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(PUBLICATION 3392)

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The burden of this paper is an affirmative answer to two questions: 1. Does the variation of the sun's radiation sensibly affect the course of temperature in terrestrial weather? 2. Conversely, does the march of terrestrial temperature support the view that the sun is a variable star?

As long ago as 1920 Clayton expressed his affirmative conclusions as to these questions in a paper [1] published by the Smithsonian Institution. I introduced Clayton's paper of 1920 with a note, from which I shall quote at the end of this discussion several paragraphs still pertinent, including the text figure which accompanied my note as the frontispiece of Clayton's paper. I returned to the same subject in 1931 in my paper [2] "Weather Dominated by Solar Changes", in which I employed solar observations made at Montezuma, Chile, 1924 to 1930, in relation to the temperature departures at Washington and other stations. I am now able to present the results of 5 more years of solar study, with a revision of the work published in my paper of 1931.

By a more discriminating scrutiny of the solar data I have eliminated some doubtful cases of solar change in the period 1924 to 1930, formerly included. Unfortunately, the solar radiation cannot yet be determined from a single day of observation with an accuracy better than about 0.3 percent. Hence, it is only by a well-supported series of quite a number of successive days' values of high apparent reliability, trending steadily in a given direction, that we may be well assured that a real and not an accidental indication of solar change is before us.

In volume V of the Annals of the Astrophysical Observatory, table 31 gives a long series of Montezuma measurements of the "solar

[1] Smithsonian Misc. Coll., vol. 71, no. 3, 1920.
[2] Smithsonian Misc. Coll., vol. 85, no. 1, 1931.

constant " of radiation ending with the year 1930. Similar measurements, as yet mostly unpublished, have been continued till the present time. Some of them have been broadcasted daily through Science Service, but they are not yet to be regarded as definitive until their further comparison and adjustments with results of other observing stations is completed. Nevertheless, they will serve for our present purpose.

This study relates to the daily departures from normal temperatures at Washington, D. C., St. Louis, Missouri, and Helena, Montana. These departures have been computed as follows: The general means of monthly averages of maximum and minimum thermometer for many years are used as printed on pages 956, 922, and 861 of World Weather Records (Smithsonian publication no. 2913). These monthly values, treated as representing the middle days of the months, were plotted on an adequate scale. Daily values were read from the smooth curves. The departures from these daily normals were then obtained for all days from January 1, 1924, to January 31, 1935, by subtraction from the current United States Weather Bureau Reports.

In order to fix the dates when sequences of rising and of falling solar emission of radiation occurred, Montezuma solar-constant values were used. As it was intended to segregate the investigations of each of the 12 months of the year separately, 12 solar-constant plots were made, each of which contained all of the values observed within a given month in all the years 1924 to 1935. Values of small weight were given the symbol " U " to identify them, and apparent sequences depending largely on such days were rejected.

That the reader may see how incomplete the record is, even from so fine a station as Montezuma, I give in figure 1 the plots for January and for April. It is believed that the reader will appreciate how hard it is to decide which are the satisfactory cases of rising and of falling sequences of solar change. After much scrutiny of the plots, the following dates were selected as zero dates of solar changes.

Before presenting the associated temperature departures for Washington, St. Louis, and Helena, attention is drawn to four criteria which should hold if solar variation really affects terrestrial temperatures.

1. Since opposite causes generally produce opposite effects, whatever curves may represent the average courses of the temperature departures following rising solar sequences, they should be opposite, as the right hand is to the left, to the average curves representing the after effects of falling solar sequences.

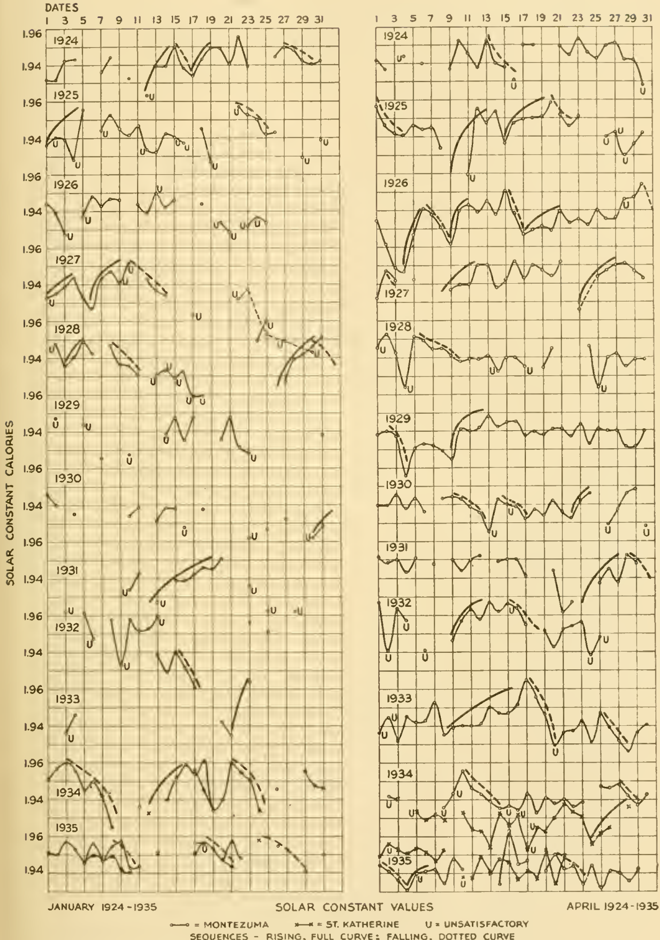


FIG. 1.—Incompleteness of available data indicating solar variation.

TABLE 1.—*Sequences of Solar Radiation Change*

Dates when sequences commenced

Year / Month		1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	Total number cases
Jan.	Rising	12, 17	1	..	1, 6	3, 26	..	30	12	..	21	12	26[a]	12
	Falling	15, 27	20	..	10	8, 30	..	..	..	..	15	3, 22	8, 18, 24	12
Feb.	Rising	5, 28	..	..	8	..	4, 22	..	12	6	..	8, 26	..	9
	Falling	..	..	..	..	..	..	..	15	15	..	20	..	3
Mar.	Rising	..	..	8	29	5, 17, 24	14	20, 30	11, 28	5	..	..	..	11
	Falling	4	16	30	26	9, 20	24	16, 25	15	..	..	6	19	12
Apr.	Rising	..	9, 15	4, 9, 17	8, 23	..	9	22	23	9	8	24	4	14
	Falling	13	1, 20	6, 15, 30	2	5	2	9, 14	28	15	17, 25	10, 27	1, 20	19
May	Rising	13	4, 16	5, 12, 20	25	4	..	16	16, 26	..	14	28	7, 13	15
	Falling	..	9, 21	2, 22	21	21	4, 14	22	22	..	3, 12, 22	..	..	13
June	Rising	13	17, 30	..	15	..	5, 12	22, 27	23	..	2	8	20	12
	Falling	..	26	..	8	7, 22	..	24	..	..	8, 18	..	12, 18, 25	10
July	Rising	12, 25	23	5, 29	15, 22	5	6, 18	5, 19, 28	..	..	..	2, 23	19	16
	Falling	15, 22	9, 21	12	25	2, 7, 17	2, 24	1, 15, 25, 30	9, 22	8	24	10	22	21
Aug.	Rising	14, 23	24	25	23	28	6	18	7, 23	..	3, 21	3, 15, 29	5	16
	Falling	4, 16	10, 22	27	18, 30	5	10, 20	..	11	..	5	20	14	14
Sept.	Rising	1, 24	14	12	12	29	12, 27	10	25	9	11	1, 19, 30	9, 15	17
	Falling	11, 19	5, 18, 30	7	22	20	..	1	14	11	9, 28	15, 26	12, 29	17
Oct.	Rising	18, 25	..	6	..	9	5	8	..	16	25	13	23	10
	Falling	..	..	13	10	..	2, 16	15	4	8, 21	17	6	..	10
Nov.	Rising	1, 6	15	..	11, 28	17, 26	5	14, 23	3, 14, 28	11, 29	6	22	4, 12	19
	Falling	10, 20	..	6, 13	..	20	3	10, 19	9, 17	8, 19	3	5, 18	8, 23	17
Dec.	Rising	6, 23	9	..	..	..	18	10, 23	..	14	..	5, 13	..	9
	Falling	2, 12, 22	4	..	7	5	22	14	6, 13	17	..	11, 20	..	12

[a] This date erroneous, but is included in the mean values and plots, having been discovered too late to correct. Its omission would have improved the general agreement.

2. Since greater causes generally produce larger effects, exceptionally wide ranges of solar variation should be associated with larger temperature ranges than the average of all the cases.

3. Since similar causes generally produce similar effects, the average results found in the years 1924 to 1930 should closely resemble

FIG. 2.—Oppositeness of temperature departures at Washington which follow average rising and falling sequences of solar variation.

in phases, though not necessarily in amplitudes, the average results found in the years 1931 to 1935.

4. Since the sun shines on the whole earth, temperature effects which fulfill criteria 1, 2, 3 should be found at all stations.

I will give first the results obtained with Washington temperatures. Figure 2 will show to what a high degree criterion no. 1 is fulfilled at Washington. Certain months, as January, March, April, October, seem to be nearly unexceptionable as regards oppositeness of features. Yet for several reasons it must not be counted as a great blemish that some of the months are less perfect examples than these. First, it is clear from figure 2 that the temperature effects, if attributable to solar changes, continue for many days after the assumed solar causes have died away. Hence, each individual case of the many whose averages are plotted in figure 2 must probably have differed decidedly from the average during its individual course because the effects of previous or immediately succeeding solar changes were still incomplete. Only in the mean of a very large number of cases, many more than the 10 to 20 of each group going to form the averages, could these vestiges of effects of previous or succeeding solar changes be totally eliminated. Second, the arrangement of results by months is arbitrary. The proper arrangement would be according to the general meteorological condition prevailing in the Northern Hemisphere. Since there are wide differences between the curves in different months, it is highly probable that the cases which are forced together by the monthly classification should not, in fact, all go together under a proper classification. Third, owing to errors in solar-constant determinations, there is no doubt that some of the solar sequences referred to in table 1 are spurious. Hence, on these three accounts it ought not to be expected that every pair of curves in figure 2 should be precisely in opposition at all points.

Figure 3 gives the mean of April results at Washington for the years 1924 to 1930. Heavy lines give the general averages corresponding to rising and falling solar sequences respectively. Light lines give the averages of the two or three cases of each sort when rising and falling solar sequences well above the average in amplitude were observed. It will be seen that the ranges of these thin-lined curves are much greater than those of the thick-lined curves representing the general averages. Thus criterion no. 2 is supported. To add to its support, a tabulation was made of 150 cases in total to show the average ranges compared to the ranges of the 46 cases among them which presented exceptionally large solar sequences. The comparison showed average amplitudes in the ratio 1 to 1.95.

As for criterion no. 3, figure 4 gives the results for rising and falling sequences in the years 1924 to 1930 as compared to the years 1931 to 1935. The reader must again be cautioned as above not to forget the influences of continuing effects of preceding and immediately succeeding solar changes, of unsuitable classification, and of

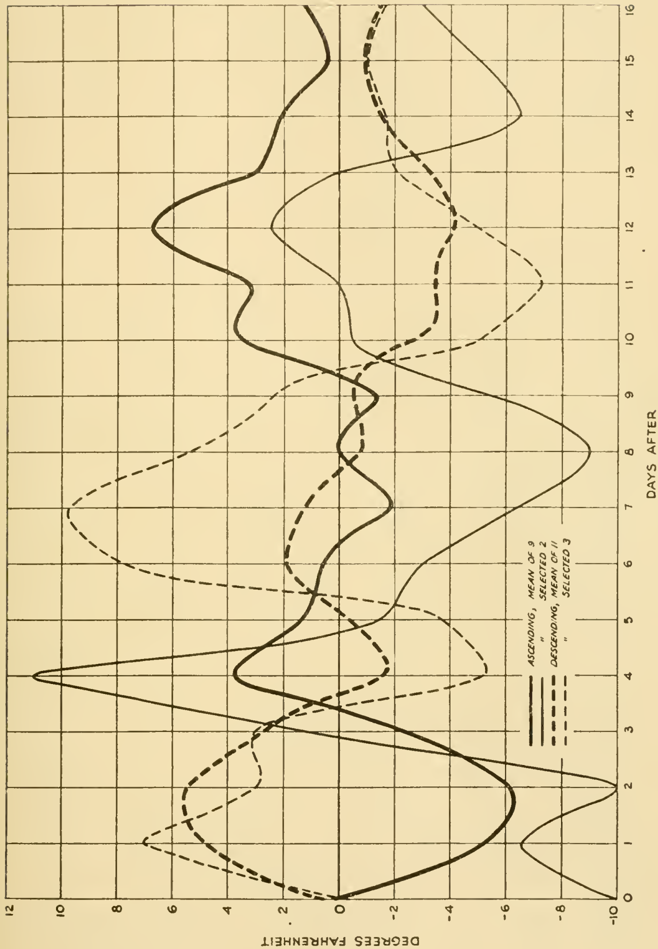
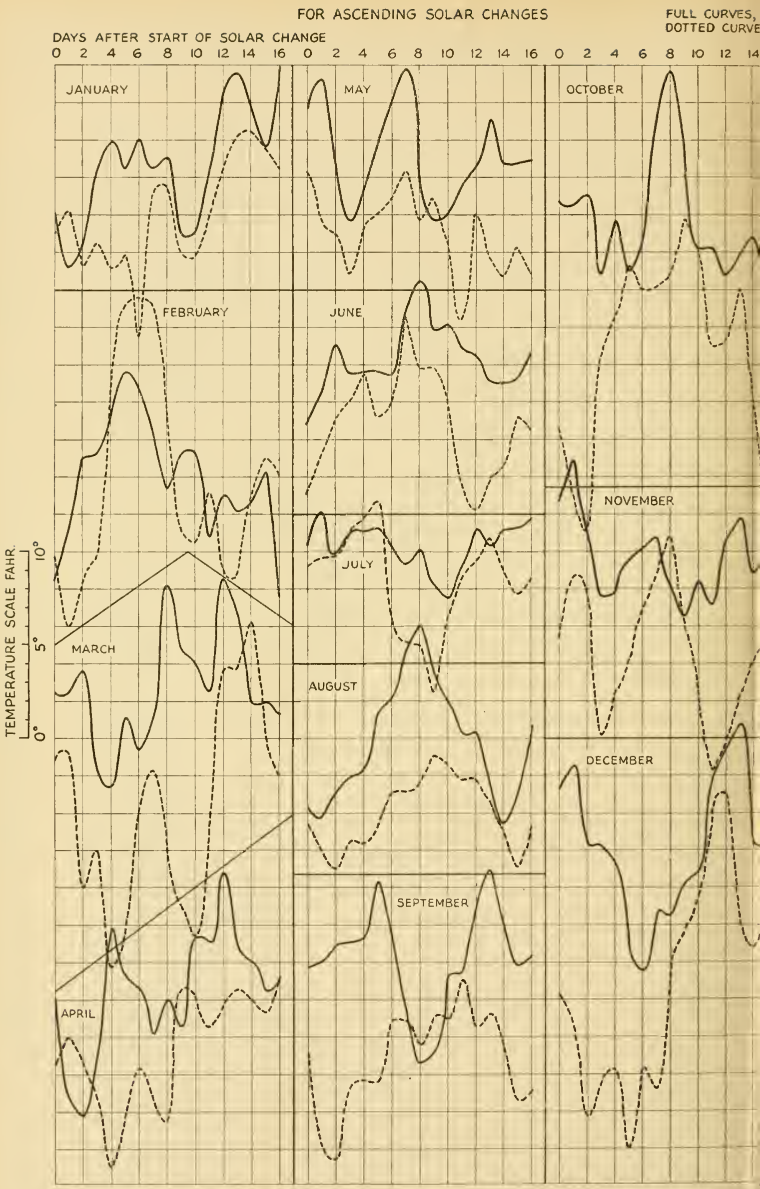
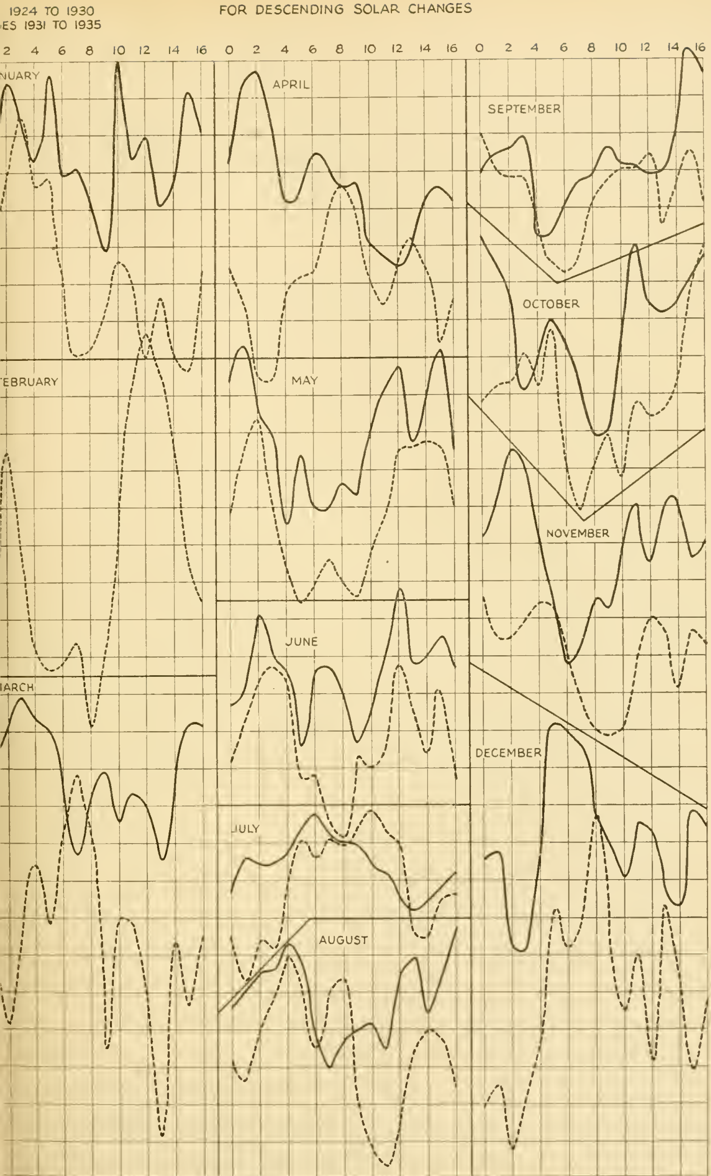


FIG. 3.—Average temperature departures following rising and falling solar variation sequences in April at Washington, 1924 to 1930, compared to selected cases of especially large solar changes. (Several critics having recommended that temperature marches following large and small solar changes should be entirely separately plotted, I have done this for April, 1924 to 1935. The result harmonizes with fig. 3.)



SOLAR VARIATION AND TEMPE

FIG. 4.—Temperature effects following solar c



DEPARTURES AT WASHINGTON

24 to 1930 compared to those 1931 to 1935.

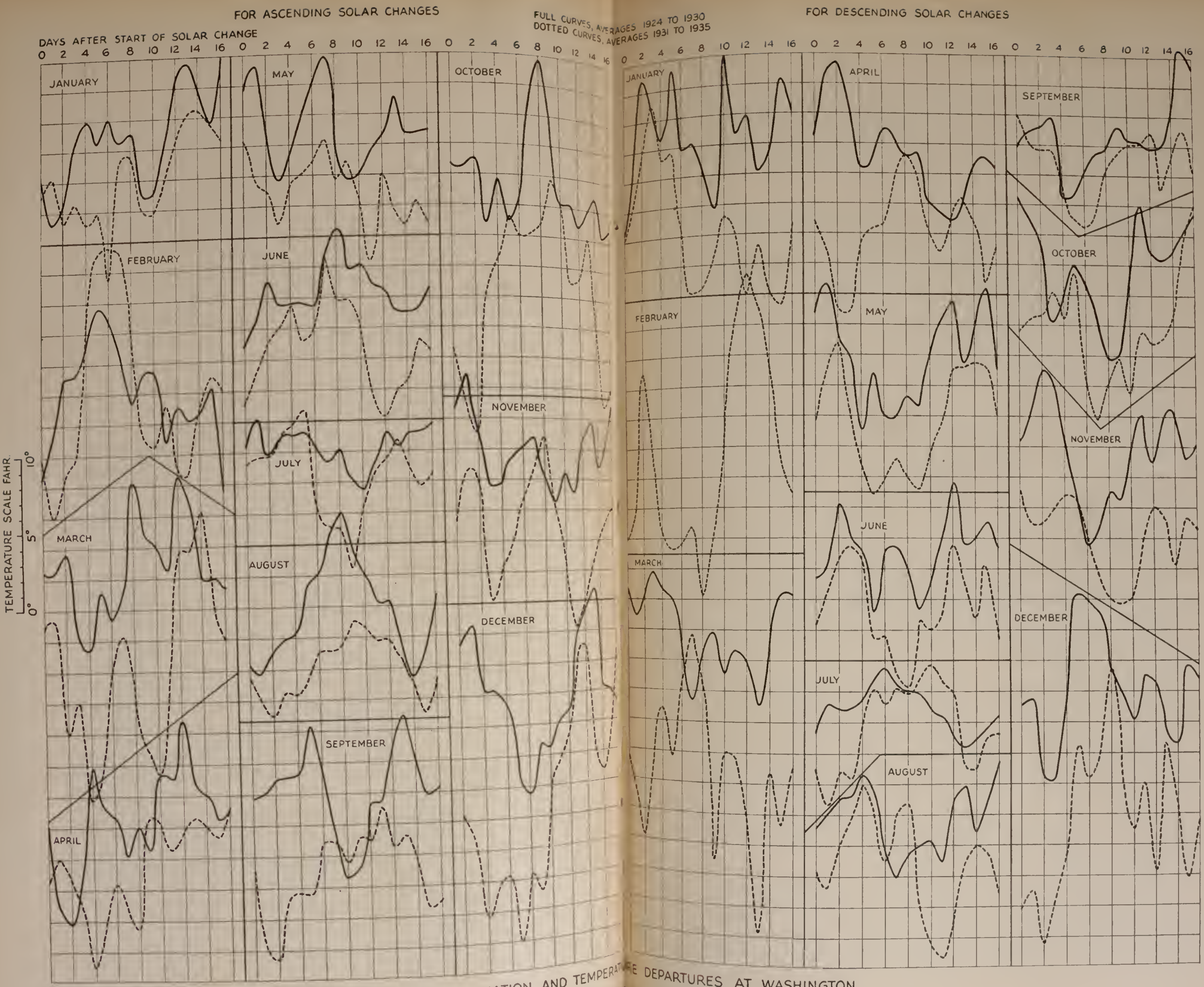


Fig. 4.—Temperature effects following solar changes 1924 to 1930 compared to those 1931 to 1935.

errors in solar-constant work which, combined, produce still more disturbing distortions in these more meager averages than those occurring in the general mean curves representing more numerous data. On the whole, however, it seems clear that the first half and last half of the data are in fair accord as to the course of temperature departures following sequences of solar change.

Reverting to figure 2, the principal contrasted temperature features corresponding to rising and falling solar sequences are large, and even surprisingly so. In many of the months, temperature changes at Washington exceeding 5° Fahrenheit are found in each curve of the pair. In some months, as October, December, and February, the larger ranges even exceed 10° Fahrenheit. Thus we have come upon departures from normal temperature which have nearly as large ranges as the largest of those ordinarily to be met with from day to day in the weather. It is easy to conceive, furthermore, that since the apparent effects last for many days, there may have been individual cases when previous or immediately succeeding solar causes would have produced temperature features in unison with those of the mean curves, whereby individual departures produced by solar causes in such cases may have been nearly or quite twice as large as those here shown. In short, if we admit, as seems justified, that these are the temperature effects produced by solar changes, then we must concede that solar changes are a main if not the principal cause of temperature changes in weather. That average changes of temperature ranging sometimes as much as 10° Fahrenheit should be thus produced is perhaps difficult to account for in theory, for the average solar changes discussed here cannot much exceed 0.5 percent. But the curves speak for themselves as to the facts.

We may now inquire whether the fourth criterion is fulfilled. Figures 5 and 6 show the general averages for 12 years, 1924 to 1935, for St. Louis, Missouri, and Helena, Montana. The same dates given in table 1 as incipient dates of solar changes were used, of course, for all stations. It will be seen at once that the oppositeness of features that confronted us in figure 2 is also found almost universally in figures 5 and 6. Without actually reproducing here the curves to show it, the reader may also be assured that our criteria numbered 2 and 3 are also fulfilled in the St. Louis and Helena data.

So the observed variations of the sun, hitherto unrecognized in making forecasts, seem to be main causes of temperature changes in weather. Their effects appear to last for at least 2 weeks. Unfortunately, this cannot be immediately tested as a new method of forecasting for 14 days in advance. For since the effects last so long, the solar conditions of a previous week as well as those of a present week combine to govern the weather of the week to come. Hence it would be necessary to have highly accurate solar-constant observations for

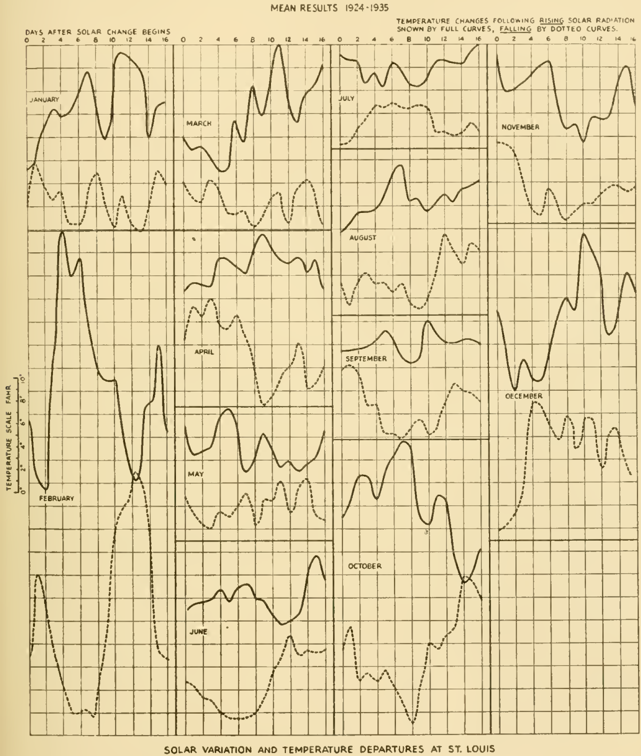
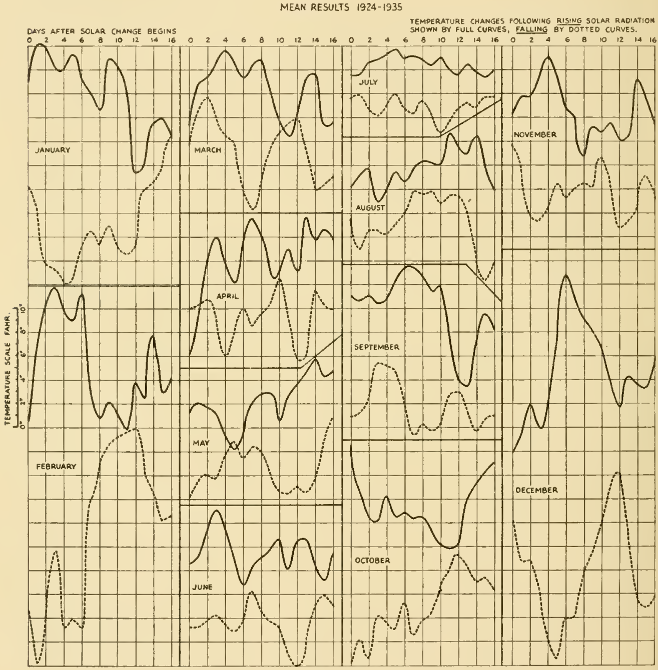


Fig. 5.—Oppositeness of temperature departures at St. Louis which follow average rising and falling sequences of solar variation.

nearly every day in the year in order to attempt to utilize this discovery for weather predictions. Unfortunately, we cannot yet command this information. Three solar-constant stations are indeed in operation, but at least 10 cooperating stations would be required for the purpose.

If means to establish and maintain 10 stations were now available, forecasting by this method could not begin until 1940. For the most accurate results depend on the use of the "short method." This is empirical, and is based on several hundred solar-constant observations by the "long method" as we now call the fundamental method of Langley. Thus the "establishment" of a station requires several years. If funds were now available, the stations could begin observing



SOLAR VARIATION AND TEMPERATURE DEPARTURES, HELENA, MONT.

Fig. 6.—Oppositeness of temperature departures at Helena which follow average rising and falling sequences of solar variation.

early in 1938, but the "short method" tables and necessary investigations of weather relationships at many stations would not be completed for forecasting purposes before the end of 1939.

I have thought of another method which may be practicable for following solar changes. As indicated by figure 1, page 29 of volume 5, Annals of the Smithsonian Astrophysical Observatory, the variation of the sun appears to be greater for the shorter wave lengths. It may be even 10 times as great at wave length 3200 angstroms as for the total radiation of all wave lengths combined. Suppose, then, that a silvered hollow ball of Corex glass should be carried by a sounding balloon to 30,000 meters elevation. Every day would be fine there, and a flux of ultraviolet rays for which silver is transparent would flow through the ball, practically as unimpeded by the atmosphere as if actually in free space. If, therefore, by a photoelectric cell, or a photographic record, the intensity of these selected ultraviolet rays could be measured to an accuracy of 1 percent, and quick intelligence of these measurements could reach the home station on the ground, the problem might be solved perhaps better than by multiplying solar-constant observing stations. Yet this new plan has several uncertain features. It would be well if both plans could be tried.

Should an accurate daily series of determinations of solar variation become available, it may well prove that several radically different temperature effects will be discovered for each given station differing with the magnitudes of the solar changes concerned. For it seems reasonable to suppose that until a solar change reaches a certain magnitude local obstacles would impede its effect on temperature. Indeed it must not be expected that the solar variation is a complete guide to weather, but rather a factor in a highly complex problem, the recognition of which may yield valuable progress in weather forecasting.

The reader will note in figures 2, 5, and 6 that the curves differ from month to month and from station to station. As stated by Clayton and others, almost immediate effects of solar changes are found at certain places on the globe which he calls "centers of action." From these the effects spread by atmospheric waves to distant localities. The paths followed by these atmospheric waves doubtless differ with secularly changing meteorological conditions governing atmospheric states in different hemispheres. Hence, doubtless, arise the differences above noted. Note for instance in the month of January that the broadest separation of the pair of curves occurs first at Helena, later at St. Louis, and last at Washington.

It was suggested above that the temperature effects discovered seem at first sight disproportionally large compared to the solar changes which induce them. However, temperatures in the temperate zones depend largely on the prevailing direction of the wind. Clayton has shown that solar changes are accompanied by wanderings of the atmospheric "centers of action." Thence come shiftings of the centers of cyclonic motions of the atmosphere, which, in their turn govern the direction of the winds at particular localities. Such displacements of the cyclones and anticyclones and wind directions so caused are probably the mechanisms involved in the large effects found in this paper.

Addenda

NOTE ON MR. CLAYTON'S INVESTIGATIONS OF THE RELATIONS OF RADIATION AND TEMPERATURE[1]

By C. G. Abbot

Nearly 40 years ago the late Secretary Langley, at that time Director of the Allegheny Observatory, made the following remarkable statement in his report of the Mount Whitney Expedition:

"If the observation of the amount of heat the sun sends the earth is among the most important and difficult in astronomical physics it may also be termed the fundamental problem of meteorology, nearly all whose phenomena would become predictable if we knew both the original quantity and kind of this heat; how it affects the constituents of the atmosphere on its passage earthward; how much of it reaches the soil; how through the aid of the atmosphere it maintains the surface temperature of this planet, and how in diminished quantity and altered kind it is finally returned to outer space."

Let us set over against this pronouncement of Langley the final conclusion of Mr. Clayton in the paper which follows: "The results of these researches have led me to believe: 1. That if there were no variation in solar radiation the atmospheric motions would establish a stable system with exchanges of air between equator and pole and between ocean and land, in which the only variations would be daily and annual changes set in operation by the relative motions of the earth and sun. 2. The existing abnormal changes, which we call weather, have their origins chiefly, if not entirely, in the variations of solar radiation."

* * * *

His whole paper deserves careful attention, but in order to fix in a striking manner in the reader's mind the strength of his case for a real correlation between solar radiation and terrestrial temperature, I would draw attention to tables 1 and 2 of Mr. Clayton's main paper

[1] Clayton, H. H., Variation in solar radiation and the weather. Smithsonian Misc. Coll., vol. 71, no. 3, 1920.

and to the little table in the Appendix. Part of the data in table 2, changed to the Fahrenheit scale, forms the frontispiece. [Here figure 7.]

* * * *

I would like to draw the reader's attention in particular to number 7 of the conclusions which Mr. Clayton states in the summary of his research. In this he points out that variations of temperature in Argentina agree well in number and in magnitude to the variations which would be expected in view of the supposed changes in the solar radiation. It is this and many other features of his research which

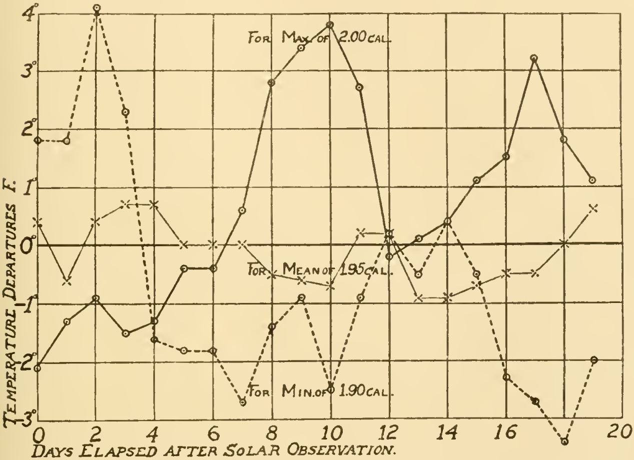


Fig. 7.—H. H. Clayton's indication, published in 1920, of the influence of solar variation on terrestrial temperature departures at Buenos Aires.

have led him to the conclusion that the weather as distinguished from the climate is governed by variations of the sun and would be predictable both qualitatively and quantitatively if we had daily accurate determinations of the solar variation. If this be true, we stand, it seems to me, on the threshold of a very important research in meteorology. What is needed is the establishment of sufficient stations for observing solar radiation, in order that, by combining the results of all of them, well-founded mean solar radiation measurements may be available every day in the year, and for a sufficient succession of years, so that quantitative studies of the dependence of weather conditions on solar variations similar to those of Mr. Clayton may be advantageously pursued.