SMITHSONIAN MISCELLANEOUS COLLECTIONS
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WEATHER PREDETERMINED BY SOLAR VARIATION

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C. G. ABBOT
Secretary, Smithsonian Institution

(PUBLICATION 3771)

CITY OF WASHINGTON
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1. SHORT SEQUENCES OF SOLAR VARIATION

Referring to my papers "The Dependence of Terrestrial Temperatures on the Variations of the Sun's Radiation" and "Further Evidence on the Dependence of Terrestrial Temperatures on the Variations of Solar Radiation,"[1] I now present new and more extensive proofs of the same thesis.

In table 24, volume 6, Annals of the Astrophysical Observatory of the Smithsonian Institution, were tabulated revised day-to-day solar-constant values, 1924 to 1939. Every value printed under the caption "Preferred Solar Constant"[2] in table 24, just cited, was meticulously scrutinized jointly by my colleagues, Messrs. Aldrich and Hoover and Mrs. Bond. Many errors of preliminary lists used in my papers of 1936 were eliminated. Several additional years of observing are now included. On all these accounts a revision and amplification of the 1936 investigation was desirable.

I shall give in table 1 the dates when sequences of rise and sequences of fall in the solar constant are believed to have begun. This table 1 is parallel to table 1 of my former paper "The Dependence of Terrestrial Temperatures on the Variations of the Sun's Radiation."[3] If the two are compared it will be found that many dates used in 1936 are still retained, that some dates of 1936 are now shifted by 1, or rarely by 2 days, and that certain dates used in 1936 are now rejected in view of more accurate solar-constant data. Only Mount Montezuma and Mount St. Katherine observations have been considered in making up table 1. The average range of the solar variation in the 440 cases tabulated below is only about 0.7 percent. The average

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

[2] For the present study all these values, and those termed "Improved Preferred," were plotted to show sequences of change. In most cases the values "Preferred Solar Constant" are more consistent with meteorological changes, so that my confidence in "Improved Preferred" values has been shaken.

[3] Smithsonian Misc. Coll., vol. 95, No. 12, 1936.

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number of days making a "sequence" of rise or of fall is 4. Hence the average day-to-day change recognized as real in table 1 is of the order of ¼ percent. This is quite at the extreme limit of the accuracy of solar-constant measurements at our best stations. Table Mountain results are not accurate enough to be used in such exacting day-to-day work.

If the reader compares with table 24, volume 6 of the Annals, he will perceive that many of the dates listed in table 1 are extrapolated or interpolated by graphical methods from fragmentary data for lack of *continuous* day-to-day lists of excellent solar-constant values. However, if all such extrapolated or interpolated dates were thrown out, it would not greatly alter the results which appear below. Doubtless some spurious "sequences" of solar-constant change are included in table 1, and some veridical ones omitted, but I believe that not many of these sequences are spurious, or more than 1 day in error in their dates. For, as will be shown below, the weather at far-separated stations responds very harmoniously to the dates given in table 1. These dates are used in all the meteorological computations on which the curves to be given below are based.

On the other hand there is little question that if *excellent* solar-constant values had been available every day for the years 1924 to 1939, many more such sequences of solar change, probably making at least 800 in all, would have been found. Hence, as a probable average, 2½ rising and 2½ falling sequences of solar change per month occur, of sufficient amplitudes to produce important weather effects. Such effects last at least as long as 17 days in each case, as will be shown.

In table 1, the months head the table. The last two figures of the designation of the year and the day of the month when the sequence begins follow for each individual case. Thus: January, rising, 1924, 12th day.

In my former papers, cited above, I investigated in each case the march of departures from normal temperature at Washington and several other stations for 17 days, beginning on the day the supposed sequence of solar change began, and extending to 16 days thereafter. My recent studies have convinced me that solar changes which have meteorological significance begin to exercise influences on weather several days before the changes in the solar constant indicate their existence. Accordingly, in the following investigation I have usually tabulated meteorological data for 20 days, beginning 5 days before the dates of solar-constant sequences given in table 1. A few tabulations and curves have covered 25 days, i.e., 20 days from the beginning of the sequences.

TABLE 1.—*Dates when sequences of rise and fall of the sun's emission of radiation began*

January		February		March		April	
Rising	Falling	Rising	Falling	Rising	Falling	Rising	Falling
24 12	24 15	24 4	27 13	24 17	24 8	24 2	24 9
18	20	27	28 11	23	19	14	18
29	26 1	27 8	29 9	30	25	25 7	23
25 1	9	28 8	30 28	25 18	25 22	15	26 15
26 3	17	17	34 21	25	29	28	29
27 1	28 5	29 2	35 16	26 5	26 20	26 10	27 16
6	14	30 18	21	27 25	28 4	24	28 6
28 9	30	32 5	36 4	28 2	20	27 7	16
28	31 16	34 12	12	24	30 16	22	29 5
31 13	34 4	26	37 8	30 24	31 30	29	32 5
34 20	36 16	35 19	23	30	34 17	28 19	15
35 3	37 6	36 8	38 1	31 22	35 23	29 9	27
10	26	37 2	39 24	28	36 4	30 21	33 4
36 21	38 14	19		32 5	20	32 9	13
29				16	37 1	33 10	34 9
37 8				35 3	10	20	17
14				16	38 9	28	35 1
31				36 9	39 16	34 7	19
38 6				37 6		35 7	27
18				12		14	38 12
26				18		25	39 4
				39 25		36 3	17
						37 8	
						38 7	
						16	
						39 7	
						25	

May		June		July		August	
Rising	Falling	Rising	Falling	Rising	Falling	Rising	Falling
24 8	24 4	24 12	24 3	24 7	24 22	24 13	24 4
12	10	26 6	20	12	30	23	31
27 10	28 6	25	26 15	23	26 12	28 22	26 10
24	20	27 4	27 10	26 5	27 26	29 15	28 5
28 3	29 21	16	29 18	17	28 3	30 24	29 8
9	33 18	28 11	31 1	27 13	19	31 20	21
13	34 5	31 22	32 16	24	26	32 22	30 28
29 1	35 4	32 23	34 4	28 5	29 1	33 18	31 15
30 15	36 13	33 16	35 12	23	12	26	32 4
33 1	30	34 8	36 16	29 4	30 1	34 2	34 8
5	37 10	14	37 6	17	33 13	11	22
35 13	38 6	24	22	32 25	34 6	35 8	35 16
38 4	24	35 19	38 5	33 10	33 5	36 9	36 17
16		23	12	19	36 26	21	24
28		37 4	39 10	34 3	37 26	39 26	37 6
39 21		30	21	13	38 20		19
		39 13		22	39 4		
		25		36 13			
				37 6			
				22			
				38 16			
				39 8			

September		October		November		December	
Rising	Falling	Rising	Falling	Rising	Falling	Rising	Falling
24 3	24 11	24 21	24 3	24 28	24 19	24 6	24 1
23	19	29	27	27 4	26 3	23	25 7
26 3	26 5	26 7	26 1	19	13	25 24	27 8
27 2	27 8	15	10	29 5	27 24	26 2	24
17	14	24	20	19	29 9	27 4	28 22
19	21	27 4	28	31 3	14	19	29 12
26	29	18	27 10	22	31 25	27	30 7
28 17	29 5	26	21	28	33 18	28 14	31 6
23	31 3	28 5	28 8	32 22	34 4	20	17
29 4	9	30 20	21	33 5	35 17	29 15	33 26
12	33 9	31 8	30 4	15	27	31 10	34 17
27	19	18	13	35 15	36 2	32 27	35 29
30 10	34 6	28	31 2	21	19	33 30	36 10
31 11	14	32 3	33 9	36 5	37 23	34 22	37 19
22	21	33 13	22	13	38 13	35 1	38 28
33 4	35 13	34 11	34 13	27	24	37 4	
13	36 20	17	36 12	37 19		38 7	
28	37 7	28	18	38 8		25	
34 10	21	35 14	37 9				
35 9	28	36 9	23				
22	38 6	16	38 5				
36 13	11	37 15					
17		38 9					
37 5							
10							
38 1							
9							
18							
22							
39 4							
11							
21							

With the assistance of Mrs. Bond, Miss Simpson, and Miss Carter, computations have been carried through for temperatures, and in certain cases barometric pressures, at Washington and several other stations, similar to those described in my papers of 1936.

In figure 1 I give a photographic reproduction of a complete computation and graphical illustration of the work for the month of March at Helena, Mont. This enables the reader to see exactly what is done with the data of a single station for one month of the year, and he is assured that the same procedure was followed with all stations in all cases.

In figures 2, 3, and 4 I give graphical summaries of the effects of *changes* of solar activity on the temperatures of Helena, Mont., Albany, N. Y., and Washington, D. C. As I have found difficulty in explaining these illustrations to visitors at the Smithsonian Institution, I shall go into great detail on points which seem to be often misunderstood and try to make these three groups of curves perfectly clear. Then subsequent illustrations of the same kind will, I am sure, be readily understood.

In the first place, there are *no solar-constant values whatever* plotted in figures 2 to 4. All the curves are plotted solely with *differences from normal temperature* as ordinates, and with successive days as the time scale of abscissae. The purpose is to show what is the average march of temperature changes during an interval of 20 days which is associated with average sequences of rise or of fall of the solar constant of radiation lasting for average intervals of 4 days for each such sequence, beginning on the zeroth day, and having the average range of 0.7 percent. As the temperature effects are found to display themselves 2 or 3 days before the solar-constant sequences of rise or of fall begin, and continue at least 2 weeks after the solar-constant sequences have begun, the temperature departures are tabulated from 5 days before until 14 days after the zeroth day of the solar-constant sequences.[4]

Expectation indicates, and experience confirms, that the effects of changes of solar activity on temperatures at a given station will differ at different seasons of the year, because many terrestrial conditions, such as cloudiness, wind direction, wind strength, snow covering, etc., alter through the year. Hence a separate investigation is made for each month of the year.

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[4] It may be that if the tabulation had been continued to cover 20 or 25 days instead of 14 after the event, significant temperature effects would have been discovered at some stations over even longer intervals. In subsequent illustrations I give some curves extending for 20 days after the zeroth day.

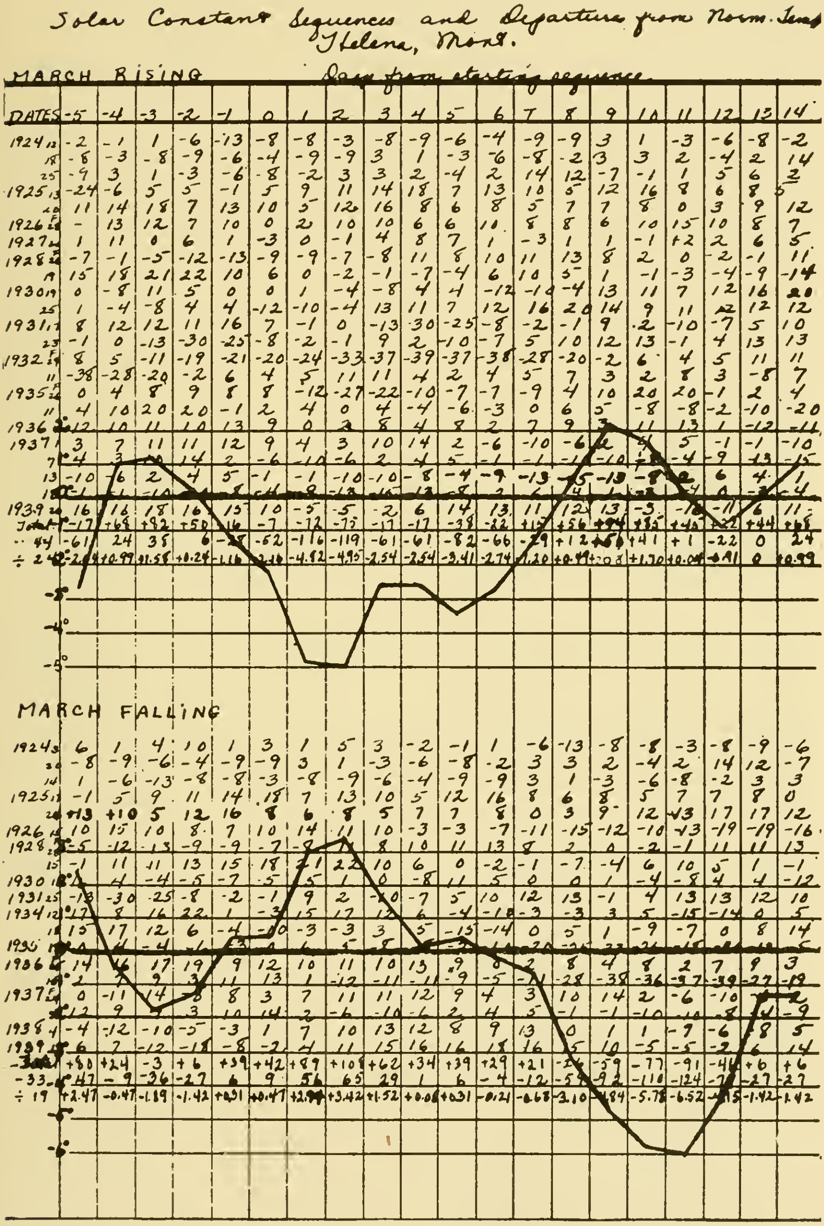


FIG. 1.—Temperature departures, Fahr., at Helena, Mont., in March, accompanying sequences of rise and of fall of the solar constant of radiation beginning zeroth day.

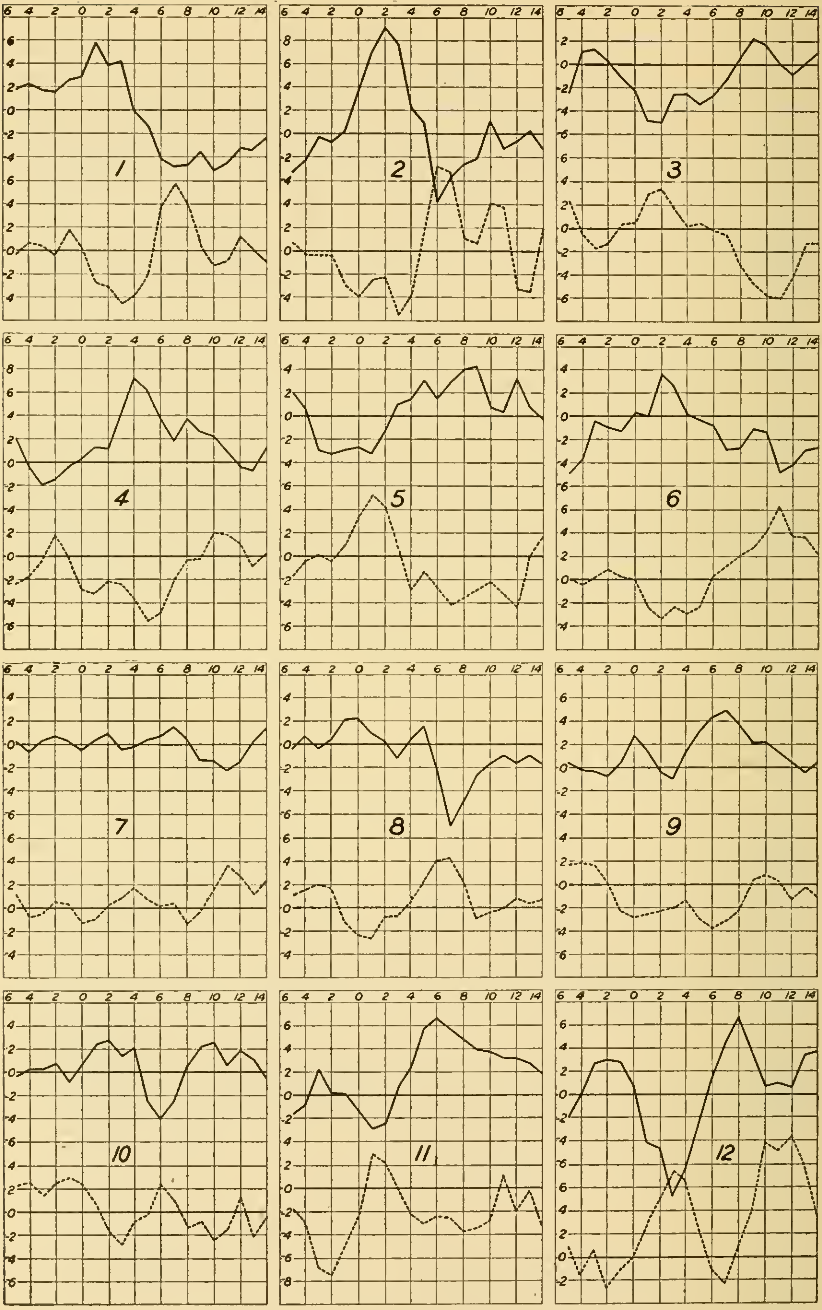


FIG. 2.—Average marches of temperature departures, Fahr., at Helena, Mont., accompanying sequences of variation of the solar constant, January to December.

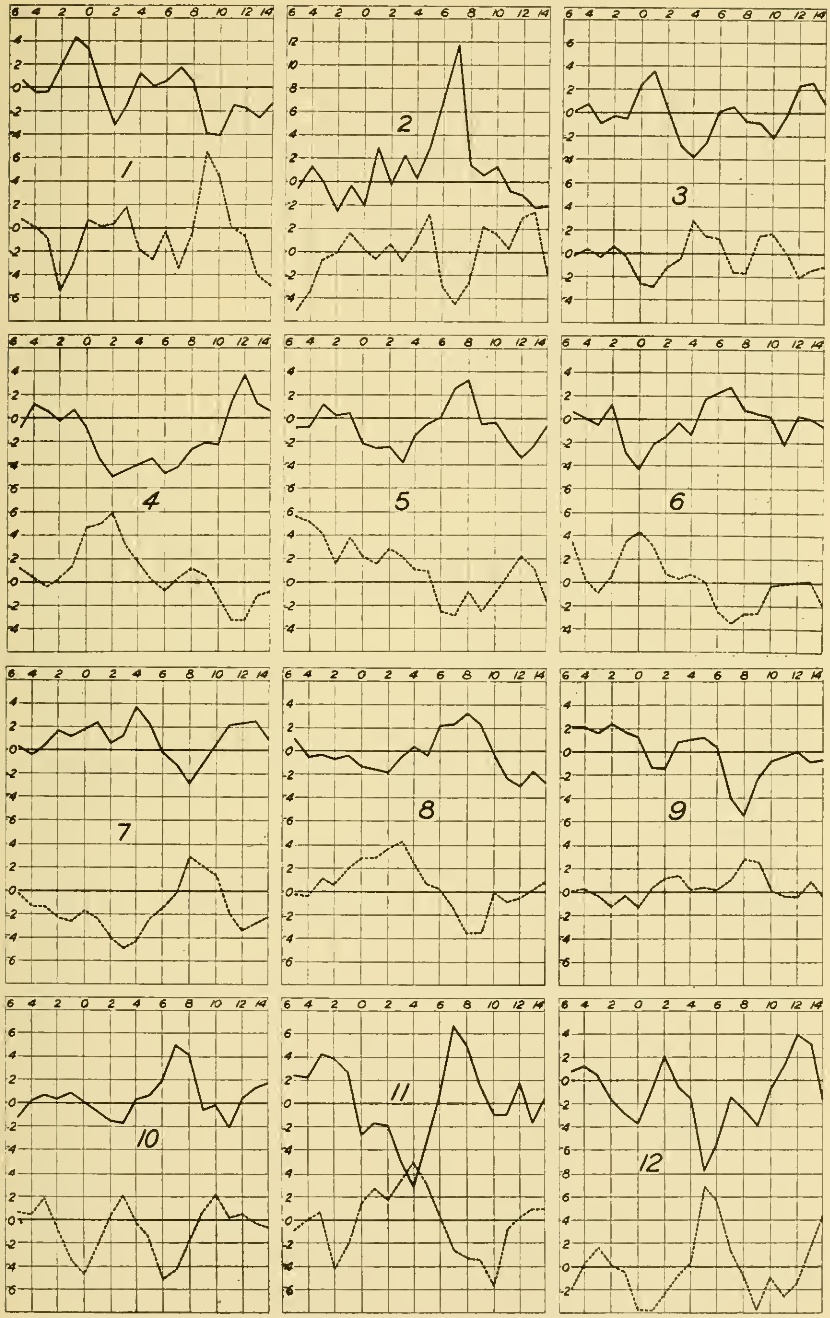


FIG. 3.—Average marches of temperature departures, Fahr., at Albany, N. Y., accompanying sequences of variation of the solar constant, January to December.

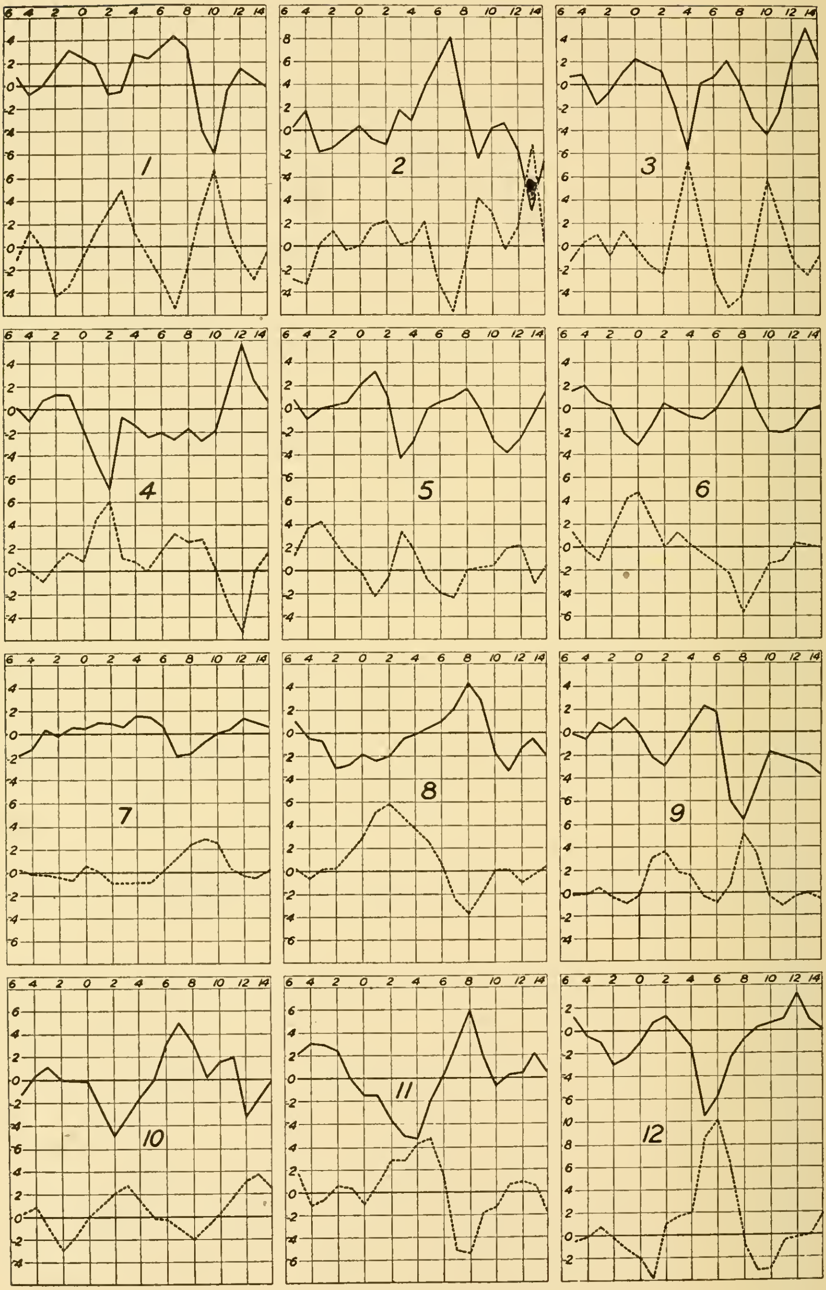


FIG. 4.—Average marches of temperature departures, Fahr., at Washington, D. C., accompanying sequences of variation of the solar constant, January to December.

Inasmuch as experience shows that solar-constant changes are associated with *large* temperature changes, and appear to influence temperatures for *many* days, it is clear that average effects can be well determined only if large numbers of separate cases are tabulated. Hence we collect all the dates when well-marked sequences of rise of solar constant occur in a given month, as March, for example, for all the years when fairly satisfactory solar-constant observations at our excellent stations Montezuma or St. Katherine are available, that is from 1924 to 1939. The procedure will be clear if the reader will compare figure 1 with the month of March in table 1. The reader will then see that for every date in the March "rising" column of table 1, a line of values of departures from normal temperature is tabulated in figure 1. The line at the bottom of the "rising" table in figure 1 is the mean of all lines given above it, and these mean values give the ordinates of the upper curve for March in figure 2. A precisely similar tabulation for all "falling" March cases given in table 1 yields the mean lower curve for March in figure 2.

Owing to the unavoidable inclusion of some spurious dates of solar-constant sequences; to the fact that the sequences used have various amplitudes ranging from 0.4 to 1.5 percent, and yet neglect those too small to observe satisfactorily but still large enough to affect temperature; to the fact that other sequences of solar-constant change than the particular one being singled out are apt to occur before or after a zeroth day at times near enough to produce considerable disturbing effects; to the fact that the total number of sequences tabulated in table 1 is divided into the two classes "rising" and "falling," and each of these classes is subdivided into 12 groups to correspond to the 12 months of the year so that comparatively few cases per group are used; and finally to the fact that though solar changes are evidently a major cause of temperature changes, variable terrestrial influences not taken into account are also important—on all of these accounts it results that accidental fluctuations are by no means fully eliminated in the mean values plotted in figures 2 to 4 and other curves of the kind. Hence the reader must use some leniency in making comparisons of "rising" with "falling" curves of temperature march, and not be too harsh if he finds these curves not *exactly* mirror images of one another. But that they do tend strongly to be so the correlation coefficient -61.2 ± 1.7 percent to be given in the next paragraph testifies.

To prove more convincingly the thesis that solar changes of opposite signs tend to produce opposite changes in terrestrial temperatures, I have computed the coefficient of correlation between temperature changes associated with rising and falling solar sequences for all months of the year from 3 days before to 14 days after the zeroth day of solar-constant change, using the three stations, Washington, Albany, and Helena. For these three American stations, in other words, I have correlated the mean values of daily temperature departures attending rising and falling solar sequences, respectively, for $3 \times 12 \times 18 = 648$ pairs. The result of the computation of the correlation coefficient is as follows:

$$r = -61.2 \pm 1.7 \text{ percent.}$$

It appears to be undoubtedly significant.

I reserve further discussion of the curves of temperature and barometric pressure in relation to solar-constant change until I have considered another well-known solar phenomenon.

There has hitherto been general reluctance on the part of astronomers and meteorologists to accept as veridical either the day-to-day changes of the solar constant recorded by Smithsonian publications, or their important effects on weather. This is due partly to the small percentage magnitudes of the reported changes, averaging for well-marked cases, as stated above, about 0.7 percent, and partly because there is no theory hitherto published in the literature which mathematically demonstrates how such small percentage changes in the solar emission could produce such major weather effects. My own explanation is that changes of the solar constant, which produce, as Clayton has shown, large geographical displacements of the atmospheric centers of action, thereby change the lines of march of cyclones and anticyclones. This alters the direction of the winds at all stations, and with that alteration the temperatures alter, as is well known.

I cannot but feel that an unbiased view of the results thus far given in this paper may convince many readers that the statistical evidence for such weather effects is strong, however feeble may be as yet the theoretical foundation. But it is still possible to add independent support to the statistical evidence, which may overcome the doubts of others who hitherto have remained unconvinced.

2. INDEPENDENT EVIDENCE OF SOLAR VARIATION

From the year 1910 through the year 1937 the Smithsonian Institution has received the publication "Observatorio del Ebro Boletin Mensual." This valuable publication contains daily records of many kinds of phenomena, including not only meteorological data, but measurements of the areas of calcium flocculi at definite distances from the center of the solar disk as photographed with the Hale spectroheliograph. It occurred to me to compute from the Ebro observations for each day of record a character figure suitably compounded from these measured areas and distances. After much trial and investigation of correlation between solar-constant values and areas of flocculi, with which I will not burden this paper, I fixed on the following formula.

The character figure is the weighted sum of the areas given in the column "S.M." of the Ebro Boletin, each area being weighted with regard to its distance from the center of the visible solar disk, according to the scheme below.

Percent radial distance, ρ	0–20	21–40	41–60	61–80	81–100
Weight of area	10	7	5	3	1

Mrs. Bond and Miss Simpson have tabulated the character figures for me of all days of Ebro solar-flocculi observations, 1910 to 1937, according to the formula just described.

It was at once apparent that these character figures showed sequences of rise and of fall. I went over the entire table, and scored in red every well-marked rising sequence, and in blue every well-marked falling sequence. In illustration I give the original data from the Boletin Mensual, the character figures corresponding, and the rising and falling sequences of calcium flocculi for the month of October 1926. For lack of red and blue printing I will use single lines opposite rising sequences of calcium flocculi, and double lines opposite falling ones.

I have chosen a month when the solar constant was observed every day and observed in common on 18 days at both of our best stations, Montezuma and St. Katherine. The observations at Ebro, unfortunately, were not so continuous. However, as the reader will see, a fall of the solar constant indicated from September 29 to October 7 was apparently accompanied by a fall of character figures for Ebro. The rise of solar constant, October 7 to October 12, seems to have been accompanied by a rise of character figures. Again the fall of solar constant October 12 to October 15 was accompanied by falling character figures, which, however, continued to fall perhaps even to October 24. Yet the absence of several days' observations at Ebro may possibly have covered up a rise of character figures to accompany the rise of solar constant which culminated on October 22. A fall of character figures from October 22 to October 24 is indicated, corresponding to the fall of the solar constant. The moderate rise of solar constant October 25 to October 28 appears to have been accompanied by a moderate rise of character figures. The low solar constant of October 30 is of unsatisfactory grade, and has no significance.

TABLE 2.—*Solar-constant data and solar-flocculi data for October 1926*

Day	Preferred solar constant	Grade	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Area S. M.	ρ	Σw (S. M.)	Sequences
1	44	c	72	57	142	41	62	53	38	78	..	..	..	..	..	..	..	..	1494	
2	48	d	66	65	144	40	64	35	36	64	..	..	..	..	..	..	..	..	1474	
3	43	b-d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
4	37	p-b	48	78	88	61	50	33	28	46	..	..	..	..	..	..	..	..	898	
5	32	d-p	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
6	34	d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
7	26	p	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
8	36	d-c	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
9	41	c-b	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
10	46	c-c	44	70	130	37	256	24	88	45	30	72	252	71	40	95	..	..	4160	
11	42	c-b	38	83	118	56	268	22	70	32	46	62	310	53	64	86	46	94	4792	
12	46	b-d	22	94	112	74	228	37	58	30	22	52	316	34	80	74	134	84	5056	
13	43	b-d	108	88	234	56	28	45	18	50	328	22	68	58	166	71	42	91	4684	
14	38	b-p	68	96	256	71	26	57	326	24	76	46	202	58	48	87	..	..	4686	
15	34	b-d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
16	37	c-d	140	94	42	85	234	57	66	36	288	32	86	61	..	..	..	..	4088	
17	39	c	30	95	260	74	40	18	262	35	122	46	18	93	..	..	..	..	2948	
18	36	b-d	186	88	28	66	254	49	132	38	26	82	10	94	..	..	..	..	2500	
19	45	d	108	96	20	80	224	66	128	41	32	67	16	82	..	..	..	..	1592	
20	41	c	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
21	43	b	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
22	52	c	78	96	112	78	50	36	16	33	34	90	..	..	..	..	..	..	910	
23	31	c-d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
24	32	c	62	55	28	22	112	62	34	97	..	..	..	..	..	..	..	..	876	
25	27	c-c	44	69	16	38	146	44	98	94	96	14	..	..	..	..	..	..	1086	
26	43	d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
27	29	c-d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
28	35	b-p	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
29	33	c-p	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	
30	22	p	110	69	182	30	32	28	54	66	16	84	..	..	..	..	..	..	2006	
31	33	d	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	....	

While I might continue to complete a direct comparison of the changes of the solar constant with the sequences of Ebro character figures, covering the interval from the year 1924 to the year 1937, such a direct comparison would be laborious and prove rather unconvincing. For the loss of many days of observation, both of the solar constant and of the areas of flocculi; the unavoidable errors occurring at the very limit of accuracy of solar-constant determinations; the extreme taxing of the judgment of one who seeks to fix the exact limits of areas of the ill-defined clouds of calcium on the solar disk; the errors due to the inequalities of photographic sensitiveness and exposure, and of astronomical seeing from day to day; the arbitrary empirical nature of the character figures themselves, which pretend to take into account the relative effectiveness of changes in different regions of the solar disk—all of these, and still other sources of error, make it impossible that a close correlation should be found between solar-constant changes and changes of the character figures.

But there remains a way of testing such a correlation, whereby the errors of individual sequences both of the solar constant and of character figures may be minimized in an assembly of great numbers of them. Taking the most well-marked sequences of character figures from 1910 to 1937, inclusive, I have computed curves of associated temperature change for Washington, comparable to those determined from solar-constant sequences, as illustrated for the month of October in figure 5. The reader is urged to bear in mind that in this new computation from sequences of character figures no attention whatever is given to the dates printed in table 1. A new and much larger series of dates is drawn from sequences of character figures alone, covering all the years 1910 to 1937, inclusive. Curves like those shown in figure 5 resulted.

In order to make a comparison readily between curves thus determined by calcium-flocculi character figures and those determined by solar constants given in figure 4, I show superposed in figure 6 the two sets of curves relating to Washington temperatures for all months of the year. One set is determined altogether from solar-constant work of the Smithsonian Institution, 1924 to 1937, and has already been given in figure 4. The other set is determined altogether from observations and measurements of the Observatorio del Ebro, 1910 to 1937. The reader may easily identify them, because all the Ebro curves are displaced 2 days to the right in the figure.

Except that the amplitude of the Ebro character figure and temperature curves is slightly less than that of the Smithsonian solar-

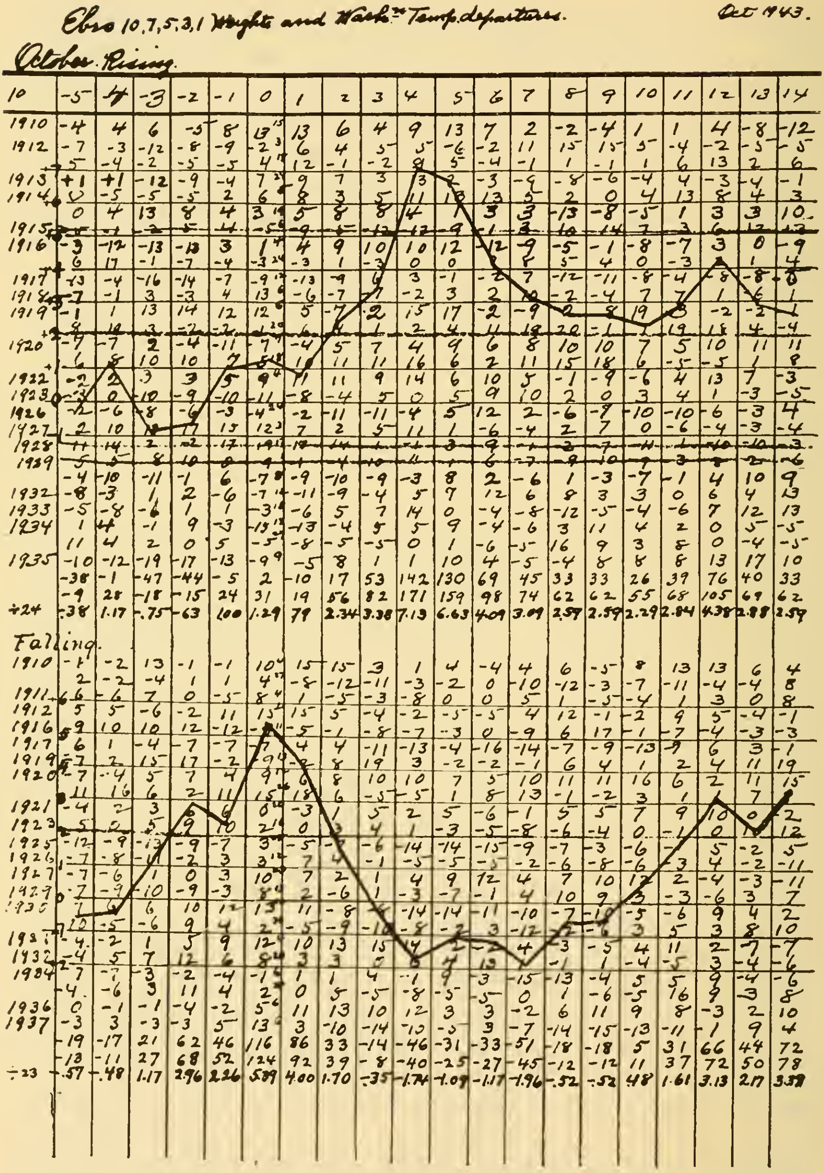


FIG. 5.—Temperature departures, Fahr., at Washington, D. C., in October, accompanying sequences of rise and of fall of the character figures of solar calcium flocculi, beginning zeroth day.

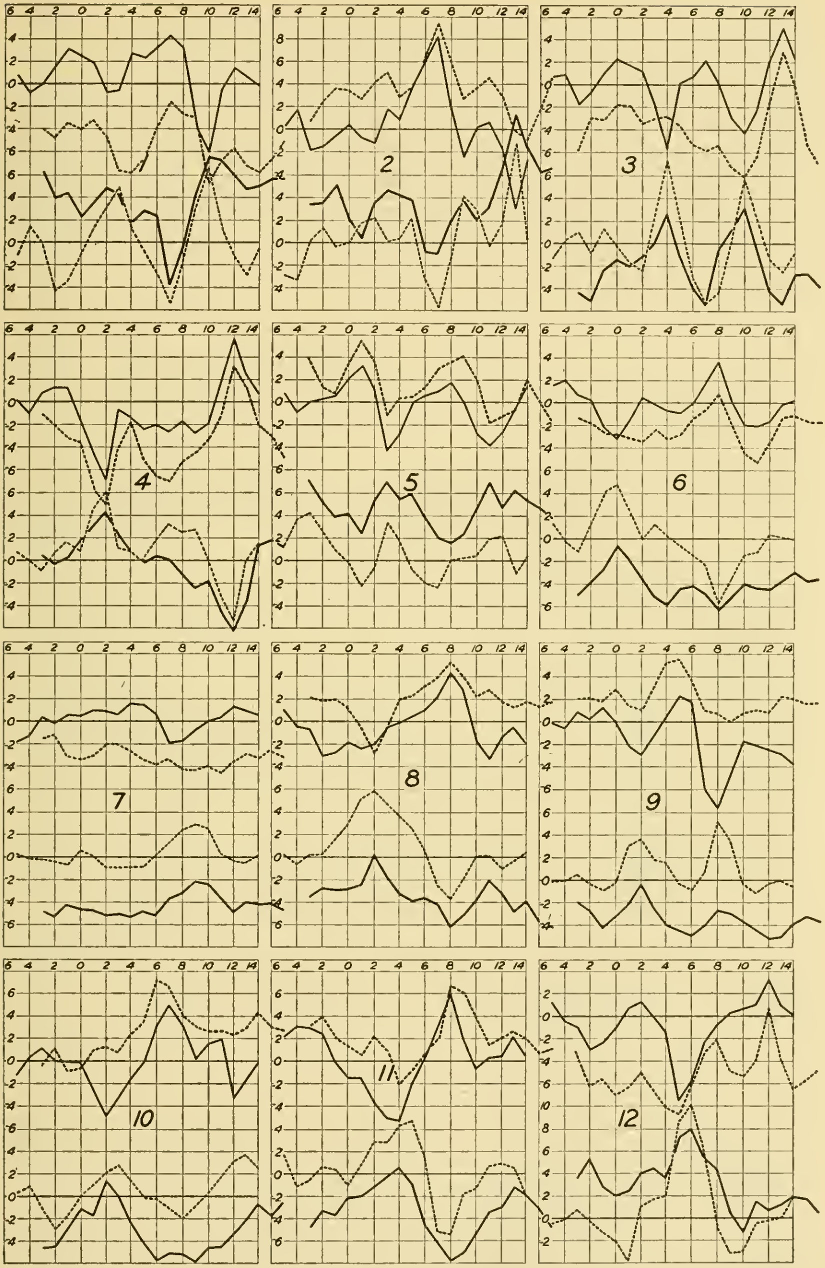


FIG. 6.—Average marches of temperature departures, Fahr., at Washington, D. C., accompanying sequences of solar change (a) of the solar constant in years 1924 to 1936; (b) of character figures for solar calcium flocculi in years 1910 to 1937, for months January to December. Ordinates are temperature departures; abscissae are days from beginning of solar-constant sequence. Flocculi band curves are displaced 2 days to right.

constant and temperature curves, doubtless because some spurious Ebro sequences were included, owing to the difficulties of measuring areas of flocculi enumerated above; and except that there is a phase difference of 2 days between the 2 sets of curves, depending on unknown peculiarities inherent individually in these two altogether dissimilar types of solar phenomena—apart, I say, from these two not surprising differences, the two sets of curves are significantly in correlation. This holds for all months of the year. The correlation coefficient, indeed, is 59.7 ± 1.9 percent.

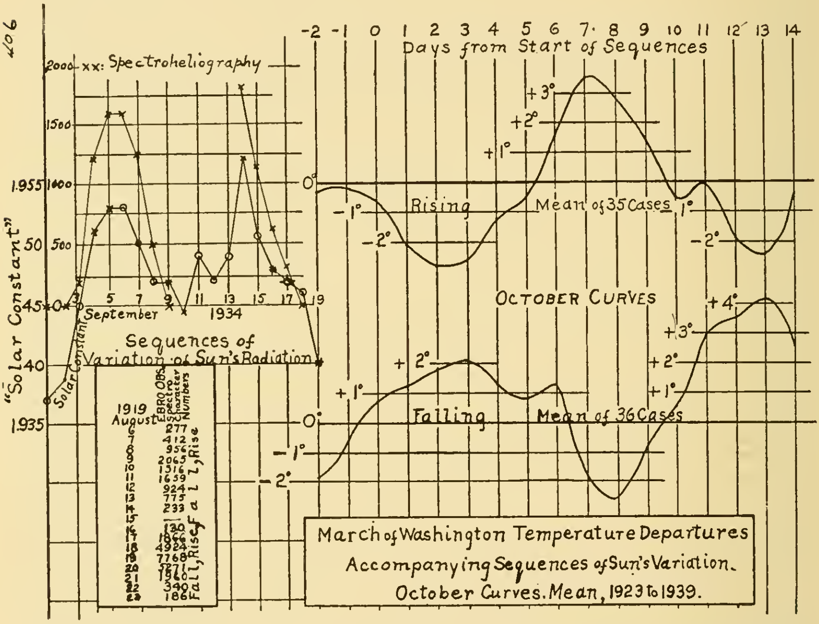


FIG. 7.—Upper left, sequences of character figures of flocculi compared with sequences of solar-constant variation, September 1934; lower left, character figures used. Right, preliminary curves of temperature departures.

3. SUMMARY OF TEMPERATURE EFFECTS OF SHORT SEQUENCES OF SOLAR VARIATION

Up to this point these investigations of the correlation between variations in solar activity and temperature departures at widely separated stations indicate the following conclusions:

1. At every station, and in nearly every month, the temperatures depart in opposite directions, attending, respectively, rising and falling solar activity. Thus comes about an axial symmetry of the pairs of curves, such for instance as subsists with one's right hand and one's left.

2. The march of the curves differs from month to month, and differs for the same month from station to station, yet the right and left symmetry nearly always prevails.

3. The effects are large. Differences of temperature of the order of 10° Fahrenheit, or more, depend on whether a rising or a falling sequence of solar activity preceded them many days before.

4. The effects of solar changes on temperature persist for many days. They may surely be traced from 3 days before to 14 days after the zeroth day of the solar sequence.

5. The coefficient of correlation of these curves for the three stations and the 12 months of the year, and from 3 days before to 14 days after the solar change, is found to be $r = -61.2 \pm 1.7$ percent.

6. Since far-separated cities respond similarly in these respects to the common system of dates given in table 1, this system of dates must have a cosmic significance. The system of dates, in other words, betrays an extraterrestrial selection, harmonious to the claim that on these dates changes in radiation occurred in the sun.

4. POSSIBILITY OF WEATHER FORECASTS BASED ON SHORT SEQUENCES OF SOLAR VARIATION

As it is thus indicated that solar changes dominate weather for many days in advance, the question immediately arises if forecasts can be made from solar-constant observations. I have made a preliminary test of this possibility. Using the basic curves reproduced in figure 4, and the dates of sequences of solar change indicated by Ebro observations, with allowance for phase difference as noted above, I have synthesized the solar influences on the temperature of Washington for the months March and April of 1911 and 1915, and the months of September and October of 1917 and 1935, and have compared these purely solar predictions which ignored entirely terrestrial influences, and covered altogether 201 days, with the known events. In making these computations I took into account, in estimating the relative amplitudes of sequences, the smallness of character figures at times of sunspot minimum; and, recalling from Smithsonian Miscellaneous Collections, vol. 95, No. 12, the demonstration that sequences of solar change of large amplitudes produce relatively large temperature effects, I made allowances for this also.

The method of synthesizing is of course simple. One writes down for 20 successive days the effect on Washington temperature according to figure 4 corresponding to each sequence of solar change revealed by Ebro character figures. Corrections for sequence intensity were made as just indicated. Summing up the several effects of the successive sequences, there results the expected march of temperature departures. It must be remembered that these computed effects correspond to solar changes alone. No allowance at all is made for unknown and unpredictable terrestrial influences on atmospheric circulation. Therefore, such purely solar predictions cannot be expected to tell the whole story accurately. Moreover no employment can be made of the weather influences of minor solar changes, too small to be certainly recognized, but yet probably not negligible.

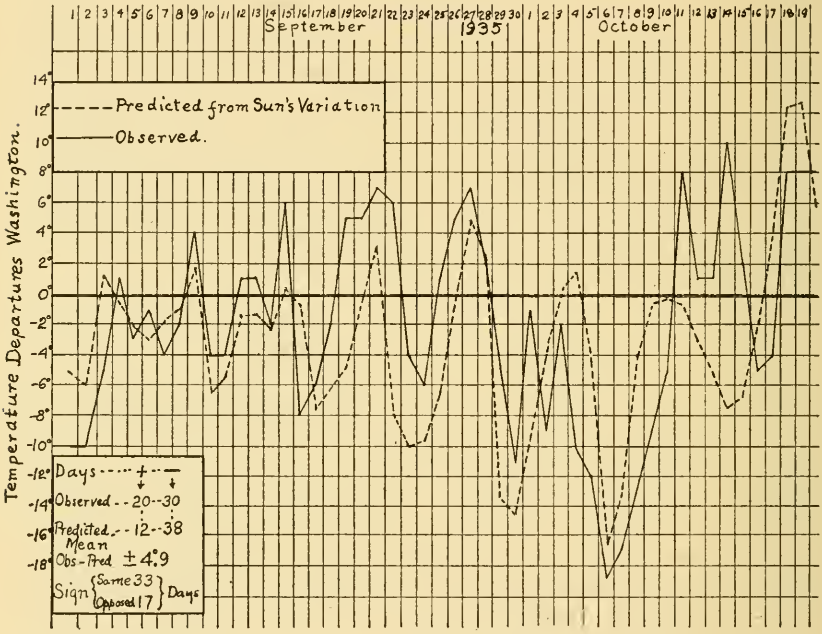


Fig. 8.—Forecast and verification of Washington temperature departures.

The result of this preliminary test of purely solar prediction, which may be regarded as a prediction 10 days in advance, is given in figure 8 and table 3.

If the reader should be persuaded that this preliminary test offers possibilities of real usefulness for weather prediction, and inquires why we do not already practice such solar forecasting, I have to reply that at present there are no means of knowing when all sequences of solar change are beginning. Our three solar-constant observing stations cannot furnish a continuous day-to-day record, nor are their combined results of sufficient accuracy to indicate surely the incidence of all significant solar changes uncontaminated by spurious additions. To make regular predictions, about 10 stations, occupying the best mountain localities available in the world for solar-constant work, would be required.

It may be suggested that the spectroheliographic observatories could furnish the necessary dates of approaching solar changes. If so, table 1 of this present paper, in combination with daily weather records, could supply the required basic curves for prediction at all localities. I have to reply that my colleague Mr. Aldrich and I have spent about 6 weeks on the measurement of Mount Wilson spectroheliographic photographs, kindly loaned by Director Adams for our study. We have regretfully concluded that many difficulties, some of which are enumerated above, prevent the determination of the solar-flocculi character figures with sufficient certainty to base predictions upon. Possibly others more experienced in such difficult estimates could do better. To us it seems, however, that solar weather forecasting must apparently await a large expansion of the solar-constant observing facilities, unless, indeed, airplane or sounding-balloon observing, or some hitherto untried method may supply means of discovering regularly all the dates when significant solar changes occur.

TABLE 3.—*General summary of a purely solar prediction of the departures from normal temperature at Washington, covering the months March and April of 1911 and 1915, and September and October of 1917 and 1935*

Total days predicted	201
Observed and predicted of same signs	139
“ “ “ “ opposite signs	62
Observed departures plus	65
Predicted “ “	64
Observed departures minus	136
Predicted “ “	137

			Percentages
Differences, Obs.-Pred.	0° to 2°	66	32.7
“ “ “	3° to 4°	43	21.3
“ “ “	5° to 6°	32	15.8
“ “ “	7° to 10°	33	16.3
“ “ “	11° to 15°	20	10.0
“ “ “ greater than 15°		8	4.0
“ “ “ less than 6°			69.8
“ “ “ more than 6°			30.3
“ “ “, general mean		5°.35	

Correlation coefficient 56.9 ± 3.2 percent.

5. ADDITIONAL DATA ON WEATHER EFFECTS OF SHORT SEQUENCES OF SOLAR VARIATION

To indicate more fully the influences of sequences of solar change on weather I give additional figures 9 to 16, some relating to temperature, others to barometric pressure. In addition to these I would refer also to the graph relating to temperature departures at Potsdam, Germany, figure 2 of my paper cited above, "Further Evidence on the Dependence of Terrestrial Temperatures on the Variations of Solar Radiation" (Smithsonian Misc. Coll., vol. 95, No. 15, 1936).

Prevailingly the opposition, or right- and left-handed symmetry already noted, is found in these illustrations. Yet there are many exceptions. Thus in the Potsdam temperature chart the months May and June exhibit parallelism rather than opposition. The same is very strongly marked for the temperature charts of Ebro for June. Other months at Ebro show mixed effects, though prevailingly opposition. In temperature tabulations at other stations parallelism occurs for certain months, and most frequently for the months of June, August, and November.

As for the charts relating to barometric pressure, they indicate on the whole a lesser degree of control over barometric pressure by sequences of solar variation than is generally to be noted with temperature departures. This is not surprising. The changes of barometric pressure are not, like temperatures, direct functions of solar irradiation. The absorption of the sun's rays within the atmosphere and on the earth's surface is a direct first-hand action. But to produce barometric effects changes of insolation first affect atmospheric temperatures, then modify thereby atmospheric circulation and barometric pressures. True, the sun has a direct effect on the barometer by tidal action too, but this is a regular periodic phenomenon, and is not of the type to produce the effects we now consider.

Nevertheless, the curves dealing with pressure changes do show, on the whole, a tendency toward that opposing symmetry of effects which is so marked with temperature departures. As notable illustrations see the barometric pressure charts for December at St. Louis and Denver. But exceptions, substituting parallelism for opposition, are numerous. Irregular curves, apparently quite uncorrelated with solar sequences are also found.

In some instances the surprising phenomenon is noted that while the temperature departures show the normal right and left symmetry of opposition, the barometric pressures show conspicuous parallelism. Cases also occur when barometric pressure curves show normal opposition, while temperature departure curves show parallelism. In illustration I cite Ebro, November and June, respectively.

Several stations are available where both elements have been studied, and I tabulate in the following table 4 the relationships observed between them. Certain symbols are used. Opposed, + ; parallel, = ; excellent, e ; good, g ; poor, p ; mixed, partly + and partly =, is indicated by ×. Lengths given refer to days before and after the zeroth day that sequences seem to exert some control over the march of curves.

It will be noted from figures 9 to 16 that the influence of sequences of solar change on weather at all stations is prevailingly much greater in winter than in summer. In fact, in many cases the amplitudes of the features of the curves relating to months from May to August are too small to fix certainly the nature of the average march of these curves, owing to the small number of cases as yet available to compute the mean values. Additional data on solar variation would have to be obtained to eliminate the confusion resulting from solar changes of contrary sign following on each other's heels, and from accidental influences of terrestrial complications.

6. DURATION OF INFLUENCES OF SHORT SEQUENCES OF SOLAR VARIATION ON WEATHER

As regards the duration of the effects of solar changes on weather, it has already been remarked that these weather effects begin at least 3 days before the solar-constant sequences begin, and at least 5 days before the calcium-flocculi areas begin to alter. It appears, therefore, that some parent change occurs in the sun, of which as yet we have no inkling. The sequences of change in the solar constant, in the areas of calcium flocculi, and in weather, are all, it would seem, caused by this hitherto unrecognized solar agency. The significant fact that weather is affected *before* the two solar phenomena just named, should lead us to an earnest search to discover the hidden agency involved.

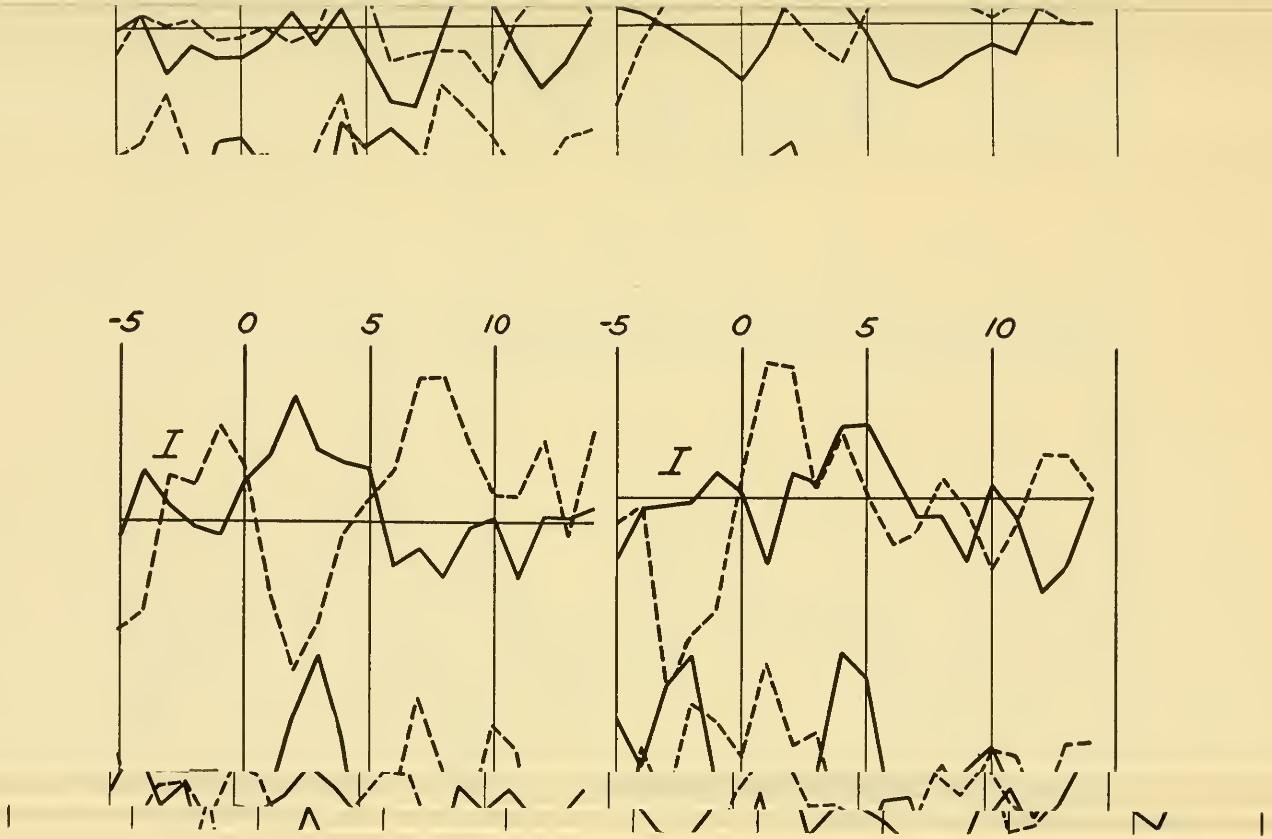
As to the duration of weather effects *after* the zeroth day of solar-constant sequences, I show several curves in figures 9 to 16 in which tabulations up to the twentieth day are illustrated. An attempt is made in table 4 to evaluate the duration of weather effects as indicated by these longer curves. On the whole it appears that the average duration is from −4 to +17 days, or 22 days in all. This gives promise of eventual use in long-range weather forecasting. See, in illustration, the temperature curves for January, June, and October for St. Louis and Salt Lake City.

I cannot but regret, as remarked above, that there are too few cases

TABLE 4.—*Opposition, parallelism, length of effects*

Station	Aspect	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Washington.....	Temp.	+e	+e	+e	+e	+e	+e	+e	+e	+e	+e	+e	+e
	Press.	+g	+g	×p	×p	+g	=g	+g	=p	×	+g	+e	+g
	Length*	−5 to 16	−2 to 16	...	...	−4 to 14	−4 to 16	−3 to 17	...	...	−5 to 19	−3 to 19	−5 to 16
St. Louis........	Temp.	+g	+g	+g	+g	+g	+g	+p	+g	×	+p	+e	+e
	Press.	+g	+e	×	×	+g	+p	=p	+p	+p	+p	+e	+e
	Length	−2 to 18	−2 to 18	−3 to 15	−3 to 16	−2 to 17	−5 to 19	...	−5 to 19	...	...	−5 to 19	−5 to 17
Denver.........	Temp	...	...	...	+e	+p	=p	+g	+e	×	+g	×	+e
	Press.	+g	+g	+e	+g	+g	+p	+g	+p	×	=p	+p	+e
	Length	...	...	...	−5	−5	...	...	−5	...	−3	...	−5
Obs. del Ebro....	Temp.	+g	+g	+g	+g	+p	=g	+p	+p	+g	×	=p	+p
	Press.	=e	=p	+p	=e	+p	+g	+g	+e	+e	+g	+g	+p
	Length	−4	−4	−5	...	...	−5	...	...	−3	...	−3	−5
Salt Lake City...	Temp.	+e	+p	+g	+g	+g	+e	+p	+g	+g	+g	+p	+g
	Length	−5 to 18	...	−3 to 18	−3 to 15	−5 to 19	−2 to 19	...	−5 to 19	−3 to 18	−5 to 18	−4	−3 to 15

* These lengths based on pressure curves. All others on temperature curves. Mean length from −4 days to +17 days, or 22 days' response to each solar impulse in the average.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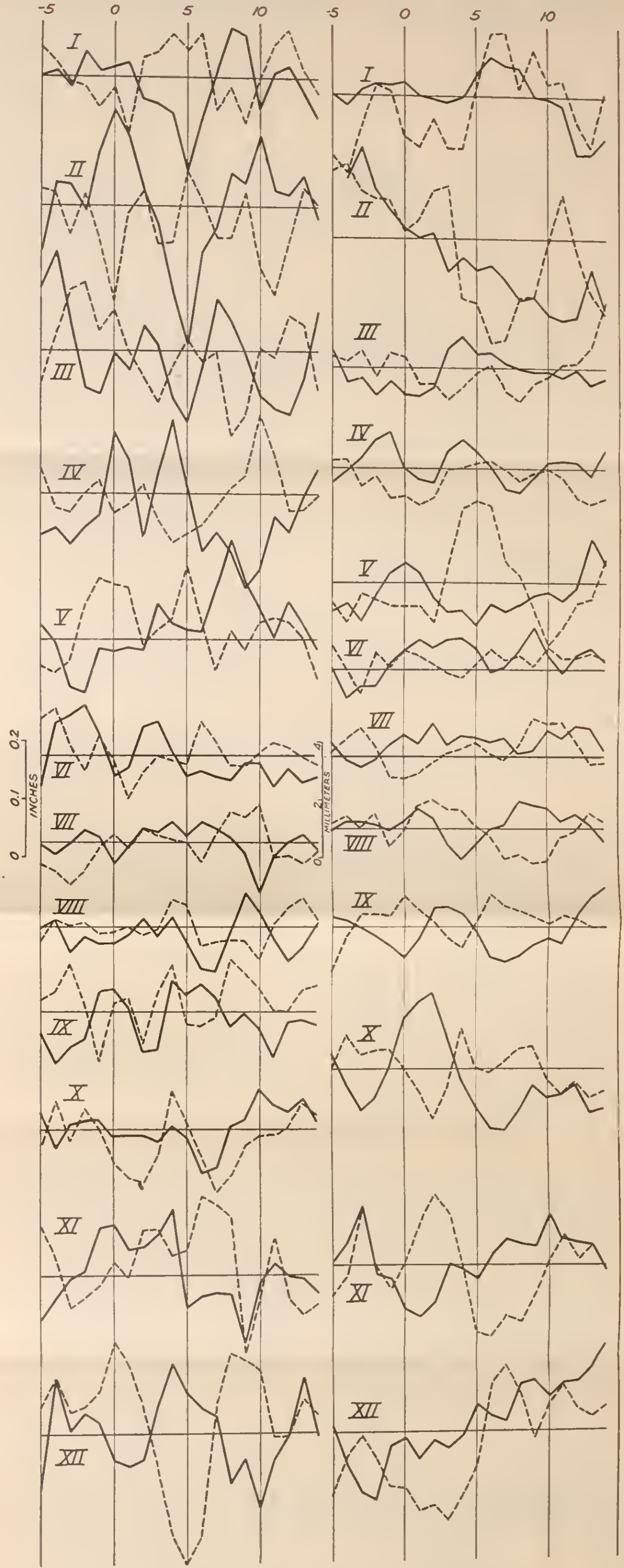


FIG. 9

FIG. 10

FIGS. 9 and 10.—Barometric departures associated with sequences of solar-constant variation for 12 months, January to December, at Denver, Colo. (fig. 9) and Observatory of Ebro, Spain (fig. 10). Full curves, rising sequences; dotted curves, falling sequences.

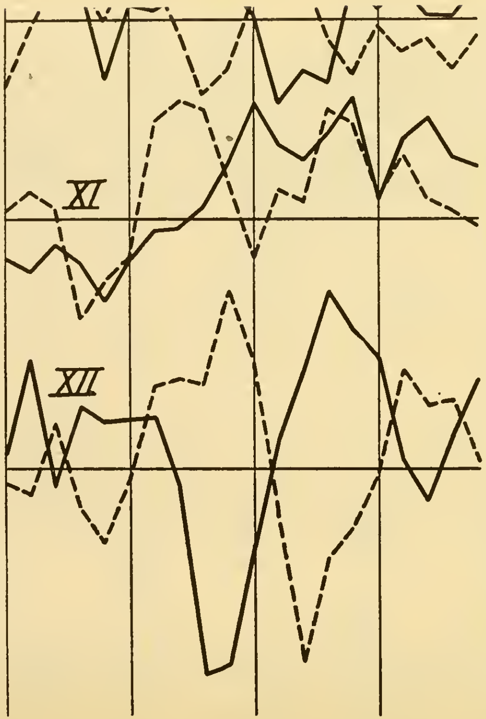


FIG. 11

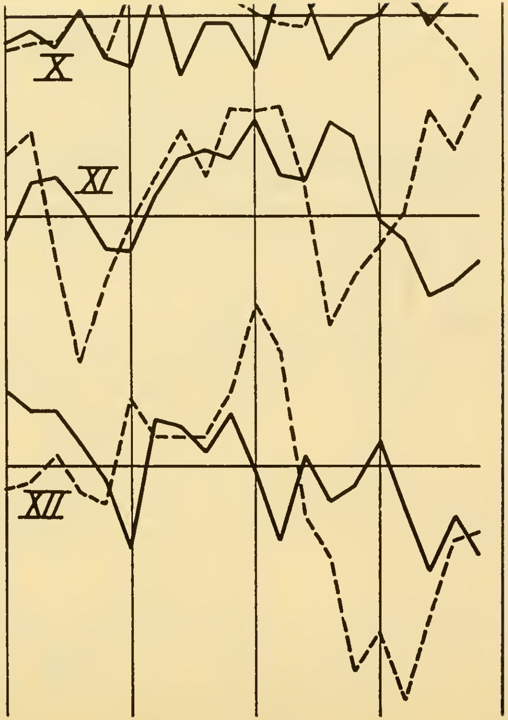
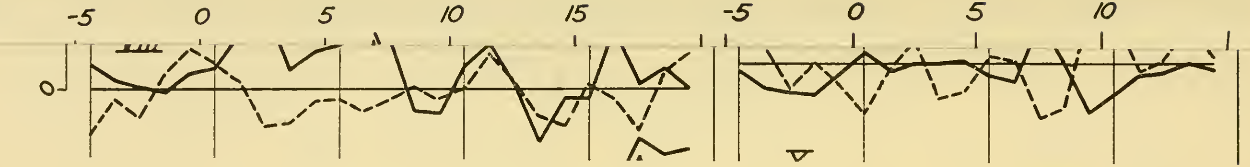


FIG. 12

FIGS. 11 and 12.—Temperature departures associated with sequences of solar-constant variation for 12 months, January to December, at Denver, Colo. (fig. 11) and Observatory of Ebro, Spain (fig. 12). Full curves, rising sequences; dotted curves, falling sequences.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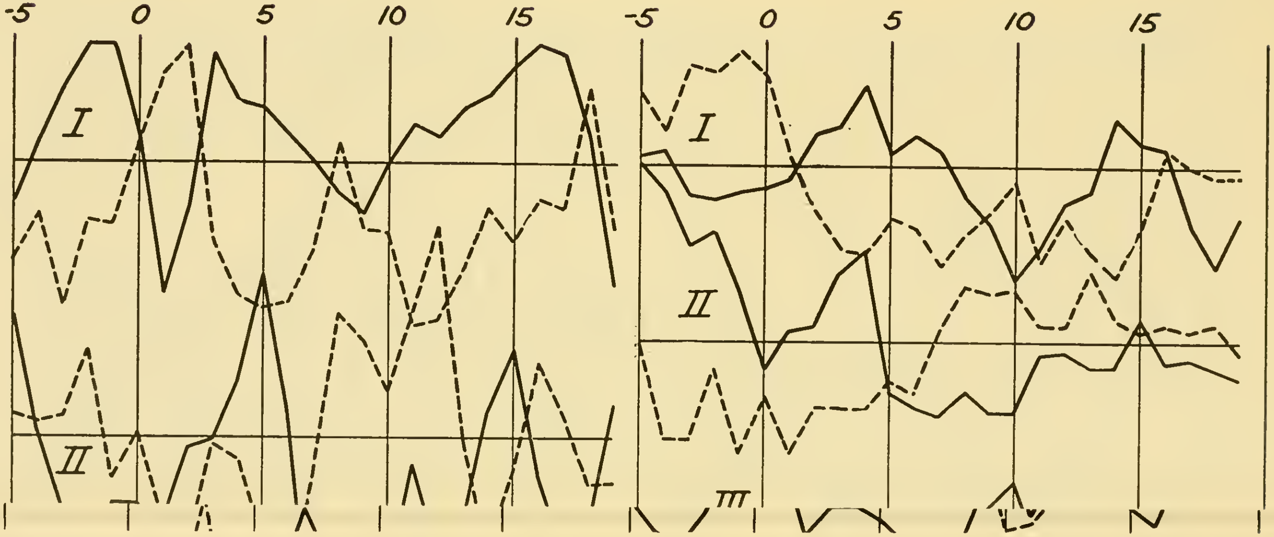
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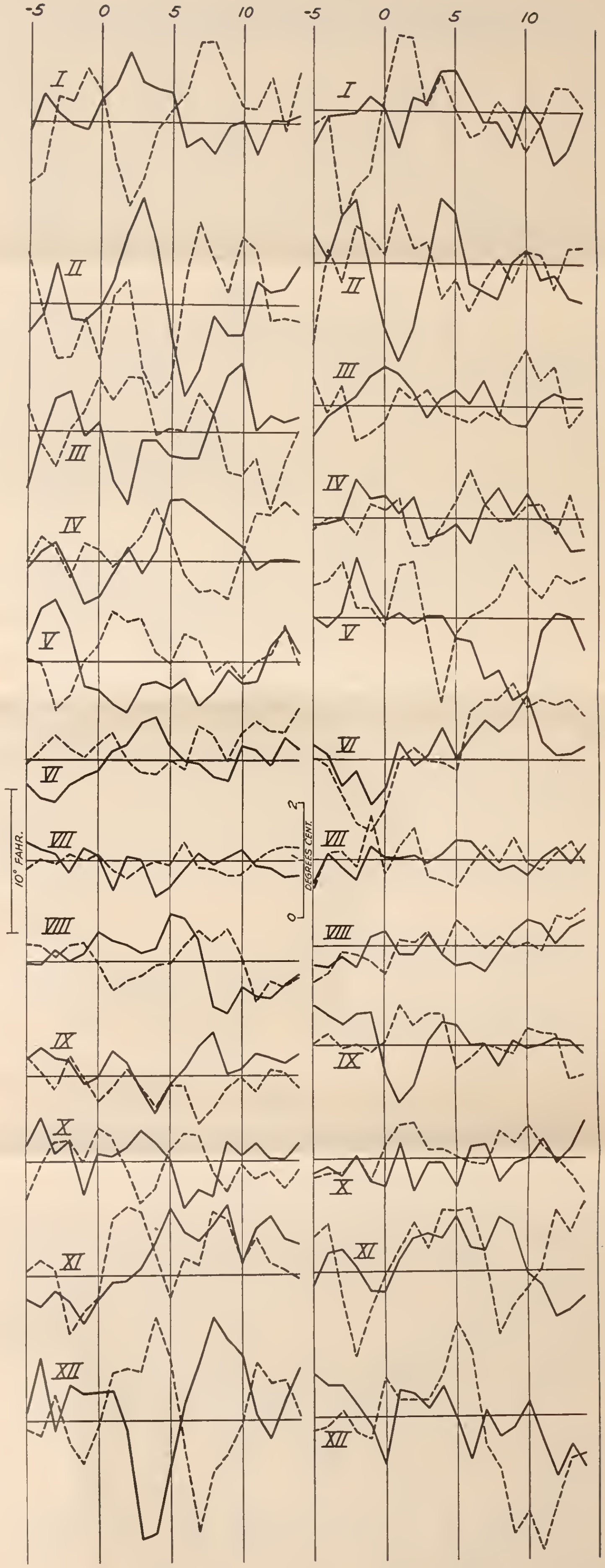

Fig. 11

Fig. 12

Figs. 11 and 12.—Temperature departures associated with sequences of solar-constant variation for 12 months, January to December, at Denver, Colo. (fig 11) and Observatory of Ebro, Spain (fig. 12). Full curves, rising sequences; dotted curves, falling sequences.

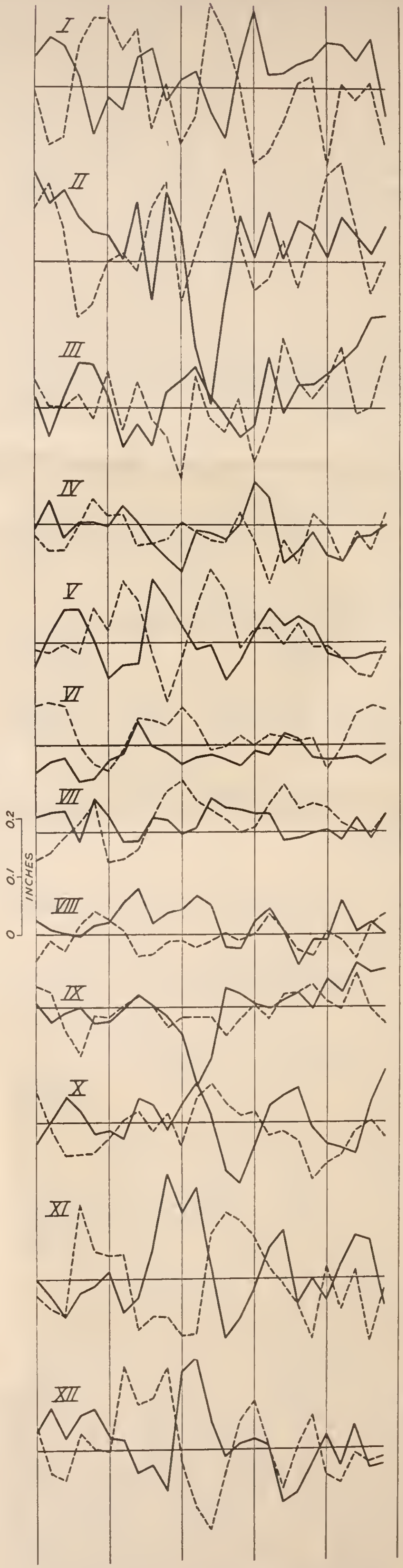

Fig. 13

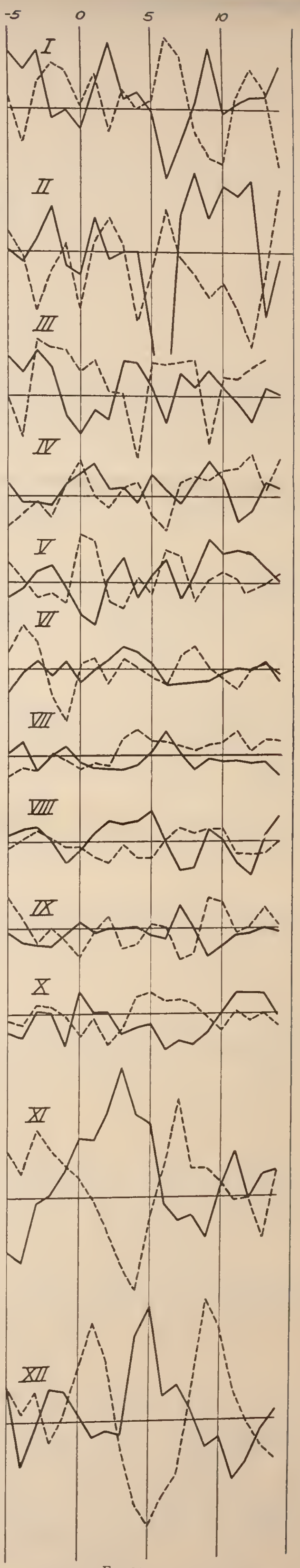

Fig. 14

Figs. 13 and 14.—Barometric departures associated with sequences of solar-constant variation for 12 months, January to December, at Washington, D. C. (fig. 13) and St. Louis, Mo. (fig. 14). Full curves, rising sequences; dotted curves, falling sequences.

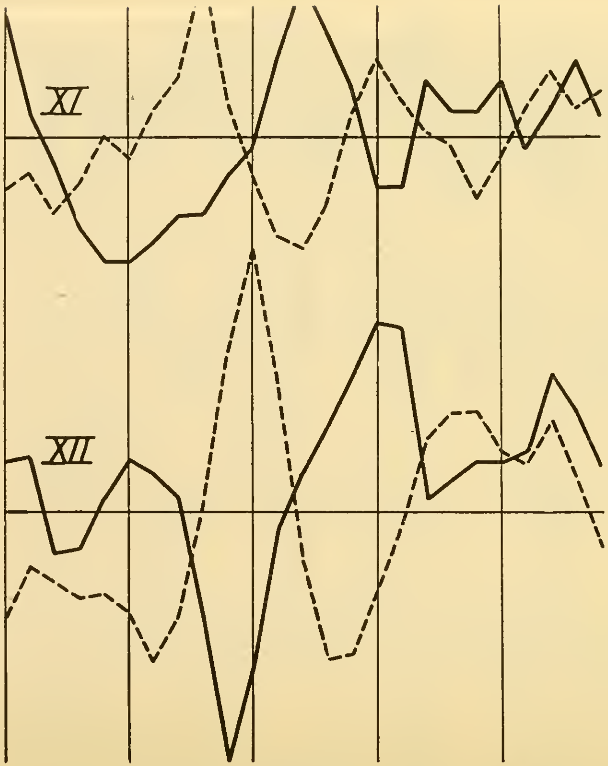

Fig. 15

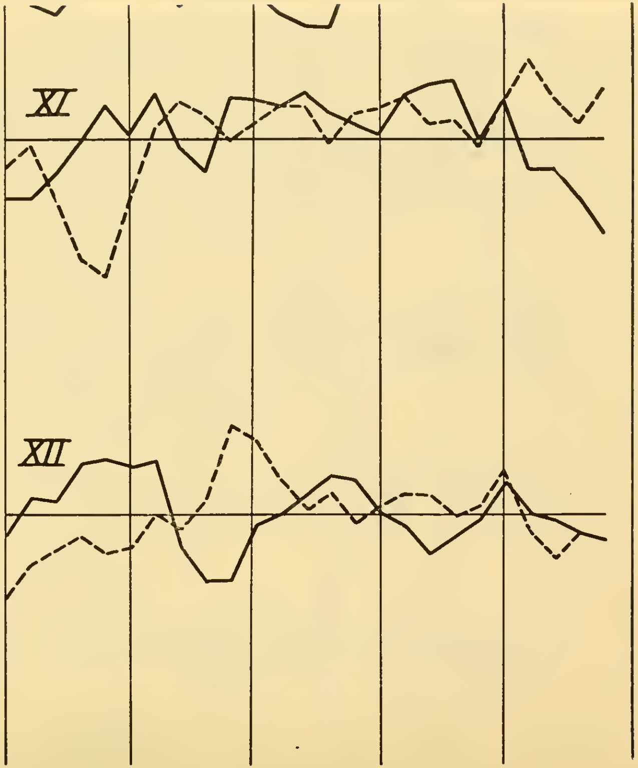

Fig. 16

Figs. 15 and 16.—Temperature departures associated with sequences of solar-constant variation for 12 months, January to December, at St. Louis, Mo. (fig. 15) and Salt Lake City, Utah (fig. 16). Full curves, rising sequences; dotted curves, falling sequences.

yet available in the individual tabulations to give satisfactory accuracy in the computations of the mean marches of the weather curves for the various months. Influences of terrestrial disturbing causes, and of solar changes happening before and after the incidence of the solar change which is treated in each case, take away very much from the definiteness of the curves. Yet I cannot but feel that the thesis of major control of weather by short-interval solar changes is demonstrated in what has been presented.

7. LONGER-RANGE MARCHES AND PERIODICITIES OF SOLAR VARIATION

Figure 17 represents the fluctuation of monthly mean values of the constant of radiation, as derived from all observations at various Smithsonian solar-radiation stations from 1920 to 1939. For details regarding its derivation the reader should consult the concluding chapter of volume 6 of the Annals of the Smithsonian Astrophysical Observatory. As indicated on page 182 of that work, these curves are for the most part plotted from "improved preferred" monthly mean solar-constant values as collected in the preceding table 27 of volume 6. Figure 14 of volume 6 gives not only the curves here shown, extending from 1920 to 1939, but also a continuation of the synthetic curve B as a prophecy through the year 1945. The data on which curve B depends are given in full in table 32 of the Annals, volume 6. They consist of tabulations of 14 regularly recurring periodicities found and evaluated from table 27 of volume 6. Their preferred lengths in months are given in table 31 of volume 6, and are as follows: 273, 91, 68, 54, 45¼, 39½, 34, 30⅓, 25⅓, 21, 11.87, 11.29, 9.79, 8⅛. Inasmuch as the interval during which solar-constant measurements had been continuously pursued was then less than 20 years, it cannot be claimed that these periods, especially the longer ones, are very accurate. But from our best knowledge of them they seem approximately, though not exactly, to be all submultiples of 273 months, as indicated in table 31 of volume 6, just cited. This master period of nearly 23 years, derived from Smithsonian researches on the solar constant of radiation, is approximately equal to two sunspot cycles of 11⅓ years. The areas included under successive sunspot-cycle curves since the year 1811 are alternately smaller and larger, as appears from figure 10 of my paper "Solar Radiation and Weather Studies,"[5] so that the double cycle is a periodicity in sunspots also. Furthermore, Hale discovered it in the variation of magnetic polarities in sunspots. It

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[5] Smithsonian Misc. Coll., vol. 94, No. 10, 1935. See also figure 26 B.

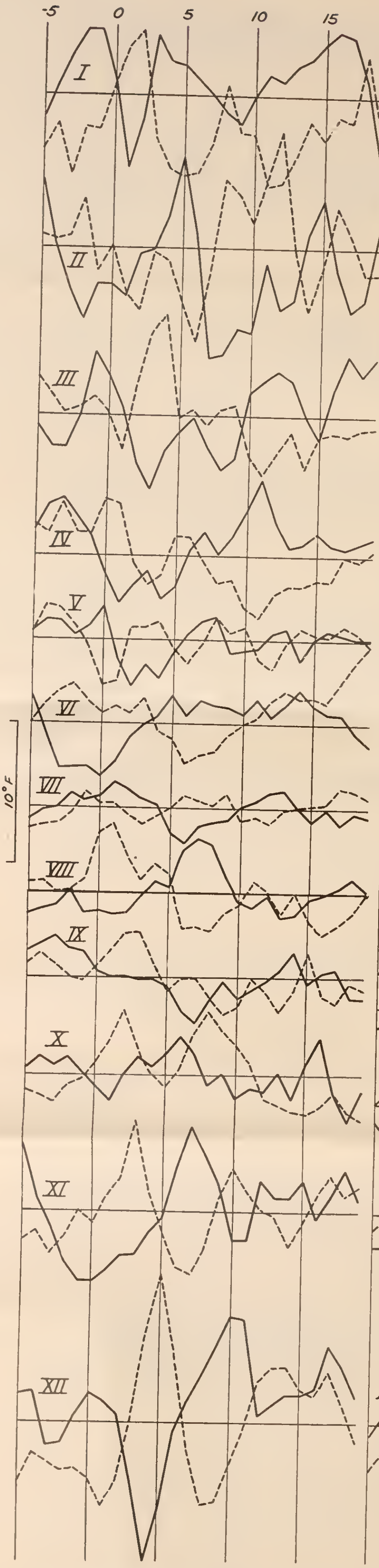

Fig. 15

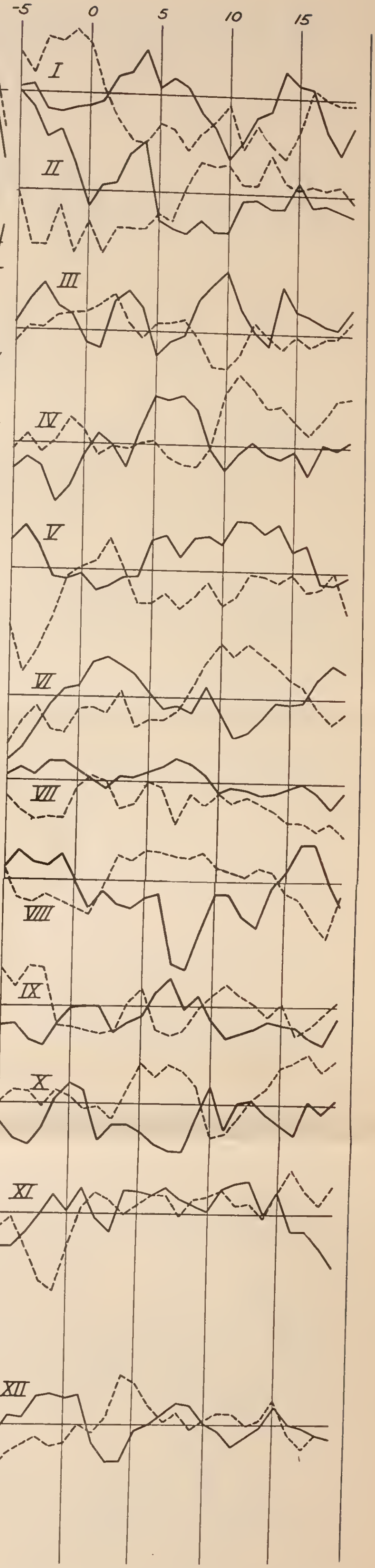

Fig. 16

Figs. 15 and 16.—Temperature departures associated with sequences of solar-constant variation for 12 months, January to December, at St. Louis, Mo. (fig. 15) and Salt Lake City, Utah (fig. 16). Full curves, rising sequences; dotted curves, falling sequences.

has also been noted by many observers in weather, in tree rings, and in other terrestrial phenomena. The double and quadruple of the 273-month period, that is 45½ and 91 years, are strongly marked, much more so than the 273-month period itself, in records of the levels of the Great Lakes.[6]

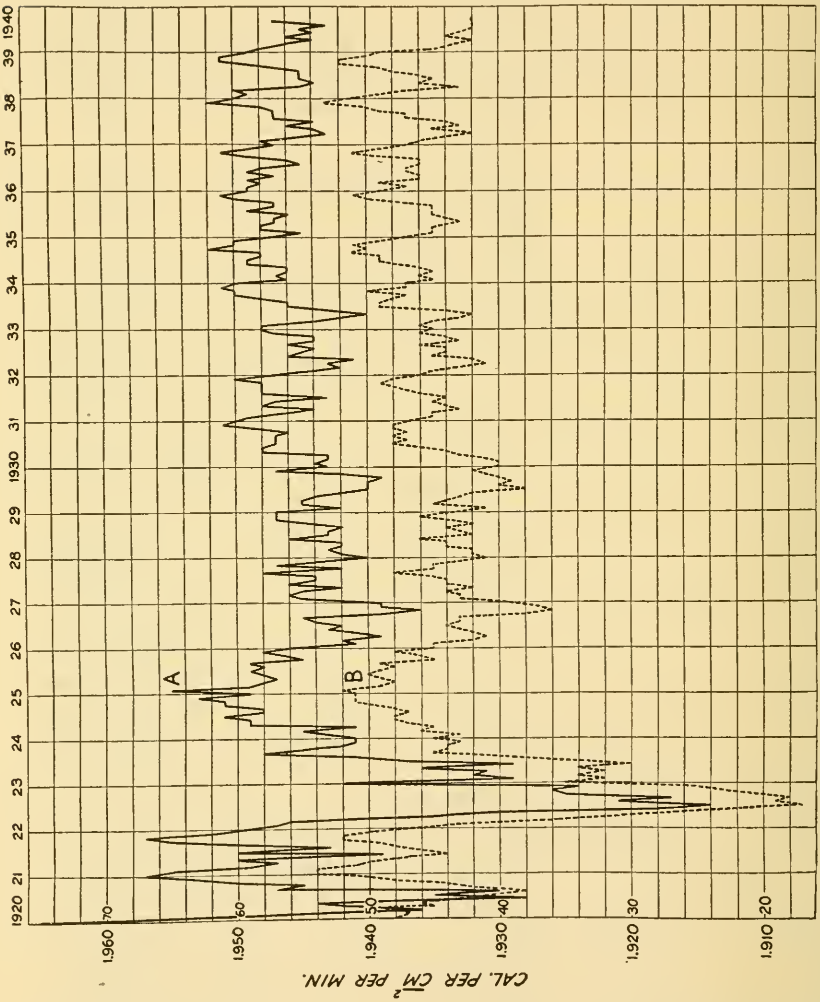

FIG. 17.—March of monthly mean values of solar constant of radiation, 1920 to 1939. A, observed; B, synthesis of 14 regular periodicities, all approximately aliquot parts of 273 months.

8. LONG-RANGE SOLAR VARIATION PREDICTED AND VERIFIED

We now have preliminary monthly mean solar-constant values derived from observations at Montezuma, Chile, our best station,

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[6] Loc. cit.

covering the interval from 1939 up to August 1943. In figure 18 I show a comparison between these new results and the forecast published in volume 6 of the Annals, figure 14. Unfortunately the apparatus at Montezuma was not kept up to highest efficiency in the years 1939 and 1940. Rather large discrepancies in these years were caused in part at least by the internally evident inaccuracy of many of the daily values on which monthly means were based. Notwithstanding this regrettable defect, the general agreement between the prophecy and the event is very satisfactory. It supports our confidence in the approximate validity of the 14 periodicities. Minor details are correlated in some instances. The verification will appear more striking if the reader will recall that the whole amplitude of variation little exceeds 0.5 percent.

As appears from figure 14, volume 6 of the Annals, a relatively large drop in the solar constant of radiation lasting through 1945, is predicted to begin October 1944. It amounts to 2.4 percent from the maximum values of 1940-41. It repeats with modifications (due to the noncommensurability of the periods) the slightly larger drop which began December 1921 and lasted through 1922. This leads us to inquire what meteorological consequences may be anticipated from so unusual a change in the solar constant, should it occur as expected. I venture to refer the reader to my paper "The Solar Prelude to an Unusual Winter," [7] from which I quote certain passages:

> We are not to look for anything so simple as a general drop of temperatures all over the world. Oceans, deserts, mountains, clouds and winds make up too complex a system for such simple reactions. Pronounced departures of some sort from normal conditions, however, we might expect.
>
> It will be recalled that the prevailing characteristic of the weather of the United States for the last couple of years or more is a condition generally warmer than normal. . . . . We start, then, with an excess of heat.
>
> Quoting, now, from Climatological Data: "The record of December, 1922, shows unusual contrasts as to the temperature and precipitation in different parts of the country. . . . .
>
> "Like the preceding December, January, 1923, was notable for the disturbed atmospheric conditions. . . . .
>
> "The outstanding feature of the weather . . . . was the almost continuously high temperature . . . . over much of the country. At the same time, however, severe winter weather was the rule over New England and much of New York.
>
> "Precipitation occurred with unusual frequency . . . . in northern districts west of the Continental Divide and from the Upper Lakes eastward. . . . .
>
> "The disturbed atmospheric conditions, so persistent during the first two months of the present winter, continued into February. . . . . The pressure distribution for the month as a whole showed marked variations from the conditions usually expected in February. . . . .

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[7] Proc. Nat. Acad. Sci., vol. 9, No. 6, June 1923.

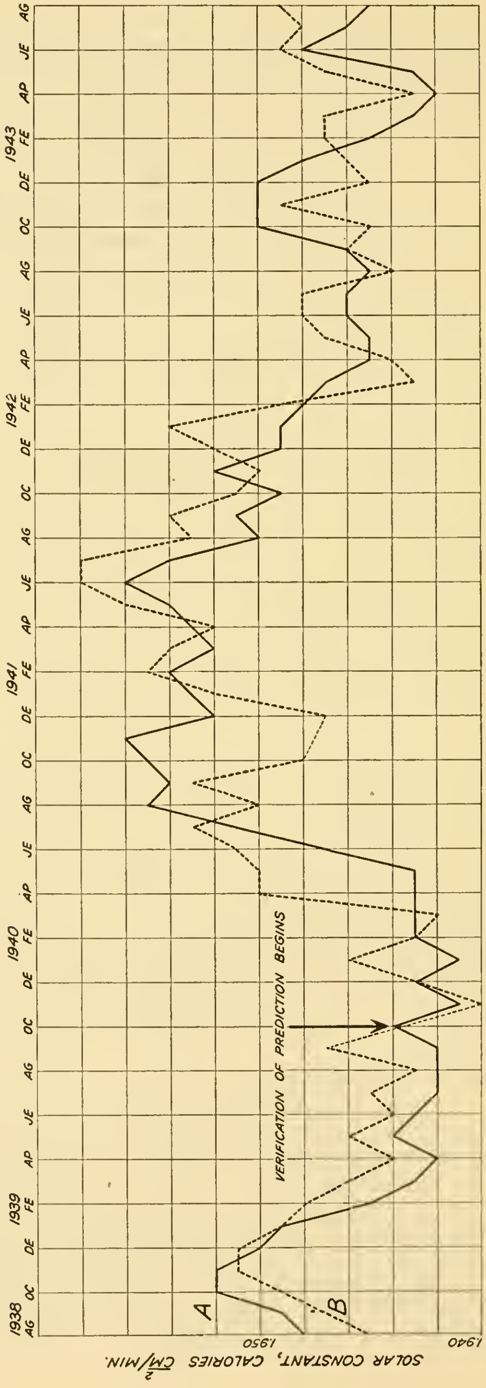

Fig. 18.—The solar constant of radiation. A, predicted; B, observed.

> "The unseasonable warmth which had continued during most of the two preceding months of the winter save over the Northeastern States, terminated with the first few days of February, and the remainder of the month was distinctly cold. . . . ."
>
> While it is far too early in the study of the relations of solar radiation and weather to state that the extraordinary solar change caused the unusual winter weather, it does no harm to draw attention to both, in the hope of attracting investigation.

With this precedent we shall follow with interest further data for comparison with the solar-constant prophecy. If it is verified, we may expect notably unusual, though as yet unpredicted, meteorological conditions to occur in the years 1945 and 1946.

9. PERIODIC SOLAR VARIATIONS AND WEATHER. (A) SEASONAL PHASE CHANGES IN WEATHER EFFECTS

Aided by Mrs. Bond, Miss Simpson, Miss McCandlish and Miss Carter in making the computations, I have made many tabulations to evaluate the influences of solar periodicities individually on weather, and to synthesize these effects into forecasts, and compare with the events. Nothing has appeared in tabulations of solar-constant values to indicate that there have been phase changes in the 14 periodicities in solar emission. Nevertheless, immediately when we began to tabulate the weather effects of the shorter solar periodicities, changes of phase became so obvious that at first I despaired of making progress in the research. It soon occurred to me that such phase changes were natural consequences of seasonal influences.

The lag with which a solar-radiation impulse will be responded to in the weather at any given station depends on local conditions, and on the march of atmospheric circulation. Thus stations in a desert region, especially one at high elevation, respond quickly, but a station on an island in a great ocean exhibits a long lag in response. Atmospheric waves of weather change travel great distances, and from different centers of primary action, to reach particular stations. Furthermore it is a matter of common experience that in the Northern Hemisphere southerly winds are accompanied by warmer, and northerly winds by cooler temperatures. Wind directions are governed by the great cyclones and anticyclones of the atmospheric circulation. Hence whatever alters the paths of these through the atmosphere, as they move from westerly to easterly, must alter the directions of prevailing winds, and the associated temperatures.

It is not to be supposed that atmospheric circulation will be identical in winter and summer. Snow coverings have much influence on the earth's radiative and temperature equilibrium. Changes of the directions of prevailing winds will therefore occur. Hence if there be, for instance, a solar period of 8 months which gives rise to a certain temperature response at a given station this winter, such response will be in different phases at the two coming recurrences of the 8-monthly periodic solar impulse next autumn and the following summer. It will not be until 2 years have elapsed that we can reasonably expect temperature response of the 8-month solar period to be in the same phase as now.

To test this hypothesis of the cause of phase changes in weather responses to solar periodicities, I made graphs of departures from normal temperatures and precipitations for a number of stations in various parts of the world. I read therefrom the positions of maxima corresponding to several of the shorter solar periods, as their lengths were then approximately known. To carry such a study forward not more than 20 years it matters little whether the true solar period in question is exactly known. In a later investigation over an interval of 140 years it does matter decidedly, as will appear.

Figure 19 shows in illustration the march of the period of 11.29 months in temperature departures at Bismarck, N. Dak., from February 1879 to March 1907. From each of the 30 curves, except the few which showed nothing definite, I read off the position of maximum as well as possible. It is not to be expected that these data will plot into a perfectly regular form, because of the influences of other simultaneously active solar periods, and of accidental terrestrial disturbances, which tend to modify the curves. However, in the mean it seems clear, as shown at the right in the illustration, that the position of maximum of the 11.29-month periodicity in Bismarck temperature departures shifts through the year. Figure 20 shows other studies of the same kind on several of the shorter periods. They were made for various stations, and during a quite other range of years than figure 19. It will be noted that the result for the 11.29-month period in Bismarck temperature departures is nearly the same in the two figures, though representing intervals of time nearly a half century apart. Another and better method of determining seasonal phase changes is used for test predictions to be referred to and will be explained below.

9 (B). PERIODIC WEATHER RESPONSES CORRECT LENGTHS OF SOLAR PERIODICITIES

With the aid of Miss McCandlish, I have investigated terrestrial responses to the solar periods rather extensively. A sample of these investigations is given in my paper "An Important Weather Element

FIG. 19.—Phase relations of periodicity of 11.29 months, years 1879 to 1906, in temperature departures at Bismarck, N. Dak.

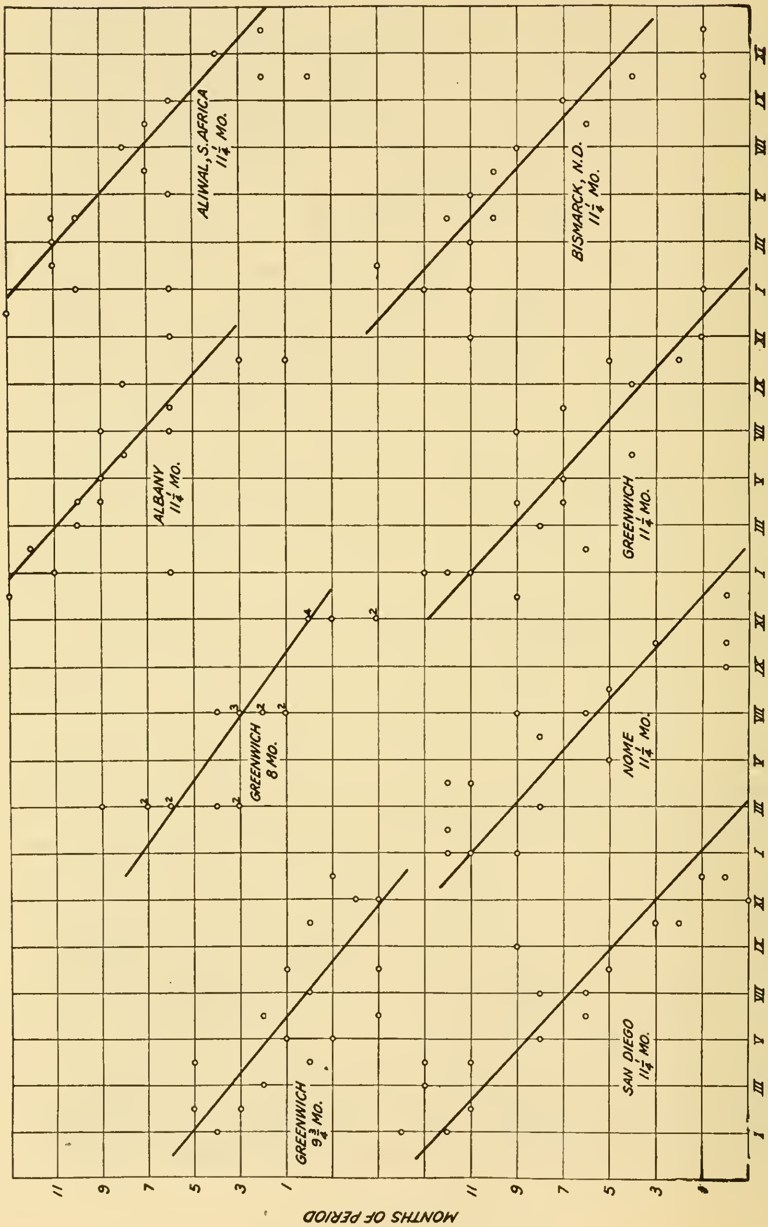

Fig. 20.—Phase relations of periodicities in terrestrial responses to solar variations, depending on seasons of the year.

Hitherto Generally Disregarded,"[8] pages 14 to 23. I repeat here, as figure 21, figure 7 of that paper, which shows that when the best length of period is found, and seasonal influences on phase are eliminated the 8⅛-month periodicity has continued with considerable amplitudes and stable phases in the temperatures of Copenhagen, Vienna, and New Haven, from the year 1700 till now. This shows that the sun's variation, which has been observed regularly only since 1918, has maintained the 8⅛-month periodicity in unchanged phases for at least 140 years. Other evidences of a similar kind indicate that others of the 14 solar periodicities are equally permanent and stable in phases. These meteorological investigations over many years enable us to improve the lengths of the permanent solar periods, which otherwise depend only on solar-constant observations since 1920.

10. PREDICTION OF WEATHER BASED ON PERIODIC SOLAR VARIATIONS

Having discovered periodicities in solar variation, and that individually they produce appreciable effects on temperature and precipitation, I have sought to determine if predictions based thereon have value.

10 (A). THE 23-YEAR CYCLE

First and simplest, a master period of nearly 23 years is approximately the least common multiple of the 14 shorter ones.[9]

Accordingly one expects to find a tendency for features of weather to repeat at intervals of 23 years. This tendency is actually found in weather records, though more distinctly in evidence at some stations than at others.

Figure 22 gives the precipitation at Peoria, Ill., since 1856, smoothed by 5-month running means, and expressed in percentages of normal. A strong tendency of individual features to repeat appears, especially in the right-hand half of figure 22. The reader will notice for the years 1934 to 1936 a dotted line which was drawn in the summer of 1934 as a 3-year prediction. Further on will be noticed a thin continuous line, drawn by Miss McCandlish and the writer in 1938 in consultation, as a second 3-year prediction. Both predictions show some correlation with the event.

Early in November 1941, at the request of an Army officer, we

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[8] Smithsonian Misc. Coll., vol. 101, No. 1, 1941.

[9] I include here the sunspot cycle, making 15 periods in all. The sunspot cycle, although not appearing in solar-constant variation, yet, as many have shown, is of meteorological significance.

used this method to predict the average precipitation over the Tennessee Valley area for the 3 months, November, December, and January. From studies of the 23-year cycles, at 10 stations distributed over the Tennessee Valley area, we predicted the average total precipitation of the area for the 3 months as 84 to 87 percent of normal. It turned out to be 87 percent normal. A critic objected that the average deviation between prediction and event for the 10 individual stations was 13.5 percent, and their average deviation between the event and 100 percent was only 16 percent. Hence, he said, there was not much value in the prediction. I replied that as the probable error of a mean is proportional to the square root of the number of observations, 10 in our case, the probable error of our prediction for the area was only about 4 percent, and the prediction was verified to within this margin. I also pointed out that the deviations from 100 percent have no such significance as he implied. For suppose the weather had been very wet during those 3 months, so that the average precipitation therein was 200 percent of normal. Then instead of 16 percent our critic's result would be 100 percent. There is no reason to say that our prediction might not still have given an average deviation of only 13.5 percent, and a probable error of 4 percent.

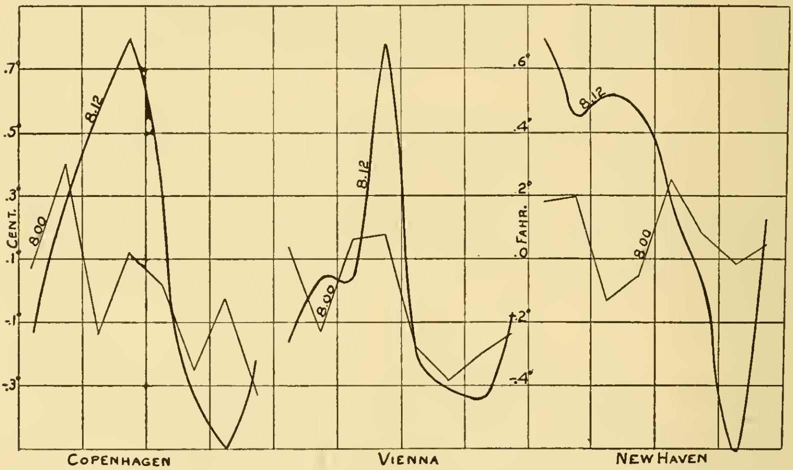

FIG. 21.—A periodicity of 8⅛ months in temperatures at Copenhagen, Vienna, and New Haven, Conn., since the year 1700 when seasonal phase disturbances are excluded.

More recently, and still using 5-month running mean values, I have reduced this simple method of prediction to a routine computation. That is to say, I no longer attempt as formerly an allowance by evalu-

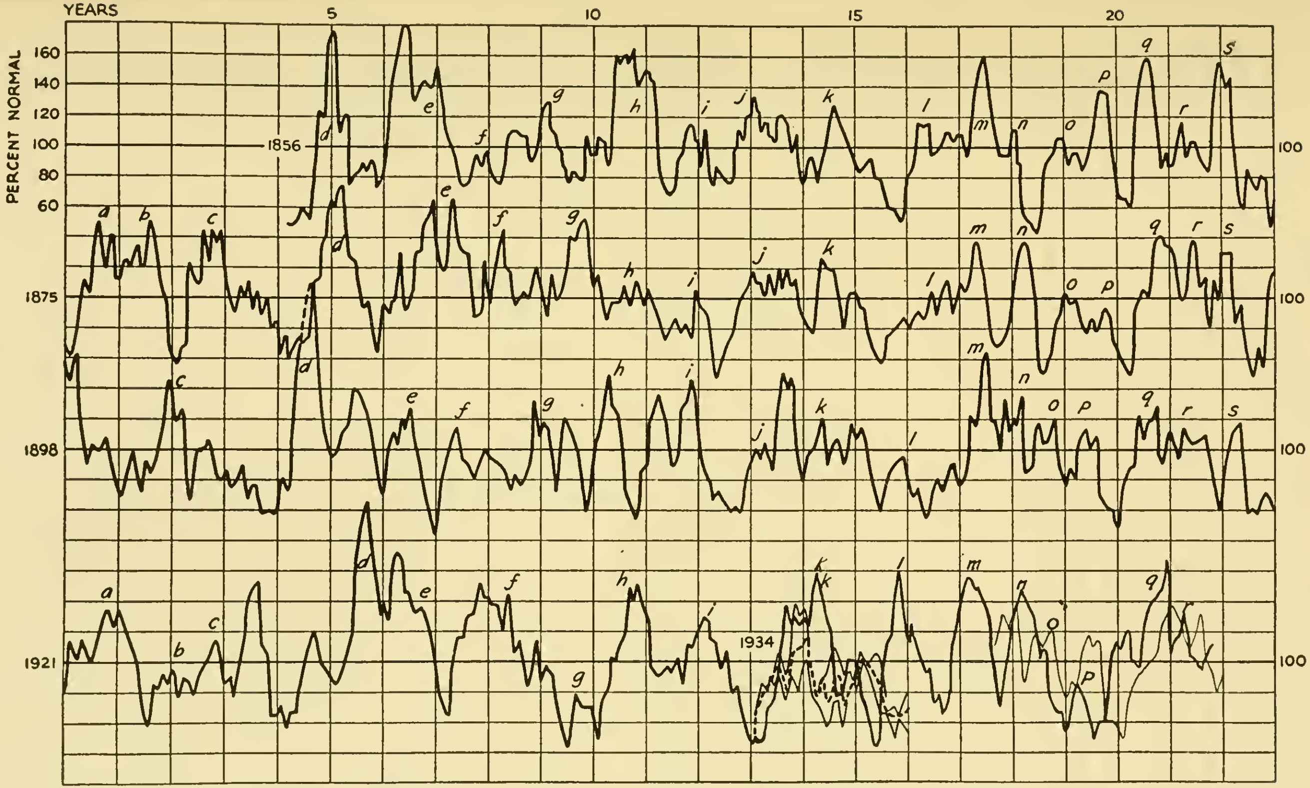

Fig. 22.—Precipitation at Peoria, Ill., smoothed by 5-month running means, arranged in 23-year cycles. Letters represent similar features in successive cycles. Forecasts (dotted line, from 1934; thin line, from 1938) made by consideration of preceding cycles.

ating the prevailing "backlash," or average displacement in phase plus or minus, at the date of predicting. Assuming a master period of 273 months, I take half the sum of the percentage precipitations of April, 46 years previously, and of February, 23 years previously, to represent the expected precipitation as of the approaching January, and similarly for other months. Similarly for temperature. Such a computation was made for the precipitation at Eastport, Me., for 96 months of the years 1935 to 1942. The average monthly deviation between prediction and event was 18 percent. Comparing with the event (all values as remarked being 5-month running means) I found the following results:

Number of months when values predicted and observed lay on the same side of 100 percent	78
Number of months when values predicted and observed lay on opposite sides of 100 percent	18
Number of months predicted and observed on opposite sides of 100 percent, but still within 18 percent of each other	6

Hence $\frac{78+6}{96} = 87$ percent of predictions were reasonably useful.

At the same time similar computations covering 8 years were made for 12 stations scattered over New England. Evaluated similarly, 803 predictions were reasonably useful, 341 unsatisfactory,[10] a combined score of 70 percent reasonably useful.

10 (B). SYNTHETIC PREDICTIONS FROM 15 PERIODICITIES

We have employed a more elaborate method than that to make purely solar predictions of long range. Although it has yielded promising results in several instances, and though we feel that it is capable of much improvement with further study, we fear that the sun's control of weather is too complex a process to be mastered without fuller knowledge of atmospheric reactions and allowance for these terrestrial factors in predictions. Our present method of making and testing purely solar long-range detailed synthetic predictions is as follows:

From such compilations as "World Weather Records" we compute 5-month running means of temperature departures, and of percentages of normal precipitation, from the earliest years onward. These we divide into the "basis group," say up to 1930, or to 1935, and the "prediction group," all subsequent to the date of division. From the basis group we compute for each of the 15 periodicities (including of course the sunspot cycle) the average form of the curve representing the periodicity, in the manner illustrated at pages 17 and 18

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[10] A few months were missing from the records.

of my paper, Smithsonian Miscellaneous Collections, volume 101, No. 1, already cited. For the shorter periods these computations take account of seasonal changes of phase in terrestrial response, as above referred to. Where not more than 5 years of prediction is proposed, the longer solar periodicities above 68 months may be omitted.

Having determined by tabulations the average forms of all periodicities employed, and introduced the phase corrections for all the periodicities shorter than 21 months, we synthesize the expected weather for the prediction group of years in the manner (except for seasonal phase shifting) as shown in table 32 of volume 6 of the Annals, where the prediction of solar variation itself from 1939 to 1945 was computed.

To explain more fully the process of determining seasonal phase shifts I give for the precipitation at Eastport, Me., a determination of the $8\frac{1}{8}$-month periodicity and its phase relations, using for this determination 5-month running means for the years 1900 to 1934, inclusive. It was proposed to be in phase as of January 15, 1935, when the intended prediction was to begin.

Our first care was to fix the dates when $8\frac{1}{8}$ months successively substracted from January 15, 1935, would fall. These dates occur for the different months of the year in the following years:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1912	1916	1901	1905	1911	1917	1900	1906	1910	1916	1901	1905
1914	1918	1903	1907	1913	1919	1902	1908	1912	1918	1903	1907
1933	1920	1922	1909	1915		1904	1927	1914	1920	1922	1909
		1924	1928	1932		1921	1929	1933		1924	1926
		1926	1930	1934		1923	1931				1928
						1925					1930

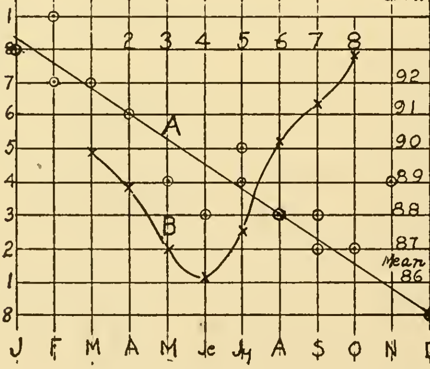
It will be understood that this selection of dates makes proper allowance for the period being $8\frac{1}{8}$ rather than 8 months. Figure 23 shows the computation of the summation forms of the $8\frac{1}{8}$-month curve for each month of the year, from 5-month running means of precipitation at Eastport. As shown, a rough preliminary curve for each month is plotted, and from these 12 curves the maxima are taken for plot A of figure 23. A curve (in this particular case a straight line) of phase change is drawn on plot A, and according to it the final table is prepared, in which the 12 summation forms are shifted for phase as determined in curve A and as indicated by slanting and upright figures in the final table of figure 23. Sums of the 8 columns are taken and divided by the total number of cases, 51, to give the mean form of the $8\frac{1}{8}$-month curve shown as curve B. In the employment of it later for purposes of prediction, the zeroth dates are projected forward from January 15, 1935, and the phase

Eastport, Ppt. $8\frac{1}{8}$ Months.

5-Month runing means.

	1	2	3	4	5	6	7	8
Jan.								
1912	90	89	99	85	87	93	84	76
1914	75	97	85	84	78	76	70	79
1933	57	70	82	89	82	104	116	126
Sums	222	256	266	258	247	273	270	281
Feb.								
1916	71	59	74	89	93	92	99	86
1918	78	72	78	74	74	91	100	90
1920	114	105	107	78	70	65	69	71
Sums	263	236	259	241	237	248	268	247
Mar.								
1901	117	127	123	115	98	87	62	89
1903	106	97	98	81	69	69	78	72
1922	67	73	78	126	121	123	118	113
1924	58	51	66	97	93	88	84	85
1926	81	78	64	63	65	106	170	117
Sums	429	426	429	476	446	473	512	466
Apr.								
1905	63	64	70	94	80	84	89	95
1907	94	95	95	95	109	115	115	121
1909	99	92	78	95	100	109	98	107
1928	72	82	96	107	109	96	91	84
1930	69	73	74	72	71	68	52	52
Sums	397	406	413	463	469	474	445	459
May								
1911	91	89	90	98	86	80	86	81
1913	94	76	73	79	79	80	87	88
1915	93	107	131	122	111	109	101	68
1932	79	83	81	85	84	73	69	70
1934	82	88	95	100	98	92	113	101
Sums	439	443	470	484	458	434	456	408
Jun.								
1917	121	109	121	83	87	73	86	74
1919	85	97	90	105	104	95	105	108
Sums	206	206	211	188	191	168	191	182

	1	2	3	4	5	6	7	8
Jul.								
1900	95	108	106	113	121	120	98	111
1902	85	79	71	96	95	101	107	121
1904	112	112	113	112	94	73	64	61
1921	53	54	76	72	71	72	76	59
1923	69	73	68	68	71	68	61	63
1925	77	102	98	92	101	100	82	80
Sums	491	528	532	553	553	534	488	495
Aug.								
1906	59	69	85	99	121	116	127	110
1908	74	76	91	107	123	125	143	125
1927	171	171	167	141	117	90	76	65
1929	72	74	85	82	78	83	81	69
1931	131	113	96	91	80	67	79	82
Sums	507	503	524	520	519	481	506	451
Sep.								
1910	56	64	70	72	80	85	66	83
1912	83	100	97	101	115	114	108	92
1914	74	77	91	86	74	83	92	94
1933	124	131	117	96	74	73	67	74
Sums	337	372	375	355	343	355	333	343
Oct.								
1916	77	85	85	84	94	82	110	106
1918	84	90	69	63	67	79	71	78
1920	81	78	72	74	80	70	66	60
Sums	242	253	226	221	241	231	247	244
Nov.								
1901	91	88	123	127	119	117	106	83
1903	80	92	101	103	100	92	83	98
1922	77	84	86	104	96	87	91	88
1924	61	55	67	68	64	66	72	66
Sums	339	319	377	402	379	362	352	335
Dec.								
1905	79	107	107	121	113	112	93	75
1907	112	105	107	97	81	72	74	68
1909	89	85	88	89	107	73	72	61
1926	121	79	68	65	76	89	120	146
1928	70	71	79	85	76	67	72	83
1930	57	64	71	74	82	99	112	121
Sums	528	511	520	531	535	512	543	554



	222	256	266	258	247	273	270	281
	281	263	236	259	241	237	248	268
	512	466	429	426	429	476	446	473
	445	459	397	406	413	463	449	474
	434	456	408	439	443	470	484	458
	191	168	191	182	206	206	211	188
	553	534	488	495	491	528	532	553
	519	481	506	451	507	503	524	520
	355	343	355	333	343	337	372	375
	226	221	241	231	247	244	242	253
	319	377	402	379	362	352	335	339
	528	511	520	531	535	512	543	554
	4585	4535	4439	4390	4464	4601	4656	4736
Mean	89.9	88.9	87.0	86.1	87.5	90.2	91.3	92.9

FIG. 23.—Computation of seasonal phase shifts, and form of curve representing the effect of $8\frac{1}{8}$-month periodicity in solar radiation on precipitation at Eastport, Me. Phase shifts, indicated by italics in table at lower right, are governed by the line A.

changes appropriate to the several months are carefully made by consulting curve A of figure 23.

In figure 24 I give such a synthesis and the event for the 15 years, 1930-1944, of the precipitation at Peoria, Ill. For the first 7½ years, 1930-1937, both as to phase and amplitude the fit is rather good. From then until January 1939 there is wide divergence, though something of the true march is indicated. During 1939 and 1940 the fit is rather good again. The prediction comes to lag so far behind the event in the later years that though the general rise of precipitation, 1940-1942, is indicated, the phases are several months in error. So the great drop of 1943 is predicted nearly 6 months before it actually arrived. This 15-year prediction was made before the lengths of the periods were revised and corrected as given in table 31 of volume 6 of the Annals. It may be that with further study and improved periods better results will be found.

Imperfect as it is, if all purely solar long-range predictions were as successful as this one for Peoria, it would seem to be worth while to make them for use of agriculture and other interests. As yet the success of the Peoria prediction is exceptional, so that it seems dangerous to submit such predictions to the public, unless they can be improved to be generally successful. Possibly meteorologists may see their way to combine solar data with terrestrial factors in a way to lead to substantial improvement. It is necessary, however, as I see it, in view of the results I have presented, to take the revolutionary step of introducing the influence of solar variation as an important meteorological element.

11. A 27.0074-DAY PERIOD IN WASHINGTON PRECIPITATION

With further reference to the influence of periodic solar changes on weather, I call attention to my paper "A 27-day Period in Washington Precipitation." [11] I show there that in the mean of 243 consecutive repetitions of a cycle of 27.0074 days, seemingly associated with the sun's effective period of rotation, the 12th day has approximately 25/8 the average precipitation of the 7th day at Washington. In the paper cited I also gave mean curves of partial groupings representing dry, medium, and wet years.

I have lately given further attention to this cycle, and have reached the conclusion that any use of it for prediction should be based on the whole series of 243 cycles, not on the subordinate partial groupings. They have insufficient statistical backing. It is indispensable

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[11] Smithsonian Misc. Coll., vol. 104, No. 3, 1944.

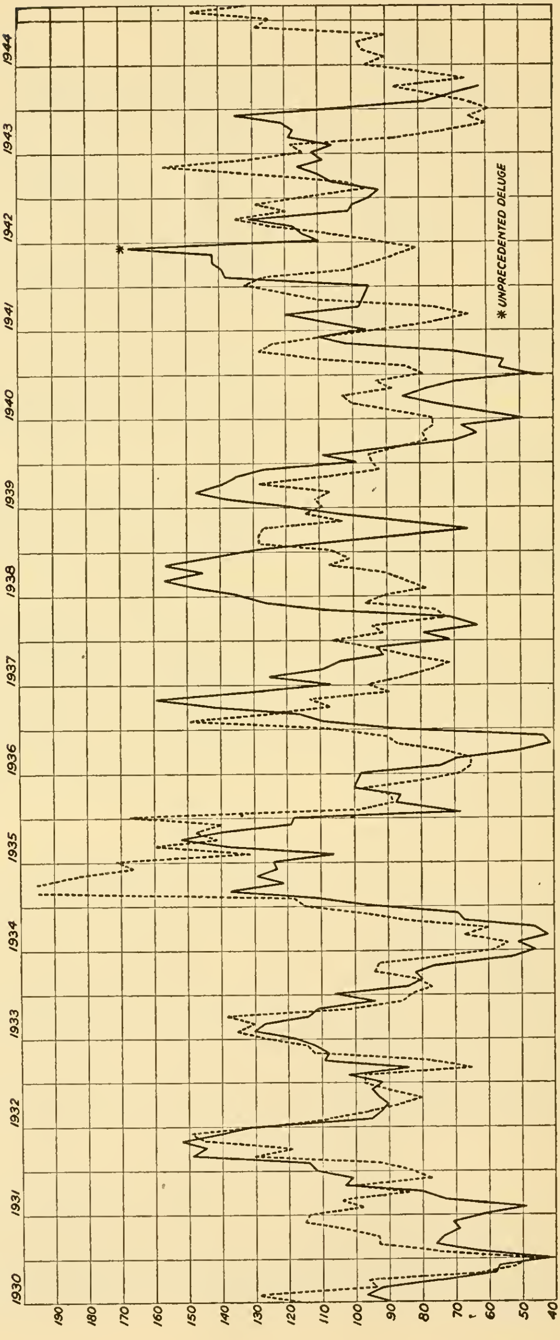

Fig. 24.—Precipitation percentages at Peoria, Ill., predicted (dotted curve) and observed (full curve). Synthesis of 15 periodicities determined from records for 1856 to 1929.

to allow for the small correction of 0.0074 day, otherwise the validity of the cycle vanishes. I give as follows the total values of precipitation over the stretch of 243 days for days 1 to 27 as computed from 243 cycles beginning January 1, 1924, and using the period 27.0074 days. The results are expressed in inches of precipitation.

Cycle day	1	2	3	4	5	6	7
Totals for 243 days........	29.30	26.68	28.03	29.21	34.99	18.04	17.05
Cycle day	8	9	10	11	12	13	14
Totals for 243 days........	22.85	24.73	21.57	22.85	45.91	32.68	22.18
Cycle day	15	16	17	18	19	20	21
Totals for 243 days........	32.91	25.70	31.47	27.48	23.22	24.45	18.25
Cycle day	22	23	24	25	26	27	
Totals for 243 days........	27.15	22.71	23.61	25.13	31.34	34.78	

My friend Dr. J. A. Greenwood, of Duke University, has been so kind as to compute for me the probability that a range from 45.91 to 17.05 should occur in the daily totals of 243 cycles. In order to do this he required to know the "variance" of Washington precipitation for groups of 243 days distributed quite at random through all months during the interval since January 1924. I met this requirement as follows. In 20 years there are 240 months. I made a first group of precipitations of the 240 *first* days of all months from January 1924 to December 1943. A second group employed their *second* days. Thus I proceeded to the third, fourth, and so on to the twenty-seventh, to set up a table of 240 columns and 27 lines. I then determined the mean precipitation per group of 240 random days in this interval to be 23.75 inches. From thence I computed the deviations of all 27 groups from this mean. Their average is ±3.00 inches.

From the squares of these deviations Dr. Greenwood computed the variance, and multiplying it by $\frac{243}{240}$ obtained 14.48 as the random variance for a group of 243 days. From this, using "Student" "t" method, the value of "t" for the discrepancy between 12th and 7th days becomes:

$$\frac{45.91-17.05}{\sqrt{28.96}}=5.37$$

with 26 degrees of freedom. From tables of "t" this implies a "chance" probability about $\frac{1}{100{,}000}$ that so large a discrepancy would occur in the totals of my 27.0074-day cycle values if it were found between two pre-selected days of the cycle. But as there are 351 ways in which such a difference might occur (as Mr. Norton of the Weather Bureau pointed out to me), the probability reduces to about $\frac{1}{300}$.

Examining the list of totals for 243 cycles given above, and making a concession to continuity in the case of the slightly lower day numbered 2, the following days of the cycle are selected as likely to have more than average precipitation at Washington:

Days numbered: 1, 2, 3, 4, 5, 12, 13, 15, 17, 18, 22, 26, 27.
Ratio of average of "Totals for 243 days" above for these to remaining days of the cycle = 1.42.

In arranging the computations for the cycle I had to make a shift of phase of 1 day each 10 years. This shift was made in January 1934 for the first time, and all totals for years preceding 1934 were shifted forward 1 day in computing the means. This brings the first day of the cycle on January 1, 1941. But with January 1944 it is necessary to make another shift of 1 day. No further shifts would occur till January 1954, unless longer evidence should tend to alter the decimal .0074. Hence the first days of cycles in 1944 occur on the following dates:

Jan. 14, Feb. 10, Mar. 8, Apr. 4, May 1, 28, June 24,
July 21, Aug. 17, Sept. 13, Oct. 10, Nov. 6, Dec. 3, 30.

From these data, and from the Weather Bureau Forms No. 1030, I prepare the following table. It gives for every month of the year 1944 the dates when, in the mean, higher values of precipitation should occur at Washington than in the mean of all other dates of 1944. The actual observations are given for the months January to April, with the ratios of mean precipitation for preferred to that for all other dates.

I have also assembled the results for the 10 years 1934 to 1943. In all these years the ratios, as just defined, exceeded 1.00 except in 1934, as follows:

Year	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	Mean	Expected
Ratio	0.99	1.93	2.16	1.70	1.40	2.88	1.14	1.06	1.20	1.06	1.55	1.42

Of the 120 months included in the assembly, the ratio exceeded 1.00 in 82 cases. Grouping as to months, the ratio, called plus when above, and minus when below 1.00, was found as follows for the 10-year summary.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Totals	Percent
Plus	8	4	8	7	4	9	9	6	8	9	5	5	82	68.3
Minus	2	6	2	3	6	1	1	4	2	1	5	5	38	31.7
													120	

It will be noted that in the list of yearly ratios low values occur at both ends of the 10-year series. This is to be expected. The Forms No. 1030 give precipitation as from midnight to midnight for every

TABLE 5.—*Dates expected to have larger than average precipitation, Washington, 1944*

(*Observed values in hundredths of an inch.*)

1944 Pfd. days of cycle	Jan. 14	Obs. ppt.	Feb. 10	Obs. ppt.	Mar. 8	Obs. ppt.	Apr. 4	Obs. ppt.	May 1, 28	Obs. ppt.	June 24	Obs. ppt.
1	14	0	10	0	8	0	4	12	1, 28		24	
2	15	48	11	44	9	0	5	T	2, 29		25	
3	16	21	12	T	10	0	6	0	3, 30		26	
4	17	0	13	0	11	0	7	T	4, 31		27	
5	18	0	14	44	12	1.08	8	3	5		28, 1	
12	25	0	21	T	19	48	15	56	12		8	
13	26	0	22	58	20	35	16	31	13		9	
15	28, 1	4, 0	24	0	22	0	18	0	15		11	
17	30, 3	0, 1.64	26	20	24	0	20	5	17		13	
18	31, 4	T, 25	27	2	25	0	21	4	18		14	
22	8	T	4	0	2, 29	0, 76	25	0	22		18	
26	12	0	8	0	6	88	2, 29	8, 0	26		22	
27	13	0	9	T	7	4	3, 30	0, 0	27		23	
Pfd. days	0.164 *	2.62	0.129 *	1.68	0.256 *	3.59	0.079 *	119				
Totals		2.96		2.48		5.44		308				
Other days	0.027 *	0.34	0.050 *	0.80	0.103 *	1.85	0.126 *	189				
Ratios	6.07		2.58		2.49		0.63					

1944 Pfd. days of cycle	July 21	Obs. ppt.	Aug. 17	Obs. ppt.	Sept. 13	Obs. ppt.	Oct. 10	Obs. ppt.	Nov. 6	Obs. ppt.	Dec. 3, 30	Obs. ppt.
1	21		17		13		10		6		3, 30	
2	22		18		14		11		7		4, 31	
3	23		19		15		12		8		5	
4	24		20		16		13		9		6	
5	25		21		17		14		10		7	
12	5		1, 28		24		21		17		14	
13	6		2, 29		25		22		18		15	
15	8		4, 31		27		24		20		17	
17	10		6		2, 29		26		22		19	
18	11		7		3, 30		27		23		20	
22	15		11		7		4, 31		27		24	
26	19		15		11		8		4		1, 28	
27	20		16		12		9		5		2, 29	

* Mean precipitation per day in inches.

day. The accumulation of the residual, 0.0074 day, is gradual, cumulating in one day change of phase each 10 years. For the years near that when the jump of one day is made, the cycle becomes less and less representative. If the precipitation values were employed from noon to noon instead of from midnight to midnight in these less favorable years, higher values of the ratios might perhaps be found.

12. SUMMARY

In the preceding paper the following principal results have been brought forward.

1. From the revised daily solar-constant values of table 24, Annals Smithsonian Astrophysical Observatory, volume 6, Mount Montezuma and Mount St. Katherine values have been studied to select dates of the years 1924 to 1939 when brief sequences of rise and of fall of the sun's emission of radiation occurred.

2. A table of 440 sequences is given. This table is divided into cases of rising and of falling sequences. Each class is subdivided into 12 groups for the 12 months of the year. The average length per sequence is 4 days. The average amplitude of change per sequence is 0.7 percent of the solar constant of radiation.

3. Corresponding to each individual case of rising and falling sequences, the departures from normal temperatures and from normal barometric pressures have been tabulated for a number of stations widely separated. These tabulations run from 5 days before to 14 days (and sometimes 20 days) after the zeroth day of the sequence.

4. Mean values for successive days have been computed for every station and every month. Photographic illustrations show the method of computation. Graphs are given of the average marches of the weather elements attending rise and fall of the solar constant.

5. The principal conclusions from the study are summarized in six paragraphs to which the reader is invited to refer. Main results: Solar changes affect weather for about 20 days; produce major effects on temperature which are generally opposite for rising and falling solar activity; and may alter temperatures by 10° to 15° F. as much as 10 days after the zeroth day, depending on whether the solar radiation has increased or decreased.

6. These results are confirmed and buttressed by a similar treatment, of the observation of calcium flocculi over the sun's disk made at the Observatory of Ebro, in Spain, for the years 1910 to 1937. The solar-constant curves and the solar-flocculi curves for temperature departures at Washington for all 12 months from the day -3 to the day $+14$, give a correlation coefficient of 59.7 ± 1.9 percent.

7. It is shown that the weather influence begins, on the average, 4 days before the solar-constant change begins, and 6 days before the areas of solar flocculi are affected. This leads to the hope that some other solar phenomenon may be found that changes simultaneously with the weather effects, and is available as a basis for a long-range detailed weather forecast of upward of 2 weeks.

Curves are given in figures 1 to 16 to illustrate and clarify these and other results.

8. From combined results of the Smithsonian solar-constant work and the Ebro flocculi photography, solar forecasts were prepared for 201 days of the years 1911, 1915, 1917, and 1935, and compared with the events. These results are summarized in a table and illustration. They give fair promise that useful forecasts could be made if daily determinations were available to record *all* solar changes.

9. Reference is made to tables 27, 31, and 32, and to the chart, figure 14, volume 6, Annals of the Smithsonian Astrophysical Observatory. These show the variation of the monthly means of the solar constant of radiation, its analysis into 14 regular periodicities, and a prediction of solar variation from 1939 to 1945.

10. In the present figure 18 the prediction is compared with preliminary monthly mean solar-constant values from Montezuma, 1939 to 1943. Good verification is shown.

11. This leads to the expectation of interesting features of weather in 1944, 1945, 1946. Prediction indicates low solar-constant values similar to those of 1922-23 when unusual weather was experienced.

12. Since the period of 273 months is the approximate least common multiple of the 14 periodicities in solar variation, and also of the $11\frac{1}{3}$-year sunspot cycle, weather features should tend to repeat in cycles slightly less than 23 years long.

13. Examples are shown confirming the 23-year cycle in weather features. It has been reduced to a rough rule-of-thumb practice, viz: The mean of the departure from normal temperatures and precipitations of April 46 years before, and of February 23 years before, indicates the departure for January of the year to be predicted. Similarly for the succeeding months.

14. Using this rule-of-thumb method, useful results for 96 months are quoted for Eastport, Me., and for 12 stations scattered over New England. For Eastport 84 months out of 96, and for New England 803 months out of 1144, yielded reasonably useful predictions by this method.

15. The individual effects of the 14 periodicities on weather are traced. For shorter periods, 8 to 21 months, changes of phase in

weather effects of solar variation occur for different seasons of the year.

16. Eliminating seasonal phase changes in weather responses, it is shown that the period of 8⅛ months has been strongly marked at Copenhagen, Vienna, and New Haven since the year 1800. Similar results are in manuscript for other solar periods. Hence it is inferred that in the sun's emission of radiation the 14 periodicities have persisted with unchanged phase for at least 140 years.

17. The individual effects of the 14 periodicities, and in addition of the sunspot cycle, are computed from records of precipitation at Peoria, Ill. (smoothed by 5-month running means) from 1856 to 1929. These are synthesized from 1930 to 1943, and compared to the event. Both in phase and amplitude the verification is good for two-thirds of the years. Improvements seem possible by adjusted periods and attention to terrestrial influences.

18. Attention is drawn to a period of 27.0074 days in Washington precipitation. Results of comparisons of its indications with the event for the 10 years 1934 to 1943 are given. A forecast of days of high precipitation for 1944 is tabulated, and verified for the first 4 months of that year, excepting April.