INFLUENCE OF ATMOSPHERIC STABILITY LAYERS ON THE EFFECT OF GROUND-BASED CLOUD SEEDING, I. EMPIRICAL RESULTS*

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As recently documented,¹ it is safe to assume that cloud seeding with silver iodide can have opposite effects on precipitation: in some conditions, say A, the precipitation is increased by seeding and in some other conditions, B, it is decreased. Neither A nor B is yet identified. The identification of these conditions A and B is, then, an important outstanding problem. A promising approach to this problem consists in a scrutiny of weather modification experiments already completed, with the primary purpose of verifying empirically the various *a priori* hypotheses underlying the current efforts at weather modification.

The basic premise of rain stimulation with AgI seeding is the discovery by Vonnegut of the ice crystal nucleating property of the AgI smoke at temperatures below the threshold of -4°C . If the seeding is done from the ground, hopes of success depend upon the presence of strong updrafts capable of carrying the AgI particles into the supercooled parts of the clouds before the AgI is deactivated by photolysis. Ordinarily, temperature inversions and isothermal layers (stability layers, for short) are obstacles to convective updrafts and are expected to prevent cloud seeding from the ground from being effective. The purpose of the present paper is to provide evidence that, at least in mountainous regions, the mechanism of the effects of cloud seeding involves some unexpected complications.

Empirical Material.—The data used originate from the randomized Swiss hail-prevention experiment Grossversuch III, performed in 1957–63 on the southern slopes of the Alps. The units of randomization were the 292 days for which, on the preceding afternoon, the forecasters expected thunderstorms. The AgI seeding was done from 20 ground-based generators, from 7:30 A.M. to 9:30 P.M., on a pulsating schedule of 5 min on and 10 min off. Figure 1 gives a schematic map of the target area, which the experimenters divided into four zones numbered from south to north. For purposes of evaluation, the gauges of zone 4 were divided into two groups labeled zone 4lo and zone 4hi, according to whether their elevation was below or above 1000 m. Zone 1 is on the edge of the Po Valley. Zone 2 might be described as being in the high foothills. Zone 3 is the deep Magadino Valley bordered by some high mountains in the south and particularly in the north. Details of the experiment have been published in seven annual reports² and also in subsequent evaluations.^{1, 3–6} Except for atypical zone 1, the day-by-day precipitation amounts, averaged over zones, and the numbers of hail reports have also been published.⁷

In order to establish the presence or absence of stability layers for each experimental day, noon radiosonde data from Milan (some 35 miles south of the target) were used. They are available for 287 experimental days and the present study is based on these days only. Table 1 gives zone-by-zone precipitation amounts for the five missing days. It is believed that the exclusion of these days can have no noticeable effect on the final results.

Table 2 lists all the experimental days for which some stability layers were established. For each layer the table gives the pressure P in millibars and the temperature T in degrees centigrade at the bottom of the layer. ΔP denotes the pressure drop and ΔT the temperature increase through the layer.

TABLE 2. *Experimental days with stability layers, Grossversuch III.*

DATE	P	ΔP	T	ΔT	DATE	P	ΔP	T	ΔT	DATE	P	ΔP	T	ΔT
1957					1958					1958				
15 06	975	30	21	0	24 05	930	18	14	0		550	14	- 6	0
16 06	766	22	8	0		828	32	7	0		508	8	- 9	0
18 06	763	20	5	0		463	17	-21	0	1959				
	635	49	- 5	0	25 05	711	11	1	0	19 05	777	19	2	1
22 06	670	18	- 1	0	26 05	607	17	- 6	2		674	11	- 6	2
	652	27	- 1	1	27 05	660	15	- 1	1	20 05	1002	2	22	2
23 06	818	33	13	0		515	15	-14	0		700	30	0	0
	763	11	12	0	30 05	335	21	-38	0	22 05	720	20	1	0
	484	11	-10	1	01 06	860	10	9	0	30 05	638	15	-10	0
24 06	753	13	5	1		717	20	1	0	01 06	946	14	13	0
25 06	862	12	8	0	03 06	700	9	1	1	05 06	816	16	7	1
09 07	923	30	22	0	10 06	728	48	0	0	06 06	575	12	- 8	0
	647	22	1	0	18 06	1008	8	24	0	17 06	850	36	8	0
16 07	643	28	- 7	0	26 06	910	15	11	0		650	12	- 3	1
17 07	535	10	-12	0		735	44	0	0	19 06	927	27	18	0
	515	37	-17	0		406	6	-20	0	20 06	990	22	18	2
20 07	943	20	15	2	27 06	MISSING				23 06	622	22	- 4	0
	720	20	0	0	30 06	822	22	8	3	24 06	900	10	15	0
21 07	587	12	-11	1		405	5	-24	1	25 06	900	15	12	1
	520	10	-15	0	01 07	785	10	8	1	29 06	468	11	-22	1
27 07	1000	15	25	1	02 07	880	12	13	0	09 07	790	20	10	0
	768	18	9	0		665	35	- 2	0		743	23	7	0
28 07	700	16	0	0		500	14	-11	0	10 07	675	17	3	0
09 08	784	22	8	2	03 07	700	18	- 1	0	24 07	986	20	22	0
	762	21	10	0		312	12	-40	1		638	41	- 4	0
	655	20	1	2	11 07	858	8	14	0	27 07	700	7	5	0
10 08	720	20	6	0		700	5	3	0		622	38	- 1	0
	620	7	- 2	2		618	31	- 2	0	29 07	969	33	17	1
	595	6	- 1	1	12 07	590	25	- 5	0		733	18	4	0
16 08	807	12	8	0		388	16	-27	0		529	16	-11	0
17 08	917	42	14	0	14 07	774	19	11	2	30 07	850	12	14	0
	753	18	4	2		512	12	-10	0		534	26	-11	0
	600	14	- 6	2	16 07	905	43	21	0	05 08	946	20	16	0
19 08	945	15	11	3		434	21	-17	0		700	7	0	0
	914	14	12	1	21 07	925	43	18	0	09 08	600	20	- 6	0
	565	15	-15	0		692	16	3	2	10 08	600	30	- 4	0
22 08	890	18	16	0	23 07	613	20	- 7	1	22 08	652	7	- 2	1
	850	10	15	0	27 07	568	13	- 4	0		520	14	-12	0
	623	13	- 3	1	28 07	MISSING				23 08	460	18	-19	0
24 08	774	14	6	1	01 08	800	42	14	0	29 08	900	14	16	1
	684	46	1	2		510	20	-10	0	30 08	682	28	0	0
	590	19	0	0	02 08	1005	5	31	0		500	16	-15	0
28 08	863	17	9	0		940	15	26	0	03 09	808	38	1	0
	600	10	-10	0		771	29	15	0		715	21	0	0
02 09	607	27	- 7	0		657	22	7	0	14 09	1002	2	21	0
03 09	940	20	11	0	07 08	MISSING				17 09	828	28	10	0
	730	20	- 1	0	08 08	970	16	19	1	18 09	913	37	11	0
	662	19	- 6	0		712	33	0	0	1960				
04 09	972	30	15	2		514	18	-12	0	17 05	870	20	10	0
	714	14	- 2	0	11 08	581	10	- 6	2		792	12	6	0
	460	18	-22	0		334	11	-34	0	06 06	613	27	- 6	0
08 09	715	15	7	0	12 08	806	14	10	0	07 06	866	16	12	0
12 09	870	16	13	1	16 08	850	6	14	0		500	18	-17	1
	854	4	14	0		764	36	8	0	09 06	796	20	6	0
	813	13	11	0	19 08	876	26	17	0	13 06	744	12	4	0
24 09	963	30	16	0	21 08	500	14	-13	0	20 06	950	43	20	0
	900	50	13	1	27 08	936	22	16	0		656	16	0	0
27 09	932	18	12	1		850	25	11	0		500	11	-13	0
	700	12	0	0		766	20	6	3	24 06	783	14	8	0
						662	26	3	0		436	8	-21	0

gory unambiguously suggested by the nature of the problem. This is the category, say C1, of days without any stability layers below the 300-mb level. On occasion, C1 will be described as the category of days with uninhibited updrafts. Other categories have to be defined in accordance with the intuitive feelings regarding the intensity of obstacles to updrafts and also in accordance with the temperatures at which these obstacles occur. First we distinguish days with only "thin" isothermal layers, characterized by $\Delta P < 40$ mb. These are regarded as weak stability layers irrespective of their number on a particular day. "Thick" isothermal layers, those with pressure differences, $\Delta P \geq 40$ mb,

TABLE 2 (continued)

DATE	P	ΔP	T	ΔT	DATE	P	ΔP	T	ΔT	DATE	P	ΔP	T	ΔT
1960					1962					1962				
26 06	700	26	- 1	0	26 05	700	20	- 8	0		714	14	0	0
29 06	700	14	0	0	27 05	750	20	- 3	0		540	24	-12	2
08 07	900	20	15	1		605	11	-14	2	06 09	926	19	17	0
	576	21	- 8	0	28 05	790	18	- 1	1		866	16	13	1
11 07	778	22	6	2	29 05	655	23	- 5	0		766	22	9	0
	407	7	-23	1		484	16	-22	1		590	25	- 3	0
15 07	830	23	8	0	31 05	926	26	11	0	07 09	690	24	3	0
	580	20	-10	0	01 06	700	10	0	0		611	19	- 1	0
	542	12	-13	1	11 06	913	27	11	1	11 09	900	22	15	3
18 07	781	12	7	1		492	22	-22	0		700	10	3	0
	635	18	0	0	12 06	700	25	- 3	2		625	35	- 3	0
30 07	946	25	16	0		623	16	- 6	1	16 09	727	27	2	3
	850	10	10	0	14 06	648	17	- 1	0	18 09	508	8	-21	0
	754	22	4	2	16 06	508	8	-15	0	26 09	900	20	6	0
31 07	661	19	- 1	1	19 06	794	19	9	0		754	27	- 4	3
01 08	995	35	16	3		446	11	-20	0		727	80	- 1	0
	458	16	-22	0	01 07	624	14	-10	1	27 09	738	14	- 2	2
05 08	800	19	7	0	10 07	710	20	6	0		724	24	0	0
	398	12	-25	0		665	25	3	0	29 09	517	22	-18	0
08 08	719	19	0	0	15 07	900	29	16	0	13 10	850	17	5	0
	400	10	-29	0		520	20	-11	0	1963				
12 08	585	17	- 8	0	21 07	778	69	7	0	21 05	768	28	- 1	2
18 08	769	21	6	1		545	10	- 8	0		740	40	1	0
26 08	700	10	4	0	22 07	620	12	- 4	1		450	12	-24	0
	500	7	-11	0	26 07	775	25	11	0	22 05	814	46	3	3
28 08	982	52	22	0	29 07	945	45	18	0	03 06	694	15	- 2	0
	548	16	- 7	0		850	34	12	0	11 06	MISSING			
04 09	571	21	- 7	0		530	8	-11	2	14 06	510	10	-17	0
17 09	566	41	-14	0	01 08	970	23	19	1	15 06	890	20	11	0
1961						772	27	8	2	16 06	920	38	13	0
17 05	693	26	- 5	0		745	30	10	0	04 07	912	26	16	0
	508	8	-19	0		585	13	- 2	2	05 07	1000	40	16	0
26 05	741	29	0	0	04 08	864	14	16	0	06 07	723	23	3	0
	662	7	- 4	0		561	19	- 6	0	23 07	446	16	-19	1
01 06	577	23	-13	0		521	21	- 9	0	26 07	1005	9	21	2
	520	20	-19	1	05 08	930	30	18	1		996	26	23	0
08 06	850	10	14	0		850	28	14	0	01 08	965	29	20	0
27 06	837	19	13	1	06 08	800	27	11	2	07 08	918	18	16	0
04 07	564	17	- 7	0		321	10	-33	0	09 08	500	12	-16	0
12 07	790	23	5	3	07 08	965	36	22	0	12 08	711	11	5	0
	534	12	-10	2		820	43	12	2	13 08	950	28	16	1
13 07	833	23	9	2		479	17	-15	0		780	10	7	2
	640	22	- 5	0	12 08	770	30	8	0	01 09	980	34	14	0
22 07	MISSING				16 08	920	70	18	0		700	14	0	0
07 08	898	24	15	1		707	7	4	0	02 09	1004	4	18	0
12 08	858	8	12	0		500	6	-10	0		850	30	9	0
03 09	760	20	7	0	18 08	913	21	17	2	03 09	946	36	15	0
04 09	850	5	10	0		600	29	- 3	0		800	20	7	0
	674	21	0	0	25 08	850	25	14	1		720	32	3	0
	512	26	-14	0		550	12	- 5	1	06 09	850	20	9	0
05 09	980	30	16	0	01 09	836	31	13	0		650	14	- 5	0
06 09	935	21	14	0	03 09	870	40	13	0	18 09	672	40	0	0
	700	6	- 1	0	04 09	800	14	9	1	19 09	1000	28	19	0
	694	15	- 1	1	05 09	860	10	10	0		624	10	- 2	0
	632	16	- 5	0										

are regarded in this study as being more or less equivalent to inversions, representing strong stability layers. Next, there is a cross classification according to temperatures at the bottom of the lowest layer. Thus our category C2 is defined as the category of days with only weak stability layers, all of them occurring at temperatures colder than -4°C . Category C3 is composed of days with only weak stability layers, at least one of which is "warm," that is, at a temperature of -4°C or warmer. The definition of the other two categories ignores thin isothermals, whatever their number, and depends only on the temperature at the bottom of the "warmest" strong stability layer. Category C4 includes

days with at least one strong stability layer, all of them cold. Category C5 is composed of days with some strong stability layers, at least one of which is "warm."

Expectations of the effects of seeding in each of the five categories of days were formulated based on the fact that in Grossversuch III the over-all average seeded precipitation exceeded that without seeding. Thus, on days without stability layers that could prevent the AgI smoke from reaching temperatures colder than -4°C , substantial increases in precipitation were expected due to seeding. Primarily this applies to category C1, with no stability layers at all. Next in line are categories C2 and C4 where the obstacles to updrafts occur at temperatures colder than -4°C . No effects of seeding, either positive or negative, were expected in category C5 with strong stability layers at temperatures warmer than -4°C .

Results.—Using the methodology described elsewhere,⁴ for each category of days just defined we made an effort to answer the following three questions: (1) Does seeding affect the frequency of rainy days (days with some rain in the target)? (2) Does seeding affect the precipitation averaged per rainy day? (3) Does seeding affect the precipitation averaged per experimental day? The results relating to (1) did not prove interesting and will not be reported in detail. With a single exception, the differences in rain frequency between days with seeding and without are somewhat spotty and far from being statistically significant. The exceptional case occurs in the category C1 of 97 days, each with uninhibited updrafts. Here, in all zones, the apparent effect of seeding is a decrease in the frequency of rain, which is greatest in zone 1. Without seeding there was some rain in 66 per cent of days compared with 46.8 per cent with seeding. The significance probability is $P = 0.089$. In other zones this probability is much larger, from 0.28 to 0.68.

Tables 3 and 4 give the estimated effects of seeding on precipitation averaged per rainy day and per experimental day, respectively. Lines marked S and NS refer to seeded and to not-seeded days. Columns N give the numbers of days used for the particular evaluation. Note that the values of N in a given column vary from zone to zone in Table 3, but not in Table 4. R stands for average rainfall (in mm) and P for significance probability. Regretfully, categories C2 and C4 contain very small numbers of observations and the P values, obtained through the application of an asymptotic test, are not reliable. This circumstance suggested the creation of a combined category of all days with stability layers C2 + C3 + C4 + C5, with a total of 190 experimental days.

It will be seen that, with the possible exception of category C2 (with unreliable significance probabilities), Tables 3 and 4 contradict expectation. Far from exhibiting large increases in rain due to seeding, days with uninhibited updrafts (C1) show decreases in precipitation of 30 per cent and more which, even though not statistically significant ($P \geq 0.14$), attract our attention. Also, very much contrary to expectation, the category C5 of 76 days with strong warm stability layers indicates increases in precipitation which, with the exception of zone 2, are significant. Finally, in the combined category of days with stability layers there is very little doubt that in the mountainous zones 3, 4lo, and 4hi, seeding increased rain by a substantial percentage, ranging from 71 per cent in zone 4hi to 100 per cent in zone 3.

Figures 2 and 3 were constructed in order to answer some questions that the

TABLE 3. *Effect of seeding on rainfall in millimeters, averaged per rainy day.*

Zone	C1			C2			C3			C4			C5			C2 + C3 + C4 + C5			
	N	R	P	N	R	P	N	R	P	N	R	P	N	R	P	N	R	P	
1	S	22	14	0.58	8	22	0.38	20	16	0.45	6	25	0.67	16	26	0.048	50	21	0.24
	NS	33	17	...	4	9	...	18	21	...	4	20	...	16	11	...	42	16	...
2	S	31	15	0.54	9	17	0.15	26	15	0.46	7	22	0.46	21	28	0.17	63	21	0.56
	NS	38	18	...	6	7	...	22	20	...	6	32	...	25	16	...	59	18	...
3	S	28	14	0.30	8	30	0.050	24	21	0.84	8	28	0.93	20	37	0.005	60	29	0.006
	NS	36	19	...	6	4	...	19	19	...	6	27	...	27	12	...	58	15	...
4lo	S	33	10	0.21	9	24	0.085	31	16	0.99	9	20	0.83	25	21	0.062	74	19	0.050
	NS	39	15	...	6	5	...	21	16	...	7	17	...	30	10	...	64	12	...
4hi	S	35	10	0.37	9	16	0.072	33	12	0.61	8	15	0.82	23	20	0.015	73	15	0.016
	NS	42	13	...	7	4	...	26	10	...	7	13	...	32	9	...	72	9	...
Entire	S	38	10	0.20	9	21	0.038	34	13	0.99	9	19	0.94	28	21	0.036	80	18	0.050
	NS	43	15	...	8	4	...	27	13	...	7	20	...	34	9	...	76	11	...

TABLE 4. *Effects of seeding on rainfall in millimeters, averaged per experimental day.⁸*

Zone	C1			C2			C3			C4			C5			C2 + C3 + C4 + C5			
	N	R	P	N	R	P	N	R	P	N	R	P	N	R	P	N	R	P	
1	S	47	7	0.17	11	16	0.14	41	8	0.45	9	17	0.45	35	12	0.049	96	11	0.12
	NS	50	11	...	10	3	...	35	11	...	8	10	...	41	4	...	94	7	...
2	S	...	10	0.32	...	14	0.074	...	10	0.52	...	17	0.56	...	17	0.22	...	14	0.48
	NS	...	14	...	...	4	...	...	13	...	...	24	...	...	10	...	...	11	...
3	S	...	8	0.14	...	22	0.041	...	12	0.71	...	25	0.74	...	21	0.025	...	18	0.013
	NS	...	14	...	...	3	...	...	11	...	...	20	...	...	8	...	...	9	...
4lo	S	...	7	0.14	...	20	0.043	...	12	0.52	...	20	0.67	...	15	0.079	...	15	0.019
	NS	...	12	...	...	3	...	...	10	...	...	15	...	...	7	...	...	8	...
4hi	S	...	7	0.22	...	13	0.057	...	10	0.48	...	13	0.81	...	13	0.077	...	12	0.028
	NS	...	11	...	...	3	...	...	8	...	...	11	...	...	7	...	...	7	...
Entire	S	47	8	0.15	11	17	0.045	41	11	0.86	9	19	0.89	35	17	0.054	96	15	0.045
	NS	50	13	...	10	3	...	35	10	...	8	18	...	41	8	...	94	9	...

FIG. 2.—Relative frequency of seeded and not-seeded nonzero precipitation in zone 3 on days with stability layers.

FIG. 3.—Distribution of temperature at bottom of lowest layer.

above results may suggest. Figure 2 gives histograms of nonzero precipitation, separately seeded and not seeded, observed in zone 3 on days with stability layers. Figure 3 provides a histogram of the temperature at the bottom of the lowest stability layer.

The above results relating to rainfall are paralleled by those on hail. The only analysis performed refers to frequency of days with some reported hail in the target. In the category of days with uninhibited updrafts, the frequency of hail days with seeding was 32 per cent, equal to that without seeding. With stability layers, seeding showed increases in the frequency of hail: with weak layers from 22 per cent to 27 per cent $P = 0.765$; with strong layers from 22 per cent to 43 per cent $P = 0.056$; and for all layers combined from 22 per cent to 34 per cent, $P = 0.093$.

Concluding Remarks.—The above empirical results raise the following questions:

(1) Can the phenomenon of increase in the rainfall, and apparently of hail, by seeding from the ground in the presence of stability layers be confirmed in other experiments?

(2) What can the mechanism of this phenomenon be? Should one think that in addition to nucleating ice crystals at low temperatures, the AgI smoke can stimulate warm rain? Or is it that, as suggested by Neiburger⁹ and supported

by Schüepp and Thams,¹⁰ stability layers occurring near high mountains stimulate, rather than inhibit, the transport of AgI to high levels with temperatures colder than -4°C ? The doubling of the frequency of hail days with seeding under strong stability layers, most of them warm, is indirect evidence in favor of the latter alternative.

(3) If the apparent decrease in rain on days with uninhibited updrafts is really due to seeding, what can the mechanism of this effect be?

Question (1) calls for a scrutiny of several already completed experiments. Questions (2) and (3) are discussed elsewhere.^{9,10}

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¹ Neyman, J., and E. L. Scott, "Some outstanding problems relating to rain modification," *Proc. Fifth Berkeley Symp. Math. Stat. Prob.*, 5, 293-326 (1967).

² Sanger, R., et al., *Grossversuch III zum Bekämpfung des Hagels im Tessin*, annual reports for 1957-1963 (Bern: Abteilung für Landwirtschaft des Eidg. Volkswirtschaftsdepartementes, 1958-1964).

³ Schmid, Paul, "On 'Grossversuch III,' a randomized hail suppression experiment in Switzerland," *Proc. Fifth Berkeley Symp. Math. Stat. Prob.*, 5, 141-159 (1967).

⁴ Neyman, J., and E. L. Scott, "Note on techniques of evaluation of single rain stimulation experiments," *Proc. Fifth Berkeley Symp. Math. Stat. Prob.*, 5, 371-384 (1967).

⁵ Thams, J. C., A. Aufdermaur, P. Schmid, and E. Zenone, *Die Ergebnisse des Grossversuches III zur Bekämpfung des Hagels im Tessin in den Jahren 1957-63*, Schlussbericht in Auftrage der "Eidg. Kommission zum Studium der Hagelbildung und der Hagelabwehr" (July 1966).

⁶ Schmid, P., and J. C. Thams, "Results of a large-scale rain stimulation experiment on the southern slopes of the Alps," *Arch. Meteorol. Geophys. Bioklimatol. Ser., A*, 16, 226-241 (1967).

⁷ "A collection of observational data," *Proc. Fifth Berkeley Symp. Math. Stat. Prob.*, 5, 446-451 (1967).

⁸ A version of this table, based on preliminary appraisals of strong stability layers by Schüepp, was reported by Neyman and Scott at the Weather Modification Design and Evaluation Conference, Bureau of Reclamation, Denver, Oct. 12, 1967.

⁹ Neiburger, M., and H. C. Chin, "Influence of atmospheric stability layers on the effect of ground-based cloud seeding, II. Hypotheses in explanation," these PROCEEDINGS, 60, 424-431 (1968).

¹⁰ Schüepp, M., and J. C. Thams, in preparation.