Analysis of Recording Raingage Data for the Israeli II Experiment. Part I: Effects of Cloud Seeding on the Components of Daily Rainfall

ABRAHAM GAGIN

Department of Atmospheric Sciences, Hebrew University, Jerusalem, Israel

K. RUBEN GABRIEL

Department of Statistics and Division of Biostatistics, The University of Rochester, Rochester, NY 14627

(Manuscript received 10 July 1986, in final form 7 February 1987)

ABSTRACT

Earlier published analyses of the second Israeli randomized experiment (1969–75) were restricted to 24-h data; this paper provides more details which are based on continuous time data from recording raingages. The present analyses confirm that when cloud tops were warmer than −21°C, seeding increased the efficiency of precipitation. In the −21° to −11°C window, both amount and duration of rainfall increased by some 50%, but no extra rain events appeared. Extra rain events were apparently initiated by seeding when cloud-top temperatures were warmer (−11°C and above); however, this did not significantly increase the amount of rainfall. No effect of seeding was found when cloud tops were colder than −21°C. It appears that seeding makes the existing process of rain formation more effective and also induces precipitation formation in some clouds that would not have precipitated naturally.

1. Introduction

The present study examines the effects of AgI seeding of clouds in Israel in detail by exploring continuous time data from standard tipping bucket recording raingages.

Cloud seeding by silver iodide, aimed at the production of static effects on cloud microstructure for rainfall enhancement, has been applied in the two consecutive long-term randomized experiments referred to as Israeli I (Gabriel, 1967, 1970; Gagin and Neumann, 1974) and Israeli II (Gagin and Neumann, 1981). Overall, target daily rainfall for all target areas was found to increase with seeding by about 15% in Israeli I and by about 13% in Israeli II. These results were significant at less than 5%. In Israeli I, the positive effects of seeding were found to be particularly large (24%) in the subarea that was located about 40 km from the line of seeding. This effect was confirmed in Israeli II, where stations at that distance from seeding were found to have had an 18% seeding effect—again larger than the overall effect. The statistical significance levels of these results were below 3%.

At the outset of these experiments (Neumann et al., 1967), the following conceptual assumptions were made: (i) The ice-crystal mechanism is the most efficient precipitation-forming process for the given regional meteorological conditions. Natural ice nuclei are responsible for the initial formation of precipitation embryos, and conditions sometimes exist in which the deficiency of a critical concentration of ice crystals causes delay in initiating precipitation or inhibits it altogether. (ii) Rain stimulation might therefore be achieved by ice-crystal formation, either through making the existing process of rain formation more effective, or through inducing precipitation formation in clouds that otherwise would not have precipitated naturally. (iii) A suitable agent in such static seeding might be AgI smoke.

Extensive physical studies accompanied the Israeli experiments (Gagin, 1981) and have shown that the treated clouds were predominantly banded, winter, and cumuliform, and their summits were mostly in the temperature range of −10° to −35°C. These clouds were found to be colloidally stable entities and required, as a necessary condition for precipitation formation, the existence of a suitable concentration of ice crystals. They responded positively to seeding, but this response depended systematically on cloud-top temperatures. Thus, maximal effects (of about 46%) occurred on days when the modal values of cloud tops had temperatures of −15° to −21°C. [This result was statistically significant at less than 1% (Gagin and Neumann, 1981).] This maximum agrees with what had been predicted by earlier theoretical studies (Neumann et al., 1967; Gagin and Neumann, 1974; Gagin and Steinhorn, 1974).

These findings correspond to those noted for static-mode seeding of orographic clouds in Colorado. In both Climax experiments, seeding was found most effective in a window of relatively warm temperatures (Mielke

---

et al., 1970, 1971). That window has been identified as about −20° to −11°C and found to correlate closely with similar cloud-top temperatures (Grant and Rauber, 1986).

Conceptual assumption (i) has been confirmed by physical studies (Gagin, 1975). Assumption (iii) has been corroborated by the success of AgI seeding in the two Israeli experiments. The present study uses Israeli II continuous-time data from recording raingages to explore the ice-crystal effect of AgI seeding in more detail, thereby checking assumption (ii).

Since the Israeli experiments used static seeding techniques, the distributions of daily cloud-top heights and temperatures were expected to shed light on the processes involved. Stratification by cloud-top temperature was to provide the following analyses: 1) testing some of our hypotheses with regard to the physics of precipitation processes and the effect of seeding on them; 2) breaking down the overall results in order to detect whether there is some physically meaningful subset of results that would provide physical plausibility to the statistical results; and 3) possibly giving some indication of the relative efficiency of seeding clouds with different properties.

Some details of the distribution of cloud-top heights and their temperatures on days with different daily amounts of rainfall were given earlier (Gagin and Neumann, 1974; Gagin, 1981). The daily modal values of the temperature of cloud tops had been used to stratify the days for a study of possible differential effects of seeding (Gagin and Neumann, 1981).

The present analysis used charts of recording raingages from the period of Israeli II to obtain the components of daily rainfall at any given locality. These components were the durations, intensities and numbers of rain events, i.e., of rainclouds. Statistical analyses applied to their daily means in the control and target areas may help in understanding the differential effects of seeding on these components. They also provide a check of the validity of assumption (ii), previously presented. Thus, an increase of the number of rain events due to static seeding could be interpreted as showing that rain was initiated in clouds that otherwise would not have precipitated naturally. Similarly, an increase in rain duration, beyond that resulting from the increased number of rain events, could be taken to indicate that static seeding affects the already precipitating clouds by increasing their precipitation efficiency. Another issue that could only be addressed by data from recording raingages was whether seeding might have been effective only, or mostly, in the hours of darkness.

In addition to the better physical insight from such studies, the knowledge obtained from recognizing the effects of seeding on rain duration and on its intensity may be important for the hydrological evaluation of the effects of cloud seeding.

2. Experimental design, data processing and statistical methods

a. *The design of the Israeli II cloud seeding experiment*

Israeli II was a randomized cloud seeding experiment conducted during the six winter rainfall seasons of 1969–75. Its primary purpose was to examine the possibility of enhancing rainfall by static cloud seeding over the catchment area of Lake Tiberias (Fig. 1). In the following, it is referred to as the target. Another area, nearer the Mediterranean, was chosen as control. Its rainfall was known to be highly correlated with that of the target, but on rainy days it was generally upwind (both at cloud base and higher up) and therefore most unlikely to be affected by seeding the target.

Each day of the winter season was randomly allocated with a probability of ½ to be seeded or not seeded. Randomization was independent from day to day, without any blocking or stratification. At the beginning of each season, the staff involved in the seeding operations were provided with a list of dates allocated to be seeded.

The precipitation data used for evaluating the results of seeding were collected by the regular raingage network of the Israeli Meteorological Service. The observers had no information on the randomized allo-

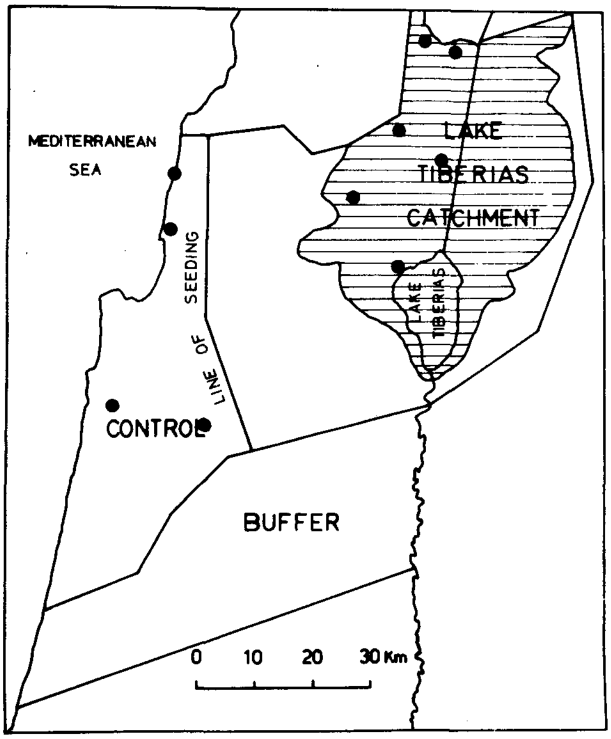

FIG. 1. Map showing the location of the recording raingages, denoted by full circles (four in the control and six in the target areas—the latter is hatched): Also shown is the line of aircraft seeding.

cations and could therefore be regarded as blind to the seeding operations.

The statistical analysis was retricted to "rainy days," which were defined, as in Israeli I, as days with some rain at any of three coastal stations in an area that was never subjected to seeding. This considerably reduced the number of days to be analyzed—to 388 in six winters—but omitted only about 1% of target and control rainfall amounts (Gabriel, 1967).

Of the 388 "rainy days" during Israeli II, 209 had been allocated to be seeded, and are referred to as "seeded," while the remaining 179 are referred to as "unseeded." Some of the 209 "seeded" days were not actually seeded, either because no suitable clouds developed or because other reasons prevented seeding. However, the statistical evaluation of the experiment included all 209 days as "seeded," because restricting the evaluation to the "actually seeded" days would have risked introducing a selection bias. (The second line of Table 1 shows that the "actually seeded" days' average rainfall was more than 10% higher than the average of all "seeded" days.)

b. *Data reduction and processing of recording raingage measurements*

The present analysis uses only data obtained from the daily charts of recording raingages, an example of which is shown in Fig. 2. The various rain events on this day are numbered consecutively. The integrated duration of rainfall for all 14 of these rain events is 164 min and the total amount of rainfall precipitated at this station on this day is 14.5 mm. Since most, if not all, rainfall in Israel is produced by cumuliform clouds, the distinction between various rain events is fairly straightforward.

For the present analysis, target rainfall characteristics are obtained from six rain-recording stations in the Lake Tiberias Catchment area and control rainfall from four rain-recording stations in the control area. (Their locations are shown in Fig. 1.) In view of the exceptionally high correlations of daily rainfall between stations within and between the target and the control (Gagin and Neumann, 1981), and considering the magnitude of the effort required for data reduction for 388 days, it was felt that this small number of stations would suffice for a reliable analysis.

To check the adequacy of these small samples of stations, we present a number of daily averages of precipitation in Table 1, both for the present small sample of raingages and for the much larger set of raingages used in the previous analysis of Israeli II (Gagin and Neumann, 1981). The day-to-day correlations between the two datasets are very high indeed, and the differences between individual days are quite small. The double ratio (DR) of the present analysis is, however, slightly higher (1.25) than that of Gagin and Neumann's analysis using daily stations of the Catchment area (1.18).

c. *Cloud top data*

Cloud-top height data from radar measurements (Gagin and Neumann, 1974; Gagin, 1981) were obtained for 249 days. Figure 3 depicts the cloud-top height distributions of the clouds forming this data base.

Cloud-top heights were not available for the other 139 days, mostly because of electronic or mechanical failures of the radar and an inability to operate the radar on days when the clouds existed only very briefly. The exclusion of the latter days may have introduced some selection bias, as relatively drier days were less likely to have had radar observations. Some idea of this bias can be obtained from Table 1, which shows that the days with cloud top data had, on the average, some 20% more precipitation than the overall average day. Obviously, the days without cloud top data are mostly marginal rainfall days in which, in all probability, seeding could not have been applied successfully. However, restriction of some analyses to days with cloud top data is unlikely to have biased the evaluation of seeding effects since the availability, or nonavailability, of radar data is presumably unrelated to the ran-

TABLE 1. Mean amounts of precipitation (millimeters) in various subsets of days.

	Number of days	Recording gages		Daily gages		Correlation	
		Control	Target	Control	Target	Control	Target
All days						0.959	0.979
All seeded days	209	8.36	8.82	8.30	8.89		
Actually seeded days	174	9.51	10.32	9.54	10.39		
with temperature data	136	9.64	10.80	9.83	10.84		
All unseeded days	179	8.57	7.24	8.05	7.32		
with temperature data	113	10.21	8.98	9.84	9.03		

Days exclude those with no rain at all at three nearby stations that should not ever have been affected by seeding; *Daily gages* data are from Gagin and Neumann, 1981; *Target* is Lake Tiberias Catchment; *Actually seeded* days exclude days allocated to be seeded but not actually seeded; *Temperatures* are modal cloud top temperatures; *Correlation* is between data of recording gages and data of daily gages.

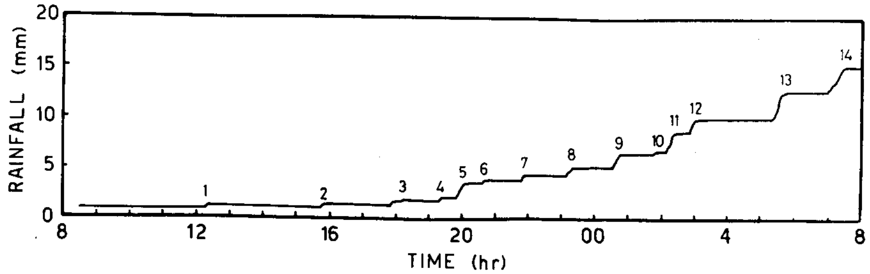

FIG. 2. An example of a chart of a recording raingage, depicting the determination of the daily number of rain events (P), the daily duration of rain (D) and the total amount of daily rainfall (R), in Jerusalem on 14 March 1984. On that day, $P = 14$, $D = 2.74$ h and $R = 14.5$ mm.

domized allocation of seeding or to the effects of seeding.

d. Statistical techniques

The main statistical tool used for the present analyses is the double ratio (DR). This compares the total amount of target rainfall on seeded days with what would have been expected from rainfall on the unseeded days and on the control. This expected amount on the target during seeding is calculated as the total control rainfall on the seeded days, multiplied by the ratio of target to control total rainfall on all unseeded days. More formally,

$$\mathrm{DR} = \frac{\text{total on target seeded}}{\text{total on target unseeded}} \times \frac{\text{total on control unseeded}}{\text{total on control seeded}}.$$

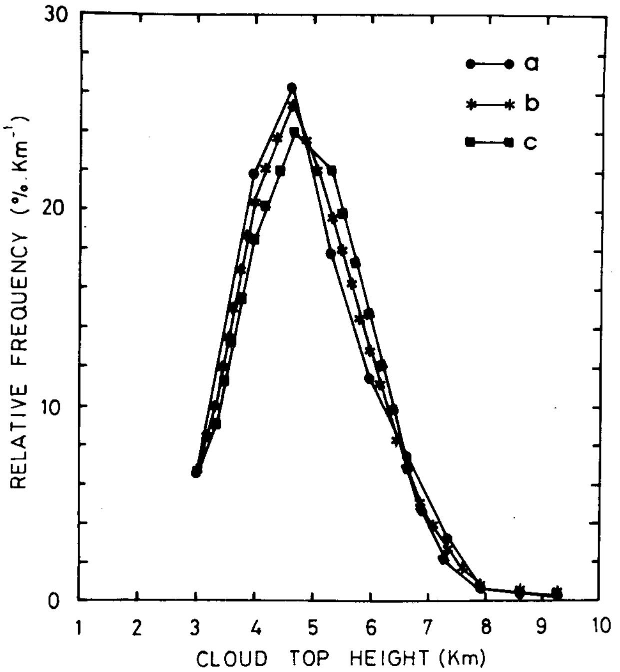

FIG. 3. The frequency distribution of cloud-top heights: curve (a) depicts the daytime clouds (0800–2000) distribution; curve (b), daily clouds (0800–0800); and curve (c), nighttime clouds (2000–0800). For definition of periods see the text.

This statistic corrects the target's seeded/unseeded rainfall ratio by dividing it by a similar ratio for the control. That correction should produce a more reliable estimate of seeding effect since the control had been chosen to be highly correlated with the target. Apart from random variations, the DR should be 1 if seeding had had no effect; if seeding had an effect, the proportion of increase of rainfall should be expressed by the difference DR − 1.

The random variation of a DR can be gauged from a large sample approximation of its standard error and by considering it normally distributed. (See Gabriel and Feder, 1969; Petrondas, 1981; and the Appendix to Gabriel and Gagin, 1987.)

Another method of assessing the significance of a DR's excess over 1 is repeatedly rerandomizing the experimental data (Brillinger et al., 1979; see also Gabriel and Feder, 1969). To this purpose, we took a sample of 1000 random reallocations of "seeding" to the 388 experimental days and calculated the DR for each of these reallocations, always using the precipitation data of the actual experiment. The significance of the observed DR was then estimated by the percentage of reallocations whose DR exceeded that calculated from the experiment's actual allocation.

Finally, some use was also made of regressions of daily target precipitation on control precipitation and other covariates. This was done in the context of comparing daytime and nighttime rainfall and will be discussed in a companion paper (Gabriel and Gagin, 1987).

e. The variables

The statistical methods described previously for daily rainfall amounts were also used for each of the other

TABLE 2. Daily means and double ratios of precipitation characteristics.

	Target mean		Control mean			
	Seed	Unseeded	Seed	Unseeded	DR (SE)	Rerandomization *P*-value
24-h rainfall (mm)	8.82	7.24	8.36	8.57	1.249 (.087)	0.6%
Duration (h)	2.21	2.18	1.58	1.83	1.175 (.077)	1.8%
Number of events	5.62	5.09	4.63	4.72	1.126 (.059)	2.3%

three variables which were used in the present analyses to measure possible responses to cloud seeding.

The three main response variables of this study were read off the recording raingage charts on a daily basis; these were the amount of rainfall, its duration, and the number of rain events, the latter being ascribed to the day on which the event began.

In addition, the intensity of rainfall was roughly gauged by each day's ratio of rainfall amount to rainfall duration. Ideally, the intensity of each rain event should have been obtained directly from the charts of the recording raingages. That, however, was not practical in view of the difficulty of measuring the slope of the curve delineating the accumulation of rainfall on the chart.

3. Results

a. Overall results

Summary statistics for the entire experiment are shown in Table 2. They confirm the overall effect of seeding on precipitation noted before by Gagin and Neumann (1981). This effect is estimated at DR − 1 = 25%, but as its standard error is 9%, the true effect may well be anywhere between roughly 10 and 40%. It is, however, clearly significant, as is also attested by the low rerandomization significance level.

Table 2 shows that seeding also significantly affected the duration of rainfall and the number of rain events per day, although these may have increased a little less than the amounts did.

b. Stratification of rainfall amounts of cloud-top temperatures

Daily rainfall data from a network of daily raingages had been classified according to the modal value of the daily distribution of cloud-top temperatures (Gagin and Neumann, 1981). Analysis of seeding effects within such temperature classes had revealed the following. There had been a maximal positive seeding effect of about 29% (significant at the 0.8% level) in the group of days with modal cloud-top temperatures in the −21° to −12°C range. In the narrower temperature range of −21° to −16°C, the apparent increase due to seeding was as high as 46% (significant at the 0.5% level). No significant seeding effect had been found on other days, i.e., when the modal values of cloud-top temperatures were either warmer than −12°C or colder than −21°C.

Analogous analyses of the present study's data from recording raingages are shown in Table 3. Not surprisingly, the results have essentially the same pattern as those of the earlier analysis. There is a positive seeding effect of 45% (±17%) on days when the modal cloud tops are in the range of −21° to −12°C, and a 53% (±24%) effect in the narrower −21° to −16°C range (both are significant at less than 5%). In the following, these categories of days will be referred to as the "broad seeding window" and the "narrow seeding window," respectively. On days outside these windows, i.e., when modal cloud tops were either warmer than −12°C or colder than −21°C, there are indications of smaller positive effects but these are not significant.

TABLE 3. Mean amounts of rainfall per day (millimeters). Target and control averages on seeded and unseeded days of various cloud-top temperatures, with double ratio (and its standard error) and rerandomization *P*-value.

Cloud-top temperature (°C)	Number of days		Target mean		Control mean			
	Seed	Unseeded	Seed	Unseeded	Seed	Unseeded	DR (SE)	Rerandomization *P*-value
All	208	178	8.82	7.24	8.36	8.57	1.249 (.087)	0.6%
Unknown	73	66	5.14	4.27	6.05	5.77	1.148 (.172)	22.9%
Known	135	112	10.80	8.98	9.64	10.21	1.274 (.098)	0.3%
−11 and above*	27	21	9.85	4.42	8.06	4.87	1.347 (.301)	19.1%
−21 to −12	38	39	10.77	9.45	9.64	12.27	1.450 (.166)	1.3%
−26 to −22	21	14	12.25	12.41	10.30	10.78	1.033 (.122)	43.9%
−27 and below*	49	38	10.66	9.87	10.24	10.97	1.158 (.159)	18.2%
−21 to −16	20	22	12.57	8.97	11.61	12.70	1.533 (.236)	5.3%

* Maximal temperature about +1°C except for 1 day at +6°C; minimal temperature −69°C.

TABLE 4. As in Table 3 except for mean rain duration per day (hours).

Cloud-top temperature (°C)	Number of days		Target mean		Control mean		DR (SE)	Rerandomization P-value
	Seed	Unseeded	Seed	Unseeded	Seed	Unseeded		
All	208	178	2.21	2.18	1.58	1.83	1.175 (.077)	1.8%
Unknown	73	66	1.40	1.40	1.12	1.33	1.192 (.140)	11.8%
Known	135	112	2.65	2.63	1.83	2.12	1.165 (.090)	5.3%
−11 and above	27	21	2.67	1.61	1.85	1.26	1.126 (.213)	30.7%
−21 to −12	38	39	2.76	2.94	1.66	2.60	1.469 (.153)	0.6%
−26 to −22	21	14	3.20	2.82	2.10	1.85	1.000 (.202)	48.8%
−27 and below	49	38	2.30	2.84	1.83	2.22	0.986 (.163)	52.4%
−21 to −16	20	22	3.33	2.79	1.92	2.46	1.531 (.208)	2.2%

c. *Duration of daily rainfall*

Similar analyses of the duration of rain per day are shown in Table 4. The results are very similar to those for rainfall amounts, showing large and highly significant seeding effects in the seeding windows (47 and 53%, respectively, for the broader and narrower windows), and no clear evidence of any effects on days outside the seeding windows. There appears to be a close correlation between the effects of seeding on amounts and on duration of rainfall.

d. *Number of rain events per day*

Table 5 presents the analysis for the number of rain events per day. This shows a different pattern from that of Tables 3 and 4: there was an increase in the number of rain events which is most evident for days when cloud tops were relatively warm (−11°C and above), and which seems to fall off for days with cooler cloud tops. There is no evidence of any increase at all in the coldest cloud top temperature category.

e. *Intensity of rainfall*

An interesting question, from both the cloud physics and hydrological points of view, is the effect of seeding on the daily means of rainfall intensity. In view of the close correlation noted to exist between the effects of seeding on amount and duration of rainfall, it is not surprising that there were no apparent effects on the intensity, i.e., on the amount/duration ratio. Table 6 shows DR close to unity and no significant effects. The present analyses do not provide direct estimates of instantaneous intensity and allow only a rough "average" calculation of the ratio of the mean precipitation to mean duration—hence conclusions must remain tentative.

f. *Summary of effects of seeding*

Combining these results, one notes two separate patterns of seeding effect. First in the windows of 5° to 10° above −21°C, seeding produced some 50% more and longer-lasting rain without increasing the number of rain events. Secondly, at higher temperatures, seeding augmented the number of rain events somewhat, but did not significantly increase amounts and duration. Third, on days with colder cloud tops, seeding had no apparent effect.

The first effect is related to duration, rather than to number of events in the seeding windows, and must therefore be regarded as an effect on precipitation efficiency of already precipitating clouds. The second effect is apparently one of initiating precipitation from

TABLE 5. As in Table 3 except for mean number of rain events per day.

Cloud-top temperature (°C)	Number of days		Target mean		Control mean		DR (SE)	Rerandomization P-value
	Seed	Unseeded	Seed	Unseeded	Seed	Unseeded		
All	208	178	5.62	5.09	4.63	4.72	1.126 (.059)	2.3%
Unknown	73	66	3.40	3.40	2.95	3.28	1.115 (.121)	19.4%
Known	135	112	6.81	6.09	5.54	5.57	1.126 (.068)	3.3%
−11 and above	27	21	5.74	3.53	4.60	3.59	1.268 (.128)	4.9%
−21 to −12	38	39	7.44	5.84	6.02	5.58	1.180 (.115)	8.1%
−26 to −22	21	14	9.25	8.33	6.13	6.54	1.184 (.169)	18.9%
−27 and below	49	38	5.88	6.93	5.42	6.30	0.986 (.111)	54.0%
−21 to −16	20	22	8.49	5.36	6.80	5.26	1.226 (.154)	11.2%

TABLE 6. As in Table 3 except for mean daily rain intensity (mm h^{-1}).

Cloud-top temperature (°C)	Number of days		Target mean		Control mean			
	Seed	Unseeded	Seed	Unseeded	Seed	Unseeded	DR (SE)	Rerandomization *P*-value
All	208	178	3.50	3.14	5.22	4.36	0.933 (.080)	78.4%
Unknown	73	66	3.34	2.61	4.68	3.35	0.919 (.158)	68.6%
Known	135	112	3.59	3.45	5.50	4.95	0.936 (.091)	74.9%
−11 and above	27	21	2.81	3.36	4.09	3.92	0.802 (.317)	72.7%
−21 to −12	38	39	3.42	3.12	5.46	5.13	1.029 (.121)	43.7%
−26 to −22	21	14	4.08	4.31	5.07	5.80	1.081 (.140)	31.3%
−27 and below	49	38	3.95	3.52	6.52	5.06	0.870 (.153)	80.2%
−21 to −16	20	22	3.43	2.98	6.41	5.20	0.933 (.182)	63.6%

warmer clouds that would not have produced it naturally. It is much less important hydrologically because these warmer clouds do not contribute much rain. It does, however, have physical significance, as it suggests that static seeding can initiate rain in clouds that would not precipitate naturally.

4. Some related physics

a. The effect of cloud-top temperatures

The rain-producing cloud systems in Israel are predominantly associated with cold, winter, low-pressure systems affecting the eastern Mediterranean region. Gagin (1981) showed that, except for some very rare cases, practically all these cloud systems consist of bands or clusters of cumuliform elements located at the cold sectors of the prevailing cold depressions. The microstructure of these rain clouds was continental in nature, and as a result had high colloidal stability (Terliuc and Gagin, 1971; Gagin and Neumann, 1974). Studies of the ice particle content of these cumuliform clouds (Gagin, 1975) have shown that ice crystal concentrations, at the tops of clouds having the summit temperature of −5° to −25°C, are clearly dependent on temperature. They have indicated that the crystal multiplication process which operates in these clouds is inefficient. That and the relatively low concentrations of ice crystals in the cloud-top temperature domain of −12° to −21°C suggest that the presence of ice crystals in such clouds, while being a necessary condition for rain embryo formation, is not sufficient for producing an efficient rain mechanism. Also, the deficiency of ice crystals at the extreme warm end of this range is the probable reason for the inability of many clouds warmer than approximately −11°C to produce any noticeable rain on the ground.

It has been pointed out in several earlier papers (Gagin and Neumann, 1974; Gagin and Steinhorn, 1974; Gagin, 1975) that in winter cumulus clouds, such as those found in Israel, the time element for the possible growth of precipitation elements is of crucial importance. In such clouds the mechanism essential for precipitation formation is that of crystal growth by deposition, followed by graupel formation and the subsequent growth of the latter by riming. The onset of riming requires that ice crystals should attain some minimum size before they can collect cloud drops (which also must exceed some minimum size in order to be collected). Moreover, ice-crystal growth is a nonlinear function of temperature whose major rapid growth domain occurs at about −15°C. In clouds with tops warmer than −12°C, the time and growth rates available for the growth of the small numbers of naturally occurring ice crystals, i.e., nucleated at about −10°C, are insufficient to render them large enough to become precipitation elements capable of falling through the updrafts. If these crystals can be made to attain larger sizes, their evaporation near the cloud tops will be avoided and their subsequent growth will enable them to reach the ground in the form of noticeable rain.

It was therefore suggested in the previously mentioned papers that static seeding of winter continental cumulus clouds could initiate rain in clouds that otherwise would not have precipitated, i.e., clouds with tops warmer than about −11°C. This could be achieved by the formation of ice crystals at the lower elevations in the clouds, where the temperature is close to −5°C—the threshold of activation of AgI. In suggesting this, it was recognized that such an effect would contribute relatively little to the total possible increase in rainfall, since such shallow clouds precipitate less than the deeper and colder clouds. The results of Table 5 appear to confirm this. However, these papers further suggested that static seeding could be particularly effective in clouds which are colder than −12°C and which contain the dendritic growth domain of about −15°C at some distance below the cloud tops, i.e., in clouds with top temperatures of about −15° to −20°C. This is borne out by the present findings (Tables 3 and 4) which show the strongest and most clearly significant effects in the −16° to −21°C temperature domain. The previously quoted papers also showed that colder clouds would be less amenable to seeding of this type, because of the efficient manner by which they naturally produce precipitation elements, in such numbers and sizes that the rate of water consumption as they grow balances the rate of condensate formation at these higher and colder elevations.

b. *Duration of rainfall*

Mean duration of daily rainfall increased in part due to the increase in the number of daily rain events and in part due to the increased duration of the individual rain events. In order to disentangle these effects, consider the seeding windows which had roughly 50% increases in mean daily duration (Table 4) and roughly 20% increases in mean daily number of rain events (Table 5). That indicates an increase of some 25% in the mean duration of an event. Independent measurements of the duration of rain from cumulus clouds, as inferred from radar tracking, indicate that a duration of 23 min is typical of cumulus clouds with tops at heights of about 5.5 km (Gagin et al., 1985). Figure 3 suggests that this height is very close to the mode for the clouds seeded in Israel and for both the broad and narrow windows defined previously.

The overall mean duration of an event may also be estimated from data for unseeded target area clouds, i.e., under natural conditions. Dividing the overall mean duration (2.18 h/d) by the mean number of rain events (5.62 per d) again yields an estimate of 23 min. One would conclude, therefore, that seeding prolonged rain events by roughly 5.7 min.

c. *Number of rain events*

Since every rain event is indicative of the passage of a rain cloud over the recording station, the results of Table 5 confirm assumption (ii). They suggest that static seeding is effective in the initiation of rain in a substantial fraction of the clouds that are on the verge of producing rain, i.e., with tops warmer than −11°C, but which cannot precipitate naturally since they are deficient of natural ice crystals capable of growing to the size of graupel particles. The introduction of the AgI seeding agent, which has nucleation threshold temperatures of −5° to −8°C, will therefore activate the formation of graupel earlier and at lower elevations, and initiate rain which will reach the ground. This effect does not occur in colder clouds which can initiate rain naturally by virtue of their greater depth.

It therefore appears that static seeding is capable of initiating rainfall in shallower clouds with tops warmer than −11°C. It can also augment the rain from clouds with intermediate summit temperatures of roughly −21° to −12°C. In the latter clouds, the augmentation of rainfall is affected mainly by increasing the clouds' duration as precipitating entities.

These findings generally agree with those for the Climax experiments, where seeding was found to have increased duration rather than intensity of precipitation (Chappell et al., 1971). However, these authors concluded that in Colorado "the main effects of seeding appear to be the initiation of a precipitation release for the warmer clouds . . . when it would not have occurred naturally"; that inference differs from our reading of the Israeli data, for which we were actually able to analyze the numbers of rain periods.

5. Summary

The present analysis confirms earlier analyses of the Israeli II rainfall-enhancement experiment. It provides additional evidence of the physical plausibility of the statistical findings of both Israeli experiments, and supports the credibility of the assumptions outlined at their outset, i.e., that static seeding will enhance rainfall by improving the efficiency of existing rain mechanisms for clouds with intermediate temperatures and initiating rain in warmer clouds that otherwise would not have precipitated.

The overall 25% increase in precipitation that occurred under seeding appears to have been an average of a number of different patterns: 1) on days with relatively warm cloud tops (above −11°C), seeding apparently initiated precipitation in clouds that would not have precipitated naturally, so the number of rain events increased, but since these are days with light precipitation neither amounts nor duration of rainfall increased much; 2) on days in the −21° to −12°C "seeding window," the effect of seeding was not one of initiating precipitation (the number of rain events did not increase), but rather one of making precipitation more efficient; it resulted in a roughly 50% increase in both duration and amount of rainfall; (3) seeding apparently had no effect at all on days with colder clouds.

Acknowledgments. This study has been supported and financed by E.M.S., a subsidiary of Mekorot Water Co. in Israel. Support for Gabriel's participation was provided by the United States National Science Foundation in Contract ATM-8314063.

Thanks are due to M. Shapira and B. Anderman for carrying out the computations and to H. Nozyce for preparing the figures.

REFERENCES

Brillinger, D., L. V. Jones and J. W. Tukey, 1978: *The Management of Weather Resources. Volume II: The Rôle of Statistics.* Weather Modification Advisory Board, U.S. Govt. Printing Office.

Chappell, C. F., L. O. Grant and P. W. Mielke, Jr., 1971: Cloud seeding effects on precipitation intensity and duration of wintertime orographic clouds. *J. Appl. Meteor.*, **10**, 1006–1010.

Gabriel, K. R., 1967: The Israeli rainfall stimulation experiment, statistical evaluation for the period 1961–65. *Proc. of the Fifth Berkeley Symposium on Mathematical Statistics and Probability. Volume V. Weather Modification,* Berkeley, 91–113.

Probability. Volume V. Weather Modification, Berkeley, 91–113.

——, 1970: The Israeli rainmaking experiment 1961–67: Final statistical tables and evaluation (Tables prepared by M. Baras). Tech. Rep., Hebrew University, 47 pp.

——, and P. Feder, 1969: On the distribution of statistics suitable for evaluating rainfall stimulation. *Technometrics,* **11,** 149–160.

——, and A. Gagin, 1987: Analyses of recording raingage data for the Israeli II experiment. Part II: Differential day and night effects of cloud seeding. *J. Climate Appl. Meteor.* **26,** 922–926.

Gagin, A., 1975: The ice phase in winter continental cumulus clouds. *J. Atmos. Sci.,* **32,** 1604–1614.

——, 1981: The Israeli rainfall enhancement experiments. A physical overview. *J. Wea. Modif.,* **13,** 108–120.

——, and J. Neumann, 1974: Rain stimulation and cloud physics in Israel. *Weather and Climate Modification,* W. N. Hess, Ed., Wiley-Interscience, 454–494.

——, and ——, 1981: The second Israeli randomized cloud seeding experiment: Evaluation of the results. *J. Appl. Meteor.,* **20,** 1301–1311.

——, and I. Steinhorn, 1974: The role of solid precipitation elements in natural and artificial production of rain in Israel. *J. Wea. Modif.,* **6,** 216–228.

——, D. Rosenfeld and R. E. Lopez, 1985: The relationship between height and precipitation characteristics of summertime convective cells in South Florida. *J. Atmos. Sci.,* **42,** 84–94.

Grant, L. G., and R. M. Rauber, 1986: Weather modification related characteristics of Colorado and Utah orographic clouds. *Tenth Conf. on Planned and Inadvertent Weather Modification,* Arlington, Amer. Meteor. Soc.

Mielke, P. A., L. O. Grant and C. F. Chappell, 1970: Elevation and spatial variation effects of wintertime orographic cloud seeding. *J. Appl. Meteor.,* **9,** 476–488.

——, —— and ——, 1971: An independent replication of the Climax wintertime orographic cloud seeding experiment. *J. Appl. Meteor.,* **10,** 1198–1212.

Neumann, J., K. R. Gabriel and A. Gagin, 1967: Cloud seeding and cloud physics in Israel: Results and problems. *Proc. of International Conf. on Water for Peace, Volume 2,* Washington, DC, 375–388.

Petrondas, D. A., 1981: On randomization tests. Ph.D. thesis, University of Rochester, Rochester, NY.

Terliuc, B., and A. Gagin, 1971: Cloud condensation nuclei and their influence on precipitation. *J. Appl. Meteor.,* **10,** 474–481.