Hail in Southwestern France. II: Results of a 30-Year Hail Prevention Project with Silver Iodide Seeding from the Ground

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(Manuscript received 4 April 1984, in final form 6 July 1985)

ABSTRACT

A nonrandomized weather modification project, hail prevention by seeding from the ground, has been run since 1952 in a large area of southwestern France. From the beginning of the experiment, the parameter proposed to measure the seeding efficiency in the area covered by AgI ground generators was the loss-to-risk ratio derived from insurance data. The analysis of the trend of this parameter in three parts of France which constitute a target, a buffer and a control area, brings to light a relative decrease of the damage during the last years in the protected area. A new statistical test for detecting a shift in precipitation series, applied after a log-transformation to the loss-to-risk ratio series, indicates a decrease significant at the 0.01 level in the damage due to hail during the period 1965–1982 in the protected area, while no significant change has been observed in the buffer area. Since there has been a large increase in the number of generators, and, above all, the setting up of better equipment since 1965, seeding is a reasonable explanation for the hail decrease.

A double-ratio calculation with the target and control data gives a value of 41% for the decrease of the damage in the seeded area. Within this area, the global result is strengthened by the positive departmental correlation between the number of seeding stations per unit area and the hail decrease. The benefit-to-cost ratio of the project appears to be about 24.

The hypothesis of a seeding effect leads to the following main physical implications: 1) The seeding effect is only perceptible in the area where the generators are distributed and not downwind of this area; this is in keeping with the observation that the ice-forming nucleus concentration is only locally increased over the seeded area. 2) At least 65% of the hail situations in southwestern France are related to cold fronts; the decrease of the hail damage corroborates the results of the Argentinian hail suppression project where a beneficial influence of AgI ground seeding was found to be significant under cold front situations.

1. Introduction

In the middle of the 1980s, weather modification is the subject of a scientific controversy concerning hail suppression by cloud seeding. On the one hand, Russian scientists claim that direct injection of artificial ice nuclei by mean of rockets in the "accumulation zone" of hail cells leads to a substantial hail damage reduction; the technique is used on a large-scale basis in several regions of the Soviet Union and their satellite countries (Burtsev, 1980). On the other hand, one national and one international project, aimed at determining through randomized experiments the efficiency of the direct injection method, have led to the conclusion that this method is probably inoperative, at least in the two experimental regions where it was tested. First, the American National Hail Research Experiment has not succeeded in decreasing hail production from storms in northeast Colorado by aircraft seeding (Knight *et al.*, 1979); in fact, after a 3-year seeding period, the American scientists concluded that the hailstorm model on which the Soviets based their method of hail prevention did not generally apply to northeast Colorado and they terminated seeding operations. Second, the international experiment Grossversuch IV, a randomized repetition of the Soviet technique using Soviet material in Central Switzerland, failed to demonstrate any significant effect after a 5-year period (Federer *et al.*, 1984).

During the same time as these experiments and discussions, the project proposed by H. Dessens (1952), was run continuously on a large scale in southwestern France. The technique consists in using silver iodide ground generators in order to produce an increase in the ice-forming nucleus concentration in the atmosphere before and during the development of hailstorms. The project began in 1952 with 19 charcoal generators forming a defense line along the Atlantic and the Pyrenees. The network was then progressively expanded; at the same time, an acetone generator was designed to replace the low-efficiency charcoal generator. In 1965, the project reached its final form, and the only improvement since that time was to use a better meteorological forecast which led to a reduction of the number of operational days.

It appears to H. Dessens that the most pertinent control of the experiment was the survey of the hail insurance data. He obtained from the French insurers the yearly publication of their data since 1944 in 13 departments of the area presumed to be under the in-

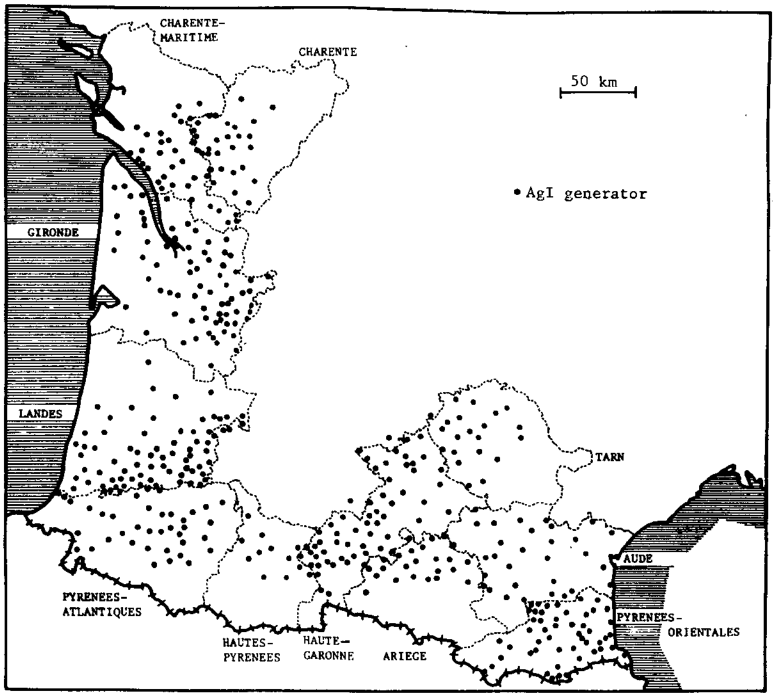

FIG. 1. The 455 stations of the ANELFA seeding network in 1984.

fluence of the seeding. The positive effect of the seeding was first observed 15 years ago, but the results were not significant because of the small amplitude of the effect and the short period (H. Dessens *et al.,* 1970).

2. Description of the experiment

a. Seeding network

The ANELFA (Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques; see Dessens, 1986; hereafter referred to as Part I) is administratively composed of departmental committees which supply financial support according to the number of seeding stations required. Consequently the ANELFA network has expanded with some geographical irregularities since 1952 (Fig. 1); it now consists of 455 stations over about 55,000 km^2 in 11 departments with a maximum density of 20 generators per 1000 km^2 in the most protected parts of the area. The generators are placed away from buildings and trees and are operated either by gendarmes and firemen or by farmers. In each department, one or two technicians, in charge of the operation, collect the seeding data and the hail reports.

The type of generator used since 1965 is the acetone vortex burner described by Dessens and Pham Van Dinh (1968). The device consists of a pressurized air bottle, a stainless steel tank and a vortex chimney in which an acetone solution is sprayed through a swirl nozzle and burned in a rotating flame. The solution consists of 98.6% acetone, 1% AgI, and 0.4% NaI (weight percentages). The counts of ice forming nuclei produced per gram of silver iodide and active at different temperatures (Pham Van Dinh, 1973) are reported in Table 1. The measurements were made by introducing a diluted sample of the aerosol produced by the generator in a cloud mixing chamber (Soulage, 1964).

The generator is used with a nozzle type Monarch NS, 0.75, 30° under a pressure of 1.3 atm.; the solution flow rate is 1.1 $l\ h^{-1}$ giving a silver iodide output of 8.8 $g\ h^{-1}$. The main advantage of this generator is its regularity of working in the field even when it is operated by unskilled labor. After many years of improvement, cases of misfire are very rare; it is also important that the generator operates without electric power, particularly in cases of severe thunderstorms leading to power failures.

b. Hail warning

According to an agreement between the ANELFA and the French Weather Service, the meteorological stations of Bordeaux and Toulouse are in charge of

TABLE 1. Nuclei of silver iodide active at different temperatures.

	Temperature (°C)			
	−15	−18	−21	−25
Nuclei ($\times 10^{14}$ per gram)	0.8	3.0	7.0	12

hail forecasting in their surrounding departments from April to October. Briefly, the ANELFA requests a forecast, issued more than 3 h before the hailfalls, of the period of possible hailstorms; if this forecast period is h_0 to h_1, the generators run from (h_0–3 h) to h_1.

Seeding is performed in all cases in which damaging hail is forecast (see Part I), except for the cases where the highest tropospheric wind velocities are less than 10 m s^{-1}. This exception prevents the seeding of thunderstorms which may produce more damage from rain than from hail. In theory, a forecast of hail may concern only one department, but the precision is generally not sufficient; thus the forecast area is the Atlantic Zone, the Central Zone, the Mediterranean Zone, or two of them, or the three together. Twenty years ago, the number of forecast hail days per department and per year was 40 to 60; thanks to progress in forecasting, it has been reduced to 20 to 30; the duration of hail forecasts has also been reduced and their mean value is now 10 h.

Despite the progress in forecasting, each year there are a few missed hail situations; for example, in the Haute-Garonne, there were 114 forecast hail days during the last 5 years (1980–1984); in the same period, the mutual insurance company suffered 24 hail days with severe damage (more than 200,000 francs per day), 8 of them not having been forecast.

c. *Data processing*

The information concerning the real-time operation of each generator and the weather report at the station (wind, thunder, hail . . .) are collected by the departmental technicians and compiled by the computer service of the ANELFA. For each case of reported hail damage, the quantity of silver iodide released during the 3 h preceding the time of hailfall in an area of 1600 km^2 around or upwind of the hailfall area is estimated; an example of the use of these data has been given by Dessens (1980).

3. Control of the experiment with the insurance data

A problem in using the insurance data for the control of the experiment is the choice of a target really corresponding to the seeded area where the loss-to-risk ratio R is available. As explained in Part I, insurance data published by Moreau (1983) consists of the risk and the loss for a group of 13 departments of Aquitaine which do not exactly coincide with the seeded area, and of the loss-to-risk ratio per department. But we also know from Moreau (personal communication, 1985) the yearly departmental distribution of the insured value, as given, for example, in Table 2 for the years 1950, 1960, 1970 and 1980; this distribution enables one to calculate the risk and the loss for all the years in each department or group of departments.

After examining the map of the departments covered by the seeding (Fig. 1), we decided to consider the target area (T) as consisting of the 13 departments except the following: 32, 46, 47, 82 (Fig. 2). These last four departments form a buffer area (B) possibly under a slight seeding influence because it is half surrounded by the target area and it was partially seeded for a few years; department 32 (Gers), which is in the hail maximum area (see Part I), withdrew from the project after a disastrous year (R = 19.6 in 1971).

The other available data are those of the whole of France (Moreau, 1983), which leads us to take France (89 departments), except for the group of 13 departments, as a control area (C), although the departments of Charente and Charente-Maritime and 4 departments of central France have also joined the ANELFA project; but it has not yet been possible to know from the insurance companies the individual data for these six departments. In summary, the control of the ANELFA experiment will be made with the following areas and insurance data:

1) Target area, (T), 9 departments: 09, 11, 31, 33, 40, 64, 65, 66, 81; 60,271 km^2. Sources of data: Moreau (1983) and Moreau (personal communication, 1985).

TABLE 2. Insured value in percentage of the total insured value for each of the 13 departments composing the target (T) and buffer (B) areas.*

Department	1950	1960	1970	1980
09–Ariège (T)	2.495	1.849	1.415	0.691
11–Aude (T)	30.163	18.421	14.497	17.103
31–Haute-Garonne (T)	16.722	13.116	11.653	9.497
32–Gers (B)	12.871	10.923	15.340	11.890
33–Gironde (T)	13.976	15.830	9.936	11.829
40–Landes (T)	2.705	2.451	8.857	11.516
46–Lot (B)	1.452	2.622	1.681	1.952
47–Lot-et-Garonne (B)	5.515	9.796	9.114	8.643
64–Pyrénées-Atlantiques (T)	1.520	7.237	10.441	8.471
65–Hautes-Pyrénées (T)	1.025	2.475	2.849	1.323
66–Pyrénées-Orientales (T)	3.122	5.372	5.121	2.948
81–Tarn (T)	3.783	4.957	3.377	4.458
82–Tarn-et-Garonne (B)	4.650	4.951	5.717	9.678

* This type of data is available for all the years.

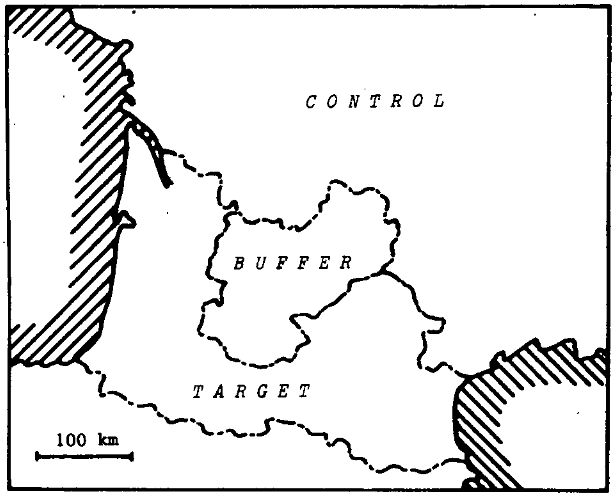

FIG. 2. The three areas used for the control of the seeding experiment. The two northern departments of the seeding network are not included in the target area due to a lack of individual insurance data, nor are the four departments of central France which are under partial seeding.

2) Buffer area, (*B*), 4 departments: 32, 46, 47, 82; 20,632 km^2. Same sources of data.

3) Control area, (*C*): France except (*T*) and (*B*), 76 departments; 469,982 km^2. Insured values I_C and losses L_C are obtained as follows:

$$I_C = I_{\text{France}} - I_{(T+B)}$$

$$L_C = L_{\text{France}} - L_{(T+B)}.$$

Sources of data: Years 1944–1950, Moreau (1983); years 1951–1971, Moreau (1983) or A.I.A.G. (Zürich); years 1972–1981, A.I.A.G. (Zürich).

Table 3 shows the loss-to-risk ratios for the three areas and also the amount of insured values in (*C*) and in (*T* + *B*). Other considerations about these data will be made in Section 4.

a. Long-term tendency of the loss-to-risk ratio

The variations of *R* in the three areas are given in Fig. 3. The trend line analysis indicates that the loss-to-risk ratio has remained unchanged in the control area; it has increased in the buffer area, but the correlation coefficient of the regression is only 0.15; and it has decreased from $R = 3.15$ to $R = 1.48$ in the target area; the correlation coefficient of the regression is now $r = 0.42$.

The observed correlation between R_T and R_C ($r = 0.53$) and between R_B and R_C ($r = 0.52$) is explained by the relative proximity of the three areas (northern France is not much concerned by hail); consequently the hail backgrounds are climatologically correlated. Moreover, when major hailstorms related to upper level jet streams occur in one of the three areas, the two others are generally concerned by the same synoptic conditions. These correlations between the *R* values in the three areas suggest the double-mass curves method to compare more accurately the time evolution of the hail damage in these areas.

b. Double-mass curves

Double-mass curve is a term used to signify a plot of the accumulated values of one variable versus the accumulated values of another. Double-mass curves are often used by hydrologists to adjust or correct precipitation records for changes in gage location, gage environment, or observation procedure; changes in slope of a double-mass curve or breaks are indicated when an appreciable change in trend for the test station occurs without a simultaneous corresponding change in trend for the associated reference (Weiss and Wilson, 1953). It seems valid to use also double-mass curves for the control of hail precipitation, but the scarcity of the hail phenomenon obliges us to consider the hail precipitation on very large surfaces in order to constitute normal annual series; this process has been introduced by H. Dessens *et al.* (1970) using as a variable the yearly loss-to-risk ratio of the hail insurance data.

The double-mass curves of *R* between (*T*) and (*C*) and between (*B*) and (*C*) are given on Fig. 4. The two curves are very similar during the 1944–1958 period; from 1959 to 1964, *R* has shown a slight tendency to increase in (*B*) while there was no change in (*T*); from 1965 on, there is a long-lasting and large decrease of *R* in (*T*) which is definitely not observed in (*B*). In fact the separation of the two curves after the year 1964 is primarily due to the year 1971; we may, however, observe that the slope of the curve "control-target" for 1971 is nearly the slope of the whole period 1965–82.

The double-mass method is meaningful in so far as it visualizes the relative variations of the variable; but if the double-mass curve analysis is useful for indicating a possible change in trend, and the approximate amount of change, this method does not provide an objective criterion of significance. The bivariate test, developed by Maronna and Yohai (1978), seems to be now the most powerful method for providing estimates of the time and amount of change in means as well as of the significance level of this change (Potter, 1981).

c. Bivariate test

The test may be applied to a serially independent sequence $\{x_i, y_i\}$ of *n* two-dimensional random vectors, each vector distributed bivariate normal. It is also assumed that the sequence is stationary, with the exception of a possible shift in mean in $\{y_i\}$ (Potter, 1981). For the three series of *R* listed in Table 3, the assumption of normality is not satisfied because of the following years of exceptional hail: 1950 in (*C*), 1971 in (*C*), (*T*) and (*B*); but if we consider the variable $\text{LOG}_{10}(1 + R)$ instead of the variable *R*, then the assumption of

TABLE 3. Loss-to-risk ratios R (%) in the control (C), target (T) and buffer (B) areas, and insured values I (millions francs) in (C) and ($T + B$).

Year	R_C (Moreau)	R_C (A. I. A. G.)	R_T	R_B	I_C	$I_{(T+B)}$
1944	1.18		4.63	5.08	127.6	12.4
1945	1.26		3.80	5.27	165.2	13.8
1946	0.62		1.90	1.09	301.7	27.3
1947	1.08		1.16	0.54	397.5	36.5
1948	1.00		2.12	1.97	754.9	59.1
1949	0.50		1.98	0.57	817	64.1
1950	3.27		4.20	3.45	1079	78.3
1951	0.88	0.88	3.15	1.90	1471	94.6
1952	1.11	1.11	3.73	2.05	1451	126
1953	0.43	0.43	2.67	1.56	1690	150
1954	0.37	0.37	1.06	1.78	1794	173
1955	1.18	1.18	3.96	3.05	1935	188
1956	0.74	0.74	2.68	2.44	1892	188
1957	0.95	0.95	3.55	2.96	2445	280
1958	0.90	0.90	3.41	3.56	2749	363
1959	0.43	0.43	1.71	3.26	3085	416
1960	0.44	0.44	2.16	3.00	3354	441
1961	0.50	0.50	1.85	3.56	3606	497
1962	0.54	0.54	1.26	2.92	4053	600
1963	0.99	0.99	3.55	4.07	4985	660
1964	0.90	0.90	2.14	2.02	4288	761
1965	1.14	1.14	1.23	1.41	4842	871
1966	1.23	1.23	1.34	2.63	5295	927
1967	1.47	1.47	2.18	4.87	5812	1125
1968	1.26	1.26	2.31	6.60	6773	1193
1969	1.04	1.04	2.68	1.22	7316	1459
1970	1.49	1.49	1.41	1.44	7902	1483
1971	2.87	2.87	5.50	15.27	9373	1845
1972		0.62	1.20	2.56	10566	1895
1973		0.67	3.06	4.59	11980	2014
1974		0.36	0.74	3.48	13726	2231
1975		1.08	1.63	1.54	15118	2400
1976		0.59	1.12	3.71	16473	2586
1977		0.92	1.90	4.25	17743	2795
1978		0.58	0.41	1.71	19213	3253
1979		0.53	0.43	2.16	22814	3577
1980		0.53	2.83	1.01	24815	3759
1981		1.25	1.87	2.66	24054	4358
1982		1.71	1.38	2.63	27180	5016
Average			2.30	3.07		

normality may be accepted despite the small data sample ($n = 39$). The assumption of stationarity is nearly satisfied for the control area as seen in Fig. 3. The assumption of independence seems also acceptable since the correlation coefficients between R on adjacent years are, respectively, 0.05, 0.03 and 0.04 in the areas (C), (T) and (B).

The step-by-step description of the procedure by which the bivariate test is applied (Potter, 1981) is given in the Appendix. The statistic T_0 used to test whether or not a shift in means has occurred, is the maximum value T_i over all $i < n$. All values of T_i are plotted in Fig. 5 for the series [(C), (T)] and for the series [(C), (B)]. The 0.10 and 0.01 critical values of T_0 for $n = 39$ are also plotted. There is no shift in mean for the buffer area at the 0.10 significance level, but there is a shift in mean at the 0.01 significance level for the target area. The result of the test for the target area gives:

$$\bar{Y} = 0.49, \quad S_Y = 0.16, \quad T_0 = 11.93 \quad \text{for}$$
$$i_0^* = 21(1964), \quad D_{i_0^*} = -0.98$$

which indicates a change in $\mathrm{LOG}_{10}(1 + R)$ in 1965, significant at the .01 level; 1965 is the most probable year of the change since T_i is maximum for this year, but we may observe that the .01 level is also reached for the preceding year.

The bivariate test usually gives directly the amount of change in mean ($D_{i_0^*}S_Y$), but the relationship is not correct if a log-transformation has been applied (in fact the test gives the change in the median since the median is not affected by the log-transformation). The change in mean could be computed from the test (Potter, personal communication, 1984), or, more easily, with the data of Table 3:

$$\bar{R}_C,\ 1944\text{–}1964 = 0.92$$
$$\bar{R}_C,\ 1965\text{–}1982 = 1.07 \text{ (16\% increase)}$$

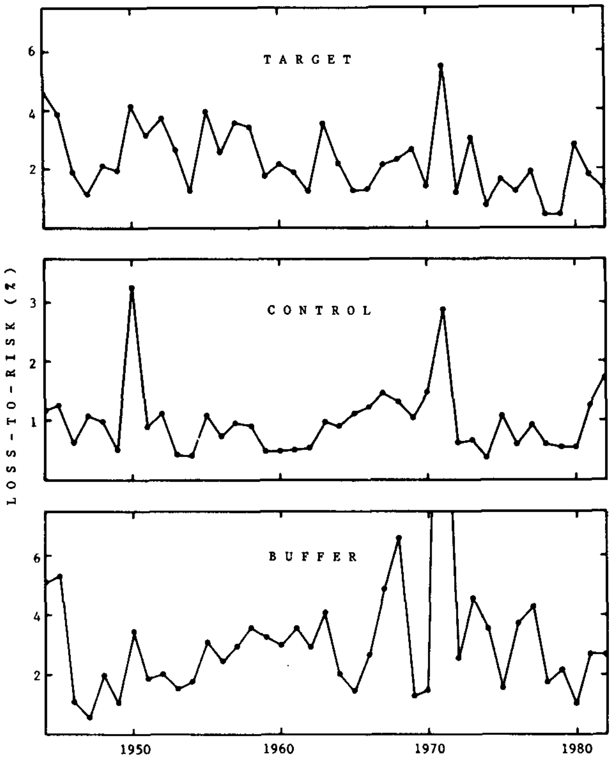

FIG. 3. Data series of loss-to-risk ratios.

$$\bar{R}_T,\ 1944\text{–}1964 = 2.70$$

$$\bar{R}_T,\ 1965\text{–}1982 = 1.84 \ (32\% \text{ decrease}).$$

Then the double ratio:

$$(\bar{R}_T,\ 1965\text{–}1982/\bar{R}_T,\ 1944\text{–}1964)/$$
$$(\bar{R}_C,\ 1965\text{–}1982/\bar{R}_C,\ 1944\text{–}1964) = 0.59$$

indicates a relative decrease of the mean loss-to-risk ratio in the period 1965–1982 from the mean loss-to-risk ratio in the period 1944–1964 amounting to 41%.

The main interest of the bivariate test for the present study is that it provides the time of the change. However, if this time had been known before, other methods like "intervention analysis" (Box and Tiao, 1975) would probably have been more powerful.

4. Discussion of results

The significant conclusion drawn from the analysis of the insurance data is that the loss-to-risk ratio in the seeded area has decreased over the last 18 years with respect to the 21 preceding years, while it has not changed in a neighboring area having the same type of climate and agriculture. Notwithstanding, are the insurance data appropriate for this evaluation, and is this result acceptable from a cloud physics point of view?

a. Qualification of the insurance data

The ability of the loss-to-risk ratio to represent the hail damage has been examined in Part I, but the discussion must be completed in order to ensure that the loss-to-risk decrease, observed since 1965 in the target area, is not due to modifications in insurance policies rather than to modifications in the hail phenomenon itself.

Three changes in the insurance policy during the period 1944–82 are known: The first concerns the roofs of the farm buildings which could be insured with the crops until 1963, but not after; the second is related to a law on the agricultural calamities, adopted on 10 July 1964; this law determines the nature of the insurable risks, its aim being an incentive for the insurance. According to Moreau (personal communication, 1985), these two changes have had no appreciable effect on R; moreover, the modifications occurred at the same time in the control, target and buffer areas. The third change has affected R considerably more: beginning in 1972, each hail loss reported by experts is subject to a 10% deductible before refunding; according to the insurance companies, the effect on R is an artificial decrease of about 20%. Since the modification affected the whole of France, the double-mass curves and the bivariate tests should not be disturbed by it; unfortu-

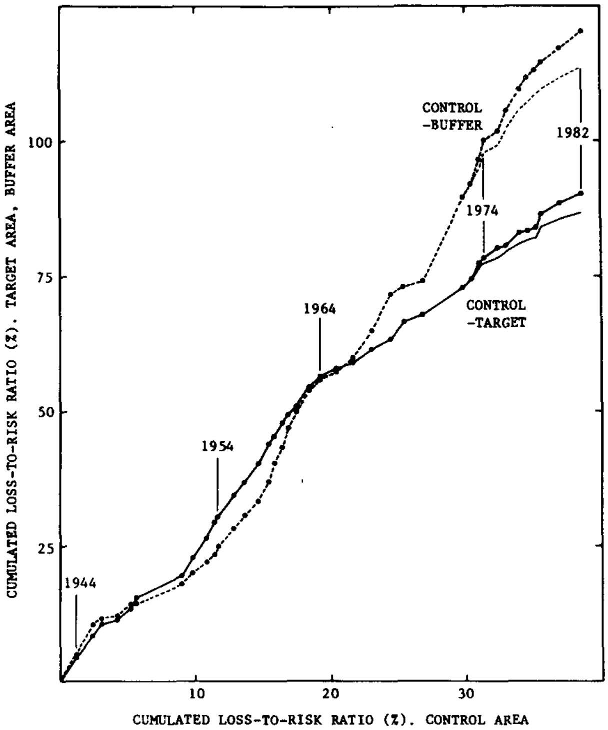

FIG. 4. Double-mass curves of the loss-to-risk ratio: target and control areas. Fine lines: probable curves with the 10% deductible also applied in T and B.

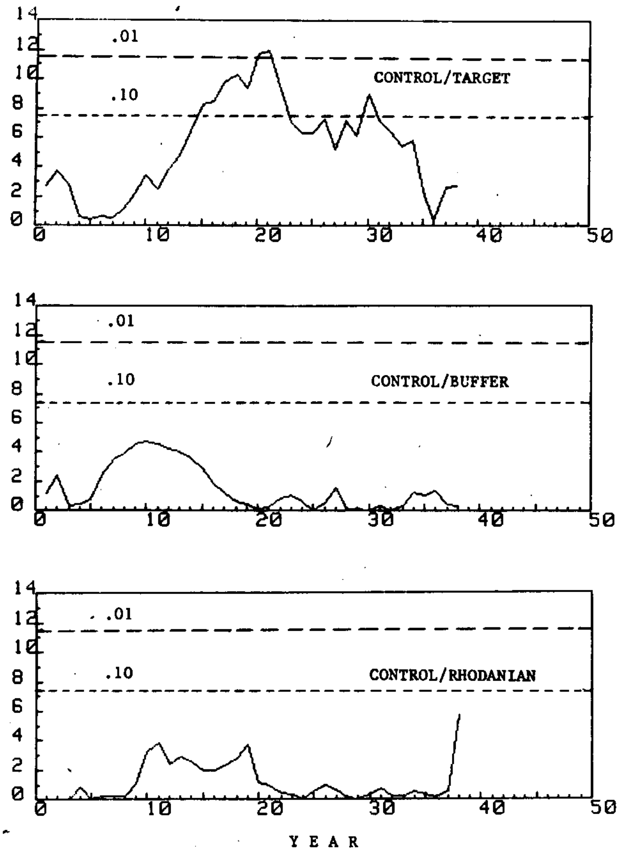

FIG. 5. Illustration of the bivariate test: values of T_i as a function of the year. The dotted lines denote the 0.10 and 0.01 levels of significance. One change is observed at the 0.01 level after year 21 (1964) in the target area. No change is observed at the 0.10 level either in the buffer area or in the Rhodanian region.

nately, Moreau (1983) continues to publish the values of R for Aquitaine without taking into account the 10% deductible, while A.I.A.G. (Zürich) gives the values of R with it. In consequence the values of R used for the double-mass curves and the bivariate test are lowered by about 20% in (C) while they are not in (T) and (B). If data were available also for (T) with the 10% deductible taken into account, the apparent effect of the seeding in (T) would be increased by about 20% since 1972; the approximate corrected curves are indicated on Fig. 4.

Besides these changes in the insurance rules, other modifications have concerned the insured crops. The distribution of the insured crops has suffered continuous evolution from 1944 to 1982 in France. However, the insurance data which would enable one to estimate the effect of these evolutions on R are not available. The main evolutions (the primary one being the regular increase of corn and fruit-tree farming) have been observed almost in the same way in different places of the (C), (T) and (B) areas, and no sudden change occurred around 1965.

Without consideration of types of insured crops, it is possible to survey the comparative evolution of insured values in the three areas:

1) *Comparative evolution in* ($T + B$) *and* C. Table 3 allows one to compare the insured values in Aquitaine with the rest of France (Fig. 6). Following the postwar refitting period of the insurance activity (1944–51), the increase of the insured value has been greater in Aquitaine than in the rest of France until 1964. As the same evolution is also observed (Fig. 6) in an unseeded region of France, a group of five departments in the Rhodanian Basin (Rho) for which the insurance data are published (Moreau, 1983), it is interesting to apply the bivariate test to this region with a control area consisting of C − Rho. The result is given in Fig. 5; there is no change since 1965 in the Rhodanian region.

2) *Comparative evolution in* T *and* B. Table 4 gives the mean percentage of the insured value in each department relative to the insured value in the 13 departments for the periods 1944–64 and 1965–82; it is possible to simulate the effect of the changes of the I values between the two periods on R_T and R_B: by taking the $\bar{I}$ values of the period 1944–64 and the departmental R values of the period 1965–82, we find $\overline{R_T} = 1.87$ and $\overline{R_B} = 3.61$; the actual values (with the exact I values of the period 1965–82) being $\overline{R_T} = 1.84$ and $\overline{R_B} = 3.54$, we can conclude that the disordered changes in the importance of the insured value in each department does not provide a possible explanation for a significant decrease of R in the target area during the second-half period.

Incidentally, the data of Table 4 allows one to observe that there is no correlation between $Q_{(\bar{I})}$, the ratio of insurance percentages between the two periods, and $Q_{(\bar{R})}$, the ratio of losses (correlation coefficient: 0.03)

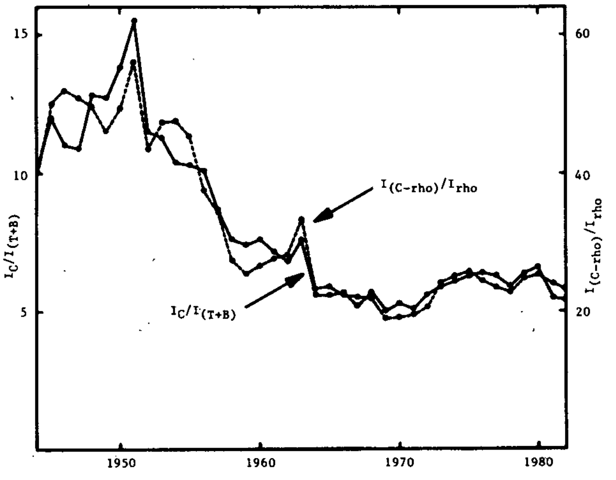

FIG. 6. Evolution of the yearly ratio of the insured crop value in the control area compared to the target and buffer areas, and to the Rhodanian region (dashed line).

TABLE 4. Evolution of insured values and loss-to-risk ratios.*

	09 (T)	11 (T)	31 (T)	32 (B)	33 (T)	40 (T)	46 (B)	47 (B)	64 (T)	65 (T)	66 (T)	81 (T)	82 (B)
$\bar{I}_1$ (%) 1944–1964	2.4	23.6	15.7	12.6	15.6	2.9	1.7	7.4	3.9	1.8	3.3	4.2	4.9
$\bar{I}_2$ (%) 1965–1982	1.1	14.2	10.8	14.1	11.7	9.9	1.9	9.6	9.7	2.1	4.0	5.1	5.8
$Q_{(\bar{I})} = \bar{I}_2/\bar{I}_1$	0.46	0.60	0.69	1.12	0.75	3.41	1.12	1.30	2.49	1.17	1.21	1.21	1.18
$\bar{R}_1$ (%) 1944–1964	2.73	3.09	2.05	2.62	3.08	1.82	4.36	2.12	1.97	2.46	3.16	2.27	3.16
$\bar{R}_2$ (%) 1965–1982	3.16	1.69	1.77	3.75	2.28	1.53	3.16	2.92	2.0	2.14	1.39	1.46	4.23
$Q_{(\bar{R})} = \bar{R}_2/\bar{R}_1$	1.16	0.55	0.86	1.43	0.74	0.84	0.72	1.38	1.01	0.87	0.44	0.64	1.34
$\bar{N}_G$	11	27	39	9	47	55	0	1	26	6	44	18	0
N_G/1000 km^2	2.2	4.3	6.1	1.4	4.6	5.9	0	0.2	3.4	1.3	10.6	3.1	0

* $\bar{I}$: mean value of the annual percentages of insured values in each department relative to the insured value in the 13 departments. $\bar{R}$: mean value of the annual percentages of the loss-to-risk ratios. $\bar{N}_G$: mean value of the annual numbers of generators in each department.

b. Seeding effect hypothesis

The seeding effect hypothesis is based upon the "beneficial competition" concept which assumes that the amount of supercooled water in the hail cloud is the limiting factor of the amount of hail produced, so the introduction of sufficient competing embryos can lead to a reduction in the size of the hailstones reaching the ground. The broadcast seeding as a seeding method was originally imposed by the problem of the identification on a given day and in a large area of the few future hail cells among the numerous storm clouds (H. Dessens, 1967). If finally we propose to explain the decrease of damages in the target area by the seeding operation, a critical discussion must introduce the following main points:

1) In some departments of the target area, the number of generators is small; this is mainly the case in 09–Ariège (5 to 10 generators until 1977), 65–Hautes-Pyrénées (8 generators in 1981) and to a smaller extent in 81–Tarn (21 generators in 1981). These departments contribute only a small amount of the insured value in the target area, as indicated in Table 2, and thus they do not have a large effect on the R parameter.

2) Although the ANELFA experiment has developed continuously from 1952, in the nine departments of the target area a break is observed in 1965; in fact, the detailed evolution of the network (Fig. 7), shows a break on that year in the number of generators and, above all, in the type of generator. The model used before 1965 had a good efficiency in the laboratory but not in the field because of the poor stability of the flame supplied by a fan; the vortex generator introduced in 1965 resolved this problem and maintains its nominal efficiency in every field situation.

3) An observation which is not favorable to the seeding effect concerns the slope of the control-target curve of Fig. 4 over the most recent period of the experiment. In spite of a continuous and regular increase in the number of generators, this slope does not keep decreasing, even if the observation concerning the 10% deductible applied to the losses in the control area since 1972 is taken into account.

4) The mean R values for each department are given in Table 4 for the periods 1944–64 and 1965–82. The mean values of the period 1965–82 are strongly affected by the high 1971 values ($R > 8$ in six departments), which explains the increase of $\bar{R}$ in the (B) departments during the period 1965–82. But in spite of these high values of 1971, we observe a decrease of $\bar{R}$ in seven departments of (T). The correlation coefficient between $Q_{(\bar{R})}$, the departmental ratio of losses between the two periods, and N_G, the number of generators in each department, is −0.56; this ratio increases to −0.66 if we consider the departmental number of generators per 1000 km^2.

The correlation between the number of generators and the hail decrease has two exceptions: 1) R decreases

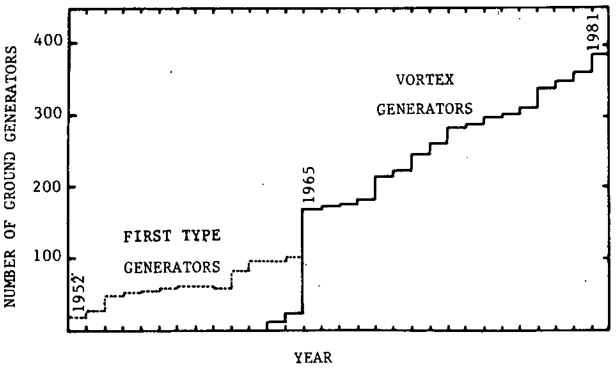

FIG. 7. Evolution of the type and number of AgI ground generators in the target area. The network was formerly equipped with charcoal generators, then from 1959 to 1964 with a first type of acetone generators.

in 46–Lot, a department which has never been seeded; 2) R increases in 09–Ariège, a seeded department; the increase in this department is due to the exceptional 1980 value ($R = 10.5$) in relation with the major storm of 14 June 1980, a nonseeded day.

5) Assuming that the decrease of the hail damage is due to the seeding, one finds it possible to estimate the benefit-to-cost ratio of the ANELFA project. In 1981, the value of the crops subject to hail damage in the target area was estimated to 9,390 million F by the agricultural administration; considering the mean value of the loss-to-risk ratio in the same area during the historical period ($R_{1944-1964} = 2.70\%$), one notes that the potential loss in 1981 was 254 million F; a loss decrease of 41% would then represent a benefit of 104 million F. When this benefit is compared with the 4.3 million F of the seeding cost, the benefit-to-cost ratio appears to be about 24.

c. Physical implications

1) The physical compatibility of the observed result with the disturbance induced by the seeding must be discussed in terms of increased ice forming nucleus concentrations in the target area. In the most protected parts of this area, which are also most covered by hail insurance, the density of generators is 1 per 50 km^2; one generator releases 8.8 g of AgI during the hour preceding the predicted hailfall; if the nuclei are concentrated in a layer 1 km thick (as there is often an inversion at an altitude of 1 km before hailstorm occurrence), the concentration of artificial nuclei active at -15°C will be $(8.8 \times 0.8 \times 10^{14}/50)$ km^{-3}, or 14 L^{-1} (Table 1). This concentration is about 10 times the natural concentration usually measured in the area (Part I, Fig. 3), and 70 times the concentration sometimes measured in the air surrounding damaging hailstorms (Soulage, 1958).

The IFN concentration increases, estimated above, are of course hypothetical, mainly because they do not take into account the controversial problem of the photo-deactivation of silver iodide nuclei (Pham Van Dinh, 1976a); but increases of the same order of magnitude, produced by ground generator networks, have been measured on several occasions:

From more than 5000 measurements of IFN concentrations in 10 years in and above various networks of burners, Soulage and Admirat (1968) concluded that a dense network of high power ground generators leads to an IFN concentration 100 times greater than the background one; they in fact recommend a network with a mesh of about 5 km (ANELFA network in the most protected areas: 7 km) and a type of generator releasing 10^{12} nuclei s^{-1} effective at -12°C (ANELFA generator: 0.2×10^{12} at -15°C). They stipulate that the vertical transfer of the air (polluted by artificial nuclei, from the ground to the base of the cloud to be seeded) only occurs for a short time (about 1 h above a certain point) when storms are forming and only over a limited region.

Pham Van Dinh (1975, 1976b), measured with an NCAR counter the IFN concentration at -15.5°C in the middle of a generator network similar to the ANELFA network and found that the concentration increases are correlated with the AgI emissions, and that on several occasions the modified concentrations were 100 to 1000 times greater than the natural.

Admirat (1979), flying above an AgI ground generator network in the Po Valley (Italy), has measured 200 ice nuclei l^{-1} at -10°C in the updraft just below cloud base of a storm, against between 1 and 1.5 far from the experimental zone; this is the greatest value he has ever measured in a hailstorm base.

The remark of Soulage and Admirat (1968) concerning a seeding effect that is brief in space and time explains why the ANELFA seeding has no observed effect on the buffer area situated downwind from the target; the physical reason of this circumscribed effect could be either a fast upward transfer of the AgI nuclei above the generator in stormy conditions and/or a high deactivation rate of these nuclei.

2) The results of the ANELFA operations must finally be compared with those of previous hail suppression projects which involved ground seeding. Two of them were randomized experiments, and, for this reason, their results are generally considered credible:

The Argentinian project was a randomized experiment conducted for five seasons between 1959 and 1964 on a 4000 km^2 plain bordering the Andes. One hundred ground generators were operated, and the tested variables were area of damage: S; average percent of damage: DPM; and total damage: DT. On days with cold frontal passages, seeding decreased DT by about 70%, and DPM and S by about 50%; for all the other days, seeding increased DT and S by about 100%, and DPM by about 40% (Iribarne and Grandoso, 1965).

Grossversuch III was a randomized experiment conducted in Switzerland for seven years (1957–63).

The 3500 km^2 test area was a valley on the southern slope of the Alps; silver iodide smoke was released from 20 ground based generators. The final report by Schmid (1967) indicates that seeding sometimes increased rainfall by large amounts; days on which there were cold frontal passages or "barrage situations" were especially favorable. The results for hail were not as conclusive as those for rain, but there were more than twice as many days with hail in some sections of the test area with seeding. Ground seeding then seems to increase both rain and hail in specific meteorological situations. However, the parameter used to determine the effect of seeding (i.e., the number of hail days) was in no way related to the amount of hail damage.

It is difficult to reconcile the results of the two projects conducted in regions with very different geographical characteristics; both conclude, however, that there is a significant effect of ground generators in cold frontal situations (Atlas, 1977). If we now remember that in the Aquitaine, cold fronts are accountable for 65% of the occurrences of severe hail damage, the seeding effect observed in the ANELFA project should be consistent with the Argentinian and Swiss results. However the climatological differences between the three areas must not be overlooked, nor must we overlook the difference in the sizes of the seeded areas.

5. Conclusions

From the observation that damaging hailstorms in southwestern France develop in an environment with low ice forming nucleus concentrations, H. Dessens proposed that it might be possible to decrease the hail damage in the whole area of Aquitaine by emitting silver iodide nuclei from a large network of ground generators activated three hours before the forecast hailfalls. The method is simple and nowadays seems more appropriate than the aircraft or rocket methods for a large area with extensive agriculture where the hail season lasts almost six months; its main physical justification is that the convective clouds which are to be seeded have their roots at low levels. Unlike the methods using aircraft and rockets, the method has the ecological advantage of being discreet; the problem of air pollution by silver iodide is now considered trivial, even in the immediate vicinity of ground generators (Lodge, 1979). Finally, when successful, the method results in a high benefit-to-cost ratio. However, one of the main difficulties is the forecast of hail situations correctly, with a delay of a few hours and a small false-alarm ratio.

Randomization is not acceptable in a project that is not financed by a research organization. Consequently, it was decided as soon as the project began to survey the loss-to-risk ratio of the insurance companies in the target area and in its surrounding area. After three decades, the result of this survey is as follows: the average of the yearly loss-to-risk ratio in the protected area has decreased during the period 1965–82 by 41%, compared to the rest of France and at a significance level of .01; at the same time, the damage has not significantly changed either in a buffer area of similar climatological and agricultural type, or in a part of southeastern France where the time evolution of insured values is similar. Since this decrease is well correlated with the expansion in the quality and quantity of the seeding, the result appears significant enough to justify its publication and to reintroduce the debate on the control of nonrandomized weather modification projects (Braham, 1979). But more research (numerical simulations and in-cloud measurements) is necessary to place the seeding effect on a sound scientific and practical basis.

Acknowledgments. The insurance data have been kindly supplied by the *Association Internationale des Assureurs contre la Grêle,* by the *Assemblée Plénière des Sociétés d'Assurances* and by the *Caisse Centrale des Mutuelles Agricoles.* The analysis of these data profited from many discussions with colleagues, and specially with J. Dettwiller (Météorologie Nationale), J. Moreau (Pool Grêle), Miss J. Pastor (Centre d'Application de la Statistique, Université de Toulouse) and Professor R. Serpolay (Observatoire du Puy de Dôme). G. Goyer (Alberta Research Council) has suggested the use of the bivariate test which was programmed by J. Noilhan. I also should like to renew my gratitude to the three anonymous reviewers whose comments have been extremely helpful. Finally, I want to acknowledge Régine Réchal for typing the two manuscripts (Part I and Part II), Serge Ribet for drawing the figures, and my daughter Nathalie for improving the English version.

APPENDIX

Bivariate Test

The step-by-step description of the procedure by which the bivariate test is applied has been kindly supplied by K. W. Potter (1981).

Let $\{x'_j\}$ be regional series of length n

$\{y'_j\}$ be test series of length n

Step 1. Standardize series:

$$\text{Let } \bar{X} = (1/n) \sum_{j=1}^{n} x'_j, \quad \bar{Y} = (1/n) \sum_{j=1}^{n} y'_j,$$

$$S_x = [(1/n) \sum_{j=1}^{n} (x'_j - \bar{X})^2]^{1/2},$$

$$S_y = [(1/n) \sum_{j=1}^{n} (y'_j - \bar{Y})^2]^{1/2},$$

$$x_j = (x'_j - \bar{X})/S_x, \quad y_j = (y'_j - \bar{Y})/S_y \quad \text{for all } j.$$

Step 2. Compute test statistics:

$$\text{Let } X_i = (1/i) \sum_{j=1}^{i} x_j, \quad Y_i = (1/i) \sum_{j=1}^{i} y_j \quad \text{for all } i < n,$$

$$S_{xy} = \sum_{j=1}^{n} x_j y_j,$$

$$F_i = n - [X_i^2 ni/(n - i)] \quad \text{for all } i < n,$$

$$D_i = (S_{xy} X_i - nY_i)n/(n - i)F_i \quad \text{for all } i < n,$$

$$T_i = i(n - i)D_i^2 F_i/(n^2 - S_{xy}^2) \quad \text{for all } i < n,$$

$$T_0 = \max[T_i] \quad i < n.$$

Also let i_0^* be the value of i for which T_i is a maximum.

Step 3. Conduct test:

Compare T_0 to the critical value for the appropriate n and the desired significance level (see Table 1 in Potter, 1981). If T_0 exceeds the critical value, reject the null hypothesis. That is, assume that the mean of y has changed in the year after i_0^* by an amount equal to $D_{i_0^*} S_y$.

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