DIURNAL AND SEMIDIURNAL ATMOSPHERIC TIDES IN RELATION TO PRECIPITATION VARIATIONS [1]

GLENN W. BRIER

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

ABSTRACT

Evidence is presented that precipitation variations in the United States are related to the solar and lunar tidal forces. The results of the statistical investigation are consistent with a mathematical model that shows how a small periodic influence can be of possible importance for the timing of an event such as the initiation of precipitation.

1. INTRODUCTION

The atmosphere undergoes some regular oscillations which are due to the gravitational effects of the moon and the combined gravitational and thermal effects of the sun. It is conventional to call these motions "tides" and to denote by S_n and L_n, respectively, the oscillation whose period is the nth part of the solar day (24 solar hours) and the nth part of the lunar day (24.87 solar hours). These tides have been studied by Chapman [4] and others. Recently Haurwitz [5] has reviewed the present state of our knowledge regarding these phenomena. In the variation of surface pressure, S_2 appears dominant as a 12-hr. oscillation on tropical barograph traces while S_1, the 24-hr. wave, generally has an amplitude about half that of S_2, with a much less regular distribution over the globe. The other surface pressure oscillations S_3, S_4, . . . L_1, L_2, . . . are smaller and are considered of no practical significance.

Although the effect of the moon on surface pressure is small, the phase and amplitude of L_2, the larger oscillation, have been determined by statistical treatment of extensive data by Chapman [4] and others. The prevailing view in meteorology has been that on such weather elements as precipitation, appreciable lunar effects were neither likely nor detectable. Recently, however, brief reports by Bradley, Woodbury, and Brier [2] and Adderley and Bowen [1], in which a statistically significant association was found between the lunar synodic period of 29.53 days, and precipitation in the United States and New Zealand, raised some questions about the possibility of detecting lunar tidal effects in precipitation. A more detailed report by Brier and Bradley [3] presented additional evidence and the suggestion that some of the other lunar periods entering into tidal theory might be important in describing or explaining the lunar-precipitation relationship. Although our knowledge of the physical processes of precipitation is not complete enough to formulate a theory to include tidal effects, at least it seemed desirable to have a general physical framework that might assist in the interpretation of the precipitation. Since it is not possible to distinguish between effects that might be due to thermal, gravitational, or other causes, this paper considers all or any of these effects as tidal which relate to the geometry of the situation, i.e., to the positions of the sun, earth, and moon. This general tidal theory provided some guidelines for performing specific statistical tests on precipitation data which are reported here with no attempt to select only those portions of the results which were "positive" or favorable (or unfavorable) to some specific hypothesis or preconceived idea.

[1] This work is closely related to the New York University project "Extraterrestrial Correlations with Meteorological Parameters" supported by the Atmospheric Sciences Program, National Science Foundation.

2. ANALYSIS AND RESULTS

SYNODIC, ANOMALISTIC, AND NODICAL CYCLES

The tidal forces acting on the earth are at a maximum at syzygy, the event of a new moon or full moon, since the moon and the sun are then in line and pulling together. The tides are further enhanced at this time if the moon is on the plane of the ecliptic and is nearest the earth in its orbit (at perigee). This precise line-up does not happen often because of the differences in the astronomical periods involved. The average length of the synodic cycle (from new moon to new moon) is 29.53 days while the anomalistic cycle (from perigee to perigee) is 27.55 days. The nodical cycle, the time it takes the moon to cross the plane of the ecliptic from north to south until it repeats, is 27.21 days. During the period 1900–1962 there were 61 instances when either new or full moon occurred within two days of perigee and within two days of crossing the plane of the ecliptic. Now if the basic cause of the reported period in United States precipitation data, 1/2 (29.53) = 14.765 days, is tidal in nature, the amplitude of this oscillation should have been greater at those 61 times, denoted here as D_0, than at the remaining

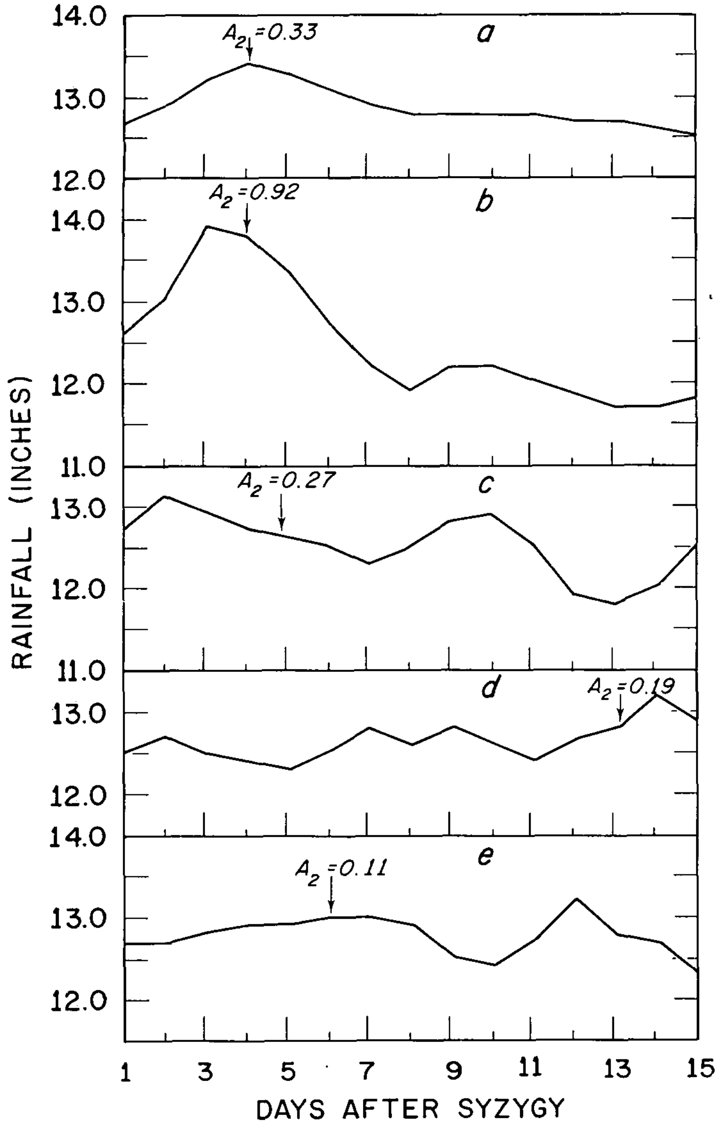

FIGURE 1.—Sixty-three years of daily total precipitation data for 150 stations in the United States summarized according to the 15 days following new or full moon. A_2 is the amplitude of the fitted 14.765-day wave and the arrows show the time of maximum. Curve (a) refers to all the data (779 synodic months). Curve (b) is for the 61 synodic months ending on D_o and 61 synodic months beginning on D_o, where D_o is the syzygy with maximum tidal force. Curve (c) is for 122 synodic months removed from D_o by 30 days, and curve (d) is for 122 synodic months removed from D_o by 59 days. Curve (e) is for 122 synodic months removed from D_o by 89 days.

times. Daily indices of the total precipitation over the United States were available for the period 1900 to 1962 and were summarized by synodic months according to how close the month came to the day D_o. The curve (a) of figure 1 shows for all the data the mean variation in rainfall during the 15 days following syzygy. This is essentially the same figure presented by Brier and Bradley [3] and was shown by them to contain a highly significant periodic component of 14.765 days. Curve (b) shows that the largest contribution to the amplitude and phase

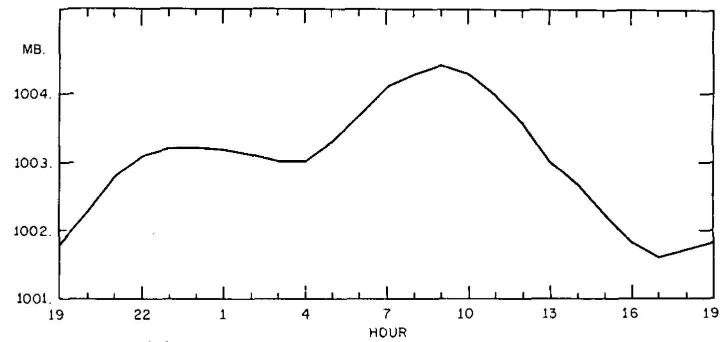

FIGURE 2.—Normal station pressure for May (1931–1940) for Raleigh, N.C., 75th meridian time. (From [9].)

of this cycle comes from the periods of increased tidal forces which are near D_o. The amplitude A_2=0.92 is about four times as great as that for the remaining cases. Curves (c) and (e) show that as the anomalistic and nodical cycles get out of "step" with the synodic cycle, the pattern shown in curves (a) and (b) becomes less distinct and less meaningful.

SYNODIC CYCLE IN RELATION TO THE SOLAR AND LUNAR DAYS

These results and those reported previously have led to the suggestion that the lunar tidal oscillations (L_1 or L_2) might be modulating or amplifying the solar (S_1 or S_2) oscillations. It is quite clear, for example, that L_2 and S_2 are in phase with each other twice every synodic month, though we may be quite ignorant of the physical details or explanation for either or both of these oscillations and their interactions. The S_1 and S_2 tides have been studied extensively for surface pressure data and taken together account for most of the mean daily surface pressure variation. A typical curve of the daily pressure variation for a station in the United States is shown by figure 2, selected from [9]. From curves such as this, one might attempt to infer for individual stations the mean daily variation of vertical motions presumably related to precipitation processes. However, a more realistic index of the mean daily variation of vertical motion might be obtained from the precipitation data, at least to the extent of determining the time of the day most favorable for precipitation occurrence. The S_1 and S_2 oscillations in precipitation are often quite pronounced but differ widely according to season, topography, etc. Numerous climatological studies of these variations have been made, both for individual stations and the country as a whole. Maps of the United States showing geographical and seasonal variations have been published by the U.S. Weather Bureau [10] and figure 3 reproduced here is from that source.

For the purpose of the investigation reported here it seemed desirable to use hourly summaries and to obtain a nationwide average on an annual basis to make the data comparable to the national curves shown in figure 1.

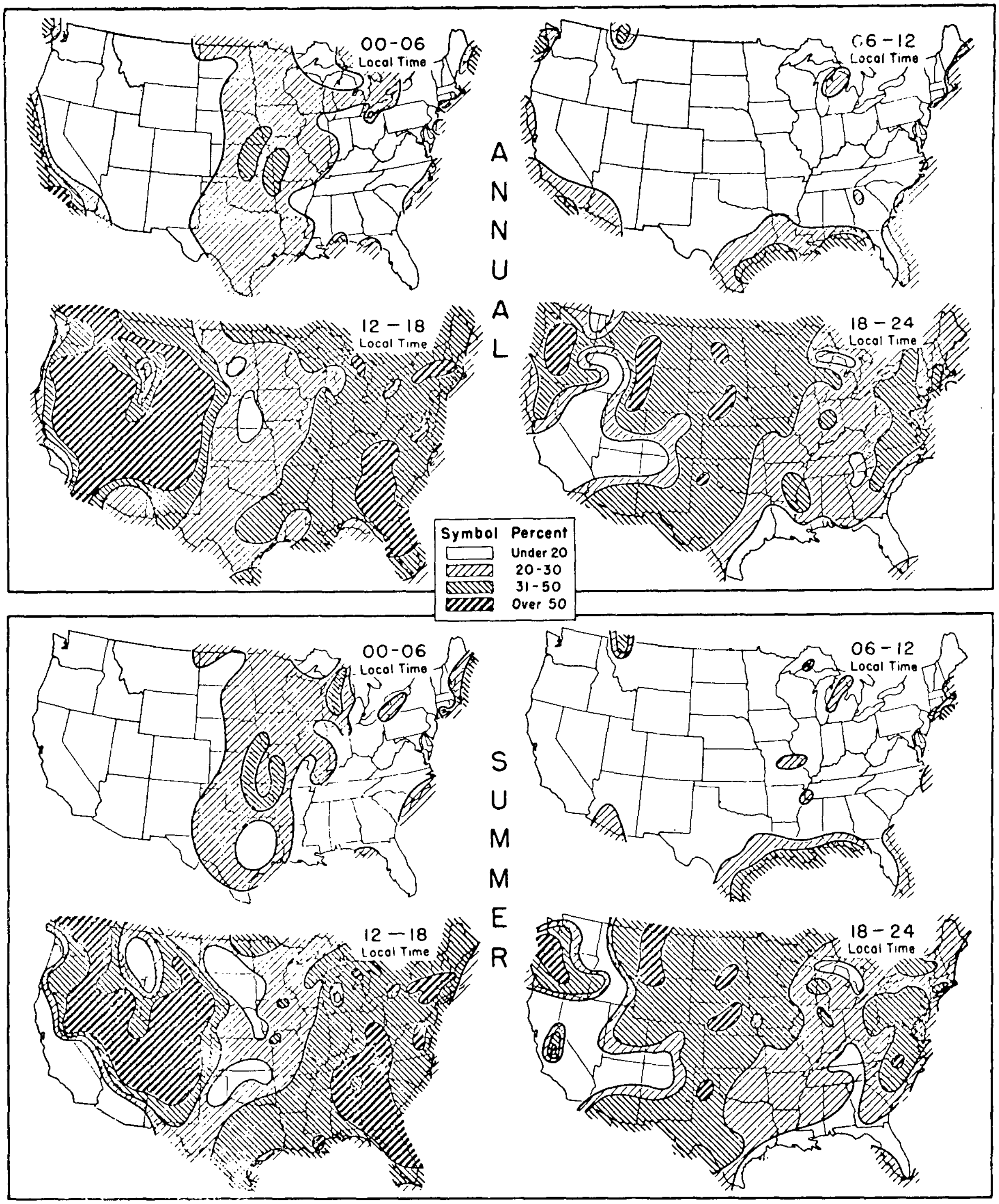

FIGURE 3.—Percentages of excessive rain occurrences per quarter day, 1904–1933. (From [10].)

This was accomplished by using annual summary tables of precipitation frequencies found in [7]. Table 1 shows an example of these data for Minneapolis, Minn. The 67 stations available were combined to obtain an estimate of the frequency of occurrence of precipitation amounts of 0.01 in. or greater according to the hour of the day. The results are shown in curve (a) of figure 4. The peak around 5:00 p.m. is not unexpected and is probably associated with the convection of late afternoon. However, the major peak is around 3:00 a.m. and appears to be not so well understood. It may be associated with the area of maximum convergence in the north central United States during the early morning hours reported by Hering and Borden [6]. In any case, the semidiurnal oscillation S_2 is clearly indicated, the phase of the fitted wave being shown by the arrows.

TABLE 1.—*Example of data used to determine a nationwide estimate of hourly precipitation frequency. Occurrences are for the average year (10-yr. total divided by 10). Values are rounded to the nearest whole number, but not adjusted to make their sums exactly equal to column or row totals. "+" indicates more than 0 but less than 0.5.*

Intensities (in.)	Frequency of occurrence for each hour of the day																								No. of days with
	a.m. hour ending at												p.m. hour ending at												
	1	2	3	4	5	6	7	8	9	10	11	noon	1	2	3	4	5	6	7	8	9	10	11	mid.	
Trace	36	38	39	43	41	41	46	48	48	45	42	43	45	42	41	40	36	33	35	38	35	35	34	37	80
.01	8	7	8	7	9	11	8	9	7	9	10	9	5	6	7	8	8	8	7	6	10	9	9	8	16
.02 to .09	10	10	9	10	10	10	11	10	11	9	10	8	9	10	9	9	9	11	8	9	8	8	9	11	39
.10 to .24	2	3	3	2	2	2	2	2	2	2	1	1	1	2	2	1	1	2	2	1	2	3	3	2	23
.25 to .49	1	1	1	1	+	+	+	1	+	1	+	+	+	+	+	1	+	1	1	1	1	+	1	1	17
.50 to .99	+	+	+	----	+	----	+	+	+	----	+	+	+	+	----	+	+	----	+	+	+	1	+	------	10
1.00 to 1.99	----	----	----	----	----	----	----	----	----	----	----	+	----	----	----	----	----	----	+	----	----	+	----	------	4
2.00 and over	----	----	----	----	----	----	----	----	----	----	----	------	----	----	----	----	----	----	----	----	----	----	+	------	1
Total	57	59	60	62	62	65	67	70	68	65	63	62	60	60	60	59	54	53	54	56	56	55	55	59	190

The lower curve of figure 4 is reproduced from Brier and Bradley [3] and shows the *daily* rainfall for the United States plotted as a function of phase of the moon (synodic decimal). This time scale can be related to the solar day time scale at the top by means of tidal theory. It is known that the maximum tidal force occurs when the moon is overhead, but actual pressure observations show that the "high tide" in the atmosphere occurs about 1 hr. after lunar transit. This means that on the day of the new moon the highest tide should occur at 1:00 p.m. and about 50 min. later on each succeeding day. Thus, about 15 days later, at full moon, the highest tide should occur about 1:00 a.m. This relationship was used to fix the solar day time scale to the synodic month time scale in figure 4. Examining curve (b), one can see that the precipitation peak falling a few days after the full moon corresponds to the time of the synodic month when the moon is overhead at around 3:00 a.m., when conditions are most favorable for precipitation. There is another peak a few days after new moon, corresponding to the time of the synodic month, when the moon is overhead near the time most favorable for precipitation in the late afternoon. The arrow on curve (b) shows that the time of the maximum of the fitted 14.765 day wave is at synodic decimal 0.17 (and 0.67) which is exactly the same as the phase determined for curve (a). The agreement between the two curves could be fortuitous but the chance is only 1 in 50 that unrelated phenomena or random data would give such a good agreement in phase.

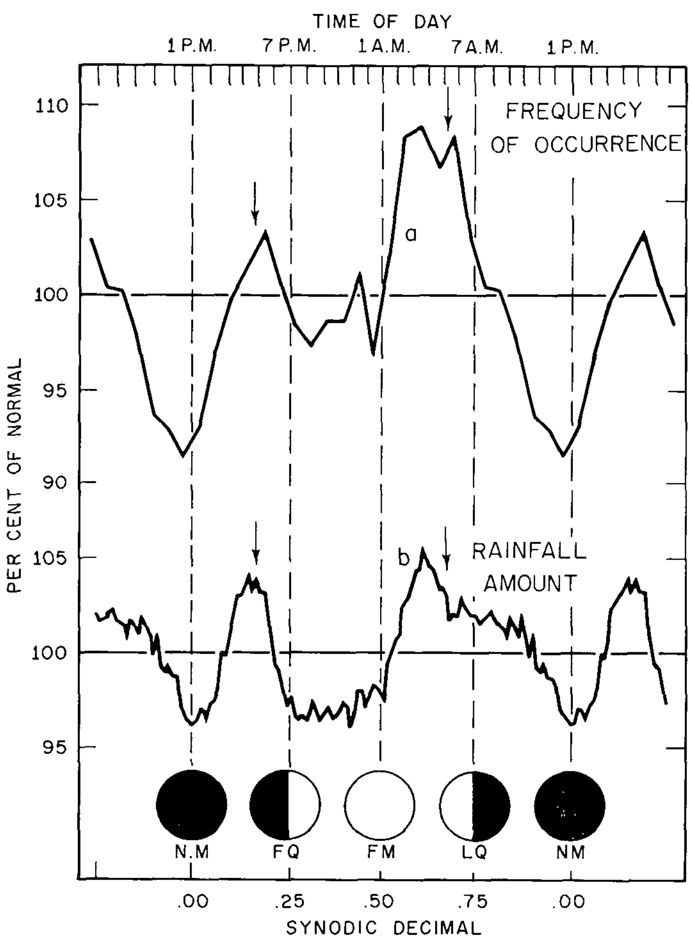

FIGURE 4.—Precipitation in the United States. Curve (a) shows for a network of 67 stations, the relative frequency of precipitation occurrence by hour of the solar day. Curve (b) shows the average daily rainfall (1900–1962) for 150 stations in the United States according to the time of the synodic month. The relation between the upper and lower time scales is fixed by tidal theory and observations of surface pressure, independent of the precipitation data.

L_2 OSCILLATION IN HIGH RAINFALL RATES

The preceding results led to consideration of the possibility of detecting the lunar tidal oscillation L_2 in hourly precipitation data. The smallness of these components in surface pressure tends to argue against this possibility and an extensive statistical analysis of hourly precipitation data for a large number of stations did not appear practicable at this time. However, from 1900 to 1920 the U.S. Weather Bureau [8] published the date and time of beginning of all occasions of excessive amounts of precipitation falling in 1 hr. or less for all stations in the United States furnished with self-registering gages. These records seemed suitable for statistical analysis. For each calendar month a selection was made of the three stations reporting the highest totals of precipitation for the storm period during which the excessive rate was measured. There was the further requirement that no two events could be selected on the same day. No geographic stratifi-

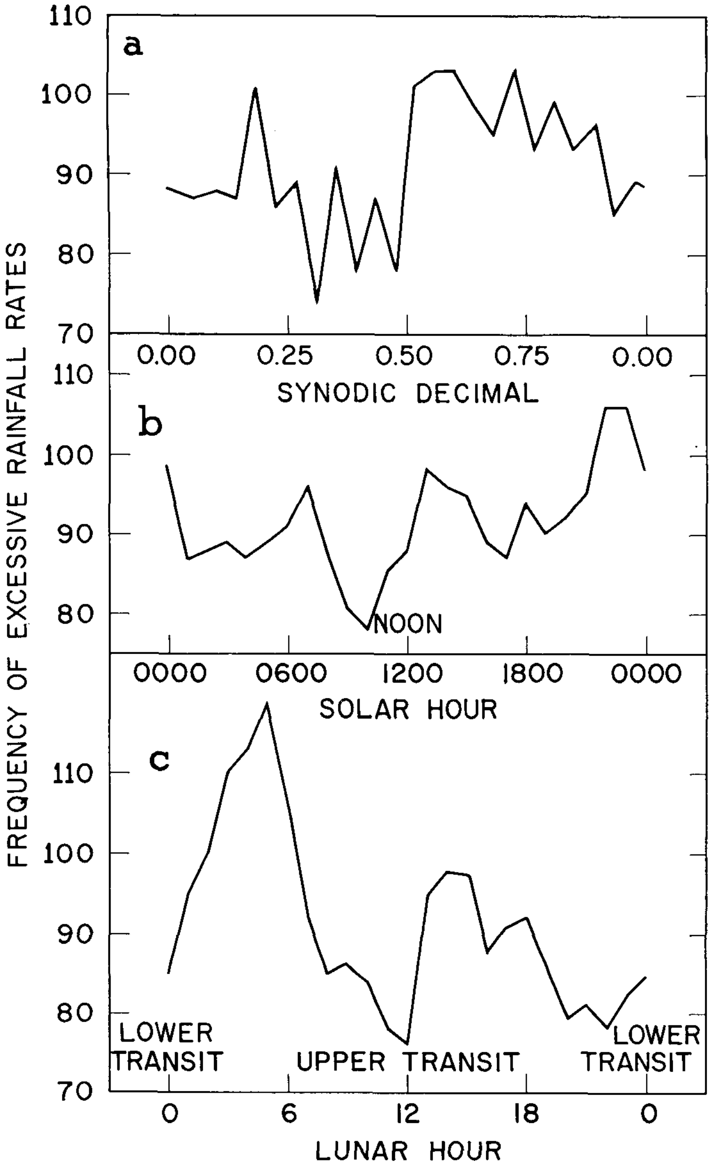

FIGURE 5.—The variation in the relative frequency of excessive amounts of precipitation falling in a period of 1 hr. or less according to: (a) the day of the synodic month, (b) the local standard time at which the excessive rate began, and (c) the time at which the excessive rate began in respect to the lunar day. Data comprise a selection for each month from 1900 to 1920 of the three first-order Weather Bureau stations reporting the highest totals of storm precipitation.

cation was attempted although the method of selection would tend to favor stations with high rainfall and stations in those parts of the country where precipitation falls in the form of rain instead of snow. However, the selection was completely objective, with no bias toward any lunar time scale. These events were then summarized according to (a) the synodic month, (b) the hour of the solar day, and (c) the hour of the lunar day.

The results are shown in the three curves of figure 5. Curve (a) shows the maximum peak in frequency of occurrence of high rainfall rates a few days after the full moon and is consistent with the results of Bradley et al.

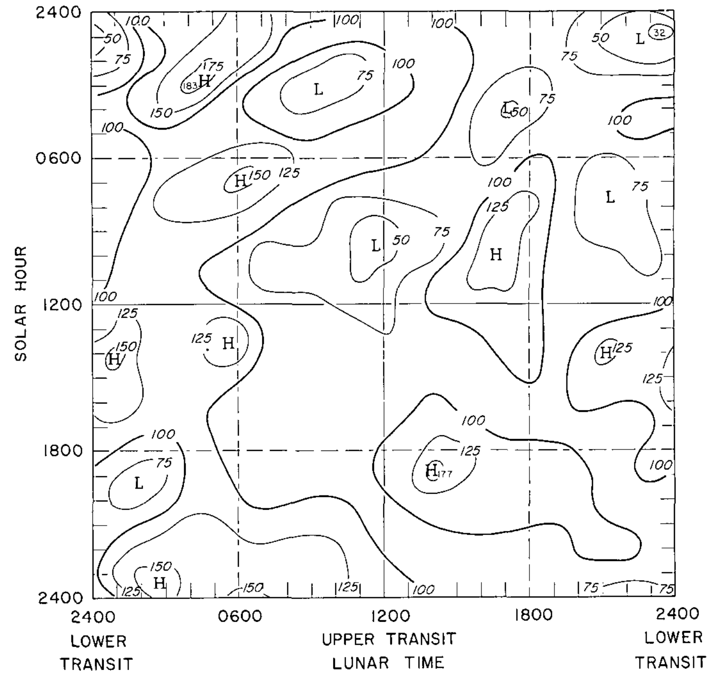

FIGURE 6.—The variation in the relative frequency of excessive amounts of precipitation falling in a period of 1 hr. or less and plotted as a function of the solar hour and lunar hour. Lunar hour 24 refers to lower transit position of the moon and lunar hour 12 to the upper transit position. Data used were the same as in figure 5.

[2]. Curve (b) shows no significant component for either S_1 or S_2 but this is not surprising in view of the averaging that has taken place and the wide variation in the United States of the phase and amplitude of the S_1 and S_2 oscillation in precipitation. The unexpected result was the magnitude and significance of the L_2 oscillation shown in curve (c). This component is highly significant ($p=0.01$), accounting for 34 percent of the variance in the unsmoothed curve, while the L_1 component accounts for only 12 percent and is not significant. The greatest frequency of excessive rates of precipitation is shown at 5 hr. after lower lunar transit with a secondary peak 2 hr. after upper transit. No explanation is available as to why the greatest rates of precipitation should occur a few hours after the tidal forces reach a maximum but theoretical studies and further statistical investigation might provide some additional insight.

Figure 6 shows the result of one study that was made to obtain an estimate of the importance of the solar-lunar hour interactions. The highest peak on this graph is at 3:00 a.m., 4 hr. after lower lunar transit. The second highest peak is about 7:00 p.m., 2 hr. after upper lunar transit. On this chart there is a range of about six fold (from 32 to 183) in the relative frequency of precipitation events in spite of the rather severe smoothing that was used which would reduce the true amplitude of any solar-lunar effect. Thus, there is a strong indication that solar hour and lunar hour should be considered jointly or in combination.

3. A POSSIBLE INTERPRETATION

As pointed out recently by Haurwitz [5], it is known that at the earth's surface the lunar atmospheric tide L_2 is about $\frac{1}{15}$ the size of the solar atmospheric tide S_2. The smallness of this as well as of other known extraterrestrial forces has led many to conclude that no appreciable weather effects are likely as a result of such lunar or solar variations since the forces involved in the day-to-day weather changes are so much greater in magnitude. Some proponents of extraterrestrial effects have made vague suggestions of "trigger" effects, but usually no detailed physical mechanisms have been described to show how the small amounts of energy in the "trigger" could be amplified to produce large effects. No attempt will be made to resolve this controversy here but it does seem possible to propose a very simple mathematical model to show how relatively small influences can be reflected in the statistics of geophysical or other natural phenomena.

Let us assume that a system changes from one state to another when some limiting influence or force F reaches a threshold or critical level F_c. This is illustrated by the solid sloping line in figure 7 where the change in state takes place at time t_1 when the increasing force F reaches the critical value F_c. An example from hydrodynamics is the transition from laminar to turbulent flow in a pipe when a critical Reynolds number is reached. An example from biology is the transition of an organism from the living state to the dead, in response to a continuous increase in the level of a toxin in the blood. Similarly, in the atmosphere we may suppose that a change from "no rain" to "rain" takes place when a limiting factor in the precipitation process reaches a certain critical value.

From figure 7, it is clear that if some small-amplitude periodic function f is added to F to produce the resultant shown by the dashed line, the time at which the change of state takes place becomes t_2 instead of t_1. The time difference t_2-t_1 depends upon the phase of the periodic force f, which in the long run can be considered random with respect to t_1. If the double amplitude (total range) of f in a given period of time is given by Δf and we assume that F is changing very nearly linearly as it approaches F_c, then the influence of f on the timing of the change in state depends upon Δf relative to dF/dt, the rate of change of F. The larger Δf is and the smaller dF/dt is, the greater is the influence of f on the exact timing of event E, the change of state. In respect to the exact timing of E it is interesting to note that the absolute magnitude of F is not involved or even the relative intensity f/F. The important factor is Δf, the total range in f, relative to the rate of change of F.

The argument is placed on a quantitative basis by a simple numerical experiment summarized in figure 8.[2] In

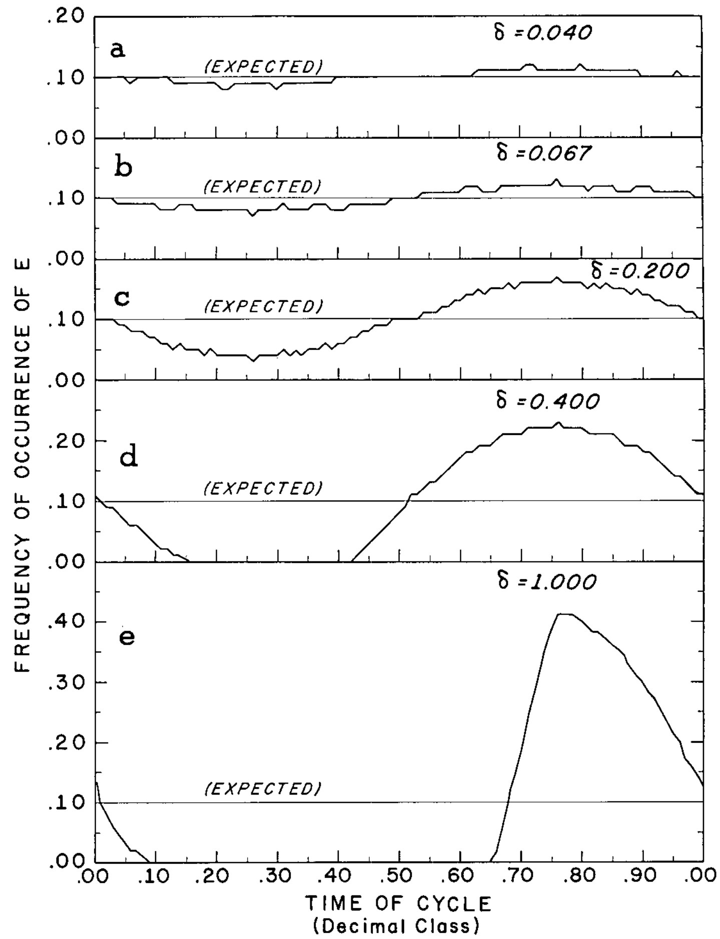

FIGURE 7.—How the time reaching a critical level F_c can be changed by the superposition of a periodic force f on a force F which is changing slowly with time.

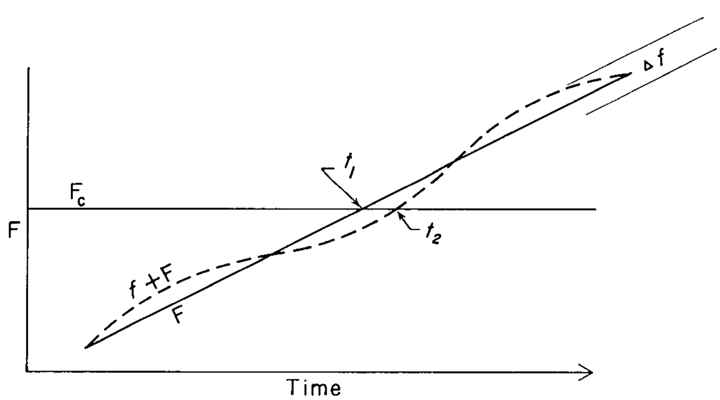

FIGURE 8.—Distribution showing relative frequency of occurrence of E (change in state) according to the decimal class of period T. Curves (a) to (e) are for various ratios $\delta=\Delta f/\Delta F$ where Δf is the total range in a cosine wave of period T and ΔF is the total change during the period T of the linearly increasing function F.

this experiment f was represented by a cosine wave ($\Delta f=2$) with a period of 100 units of time and the slope dF/dt was permitted to vary over a large range. The curves plotted are for various values of ratio $\delta=\Delta f/\Delta F$ where ΔF is the total change in the linear function F

---

[2] I wish to thank E. N. Lorenz for pointing out that the same results can be obtained analytically. With δ sufficiently small, the combined curve $F+f$ has no negative slope and thus the probability of the event is simply proportional to the slope of $F+f$, forming a sine curve. For large δ the probability is obviously zero for some phases of f and proportional to $F+f$ for the remaining phases.

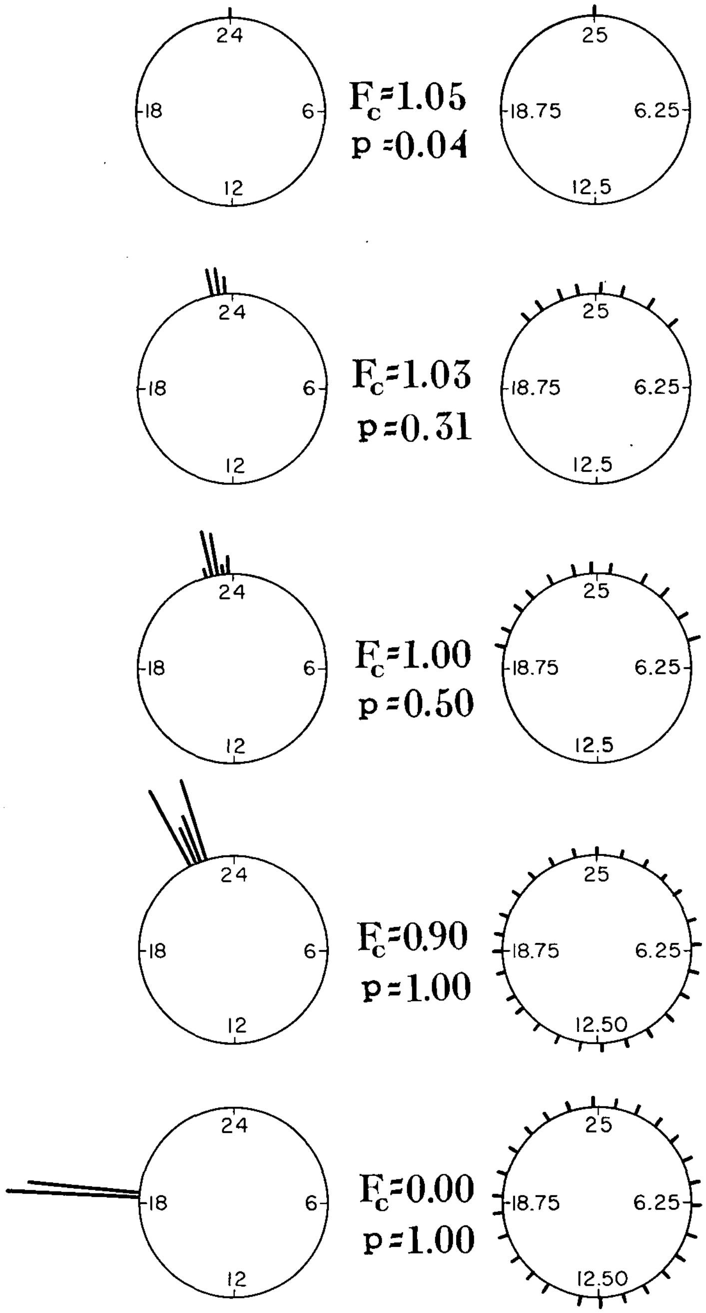

FIGURE 9.—Distribution of events E in respect to the phase of a 24-hr. and 25-hr. cosine wave with amplitudes 1.00 and 0.05 respectively. Events E are defined as the time when the critical level F_c is first equalled or exceeded and the length of the bars on the "clock" dials indicate the relative frequency of these events as F_c varies from 1.05 to 0.00.

during an interval of 100 units of time, the length of period of the cosine wave. Curve (a) is for the case when f has a total range of 1/25th of the change of F in the period and shows the expected distribution of events E according to the time of the periodic function which reaches its maximum at 0.

The expected frequency is 0.10 since in computing these curves the frequency counts were smoothed by using 10-unit moving totals for the 100 classes involved. Thus, if the periodic function f has no influence, one would expect to find 1/10th of all events E in any interval of time which is 1/10th of the total period T of the cosine wave. Curve (a) shows variations that range from about 30 percent below to 30 percent above expectation. For $\delta=0.20$ the variations from expectation are as great as $\pm$ 70 percent. It will be noticed that the maximum frequency of events E comes between 0.70 and 0.80, as expected, because this is the point during the cycle when f is increasing in magnitude most rapidly.

An obvious extension can easily be made to the case when both F and f are periodic with periods T and τ and amplitudes A and a respectively. A proper choice of F_c (producing sufficiently rare events) will result in a systematic distribution of events E in respect to the phase of cycles T and τ which will be practically independent of the amplitudes A and a. In other words, the time of occurrence of event E will depend jointly on the phases of cycles T and τ and not on the relative amplitude A/a

This is illustrated in figure 9 where T and τ were chosen as 24 hr. and 25 hr., respectively, with $A=1.00$ and $a=0.05$. When $F_c=1.05$, event E occurs only one day out of 25 ($p=0.04$) and the timing of this event, as shown by the two clocks, is as much determined by the phase of the 25-hr. wave as by the phase of the 24-hr. wave. As F_c approaches zero, the relative influence of the 25-hr. wave decreases and the phase of the 24-hr. wave becomes dominant.

It is not necessary, of course, for the superposed force f to be sinusoidal, or for that matter to be either periodic or continuous. For example, one might have discrete impulses such as might be produced in atmospheric processes by the sudden influx of solar particles or by an attempt by man to modify the weather by seeding clouds. In regard to the possible influences of such quantities on the *timing* of weather events that involve a change in state, it appears that the relevant factor is the magnitude of the time variation of those impulses or forces in relation to the rate of change of the other forces existing when critical levels are being approached. In the context of this paper, which is concerned with examining the evidence relating lunar tides to precipitation, it is suggested that since the lunar tides represent real physical forces it is reasonable to expect them to *affect the time that rainfall begins* when conditions otherwise become favorable for rainfall. This is quite different, of course, from contending that lunar tides *cause* precipitation in a direct manner.

4. SUMMARY AND CONCLUSIONS

In examining tidal theory as a possible general physical framework to assist in the interpretation of the association found between precipitation and the lunar synodic month, three separate lines of evidence have been presented.

The first of these is concerned with the stratification of 63 years of daily precipitation data for the United States according to the magnitude of the tidal forces. Theory predicts that maximum effects should be observed at the time of syzygy when the moon is at perigee and on the plane of the ecliptic. This involves the synodic, anomalistic, and nodical periods of the moon which enter into tidal theory. The precipitation data show that the 14.765-day cycle has its maximum amplitude during the periods when these "ideal" conditions prevail. At these times the average amount of precipitation over the United States was 20 percent higher two days after syzygy than it was two days before. These results suggest that it might be profitable to determine the vertical and horizontal tidal forces on a daily or hourly basis for a long period of time and study them in relation to precipitation.

The second type of evidence has to do with the interaction between the lunar tides L_1 and L_2 and the solar tidal oscillations S_1 and S_2. The lunar and solar oscillations are in phase with each other every 14.765 days (twice a synodic month); therefore, one might expect that peak precipitation would occur on those days when the lunar tides are at a maximum at the time of the solar day most favorable for precipitation. Climatological data show that for the country as a whole, the most favorable time for precipitation is about 3:00 a.m. solar time and that the second most favorable time is about 5:00 p.m. The 63 years of daily precipitation data for the United States show that the maximum precipitation occurs on those days of the synodic month when upper lunar transit occurs shortly before 3:00 a.m. and shortly before 5:00 p.m. Since the L_1 and L_2 oscillations depend upon latitude (as well as other factors) and the S_1 and S_2 oscillations in precipitation vary widely over the earth and from season to season, it follows that different stations or geographical areas might show considerably different patterns of the distribution of daily rainfall during the synodic month. Investigators should be extremely cautious in extrapolating the average results for the United States to other areas or to individual stations.

The final bit of evidence presented here is the lunar L_2 oscillation in the hourly data for excessive rates of precipitation and the interaction of the lunar hour with the solar hour. Whether or not L_2 is detectable in other hourly rainfall data is yet to be determined. It may be that L_2 is important in the precipitation processes only when all other conditions are favorable to rainfall, and that tidal forces affect the timing of the precipitation by triggering some instability, thus making it unnecessary to invoke new or little-understood complex physical mechanisms involving such things as meteoritic dust, for example.[3] A colleague has suggested that ". . . with the lunar semidiurnal pressure oscillation well established, and the temperature oscillation and the oscillation in the wind that should accompany this found, an effect of the moon on precipitation should probably be expected." The mathematical model and numerical example discussed in section 3 suggest that relatively small periodic influences can produce real and detectable variations in frequency data of this type.

Although all of the foregoing evidence is consistent with general tidal theory and the deductive arguments of section 3, it cannot be concluded that gravitational tidal forces are the actual causes of the phenomena. The important variables in the tidal equations are the distances to the sun and the moon and their zenith angles. These same variables are important in other physical models that might be examined. Although it may be difficult to discover the exact physical mechanisms responsible for the lunar-precipitation relationship, tidal theory has provided a convenient framework to synthesize some of the observations and has led to further investigations from which it appears that additional clues have been obtained.

[3] This is not intended to imply that processes such as the lunar modulation of freezing nuclei counts, for example, should be excluded from consideration.

ACKNOWLEDGMENTS

I am grateful to Thomas H. Carpenter and Willian Kiser for their assistance, especially in connection with the computer programs and to Miles Harris and Donald Bradley for many stimulating and valuable discussions.

REFERENCES

1. E. E. Adderley and E. G. Bowen, "Lunar Component in Precipitation Data," *Science*, vol. 137, No. 3522, Sept. 7, 1962, pp. 749–750.
2. D. A. Bradley, M. A. Woodbury, and G. W. Brier, "Lunar Synodical Period and Widespread Precipitation," *Science*, vol. 137, No. 3522, Sept. 7, 1962, pp. 748–749.
3. G. W. Brier and D. A. Bradley, "The Lunar Synodical Period and Precipitation in the United States," *Journal of the Atmospheric Sciences*, vol. 21, No. 4, July 1964, pp. 386–395.
4. S. Chapman, "Atmospheric Tides and Oscillations," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 510–530.
5. B. Haurwitz, "Atmospheric Tides," *Science*, vol. 144, No. 3625, June 19, 1964, pp. 1415–1422.
6. W. S. Hering and T. R. Borden, Jr., "Diurnal Variations in the Summer Wind Field over the Central United States," *Journal of the Atmospheric Sciences*, vol. 19, No. 1, Jan. 1962, pp. 81–86.
7. U.S. Weather Bureau, *Climatography of the United States* No. 82, "Decennial Census of United States Climate—Summary of Hourly Observations," (by stations), 1962–1963.
8. U.S. Weather Bureau, *Monthly Weather Review*, vols. 28–48, 1900–1920.
9. U.S. Weather Bureau, "Ten-Year Normals of Pressure Tendencies and Hourly Station Pressures for the United States," *Technical Paper* No. 1, Washington, D.C. 1943.
10. U.S. Weather Bureau, "Thunderstorm Rainfall," *Hydrometeorological Report* No. 5, in cooperation with the Engineering Dept., Corps of Engineers, Washington, D.C. 1947.

[*Received May 20, 1964; revised September 28, 1964*]