NOTES AND CORRESPONDENCE

Climate-Based Representations of Summer Rainfall in Illinois

STANLEY A. CHANGNON, JR.

Climate & Meteorology Section, Illinois State Water Survey, Champaign, Illinois

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ABSTRACT

Historical (1901–85) summer (June–August) rainfall data in central Illinois were used to construct three typical rain conditions: one representing the typical dry summer (based on the driest 20% of the summers of the past 85 years), a typical wet summer (from the 20% wettest), and the near-average summer rainfall conditions (the 20% nearest the long-term average). Monthly rain totals for each type were established first, then daily rain frequencies were used to define all individual rain day amounts, and historical rain-day amounts by date were used to assign rain days to dates throughout the three types of summers. In-day conditions relating to rainfall rates, time of rain, and durations were constructed for each day of rain. The resulting three summer rainfall conditions are being used to guide applications of water onto agricultural test plots (protected from natural rains) to measure crop yield effects from weather modification but the approach and system could serve other applications like effects of climate change.

1. Introduction

Detailed climatologically based reconstructions of summer rainfall conditions were desired for studying relationships between rainfall and other conditions like crop yields, and for simulating how rain changes (due to any cause) would affect crop production or other weather-sensitive processes. Therefore, we sought to define typical dry, typical wet, and average summers in central Illinois. Normal monthly rainfall values are readily available for most locales, but we wished to define the incidence of rain on each summer day, including the amount, time of occurrence, rate, and duration. This paper describes the climatological analyses of historical data, and existing published information, at Urbana, Illinois, that were used to construct a typical dry summer, a typical wet summer, and the typical summer (June–August) rain conditions.

The primary application of the climatic reconstructions, or models, related to a unique agricultural test plot facility allowing discernment of how varying levels of rainfall affect crop (corn and soybean) production. The Urbana facility allows for the control of the amount, time, and rate of rainfall applied to the crop test plots (Banwart 1987). The field facility is a series of 36 plots in a 13 m × 45 m area which can be rapidly covered, or uncovered, by a mobile (engine driven) aluminum framework mounted on wheels. This framework is covered by clear plastic. During nonrain periods, the movable cover is off the test plots, but when rain begins, an automatic rain switch activates the motors which move the covering over the test plots to avert any natural rain. A suspended sprinkler system of 36 nozzles is installed in the aluminum framework with each nozzle connected to individual control pumps and water supplies. This system allows application of simulated rainfall amounts at any time and rate to each of the 3 m × 3 m test plots. In the 1987 use of the models, 18 plots were for soybeans and 18 for corn. Eighteen plots (nine corn, and nine beans) were subjected to the three above types of summer rainfall conditions (allowing three replications of each), and to measure potential yield effects of increased rainfall, the 18 other plots were subjected to 25% increases in the three typical summer's daily rainfall amounts.

2. Model development

For the crop plots applications, we wished to reconstruct the singular, most likely types of summer rain conditions (in three classes), and then use them repeatedly in a fixed design over several years of trials. The wet, average, and dry rain conditions were not models to be regenerated stochastically for repeated running in agricultural models such as those of Bruhn et al. (1980). We used analyses of a long (85 years) and high quality historical dataset to select the dates of rain/no rain, the daily amounts of rain, the hours and times of day of rain, and the rain rates. We did not use complex statistical modeling of rain days. As Buishard (1978) notes, there are a variety of processes for generating daily rainfall sequences and most features of rainfall (daily process) are hardly sensitive to the rain

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Corresponding author address: Dr. Stanley A. Changnon, Climate and Meteorology Section, Illinois State Water Survey, 2204 Griffith Drive, Champaign, Illinois 61820-7495.

model chosen. He recommends that the process chosen should fit the available database and the application desired. After considering various processes and our applications, we chose to construct ours in a climatological frequency fashion rather than to use Markov chains (or other complex statistical processes) for the distribution of wet/dry days and the amounts of rain on wet days.

The development of each summer type began with the month time scale and then moved to days and finally to the hour time scale. We first developed the mean summer rainfall and then the mean amounts per month (June, July and August) in the average, "near normal" summer, those in the typical wet summer, and those in the typical dry summer. The monthly totals were established as "targets" for the sum of the daily rain values. We also chose to first do the detailed daily analyses for the near-average summer conditions, then to develop the dry and the wet summer daily values. We matched their rain dates to those established for the near-average summer conditions. This was necessary to achieve comparable crop effects between wet and average, dry and wet, and dry and average summers wherein timing of rain is critical. Historical rain days data for the period 1901–85 were used to define the frequency distributions of daily rainfall amounts, and then to distribute these amounts on various dates in the 92 summer days. Finally, climatic information on rainfall rates, durations of rain events, and time of day of rain were used to develop the diurnal distributions. All of these data were used to "construct" the three summer rain conditions.

a. Monthly conditions

The wet, near average, and dry summers total rainfall values were defined as follows: those amounts in the wettest 20% of the past 85 summers (17 summers) were classified as the "wet summer"; the 20% with rain nearest to the 85-yr average were classified as the "average summer"; and those found in the 17 driest (20% of the 85) summers were considered representative of the "dry summer." The monthly values composing the 17 wet, 17 average, and 17 dry summers identified were used to calculate the mean monthly rain values in each type of summer in 1901–85.

b. Daily rainfall levels

The frequency distributions of rainy days were determined for each type of summer by analysis of all the months in the 1901–85 sample. There were 2205 days with measurable rain (≥ 0.25 mm), or 28.2% of the total days (7820). The daily amounts were fit to the gamma distribution, and the predicted probabilities of daily values well described the observed conditions. Table 1 presents the average frequencies for the three types of summers for six rain day levels.

The next analytical step focused on constructing the "average" summer conditions. Inspection of the monthly frequency distributions indicated that the daily rain amount distributions for 2.5-mm increments were a good basis for calculating the individual daily amounts, at least up to 22.5 mm. Analyses began with the light rainfall events during each of the three summer months. As shown in Table 1, the average summer type had 26 days with ≥ 0.25 mm. The average summer values for the 0.25 to 2.5 mm level reveals that 10 days were in this range. In this "lowest" rainfall category, the values selected for use in the "average summer condition" were based on historical frequencies; these were determined to be 0.3, 0.5, 0.8, 1.0, 1.3, 1.5, 1.8, 2.0, 2.3, and 2.5 mm. Their total was 14.0 mm.

These ten values were then distributed amongst the 3 months according to the monthly frequencies of rain days in this range. Thus, 4 of these rain days (Table 1) were assigned to June, 3 to July, and 3 to August. The ten amounts (listed above) were distributed among the months according to the magnitudes of the average monthly rainfall amounts; that is, the June average rainfall is 100.9 mm (Table 2) which is 37% of the average summer total of 278.5 mm; the July average is 86.4 mm which is 31%, and the August average is 91.2 mm which is 32%. The sum of these ten daily values (14.0 mm) was multiplied by the June percentage (37%), resulting in 5.1 mm as a target for June. Four values were selected from the ten available (listed

TABLE 1. Average number of rain days for Urbana in the typical wet, near-average, and dry summers.

	Days with measurable amounts, ≥0.25 mm			Days with 0.25–2.5 mm		
Month	Wet	Average	Dry	Wet	Average	Dry
June	12	10	10	4	4	4
July	10	8	7	3	3	3
August	10	8	7	2	3	3
Total	32	26	24	9	10	10

	Days with 2.6–7.5 mm			Days with 7.6–12.5 mm		
	Wet	Average	Dry	Wet	Average	Dry
June	4	3	3	1	1	1
July	3	2	2	1	1	1
August	4	2	2	1	1	1
Total	11	7	7	3	3	3

	Days with ≥22.8 mm			Days with ≥2.6 mm		
	Wet	Average	Dry	Wet	Average	Dry
June	1	1	1	2	1	1
July	1	1	1	2	1	0
August	2	1	1	1	1	0
Total	4	3	3	5	3	1

above) that combined to total 5.2 mm (those selected for June were 0.5, 0.8, 1.3, and 2.5 mm). This process was repeated for July and August to assign their daily values, totaling 4.4 mm in July and 4.5 mm in August.

This process of partitioning daily rainfall values by months was then repeated for those values in all other 2.5-mm rain intervals above 2.5 mm. The 2.6- to 5.0-mm level had 4 rain days in the average summer (2 in June, 1 in July, and 1 in August); and the 5.1- to 7.5-mm category had three rain days (and 1 in each month). Their combined values, 2.6 to 7.5 mm, are shown in Table 1. Frequency analysis of the historical values in each class was again used to determine the values selected. This was 3.1 and 3.9 mm for the 2.6–5.0 range, and 6.4 mm for the 5.1–7.5 category.

As shown in Table 1, the 7.6–12.5, 12.6–22.5, and ⩾22.6 mm categories averaged 3 rain days per average summer. The rain day values (between 7.6 and 22.5 mm) were selected based on the frequency distributions for the 7.6–12.5 and 12.6–22.5 mm levels. They were partitioned between months by how well they approximated the average monthly totals. The June values selected for the average summer were 11.5 and 20.8 mm; the July values were 8.9 and 22.0 mm; and those for August were 11.8 and 21.1 mm.

The final rain days to be assigned were those ⩾22.6 mm. We chose to stop the frequency analysis at the 2.5-mm categories at this level because of the rarity of rain days above this level. As shown in Table 1, the average summer experienced one such day in each month. The rain magnitude for each day was established by summing all the other daily values already assigned (described above), and then subtracting this total from the monthly average total. For example, in June the nine daily rain values already selected (and less than 22.6 mm) totaled 50.8 mm. This value, subtracted from the 100.9 mm average for June, yielded the >22.6 mm value used, 50.1 mm. Similar identification of these heavy rain days can be noted in Table 2 with 50.8 mm in July, and 45.5 mm in August.

c. *Temporal distribution of rain days*

The summer rain days for each month then had to be assigned to dates in each month. Analysis showed that 54% of all summer rain days at Urbana were in

TABLE 2. Modeled summer daily rainfall values (mm) for Urbana in typical average, dry, and wet summer conditions.

	June			July			August		
Date	Average	Dry	Wet	Average	Dry	Wet	Average	Dry	Wet
1									
2						0.5	1.5	0	5.8
3	3.9	3.3	6.0				21.1	10.1	22.1
4	20.8	14.6	30.8	0.3	0.2	2.3			
5				50.8	20.4	50.7			
6									
7									
8	3.1	3.0	7.2						
9				8.9	3.0	10.2			
10	0.8	0.8	1.0			5.1	3.9	2.3	5.1
11									
12									
13							1.0	0.8	4.8
14	50.1	29.3	63.7	2.3	0	6.3	45.5	21.1	58.2
15	0.5	0.5	0.5						
16									
17									
18							2.0	1.9	2.2
19	1.3	1.0	2.5						
20									
21				1.8	0.8	2.3			0.2
22				20.0	11.0	32.7			
23	11.5	8.7	16.5						
24							11.8	7.1	12.6
25									10.2
26	2.5	2.3	6.9						
27	6.4	6.3	7.4	3.9	2.0	5.3			
28							4.4	4.3	5.3
29			0.3						
30			11.3	6.4	6.3	12.7			
31									
Total	100.9	69.8	154.1	86.4	43.7	128.1	91.2	47.6	124.5

pairs, but only 2% were in a sequence of 3 days of rain. Therefore, more than half of the 10 rain days in the average June (6 of the 10) were used to form three pairs of rain days with two pairs in July (54% × 8 days = 4) and two pairs in August. Each pair was constructed to consist of a relatively high and a moderately lower value, since 68% of the historical 2-day sequences had one amount being greater than ten times the other value. Hence, five of the seven pairs of rain days in the average summer were selected so that one value was more than ten times greater than the other value in the pair. Analysis further revealed that in 64% of the cases, the first-day value of the pair was less than the second day value. Hence, in five of the seven pairs, the amounts were selected to be in a low-then-high sequence with those in the other two pairs being in a high-low sequence. The previously selected daily amounts for each month were thus grouped in pairs.

Further information to establish the temporal distributions of the rain days throughout each month was obtained from calculations of the average daily rainfall per date, and from studies of probabilities of dry and wet days for 1- to 7-day durations for Urbana (Feyerherm et al. 1966) based on the Markov chain probability model. These identified parts of each month apt to be in wet periods ($\geqslant 0.25$ mm day^{-1}). Initially, the mean daily rainfall was calculated for each date in 1901–85, and these revealed certain periods that had proportionately higher (and lower) values than that expected ($\sim$3.3% per day). The five wetter periods including their historical percentages of monthly totals and their expected totals are listed in Table 3. The wet day probabilities on the dates selected were also at least 10% higher than on other dates in summer.

The rain days and amounts assigned to each month were concentrated in these wet periods. The daily amounts already assigned to each month were selected to produce totals that approximated the historical percentages of the total rain in each wet period. These rain day values are listed in Table 2, and the resulting totals, expressed as a percentage of the monthly total, appear in Table 3. The number of rain days selected to be in each wet period was set to exceed the expected number if the days had been evenly distributed throughout the month. These expected and selected daily frequencies are also shown in Table 3. The rain days assigned to these five periods, as well as the remaining rain days of each month were distributed to dates by the following procedure.

The final assignment of the rain days to actual dates in each was partly controlled by the selection of the seven pairs of rain days previously described, and by the amounts (and days) selected to be in the five wetter periods (Table 3). The distribution of the number of dry days between wet days during 1901–85 was calculated and used to array the rain days. This analysis showed that 22% were 0 days apart (pairs); 8%, 1 day apart; 18%, 2 days; 27%, 3 days; 14%, 4 days; 6%, 5 days; 3%, 6 days; and 2%, 7 days or longer. These percentages were used to array the rain days during the average summer. There were seven periods selected with 0 separation (the 7 rain day pairs), one with 1 dry day, five periods with 2 dry days, eight with 3 dry days, and two periods each with 4, 5, and 6 dry days. This array closely approximated the historical (85-yr) distribution. A coin toss (between the two highest zero day probabilities, sequences of 2 and 3 dry days) was used to establish the first rain day in June (on 3 June, Table 2). Thereafter, assignments of dry day periods through 31 August were made by blindly selecting numbered slips of paper such that the frequency of numbers matched the established frequency (one slip with 1 dry day, five slips with 2 dry days, etc.). The actual rain day amounts (and pairs) were also listed on the individual slips and drawn to distribute the values on rain dates with the slips for the rain days for the wet periods in a separate blind draw. This process confirmed to the previous choices of rain day pairs and assignment for days of rain in the wet periods.

Table 2 presents the resulting distribution of rain days for the average summer in Urbana. Also shown are the values that were constructed for the typical dry and wet summers.

d. *Rain-day conditions for wet and dry summers*

Subsections 2b and 2c have described in detail how the average summer daily rains were determined and assigned to date. Determination of the rain day values for the typical wet and dry summers was based upon

TABLE 3. Assignment of rain days and rain amounts to historical wet periods in average summer.

Period	Rainfall amount as a percentage of the monthly totals: Historical percentage	Expected percentage	Assigned percentage	Rain days: Expected frequency	Selected frequency
7–15 June	47	30	54	3	4
23–27 June	22	16	20	2	3
2–7 July	39	20	58	1	2
1–3 August	20	10	22	1	2
10–18 August	54	30	57	3	4

several criteria in a manner similar to that for the average summer. First, the dry and wet summer monthly rainfall totals were used as targets for the sum of the daily values. These monthly values for the typical wet and dry Junes, Julys, and Augusts appear in Table 2.

We chose to use the same date distributions established for the rain-days in the average summer (Table 2) for the wet and dry summer conditions; i.e., the daily rain magnitudes in wet and dry summer conditions would be different from those of the average summer, but not the dates. This was essential to serve the comparisons desired for the crop plot tests. However, as noted below, certain increases and decreases in the number of rain days were made to fit the historical averages of the wet and dry rain day frequencies.

The averages of the rain-day frequencies at the levels shown in Table 1 were followed. The process used in the dry July illustrate the procedure followed for each dry month. Table 1 data show that July in a typical dry summer has 7 rain days (⩾0.25 mm), one less than the average summer. This meant that for a dry July, one rain day had to be deleted from those selected for the average July (to match a dry July condition). A day with a relatively low value, 2.3 mm on 14 July (average summer), was selected for deletion, as was one day in August.

The historical rain-day frequencies for the 17 dry summers were used to identify distributions for each of the 2.5-mm intervals from 0.25 mm to 22.7 mm. These values were then arrayed against the daily amounts in the average rain, as listed in Table 2, to ensure that the value assigned to a date was equal to or less than the value in the average summer.

In a similar fashion, the daily values in the wet months were constructed and arrayed with the dates of rain for the average summer. The guiding criteria ensured that the readjusted values met the monthly averages for the wet summer rain day frequencies (Table 1), and that their totals matched the monthly totals in Table 2. Historical wet-summer daily rainfall distributions were used to select the values in the 2.5-mm interval. These were assigned to dates of the average summer rain days such that their totals equaled or exceeded the average summer values. The 6 additional rain days in the wet summer [32 vs 26 with ⩾0.25 mm (see Table 1)] were assigned by the monthly average frequencies with 2 in June, 2 in July, and 2 in August. The criteria used for these 6 days first matched the historical single and paired rain day frequencies (about 54% paired); hence, 3 of these added rain days were used to form pairs, and the other 3 days were left as single events. They also were not assigned to the five wet periods (Table 3) since the assigned rain values already exceeded the historical values. We further limited the dry day spacing to 1 or 2 days between the new and already existing rain days. With these criteria, candidate dates for each month (such as 1, 17 June etc.) were entered on slips of paper and then the two dates blindly selected. The dates selected for the two added days in June were the 29th and 30th, forming a pair. Another rain-day pair with the third rain day was set on 25 August, and the other single rain days were selected by the same process with two in July and one in August.

e. In-day rain distribution

Once the daily rainfall amounts were assigned to dates, the diurnal rainfall distributions were needed. These related to rainfall rates, times of rain, and duration of rain events, and past studies provided the information needed. However, we decided not to attempt to construct varying rainfall rates during each individual rain period but to assign varying fixed rates for different rain days based on the magnitude of the daily totals.

The average point duration of summer rains is 2.5 h per day (Changnon 1963). This value multiplied by 26 days (the average number in an average summer, Table 1) produced 65 rain hours per summer or rain 3% of the time. The 278.5 mm of summer average rainfall, when divided by 65, yields a mean rainfall rate of 4.3 mm h^{-1}. The system for applying water could not be set to handle a wide variety of rates nor changing rates during each rain event (day). Hence, after inspection of the past data on Urbana rain rate distributions (Huff 1949), we established four rain rate submodels, as follows:

model A: If the daily rain total was 0.3–2.5 mm, the median rain rate is 2.5 mm h^{-1}.

model B: If the daily rain total was ⩾2.6 and ⩽6.3 mm, the median rain rate is 3.8 mm h^{-1}.

model C: If the daily rain amount was ⩾6.3 and ⩽22.7 mm, the median rate is 5.1 mm h^{-1}.

model D: If the daily rain amount is ⩾22.8 mm, the rain rate was 7.6 mm h^{-1}.

These four submodels of rates were assigned to the rain-day values of the typical summers.

The final in-day rain condition issue related to the time of rainfall during the day. The historical (85-yr) data did not include hourly values to derive diurnal distributions for the wet, average, and dry summers. However, the average diurnal distribution of summer rainfall in the Urbana area based on 20 years of data (Huff 1971) was available, and employed to establish general diurnal distributions. The results show that between the hours of 0900 and 1300 LST, each hour receives 3% of the rain, on the average. This is a low incidence period. Between 1300 and 2000 LST, each hour receives about 4% of the rain, and between 2000 and 0900 LST each hour receives about 5% of the total rain (the third and wettest period of the day). This distribution reflects a nocturnal maximum and a midday minimum, such that 62% of the summer rain falls in the 13 h from 2000 to 0900 LST, 26% from 1300 to 2000 LST, and 12% from 0900 to 1300 LST.

These percentages were used to distribute the rain occurrences in a repeated 6-day sequence of rain days from 1 June through 31 August. The sequence approximated the average diurnal distribution with three events at night (2000–0900 LST), two in the afternoon (1300–2000 LST), and one in the morning (0900–1300 LST). The order of these was determined by putting each option on one of six slips of paper, and then selecting them blindly. The sequence selected was afternoon, night, afternoon, night, night, and morning. The hours selected for afternoon and night rain periods were varied as to starting hour. The sequence used was as follows: Beginning with the first rain day (3 June, Table 2) the rain began at 1300 LST. On the second day, rain began at 0500 LST. On the third rain day in the sequence, the afternoon rain was set to begin at 1600 LST. On the fourth and fifth rain days in the six-day sequence, rain began at 2000 LST on day 4, and at 0100 on day 5. On the sixth rain day, rain began at 0900 LST. When the sequence of six days was completed, the same sequence of hours of occurrence was repeated. With 26 rain days in the average summer (Table 1), the sequence was repeated four times with the last 2 days beginning the fifth sequence.

Use of these in-day conditions with the daily amounts in the average summer for June (Table 2) is illustrated in this sequence:

3 June: Rain of 3.9 mm fell (rain rate model B) beginning at 1300 LST at a rate of 3.8 mm h^{-1}. The rain required 62 min to occur (or until 1402 LST to be completed).

4 June: Rain of 16.8 mm began at 0500 LST at 5.1 mm h^{-1} (model C) lasting 200 minutes (or until 0820 LST).

8 June: Rain of 6.4 mm began at 1600 LST at 5.1 mm h^{-1} rate (model C), requiring 75 minutes to fall (ending at 1715).

11 June: Rain of 0.8 mm began at 2000 LST at 2.5 mm h^{-1} rate (model A), requiring 20 minutes to occur (ending at 2020).

14 June: Rain of 47.3 mm began at 0100 LST at 7.6 mm h^{-1} rate (model D) requiring 375 minutes to fall (ending at 0715 LST).

3. Use of summer rain types

The rain conditions for three typical summers in central Illinois were used in 1987 to select the rainfall amounts for applications at the dates and times specified over agricultural test plots where corn and soybeans were grown. Three replications of each summer condition existed in the test for each of the two crops.

For the tests of rain modification effects, additional rain (water) was applied (with three replication plots) for corn and soybeans. A 25% rain-increase level was selected as representative of potential weather modification capabilities, and each daily value shown in Table 2 was increased by 25%. The guideline followed was to add whatever water was prescribed at the end of the scheduled rain period. The yield results, all from the same soil type and variety, will allow us to compare how the treatment affected yields during three typical Urbana summers with modifications.

This model will also be used in testing crop-yield weather models, and for comparing these models with actual yields from the plots. Other applications are envisioned for simulation tests of crop effects from potential future climate changes.

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