 major hail days having occurred in the Midi-Pyrénées region from 1988 to 2004 confirms the results already published (Dessens 1998): hail cells seeded by generators networks with a density of about 10 generators par 1000 km² produce 40% fewer hailstones larger than 0.7 cm and 50% less kinetic energy. The reduction in crop losses is of the same order (Dessens 1998). Until now, the respective localization of the developing hail cell and of the resulting hailfall is determined with a mean storm displacement estimated from wind soundings. An improvement in the control could certainly be obtained from a better knowledge of the ice-forming nuclei dispersion in the lower atmosphere, and from hailstorm simulation. To this aim, an application of the Meso-NH simulation model (Pinty et al. 2001) is now underway at the Laboratoire d'Aérologie of the University of Toulouse in collaboration with the ANELFA.

A more global and simple correlation between the mean seeding for a day and the mean number of hailstones in the hailfalls of that day is becoming statistically significant. With a data sample increasing year after year, it will soon be possible to work on the Principal Component Analysis for the major hail days by considering as variables the altitude of the 0°C, the wind shear, etc…, and the seeding intensity.

By developing its differential method, the ANELFA wants to demonstrate the possibility of hail prevention control without randomization. The new results of the French program are coming at a time of increasing confidence in hail prevention operations (American Society of Civil Engineers 2003, World Meteorological Organization 2005), and they could be useful to the development of experimental or operational programs in other countries.

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