THE EFFECT OF NATURAL RAINFALL VARIABILITY IN VERIFICATION OF RAIN MODIFICATION EXPERIMENTS

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1. Introduction

Operation of two concentrated raingage networks in central and southern Illinois in recent years has provided a unique set of data to determine the natural variability of rainfall in time and space. The central Illinois network has been in continuous operation for the past eleven years, whereas the southern network has been operated for eight years. Definition of the natural rainfall variability is essential in the planning and evaluation of rain modification experiments in which rainfall measurements are employed to verify the results of seeding. This paper is devoted primarily to illustrating the magnitude of the natural variability in midwestern, warm season rainfall and the influence of this variability upon the interpretation of rain modification experiments. The results presented here should be applicable also to other areas of similar rain climate and topography. The vast reservoir of data from the networks has only been barely tapped in the analyses presented in this paper. Further expansion of the analyses is planned for the future.

In this particular study, storm rainfall data from the two raingage networks during the summer season (June to August) were employed. These data were classified into two categories consisting of (1) air mass or nonfrontal storms, and (2) all summer storms combined. The air mass category was selected for special attention because some scientists have suggested that nonfrontal convective rainfall offers the greatest opportunity for augmentation through seeding activities. However, others have attempted to seed all types of rainfall; and, for this reason, an evaluation of the natural variability for all summer storms was performed also. In Illinois more than 75 per cent of the average summer rainfall comes from thunderstorms, and much of the remaining rainfall is from rainshowers [2].

The analysis was based on five years, 1960–64, of southern Illinois data from the Little Egypt Raingage Network, which consists of 49 raingages in a 550 square mile area, and on ten years, 1955–64, of central Illinois data from the East Central Illinois Network consisting of 49 raingages in 400 square miles [4]. As shown in figure 1, both networks occupy square shaped areas with nearly equal gage spacing.

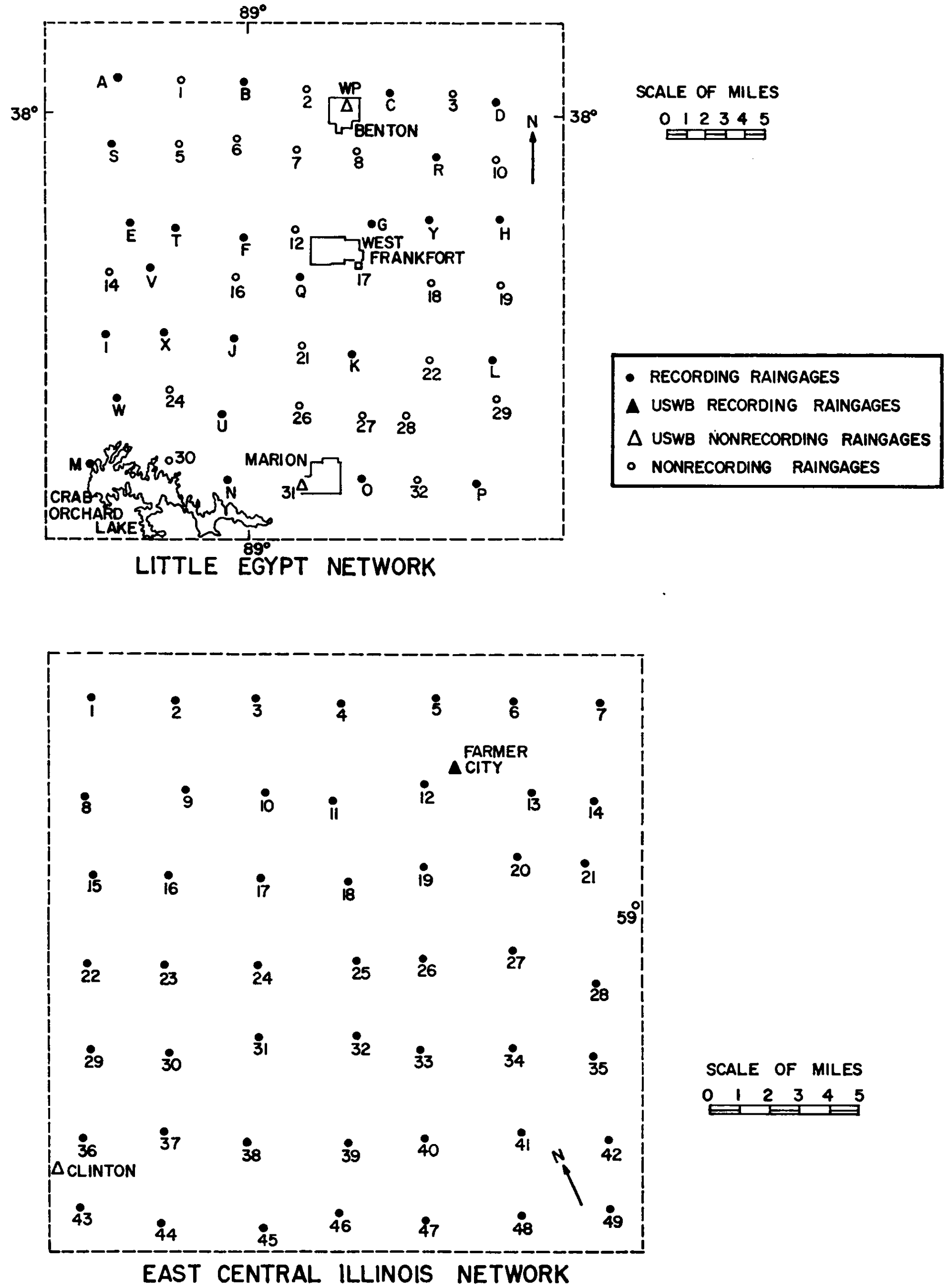

FIGURE 1

Raingage networks.

Summer rainfall data were chosen for this particular study because of (1) the predominance of convective rainfall in summer, (2) the economic agricultural need for summer rainfall, and (3) the high frequency of air mass rainfall activity in the Middle West during summer.

2. Analytical procedures

Any storm producing measurable rainfall at any network raingage in the summer season was included in the natural variability study. A storm is defined as a rain period separated from preceding and succeeding rainfall by six hours or more. Thus, it is possible to have more than one storm on the network on a calendar day. The average network rainfall for each storm was the basic measure of storm rainfall employed in the analysis.

The summer data from both networks were analyzed for the 1960–64 period because it coincides with the southern Missouri cloud seeding experiments by Braham [1]. The 1955–59 data from the East Central Illinois Network were analyzed for comparisons with the 1960–64 results. The use of five year periods to express the results was also governed by the fact that other modification experiments have had durations of approximately five years [6].

The Little Egypt Network data for the five year period were grouped by a randomized sampling procedure into hypothetical seeded and unseeded storms. This grouping was achieved by the procedure used by Braham and others in actual seeding experiments. From a chronological listing of the storms (table I), the first storm in 1960 was designated as either a seeded or unseeded situation by selection from a table of random numbers. Then the second storm was automatically placed in the opposite group. Succeeding pairs of storms were grouped in a similar manner throughout each summer in the five year period. This resulted in an equal number of storms in both groups (seeded and unseeded) for the five year period.

As mentioned earlier, the selections were performed for both air mass and for all summer storms combined. Thus, two sets of Little Egypt Network storm data were analyzed for the five year period of 1960–64. Similar sets of data from the East Central Illinois Network (see table II) were selected for the two five year periods and for the ten year period which combined the two five year periods. By repeating the hypothetical randomized seeding experiment a number of times on the same set of data, such as the air mass storms from the Little Egypt Network, a measure of the frequency distribution of the percentage differences between the hypothetically seeded and unseeded storms due to natural rainfall variability was obtained for each sampling period and each storm classification in the two networks. The East Central Illinois Network was also subdivided into areas of 50, 100, and 200 square miles for comparison of the natural variability among areas of various sizes which might be employed in rain modification studies.

TABLE I

ALL STORMS ON LITTLE EGYPT NETWORK (SUMMER SEASON) 1960–64
Air mass indicated by asterisks.

Date	Network Average	Date	Network Average	Date	Network Average
1960		*1961*		*1962*	
6/1	.02	6/2–3	.49	6/1	.25
6/5	.001	6/5	.02	6/2	.24
6/10*	.001	6/6*	.02	6/4*	.004
6/11	.12	6/6*	.34	6/5–6*	.21
6/12*	.08	6/7*	.14	6/6*	.17
6/12–13	.42	6/7*	.37	6/6–7	.83
6/13	1.72	6/8*	.33	6/8	.15
6/14*	.05	6/9*	.33	6/9*	.03
6/16	.01	6/9*	.35	6/9	.03
6/16	.01	6/12*	.01	6/10	.50
6/17	.003	6/13–14*	.50	6/10	.04
6/17*	.001	6/14	.76	6/11*	.09
6/23*	.003	6/14–15	1.06	6/11–12	.04
6/23–24	.27	6/20	.002	6/18	.06
6/24*	.001	6/30	.06	6/18–19	.06
6/27*	.06	7/2	.16	6/21*	.12
6/27–28*	.05	7/6	.27	6/22*	.003
6/28–29	2.13	7/11*	.25	6/22*	.003
6/30	.04	7/13	.29	6/23*	.40
7/1	1.10	7/13*	.02	6/23*	.02
7/3	.02	7/14	.05	6/24*	.51
7/4*	.001	7/14	.46	6/25*	.003
7/10*	.14	7/15*	.07	6/25*	.02
7/22*	.08	7/16	.41	6/26*	.02
7/22*	.21	7/18*	.02	6/27*	.02
7/23*	.07	7/18*	.08	6/28*	.01
7/25	.32	7/19	.21	6/29*	.001
7/25–26	.24	7/19	.01	7/2*	.14
7/27*	.29	7/20	.44	7/3*	.001
7/28*	.001	7/21*	.02	7/4	.10
8/4*	.29	7/22*	.05	7/5	.01
8/6	1.13	7/23	.11	7/6	1.09
8/7*	.003	7/24–25*	1.50	7/7*	.01
8/7*	.01	7/27	.003	7/7*	.002
8/8	.19	7/28	.18	7/8	.001
8/9*	.002	7/30*	.01	7/11–12	.84
8/9	.01	8/1*	.002	7/13*	.03
8/10	.04	8/2	.24	7/15	.38
8/17*	.002	8/3 or 4	.02	7/16	.07
8/18	.07	8/5	.01	7/24*	.001
8/18–19	.45	8/9–10*	.75	7/25	.002
8/19*	.01	8/10–11*	.01	7/28	.002
8/20*	.18	8/11	.14	7/29	.20
8/20	.67	8/11–12	.13	7/30	.06
8/21*	.003	8/15*	.01	8/4	.14
8/21*	.003	8/17*	.01	8/5*	.01
8/28*	.01	8/19–20	.27	8/6*	.02
8/29	.04	8/22–24*	.45	8/7*	.02
8/30*	.002	8/31*	1.78	8/7	.002

TABLE I (Continued)

Date	Network Average	Date	Network Average	Date	Network Average
8/11*	.001	7/26*	.09	6/29–30*	.41
8/16	.55	7/27*	.007	7/2*	.03
8/22	.13	7/28*	.36	7/3	.12
8/23*	.19	7/28–29	.77	7/5	.03
8/24–25	2.10	7/31*	.21	7/6	1.04
8/30*	.09	8/9	1.27	7/7	.06
8/31	.35	8/10	.07	7/9*	.09
		8/10*	.08	7/11–12	.73
1963		8/12	.16	7/18*	.04
6/10	.79	8/12	.26	7/18–19*	.16
6/13	.32	8/18	.01	7/21*	.59
6/15–16	1.35	8/19	.23	7/21–22*	.003
6/20*	.17	8/19	.08	7/23*	.002
6/25*	.02	8/25*	.02	7/25*	.02
6/26*	.002	8/28	.01	7/27*	.004
6/27*	.01	8/28–29	.29	7/28*	.31
6/28*	.25			7/29*	.004
6/30*	.23	*1964*		7/31	.01
7/1*	.17	6/1*	.01	8/3*	.001
7/2*	.01	6/2*	.01	8/4	.06
7/2	.02	6/4–5	.07	8/21–22	.62
7/4	.001	6/5–6*	.40	8/22	.01
7/4	.01	6/6*	.002	8/25	.52
7/7	.02	6/6*	.003	8/25	.11
7/7	.11	6/6*	.01	8/26	.003
7/7	.21	6/12	.09	8/27	.60
7/13	1.26	6/13	.16	8/28*	.002
7/14	.01	6/14*	.04	8/30	.05
7/17–18	.73	6/15	.27		
7/20	.10	6/17–18	.73		

3. Results of analyses

3.1. *Air mass storms on Little Egypt Network.* For the five year period, 1960–64, 116 air mass storms in which one or more raingages recorded measurable precipitation occurred during the summer months on the Little Egypt Network. Network average rainfall in these storms ranged from 0.001 inch to 1.78 inches. These 116 storms were divided into two groups of hypothetically seeded and unseeded storms through use of the randomization procedure described in the last section. Comparison was made between the five year total rainfall in the two groups, as calculated by summing the network average rainfall in each storm. This hypothetical randomized seeding experiment was repeated 50 times on the 116 storms to obtain an estimate of the frequency distribution of the natural rainfall differences between two sets of data drawn randomly from the same population. In this case, each set contained 58 storms.

A distribution curve derived from the 50 cases is shown in figure 2, in which probability in per cent is plotted against the ratio of total rainfall in the seeded

TABLE II

ALL STORMS ON EAST-CENTRAL ILLINOIS NETWORK 1955–64
Air mass indicated by asterisks.

Date	Network Average	Date	Network Average	Date	Network Average
1955		6/26	.11	7/31*	.002
6/2–3*	.03	7/2–3	.53	8/1*	.04
6/3*	.003	7/3–4	.21	8/3–4	.28
6/4	.19	7/4–5	.25	8/10	.004
6/5	.14	7/6*	.01	8/11*	.03
6/6–7*	.34	7/8	.85	8/12	.001
6/7–8	.62	7/8*	.01	8/14*	.06
6/9	.001	7/12*	.22	8/15	.03
6/9*	.16	7/12–13	.005	8/16–17*	.01
6/10–11	2.23	7/15	.59	8/23–24	.32
6/12	.03	7/16	.26	8/27	.001
6/13	.002	7/18*	.07	8/27	.002
6/14*	.04	7/19*	.05	8/28	1.00
6/22	.14	7/22*	.03		
6/25	.12	7/25	.04	*1958*	
6/27*	.001	7/26	.01	6/1*	.001
7/2	.24	7/28	.01	6/8	.03
7/4*	.06	7/31–8/1	2.64	6/8	.51
7/5*	.23	8/3	.27	6/9	.01
7/6–7*	.07	8/8–9	.54	6/9–10	2.52
7/9	.02	8/13	1.69	6/11	.03
7/14*	.88	8/16*	.39	6/12–13	.66
7/15	.004	8/19*	.005	6/13	.39
7/16*	.12	8/29*	.13	6/14	.002
7/17*	.23	8/30*	.30	6/15*	.004
7/18*	.001	8/30–31	.21	6/17*	.75
7/23–24	1.29			6/18*	.005
8/1*	.01	*1957*		6/19	.18
8/2*	.19	6/3*	.003	6/20	.09
8/6	.04	6/6*	.01	6/22–23*	.22
8/10	.001	6/6*	.001	6/24*	.05
8/20*	.03	6/7	.12	6/24–25	1.51
8/21–22	.67	6/8	.003	7/2–3	.83
8/29–30	1.37	6/10–12	1.03	7/4*	.001
		6/12*	.004	7/5	.001
1956		6/12–14	1.47	7/5	.02
6/1*	.03	6/14	.44	7/7	.01
6/7	.16	6/15*	.06	7/8*	.001
6/12*	.002	6/16*	.005	7/10	2.38
6/13*	.003	6/17*	.28	7/11	2.11
6/14*	.01	6/18	.11	7/14*	.01
6/14*	.001	6/26–28	2.82	7/14*	.01
6/14–15*	.004	6/28	.02	7/14–15	.57
6/15*	.001	6/29*	.004	7/15	.34
6/15*	.06	7/4	.04	7/17	.08
6/16–17*	.02	7/13–14	.70	7/20	.79
6/17–18*	.17	7/15	.002	7/24	.01
6/18–20	.75	7/16–17	.54	7/27*	.01
6/20*	.01	7/22–23	.70	7/27–28	.86
6/21–22*	.17	7/27–28*	.01	7/28	.001
6/22*	.58	7/29–30	.06	7/30	.19

TABLE II (Continued)

Date	Network Average	Date	Network Average	Date	Network Average
7/30–31	.72	8/29*	.007	*1961*	
8/1	.14	8/29	.59	6/2	.003
8/1–2*	1.05			6/5*	.07
8/6	.14	*1960*		6/6–7*	.80
8/7	.53	6/1	.01	6/7–8*	.83
8/11*	.25	6/4–5	1.17	6/8*	.41
8/15	.21	6/11*	.001	6/12*	.001
8/15–16	.004	6/11*	.22	6/13	.39
8/17*	.07	6/11–12	.17	6/14	.01
8/20*	.02	6/12–13	.20	6/19–20	.84
8/22*	.001	6/13–14	.27	6/22	.01
8/23–24	.05	6/16	.58	6/24–25*	.05
8/24	.001	6/17	.004	6/30*	.001
8/26*	.001	6/16–17*	.02	7/1–2*	.04
8/27*	.001	6/19	.04	7/4	.18
8/27–28*	.001	6/19	.33	7/5	.001
8/28*	.004	6/20–21	.80	7/6	.04
8/30–31	.10	6/21	.01	7/12*	.04
		6/22	.38	7/13	.11
1959		6/22–23	1.93	7/14	.01
6/10*	.16	6/23	.02	7/18	.001
6/11*	.19	6/27*	.12	7/19	.56
6/16	.001	6/28*	.001	7/21–22	.97
6/16	.001	6/28	.14	7/22–23	1.04
6/20	.002	6/29	.001	7/27	.60
6/26*	.06	7/1	.55	7/27–28	.45
6/29*	.001	7/3	.01	7/29	.02
6/30	.01	7/6*	.003	7/31*	.001
7/1	.08	7/9–10*	.68	8/1–2	.35
7/4*	.01	7/12–13	1.06	8/3*	.003
7/5	.002	7/19*	.08	8/4*	.002
7/9	.004	7/23*	.15	8/5	.20
7/11*	.07	7/24	.04	8/10*	.05
7/16*	.001	7/25*	.16	8/11	.02
7/17*	.21	7/26*	.13	8/17*	.01
7/18	.16	7/26–27	.16	8/19	.21
7/19*	.01	8/3*	.001	8/22*	.02
7/21*	.004	8/3–4*	.69	8/23*	.002
7/22–23*	1.41	8/4	.01	8/28	.01
7/26–27*	.38	8/6	.28		
8/3	.001	8/6*	.003	*1962*	
8/3	.02	8/14*	.15	6/3	.03
8/4	.01	8/16–17	.02	6/4	.16
8/5–6	.65	8/18	.02	6/4*	.03
8/7	.02	8/19*	.001	6/8	.01
8/15–16*	.92	8/19*	.45	6/8–9*	.34
8/17	.22	8/20*	.03	6/9*	.04
8/22*	.02	8/20–21*	.07	6/9–10	1.00
8/24*	.02	8/21*	.001	6/12	.01
8/25*	.01	8/23*	.001	6/22*	.03
8/27*	.11	8/29	.02	6/29*	.08
8/27–28*	.003	8/30*	.001	7/1	.37

TABLE II (Continued)

Date	Network Average	Date	Network Average	Date	Network Average
7/2–3	1.77	6/13	.03	6/12	.37
7/8	.08	6/19*	.21	6/12	.06
7/11	.89	6/28*	.02	6/13	.03
7/13	1.57	7/1*	.73	6/14	.20
7/13–14	.04	7/5–6	1.29	6/15	.08
7/14	.10	7/12–13	1.49	6/18	.02
7/15	1.27	7/17*	.003	6/19–20	2.27
7/15	.002	7/19*	.001	6/21	1.24
7/15	.003	7/19–20	.78	7/3	.15
7/16	.01	7/26*	.01	7/5	.02
7/22	.02	7/28*	.001	7/6	1.60
7/22–23	.82	7/28	.07	7/7	.16
7/28*	.01	7/31	.49	7/8*	.22
8/5	.08	8/5	.003	7/11–12	.43
8/5–6	.50	8/5–6	.80	7/13–14*	.09
8/6*	.004	8/6	.01	7/14*	.22
8/7	.001	8/8*	.83	7/18*	.41
8/8–9	.31	8/12	.21	7/21*	.01
8/21	.19	8/18–19	1.36	7/22*	.001[1]
8/24–25	.87	8/24*	.08	7/25	.20
8/31	.04	8/25	.03	8/10	.65
		8/25	.02	8/10	.01
1963		8/28	.48	8/11	.05
6/4*	.35			8/19	.16
6/5*	.04	*1964*		8/20*	.10
6/7	.25	6/2*	.23	8/21	1.00
6/9*	.02	6/6*	.05	8/25	.81
6/10	.23	6/6*	.11	8/30*	.13
6/12	.003	6/7*	.005		

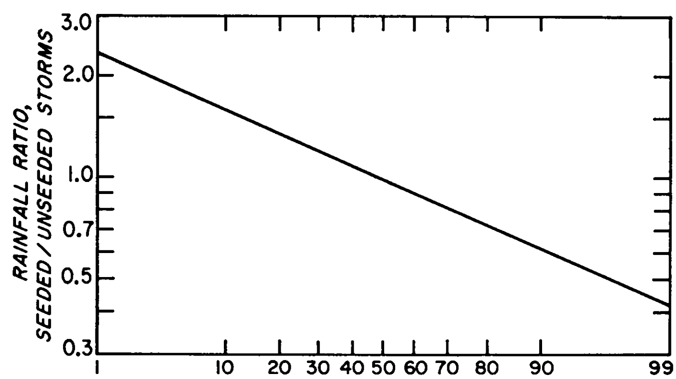

FIGURE 2

Distribution of differences between hypothetically seeded and unseeded air mass storms on Little Egypt Network.

storms to total rainfall in the unseeded storms for the five year sampling period. Figure 2 indicates that a rainfall increase of 50 per cent, due entirely to natural rainfall variability, can be expected in the seeded sample in approximately 14 per cent of the experiments carried out under similar circumstances. Similarly, a 20 per cent increase resulting from natural rainfall variability will occur in approximately 30 per cent of five year experiments involving seeding of summer air mass storms in the Midwest or similar climatic areas. Estimates of 10 to 20 per cent increase in rainfall from cloud seeding are frequently quoted in the literature, as a result of the experience of commercial cloud seeders and of investigations by research groups. Figure 2 clearly illustrates the difficulty in verifying such claims of rain increases from seeding operations when detailed surface rainfall data are used for verification.

Decker [3] has reported on rainfall analyses used to evaluate the results of Braham's five year seeding experiment in Missouri, 1960–64, which was carried out under conditions of climate, season, and rainfall type similar to the hypothetical experiments used to produce figure 2. Decker used two methods of defining the seeding area, based upon wind profiles on operational days. In one case, he obtained a rainfall ratio of 0.59 for the five year period and, in the other case, the ratio of seeded to unseeded rainfall was 0.45. Figure 2 indicates that the probability of such decreases on the seeded sample due to natural rainfall variability is eight per cent and two per cent, respectively. Thus, the Illinois hypothetical experiments indicate a strong likelihood that the five year total rainfall in the target area was decreased through seeding in the Missouri experiments.

The spatial variability of rainfall arising from natural causes is illustrated in figure 3. In this figure, the total rainfall pattern resulting from air mass storms during five summers, 1960–64, is shown for the Little Egypt Network of 550 square miles which represents approximately one per cent of the area of the state of Illinois. The pattern is expressed in terms of percentage of network average rainfall for ease of interpretation. Thus, for example, in the northwestern part of the network, the five year amounts exceeded 120 per cent of the network average rainfall, whereas in parts of the north central, central, and south central regions of the network amounts were less than 80 per cent of the network average. Actually, point amounts ranged from 78 per cent to 135 per cent of the average. The network average rainfall for five years from air mass storms was 14.83 inches. Figure 3 clearly illustrates the problem involved in verifying precipitation increases over small areas from seeding of convective clouds in the Midwest and areas of similar cloud and rainfall climates.

Figure 4 further defines the pattern of figure 3 through plotting the percentage of the network area against per cent of network mean rainfall. This is a form of area depth curve which is used frequently to express rainfall distribution in hydrologic studies. This curve shows that 5 per cent of the area had five year totals of air mass rainfall exceeding 122 per cent of the network average rainfall, 10 per cent of the area exceeded 112 per cent of the average, and 20 per cent exceeded 107 per cent of the areal average. Similarly, 5 per cent of the area had rainfall less than 83 per cent of the network average, 10 per cent was less than 87 per cent of the 550 square mile average, and 20 per cent was less than 92 per cent of the average.

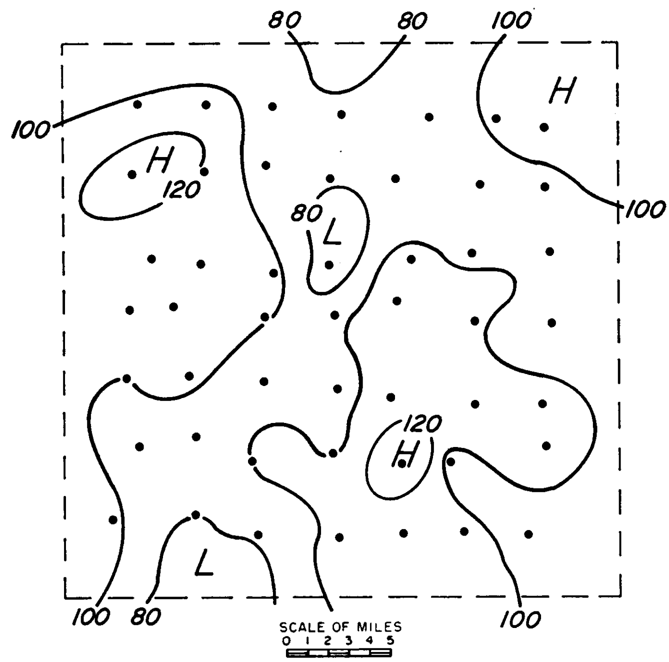

FIGURE 3

Per cent of average network rainfall in summer air mass storms on Little Egypt Network.

Another characteristic of convective rainfall that must be recognized in rain modification experiments is the tendency for a relatively large portion of the total storm rainfall, on a given area for a given period of time, to result from a small portion of the total number of storms. An example of this tendency is illustrated in figure 5, in which cumulative per cent of the total number of storms is plotted against cumulative per cent of total air mass rainfall on the Little Egypt Network during the summers of 1960–64. During this five year period, 34 per cent of the total rainfall occurred in 5 per cent of the storms, over 50 per cent fell in 10 per cent of the storms, and 75 per cent occurred in 20 per cent of the storms. Thus, it is apparent that a relatively few storms established the air mass rainfall pattern during a rather substantial sampling period of five years, frequently considered adequate to evaluate seeding experiments.

Figures 6 to 9 are for random sampling trial number 1 of the 50 air mass trials and are similar to figures 3 to 5. That is, they show the network patterns ex-

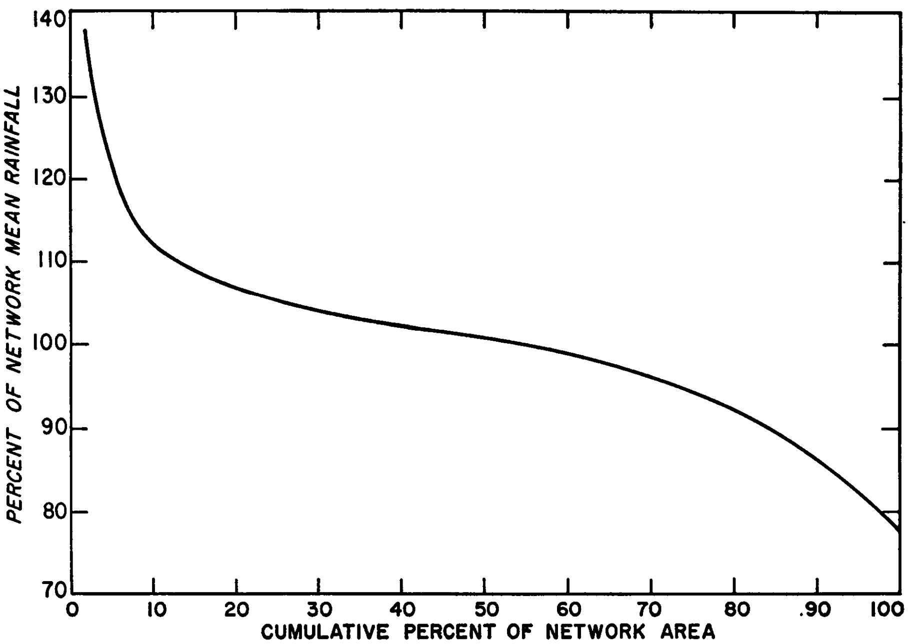

FIGURE 4

Areal distribution of air mass rainfall in summer storms on Little Fgypt Network.

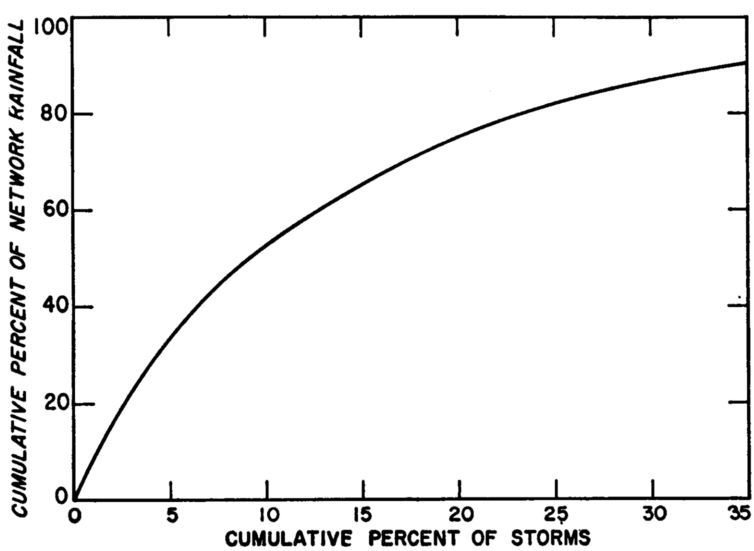

FIGURE 5

Relation between storm frequency and five year total rainfall in all air mass storms on Little Egypt Network.

pressed in per cent of areal mean rainfall for the hypothetically seeded and unseeded storms, the percentage area depth relations in each set of storms, and the relation between percentage of total rainfall and percentage of storm occurrences. A hypothetical rainfall increase of 59 per cent was obtained for the "seeded" storms in this trial.

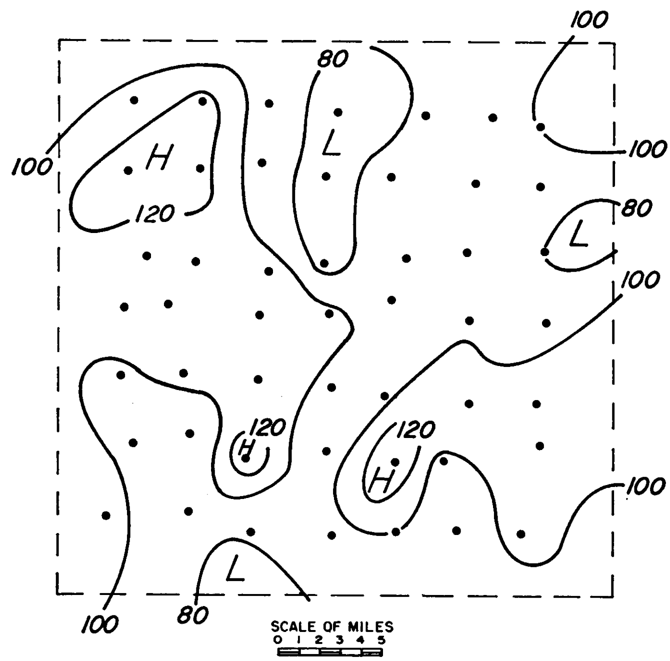

FIGURE 6

Per cent of average network rainfall in hypothetically seeded air mass storms of trial 1 on Little Egypt Network.

Figure 8 indicates slightly greater variability within the network for each set of storms than shown by figure 4, in which all data are combined. Except near the lower end, the two hypothetical curves do not depart substantially from each other.

Figure 9 shows that the "seeded" storms received somewhat more of their total rainfall from the heavier storms (left portion of curves) than the "unseeded" group in this particular trial. However, a crossover occurred when 60 per cent of the total rainfall was reached. Thus, the "seeded" group received more rainfall in the heaviest 10 to 12 per cent of the storms during the five years, after which the "unseeded" group had greater amounts of rainfall in the lighter storms. If this were an actual seeding experiment instead of a hypothetical experiment on natural rainfall distribution, one might conceivably draw some rather significant inferences from figure 9.

The preceding examples illustrate some of the problems imposed upon rain modification experiments by natural rainfall variability in air mass storms of the type encountered during the warm season in the Midwest. Many more examples could be prepared to illustrate the problem further, but time does not permit further pursuance of it here. In the following section a brief discussion is given

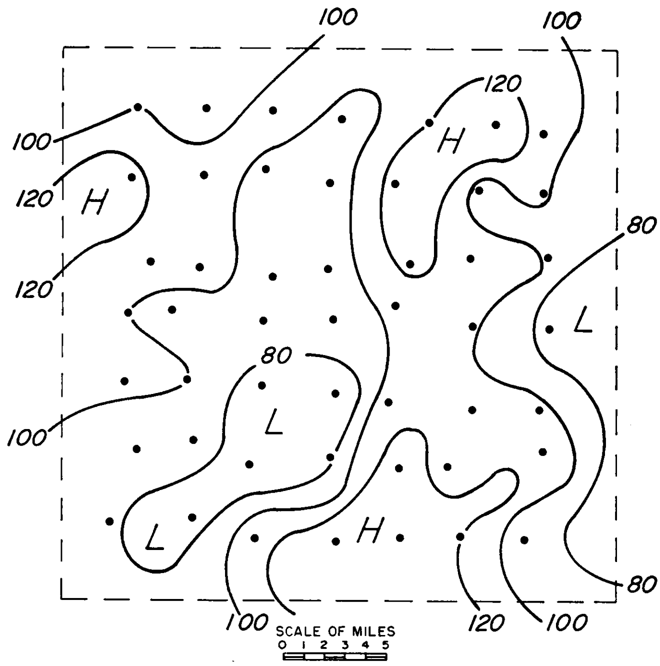

FIGURE 7

Per cent of average network rainfall in hypothetically unseeded air mass storms of trial 1 on Little Egypt Network.

of the effects of natural variability when all types of summer storms are combined in a hypothetical seeding experiment.

3.2. *All storm rainfall on Little Egypt Network.* Next, a series of ten trials were made on all summer rainfall in the Little Egypt Network during 1960–64 through use of the randomized selection procedure described earlier. The basic sample consisted of 231 storms from which a network average of 51.21 inches of rain fell during the five year period. The results are summarized in table III which shows a median of 21 per cent with a range of 1 to 32 per cent among the ten selections. In the first ten selections of air mass storms, a median of 35 per cent was obtained and the 50 test median was 30 per cent. Thus, an appreciable decrease in percentage difference is indicated when all storms are combined to provide a much larger sample. However, the median of 21 per cent

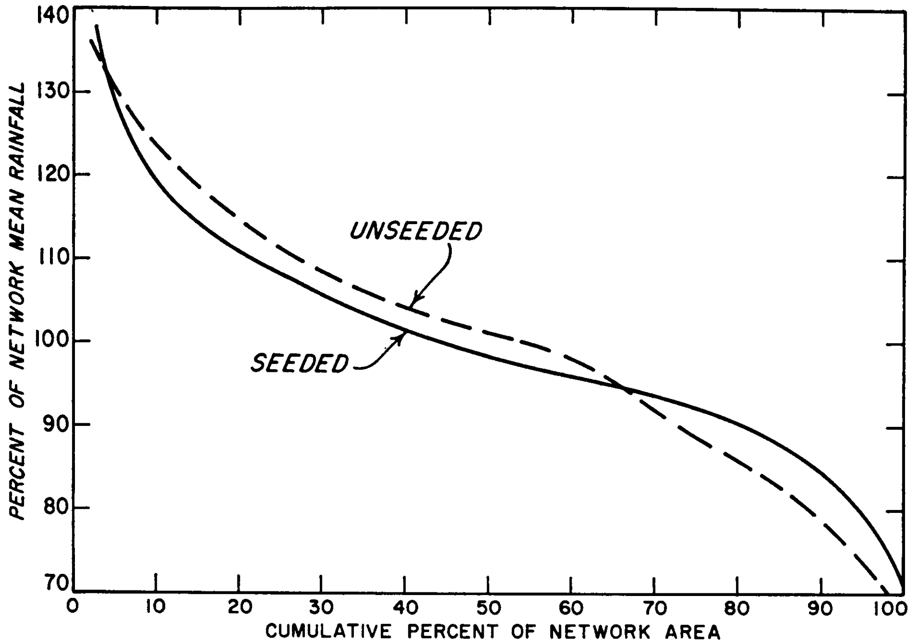

FIGURE 8

Areal distribution of air mass rainfall in hypothetical sets of trial 1 on Little Egypt Network.

is still a very substantial difference, and is near the upper limit of rain augmentation usually quoted in the literature.

TABLE III

FIVE YEAR TOTAL RAINFALL COMPARISONS, ALL STORMS, LITTLE EGYPT NETWORK, 550 SQUARE MILES, JUNE–AUGUST, 1960–64

Test	Total Rainfall (in) Seed	No Seed	Per Cent Difference
1	21.84	29.37	−26
2	29.12	22.09	+32
3	27.64	23.57	+17
4	27.65	23.56	+17
5	21.66	29.55	−27
6	25.67	25.54	+1
7	22.33	28.88	−23
8	22.70	28.51	−20
9	24.64	26.57	−7
10	21.84	29.37	−26
Median			21%
Range			1 to 32%

The spatial variability of total summer rainfall in the five year period on Little Egypt Network is shown in figure 10, again expressed in terms of per cent of average network rainfall. Comparison with a similar map for air mass rainfall in figure 3 shows that the areal variability is somewhat less for all storms than for air mass storms, as expected. Actually, point values ranged from 88 to 118 per cent for all storms compared to 78 to 135 per cent for air mass storms.

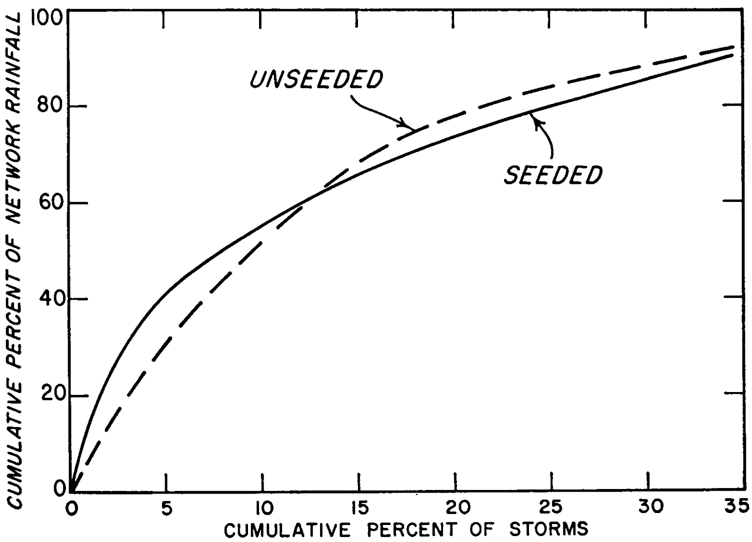

FIGURE 9

Relation between storm frequency and total rainfall in sets of trial 1 on air mass rainfall in Little Egypt Network.

3.3. *East Central Illinois Network.* Data were available for ten years, 1955–64, on the East Central Illinois Network (figure 1), so that computations were made for two five year periods and a ten year period for comparison purposes. Also, the 1960–64 data permitted comparisons with the Little Egypt Network whose rainfall climate varies somewhat from that of the East Central Illinois Network. For example, in the East Central Illinois Network, approximately 36 per cent of the summer storms during 1960–64 were air mass storms as compared to 50 per cent on the Little Egypt Network. Approximately 21 per cent of the rain occurred from air mass storms in the central Illinois area as compared to 39 per cent in southern Illinois.

Table IV summarizes the results of ten random sampling tests on air mass storms and all storms for each of the five year periods and the ten year period. In the 1955–59 period there was a total of 198 storms of which 92 were air mass storms. Network average rainfall totaled 54.76 inches in all storms and 11.17

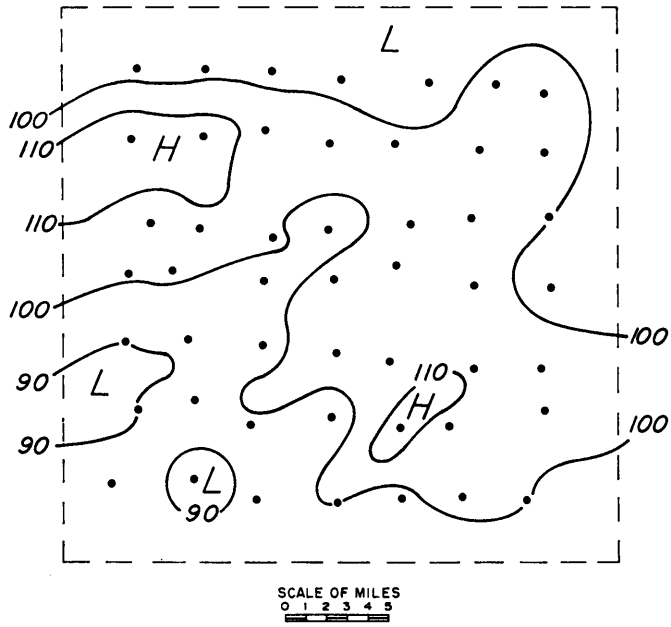

FIGURE 10

Per cent of average network rainfall in all summer storms on Little Egypt Network.

inches in the air mass storms. In 1960–64, air mass storms occurred 65 times in a total of 179 storms. Total rainfall averaged 10.66 inches in the air mass storms and 51.08 inches in all storms combined.

TABLE IV

PERCENTAGE DIFFERENCES BETWEEN HYPOTHETICALLY SEEDED AND UNSEEDED STORMS ON EAST CENTRAL ILLINOIS NETWORK, 1955–64

	Percentage Differences in Air Mass Storms			Percentage Differences in All Storms Combined		
Test	1955–59	1960–64	1955–64	1955–59	1960–64	1955–64
1	41	7	27	9	14	1
2	51	4	33	8	7	7
3	2	48	28	0	32	14
4	15	11	13	24	7	16
5	176	31	40	4	1	3
6	39	29	34	0	16	8
7	55	9	31	1	6	3
8	35	5	20	35	28	10
9	18	38	12	15	26	21
10	150	29	35	15	39	8
Median	40	20	29	9	15	8
Range	2–176	4–48	12–40	0–35	1–39	1–21

The percentage differences in table IV show a wide range among the ten tests in each of the five year periods. As expected, the percentage differences are appreciably lower for all storms combined than for air mass storms which account for a small percentage of the total rainfall. The lowest percentages were obtained with the ten year sample of all storms combined, but even here a difference of 21 per cent was drawn in one of the ten tests, and as pointed out previously, this appears to be near the upper limit of most estimates of rain increase from seeding over a substantial period of time. Comparison of 1960–64 data on the two networks shows higher percentage differences on the Little Egypt Network in southern Illinois where air mass rainfall occurs more frequently, and accounts for a larger percentage of the total summer rainfall.

3.4. *Relation between area and percentage differences.* A limited study was made of the effect of the size of sampling area on the percentage differences obtained from two sets of data randomly selected from the same period of rainfall. For this purpose, the East Central Illinois Network of 400 square miles was subdivided into areas of 50, 100, and 200 square miles. Percentage differences were obtained for these subareas at the same time as the 400 square mile tests were made; that is, each test contains the same set of storms in each area from 50 to 400 square miles. The period from 1960 to 1964 was used in these areal comparisons, and the comparisons were made for both air mass storms and all storms. Results are summarized in table V. Except for the results on the

TABLE V

FIVE YEAR COMPARISON OF PERCENTAGE DIFFERENCES FOR AREAS OF 50 TO 400 SQUARE MILES IN EAST CENTRAL ILLINOIS NETWORK, JUNE–AUGUST, 1960–64

	Per Cent Difference for Given Area (sq mi) in Air Mass Storms				Per Cent Difference for Given Area (sq mi) in All Storms			
Test	50	100	200	400	50	100	200	400
1	28	28	25	7	8	7	7	14
2	49	30	26	4	4	2	2	7
3	33	34	25	48	61	69	56	32
4	16	27	31	11	1	5	5	7
5	34	42	45	31	0	0	4	1
6	10	7	9	29	10	12	10	16
7	52	49	54	9	10	9	11	6
8	27	21	20	5	19	20	14	28
9	8	12	8	38	24	27	24	26
10	46	42	45	29	47	43	45	39
Average	30	29	29	21	18	19	18	18
Median	30	29	26	20	10	11	11	15
Range	8–52	7–49	8–54	4–48	0–61	0–69	2–56	1–39

400 square mile area, no appreciable differences were found in the means or medians of the air mass storms (table VI). With all storms combined, only small differences were found among all four areas. However, it is interesting to note that in some of the specific tests relatively large changes in percentage differences

TABLE VI

FIVE YEAR COMPARISON OF PERCENTAGE DIFFERENCES IN AIR MASS STORMS FOR SEVERAL GAGE DENSITIES ON EAST CENTRAL ILLINOIS NETWORK, JUNE–AUGUST, 1960–64

Test	Percentage Difference for Given Gage Density (sq mi/gage) 8	50	100
1	7	30	31
2	4	26	22
3	48	17	26
4	11	40	56
5	31	44	51
6	29	13	9
7	9	55	57
8	5	16	15
9	38	5	10
10	29	43	47

did occur between areas. Test 2 of the air mass storms is an outstanding example. Here, the percentage differences decrease from 49 per cent on the 50 square mile to 4 per cent on the 400 square miles. If this particular set of data had been associated with a five year seeding experiment on air mass rainfall in this network, interpretation of the results would have been very interesting.

3.5. *Sampling errors resulting from gaging deficiencies.* Huff and Neill [5] have shown the effect of raingage density upon sampling errors in the determination of areal mean rainfall on areas of 25 to 400 square miles. Review of this study indicated that inadequate gage density could be an important source of interpretive error in the evaluation of cloud seeding experiments which are based upon observed increases or decreases in rainfall in the seeding region. Consequently, a limited study was undertaken to illustrate the possible influence of the gage density factor. For this purpose, summer rainfall data were used for air mass storms and all storms combined on the East Central Illinois Network during 1960–64.

In accomplishing this study, percentage differences between hypothetically seeded and unseeded storms in Tests 1 to 10 (table IV) were recalculated through use of 4 and 8 gages instead of the 49 gages on the network of 400 square miles. The four and eight gages were selected to form as uniform a network as possible within the framework of the existing network. Four gages provide a gage density corresponding to 100 square miles per gage which is more than twice the average gage density of the climatological network of the U. S. Weather Bureau in Illinois. The eight gage test network then represents a density of over four times that of the climatological network.

Results of the gage density study are summarized in tables VI and VII. For the air mass storms (table VI), the best estimate of the percentage differences

TABLE VII

FIVE YEAR COMPARISON OF PERCENTAGE DIFFERENCES IN ALL SUMMER STORMS FOR SEVERAL GAGE DENSITIES ON EAST CENTRAL ILLINOIS NETWORK, 1960–64

Test	Percentage Difference for Given Gage Density (sq mi/gage) 8	50	100
1	14	12	11
2	7	10	6
3	32	48	52
4	7	17	24
5	1	11	2
6	16	11	1
7	6	11	10
8	28	24	37
9	26	27	20
10	39	44	44

between the five year rainfall totals for the hypothetically seeded and unseeded storms is shown in column 2. These percentage differences are based upon a gage density of eight square miles per gage (49 gages) in the 400 square miles, and, based upon the 1957 study of Huff and Neill, are assumed to provide a highly accurate measurement of the true differences. Columns 3 and 4 of table VI then show the percentage differences calculated from the sparser gage densities of 50 and 100 square miles per gage.

Interpretation of tables VI and VII can be further clarified by the following example. In test 1 of table VI for air mass storms, the best estimate of the percentage difference between the hypothetically seeded and unseeded samples is seven per cent (column 2). However, when the percentage difference in this test was recalculated through the use of eight gages (50 sq mi/gage), a value of 30 per cent was obtained (column 3). This percentage is over four times the best estimate of seven per cent. Similarly, use of only four gages in the network of 400 square miles (100 sq mi/gage) resulted in a percentage difference of 31 for test 1 in table VI (column 4). Examination of the percentage differences with the various tests of table VI emphasizes the relatively large sampling errors which may result from the use of an insufficient number of gages to measure accurately the rainfall distribution in such areas. The implications of these findings in evaluation of cloud seeding experiments conducted on midwestern air mass storms is obvious.

Table VII is similar to table VI and shows results for all storms combined during the summers of 1960 to 1964. Here, the errors are, in general, smaller than found with the air mass storms, as expected. However, the errors introduced from inadequate gaging are still very substantial in several of the tests. The smaller errors are due to two causes. First, a much larger sampling is integrated into the study when all storms are used. Secondly, air mass storms, in general are more scattered spatially than frontal storms, encompass less area on the average than frontal storms, but are also capable occasionally of producing very heavy point rainfall amounts. Thus, the natural variability tends to be considerably greater in the air mass storms, and a denser network is needed to define reliably the areal distribution of surface rainfall.

4. Applicability of Gamma distribution

The degree of fit between the distribution of the sampled rainfall data and the Gamma distribution was tested, since several statistical methods for evaluating seeding experiments are based on the assumption that storm rainfall data are Gamma distributed. The distribution of the network average rainfall values for the 231 summer rainstorms in the Little Egypt Network was compared with the Gamma distribution fitted to the data by the maximum likelihood method, and the resulting frequencies are shown in table VIII. Considerable disagreement

TABLE VIII

OBSERVED FREQUENCIES OF ALL SUMMER STORMS AND EXPECTED FREQUENCIES ACCORDING TO THE GAMMA DISTRIBUTION

Storm Average Network Rain (inches)	Number of Storms Observed Frequency	Expected Frequency
$\geqq 0.91$	13	11.3
.64–.90	10	10.6
.47–.63	9	12.2
.37–.46	11	11.1
.30–.36	9	9.9
.24–.29	15	12.9
.17–.23	15	17.1
.14–.16	10	11.3
.11–.13	8	13.6
.07–.10	18	17.8
.04–.06	19	25.6
.03	5	10.9
.02	19	11.3
.01	28	12.5
.005–.009	1	8.6
.002–.004	28	13.2
.001	13	21.0

is found between the expected and observed frequencies in the class intervals below 0.07 inch. Application of the chi square test to the data in table VIII produced a value of 60 which indicates that the network rainfall data from southern Illinois, presumed to be representative of summer season conditions throughout much of the Middle West, does not fit a Gamma distribution. A better chi square value can be obtained by combining the rainfall classes into fewer intervals, but this procedure disguises the bimodal character found in the low rainfall values.

5. Summary and conclusions

Rainfall data from two concentrated raingage networks encompassing areas of 400 and 550 square miles in Illinois were used to evaluate the effect of natural rainfall variability upon the verification of cloud seeding experiments. Summer convective rainfall for periods of five to ten years were used in the study. Hypothetical seeding experiments were conducted upon air mass storms and upon all rainstorms combined for the sampling periods.

A series of 50 hypothetical seeding trials were conducted on air mass storms in southern Illinois for the five year period, 1960–64, through use of a randomized sampling procedure. Results showed a median difference of 30 per cent for the 50 trials between the hypothetically seeded and unseeded storms from the 116 storm sample. This difference, of course, was due entirely to natural rainfall variability. Similarly, all storms were combined in the network to provide a 231 storm sample for the five years, and a series of ten trials were performed on these data. A median difference of 21 per cent was obtained with this larger sample. A set of ten trials on a ten year sample of 377 storms in central Illinois produced a median difference of nine per cent. However, the ten year sample of 157 air mass storms in central Illinois showed a median of 29 per cent for ten random tests on the data.

Limited analyses were performed to ascertain the influence of size of sampling area and of raingage density within a sampling area upon the evaluation of cloud seeding experiments. Results showed that gage density is a highly important factor in such evaluations and that size of sampling area can materially influence the results in some cases.

Results of this study provide quantitative information on the degree of natural variability in warm season, convective rainstorms. Indications are that sampling periods of five to ten years are inadequate to define rainfall changes of 10 to 20 per cent resulting from cloud seeding efforts when verification is based upon analyses of surface rainfall. Therefore, it is imperative that other methods of verifying the results of cloud seeding be developed, if evaluation is to be accomplished within a period of only a few years such as used in this study.

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