SEEDING OPTIMIZATION FOR HAIL PREVENTION WITH GROUND GENERATORS

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Abstract: An evaluation method of hail prevention by silver iodide ground seeding generators is developed. The method is based on correlations between the point hailfall intensities measured with hailpads and the silver iodide released prior to the hailfalls in the “feeding areas” where the hail cells developed. The time unit for the correlations is the day, but days can be aggregated together after data normalization. Former evaluations have shown that the number of hailstones larger than 0.7 cm is mainly responsive to the amount of seeding material released in a 13-km radius area centered on the place where the storm was developing 80 min before the hailfall, and that the seeding effect can be detected only for the days with at least 15 hailed pads.

In this paper, the method is applied to 24 major hail days with seeding recorded in the past 20 years in a hailed region north of the Pyrenees. For each day, 15 to 42 point hailfalls have been recorded, and they are used to compute the best negative daily correlation between hailfall intensity and seeding amount by moving the feeding area around its first approximate position. With this seeding area optimization, all the daily correlations are negative (more seeding, less hail), but they are weak, with a correlation coefficient reaching about r = -0.3 in only half of the cases. For the whole hailfall sample (561 hailfalls), the correlation computed with the ideal feeding areas determined as indicated above is r = -0.22, significant at the 0.01 level, subject to the data independency hypothesis. In average, the distance from the middle of the feeding area to the hailfall corresponds to a storm travel time of 66 min, but a numerical simulation of the seeding particle trajectories with the Meso-NH model suggests that the generators must be started at least 45 min before the storm travels above them.

1. INTRODUCTION

In France, seeding hailstorms from silver iodide ground generator networks has a long practice, since the ANELFA (Association Nationale d’Etude et de Lutte contre les Fléaux Atmosphériques) has been developing its field experiment since 1952 without interruption. It was only a few years ago, however, that the evaluation of the project was physically quantified by comparing the point hailfall measured parameters to the silver iodide amounts released before the hailfall time in the area where the hail cell was developing.

The evaluation of the seeding effect is made with an *a priori* hypothesis: greater amounts of seeding material presumably delivered to the storm lead to smaller hail intensities (as measured either by hailstone number or kinetic energy). After observing that, in general, hail is less severe at points located at the NE of well-seeded areas (most of the hailstorms are moving from SW to NE in France), the following method was designed when hailpad data became available. For a day with several hailfalls, to each point hailfall determined by its number of hailstones larger than 0.7 cm is associated the silver iodide amount released in a circle centered where the hail cell was presumed to be developing before the hailfall (the “feeding area”). Data normalizations with the mean daily values of these parameters allow to aggregate hail days together.

With the first 10 years of hailpad data, the hailfalls were determined to be mostly responsive to the seeding performed in a circle where the hail cell is located T = 80 min before the hailfall, and the circle area including the most efficient seeding stations was found to have a radius of R = 13 km (Dessens 1998). A refinement of the method was developed later, when a sensitive test showed that a significant effect is detected only for the major hail days with at least 15 point hailfalls recorded (Dessens et al. 2006). The present work is a re-examination of these major hail days with seeding activity. Since it is most probable that the position and the radius of the circle giving the best correlation between the seeding and the hailfall intensity change from one day to the next, the daily correlations will be computed with the first approximation parameters (T = 80 min, R = 13 km), then with parameters varying around these values. The circle will also be moved to the right and left of the storm trajectory.

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Table 1. Storm and hailfall parameters for the 24 major hail days. From left to right: case number (with asterisk for supercells), date, storm propagation (direction and velocity), number of point hailfalls, maximum hailstone diameter, mean number of hailstones larger than 0.7 cm, mean kinetic energy, storm travel time between the feeding area and the hailfall, correction for the direction, feeding area radius, and seeding/hail correlation coefficient.

	Day	α °	V km/h	n	Dmax cm	N /m²	Em J/m²	T min	Δα °	R km	r
1	17/05/90	261	34	22	2.5	1007	50.2	60	10	13	-0.20
2	13/08/90	280	36	17	1.5	296	13.3	60	10	10	-0.37
3	27/09/92	205	30	28	3.0	2077	165.8	60	10	13	-0.32
4*	05/07/93	263	49	16	3.7	645	131.5	90	0	13	-0.16
5	16/05/94	234	64	20	2.0	803	32.3	70	0	13	-0.36
6*	18/06/94	244	46	20	4.4	1392	177.7	70	-10	10	-0.31
7	31/07/94	230	36	16	3.7	1318	90.0	50	10	10	-0.42
8*	02/07/95	244	50	26	4.0	1682	183.6	50	10	16	-0.21
9	17/05/97	221	33	15	1.7	1144	52.9	60	0	13	-0.20
10*	02/07/98	263	65	40	3.3	2054	147.8	90	0	10	-0.30
11	26/09/98	227	62	15	3.3	1091	129.8	70	0	13	-0.21
12	29/04/99	247	40	43	2.6	1479	87.1	70	0	13	-0.48
13*	07/05/99	261	55	25	4.4	2024	191.2	80	0	13	-0.10
14	18/05/99	215	38	42	2.1	1211	63.2	90	-10	13	-0.14
15	02/06/99	258	59	23	2.5	1661	95.3	60	10	16	-0.36
16	13/05/00	280	33	20	2.0	1036	52.6	60	10	16	-0.23
17	01/06/03	230	23	21	4.0	843	55.7	60	0	10	-0.28
18*	28/08/03	245	59	36	3.3	1317	122.5	60	10	13	-0.23
19*	13/05/05	232	44	18	1.6	2091	78.1	70	-10	16	-0.21
20	28/07/05	228	48	19	3.9	831	189.6	90	0	13	-0.29
21	15/04/06	282	47	16	2.4	2723	137.3	50	0	10	-0.17
22	21/07/06	270	33	23	4.3	1911	158.6	50	0	13	-0.39
23*	27/07/06	235	55	18	2.4	2019	103.8	60	10	13	-0.29
24	17/04/07	108	15	22	1.6	727	32.2	50	10	13	-0.01

2. DATA SAMPLE

The Midi-Pyrenees region is one of the most heavily hailed areas of France (Dessens 1986). It is there that the ANELFA has had its longest experience in seeding operation and hailpad measurements, with 152 ground generators and 336 hailpad stations operated in an area of 16,000 km². The climate is oceanic, but altered by the Pyrenees in the south and by the Mediterranean in the east. The topography is marked by the Garonne valley and by many smaller valleys coming from the Pyrenees. Except near the mountains, the altitudes range from 100 to 600 m above sea level. At the end of the 2007 hail season, 2495 point hailfalls have been recorded in this area, 561 of them having occurred on 24 days with seeding activity and at least 15 point hailfalls (Table 1). For details concerning the seeding and the hail measurement, one can refer to Dessens et al. (2006), and only a brief description of these activities is given below.

2.1 Point hailfall intensity

Each point hailfall measured with the hailpad network is characterized by the total number of hailstones larger than 0.7 cm, Ni (m^{-2}), or by the total kinetic energy computed with all the hailstones, including those from the 0.5-0.7 cm diameter range. Since the data normality is, in general, better with the first parameter, the correlations are computed with it, but the seeding efficiency will also be estimated from the kinetic energy because this parameter is of a more general use. When days are aggregated together, the Ni values are replaced by their normalized values, Ni – Nm, Nm being the daily mean value of Ni (Dessens 1998).

2.2 Storm propagation

Since the object is to compare the hailfall intensity with the seeding material injected in the hail producing cells, the propagation parameters of the storm (direction and velocity) must be known. These parameters are, in general, well determined for the long trajectory hailstorms, usually of the supercell type. The direction is defined at a precision better than 5° with the observation of crop damages, and the velocity is computed from the hailfall time recorded by the observers. The direction and velocity of the multicell storms are not so easy to determine, and it is, in general, necessary to estimate at least one of these parameters from the sounding data after determining a general propagation rule for the hailstorms. This rule indicates that a severe hailstorm in southwestern France moves in a direction of 31° to the right of the wind at the 600 hPa level, and at a speed 18% lower that the wind velocity at the same level (Dessens 1998). In a further evaluation (Dessens et al. 2006), it was however observed that a 27° deviation gives better correlations between the seeding and the hail intensity, so this value is used in the present study.

The data sample examined in this paper is relative to 24 hail days for which the storm direction was directly observed in 11 cases and the velocity in 8 cases. In the other cases, the parameters were computed from the wind data of the nearest sounding made in the upflow air mass at 00UTC and 12 UTC at Bordeaux, Zaragoza, or, in one case, Nîmes. Table 1 gives the propagation parameters, α and V, for each of the 24 hail days.

2.3 Seeding amount.

The seeding stations are equipped with a vortex generator burning 1.1 l/h of a silver iodide-sodium chloride solution, which corresponds to a release of 8.6 g/h of pure silver iodide in the atmosphere. The seeding parameter, Si, used for the correlation with a point hailfall parameter is the total weight of silver iodide burnt for the 3 hours preceding the hailfall by the generators included in the circle considered as the hail cell development area. For example, for a circle with a 13 km radius, if there are 5 generators really burning during the 3 hours, the seeding amount is 5 x 8.6 x 3 = 129 g/531 km². In case of a late warning or generator deficiencies, this amount can be reduced, even down to 0. The Si values are replaced by their normalized values, Si – Sm, when days are aggregated together.

3. LOCALIZATION OF THE RESPONSIVE SEEDING AREA

In order to locate the feeding area, the method first consists in computing the point-to-point correlations between the number of hailstones larger than 0.7 cm at each hailfall point, Ni, and the seeding amount released during the 3 hours preceding this hailfall in the circle with a 13 km radius centered where the hail cell was presumably developing 80 min before the hailfall, Si. There is one data pair for each hailed pad, and the adjustments regarding travel time and direction and size of circle are the same for every hailpad included for a given day. It is worthy to note that the pads possibly receiving no hail as a consequence of the seeding are not included in the analysis.

Figure 1 illustrates the method for a day with 20 hailfalls recorded between 14.45 and 19.30 local time. The axis center is one of the 20 points, it received Ni = 39 m^{-2} hailstones. With the propagation parameters given in table 1, Fig. 1a locates the generators in the 13-km radius area centered at the place where the storm was 80 min before. For that day and that hour, the generator activity reports give a seeding amount Si = 224 g/3hr (one generator was not correctly running). The correlation coefficient computed with the 20 data pairs is found to be r = -0.31. The first step of the optimization consists in computing the correlations with the seeding amount in the circles located nearest and farthest from the hailfall point, at distances corresponding to travel times of respectively 70 and 90 min. If the correlation is found to be better (that means nearest to -1) for example at 70 min, then the correlation is computed at 60 min, and so on until the correlation stops decreasing (Fig. 1a). In the illustrated case, the correlation increases to r = -0.36 for 70 min (Si = 127 g/3h), but decreases to r = -0.20 for 90 min. A travel time of 70 min is then retained for the second step.

In the second step, one checks if the correlation improves when moving the circle with a deviation of 10° to the right and to the left of the direction from which the storm comes (Fig. 1c). In the last step, the circle with a 13 km radius giving the best correlation is changed for circles with a radius of 10 and 16 km (Fig. 1d). In the illustrated case, the correlation does not increase during the second and third steps. Table 1 gives the correlation coefficients, r, computed with the ideal parameters. For the example of May 16, 1994 presented in Fig. 1, the most responsive area is a circle with a 13 km radius and a center at 74 km in the exact direction of the incoming storm.

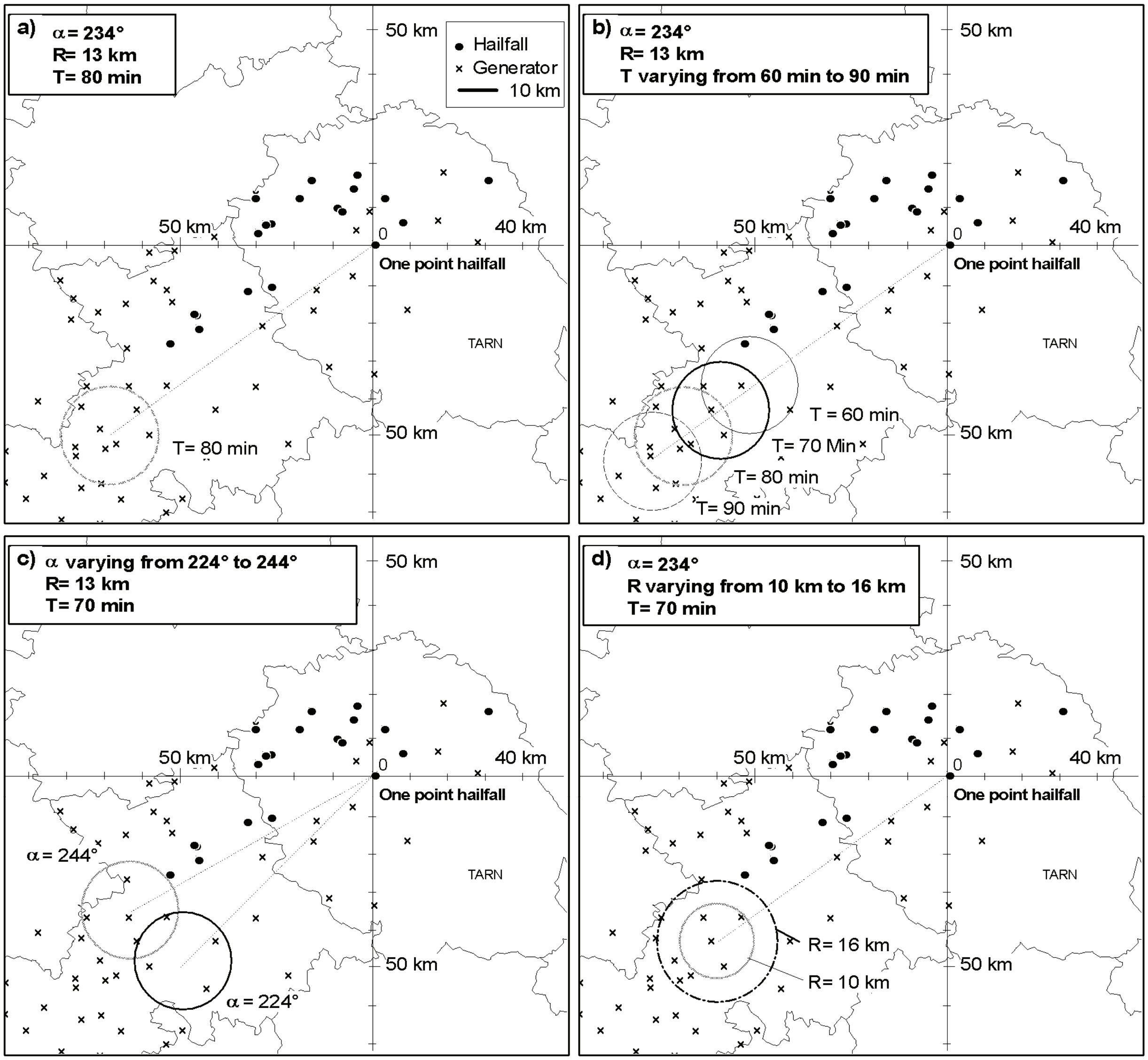

Fig. 1. Daily adjustment of the circle giving the best seeding/hail correlation. Example for May 16, 1994. The point hailfall location at the center is Cadalen, Tarn, hailed at 19.00 local time.
a) circle corresponding to the standard 80 min storm travel time
b) circles tested for longer and shorter travel times
c) circles tested for different directions
d) circles tested for different radiuses

Considering the most responsive areas defined as described above, all the daily r values are negative (Table 1), but they are weak, being statistically significant at the 0.05 level in only two cases. These negative correlations, however, seem sufficient to correctly locate the area where the seeding is most efficient. The average time between the seeding and the hailfall decreases from 80 to 66 min. The correction for the storm direction is 3°, which could mean either that storms are more feeding on their left side, or that their deviation from the wind at the 600 hPa level is 30° rather than 27°. The mean circle radius determining the most sensitive area, R = 13 km, remains unchanged. In fact, a detailed examination of the correlations shows that the correlations are very sensitive only to the first parameter (time).

Figure 2 shows the relative positions of the circle centers corresponding to the best seeding conditions for each day. With the axis origin as the geographical position of a hailfall, the points give, for each day, the center of the best seeding area relative to this hailfall. The gravity center of all the points is at (x = -42 km, y = -18 km).

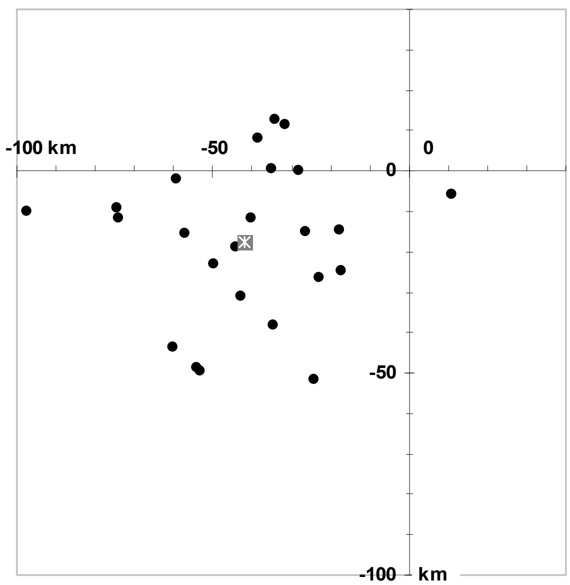

Fig. 2. Centers of the best feeding areas relative to a hailfall at point (x = 0, y = 0) for the 24 hail days. The gravity center is pointed with an asterisk.

4. STORM TYPE CORRELATIONS AND AVERAGE RESULTS

As everywhere in the world, damaging hail in France is produced by supercell storms, multicell storms, and storms intermediate between these main two types. The days with one or several supercell storms are marked with an asterisk in the first column of Table 1. Since, by definition, the supercell storms produce long trajectories of damages, their propagation parameters are, in general, available from the observations, and, in the absence of radar data, it is not necessary to infer them from the soundings. In three cases (Nos 16, 22, 24), most of the hailfalls occurred after local midnight local time (22.00 UTC), while, in general, the maximum frequency of hailfalls is in the late afternoon.

It appears from Table 1 that the seeding response is comparable for the supercell and the other hailstorms, and also for two of the three night cases. For the third night case N° 24 with a nearly zero correlation, the propagation parameters are doubtful: the velocity was low, and, in the middle of the night, the hailfall times are not well recorded by the observers. Moreover, for this case only was the wind flow from the east, so the radiosounding data of Nîmes, about 300 km away from the hailstorms, are used.

For each of the No 10 and No 12 days, the correlations are significant at the 0.05 level. The storm of July, 2, 1998 was absolutely characteristic of an isolated supercell. It moved at 65 km/h over more than 140 km. On the contrary, the storm of April, 29, 1999, was rather a multicell storm moving at 40 km/h over a diffuse trajectory of 60 km. This last case has been the subject of a detailed numerical simulation by Wobrock et al. (2003).

With the normalized values (Si – Sm) and (Ni – Nm), one can draw a scatter plot of the 561 hailfalls (Fig. 3). The interesting first observation is that the strongest hailfalls (large Ni – Nm values) are concentrated on the left side of the figure (less-than-average seeded hailfalls). The linear regression has a correlation coefficient r = -0.22, a value statistically significant at the 0.01 level if the data are independent. This problem of independence is discussed in a former paper (Dessens 1998). With a mean distance of 7 km

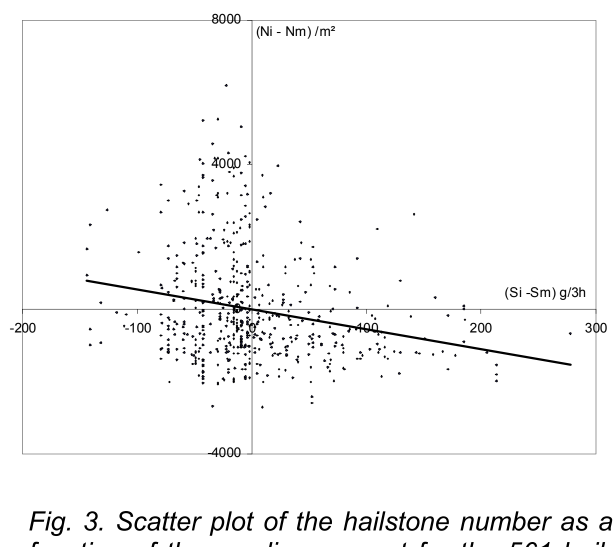

Fig. 3. Scatter plot of the hailstone number as a function of the seeding amount for the 561 hailfalls.

between two hailpads, the dependence of the data appears to be low but can lead to some overestimation of the significance of the correlation between seeding and hail.

If one wonders what happens if the regression line is extrapolated to estimate how much seeding would be required to drive the hail amount to zero, even if it is pure speculation, the regression equation is:

$$Ni - Nm = -5.57\ (Si - Sm), \qquad (1)$$

with $Nm = 1430\ m^{-2}$, $Sm = 50.3$ g/3h, which gives $Ni = 0$ for $Si = 307$ g, a seeding obtained with 12 generators per 531 km². This extrapolation is evidently highly hazardous due to the correlation weakness.

The seeding effect can be computed more reasonably by comparing the hailfalls seeded less than average to those seeded more than average. The detailed computation is given in Dessens et al. (2006). For the 24 days taken together, the reductions in the hailstone number and in the kinetic energy amount to 41 and 48% respectively, these reductions being obtained by a seeding amount of 137 g of silver iodide burning for 3 hours in an area of 531 km², which corresponds to 5.3 generators located in the same area. These results are not much better than those found by Dessens et al. (2006) with a smaller data sample, but their statistical significance level is better (0.01 instead of 0.05, always subject to the independency hypothesis). They concern the most serious hailfalls recorded during the 20 years of measurements since their mean kinetic energy is 108 Jm^{-2}, to be compared with 67.8 Jm^{-2} for the other hailfalls.

5. PHYSICAL MEANING

The fact that a hailfall appears to be mainly responsive to the generators burning under the storm about one hour before the hailfall requires some physical interpretation. Yuter and Houze (1995) proposed a conceptual model of a multicellular storm based on radar observations made in Florida. This model introduces the notion of "particle fountains" in order to explain the concurrent microphysical evolution of the storm. A particle fountain is an updraft having its root in the surface layer. Updraft parcels stopping at warmer levels might contain a hydrometeor mass in the form of liquid water droplets. Updraft parcels that reach upper levels progressively contain more ice. The particles (droplets or ice) that fall out of the updraft parcels continue their fall through the environment of a predominantly weak vertical velocity that dominates the region between the few strong updrafts and downdrafts. There are so

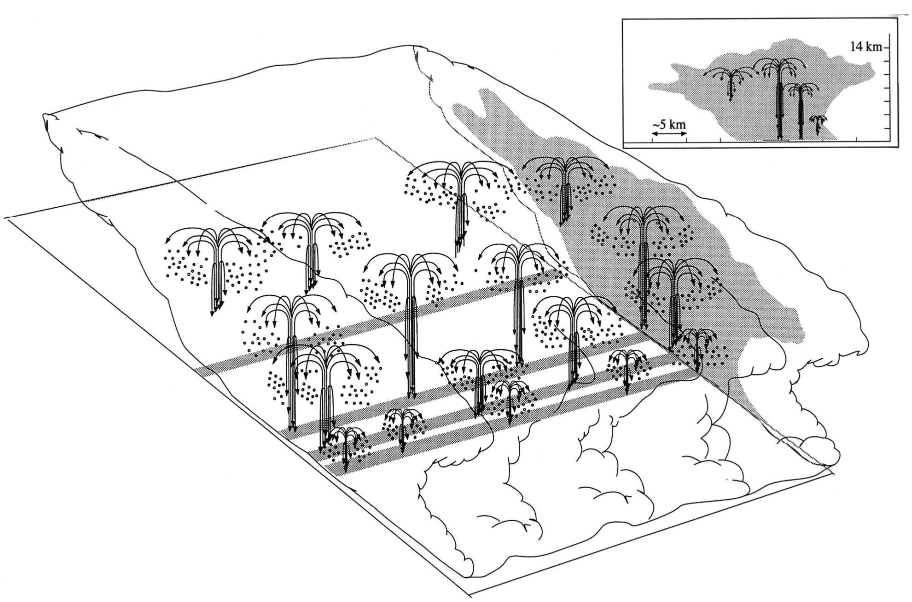

Fig. 4. Conceptual model of a set of particle fountains in a multicellular storm in perspective view. Shaded area represents radar reflectivity echo along a cross section perpendicular to the line of the storm. Cloud boundary indicated by scalloped outline. Inset shows approximate scales and arrangement of largest particle fountains relative to radar echo (from Yuter and Houze, 1995).

many particle fountains in this model (Fig. 4) that the seeding of all the updrafts can be performed only from generators that have been started early enough to seed the whole boundary layer before the storm develops.

A numerical simulation made for the ANELFA at the Laboratoire d'Aérologie of the Université de Toulouse (Lascaux and Richard 2006) will complete the description of the seeding process. The French non-hydrostatic model, Meso-NH (Richard et al. 2003), has been used to determine the back trajectories of the particles reaching the core of a storm. Two simulations have been performed in a preliminary research, one for the ideal simplified case described by Klemp and Wilhelmson (1978), the other for the severe hailstorm of May 21, 2004, in the Midi-Pyrénées region. The simulation considers two interlinked domains of respectively 8 and 2 km horizontal resolution, and has 55 altitude levels with the first one at 10 m above the ground. For the real storm, the model is initialized and forced with the ARPEGE data of Météo-France. The simulation correctly reproduces the observations made on that day: 22 point hailfalls have been recorded in the afternoon, and the day is not included in the 24-day sample only because there was no seeding at all in the network. The storm was of an intermediate type between the supercell and the multicell. According to the radiosounding of Bordeaux, 12.00 UTC, the cloud base and the 0°C isotherm level were respectively at 1000 m and 2800 m above the mean ground level.

Two main results can be drawn from both simulations:

- The air trajectories finishing inside the hail cloud at an altitude of 5 km come either from the same level behind the advancing cloud, or from the boundary layer (below 1 km) in front of the storm. The existence of the horizontal trajectories is interesting for the purpose of aircraft seeding, while the ground seeding is concerned by the trajectories coming from the lower levels.

- In the simulation of May 21, 2004, where the storm was moving at about 40 km/h, 45 to 60 min are needed for a particle released near the ground to reach the cloud. While the correlation method presented in this paper correctly locates the efficient seeding area, it seems that the nuclei entering the cloud are those produced in the same area 45 to 60 min before the passing of the cloud (Fig. 5). Once again, this observation justifies that the seeding must begin at least 3 hours before the hailfalls.

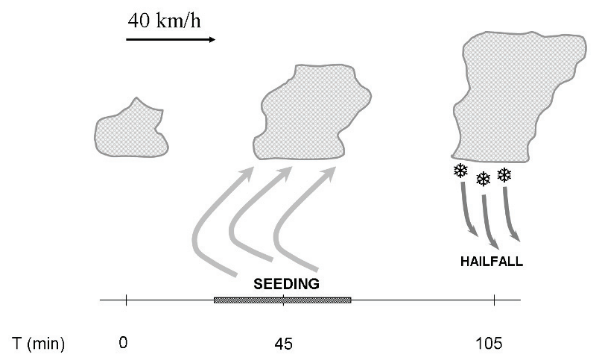

Fig. 5. Schematic disposition of ground seeding relative to hailfall. It takes 45 to 60 min for the seeding material to reach the cloud before it passes above the seeding area (numerical simulation), then 60 to 70 min more to affect the hailfall (seeding/hail correlation).

6. CONCLUSION

The work presented in this paper aims at a better understanding and targeting of hail prevention by silver iodide ground seeding. It started from previous results showing that, in average, hailfalls are responsive to silver iodide emissions from ground generators located in a circle of 13 km radius located where the developing hail cells are 80 min before the hailfall. The present study consisted in considering only the major hail days and in trying to determine if the correlation between seeding and hail intensity improves when the circle is moved around this mean position and when its radius is changed.

For the 24 major haildays examined in this paper, the correlation is mainly sensitive to a change in the time parameter. The mean value for this parameter reduces from 80 min to 66 min, which suggests that hailstones are growing faster in the most severe hailstorms. When the storm propagation is deduced from the wind velocity at the 600 hPa level, a mean shift of 30° to the right for these severe storms appears to be more appropriate than the 27° deviation considered before. For the third parameter, the former evaluation of R = 13 km for the radius of the area most responsive to the seeding remains unchanged. The implication for hail prevention of this new evaluation is that, in the Midi-Pyrénées region, the seeding should be concentrated about 45 km to the southwest of the areas to be protected from the most severe hailstorms.

With the ideal circles as the seeding areas, the correlation computed for all the days together remains weak (r = -0.22 for the 561 data pairs) but indicates a positive association between seeding and reduced hail defined by the number of hailstones larger than 0.7 cm. This average result confirms a former one based on a smaller sample of severe hail days. In the future, the ANELFA control method of seeding prevention should be improved thanks to a more exact knowledge of the silver iodide emissions obtained by continuously measuring the temperature of each generator chimney. Moreover, the storm propagation will be determined from radar data, and not only from ground observations or sounding measurements.

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