Night Versus Day Cloud Seeding in Langmuir's Periodic Experiment

WALLACE E. HOWELL

Office of Atmospheric Resources Management, Division of Research, Bureau of Reclamation, U.S. Department of the Interior, Denver, CO 80225

(Manuscript received 8 December 1977, in final form 10 June 1978)

ABSTRACT

During the last ten 28-day cycles of Langmuir's periodic seeding experiment, beginning 15 October 1950, silver iodide smoke generators were operated one day each week from 1600 to 2400 LT on odd-numbered cycles and from 0800 to 1600 LT on even-numbered cycles, to see if daytime inactivation of the smoke would affect the outcome. However, the differences between nighttime-seeded and daytime-seeded cycles went unanalyzed. Analysis of previously published data now shows that the weekly periodicity of precipitation was greater during nighttime-seeded than during daytime-seeded cycles, especially in the block of analysis regions east–northeastward from the seeding site at Alamogordo, New Mexico. The same was true with respect to periodicity of temperature at the 70 kPa level over Omaha, Nebraska. Between nighttime-seeded and nonperiodic-seeded cycles there was a greater difference than between daytime-seeded and nonperiodic-seeded cycles. Whether these differences were caused by seeding remains unsettled. No accepted theory supports the hypothesis of effect, but if it were true it would be of immense importance.

1. Introduction

On 12 October 1950, a delegation from the National Academy of Science visited Irving Langmuir at his Schenectady laboratory to hear a presentation of preliminary results from the periodic cloud-seeding experiment then just completing its twelfth 28-day cycle. They went away unconvinced of a connection between the weekly release of silver iodide (AgI) smoke from Socorro (later Alamogordo), New Mexico, and the unusually strong weekly periodicity in precipitation over a large part of the central United States during February, March and April of that year (Langmuir, 1962). To furnish, if possible, more convincing proof, Langmuir changed the seeding schedule beginning three days later. Instead of one AgI smoke generator operated between 0800 and 1600 on Tuesdays, Wednesdays and Thursdays, for the next ten 28-day cycles three generators were operated one day a week at Alamogordo on the following schedule (Langmuir, 1962, pp. 545–547):

Cycle	Seeding schedule
13, 17, 21	Mondays, 1600–2400
14, 18, 22	Mondays, 0800–1600
15, 19	Fridays, 1600–2400
16, 20	Fridays, 0800–1600

The entire experiment ended with cycle 22.

The purpose of the eight-week alternations between Mondays and Fridays was to see if the phase of the weekly periodicity in widespread precipitation and associated weather elements would show a corresponding shift. The purpose of the four-week alternations between nighttime and daytime seeding was to see if evidence of photodeactivation of the AgI by sunlight, then under study (Inn, 1951), could be found in the behavior of widespread weather. Subsequently, both Langmuir (1962) and the U. S. Weather Bureau (Brier, 1955) made analyses of the Monday–Friday phase shifts. Curiously, Langmuir's analysis does not mention night–day differences, nor did the Weather Bureau investigation extend to these differences (Brier, personal communication). While reviewing the periodic-seeding experiment in preparation for the workshop on wide-area effects of cloud seeding, held at Fort Collins, Colorado, 8–12 August 1977, the author was struck by this omission and set out to see what Langmuir and Brier might have found had they pursued the matter. In what follows, he has used all the published evidence he could find that bore on this topic. His inquiries of surviving participants and the National Weather Service for unpublished data bore no fruit.

2. Prologue

In investigating the periodicity of precipitation, Langmuir first turned his attention to 20 Weather Bureau reporting stations in the east-central United States where he saw a periodicity appearing in the early months of the experiment. Later he divided the rest of the country into regions, selecting 5–13 Weather Bureau stations in each region, and calculated the average precipitation for each day in each region. He

TABLE 1. Periodicities of 28-day cycles by analysis regions [after Langmuir, 1962, tables 12-III, 12-VI, 12-VII and V (p. 485) and Fig. 1 (p. 471)].

	Periodic-seeded cycles during night-day alternations									
Region	13	14	15	16	17	18	19	20	21	22
A	0.48	0.10	0.41	0.20	0.39	0.03	0.35	0.29	0.37	0.38
B	0.23	0.19	0.22	0.40	0.46	0.48	0.12	0.16	0.16	0.44
C	0.52	0.07	0.08	0.16	0.38	0.45	0.41	0.26	0.28	0.52
D	0.13	0.26	0.38	0.15	0.13	0.43	0.32	0.24	0.18	0.48
E	0.39	0.22	0.40	0.25	0.28	0.41	0.33	0.20	0.34	0.24
F	0.28	0.33	0.40	0.18	0.30	0.35	0.30	0.20	0.15	0.30
G	0.27	0.27	0.55	0.11	0.39	0.37	0.16	0.31	0.20	0.57
H	0.48	0.26	0.29	0.25	—	0.66	0.38	0.16	0.63	0.25
I	0.49	0.22	0.32	0.18	0.28	0.36	0.74	0.32	0.32	0.24
J	0.38	0.16	0.53	0.23	0.25	0.24	0.51	0.37	0.72	0.64
K	0.16	0.33	0.25	0.39	0.60	0.41	0.45	0.31	0.31	0.30
M	0.20	0.12	0.24	0.33	0.21	0.07	0.53	0.46	0.39	0.34
N	0.34	0.14	0.17	0.19	0.39	0.36	0.09	0.57	0.30	0.40
O	0.25	0.32	0.29	0.14	0.52	0.12	—	0.41	—	—
P	0.27	0.16	0.39	0.19	0.43	0.28	0.42	0.33	—	—

	Nonperiodic-seeded cycles of first epoch							
Region	1	23	24	25	26	27	28	29
A	0.278	0.053	0.30	0.202	0.47	0.18	0.387	0.17
B	0.210	0.240	0.16	0.180	0.35	0.30	0.161	0.21
C	0.285	0.268	0.44	0.040	0.39	0.06	0.386	0.21
D	0.295	0.412	0.25	0.110	0.45	0.29	0.257	0.28
E	0.187	0.170	0.16	0.270	0.31	0.20	0.450	0.22
F	0.254	0.330	0.25	0.380	0.22	0.52	0.149	0.36
G	0.347	0.330	0.19	0.280	0.11	0.42	0.216	0.30
H	—	0.053	0.24	0.080	0.38	0.16	0.135	0.18
I	—	0.414	0.24	0.320	0.31	0.37	0.520	—
J	—	0.134	0.48	0.260	0.33	0.41	0.206	0.38
K	0.305	0.310	0.21	0.380	0.41	0.20	0.236	0.45
M	0.046	0.260	0.13	0.360	0.16	0.47	0.300	0.36
N	0.107	0.270	0.18	0.340	0.45	0.40	0.382	0.20
O	0.127	—	—	0.150	0.19	0.68	0.441	0.28
P	—	—	—	—	—	0.58	0.063	0.27

	Nonperiodic-seeded cycles of second epoch							
Region	30	31	32	33	34	35	36	37
A	0.152	0.606	0.071	0.587	0.263	0.197	0.289	0.110
B	0.265	0.444	0.341	0.161	0.425	0.228	0.547	0.261
C	0.251	0.138	0.045	0.726	0.339	0.279	0.310	0.077
D	0.226	0.395	0.184	0.373	0.182	0.406	0.374	0.134
E	0.316	0.542	0.192	0.591	0.391	0.361	0.498	0.032
F	0.161	0.632	0.319	0.550	0.288	0.345	0.477	0.326
G	0.138	0.394	0.377	0.302	0.454	0.167	0.396	0.523
H	0.134	0.295	0.122	—	0.251	0.292	0.286	0.430
I	0.351	0.335	0.173	0.560	—	0.247	0.290	0.440
J	0.145	0.348	0.366	0.765	0.182	0.379	0.226	0.305
K	0.440	0.214	0.468	—	0.077	0.134	0.263	0.141
M	0.118	0.207	0.468	0.753	0.100	0.298	0.453	0.640
N	0.152	0.673	0.657	0.654	0.184	0.232	0.362	0.184
O	0.394	0.550	0.319	0.680	0.406	0.570	0.333	0.000
P	0.490	0.448	0.187	0.631	—	—	—	—

omitted much of the southwest, explaining that there were too few days of measurable precipitation there to permit carrying out the intended analyses.

As a measure of the periodicity of a 28-day cycle, Langmuir at first fitted a 7-day sinusoidal wave to the daily precipitation amounts by the method of least squares and calculated the Pearsonian coefficient of correlation between the daily precipitation amounts and the corresponding values obtained from the fitted wave. Later, to sharpen the focus on the weekly periodicity, he substituted Fisher-Yates (1948) ordinal scores for the precipitation values (assigning identical lowest scores to all zero precipitation amounts) and reduced the measure of variance by the amount allocable to

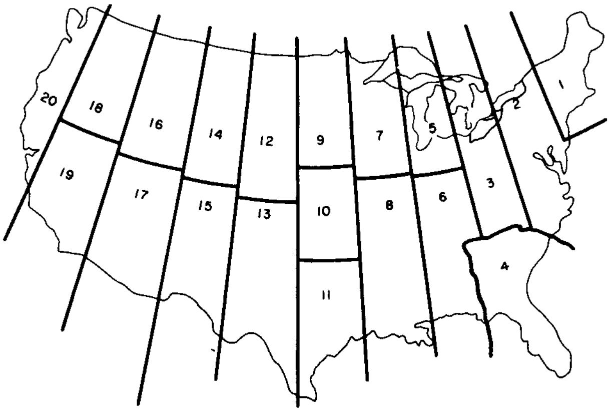

FIG. 1. Weather Bureau analysis regions for periodic seeding experiment.

averaged week-to-week differences. By this change, information about amplitudes was apparently sacrificed; at any rate, Langmuir did not publish it for cycles after the sixth. He elaborated these methods while investigating the results of cycles completed before 30 April 1950 and appears to have applied them consistently in the calculations for all cycles. The reader who wishes to pursue the details further is referred with the author's sympathy to Langmuir's own descriptions.

Table 1 shows the calculated results as Langmuir published them. He explained the missing values for regions O and P as caused by too few nonzero precipitation amounts on the Pacific Coast in summertime to permit calculations to be made. He did not explain the other missing values.

Langmuir also calculated and published the phase of the fitted wave for each cycle and region. However, although he expected a phase shift to accompany alternations of seeding betweeen Mondays and Fridays and sought for such phase shifts in his analysis, he stated no such expectation with respect to the night-day alternations nor is there a hypothetical basis for such an expectation. Therefore, no attention was paid to phase information in undertaking a further analysis.

In his analyses, Langmuir distinguished between two nonperiodic-seeded epochs. The first epoch embraced cycle 1 (which was to have been the first seeded cycle but was called nonseeded because difficulties with equipment and supplies prevented keeping the seeding schedule) and cycles 23–29 immediately following termination of the experiment. The second epoch embraced cycles 30–37, and included two cycles (31 and 33) when very high 7-day periodicity occurred, one of which was the object of special study by the Weather Bureau (Hawkins, 1952; Brier, 1954). The 7-day periodicity was stronger during the second epoch as a whole, with a mean correlation coefficient of 0.34 compared with 0.28 during the first epoch.

Despite widespread commercial seeding during and after the latter half of the periodic seeding experiment,

TABLE 2. Amplitudes and periodicities for Weather Bureau region 4 during cycles 13–22 (after Brier, 1955).

Cycle	Amplitude	Periodicity
13	26.63	0.930
14	8.85	0.341
15	15.23	0.892
16	7.72	0.469
17	13.24	0.703
18	22.26	0.573
19	17.72	0.621
20	6.06	0.550
21	9.96	0.505
22	31.46	0.860

Langmuir considered the first epoch representative of nonperiodic seeding. He expressed belief that periodicity during the second epoch was accentuated by seeding timed to coincide with storms but that, without a regular seeding schedule, the period vacillated over a wide range up to 10 days.

The Weather Bureau applied the same method of calculation (but without removing the week-to-week variance) to obtain the periodicity and amplitude of the 7-day wave of precipitation for 20 regions of the United States (as shown in Fig. 1) for each 28-day cycle. Brier (1955) reported that only in region 4, comprising the states of South Carolina, Georgia and Florida, was apparently significant periodicity found. Table 2 shows these data. Data for the other regions were not published. The Weather Bureau also calculated the periodicity of the 70 kPa temperature at Omaha, Nebraska, both for cycles 13–22 and for 200 28-day cycles between 1935 and 1949 when no periodic seeding was done. The results, as shown in Tables 3 and 4 are repeated from Brier (1955, Tables 5 and 6). This then was the whole of the inheritance from the past that could be brought to bear on an analysis of nighttime/daytime seeding differences.

3. A further analysis

As a first step, the differences between the means of the periodicities of the nighttime-seeded and daytime-

TABLE 3. Frequency distribution of the square of the periodicity of 70 kPa temperature at Omaha (after Brier, 1955).

Interval	1935–42	1942–49	Total
0.00–0.049	36	31	67
0.05–0.099	22	28	50
0.10–0.149	18	19	37
0.15–0.199	12	8	20
0.20–0.249	6	3	9
0.25–0.299	3	2	5
0.30–0.349	1	6	7
0.35–0.399	2	1	3
0.40–0.449		1	1
0.45–0.499			
0.50–0.549		1	1
	100	100	200

TABLE 4. Squares of periodicities of 70 kPa temperature at Omaha for cycles 13–22 (after Brier, 1955).

Cycle	13	14	15	16	17	18	19	20	21	22
Periodicity squared	0.23	0.07	0.13	0.00	0.24	0.04	0.19	0.11	0.12	0.01

seeded cycles were calculated for each of Langmuir's regions and a measure of the significance of these differences was obtained by applying the Mann-Whitney rank test. The results are shown in Fig. 2. The numbers in parentheses are the probabilities representing a one-tailed test; values close to zero or one suggest rejection of the null hypothesis (no effect) in favor of the posited hypothesis or its contrary, respectively. The contiguous block of five regions with positive differences (stronger periodicity during nighttime seeding) with a strong measure of significance near its center argues for acceptance of Langmuir's original expectation. Outside of this block, none of the other regions shows a change as large as that in four of the regions in the central block.

The next step was to calculate the differences in periodicity in the same manner between the nighttime-seeded cycles and the nonperiodic-seeded cycles that Langmuir considered. The results are shown in the two maps of Fig. 3. Similar maps were made also for each nonperiodic-seeded epoch separately but yielded no further substantial information. It is interesting to note that the largest positive difference in periodicity during nighttime seeding appeared in the region where intense flooding occurred during the experiment that has been cited as one reason for its discontinuance (Byers, 1974).

Next, attention was turned to the data presented by Brier (1955) for the Weather Bureau's region 4. The result, shown in the summary Table 5, shows a weak difference in amplitude and a stronger one in periodicity, both in favor of the nighttime-seeded cycles.

The final analysis was of Brier's data for the 70 kPa temperature at Omaha. Comparison between nighttime-seeded and daytime-seeded cycles listed in Table 4 (Brier's Table 6) resulted in a clean sweep for the former, the nighttime-seeded periodicities being more than twice as great as the daytime-seeded ones. To extend the comparison to the nonseeded cycles of Table 3 (Brier's Table 5), a rank list of nonseeded cycles was reconstructed from the table and plotted as a cumulative graph. This was combined with the data of Table 4 (Brier's Table 6) and the rank lists so obtained were subjected to the Mann-Whitney test with the results shown in Table 5.

4. Discussion

The results of these analyses are gathered together in Table 5 in the form of answers to the three questions one may ask about differences among nighttime-seeded, daytime-seeded and nonperiodic-seeded cycles. As in the maps, the probabilities represent a one-tailed test by

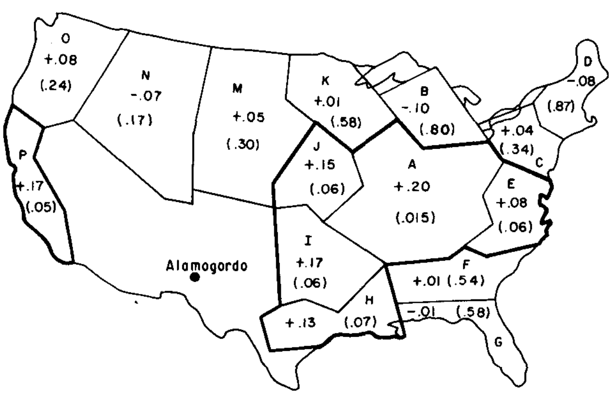

FIG. 2. Differences in means of periodicities between nighttime-seeded and daytime-seeded cycles, and probabilities by a one-tailed test (in parentheses). Heavy outlines enclose regions with probabilities nominally significant at the 10% level.

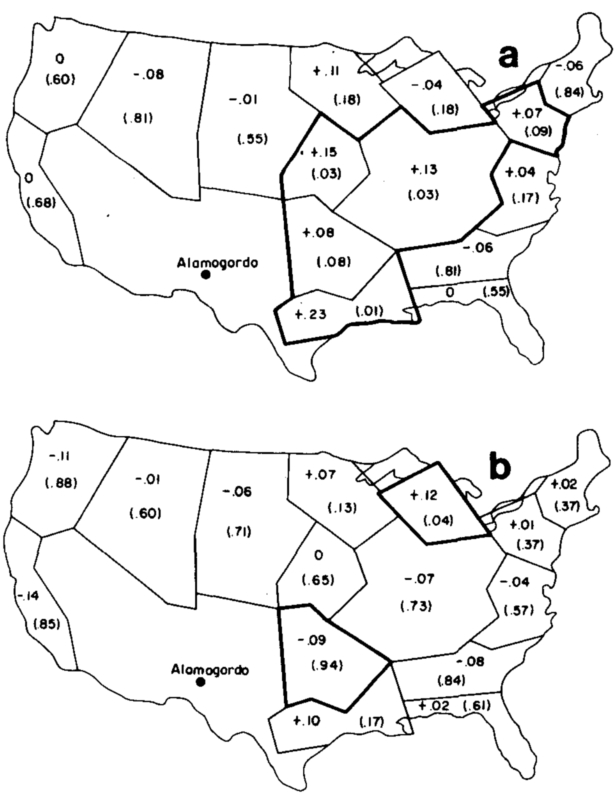

FIG. 3. Differences in means of periodicities between nighttime-seeded and nonperiodic-seeded cycles (a) and between daytime-seeded and nonperiodic-seeded cycles (b), and probabilities by a one-tailed test (in parentheses). Heavy outlines enclose regions with probabilities nominally significant at the 10% level.

TABLE 5. Summary of results.

IS THERE A DIFFERENCE BETWEEN NIGHTTIME-SEEDED AND DAYTIME-SEEDED CYCLES?		
In periodicity of precipitation		
By Langmuir regions	See map (Fig. 2)	
Sum of 15 Langmuir regions	Yes (+)	$P=0.015$
Weather Bureau region 4	Likely (+)	$P=0.06$
In amplitude of precipitation		
Weather Bureau region 4	Perhaps (+)	$P=0.23$
In periodicity of temperature aloft	Yes (+)	$P=0.005$
IS THERE A DIFFERENCE BETWEEN NIGHTTIME-SEEDED AND NONPERIODIC-SEEDED CYCLES?		
In periodicity of precipitation		
By Langmuir regions	See map (Fig. 3)	
Cycles 13, 15, 17, 19, 21, vs all nonperiodic-seeded cycles, all regions	Yes (+)	$P=0.03$
Cycles 13, 15, 17, 19, 21 vs 1, 23–29	Yes (+)	$P=0.005$
Cycles 13, 15, 17, 19, 21 vs 30–37	No	$P=0.69$
In periodicity of temperature aloft		
vs 200 cycles, 1935–49	Yes (+)	$P=0.015$
IS THERE A DIFFERENCE BETWEEN DAYTIME-SEEDED AND NONPERIODIC-SEEDED CYCLES?		
In periodicity of precipitation		
By Langmuir regions	See map (Fig. 3)	
Cycles 14, 16, 18, 20, 22 vs all nonperiodic-seeded cycles, all regions	No	$P=0.47$
Cycles 14, 16, 18, 20, 22 vs 1, 23–29	No	$P=0.60$
Cycles 14, 16, 18, 20, 22 vs 30–37	Yes (−)	$P=0.95$
In periodicity of temperature aloft		
vs 200 cycles, 1935–1949	Yes (−)	$P=0.95$

the Mann-Whitney method of the hypotheses that seeding increased the periodicity, nighttime seeding more so than daytime.

These results confirm that the nighttime-seeded cycles did indeed have a stronger 7-day periodicity of precipitation and associated temperature aloft than did either the daytime-seeded or the nonperiodic-seeded cycles. The difference is especially clear in the block of contiguous regions immediately downwind from the seeding site. Outside of this block, the distribution of probabilities is not inconsistent with chance.

Whether the differences exhibited here were caused by the seeding remains unsettled. No acceptable theory or supporting evidence has emerged save that from this unique experiment itself. Many meteorologists consider it inconceivable that the AgI smoke generators at Alamogordo could have had any such effect in the face of widespread commercial seeding conducted day and night during cycles 13–22. On the other hand, if the periodic-seeding hypothesis is perhaps true, its importance overshadows that of every other weather-modification hypothesis so far posited or experiment so far undertaken. Without access to the calculations that must have underlain the published data, one can only speculate what more these might tell. One wonders about the likelihood of such a sequence of events occurring by chance during a designated 280-day period. One wonders why evidence as obviously suggestive as that of Table 4 was not investigated. Perhaps the spirit of those times, which made it possible to omit all reference to the periodic experiments from the otherwise comprehensive reviews of weather modification published by the National Academy of Sciences and the official statements on weather modification by the council of the American Meteorological Society, put off potential investigators. Finally, one wonders what might have been the outcome of the periodic-seeding experiment as a whole if all the seeding had been done at night. The present results only deepen the mystery.

REFERENCES

Brier, Glenn W., 1954: 7-day periodicities in May 1952. *Bull. Amer. Meteor. Soc.*, **35**, 118–121.

——, 1955: Seven-day periodicities in certain meteorological parameters during the period 1899–1951. *Bull. Amer. Meteor. Soc.*, **36**, 265–277.

Byers, H. G., 1974: History of weather modification. *Weather and Climate Modification*, W. N. Hess, Ed., Wiley (see p. 20).

Fisher, R. A., and F. Yates, 1948: *Statistical Tables for Biological, Agricultural, and Medical Research.* Oliver & Boyd, Ltd., 138 pp.

Hawkins, H. F., Jr., 1952: On the weather and circulation of May 1952, including a study of some recent periodicities. *Mon. Wea. Rev.*, **80**, 82–87.

Inn, Edward C. Y., 1951: Photolytic inactivation of ice-forming silver iodide nuclei. *Bull. Amer. Meteor. Soc.*, **32**, 132–135.

Langmuir, Irving, 1962: *Collected Works of Irving Langmuir.* C. Guv Suits, Ed., Vol. 11, Pergamon Press, 597 pp.