SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 101, NUMBER 1

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CITY OF WASHINGTON
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I wish to present evidence that, though small in percentage, the variation of the sun's output of radiation is an effective weather element.

THE VARIATION OF THE SUN

In other papers I have described the means used since 1902 by Smithsonian observers to measure the energy contained in solar radiation, to estimate the losses which the solar beam suffers in traversing the atmosphere, and to evaluate the "solar constant of radiation." The solar constant may be defined as the average intensity of solar radiation in free space at mean distance of the earth from the sun. Expressed in heat units its value is about 1.94 calories per square centimeter per minute.

By many thousands of determinations, Smithsonian observers have found that the solar constant changes from day to day and from month to month around its mean value. The extreme range of these excursions thus far observed is 5½ percent. Monthly mean values since 1920 have an extreme range from 1.91 to 1.96 calories or 2½ percent. Superposed on these fluctuations of monthly means are departures of a few days in length dependent to a great extent on the rotation of the sun. These short-interval changes, superposed on the changes indicated by monthly mean values, widen the extreme limits of solar variation to those given above as 5½ percent.

The Smithsonian Institution operates several desert mountain solar-observing stations. Two of these, long occupied, are Table Mountain, Calif. (prior to 1926 at Harqua Hala, Ariz.), and Montezuma, Chile. These stations are at elevations of 7,500 and 9,000 feet, respectively. About 80 percent of all the days of the year are nearly cloudless at these stations, though not always of first-rate quality for solar-constant work.

Figure 1 gives the march of the monthly means of the solar constants from (A) combined results of Harqua Hala and Table Mountain, and (B) from Montezuma. The curves cover the years 1920 to 1939.

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The preparation of figure 1 was delayed in order to use later results of the revision of solar-constant values. Individual daily values, however, will still be under consideration and revision for several more months, so that even the curves shown in figure 1 are not final. Yet they are improved and differing somewhat from those shown in figure 8, which was prepared at an earlier stage of the revision.

Figure 1 employs revised Montezuma data, beginning with September 1923, and revised Table Mountain data, beginning with December 1925. Montezuma data from August 1920 to August 1923 are taken from table 31 of volume 5 of the Annals of the Astrophysical Observatory.

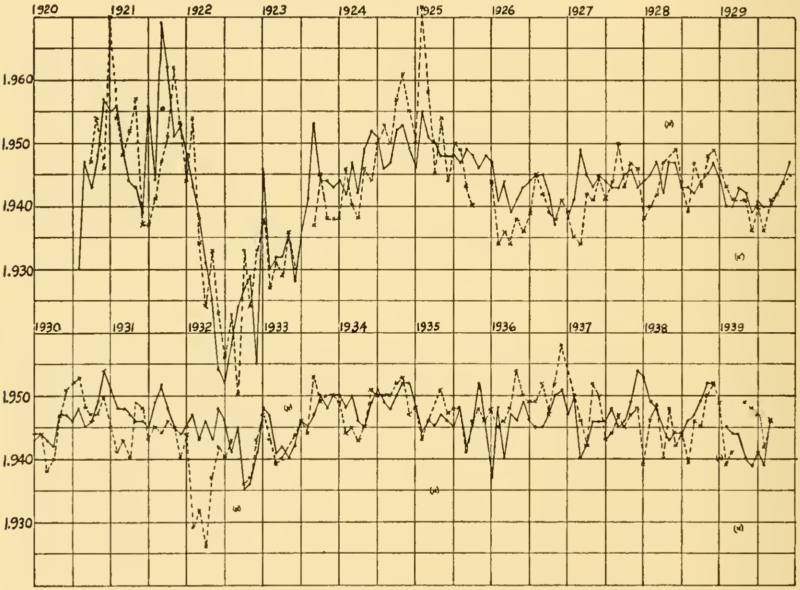

FIG. 1.—Solar constant monthly means. Dotted curve North America, full curve South America.

The Harqua Hala data employed in figure 1 are not fully satisfactory. They are derived as follows. Table 29-a of volume 5 of the Annals gives daily "long-method" Harqua Hala solar constants, from which monthly mean values were computed. The resulting monthly means, when compared with simultaneous Montezuma "short-method" data given in table 31 of volume 5 of the Annals, indicate an average deficiency of 0.004 calorie in scale for the Harqua Hala "long-method" data. Referring to table 1 of my paper "Provisional Solar Constant

Values,"[1] the monthly mean "short-method" Harqua Hala values were recomputed from October 1920 to November 1924. Daily values marked "U" were omitted from the means. Upon comparing these monthly "short-method" means with the simultaneous monthly "long-method" means from table 29-a of volume 5 of the Annals, there seemed to be no marked difference in scale up to December 1922, but thereafter there was found to be an average deficiency in the "short-method" monthly means of 0.008 calorie up to January 1924, and of 0.023 calorie, February 1924 to October 1925. It is not possible now, without a very tedious and thorough examination of the original records to detect the cause of this change of scale, but an allowance was made, as follows.

The "short-method" daily values are much more numerous than the "long-method" ones, and are also regarded as less subject to accidental errors. Hence, I preferred to use them for figure 1. Taking account of the discrepancies of scale just mentioned, the Harqua Hala results plotted in figure 1 are based on the "short-method" daily values, but are reduced to the Montezuma scale by adding 0.004 calorie for the interval October 1920 to December 1922, and 0.004+0.008=0.012 calorie from January 1923 to January 1924. From February 1924 to October 1925 there was added 0.004+0.023=0.027 calorie.

The interval December 1924 to December 1925, at which latter month the revised Table Mountain values begin, is not covered in "Provisional Solar Constant Values."[1] This interval has been nearly closed by using hitherto unpublished Harqua Hala "short-method" monthly means. Comparison with "long methods" determines their scale corrections in the same manner explained above, and I increased these "short-method" monthly means, as stated above, by 0.027 calorie. As the Harqua Hala data are obviously less eligible, I give the average monthly mean differences from Montezuma values for the interval 1920 to 1925, inclusive, separately from those for 1926 to 1940. But all are used in combination in the grand mean for the interval 1920 to 1940.

Mean (Montezuma—Harqua Hala) 1920 to 1925 = ±0.32 percent
Mean (Montezuma—Table Mt.) 1926 to 1940 = ±0.20 "
Grand mean, 1920 to 1940 = ±0.24 "

Notwithstanding differences of 1,500 feet in altitude, 4,600 miles in latitude, summer conditions at the one station simultaneous with winter conditions at the other, 34° of north latitude against 22° of

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[1] Smithsonian Misc. Coll., vol. 77, No. 3, 1925.

south latitude, these independently derived monthly means, which rest on determinations of approximately 5,000 separate days at each station, agree to within an average monthly difference of 0.24 percent. Fluctuations are shown of $2\frac{1}{2}$ percent in the solar constant which are common to both stations.

As computed from the average monthly differences, the probable error of a monthly mean value derived from the work of two stations is $\frac{0.84 \times 0.24}{\sqrt{2}} = 0.14$ percent. Thus the range of variation found is 18 times the probable error of the determination. In many cases the two stations unite to show continued trends of increasing or of decreasing solar-constant values during many months. In such cases, successive values support each other, so that the probability with which such trends may be ascribed to observational error is further reduced. These facts support the validity of solar variation.

I conceive, however, that evidences of the reality of solar variation, stronger even than this agreement between results of high accuracy from two far-separated stations, are to be found in correlations of these results with other phenomena, both solar and terrestrial. I shall discuss these below.

But before presenting the most striking of these correlations I will refer to many supporting evidences of solar variability heretofore published. Though these evidences individually may not all be weighty, yet taken altogether they are highly convincing, on the principle of the well-known fable of the bundle of fagots. I present them in figure 2 and give appropriate references to the literature, in what follows, covering these and other cases of similar bearing.

Figure 2 has reference letters, A, B, C, D, E, F, G, for convenience in citing evidence of different kinds.

A, B. SOLAR CONSTANT AND SOLAR CONTRAST

Graphs A and B relate to the contrast of brightness along the radius of the solar disk. We were accustomed at Mount Wilson to allow a large solar image to drift centrally across the slit of the spectrobolometer. In this way on each day of observation of the solar constant, we recorded the relative brightness of the sun's disk along its E-W diameter for a number of wave-length regions of the spectrum. For each chosen wave length, results of many days in the year 1913 gave the average march of brightness from center to limb of the sun's disk. The observed march on each individual day was then compared with this average. In figure 2 we see that on September 22, 1913, a day of high solar-constant value, the contrast of brightness, limb to center, was greater than normal, while on October 20, a day of low

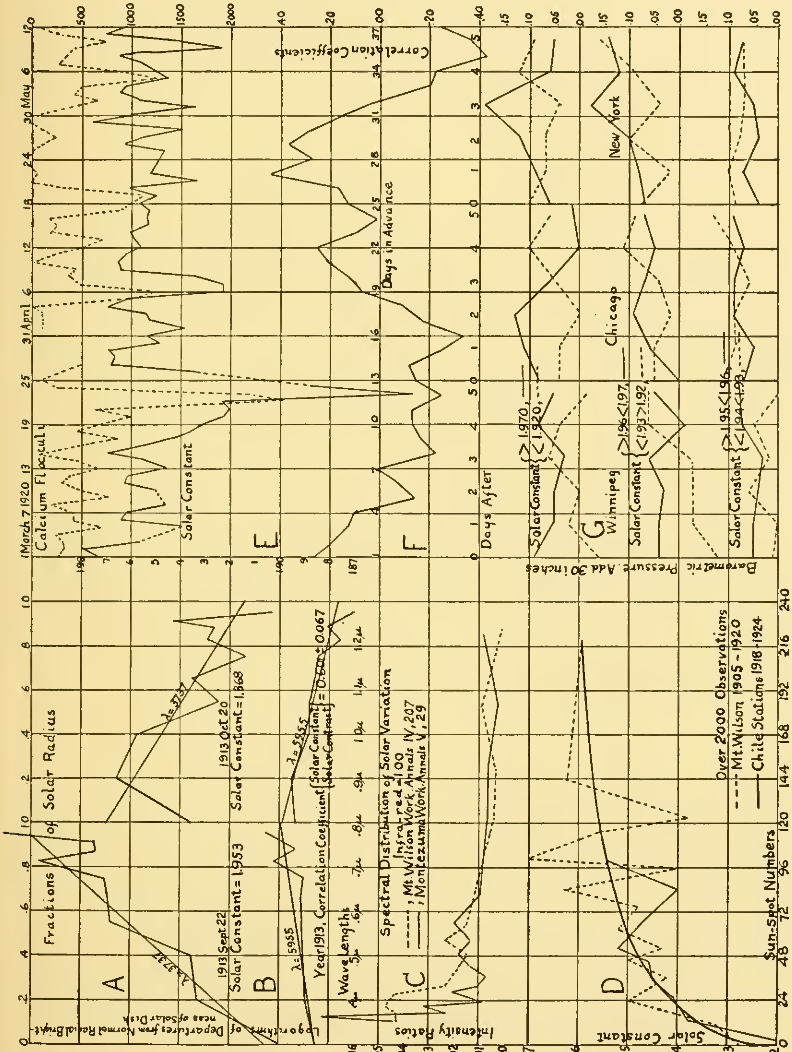

FIG. 2.—Various evidences of solar variation and its effects.

solar-constant value, the contrast was less than normal. The effect was far greater at wave length 3737 than at wave length 5955. This is as was to be expected, whether we regard the change of the solar constant as having been caused by change of the effective temperature of the sun's radiating layers, or by a change in the absorptive qualities of the sun's outer layers. Either change should affect shorter wave lengths most. This observation naturally leads us to graph C. But first let it be pointed out that from all wave lengths and all days of observation in the year 1913 there resulted a correlation coefficient of 0.601 ± 0.067 between solar-constant and solar-contrast changes. (See Annals, vol. 2, pp. 214-217, 1908; vol. 3, pp. 153-165, 1913; vol. 4, pp. 183, 184, 217-257, 1922; also Smithsonian Misc. Coll., vol. 78, No. 5, 1926.)

C. SPECTRAL DISTRIBUTION OF SOLAR-CONSTANT CHANGES

As foreshadowed by a comparison of graphs A and B, we are to expect that with increased solar-constant values the shorter wave lengths of the spectrum will show most increase. Graph C gives comparisons of this kind culled from results of Mount Wilson and early Montezuma work. Although the day-to-day solar-constant changes that figure in the comparison average little more than 0.5 percent, and though accidental errors make the graphs rather rough, both stations yield the same general indication, namely, that solar-constant increase is almost wholly confined to the visible and ultraviolet spectrum, and may be 10 or more times as great in percentage for wave lengths less than 3500 as for the total radiation. An unpublished investigation recently made with the latest revised Montezuma results confirms this conclusion. (See also Annals, vol. 2, pp. 105, 106, 1908; vol. 3, pp. 131-133, 1913; vol. 4, pp. 204-207, 1922; vol. 5, p. 29, 1932.)

D. SUNSPOTS AND THE SOLAR CONSTANT

The graph correlates the sunspot numbers of Wolf and his successors with over 2,000 observations of the solar constant of radiation made at Mount Wilson and in Chile between the years 1905 and 1924. The tendency is toward the conclusion that higher sunspot numbers are associated with higher solar-constant values. But, as graph E clearly indicates, on March 23, 1920, the central passage of an enormous sunspot acted strongly to diminish the solar constant. (These contrary tendencies are discussed by A. Ångström, Astrophys. Journ., vol. 55, pp. 24-29, 1922.)

E. OTHER SOLAR-SURFACE PHENOMENA AND THE SOLAR CONSTANT

In this graph we compare the solar-constant values of successive days, March 1 to May 11, 1920, observed at Calama, Chile, with the areas of calcium flocculi within 15° of the central meridian of the solar disk as measured at the observatory of Ebro in Spain. The dates given are for the solar-constant values. The dates of the calcium flocculi are displaced forward by one day in order to make best agreement. (See also Smithsonian Misc. Coll., vol. 77, No. 5, p. 22, fig. 14, and p. 23, fig. 16, 1925; vol. 77, No. 6, pp. 42-54 and 59-63, 1925; also Proc. Nat. Acad. Sci., vol. 26, No. 6, pp. 406-411, 1940).

F. THE SOLAR-ROTATION PERIOD AND THE SOLAR CONSTANT

This graph shows the march of correlation coefficients computed between the zero day and the days 1-37 thereafter, for all solar-constant values observed at Mount Wilson in the year 1915. The solar-rotation period is very plainly associated with a range of correlation coefficients from -0.40 to $+0.40$, or 0.80 altogether. (See Smithsonian Misc. Coll., vol. 69, No. 6, 1918, where the same phenomenon appears in the years 1910 and 1916, though less strongly marked; see also Smithsonian Misc. Coll., vol. 71, No. 3, p. 21, fig. 5, and pp. 41, 42, 43, 1920.)

G. ATMOSPHERIC PRESSURE AND THE SOLAR CONSTANT

This graph shows for three meteorological stations that the barometric pressure follows opposite courses after high and low solar-constant values, respectively. At Winnipeg the greatest opposition occurs on the zero day, at Chicago on the second, and at New York on the third day after the solar-constant influence. It is confirmatory of the value of this evidence that the greatest oppositions of pressure effects are found attending the widest departures of the solar constant, and that the oppositions of pressure effects consistently diminish as the solar-constant departures become less. (See also Smithsonian Misc. Coll., vol. 89, No. 15, pp. 13-35, 1934; also Bull. Amer. Meteorol. Soc., vol. 21, No. 6, p. 257, et. seq., 1940. See also figs. 1, 2, 11, 12, 16 of Smithsonian Misc. Coll., vol. 77, No. 5, 1925.)

A summary of many evidences of solar variation is given by H. H. Clayton (Smithsonian Misc. Coll., vol. 78, No. 4, pp. 50-62, 1926.)

A physicist to whom I showed figure 2 informed me that he considered graph F, which connects solar-constant variation with the sun's rotation period, to be the most convincing of all evidences of solar variation. Feeling that others may have the same view, I have obtained new evidence of this kind as given in figure 3. The curve F of figure 2 derives from Mount Wilson observations of 1915. In figure 3 I employ the revised solar-constant data, as yet unpublished.

They are derived by combining results of daily observations at both Montezuma and Table Mountain, in the years 1929, 1930, 1931 as revised by my colleagues, Messrs. Aldrich and Hoover, and soon to be published in Volume 6 of our Annals.

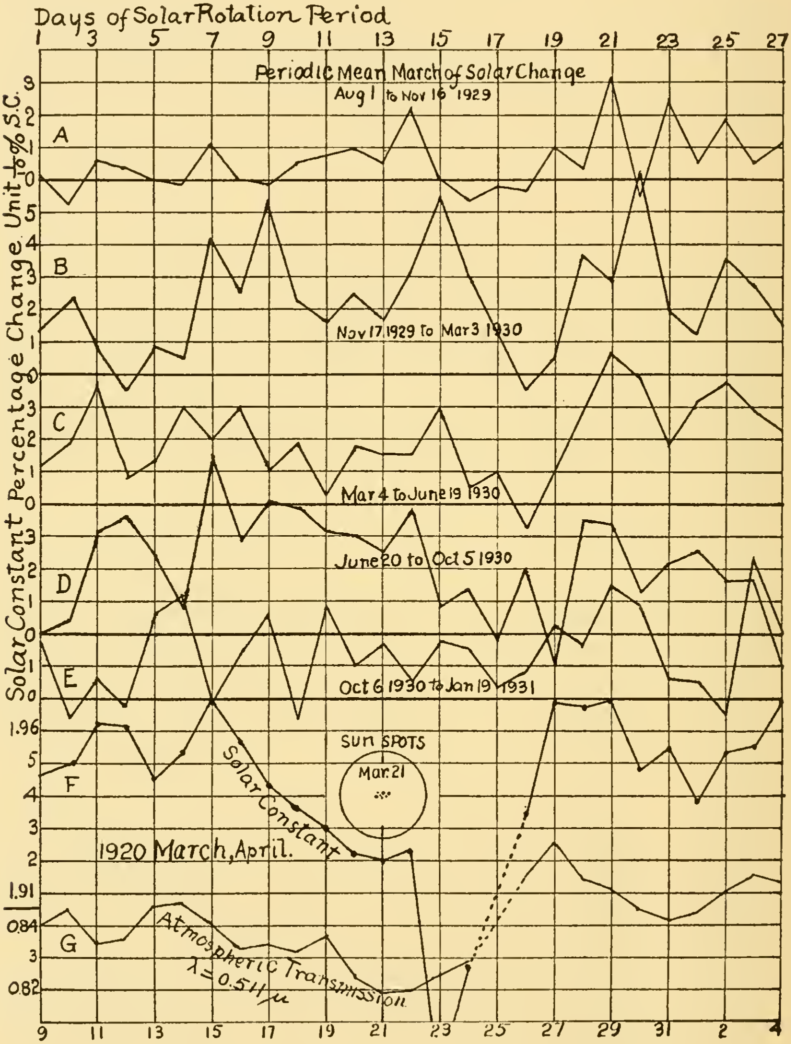

FIG. 3.—Solar rotation and solar variation. Note the rise of radiation at the 19th day, curves A-E.

The data used to obtain figure 3 also yield by the method of correlation coefficients the fact that the solar constant has a 27-day periodicity of variation. The correlation coefficient between day 1 and day 27 from November 17, 1929, to October 5, 1930, is 45.5±7.5 percent. By plotting the marches of means, each of four consecutive periods of 27 days, as in figure 3, they give the amplitudes of variation. The maximum amplitude at this time was about 0.5 percent.

My friend, the physicist, asked me to interpret for him the physical explanation of this 27-day period in solar variation. I replied that I conceive there is an emanation from the sun, especially active in sunspot regions, and emitted approximately normally to the solar surface. This emanation produces either scattering or absorbing, or both, for solar rays. Its columns are shot outward from the sun for hundreds of millions of miles, and take roughly conical shapes, with vertices at the sun's surface. As the sun rotates, these columns sweep through space, and when issuing from highly active regions of emission central to the solar disk, as occurred about March 22, 1920, the columns reach the earth and the solar constant is *diminished* by several percent.

The atmospheric transmission at such times is also materially reduced. The curves F and G of figure 3 show the position of the immense sunspots which prevailed on March 21, 1920, the depression of the solar constant on that day, and the simultaneous decrease of atmospheric transmission for homogeneous spectral rays at that time. The reader will, of course, understand that if the apparent decrease of atmospheric transmission were spurious, the effect of such an error would have been to *raise,* not *lower,* the solar-constant value computed.

The graphs in figure 3 should be compared with graph E of figure 2, that the reader may appreciate how frequently phenomena observed photographically near the center of the sun's disk are attended almost simultaneously by *depressions* of the solar constant. The sun's rotation brings these occurrences along every few days, and is the most prolific and readily understood cause of the fluctuation of the solar constant. The periodic long-range solar changes, which we shall describe further in what follows, are by no means so easy to understand. They seem to present features which are contradictory to expectation. These unexpected and contradictory phenomena will be discussed in the forthcoming Volume 6 of our Annals.

Solar rotation may also bring *increases* of solar radiation of 27-day periodicity, as shown beginning at the 18th day in curves A to E of figure 3. These increases occur (a) when the sun's rotation brings over the limb a sunspot group previously invisible, or (b) when new sunspots form or increase in size on the visible solar disk. Mount Wilson Observatory photographs, kindly loaned me by Dr. W. S. Adams, show that one or more of these phenomena occurred after the 18th day of each of the rotation periods dealt with in curves A to E of figure 3. Shorter lived cases also occur. See days 9, 15, B.

PERIODS IN SOLAR VARIATION

In order to introduce other solar and meteorological correlations above referred to, I now remind the reader that I published several years ago my discovery of a number of regular periods in the observed solar variation.[2] Several of these periods have been confirmed to within the error of determination by T. E. Sterne,[3] using other methods than mine.

I called attention, in my paper just cited, to the fact that the periods in solar variation, as I there determined them, had approximately a least common multiple of 23 years. This is approximately two sunspot periods of 11+ years. I mentioned also that the sunspot numbers themselves indicate a master cycle of two sunspot periods. I now give further evidence thereon, derived from summations I have made of monthly sunspot numbers published recently by W. Brunner, of the Observatory of Zurich.[4]

Beginning with the sunspot minimum in the year 1810, the comparative intensities of the 12 succeeding 11-year sunspot periods, as measured by the areas included under sunspot-number curves, are as follows. The 12th period being still incomplete, its area as given below is too small. The areas are given in arbitrary units.

Number of period.....	1	3	5	7	9	11	Total areas
Area	2354	6501	5451	3804	3739	4118	25967

Number of period.....	2	4	6	8	10	12	Total areas
Area	3879	6998	6222	4651	4412	5068	31239

Each odd-numbered area is smaller than the next succeeding even-numbered area, and the totals representing the relative average intensities of odd- and even-numbered sunspot periods from 1810 to 1940 are approximately as 5 to 6. This shows that for the last 130 years there has been a cycle in sunspot intensities comprising two 11-year periods. The average length of these periods since 1810 is 11.3 years.

The second correlation above referred to relates to G. E. Hale's observations of magnetism in sunspots. Hale found that sunspots prevailingly appear in pairs, of which the two members are of opposite magnetic polarity. During each 11-year sunspot period polarities per-

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[2] Smithsonian Misc. Coll., vol. 94, No. 10, 1935.

[3] Proc. Nat. Acad. Sci., vol. 25, No. 11, 1939, and vol. 26, No. 6, 1940.

[4] See Terrestrial Magnetism and Atmospheric Electricity, September 1939.

sist unchanged with reference to advancing and following positions in solar rotation. But the polarities reverse at the beginning of each successive 11-year period. Hence, the double sunspot period of approximately 271 months is also the complete cycle in sunspot magnetism.

Various weather phenomena are also correlated with this complete sunspot cycle. Numerous meteorologists have noted a 23-year period in weather phenomena.[5] I give in figure 4 an example of 23-year periodicity in tree-ring widths. These curves I have computed by combining results from five localities in Southern California and Nevada including about 40 trees in all. The results are from data published by A. E. Douglass. I reproduce here also in figure 5 my illustration given as figure 33 in my paper "Solar Radiation and Weather Studies," already cited.

According to my former Smithsonian researches, the well-verified solar cycle of about 23 years which is accompanied by terrestrial effects, is the approximate least common multiple of 12 regular periodic variations of solar radiation.

In his first paper on these periodicities, Dr. Sterne found high probabilities in favor of my periods of $9\frac{3}{4}$, $11\frac{1}{4}$, 21, 25, $39\frac{1}{2}$, 46, and 68 months. The data were insufficient to enable him to test periods of 92 and 276 months. He found little evidence favorable to my periods of 7, 8, or 34 months. I am disposed to agree with him as to the elimination of periods of 7 and 34 months, but shall submit further evidence below favorable to a period of about 8 months.

However, the interval of 20 years, during which high-grade solar-constant observations have been carried on, is too short to fix accurately the lengths of the solar periods, or to indicate whether they continue indefinitely without shifting of phases, or changing of amplitudes. I desired to use long meteorological records to throw light on the first two of these interesting questions, but was at first balked, as meteorologists have frequently been, by changes of phase in the terrestrial periodicities which are supposedly associated with those in solar radiation.

CAUSE OF SOME PHASE CHANGES IN TERRESTRIAL PERIODS

It occurred to me that if, as is indicated by the 20-year analysis of solar variation which I shall present below, the solar periods follow on without changes of phase, then such a period as 8 months, if it has a maximum in January 1900, must have others in September 1900

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[5] See Wild, Die Temperatur Verhältnisse des Russische Reiches, p. 279, 1881; also Quart. Journ. Roy. Meteorol. Soc., vol. 62, p. 481, 1936; also Douglass, Climatic cycles and tree growth, vol. 2, pp. 131, 132, 1928.

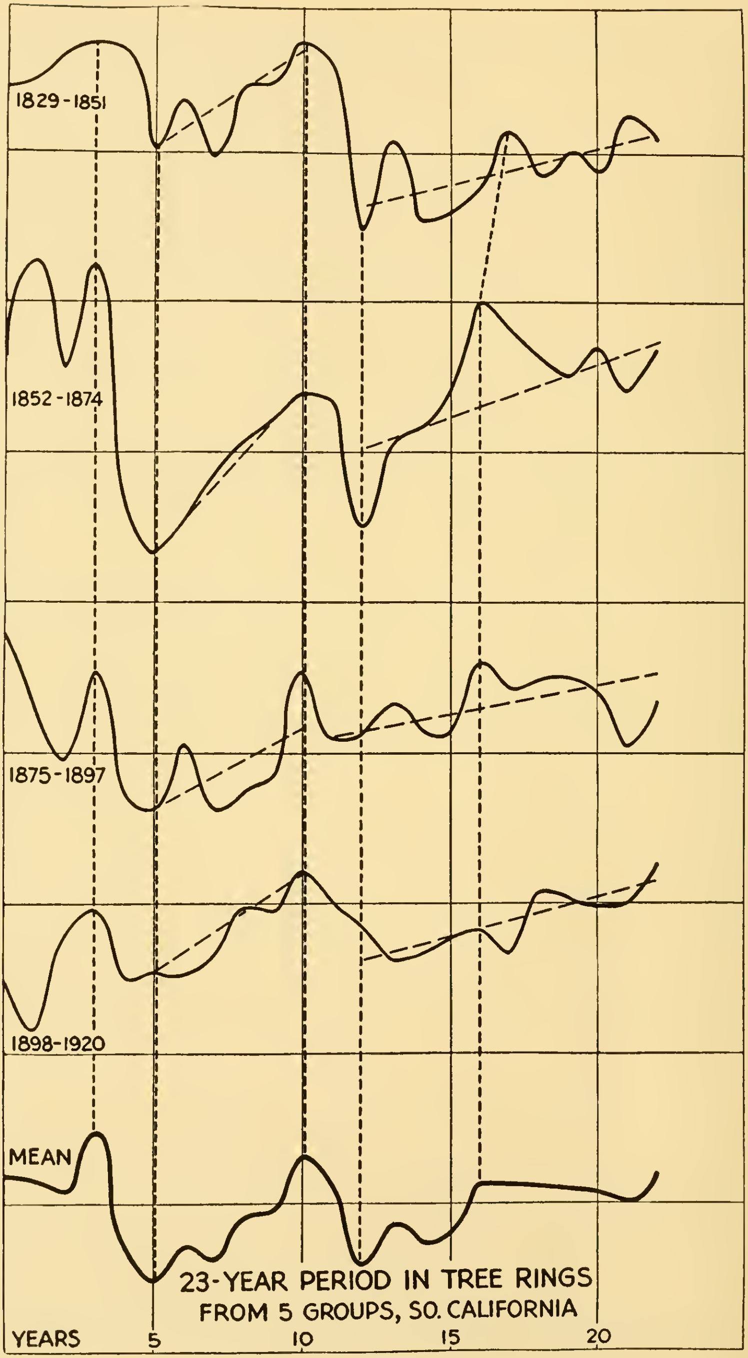
1829-1851
1852-1874
1875-1897
1898-1920
MEAN
23-YEAR PERIOD IN TREE RINGS
FROM 5 GROUPS, SO. CALIFORNIA
YEARS
5
10
15
20

Fig. 4.

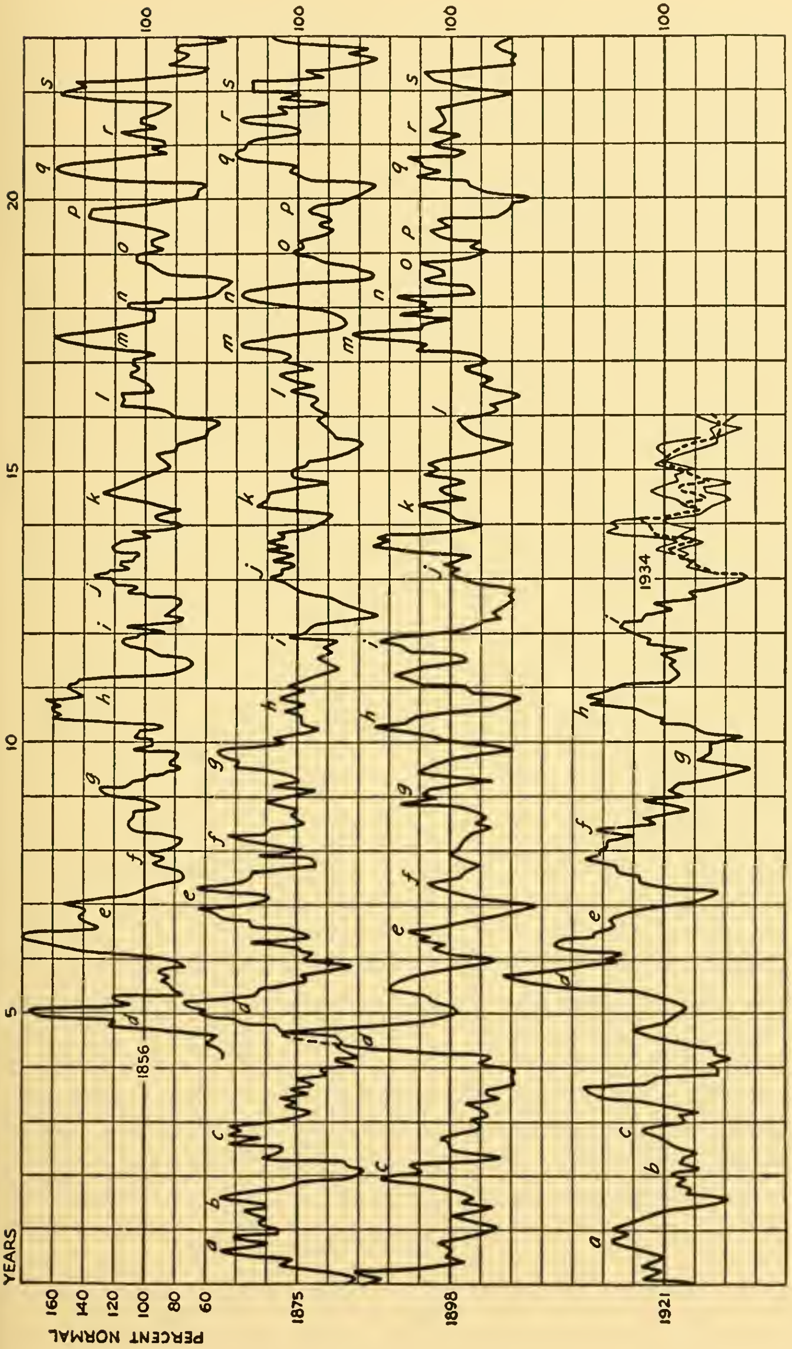

FIG. 5.—The 23-year cycle in precipitation at Peoria, Ill. Corresponding features indicated by letters.

and in April 1901. It might very well be that the changed conditions, as regards snow covering and atmospheric circulation, in these months of three different seasons of the year, would tend to produce changes of phase in the terrestrial response of the weather elements to the regularly recurring solar cause.

I tested this hypothesis for several periods and for a variety of weather stations as indicated in figure 6. In all the graphs of figure 6 the abscissae are the months of the years in which the solar cause recurs, and the ordinates are the months of the period in which the terrestrial response is observed. The latter data were obtained in each case by plotting the successive months of departures from normal weather since 1920 in separate graphs, each of the length to include only one recurrence of the period in question. In each such plot the maximum point was located, and serves to establish one point among the ordinates in figure 6.

Of course the influences of any terrestrial modifying causes, and the influences of other solar periods, would often tend to displace maxima in these working graphs. Hence it is not surprising that the points plotted in figure 6 do not fall exactly upon the straight lines drawn. But it is plain that these straight lines tend strongly to represent the mean indications of the groups of points. I conclude, therefore, that for various solar periods, and for many terrestrial stations, changes of phase in the weather periods, associated with the periodic solar variations, are due to seasonal terrestrial influences, and not to changes of solar phases.

This conclusion reached, phase changes may be eliminated from computations. Consider, for instance, the period of 21 months. Whatever solar phase for this period was operative in January 1900, that same solar phase will have been operative in January of each 7th year, counting from 1900, both before and after, provided successive occurrences of the solar periods do not themselves shift in their phase relations. Similar considerations enable us to compute the years when recurrences of each of the other subordinate solar periods had approximately the same relations to the months of the year. These computations having been made, we were able to select all of the approximately comparable recurrences of each of the solar periods, from the year 1800 to the year 1940.

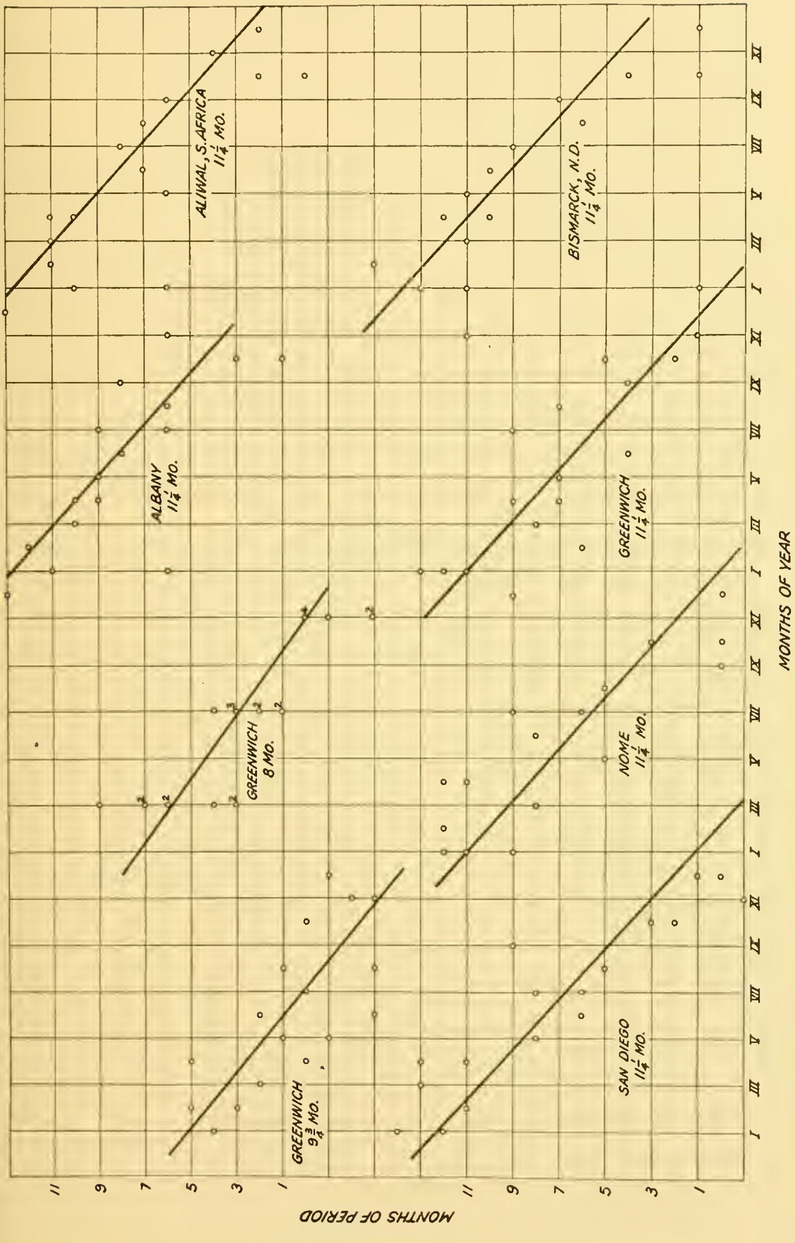

Fig. 6.—Phases of terrestrial effects governed by season of the year when solar causes occur.

METEOROLOGICAL EVIDENCE ON THE REALITY OF PERIODIC SOLAR VARIATIONS, AND ON THEIR EXACT LENGTH

In order to illustrate and develop the evidence, let us make four assumptions, subject to verification.

1. There is a periodic *solar* variation of about 8 months.
2. Its phases are unchangeable.
3. It produces appreciable changes in temperature and precipitation.
4. Its effects on weather are of changeable phase, depending on the relation of the unchangeable solar phases to the season of the year.

If the period is about 8 months, it will recur at the same season of the year after about 24 months. Hence, we shall compare together weather intervals, each 8 months long, which recur at intervals of 2 years. Proceeding in this way, let us employ the departures from normal temperature at Copenhagen, Denmark, beginning with 1800 and smoothed by 5-month consecutive means. These departures have been derived with reference to mean values computed for the interval 1800 to 1932. Thus is formed the following table in which maxima are indicated by bold-faced type, minima by italics.

To test the preferred period we adopt January 1900 as a base date, and working both ways from it, we compute a series of dates $8\frac{1}{8}$ months apart, extending backward to 1798 and forward to 1937. These dates fall in every month of the year. To study them with regard to the seasons and to the passage of the century, the departures for 8-month intervals, beginning with each of these dates, have been arranged in 24 groups. January and February dates taken together are segregated into four groups, covering the years 1800 to 1833, 1834 to 1867, 1868 to 1901, and 1902 to 1935. A similar grouping has been made for each succeeding pair of the months of the year.

The following table gives the data for November and December by individual group means, as well as by the grand mean, and gives the grand means for all other pairs of months. It is seen that there is no progressive side shift of the individual means for November and December. The same is true for the other pairs of months. There is, however, a marked shifting of terrestrial phases governed by the different seasons at which identical solar phases recur. This is indicated in the table by positions of the bold-face and italic numbers corresponding, respectively, to maxima and minima.

The numerical results just set forth appear to confirm the reality of all four of the assumptions made above. The several grand mean values indicate $8\frac{1}{8}$-month periodicities with ranges of from 0°.47 to 1°.44 Centigrade throughout an interval of 139 years. The range depends on the time of the year at which identical solar phases recur.

TABLE 1.—*Copenhagen temperature departures, smoothed. Test of 8-month period*

Values of January to August only

Unit: 1/10 degree C.; for means, 1/100 degree C.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
1800	—19	—17	—47	33	29	—12	— 4	15
2	—15	—11	22	10	—15	—17	—33	6
4	18	—21	—25	— 8	11	3	5	11
6	17	19	— 4	—19	8	—20	—15	9
8	8	—11	—19	—17	9	9	24	26
10	1	— 5	— 2	—16	—27	— 4	8	6
12	— 1	13	—18	—32	—14	— 4	—21	2
14	—53	—53	—29	4	—30	—15	10	— 2
16	4	—22	— 4	— 6	—27	—15	2	—14
18	14	15	20	—21	— 3	11	14	— 2
20	—32	1	— 4	12	0	—15	— 7	— 3
Mean	—53	—64	*—100*	—39	—54	—72	—15	+49

Table of Means

1800 to 1820	—53	—64	*—100*	—39	—54	—72	—15	+49
1822 to 1842	*—71*	— 6	**105**	42	8	15	— 4	18
1844 to 1864	*—76*	4	—17	— **1**	— 9	—11	—52	—30
1866 to 1886	**127**	115	44	85	*—27*	4	35	24
1888 to 1908	**123**	59	25	1	— 1	17	—25	*—64*
1910 to 1930	74	108	**133**	96	58	*—59*	46	—16

The maximum appears to shift 11 months and the minimum 19 months to the right in 110 years. With such large shifts one cannot exactly determine the proper correction to the period with one trial. These shifts however indicate: By the maximum, $\frac{11 \times 8}{100 \times 12} = \frac{1}{15}$ month. By the minimum, $\frac{19 \times 8}{110 \times 12} = \frac{1}{9}$ month. Further trials led us to fix on the correction $\frac{1}{8}$ month, and to prefer the period $8\frac{1}{8}$ months.

TABLE 2.—*Copenhagen temperature departures, smoothed. Test of 8½-month period*

Values of all months employed. Means given only

Unit: 1/100 degree C. throughout

Years	November–December beginnings							
1798 to 1833	*—19*	24	21	*7*	**84**	11	18	— 6
1833 to 1868	*—153*	—55	—48	— 4	—10	—75	—41	—66
1868 to 1903	20	85	88	**103**	33	*77*	*—23*	— 3
1903 to 1937	*—102*	20	36	**44**	29	— 4	— 5	—20
1798 to 1937	*—79*	22	29	**65**	41	3	—15	—29

1798 to 1937								
Nov. and Dec.	*—79*	22	29	**65**	41	3	—15	—29
Jan. and Feb.	4	— 3	*—32*	34	**59**	— 1	— 7	6
Mar. and Apr.	—29	—29	*—64*	—19	*—66*	—39	—29	**15**
May and June	— 1	45	44	4	*—12*	24	33	**46**
July and Aug.	29	38	—24	— 1	—12	16	8	*—31*
Sept. and Oct.	24	32	**52**	6	*5*	18	40	42

That there is here no progressive secular displacement of the phases of means of groups beginning at a constant season of the year, is shown by the extended table for November–December. But groups beginning at different seasons of the year do show displacement of phases with respect to one another.

This difference in amplitude is due not so much, I think, to a difference in effectiveness per se of the solar cause, as to a fitfulness of the terrestrial dealings with it. From this latter cause individual periods which are combined together in the seasonal means clash together in phase, and so reduce the ranges of the mean.

WEATHER RESPONSES TO THE SUBORDINATE SOLAR PERIODS

We have made use of monthly temperature records[6] from Copenhagen, Vienna, and New Haven, beginning with the year 1800, to investigate the weather responses to 7 of the 10 periodic solar variations. We have first computed the years when the temperature responses to the assumed solar periods must be in approximately corresponding phases, provided that the solar periods recur without displacements of phase and that they have the lengths we had attributed to them.

Before particularly discussing these investigations, I shall make a few remarks on the nature of the periods I have in mind. Many investigators show strong preference for the use of sine and cosine forms in studying periodicities. While it was shown long ago that any curve, however irregular, may be represented by a summation of a series of sine and cosine terms, this is an entirely forced and arbitrary mathematical device. It is so elaborate, in the case of recurring periodic curves of irregular form, that if adhered to with the use of series having sufficient terms to give a true representation, one could not, with ordinary means, find time for such a research as I contemplate here.

It has seemed to me not only simpler, but truer to the actual facts, to test the validity of periodicities, and to express the forms of them, by tabulations of actual ordinates and abscissae, determined in records of the phenomena. One uses enough repetitions of the proposed period in each table to yield a fairly representative mean form, if indeed there results a plausible form, indicative of a real period. Then by comparing the mean forms determined by successive tabulations, one sees whether the proposed period persists throughout the entire interval investigated. By this means one learns whether to reject the period as nonexistent. But one also often detects lateral shiftings in the same sense, among the curves determined by successive tabulations. These shiftings enable a correction to the length of the assumed period to be computed. Then a new tabulation may be made with the improved

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[6] World Weather Records, Smithsonian Institution, 1927 and 1934.

period, and, if necessary, a further correction to its length may be made and subjected to a new test by tabulation.

When a very long interval is under consideration, in the examination of relatively short periods, there will be so many repetitions that very exact lengths of the periods must be found, or else in the mean of all recurrences the amplitudes of the periods will disappear. As a corollary it will be plain that of two periods slightly different in length, that is the better for which the average amplitude over a very long interval is the greater.

When using odd lengths of periods, such as 9.79 or 11.29 months, we have first to prepare a table showing the exact day of ending of each recurrence. Thus in our tabulation we must occasionally repeat a month, or omit a month, so as to keep always within ½ month of the true times when the periodicity recurred.

TABLE 3.—*Average march of two assumed periodicities, Copenhagen and New Haven, 1800-1932*

Station	Assumed period Months	I	II	III	IV	V	VI	VII	VIII	Range
Copenhagen..	8.00	0°.10	0°.41	—0°.14	—0°.12	—0°.08	—0°.25	—0°.02	—0°.33	0°.74 C.
	8.12	—0°.14	0°.29	0°.55	0°.79	0°.33	—0°.33	—0°.50	—0°.22	1°.29 C.
New Haven..	8.00	0°.18	0°.20	—0°.13	—0°.04	0°.25	0°.08	—0°.02	0°.04	0°.38 F.
	8.12	0°.69	0°.45	0°.52	0°.46	0°.17	—0°.08	—0°.62	0°.13	1°.31 F.

To illustrate the necessity of accuracy in the lengths of periods when treating of periodicities in so long an interval as 132 years, I give the results of two sets of analyses. In the first the period of 8.00 months is assumed to exist in the departures from normal temperatures computed for the interval 1800 to 1932 from records of Copenhagen and New Haven. In the second the period is taken as 8.12 months. To avoid seasonal influences, the comparison includes only periods when the solar pulse was in identical phases and running from January to August. Equal numbers of such periods were used in computing each of the results shown in table 3.

It will be seen that in each of the analyses, based on an assumed period of 8.12 months, there results a fairly regularly defined periodic curve of considerable amplitude. The other analyses based on 8.00 months are much less satisfactory. I conceive that the excellent showing of the period of 8.12 months for each of two far-separated stations, and throughout an interval of 132 years, is satisfactory proof of the validity of this period in weather.

To further emphasize and explain the preceding discussion:

With an 8-month period there are 66 even-numbered years from 1800 to 1932 when the terrestrial response should be in the same phase in January. Six tables may be prepared from monthly means of temperature departures at Copenhagen, each covering 11 recurrences. In each table there will be in each line departures for the 8 successive months, January to August, making 8 columns, each column 11 lines long. Taking the mean values of the 8 columns of departures, we obtain the average march of the 8-month period in Copenhagen temperature departures for an interval of 22 years. On comparing the 6 mean curves thus obtained we found a slight displacement of maxima and minima from epoch to epoch indicating that not 8.00 but approximately $8\frac{1}{8}$ months is the true period. We have repeated the computation at Copenhagen, at Vienna, and at New Haven with the period $8\frac{1}{8}$ months and employing only such epochs (37 in number) as bring corresponding solar phase dates within less than ±1 month of January 1. Thus we find the curves given in figure 7 representing the interval 1800 to 1932. The period $8\frac{1}{8}$ months suits all three stations. But compare the ranges of these 3 curves of $8\frac{1}{8}$ months period with the ranges of the other 3 curves of 8.00 months period also given in figure 7. Evidently this slight difference in length of period is highly important for so long an interval as 132 years.

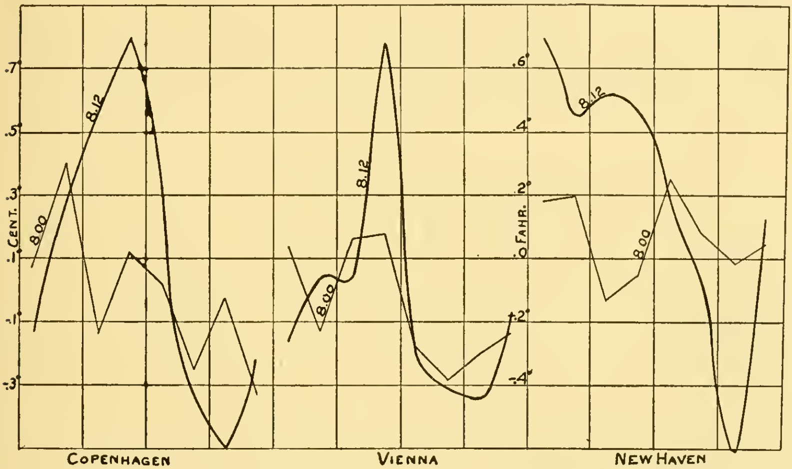

FIG. 7.—Greater amplitudes of periodic curves when precise period is found.

I shall postpone a more detailed report of this investigation which concerns the determination of the exact lengths of the periods. It will probably be published in Volume 6 of the Annals of the Smithsonian Astrophysical Observatory, now in preparation. However, the computations from the three stations, Copenhagen, Vienna, and New Haven, agree very well as to the best lengths of the 10 solar periods.

CONSTANCY OF PHASE IN SOLAR PERIODIC VARIATION

Having observed the solar constant daily for only 20 years, it would be uncertain, if it were not for the meteorological evidence just described, whether the solar periodic variations continued for long intervals, such as a century, without displacements of phase. But if there were frequent displacements of phases in the solar periods then the numerous repetitions of the responding periods in the weather during 132 years would bring out the discrepancy. They would not in that case yield periodic mean weather curves of considerable amplitudes, such as would, if synthesized, reproduce to a considerable extent the range of actual weather fluctuations. So many repetitions, if the periodic causes had different phases, would tend to flatten the general mean curves toward zero amplitude.

Table 4.—*Possible range of solar temperature effects*

Station		Period, months							Sums
		8.12	9.79	11.29	21.00	25⅓	39½	45¼	
		Amplitude in degrees							
Copenhagen	C.	1°.29	0°.79	1°.40	0°.47	1°.00	1°.16	0°.63	6°.74 C.
Vienna	C.	1°.13	1°.20	1°.87	2°.01	0°.99	1°.25	1°.00	9°.45 C.
New Haven	F.	1°.31	1°.90	3°.30	0°.90	1°.70	0°.58	0°.90	10°.59 F.

Accordingly it is of much interest to assemble the mean periodic weather curves of Copenhagen, Vienna, and New Haven representing the interval of 132 years and see how wide ranges they could produce from extreme crest to extreme trough if made to recur till all came simultaneously to maxima at one epoch, and to minima at another. This assembly is given in table 4. It shows, when we consider only 7 of the 10 known periods, that they are of sufficient combined range to account for the full ranges of smoothed monthly mean temperature departures from the normal at Copenhagen, Vienna, and New Haven. I suppose that the observed ranges of temperature departures from the normal at these stations are actually less than might result from solar variation alone for the following reason. Since there are terrestrial phase changes as explained above, and since the periods are not exactly commensurable, the 10 periodic solar causes, in fact, are never in complete harmony of phase as to maxima and minima of their temperature effects. Weather changes produced by solar variation, in other words, can never exactly repeat, because of terrestrial phase changes, and of the noncommensurability of the solar periods.

ANALYSIS AND SYNTHESIS OF SOLAR VARIATION

These meteorological researches having, as I conceive, fixed the lengths of the solar periods with considerable accuracy, I now present the analysis of the curve of solar variation for the years 1920 to 1939. It is derived from Montezuma observations alone after the year 1923 and from combined results of Montezuma and Harqua Hala from 1920 to 1923. I used these data from our best station of the years 1923 to 1939 for this purpose before the completion of revisions of data from other stations. As shown in figure 1, the agreement of the monthly means from different stations is so good that I have no reason to think the results would be much changed had the final data combined from all stations been available.

In figure 8, curve A comprises these monthly mean observations of the solar constant for 20 years. The analysis of the curve was made as described in my paper "Solar Radiation and Weather Studies,"[7] and in my paper "The Variations of the Solar Constant and Their Relations to Weather."[8] Seven of the periods used were those given above, and, in addition 68, 91, and 276 months. The results of the analyses are printed in the legend for figure 8. In making these analyses, we verified the constancy of the phases by dividing the 20 years of data into several parts for the shorter periods.

Curve B is computed by synthesizing the 10 periodic curves indicated by numbers below it. It is obviously very like curve A. The average monthly deviation for 240 months between curves A and B is 0.0026 calorie, or 0.13 percent.

AMPLITUDES OF THE SOLAR PERIODS

Having satisfied ourselves, as explained above, that there has been no notable change in the orderly succession of phases in the subordinate solar periods for 140 years, it is of interest to know if the amplitudes of these periods also remain unchanged. Here we have to rely on the solar observations of the past 20 years alone. So far as we see, the meteorological records cannot help to solve this question.

It would be expected, by analogy with the sunspot numbers, that these amplitudes will change. Our meager data of only 20 years dura-

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[7] Smithsonian Misc. Coll., vol. 94, No. 10, 1935.

[8] Quart. Journ. Roy. Meteorol. Soc., vol. 65, No. 280, 1939.

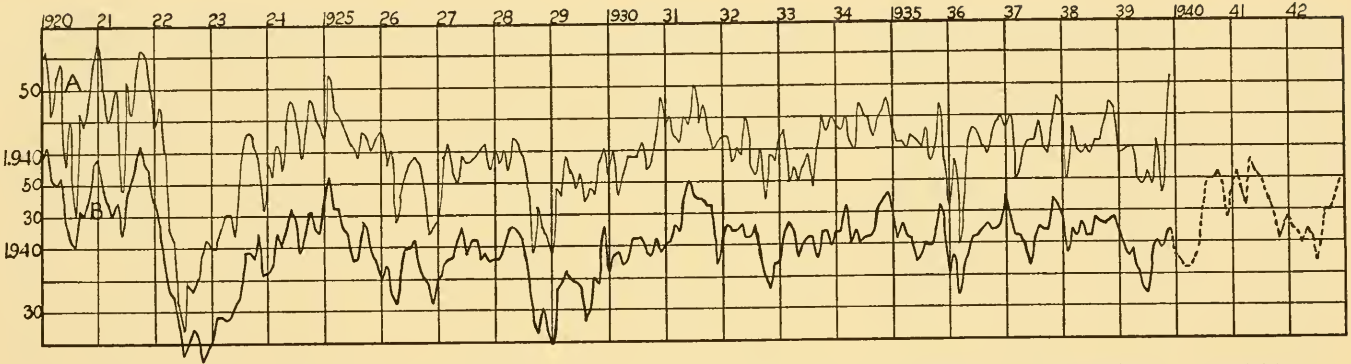

Fig. 8.—Curve A, monthly mean solar-constant values, Montezuma, Chile; Curve B, synthesis of the following 10 periodicities, beginning January 1920. Unit, $\frac{1}{10{,}000}$ calorie; phases below begin January 1926.

Length in months

8⅛: —8, 3, —6, —7, 7, 16, 3, —9.
9.79: 7, 3, —3, —11, —7, 4, —3, —3, 7, 4.
11.29: —11, —12, —18, —14, 8, 19, 17, 11, 19, —10, —8.
21.00: —15, —7, —6, —11, —18, 4, 8, 13, —9, 5, 5, —8, 9, 23, 18, —8, 24, 2, —6.
25⅓: 0, 11, 16, (23), 30, 16, —1, 2, —11, —25, —22, —26, —12, —10, —3, 20, 11, 15, —8, —15, —4, —25, 6, 4, 12, 18.
39½: —40, —45, —57, —68, —68, —53, —11, —7, —4, —4, —3, —3, —2, —2, —1, 1, 3, 22, 30, 42, 41, 41, 34, 35, 37, 41, 45, 53, 61, 51, 41, 11, —5, —17, —27, —35, —40, —45, —44.
45¼: —10, —15, —20, —24, —25, —25, —25, —24, —23, —22, —18, —15, —10, —6, —5, —2, 0, 0, 0, 3, 5, 6, 7, 8, 9, 10, 11, 11, 12, 13, 14, 14, 14, 15, 15, 15, 15, 15, 15, 15, 14, 10, 7, 0, —4.
68.00: 36, 27, 22, 16, 18, 19, 20, 21, 16, 14, 8, 7, 6, 7, 8, 10, 12, 13, 12, 12, 10, —1, —3, —12, —19, —23, —30, —34, —43, —49, —53, —54, —57, —56, —54, —48, —44, —34, —33, —24, —20, —13, —10, —9, —3, —1, 2, 5, 7, 7, 11, 12, 13, 14, 14, 15, 15, 15, 15, 15, 14, 12, 11, 7, 60, 56, 52, 42.
91.00: 10, 18, 22, 24, 24, 22, 20, 18, 17, 15, 15, 44, 10, 7, 5, 0, —5, —8, —12, 8, 10, 16, 18, 18, 17, 14, 10, 0, —5, —5, —8, —8, —8, —7, —6, —6, —6, —6, —5, —4, —3, —4, —5, —8, —10, —14, —15, —18, —23, —24, —22, —20, —18, —17, —15, —13, —12, —10, —9, —8, —7, —6, —5, —5, —4, —4, —3, —2, —1, —1, 0, 2, 3, 3, 3, 3, 3, 4, 4, 4, 4, 3, 2, 1, 0, —3, —5, —5, —3, 0, 5.

23-year: —24, —40, —36, —3, —5, —16, —2, 24, 29, 17, —4, —6, 16, 33, 39, 41, 39, 34, 29, 7, —14, —20 —18.

tion cannot give indications as to the longer periods. But we have explored the 8.12-, 9.89-, and 11.29-month periods as to their amplitudes since 1920. For this purpose we prepared tables of 10 lines for the 8.12-month period, of 8 lines for the 9.79-month period, and of 7 lines for the 11.29-month period. Taking the mean values for these several arrangements, we can compare average amplitudes at three epochs during the 20 years of observation. Of course, the mean values for tables of so few lines are not very reliable, considering that influences of accidental error and of interference by others of the 10 periodicities are simultaneously operative. But for such worth as they may have the comparative results are as follows:

Relative amplitudes of solar periodicities in three epochs

	Periodicity, months		
Epoch	8.12	9.79	11.29
Jan. 1920–June 1926	49	83	105
July 1926–Dec. 1932	26	39	39
Jan. 1933–June 1939	36	38	54

All three periodicities seem to be stronger in the first epoch, 1920-1926, than later. But the data are not sufficient to be decisive.

SYNTHETIC WEATHER PREDICTIONS

It appears that 10 periodic variations of the sun have persisted in regular phase relations for 20 years, and probably for 140 years. They are each apparently associated with periodic departures from normal temperatures, and also (although to save space we have not illustrated it) with periodic departures from normal precipitation. For the periods of shorter lengths these departures from normal weather conditions exhibit phase changes. But these phase-changes in weather seem to depend on the season of the year when the solar cause operates, and can be allowed for on that basis. The solar periodicities may not be of uniform amplitude as they recur, but this matter is uncertain as yet.

These facts led me to consider if weather might be predicted by a synthesis of the average effects of the periodic solar causes, just as the solar variation is itself predicted for the last years shown in figure 8.

With the assistance of Miss N. M. McCandlish in the computing, we have tried 5-year predictions for various stations, both for precipitation and temperature. Using only the recorded weather data up to December 1934 as a basis for the forecasts, we have made synthetic predictions for the later years, 1935 to 1939. These predictions were then compared with the observed weather records of 1935 to 1939, but these latter records had no part in influencing the computations of synthetic weather indications.

In illustration of the method I give in table 5 the components of a synthetization of 1 year in the precipitation of Peoria, Ill. In figure 9 I give predicted and observed weather for 5-year periods in several stations. As these long periodicities cannot have to do with the vicissitudes occurring within individual months, I use 5-month running means of departures in weather data in these illustrations.

Considerable similarity appears between predictions and events. On the average about two-thirds of the months of a 5-year prediction seem to show fairly good correspondence. Some stations turn out better than others. For another somewhat better synthetic prediction of the precipitation at Peoria, Ill., not here illustrated, I have worked out the correlation coefficient between prediction and event over a 60-month interval. It results 70 ± 5 percent.

TABLE 5.—*Synthesis of precipitation, Peoria, Ill., for the year 1938*[a]

Percentages of normal. 5-month running means

Period, months	8	$9\frac{3}{4}$[b]	$11\frac{1}{4}$[b]	21	25	$39\frac{1}{2}$	46	68	Forecast (Product)[c]	Observed
Jan.	97	82	100	98	122	123	101	95	112	134
Feb.	98	86	100	93	121	120	97	100	110	147
Mar.	98	90	101	93	108	122	122	96	128	156
Apr.	98	95	99	103	91	139	137	87	143	145
May	100	103	101	112	85	121	137	84	138	156
June	103	103	106	114	76	125	144	80	140	143
July	103	101	97	111	81	116	138	88	128	131
Aug.	103	95	93	108	88	106	105	94	90	109
Sept.	102	99	93	101	97	77	97	98	67	86
Oct.	101	103	96	92	101	69	89	104	59	66
Nov.	97	103	97	95	104	79	102	102	79	85
Dec.	98	106	98	93	95	102	99	96	87	103

[a] The periods used differ slightly from those now preferred.

[b] Where dashes are inserted in these columns, changed forms of periods begin, according with the control of periods by season of the year, above explained.

[c] This forecast would be improved if it lay 10 percent higher. Its range of 84 percent compares with the observed range of 90 percent favorably, and its phases are quite correct.

What seems to me particularly significant in these comparisons is this: The range of departures forecasted is nearly as great as the range observed. If the solar variations were negligible in their effects, or even nonexistent, then the average weather effects corresponding to them over a period of 20 to 50 years, which are the basic elements in our forecast, would also tend to be negligible. Moreover, if they had no common thread of causation connecting the several solar periods with the weather, then the synthesis of these supposed spurious or negligible average weather periodicities would tend to be zero. On the contrary we find their synthetization gives values of weather departures which show nearly the same ranges and phases as the actual weather records. To me this indicates that the variation of the sun is actually a principal cause of weather changes.

This method of forecasting by synthesis of periodic effects, like that about to be mentioned, while hopefully successful in many cases, shows bad timing or dissimilarity with events in others which destroys its usefulness. There appears to be some other variable, as yet obscure, which must be discovered and applied before valuable forecasts can be made consistently by this method.

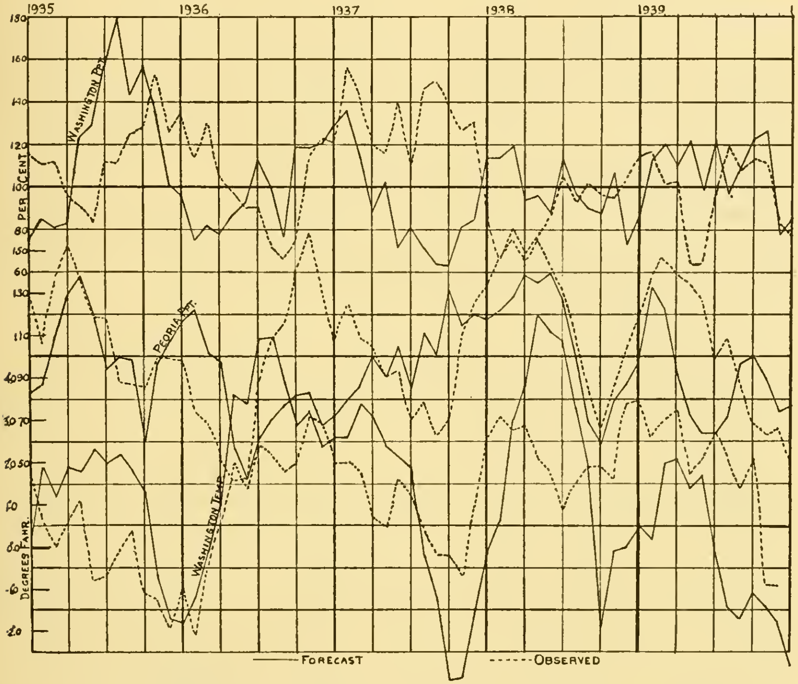

FIG. 9.—Predictions of weather based on the previous effects of 10 periodic changes in solar radiation.

WEATHER FORECASTS BASED ON 23-YEAR CYCLES

With further regard to long-range forecasts depending on solar variation, as I remarked above, the solar periodicities approach rather closely to a least common multiple in 23 years. But this relationship is not exact. Moreover, the seasonal phase change of terrestrial response to corresponding solar causes of weather effects complicates the matter. Hence the phases and amplitudes of weather features should not exactly recur at intervals of 23 years, even if there were no other terrestrial complications. Yet the tendency to a repetition of weather features each 23 years, such as is shown in figure 5, itself affords a method of long-range forecasting which gives some promise of usefulness. It may be compared in its results with the synthetic method explained above.

In applying this method, one must first determine with what displacements in phase the weather features happening recently occur with respect to those of 23, 46, and 69 years ago. Also one must be guided as regards amplitudes by those former appearances. One pieces his prediction onto the curve of departures as it stood at the time the forecast began, and thus accepts the prevailing trend, whether positive or negative, as a point of departure.

I now give in figure 10 several examples of forecasts and events with which I have tested this method in the past 6 years. Here, as in figure 9, the data used are 5-month running mean values of departures from the normal.

The forecasts shown in figure 10 were all made previous to the events. While records of 23 or 46 years preceding are shown in the figure by way of illustration, other preceding data were also considered in making the predictions.

It will be seen that the forecast for 1934, 1935, and 1936 of precipitation at Burlington, Vt., is very good. Other forecasts have lesser accordance with events. As a rule, precipitation seems more amenable to this kind of forecasting than temperature. This is also the case with synthetic forecasts previously explained. However, in almost all cases of failure, the trouble seems to be, not that coming weather features were unperceived, but that differences of timing of as much as 3, or even 4 months occur, as between the prediction and the event. This of course destroys the usefulness of the method.

It appears that other factors, still obscure, must be discovered, whereby these errors of timing may be anticipated and corrected, before this method of forecasting can be very useful. Nevertheless there seems to me to be so much evidence that the periodic solar variations, and their cycles of approximately 23 years and multiples thereof, are governing influences over weather, that I cannot but hope that experts in meteorology will take up this clue, and go forward to greater success, by combining with it their own knowledge of atmospheric processes.

Much more might be said of these long-range solar periods, and their application to weather forecasts. Indeed, without additional details, the statements made here may be thought by some readers to rest too much on the good faith of the narrator. But this paper has already exceeded its intended limits, and as I wish still to bring up the subject of short-time solar changes and their weather effects, I will say no more of very long-range weather prediction.

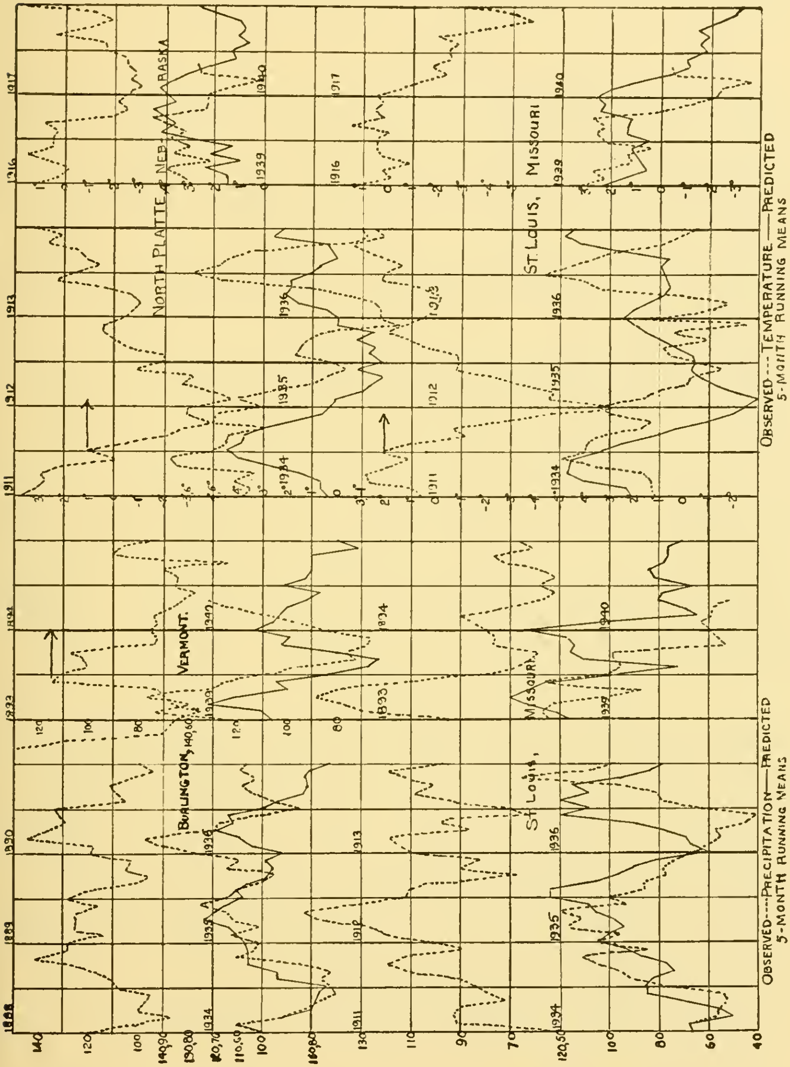

Fig. 10.—Predictions of weather based on the 23-year cycle.

SHORT-INTERVAL SOLAR CHANGES

The sun is not equally bright at all points on its surface. This is visually obvious with regard to sunspots and faculae. My colleagues, Fowle and Arctowski, as well as H. H. Clayton, have demonstrated correlation between solar appearances and variation of observed solar radiation.[9] As the sun rotates upon its axis in approximately 27 days, a succession of unequally radiant solar surfaces is presented toward the earth. This leads to irregular variations of the solar constant of short intervals. There is a tendency, also, to create families of solar changes of about 27 days' period. However, the changes in the sun's surface are so rapid that generally new distributions of brightness take place before more than one or two solar rotations are completed. The local variations of solar brightness usually produce very small percentage changes in the sun's total radiation. On these accounts it is only rarely that the 27-day period can be distinctly shown by our still unsatisfactorily accurate solar-constant values. However, some good cases are on record.[10]

In two papers I have discussed the effects of short-interval solar variation on the temperatures of Washington, St. Louis, and Helena in the United States, and Potsdam in Germany.[11] Now that longer series of daily solar-constant values are available, I have recently repeated in part the computations described in these papers, using 20 years instead of 12 years of observations. The results of these recent studies do not alter the conclusions that opposite trends of temperature follow, respectively, rising and falling sequences of solar change, and that these temperature changes are of major significance. I have treated the subject as well as I can in my paper in reply to Paranjpe and Brunt,[12] and will now quote therefrom:

> Referring to figure 1 of my just cited paper, here reproduced,[13] the reader will find there two curves for each month of the year showing departures from normal temperature at Washington, D. C. In each month the curves show a well-marked opposition like the right and left hands. The separations of the curves in the months January, February, March, April, May, June, August, October, November, and December range from 14° to 24° F., and evidently constitute major departures from normal temperatures. Similarly, results showing in almost all cases opposition like the right and left hands, but differing widely in actual march of the pairs of curves, are shown for St. Louis, Helena, and Potsdam in other illustrations in the cited publications. The curves are computed for all these cities starting from identical dates, 320 in number, scattered over 12 years. Some 10 to 20 cases are combined in each curve shown. The

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[9] See Smithsonian Misc. Coll., vol. 77, No. 5, pp. 21-23, 1925; also Proc. Nat. Acad. Sci., vol. 26, No. 6, pp. 406-411, 1940.

[10] See, for instance, Smithsonian Misc. Coll., vol. 69, No. 6, pp. 7-8, Sec. (3), and the curve for 1915, fig. 1, 1918. See also my paper in Science, April 11, 1941.

[11] Smithsonian Misc. Coll., vol. 95, No. 12 and No. 15, 1936.

[12] Quart. Journ. Roy. Meteorol. Soc., vol. 65, No. 280, 1939.

[13] Here again reproduced as figure 11 of this paper.

data of temperature departures in each case cover 16 days following the starting date selected.

How were these 320 dates selected? They are chosen as dates when solar variations commenced. As shown in figure 1 and table 1 of "The Dependence of Terrestrial Temperatures on the Variations of the Sun's Radiation," they comprise all the dates during 12 years when good consecutive solar-constant observations, made mostly at Montezuma, Chile, began to indicate rising or falling sequences of the sun's output of radiation. The range of these sequences is only about 0.7 percent of the solar constant. Owing to the interference caused by changes in atmospheric transparency, superposed on the inevitable accidental errors of measurement, it is highly probable that some of these 320 cases are

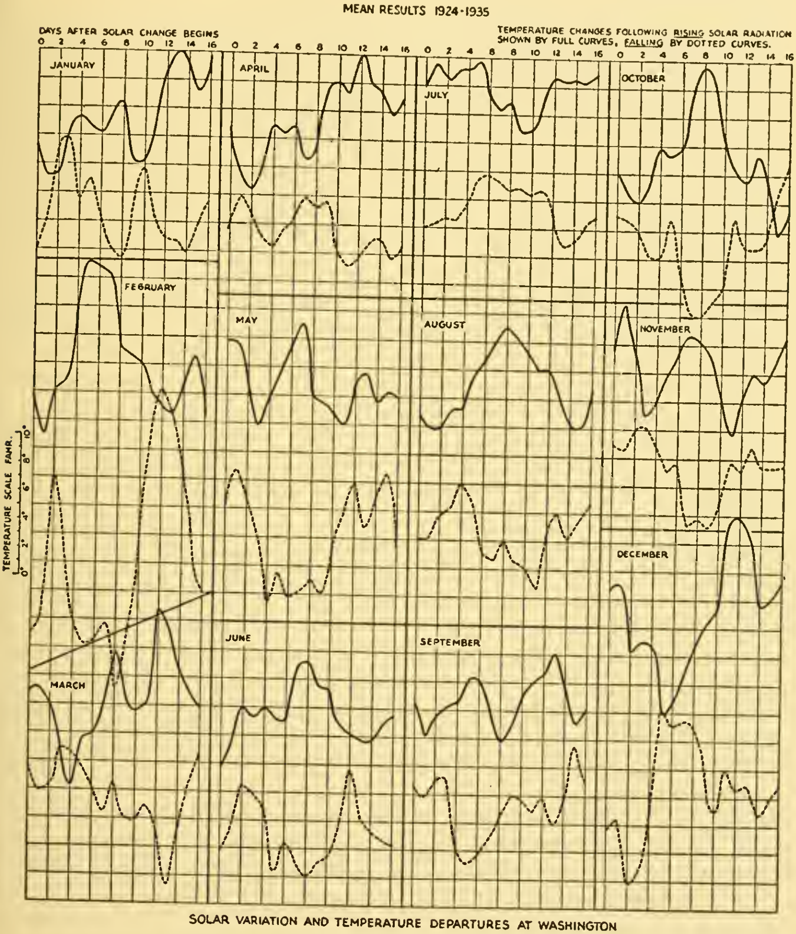

FIG. 11.—Oppositeness of temperature departures at Washington which follow average rising and falling sequences of solar variation.

spurious. If the spurious cases could be eliminated the average temperature departures would doubtless be increased above their already large magnitudes.

The plain inference from these data is that short-interval solar changes are major causes, controlling weather for many days. It is so unexpected that I made other checks, described as follows:

. . . . as I showed in my paper, "The Dependence of Terrestrial Temperatures on the Variations of the Sun's Radiation," above cited, not only do several cities show large opposing trends of temperature following rising and falling sequences of observed solar variation, but 46 cases of unusually great observed solar changes were followed on the average by 1.95 times as large temperature changes in the same phases as the mean of 150 cases of all amplitudes. Again, the average trends of temperature following solar changes, as observed in the years 1924 to 1930, were nearly identical in phase, magnitude, and form with those observed in the years 1931 to 1935.

But now I offer a new evidence which I think is even more convincing. If, in reality, the observed variations of the sun were real, and influenced temperatures greatly for 16 days *after* their incidence, there still seems no reason to think there should have been any unusual temperature effects immediately *before* their occurrence. I have therefore computed for each of the 320 dates the march of temperature departures from normal for 16 days *preceding* the dates in question. I have then computed correlation coefficients for Washington as between the average marches of temperature attending rising and falling solar sequences, both *after* and *before* the beginnings of the sequences of solar change.

To fix ideas, I recall that in each division of this test there are 24 lines comprising 17 values each, two lines for each month of the year, selected from the 12 years 1924 to 1935. These pairs of 24 lines of the divisions are separated into two types, one type containing 17 values for days following, and 17 for days preceding the beginning of sequences of observed *rising* solar radiation. The other type comprises 17 values for days following and 17 values for days preceding the beginning of sequences of observed *falling* solar radiation. Two correlation coefficients are to be computed, one including the 204 values of the two contrasted types *following* the supposed critical dates, the other for the 204 values of the two types *preceding* them.

In order to avoid diluting the correlations by including extraneous influences due to previous conditions, each line was first reduced to the level of zero temperature departure, by adding to all 17 values in that line a constant quantity such as to make the average temperature departure for that line zero.

Having thus arranged the values, correlation coefficients were computed between the two types for the two divisions. They resulted as follows:

After appearance of solar change, $r = -54.3 \pm 4.9$ percent, which is significant.

Before appearance of solar change, $r = +11.1 \pm 6.0$ percent, which is meaningless.

The inference is obvious that the 320 dates, above described, were dates of real significance, since no other consideration was used in selecting them, and it is difficult to avoid the conclusion that they were dates when real solar changes began.

Are such small solar changes adequate to produce the apparent effects?

Sir George Simpson in his classic paper, "Further Studies in Terrestrial Radiation" (Simpson, 1928), concludes that 1 percent change of solar radiation might make up to 2° C. average change in the radiative temperature of the earth's surface, but he says that this change would not be distributed uniformly. As a matter of fact, the temperature at any single station is strongly associated with the direction of the wind. The direction of the wind depends on the location of the station with respect to cyclonic centers. Any cause which alters the paths of cyclonic wind movements, alters wind directions and temperatures greatly. Clayton, from statistical studies, finds that variations of the sun, whether indicated by sunspot numbers or by solar-constant observations, are associated with large geographic changes of the centers of the barometric lows and highs. Hence, although a 0.7 percent change of solar radiation cannot produce all over the earth's surface coincidentally a change in the same direction of 5° or 10° F. in temperature, it may very well produce on a given day a rise of 5° or 10° in one place, accompanied by a fall of 5° or 10° in another place. And this indeed is quite in agreement with the comparative results given in figures 1 and 6 of my paper, "The Dependence of Terrestrial Temperatures on the Variations of the Sun's Radiation."

SUMMARY

The preceding paper covers the following points:

1. Evidence that solar variation has been observed by independent stations in the northern and southern hemispheres with amplitudes as much as 18 times the probable error of the mean of the observations as deduced from their average differences.
2. The reality of solar variation is confirmed by many other correlations, including studies of the distribution of brightness across the sun's disk, the spectral distribution of apparent solar variation, its relation to sunspot numbers, and to faculae and flocculae, the 27-day period in solar variation, and relations to atmospheric temperature and pressure.
3. Ten long periods in solar variation are found, ranging from 8 to 273 months. These have nearly a common multiple in 273 months.
4. These solar periods are traceable in terrestrial temperature and precipitation, but phases of terrestrial responses vary with seasons.
5. By analysis of temperature and precipitation records of Copenhagen, Vienna, and New Haven, it is shown that the solar periodicities continued with unaltered phase for at least 140 years, and produced temperature responses apparently competent in their aggregate to account for the total range of departures from normal temperature.
6. Attempts to forecast weather conditions for 5 years in advance by evaluating the solar influences from past weather records and synthesizing them, proved fairly successful.

7. Attempts to forecast weather conditions for 3 years in advance by using the master cycle of 23 years proved fairly successful.

8. Day-to-day changes in solar radiation, largely influenced by the sun's rotation, appear to be major factors in controlling weather for 2 weeks in advance.