Analysis of Recording Raingage Data for the Israeli II Experiment. Part II: Differential Day and Night Effects of Cloud Seeding

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ABSTRACT

This paper reports separate analyses of daytime and nighttime precipitation based on data from recording raingages of the second Israeli randomized experiment. These analyses seemed important because there are a number of hypotheses on the differential effects of AgI seeding during the day and at night, and because about half of the seeding of this experiment was done at night. Our findings are unfortunately equivocal because of the large variability of the data which had to be broken down by categories of modal cloud-top temperatures and 12-h (day/night) periods. The increase of precipitation efficiency that had been noticed (on 24-h data) to occur in the −12° to −21°C window appears to have been larger at night, but the difference is not significant. The increase in the number of rain events for warmer clouds may have been only a daytime effect, but again, the present data are not conclusive.

1. The issue of day-night differentials in cloud seeding effects

The success of the two successive Israeli rainfall augmentation experiments has been remarkable, especially against the background of many other experiments whose results were, at best, equivocal. There have been conjectures about its causes, arguments that it resulted from especially favorable meteorological conditions in that region (Gagin, 1981; Silverman, 1986), and speculation that its seeding operations had been particularly effective. In this context, a distinctive feature of Israeli cloud seeding has been that it was carried out around the clock, at all times when suitable clouds seemed to appear. Indeed, more than 50% of the seeding during Israeli I was carried out at nighttime (Gabriel and Neumann, 1978), as was some 44% of Israeli II seeding. This has undoubtedly led to more intensive seeding than in other experiments, which in itself could be a factor producing larger, and therefore more significant, effects. However, the Israeli success could possibly have been due, at least in part, to particular effectiveness of nighttime seeding.

Cloud seeding with AgI particles might have different effects on rainfall during the day and during the night. A possible mechanism that might produce such differential effects is the deactivation due to solar ultraviolet radiation that was thought to reduce the activity of AgI nuclei dispersed into the atmosphere during daylight hours (Inn, 1951; Reynolds et al., 1951; Vonnegut and Neubauer, 1951; Reynolds and McWhirter, 1952; Smith and Heffernan, 1956; Smith and Seely, 1955; Rowland, 1964). Super and McPartland (1975) have, however, concluded from experimental data obtained under field conditions that cloud seeding material produced by complexes of AgI in acetone solution does not rapidly lose its nucleating ability during daylight. They further stated that such "decay is no more than a factor of 2 per hour and may be even nonexistent." A reanalysis of data from Langmuir's periodic experiment for day versus night differentials was carried out by Howell (1978), but his study could not definitively attribute these differences to seeding.

The present paper explores the possibility that seeding might have had different daytime and nighttime effects in Israel. It does so on the basis of data from the Israeli II experiment, for which a number of recording raingage stations, six in the target and four in the control area, have been analyzed in detail (Gagin and Gabriel, 1987: hereafter referred to as GG). For the present analysis, each of the "rainy days" of the experiment was split into "daytime," defined as 0800–2000 h and "nighttime," defined as 2000 to 0800 of the following morning. (All times given in this report are LST unless otherwise indicated.) This fits in well with the operational protocol of Israeli II which defined an experimental day as 24 h from 0800. Of course, this rigid 12 h-split does not correspond precisely to that between daylight and darkness hours, but it may serve as a reasonable approximation to it.

2. Methods of analysis

Analyses of rainfall amounts, duration and number of rain events, corresponding to those of GG for entire days, are here done separately for daytime and for nighttime data. As in GG, the data are stratified by modal cloud-top temperature (Gagin and Neumann, 1981). Clearly, the day and night results of the present analysis must average out to those for the entire days, as given in GG, but their differences may provide interesting information on the way seeding affected precipitation.

The subdivision of data into daytime and nighttime precipitation reduces the precision of the comparisons. Whereas almost every 24-h period had some precipitation, many such periods had either completely dry days or completely dry nights. This greatly increased the noise in the separate day and night analyses and often, especially with ratios such as intensities, produced inconsistent results in which the 24-h statistic was smaller (or larger) than both the day statistic and the night statistic. We therefore decided against presenting intensity estimates for this paper's night/day comparisons. Also, we have some misgivings about the data for the narrow window (−21° to −16°C) in which each 12-h period may have had too few rain events to allow reliable estimates.

Several analyses of the three basic response variables were carried out, using a variety of methods, from exploratory data analysis techniques such as moving medians (Cleveland and Kleiner, 1975; see also Graedel and Kleiner, 1985), nonparametric tests such as the Wilcoxon or Mann-Whitney two-sample test, and the double ratios

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

(Gabriel and Feder, 1969; Petrondas, 1981), as well as regression methods in which the adjustment of target rainfall for control rainfall is done separately for each day, or rather, for each 12-h period. These regression methods gauge the effect of seeding by calculating a regression coefficient onto an index that equals +1 on seeded days and −1 on unseeded days. The various analyses should complement and cross-check each other, although regression allows inspection of the apparent effects on different dates, whereas the DR is based on totals for the entire experiment.

The results from the various analyses were so very similar that we saw no need to report them all. Hence we present only the DRs. The multiplicity of methods of analysis caused no problem in this investigation, but we are concerned that we have 30 different statistical tests of seeding effect, since there are three response variables (amount, duration, and number of events), five categories of cloud-top temperatures, and two datasets, one for day- and one for nighttime. We tested each of the 30 DRs at the 5% level for departure from the value of unity which is what would be expected under the hypothesis that seeding has no effect. Clearly, the probability of finding *some* significant DRs among all these was well above 5%. To avoid misleading conclusions we tried to check whether the significant results fitted a coherent pattern rather than appearing "at random."

The DR statistics for the three response variables and several cloud-top temperature categories are given for night and daytime data in Tables 1 to 3. These tables also list approximate standard errors of the DRs, which were calculated according to the second-order approximation due to Gabriel and Feder (1969). That allows a test of the significance of each DR and also of the ratio of each nighttime DR to the corresponding daytime DR (that would be a test of night/day differentials in seeding effects). The results of these tests are indicated in the tables by a one-sided *P*-value against the alternatives of a positive effect or, for ratios of DRs, for a larger nighttime effect. [The approximate *P*-values for significance testing were calculated on the logarithms, as suggested by Petrondas (1981)—see Appendix.] Thus, a *P*-value of less than 5% (1%) indicates that a test is significant at 5% (1%); a larger *P*-value indicates a nonsignificant result.

Of course, all these "tests" must be treated with reserve since the underlying hypothesis of no day-vs-night differential in seeding effects was not stated prior to the experiment. It was, however, suggested by other studies, such as Howell's (1978), rather than by inspection of the Israeli data. Thus, the analysis is not really confirmatory in the full sense, and significant results would be only *suggestive* of a differential.

The results of this paper refer to only 386 of the 388 rainy days of Israeli II; 2 days with small amounts of precipitation were omitted because of some doubts regarding the observations.

3. Results

a. All days

The analysis of 24-h rainfall in GG has established a significant seeding effect of about 25%. (This is slightly higher than earlier estimates because GG analyzed a more restricted target area.) Tables 1, 2, and 3 show no evidence of a night/day differential in these effects on either amounts, durations or the number of rain events per day. These conclusions can be drawn from the data on all days, as well as from the more restricted dataset for which cloud-top temperatures were available.

b. Days with cloud-top temperatures in the seeding window

As shown in GG, seeding is effective when cloud tops are in the windows of above −21°C temperatures, especially in the narrow window of the −21° to −16°C

TABLE 1. Double ratios of mean amounts of rainfall (millimeters), their standard errors (parentheses, millimeters) and P-values.

Modal cloud-top temperature (°C)	Number of days		Double ratio (DR)			
	Seeded	Unseeded	24 h	Daytime	Nighttime	Night/day
Total	208	178	1.249 (.087) $P = 0.005$	1.224 (.111) $P = 0.03$	1.263 (.100) $P = 0.01$	$P = 0.42$
Unknown	73	66	1.148 (.172) $P = 0.21$	1.047 (.231) $P = 0.42$	1.213 (.189) $P = 0.15$	$P = 0.31$
Known	135	112	1.274 (.098) $P = 0.007$	1.277 (.124) $P = 0.02$	1.273 (.114) $P = 0.02$	$P = 0.51$
−11° and above	27	21	1.347 (.301) $P = 0.16$	1.813 (.372) $P = 0.05$	1.029 (.352) $P = 0.47$	$P = 0.87$
−21° to −12°	38	39	1.450 (.166) $P = 0.01$	1.385 (.175) $P = 0.03$	1.553 (.221) $P = 0.02$	$P = 0.34$
−26° to −22°	21	14	1.033 (.122) $P = 0.39$	0.839 (.246) $P = 0.76$	1.169 (.234) $P = 0.25$	$P = 0.16$
−27° and below	49	38	1.158 (.159) $P = 0.18$	1.164 (.237) $P = 0.26$	1.147 (.156) $P = 0.19$	$P = 0.52$
−21° to −16°	20	22	1.533 (.236) $P = 0.04$	1.257 (.242) $P = 0.17$	1.746 (.284) $P = 0.02$	$P = 0.19$

range. Tables 1–3 essentially show that it is about equally effective in night- and daytime. There are slightly, but not significantly, higher nighttime DRs for amounts and duration—Tables 1 and 2—but no night-vs-day difference in the DRs for the number of rainy events—Table 3. This may indicate longer and wetter seeded rain events at night, but such a conclusion cannot be inferred with confidence from the present data. It should be noted in this connection that the difference between daytime and nighttime cloud-top height distributions was negligible (Gagin and Gabriel, 1987, Fig. 3).

This experiment cannot, therefore, resolve the question about the differential effect of seeding at nighttime and in daytime when cloud tops are in the seeding window. Nighttime rainfall amounts and durations may or may not have been more affected by seeding than daytime amounts and durations.

TABLE 2. As in Table 1 except for mean duration of rainfall.

Modal cloud-top temperature (°C)	Number of days		Double ratio (DR)			
	Seeded	Unseeded	24 h	Daytime	Nighttime	Night/day
Total	208	178	1.175 (.077) $P = 0.02$	1.172 (.100) $P = 0.06$	1.175 (.096) $P = 0.05$	$P = 0.49$
Unknown	73	66	1.192 (.140) $P = 0.11$	1.008 (.220) $P = 0.48$	1.320 (.159) $P = 0.04$	$P = 0.16$
Known	135	112	1.165 (.090) $P = 0.04$	1.219 (.112) $P = 0.04$	1.118 (.115) $P = 0.17$	$P = 0.71$
−11° and above	27	21	1.126 (.213) $P = 0.29$	1.624 (.266) $P = 0.03$	0.809 (.301) $P = 0.76$	$P = 0.96$
−21° to −12°	38	39	1.469 (.153) $P = 0.006$	1.416 (.189) $P = 0.03$	1.544 (.198) $P = 0.01$	$P = 0.37$
−26° to −22°	21	14	1.000 (.202) $P = 0.50$	0.881 (.234) $P = 0.71$	1.001 (.238) $P = 0.50$	$P = 0.35$
−27° and below	49	38	0.986 (.163) $P = 0.54$	0.933 (.207) $P = 0.63$	1.022 (.209) $P = 0.46$	$P = 0.38$
−21° to −16°	20	22	1.531 (.208) $P = 0.02$	1.275 (.269) $P = 0.18$	1.786 (.244) $P = 0.008$	$P = 0.18$

TABLE 3. Double ratio of mean number of rain events, their standard errors (parentheses), and P-values.

Modal cloud-top temperature (°C)	Number of days		Double ratio (DR)			
	Seeded	Unseeded	24 h	Daytime	Nighttime	Night/day
Total	208	178	1.126 (.059) $P = 0.02$	1.158 (.071) $P = 0.02$	1.094 (.079) $P = 0.13$	$P = 0.70$
Unknown	73	66	1.115 (.121) $P = 0.18$	1.114 (.159) $P = 0.25$	1.116 (.147) $P = 0.23$	$P = 0.50$
Known	135	112	1.126 (.068) $P = 0.04$	1.164 (.080) $P = 0.03$	1.086 (.093) $P = 0.19$	$P = 0.71$
−11° and above	27	21	1.268 (.128) $P = 0.03$	1.325 (.103) $P = 0.003$	1.167 (.149) $P = 0.15$	$P = 0.76$
−21° to −12°	38	39	1.179 (.115) $P = 0.08$	1.241 (.127) $P = 0.04$	1.115 (.164) $P = 0.25$	$P = 0.70$
−26° to −22°	21	14	1.184 (.169) $P = 0.16$	1.050 (.146) $P = 0.37$	1.289 (.231) $P = 0.14$	$P = 0.23$
−27° and below	49	38	0.986 (.111) $P = 0.55$	0.986 (.152) $P = 0.54$	0.978 (.153) $P = 0.56$	$P = 0.52$
−21° to −16°	20	22	1.226 (.154) $P = 0.09$	1.203 (.181) $P = 0.15$	1.246 (.189) $P = 0.12$	$P = 0.45$

c. *Days with relatively warm clouds*

The only effect of seeding noted by GG for days with relatively warm clouds (tops above −12°C) was a significant increase in the number of rain events. Table 3 shows this to be a highly significant effect in daytime only. Interestingly, there are also some daytime effects on amounts (P = 5%), and on duration (P = 3%). Nighttime precipitation with such clouds, on the other hand, does not seem to have been affected at all by seeding.

d. *Days with colder clouds*

Seeding seemed not to have an effect on rainfall when cloud tops were colder than −21°C, according to GG. Both daytime and nighttime data support this no-effect pattern: only one of the DRs in those lines of Tables 1–3 is anywhere near significance, and that particular nighttime DR is rather similar to the DR for the next temperature category, which is the seeding window. It probably only suggests that the real range of seeding effects does not correspond exactly to that used to define the windows.

TABLE 4. Correlations of daytime with nighttime precipitation.

Modal cloud-top temperature	Target		Control	
	Seeded	Unseeded	Seeded	Unseeded
All known	0.40	0.38	0.38	0.17
−11° and above	0.71	0.56	0.54	0.52
−21° to −12°	0.41	0.34	0.45	0.18
−26° to −22°	0.17	0.48	0.25	0.36
−27° and below	0.32	0.31	0.34	0.02

e. *Independent or compensatory day and night effects*

If nighttime and daytime rainfall were affected differently by cloud seeding, that might be reflected in a differences of averages, or it might result in a redistribution of the individual days' precipitations between day and night. For example, seeding might delay rainfall from daytime to nighttime. If so, the night–day correlation should have been reduced under seeding. Table 4 does not support this idea. Hence, it would seem that if seeding had any effect it would act separately on daytime and nighttime precipitation, and not in some compensatory manner.

4. Conclusions

The data neither support nor reject the hypothesis that seeding affected nighttime precipitation more strongly than daytime precipitation. They confirm that the seeding effects in the window of above −22°C cloud tops were strong at night, but are equivocal on whether such effects were weaker in daytime. The effects at these temperatures were to increase duration and amount of rainfall, rather than the number of rain events, and might be ascribed to an increase in efficiency of already precipitating clouds. It is possible that seeding increases efficiency at night, more so than in daytime.

At warmer temperatures seeding may have initiated precipitation, as evidenced by the increased number of rain events (GG). There is no clear evidence that this happened more or less in daytime or at night.

No night/day differences in seeding effects are evident at colder temperatures.

It is difficult to trace clear patterns from data that are subject to so much random variability (as is evident from the standard errors). Our analysis of Israeli II data from recording raingages does not allow unequivocal conclusions about night-vs-day differences in seeding effects. There are some suggestions, but these are not conclusive.

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APPENDIX

Statistical Inference with the Double Ratio Statistic

Consider a target/control randomized seeding experiment. Let $i(=1,\cdots,n)$ index the experimental days and $\theta_i = 1$ or 0 according to whether or not the day was assigned to be seeded. Write Y_i and X_i for the i-th day's rainfall observations on the target and control, respectively. The double ratio statistic is then defined as

$$\mathrm{DR} = \frac{\mathrm{sum}\{\theta_i Y_i\}}{\mathrm{sum}\{(1-\theta_i)Y_i\}} \times \frac{\mathrm{sum}\{(1-\theta_i)X_i\}}{\mathrm{sum}\{\theta_i X_i\}},$$

where each sum runs from $i = 1$ to $i = n$.

Gabriel and Feder (1969) studied the randomization distribution of DR and approximated its variance by

$$S^2 = 4\ \mathrm{sum}\{D_e^2\},$$

where

$$D_e = (Y_e/\mathrm{sum}\{Y_i\} - X_e/\mathrm{sum}\{X_i\}).$$

This result has been used in a number of studies for approximate tests of significance of double ratios. Note that S, the square root of S^2, is quoted in Tables 1–4 of the present paper as the approximate standard error of the DRs in those tables.

Petrondas (1981) has since studied the distribution of DR more carefully and has shown S to underestimate the standard error slightly. He found, however, that it is more nearly equal to the standard error of the natural logarithm of the DR, and that the latter has a more nearly normal distribution than the DR itself. It follows that more reliable statistical inferences can be made by considering that log(DR) is approximately normal with standard error S.

This leads to the following tests: 1) For a test of the hypothesis that the "true DR" is 1, use statistic

$$Z = \log(\mathrm{DR})/S,$$

and refer it to the standard normal distribution. 2) For a test of the comparison hypothesis that two "true DRs" are equal, use their estimates DR_1 and DR_2 and the estimates S_1 and S_2 of their standard errors to calculate statistic

$$Z = \{\log(\mathrm{DR}_1/\mathrm{DR}_2)\}/\mathrm{sqrt}\{S_1^2 + S_2^2\}$$

and refer that to a standard normal distribution.

These techniques were used in this paper to calculate P-values (probability that a standard normal variable exceed the computed statistic Z). These are shown in Tables 1–3. Analogous reasoning leads to confidence statements such as the following: with 95% confidence, assert that the true DR lies approximately in the interval

$$[\mathrm{DR}\exp(-1.96S), \mathrm{DR}\exp(+1.96S)].$$

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