The Lunar Synodical Period and Precipitation in the United States[1]

GLENN W. BRIER

U. S. Weather Bureau, Washington, D. C.

AND DONALD A. BRADLEY

New York University

ABSTRACT

A cycle of 14.765 days, one-half of the lunar synodic month, can be demonstrated in the precipitation data for the United States for the period 1871–1961. Numerous rigorous statistical tests show that the association is real and an estimate is obtained of the magnitude of the lunar effect. Geographical, seasonal and other sources of variation in the effect are suggested by the data. No other periodicity with comparable amplitude was found by the statistical analysis, but there is evidence that the lunar synodic cycle interacts with the nodical cycle.

1. Introduction

The effect of the moon's gravitational force on the ocean tides has been known for centuries. A lunar tide in the barometric air pressure measured at the earth's surface was demonstrated over 40 years ago but its amplitude was found to be so small that it is not considered to be of any practical importance in day-to-day weather changes. Nevertheless, the demonstration of the existence of the lunar air tide by careful statistical analysis of extensive data was a scientific achievement of considerable theoretical interest and much research has been stimulated as a result of it. Since the effect of the moon on atmospheric pressure at the earth's surface is small, the prevailing view in meteorology has been that on weather elements such as temperature or precipitation no appreciable effects were either likely or detectable. The notion of a lunar influence on weather has a long history, but at best only suggestive evidence of its reality has been brought forward at acceptable levels of scholarship. The statistical evidence presented has been quite unsatisfactory because of the scarcity of data or its lack of representativeness, and valid tests of significance to distinguish the observed fluctuations from chance have not usually been applied. It is the purpose of this paper to describe an investigation of a possible lunar-rainfall relationship which was intended to be relatively free of the limitations so characteristic of many previous studies.

Preliminary results of this investigation have been reported by Bradley, Woodbury and Brier (1962) in a brief report but space did not permit a complete documentation of the evidence on which their conclusions

---

were based. Some interest was generated by the report and it is hoped that this paper can help place this provocative subject in its proper perspective by providing more quantitative information and by presenting some additional statistical analyses which may give some clues ultimately leading to a greater physical understanding of the relationship found.

2. Description of data

The basic data used in the first and major part of this study were the dates of occurrence of the maximum 24-hr precipitation amounts for 1544 weather stations in the continental United States which continuously operated over the 50 years, 1900–1949. These data were published by Jennings (1952). For each station, 12 dates are listed, one for each calendar month. Since some of these stations existed prior to 1900, 2471 of the maximum dates occurred before 1 January 1900. These were eliminated, leaving a total of 16,057 entries representing 6710 individual dates for the period 1900–1949. These data are considered to be highly representative of the chronology of heavy precipitation in the United States; they have been designated for convenience as a "Storm Catalogue" and are referred to as the "SC data" in the remainder of this paper. Each of the 18,262 days of the period from 1 January 1900 is characterized by a number, ranging from 0 to about 40, indicating the number of stations reporting a maximum rainfall on that day.

The second type of data used was based on the daily precipitation records of 4 stations with observations dating back to 1871 (Boston, New York City, Toronto and Washington, D. C.) Although the primary statistical analysis was not based on these data, the dates of ex-

treme precipitation for these stations were compared with the SC results. Furthermore, the inclusion of data for the 30 years prior to 1900 for these stations (which were the only ones immediately available), made possible a completely independent check of the results found for the 1900–1949 period.

In addition to the data described above, use was made of a daily index of United States precipitation for the period 1900–1959. This index was based on the total amount of precipitation observed each calendar day at approximately 100 stations more or less evenly distributed over the country. The frequency distribution of these daily precipitation data was found to be highly skewed and was normalized by means of the well-known cube-root transformation (see Howell, 1960). These data were not available for analysis at the beginning of the project but it appears that this daily index (hereafter referred to as the USP index) will be very useful in further studies.

3. Analysis and results

a. Lunar synodical period and the U. S. Storm Catalogue. The original design of the investigation called for an analysis of only the first 25 years of the SC data according to the lunar synodical period. The angular difference between the apparent longitudes of the moon and the sun at Greenwich noon was determined for each day of record and expressed as hundredths of the synodical month, which averages 29.53 days. When their longitudes coincide, at the event of new moon, the "synodic decimal" is 0.00 and when full moon takes place, the decimal becomes 0.50. This procedure was facilitated by using an ephemeris prepared by Carpenter (1962). The computations were programmed for a computer directly from Brown's expressions, using the improved fundamental arguments of lunar motion adopted by the International Astronomical Union in Rome, 1952.

During the period 1900–1924 there were 7856 cases of maximum precipitation records and these data were tabulated according to the 100 synodic decimal classes. The occurrence of the classes varies slightly because of variations in the lunar orbit, and slight adjustments amounting to about two per cent were necessary to assure comparability. For visual presentation in the earlier report, a ten unit moving total of the frequencies within successive classes was obtained. To avoid criticism on the use of moving totals, 25 non-overlapping classes were used for statistical analysis. These results are shown by the solid curve A in Fig. 1. The dashed curve shows the fitted harmonics corresponding to one cycle and two cycles per 29.53 days. The analysis of variance (AOV) shown in Table 1 indicates a highly significant amplitude ($p<0.01$) for the wave corresponding to a period of $29.53/2=14.765$ days. If the "error" degrees of freedom are arbitrarily and severely reduced from 22

to as few as 5 because of persistence in the original data, the results are still significant. Actually, the autocorrelation in the original series is only 0.36 at lag one and practically zero at lag 3.

Although this evidence for the existence of a lunar effect might appear to be convincing, it was considered important to test the 25 years of remaining SC data. A similar analysis for the period 1925–1949 gave results shown by curve B of Fig. 1. Again, the AOV indicated a highly significant amplitude ($p<0.01$) for the 14.765 day wave. The correlation between curve A and curve B turned out to be 0.707 which is highly significant, even though the number of independent pairs is considered as 5 instead of 25. Another significance test, which avoids the question of any persistence in the original data and is independent of the AOV amplitude test, is the phase test. For the two independent periods A and B, the phases of the 14.765 day curve as determined by the harmonic analysis were 102.2 deg and 94.3 deg, a difference of 7.9 deg. Thus, the appropriate probability is given by $p=2(7.9°)/360°=0.04$.
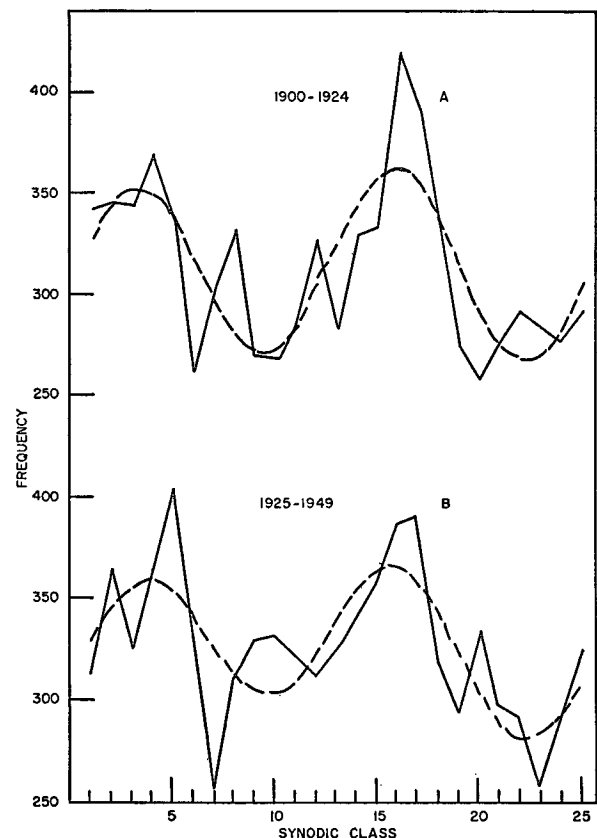

FIG. 1. The 50 years of Storm Catalogue data summarized in separate 25-year series according to the lunar synodic month divided into 25 classes, the new moon being at class 1. The ordinate represents the frequency of reports of extreme precipitation and the dashed curves are fitted by harmonic analysis to the observed frequencies shown by the solid curve.

TABLE 1. Analysis of variance (AOV) for SC data summarized according to the lunar synodic month and into separate series (a) 1900–1924 and (b) 1925–1949.

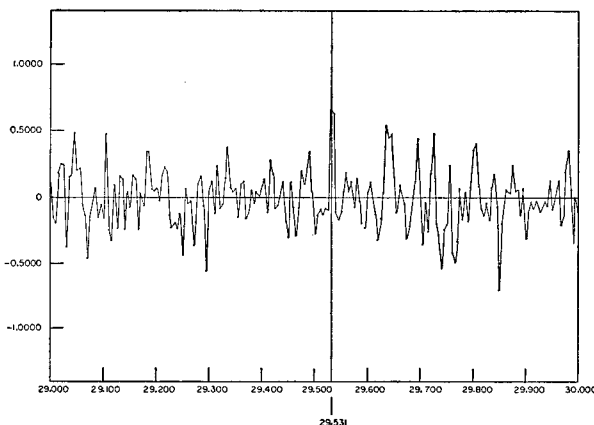| Series	1900–1924					1925–1949			
Source of variance	Degrees freedom	Sum of squares	Mean square	F		Degrees freedom	Sum of squares	Mean square	F
Frequency 1 (29.53 days)	2	17	8.5			2	77	38	
Error	22	1716	78			22	1272	58	
Total	24	1733				24	1349		
Frequency 2 (14.7 days)	2	962 56%	481	13.7		2	610 45%	305	9.0
Error	22	771	35			22	739	34	
Total	24	1733 $P<0.01$				24	1349 $P<0.01$		

FIG. 2. A plot of a sample of the 800 correlation coefficients computed between 2 separate 25-year series of the Storm Catalogue data according to various trial periods ranging from 27.000 days to 30.895 days.

Another test was to determine the fraction of variance accounted for by the 14.765 day harmonic wave during the 50 year period. From 1 January 1900 to 19 December 1949, there were a total of 618 synodic cycles in 18,250 days. By chance, one would expect to find $2/18,249 = 0.00011$ fraction of the variance accounted for by a particular frequency. Because of "red noise" or persistence in the original daily SC data, one would expect some suppression of relative variance at higher frequencies and consequent inflation at lower frequencies, as compared to the even distribution of relative variance across all frequencies shown by the "white noise" spectrum. For these data, the lag-one auto correlation was 0.36 and the procedure of Gilman, Fuglister and Mitchell (1963) was used to estimate an appropriate "noise" variance of 0.000157. The actual variance accounted for by the wave with a frequency of 1236 cycles

in 18,250 days was 0.001303. This gives a variance ratio of 8.30 which corresponds to a significance level of $p = 0.0002$. For other frequencies, ranging from 1196 to 1296 cycles per 18,250 days, the average variance accounted for by the harmonic waves was 0.000177 which is very close to the "theoretical" estimate of 0.000157 given above. Thus, there is no reason to doubt either the validity or the power of this test. The smallness of the correlation,

$$r = (0.001303)^{\frac{1}{2}} = 0.036$$

shows the need for a rather sensitive test, especially if data less extensive in time or space are used to examine a possible lunar effect.

In addition to the lunar synodical period of 29.53 days, there are other cycles near this length related to the tides. The mean anomalistic period, from perigee to perigee, is 27.55 days and the mean sidereal period, from fixed star to fixed star, is 27.32 days. The moon crosses the plane of the ecliptic about every 13.60 days, $\frac{1}{2}$ of the nodical month. The average solar rotation period is known to be about 27 days so it appeared possible that some of these periods or their harmonics might exist in the data. This question was examined for the SC data by testing for periods ranging from 27.000 days to 30.995 days in intervals of 0.005 day, using a high speed electronic computer. This was done the same way that the lunar synodical period was examined, by dividing the 50 year record into two independent series, 1900–1924 (A) and 1925–1949 (B). The consistency between these two series was examined by computing the correlation coefficient between the 25 values of curves A and B, similar to those shown in Fig. 1. A portion of these results is shown in Fig. 2. Out of the total of 800 correlation coefficients computed, the highest one was
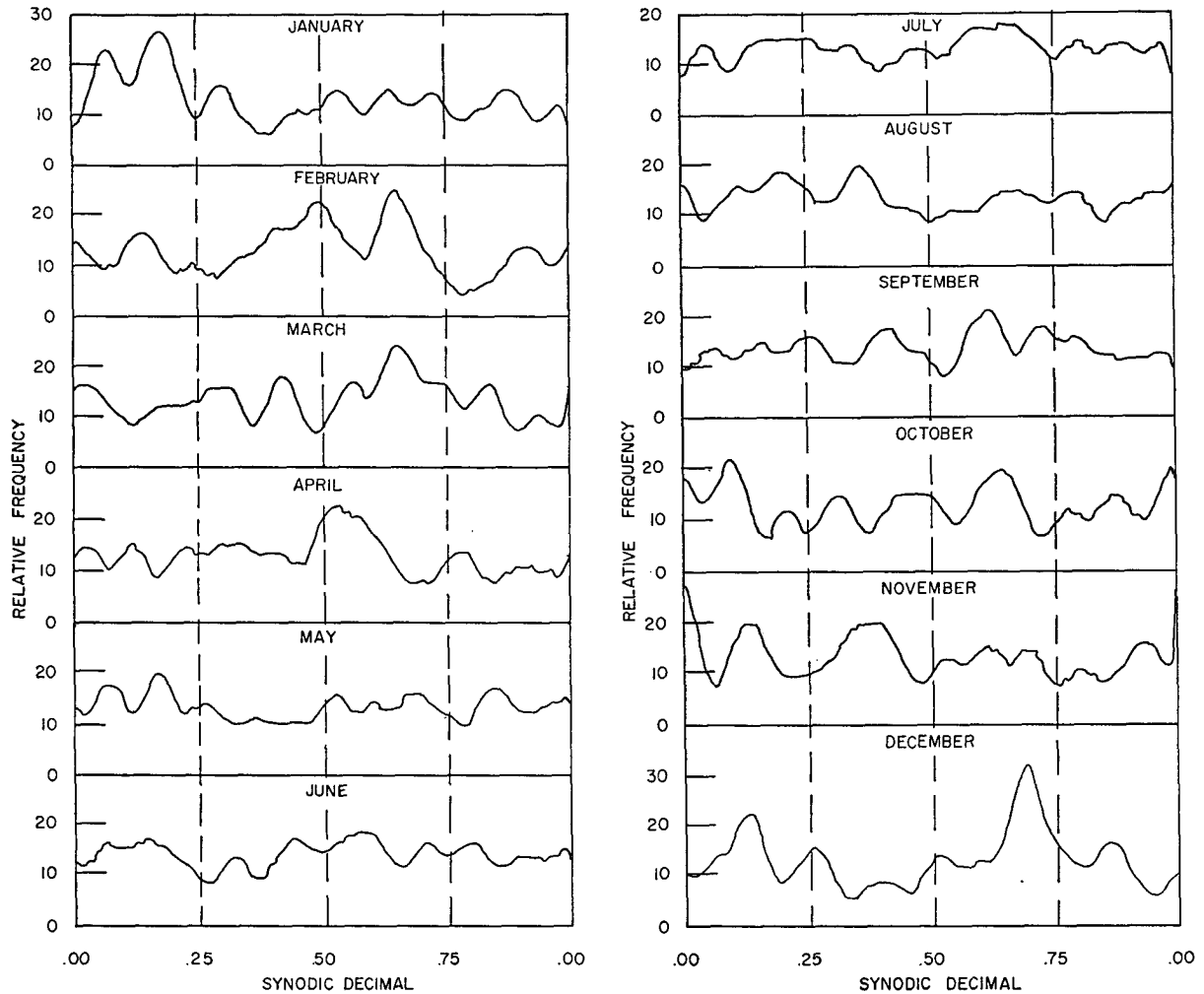
FIG. 3. The Storm Catalogue data according to the lunar synodical month arranged by the 12 calendar months.

at 29.530 days and the second highest was at 29.535 days. The lunar synodical period averages 29.530589 days. No other correlation coefficient in the entire sample was higher than 0.60 and no harmonic wave showed an amplitude as great as the one for the 14.765 day period. It should be clear, of course, that the examination of the data for so many periods was not for the purpose of finding weather cycles but to provide a sound basis for an objective appraisal of the reality of the 14.765 day cycle. Thus, we are led to conclude that there is something unusual or unique in the SC data with respect to the lunar synodic period.

b. Variations according to seasons, geographic areas, and the solar cycle. It was felt that a little greater understanding of the possible lunar effect on precipitation might be obtained if the SC data were stratified according to various criteria. It was recognized that any such subdivisions of the data might reduce the signal-to-noise ratio to a point where statistical significance could not be demonstrated. However, it seemed desirable to get estimates of how a possible lunar effect might vary
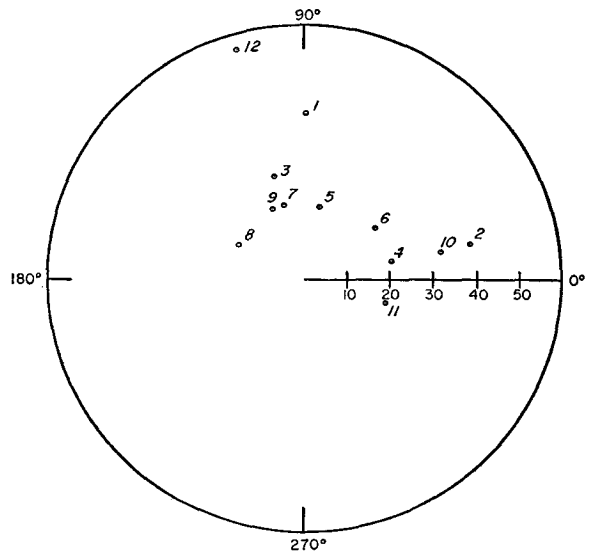

FIG. 4. The 14.765 day cycle in the SC data shown in a polar graph to illustrate the variation in amplitude and phase for the twelve calendar months. Point 1 is January, 2 is February, etc.
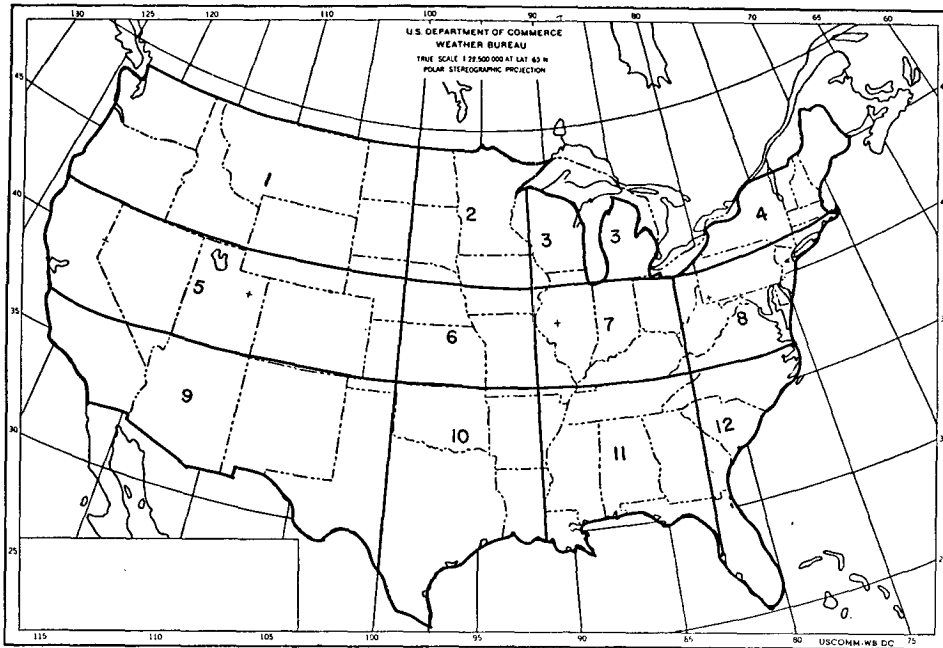
FIG. 5. The geographical division used for the SC data analysis. There are approximately an equal number of stations reporting in each area.
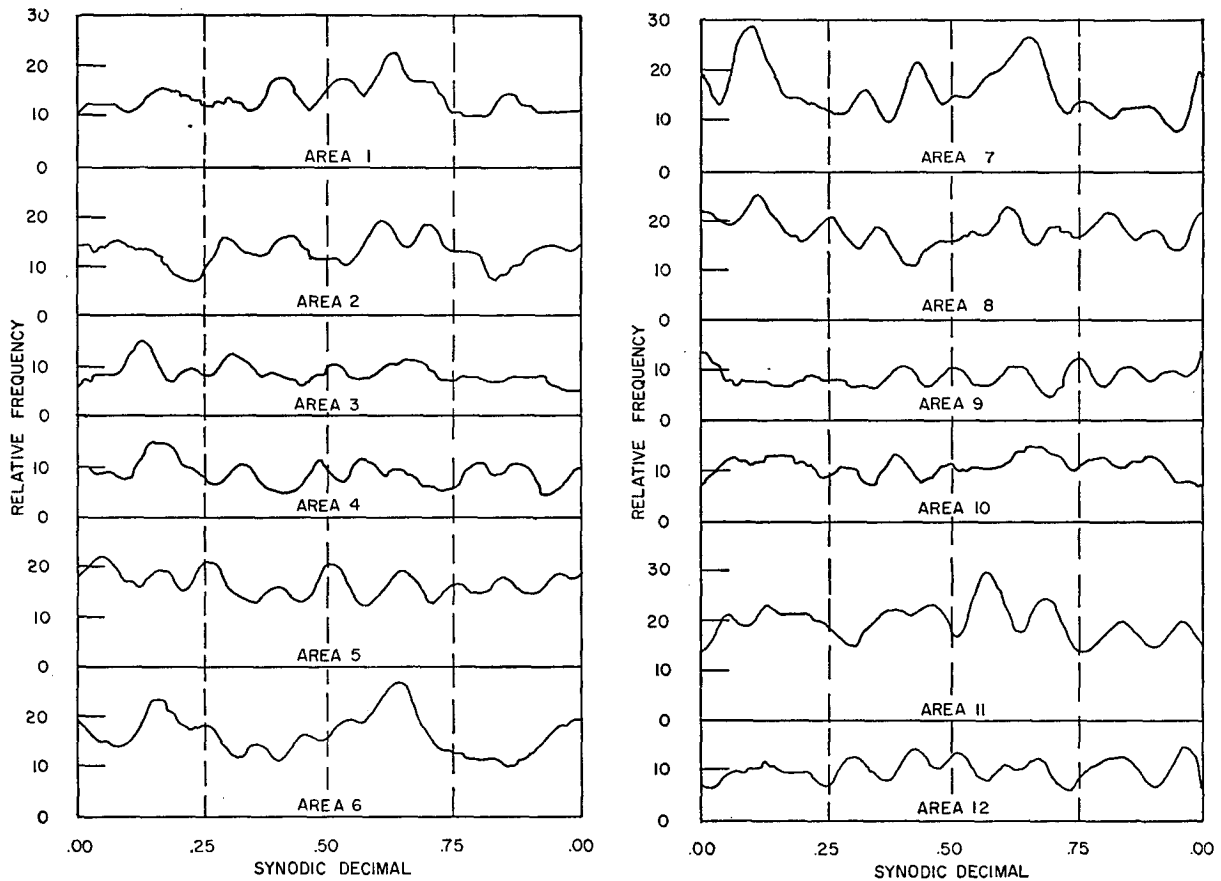

FIG. 6. The SC data according to the lunar synodical month and arranged by the 12 geographical areas shown in Fig. 5.
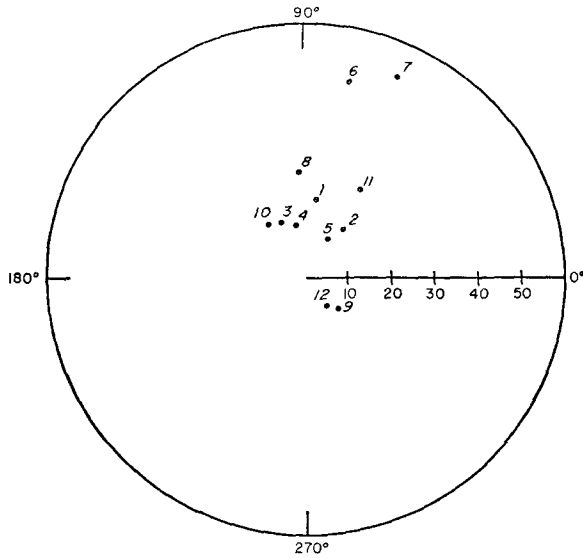
FIG. 7. Polar graph of the 14.765 day cycle in the SC data illustrating the variation in amplitude and phase for the 12 geographical zones.
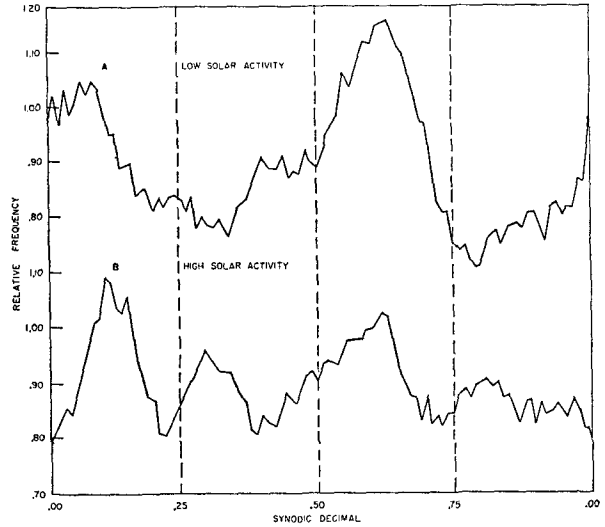

FIG. 8. The SC data according to the lunar synodical month for years of low solar activity (A) and high solar activity (B). The plots are in terms of ten-unit running averages of frequencies tabulated within 100 equal divisions of the synodical month.

under different conditions. The first results, presented in Fig. 3, show the variations according to months of the year. Fig. 4 shows the amplitude and phase of the 14.765 day wave as fitted to the 12 curves of Fig. 3.

Another summary was made according to the 12 geographical zones shown in Fig. 5, and the resulting curves for the individual zones are shown in Fig. 6. In Fig. 7 the amplitude and phase of the 14.765 day cycle for the data are shown. Another stratification was suggested by the results of a study of tropical rainfall by Berson and Deacon (1963) which indicated a possible modification of a lunar effect by variable solar radiation. In the study reported here the SC data were divided into 2 sets of 25 years according to whether the annual sunspot number was above or below the median for the 50 years. The results of this analysis are shown in Fig. 8. For the years of low solar activity, the 14.765 day wave accounts for 65 per cent of the variance of the curve, a highly significant amount. The same wave accounts for only 14 per cent of the variance in the curve based on the years for high solar activity. However, it should be pointed out that the phase of this wave differed by only 0.35 day from that found for the years of low solar activity.

No evidence was found of any real cycle in the neighborhood of 27 days, the approximate period of solar rotation. Although an examination was made of other lunar cycles, none of these showed results as significant as the synodic cycle. There was evidence that the nodical cycle of 27.2122 days interacted in some complex manner with the synodic cycle. (The nodical period is concerned with the position of the moon with respect to the plane of the ecliptic. Twice in each nodical month the moon crosses this plane, and if this happens at the time of a new or full moon, an eclipse
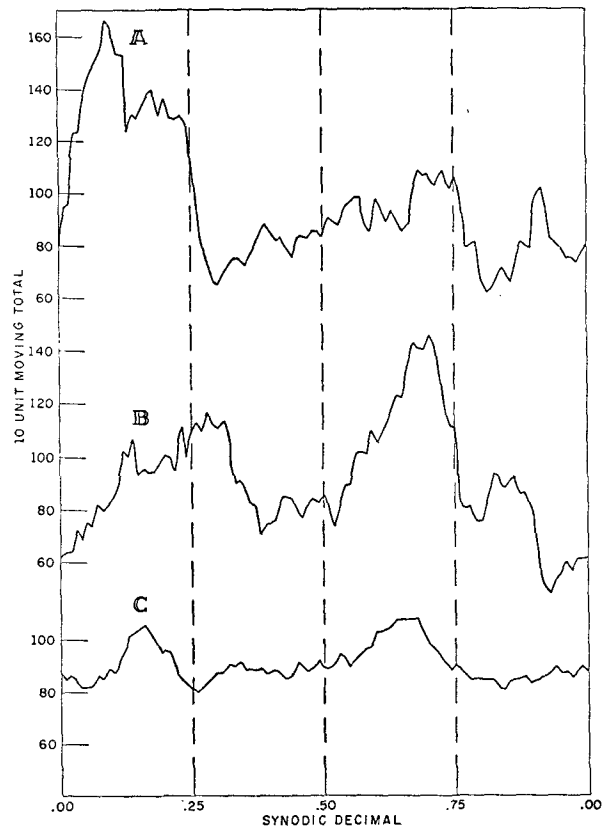

FIG. 9. The SC data according to the lunar synodical month and the position of the moon with respect to the nodical cycle. Curve A refers to the 10 per cent of the time when the moon is nearest the plane of the ecliptic but crossing from north to south. Curve B is analagous but the crossing is from south to north. Curve C refers to the 80 per cent of the time when the moon is farthest from the plane.
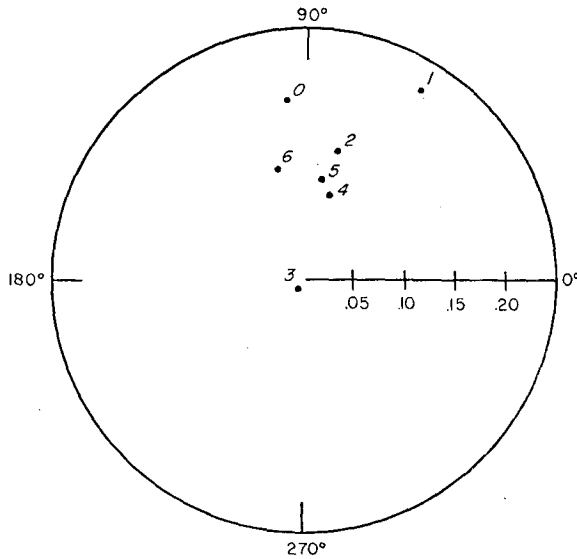
FIG. 10. Polar graph showing variation in amplitude and phase of the 14.765 day cycle for the periods (0) 1871–1899, (1) 1900–1909, (2) 1910–1919, (3) 1920–1929, (4) 1930–1939, (5) 1940–1949, (6) 1950–1959.
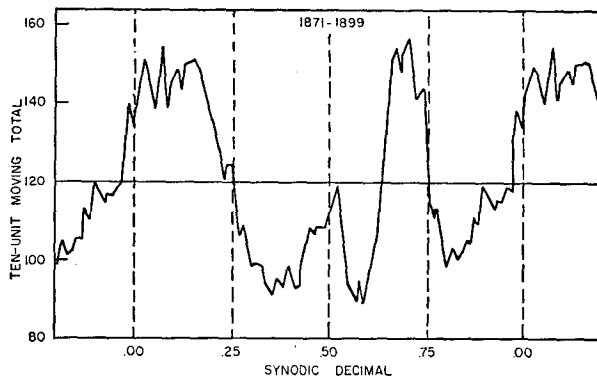

FIG. 11. The distribution of 1200 synodic decimals over the 29 years (1871–1899), consisting of the decimals for the 300 "wettest" days recorded at 4 major stations (Boston, New York City, Toronto and Washington, D. C.).
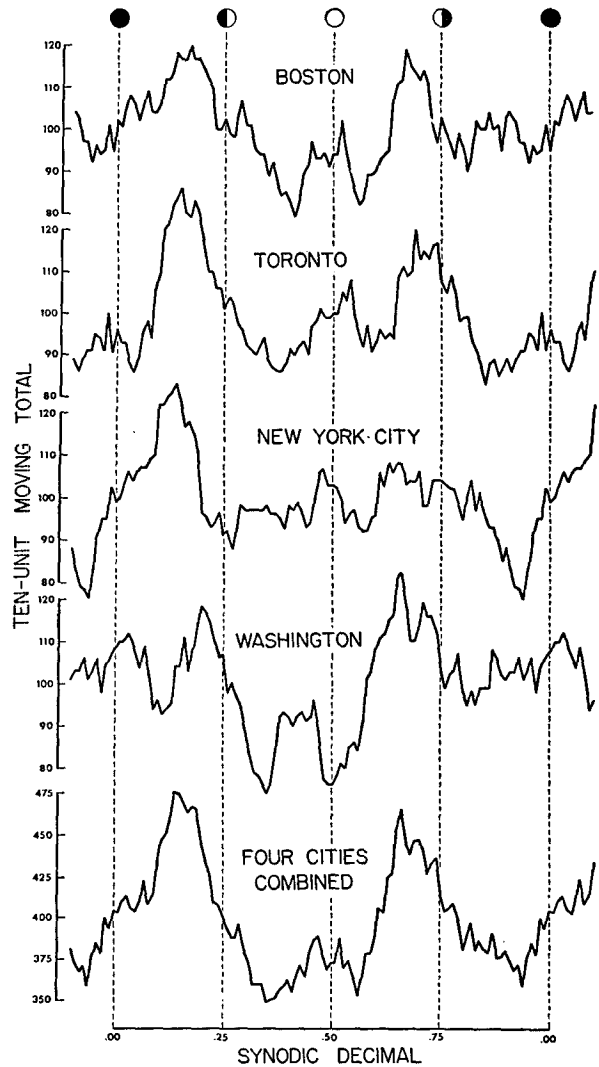

FIG. 12. Distribution of positions of the moon with respect to the sun on the 1000 dates of heaviest daily precipitation recorded at each of four cities over the 91 years 1871–1961. The plottings are in terms of ten-unit running sums of frequencies tabulated within 100 equal divisions of the synodical month. The moon's position on each date taken as of Greenwich noon. The lowermost curve consists of the arithmetic addition of the individual curves for Boston, Toronto, New York City and Washington, D. C.

occurs.) Fig. 9 shows the SC data arranged according to the synodic cycle and stratified according to whether the moon is near the plane of the ecliptic or not.

c. Test on independent data. Even though a statistical analysis of data may show that a particular effect is significant, it is usually desirable to have an additional sample of data for further checking. Any "real" periodicity should maintain its phase during other intervals of time, making proper allowance, of course, for sampling variations. The SC data ended in 1949 but additional precipitation data were available for the period 1950–1959 in terms of the USP index. The amplitude and phase of the 14.765 day wave was determined for the 10-year period 1950–1959 and the result is shown plotted as point 6 in Fig. 10. Points 1–5 show the results

when the 50 years of SC data are divided into 5 separate periods of 10 years each. The point numbered 0 is the result of a similar analysis made on the 300 "wettest" days recorded at Boston, New York City, Toronto and Washington, D. C., for the period 1871–1899 (Fig. 11). Except for the third period of the SC record, when the amplitude was practically zero, the phase of this wave has remained essentially constant.

Data for the 4 cities discussed above were also readily available for a 91-year history (1871–1961). Although these data are not completely independent of the 50 year SC data, they contribute very little to the SC results. That is, the removal of the Boston, New York,
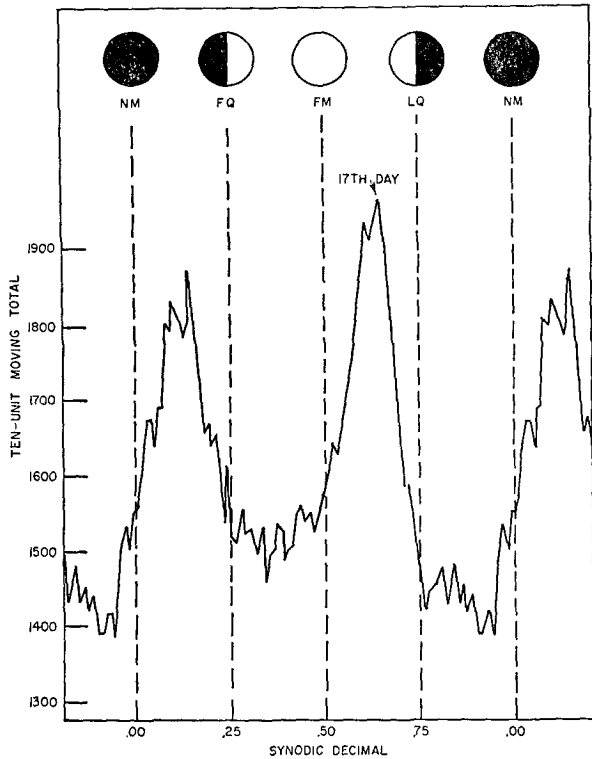
FIG. 13. Distribution of the synodic decimals for 16,057 record dates of maximum 24-hr precipitation at 1544 U. S. stations, 1900–1949. The ordinate represents frequencies in terms of 10 unit moving totals.
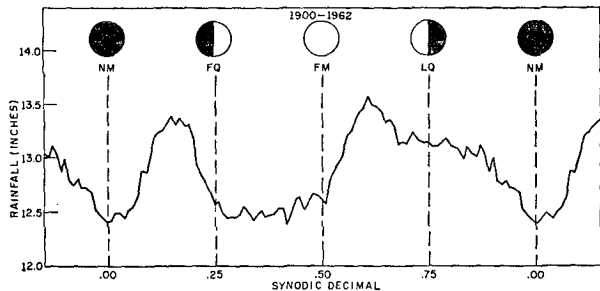

FIG. 15. The total rainfall for a network of more than 100 stations in the United States summarized according to the lunar synodic month for the period of record 1900–1962.
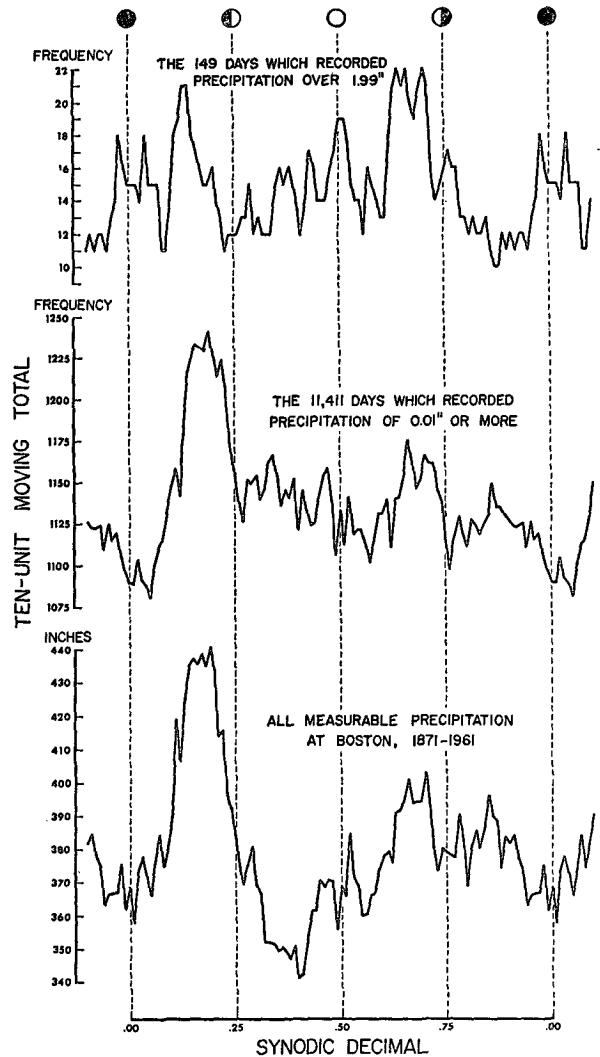

FIG. 14. Summaries of Boston's 1871–1961 precipitation records in terms of lunar phase. The uppermost curve shows the distribution in synodic decimals of the 149 days of heaviest precipitation during the 91 years. The middle curve shows the distribution of lunar positions for every day on which any measurable precipitation was observed, without regard for specific amount. The lowermost curve is yielded by arithmetic totaling of all amounts of precipitation recorded.

and Washington records from the SC would have practically no effect. With these extreme rainfall data, the correlation is low even between stations less than 100 miles apart. Unless the lunar "effect" is a real one, one would not expect to be able to detect evidence of it in the records of individual cities since the variation in daily rainfall at individual stations is so large. Fig. 12 shows the curves for the individual cities which can be compared with the curve based on the entire 50 years of SC data shown in Fig. 13. Harmonic analysis of the "national curve" shows a dominant wave having a frequency of two cycles per synodical month, with maxi-

mum enhancement of precipitation at synodic decimals 0.11 and 0.61. This same wave dominates the curve for the four cities combined and is the largest harmonic for the individual curves of Boston, New York City and Toronto. Again, the maximum enhancement of precipitation, as shown by the fitted harmonics, comes at 0.13 and 0.63 for New York City, and at 0.17 and 0.67 for Boston, Toronto and Washington. An inquiry with respect to the Boston record prompted us to examine this record in more detail. The coefficient of correlation between the Boston curve in Fig. 12 and the national curve (Fig. 13) is 0.42. Other results of this supplementary analysis are shown in Fig. 14.

4. Discussion and conclusions

An effect of the moon on weather has been suggested by many investigators and the antecedents reach far back into antiquity.[2] It seems to be pointless, however, to make a weighty case in behalf of "ancient knowledge" by citing endless references to a belief in moon–weather relationships among bygone people and civilizations that used a lunar calendar. But there are isolated instances of provincial folklore which are sometimes provocatively accurate and such items have their anecdotic interest. A few old wives' tales and agricultural superstitions may well have arisen from cumulative and intuitive "observation" of a sort. Admittedly, a modern scientific theory to explain results of the type presented here would be much more satisfying than reliance on the statistical tests alone, regardless of their significance. Quantitative theories and physical hypotheses for rigorous testing will come in due time, as further clues are uncovered. No attempt will be made in this paper to give meteorological interpretation or to suggest physical explanations of the findings. The authors cannot resist the temptation to borrow a remark from the classic by Fielding (1748), ". . . it is our province to relate facts, and we shall leave causes to persons of much higher genius."

The various tests on the SC data clearly show the statistical significance of the 14.765 day cycle. Presumably the causal factor is lunar, but this cannot be demonstrated by statistical analysis alone. The amount of precipitation data available makes it possible to determine the length of the cycle to within 0.01 day, so it seems rather unlikely that the effect is due to a force unrelated to the lunar synodic month. Since the AOV shows that the average amplitude of the effect is quite small, it is obvious that it has no great immediate forecasting value for day-to-day rainfall. Also, it is easy to see how such an effect escaped earlier detection when relatively short records or individual stations were examined. It may appear contradictory that such effects can be small and at the same time be reflected in curves such as Figs. 11, 12 and 13 which show cyclical fluctuations greater than 20 per cent in amplitude. This may be partly a consequence of using extreme values such as the highest daily rainfalls recorded or the 10 "wettest" days each year at individual stations. It was shown by Brier (1964) that even a very low correlation between a dependent variable y and an independent variable x can produce rather large (and real) fluctuations in the extreme values of y when they are considered as a function of x. However, this statement is not meant to minimize the possible physical importance of x in contributing to the variations in y.

The results of the SC analysis are further confirmed by the precipitation data for the independent periods 1950–1959 and 1871–1899. The USP data which were used to test the 1950–59 period were also available for the period of the SC data (1900–1949) and showed essentially the same results. The data for Boston, New York City, Toronto and Washington, D. C., indicate that during the past 90 years there has been no significant shift in phase of the wave with a period of 14.765 days. Although it might not be possible to demonstrate conclusively the lunar effect in the 91-year histories of these stations individually, it did seem relevant to inquire whether there was a discernible lunar modulation on precipitation activity at these stations and to determine to what extent the observed variations, if any, were comparable to the pattern of activity in the United States generally as illustrated by Fig. 13. The curves shown and the statistical analysis give support to the earlier statement by Bradley *et al.* (1962) that "such stations as New York City, Washington, Boston and Toronto, clearly exhibit the same lunar-month pattern of fluctuation."

The curve shown in Fig. 13, based on the SC data, may be difficult to interpret in terms of the magnitude of a synodic effect. For this reason, it was felt desirable to produce a summary of all 63 years of the USP data in terms of inches of rainfall. The results, shown in Fig. 15, indicate that the average amount of rainfall was about 10 per cent higher a few days after the full moon than a few days before.

The analysis of the SC by the 12 calendar months gives a suggestion that there may be a seasonal variation in the phase and amplitude of the 14.765 day cycle but further work will be necessary to determine the reality of this effect. Likewise, the geographical division of the data suggests a maximum influence of the synodical cycle in the midwestern or central portions of the United States. A study of the phase information in Fig. 7 does not suggest a regular movement of a wave pattern across the United States. Although some constancy of phase or consistency is shown, Fig. 6 indicates that a lot of noise or unexplained variation remains. For example, the curve for zone 4 contains the data for Boston, but it does not bear a very close resemblance to the curve for Boston shown in Fig. 12.

The difference in the amplitude of the cycle during various phases of the solar activity suggests another possible modifying influence. The results presented in Fig. 9 suggest that the relationship between rainfall and the synodic cycle is dependent upon the moon's position relative to its nodes, since the amplitude of the synodic "effect" is several times greater when the moon is near the plane of the ecliptic than when it is farther. This is not entirely unreasonable physically, since it is known that the tidal forces on the earth and its atmosphere are enhanced slightly at the time of new moon or full moon when the moon is near its nodes. Further study of effects

---

[2] The major rainfall peak shown on the 17th day of the lunar month in Fig. 13 suggests an interesting coincidence, for it is written that "in the second month, the seventeenth day of the month, the same day were all the fountains of the deep broken up, and the windows of heaven were opened. And the rain was upon the earth forty days and forty nights." [*Genesis* 7: 11–12].

of this type is needed and methods are being developed to examine the data for complex and non-linear effects. If it is found that a lunar effect on precipitation is not constant in time (or space), but is being modulated by other factors, then it obviously follows that the statistics presented here tend to underestimate the true magnitude of the lunar factor.

Acknowledgment. The authors are grateful to Thomas H. Carpenter and William Kiser for their assistance, especially in connection with the computer programs. Thanks are due to Dr. Max A. Woodbury for his interest and support.

REFERENCES

Berson, F. A., and E. L. Deacon, 1963: Heavy rainfalls and the lunar cycle. In press.

Bradley, D. A., M. A. Woodbury and G. W. Brier, 1962: Lunar synodical period and widespread precipitation. *Science*, **137**, 748–749.

Brier, G. W., 1964: Techniques for data analysis. *Proceedings of the Symposium on Environmental Measurements*, Robert A. Taft Sanitary Engineering Center, Cincinnati, in press.

Carpenter, T. H., 1962: *Decimal ephemeris of sun and moon 1870–1962.* U. S. Weather Bureau, Washington, D. C.

Fielding, H., 1748: *The history of Tom Jones.* London, J. M. Dent and Sons, Ltd., 885 pp.

Gilman, D. L., F. J. Fuglister and J. M. Mitchell, Jr., 1963: On the power spectrum of "red noise." *J. atmos. Sci.*, **20**, 182–184.

Howell, W. E., 1960: A comparison between two transformations used in normalizing meteorological data. *J. Meteor.*, **18**, 242–246.

Jennings, A. H., 1952: Maximum 24-hour precipitation in the United States. *U. S. Weather Bureau Technical Paper No. 16*, 284 pp.