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During the past 3 years increasing evidence has been disclosed that outbreaks of new sunspots are closely related to weather changes on the earth. In the winter of 1943 it was noted that several marked outbreaks of sunspots were followed by cold waves in the United States. Defining cold waves as a fall of temperature of 20 or more degrees in 24 hours, it was found that sunspots showed a marked increase pre-

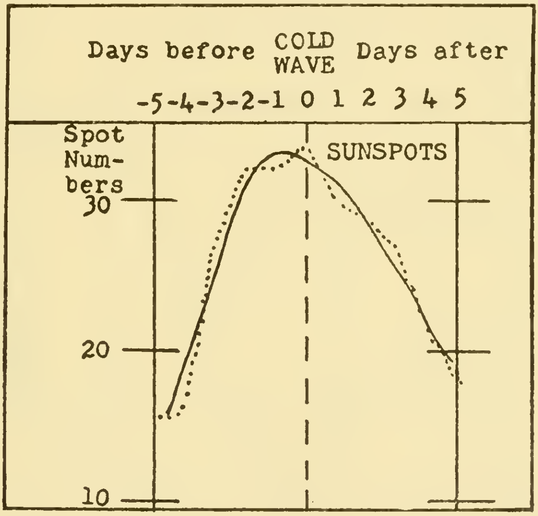

FIG. 1.—Average sunspot number preceding and following the coldest day in each cold wave at Minneapolis. Winter of 1942-43.

ceding the cold waves at Minneapolis and reached a maximum about 1 day before the coldest day.[1] This finding is illustrated by figure 1. The full curve represents the smoothed average result from six cases.

Another method of approach was to take maxima of spots, exceeding 50 on the Zurich scale, and average the departures from normal temperature at several widely distributed stations in the United States for the days of maxima of spots, for 5 days preceding and 12 days following. The results are shown in figure 2. The dotted curve shows the averages of sunspots, and the solid curves show the averages

[1] Supplement to Solar Relations to Weather, by H. H. Clayton, April 1943.

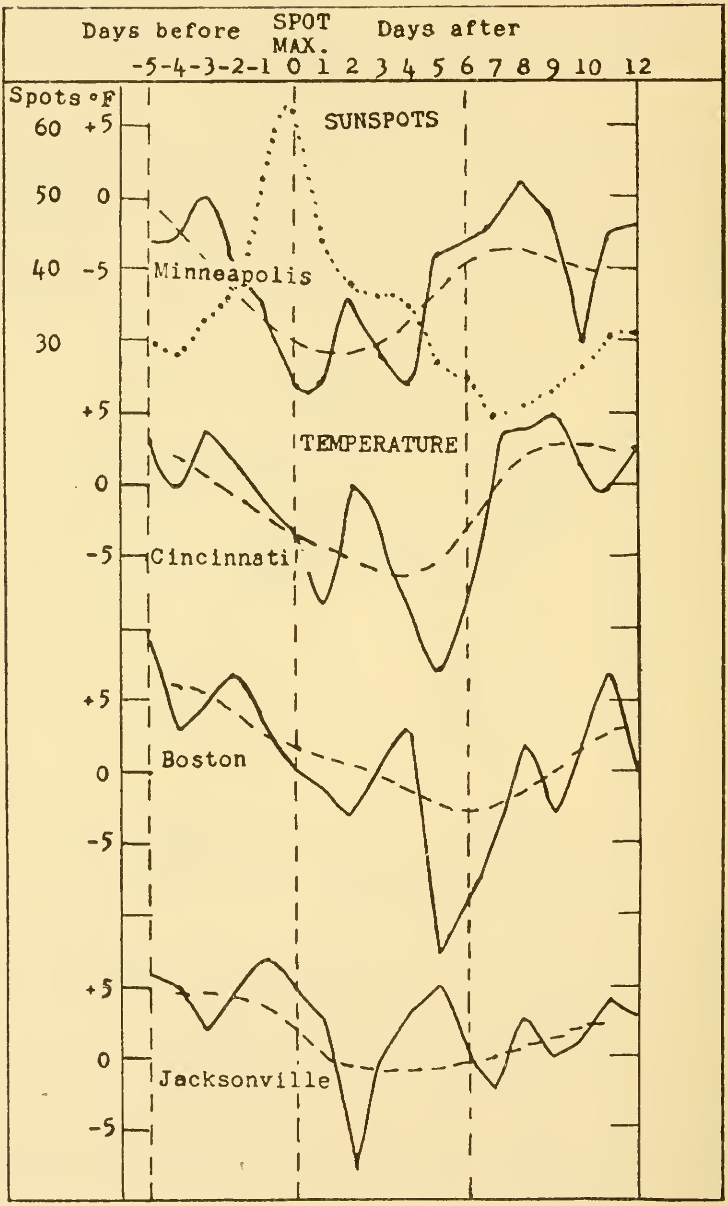

FIG. 2.—Mean temperatures at Minneapolis, Cincinnati, Boston, and Jacksonville, preceding and following marked maxima in sunspots. Winter of 1942-43.

of the departures from normal temperature at Minneapolis, Cincinnati, Boston, and Jacksonville during the winter of 1942-43. Minima of temperature followed maxima of sunspots 1 and 3 days later at Minneapolis and occurred successively later at stations farther south and east. The lowest temperatures reached Boston 5 days after the peak of sunspot activity and 6 to 7 days later at more southern stations on the Atlantic Coast.

The results show that, *following outbreaks of new sunspots, colder weather develops north of the United States and moves southeastward in the form of a wave.*

A striking example of the relation between sunspot changes and changes in temperature occurred in February 1943. There were two outbreaks of sunspots, each followed by a severe cold wave. Figure 3 shows the areas of sunspots for that month in the upper part of

TABLE 1.—*Sunspot areas and 1- and 2-day changes in these areas during February 1943*

Date, February..	5	6	7	8	9	10	11	12
Area............	36	60	12	121	521	921	878	908
1-day change....	...	+ 24	− 48	+109	+400	+400	− 43	+ 30
2-day change....	...	...	− 24	+ 61	+409	+800	+357	− 13
Date, February..	13	14	15	16	17	18	19	20
Area............	794	727	739	581	491	97	96	472
1-day change....	−114	− 67	+ 12	−158	− 90	−394	− 1	+376
2-day change....	− 84	−181	− 55	−146	−248	−484	−395	+375
Date, February..	21	22	23	24	25	26	27	28
Area............	865	994	994	1090	1125	1550	1551	1611
1-day change....	+393	+129	00	+ 96	+ 35	+425	+ 1	+ 60
2-day change....	+769	+522	+129	+ 96	+131	+460	+426	+ 61

the diagram. These areas were measured by the United States Naval Observatory and are from the records published in the Monthly Weather Review. It is seen from this curve that there were marked increases in sunspot areas between February 8 and 10, and again between February 19 and 21.

The observed areas of the sunspots and of 1- and 2-day changes in area are given in table 1.

One-day changes are shown in figure 3 by the broken curve and two-day changes by the full curve near the middle of the diagram. These curves are inverted—that is, increases are plotted downward for easier comparison with temperature. Departures from normal temperature at Boston 5 days later are plotted in the lower part of the diagram. The temperatures were taken from a report of the Weather Bureau at Boston. The table and diagram are from my report to Dr. Charles F. Brooks and to the Weather Bureau of results found in a wartime research project for the War Department.

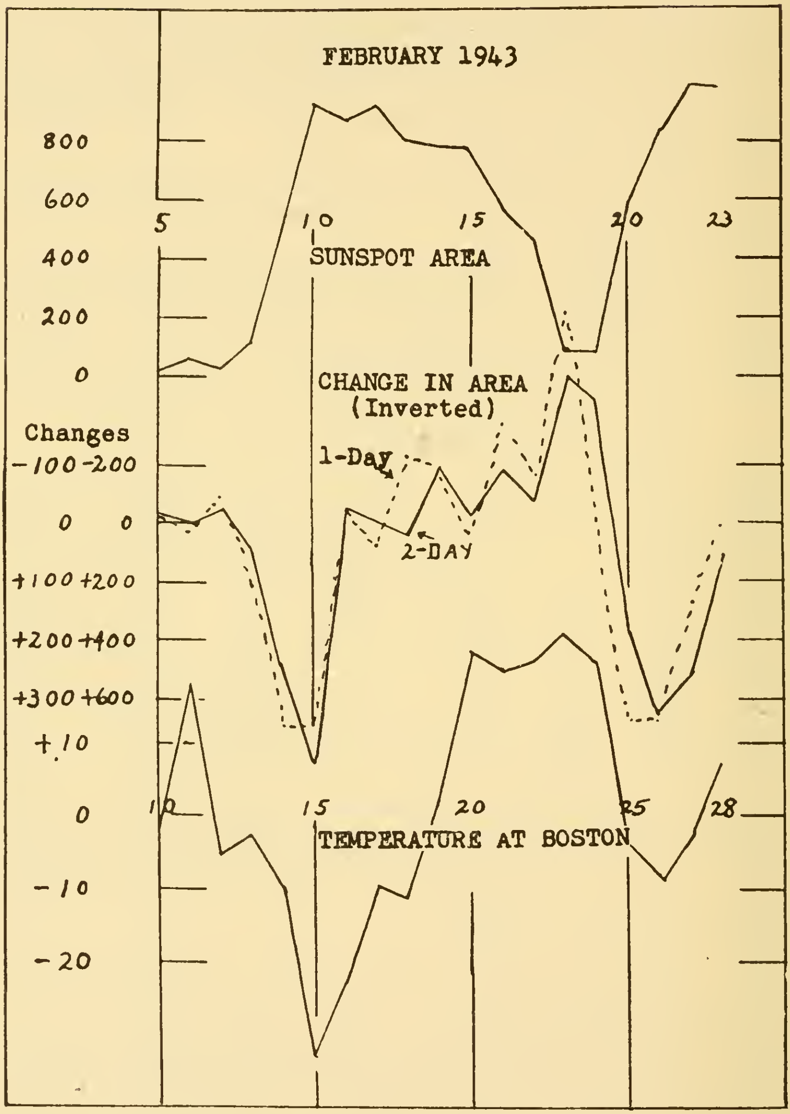

FIG. 3.—Relation of changes in area of sunspots to departures from normal temperatures at Boston during February 1943. Sunspot changes are inverted and time of temperature displaced 5 days to allow for lag.

The plots of 2-day changes in sunspot areas in figure 3 show a striking resemblance to the departures from normal temperature 5 days later at Boston. The correlation between the two sets of data is −0.76 for the 22 days from February 7 to February 28.

From this comparison it is evident that *atmospheric changes are influenced not so much by the absolute amount of sunspots as by the changes in the amount.* As will be seen later this rule holds true not only for short-period changes, but also for long-period changes in sunspots. The temperature at Boston on February 15 fell about 30° below normal. This was the severest cold wave of the winter 1942-43. On February 18 this area of sunspots passed off the west limb of the sun and was followed 5 days later by the highest temperature of the month at Boston. On February 20 a new outbreak of spots was observed on the sun followed 5 days later by a marked fall of temperature at Boston. The area of spots first seen on February 9 became visible again by solar rotation on March 4 and was followed by temperatures about 15° below normal on March 9.

My drawings of this outbreak of sunspots on February 8 to 10 made with an object glass of 4 inches are shown in figure 4. The sun's axis of rotation was tilted about 20° to the earth's axis, and the spot areas moved from east to west across the sun. The first appearance of this area of spots was a small spot northeast of the sun's center on February 8. It developed into a large group by the morning of February 10. My drawings for those dates are shown at the top of the diagram, figure 4. On February 12 this area of spots had moved by solar rotation to the central meridian of the sun. By February 16 it was near the western edge and disappeared on February 18. On March 4 it reappeared on the eastern edge of the sun much diminished in area. Few of these outbreaks last more than one or two rotations of the sun and many of them only part of a rotation period of 27 days.

Another diagram, figure 5, shows 2-day changes in sunspots and 2-day changes in temperature at Chicago and Boston in December 1944. The plot of temperature at Chicago is displaced 4 days to the left and that at Boston 5 days to the left in order to make them coincide with sunspot changes.

These graphs, figures 3 and 5, represent the average or normal lag of temperature during winter and spring following marked changes in sunspots. This fact is confirmed by averages following sunspot changes of 30 or more during the 6 years 1935-1940. The lag in summer and autumn at Boston is greater than 5 days. The origin of the anticyclones in those seasons is nearer the Poles or else is in the

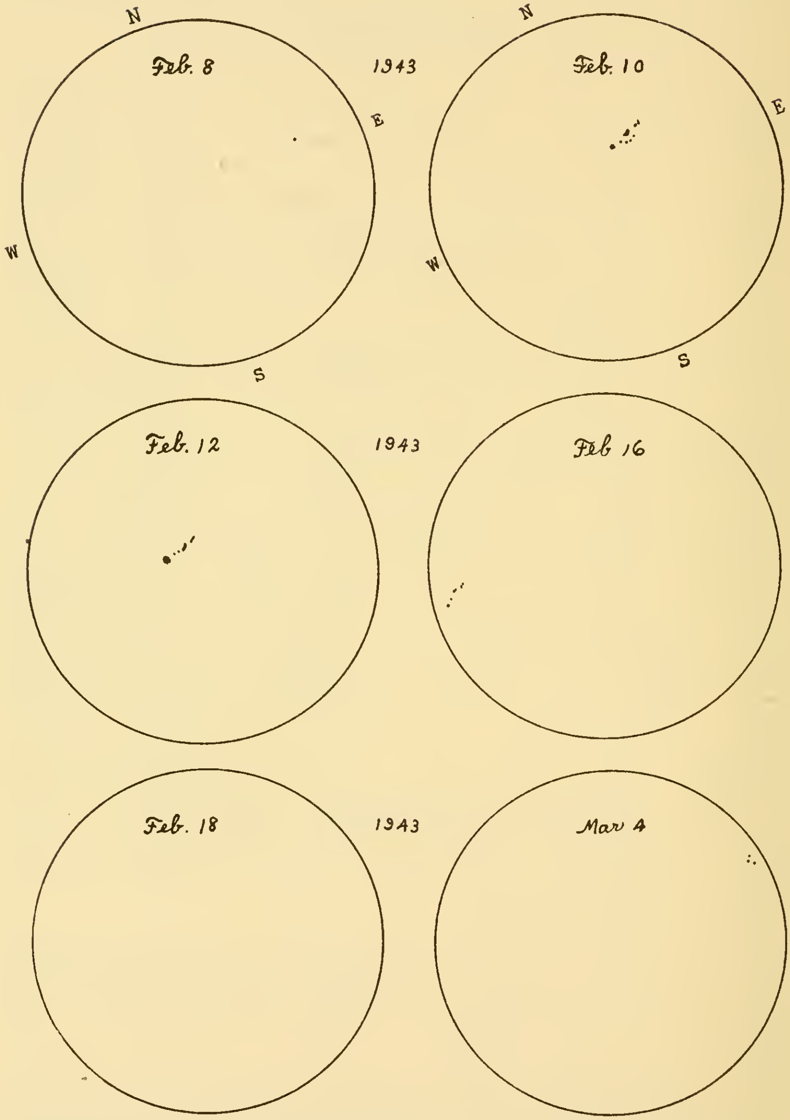

FIG. 4.—Drawings of sunspots between February 8 and March 4, 1943.

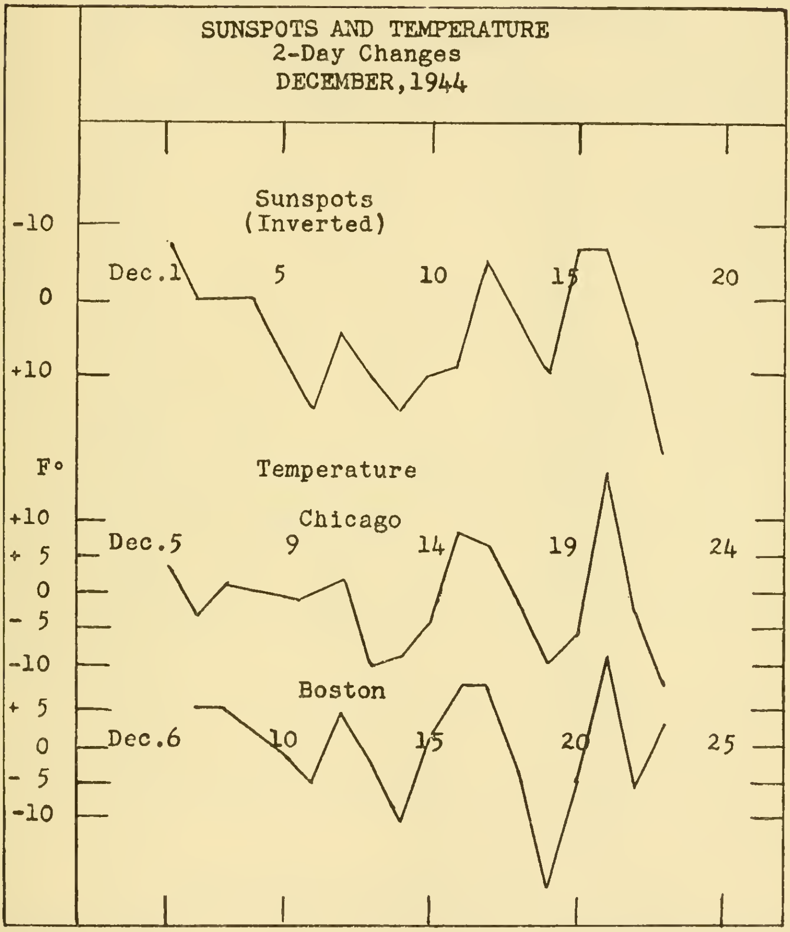

FIG. 5.—Two-day changes in sunspots compared with two-day changes in temperature at Chicago and Boston. (Sunspot changes are derived from the means of 15 observers in the United States, collected by N. J. Heines and published by the Carnegie Institution.)

area of permanent high pressure in the western Pacific. Occasionally the anticyclones come southward more rapidly over Hudson Bay. The average fall of temperature at Boston following marked increases in sunspots is about twice the standard deviation.

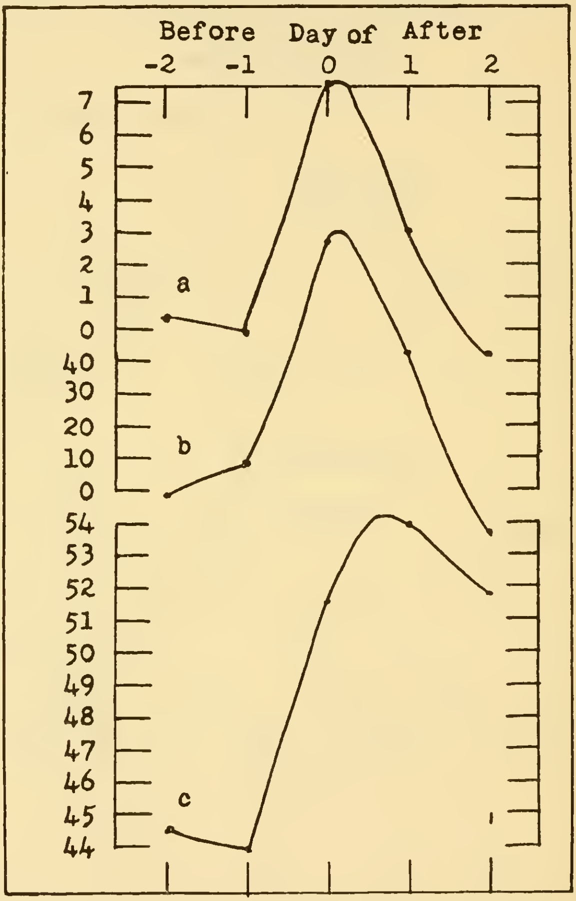

FIG. 6.—New outbreaks of sunspots in relation to (a) 1-day changes in relative sunspot numbers (Zurich); (b) 1-day changes in sunspot areas (U. S. Naval Observatory); (c), mean relative sunspot numbers (Zurich).

Changes in sunspot numbers and in sunspot areas are closely related to new outbreaks of spots. Figure 6 (curves *a* and *b*) shows a plot of the average daily changes in sunspot numbers and in sunspot areas on the days of first appearance of new spots and for the 2 days preceding and following. However, the absolute number of spots continues to increase for 2 days after the first appearance of the new spots. This fact is shown by curve *c*. Hence, 2-day changes in most cases show the full amount of the solar change better than 1-day changes, although the larger amount of the change takes place in 1 day.

Since falls of temperature are usually associated with rises of atmospheric pressure, the next step in the investigations was to find the relation between sunspots and new rises of pressure in high latitudes of the earth. These new rises of pressure form anticyclones and the maps published in the United States Monthly Weather Review show that these new anticyclones usually appear first in North America at some point north of 60° latitude.

Two years were selected for study, one 1936, when sunspots were increasing in intensity, and 1941, when sunspots were decreasing. The dates and positions of the first appearance of anticyclones were taken from the Monthly Weather Review for these 2 years. They were all north of 60° except during the 3 months July-September, when anticyclones first appear most frequently in latitude 40° to 50° N. and longitude 115° to 155° W. Taking the first appearance of the anticyclone as zero day, the average daily changes in sunspots were found for that day and for 2 days preceding and 2 days following.

Cyclones originate most frequently over the oceans. Within the United States and adjacent waters, new cyclones appear most frequently over the Gulf of Mexico and adjacent land surfaces and over the Gulf Stream. Counting the first day of appearance of the cyclone as zero day, the average daily change in sunspots was found for that day and for 2 days preceding and following for the years 1936 and 1941.

The average daily changes in sunspots accompanying new anticyclones and cyclones are given in table 2 and plotted in figure 7.

TABLE 2.—*Mean change in sunspot numbers observed at Zurich on days of first appearance of new anticyclones in North America*

Days	−2	−1	Day of	+1	+2	Cases
I. New anticyclones (morning map) north of 60° N.						
Mean of year 1936	−2.7	2.4	−0.3	−0.3	1.7	49
" " " 1941	−3.9	3.0	−1.1	−1.8	0.9	39
II. New cyclones (morning map) 20°–40° N. and 50°–100° W.						
Mean of year 1936	2.0	5.6	−1.4	4.4	1.6	31
" " " 1941	−5.2	4.2	1.8	0.1	−2.6	21
III. New anticyclones (evening map) north of 60° N.						
Mean of year 1936	1.1	2.3	6.1	1.6	0.2	11
" " " 1941	−0.6	−0.9	1.4	−4.1	2.1	14
IV. New cyclones (evening map) 20°–40° N. and 50°–100° W.						
Mean of year 1936	1.4	2.6	2.1	−4.3	−3.1	17
" " " 1941	−0.5	0.1	−2.0	0.6	−1.5	20

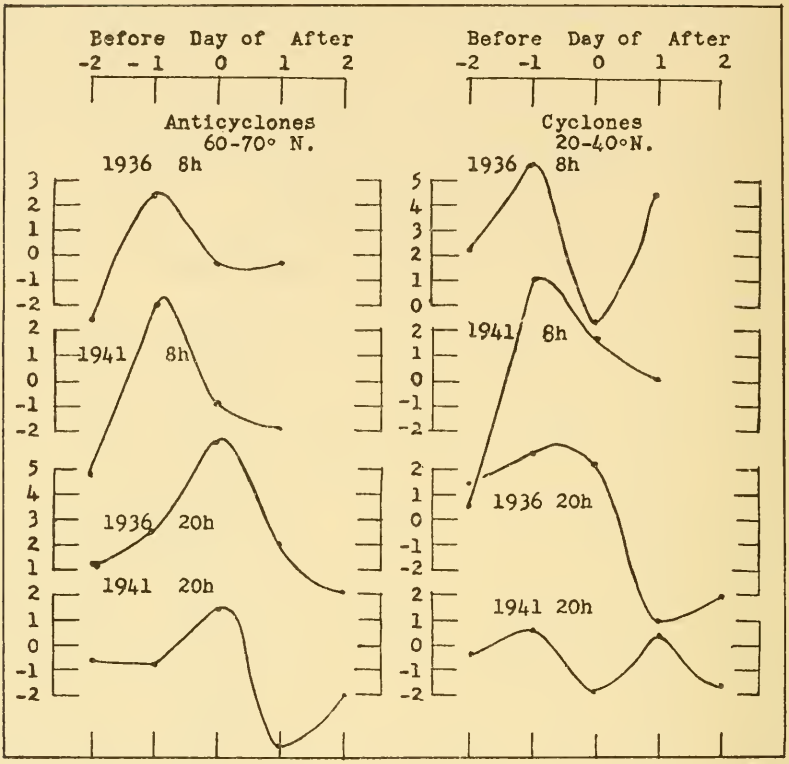

FIG. 7.—Mean daily changes in sunspots on days of origin of anticyclones and cyclones in North America and on the 2 days preceding and following. 8^h = by morning map; 20^h = by evening map.

The frequency of origin of anticyclones and cyclones in different longitudes for the 2 years 1936 and 1941 is given in table 3 and is plotted in figure 8.

TABLE 3.—*Frequency of origin of anticyclones and new cyclones in different longitudes*

Anticyclones

Between latitudes 60° and 75° N.

Longitude W.	91°–100°	101°–110°	111°–120°	121°–130°	131°–140°	141°–150°
1936........	3	5	17	9	6	3
1941........	8	6	9	11	3	1

New cyclones

Between latitudes 20° and 40° N.

Longitude W.	60°–70°	71°–80°	81°–90°	91°–100°
1936	7	15	12	12
1941	6	12	23	10

This plot shows that anticyclones in North America originate most frequently near longitude 120° W. at about 65° N. In the average they reach the Atlantic Coast of the United States about 5 or 6 days later. They may, however, originate in any longitude. The place

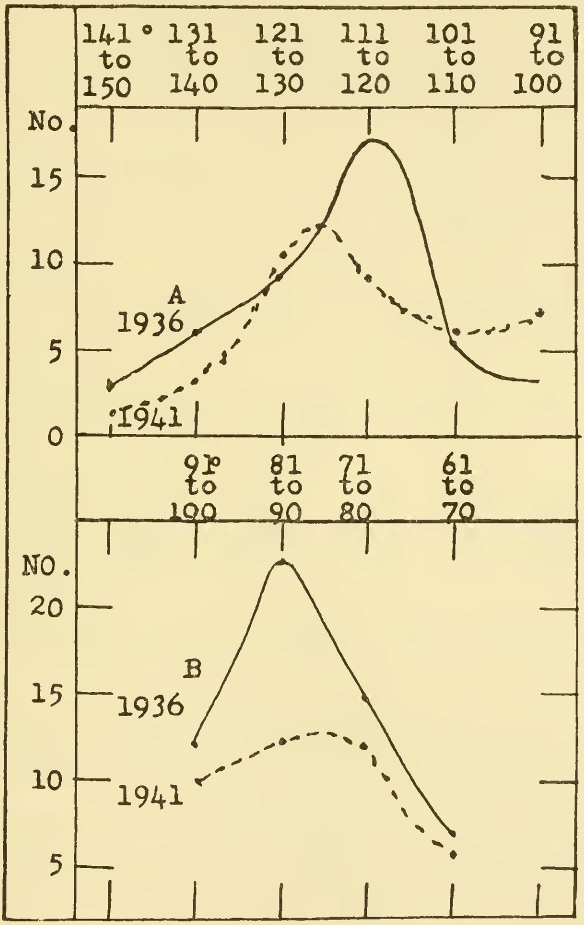

Fig. 8.—A, frequency of origin of anticyclones at different longitudes in North America north of 60° latitude, 1936 and 1941; B, frequency of origin of cyclones in the eastern United States and adjacent oceans south of 40° latitude, 1936 and 1941.

of their origin must hence be determined in part by temporary local conditions.

The origin of new cyclones in the region selected for examination occurred most frequently near 80° W., 30° N., that is, near the Gulf Coast of the United States. There was a greater number of anticyclones and cyclones in 1936 than in 1941, and the area of most frequent occurrence was somewhat farther east. In 1936 the sunspots were approaching a maximum and rapidly increasing in number, whereas in 1941 they were diminishing. Hence, the greater number of anticyclones and cyclones in 1936 than in 1941 may be additional evidence of a relation between sunspots and weather.

The pressure in the central area of moving anticyclones and cyclones varies from day to day. The question of whether the pressure rose in moving anticyclones and fell in moving cyclones with increased sunspot activity was next investigated. To do this the changes in the central pressure from day to day were taken from the maps in the Monthly Weather Review and the positions of the anticyclones and cyclones noted. Then for anticyclones in the region 50°-70° N., 90°-150° W. (except in summer) the data were tabulated in reference to outbreaks of sunspots. For cyclones the data were obtained for the region 20°-40° N. and 50°-100° W. throughout the year. These were the regions of greatest frequency of origin of

TABLE 4.—*Changes in pressure in millibars at centers of moving anticyclones and cyclones in relation to solar outbreaks*

	Before		Day of	After	
Day	−2	−1	0	1	2
Anticyclones 1936	+1.4	−0.3	−0.7	−0.8	−0.8
" 1941	−0.5	+1.8	+2.1	−0.9	−1.7
Cyclones 1936	−0.3	−4.4	−5.1*	−3.7	−3.0
" 1941	−0.4	−1.6	−3.1*	−0.6	−0.2

* Minima.

anticyclones and cyclones, respectively. The results are given in table 4.

An average rise in pressure in the central area of moving anticyclones was distinctly evident in 1941, but was not apparent in 1936. The reason may have been that the pressures in the central areas were given in more detail in 1941 than in 1936.

The fall of pressure in cyclones attending new outbreaks of sunspots is plotted in figure 9 for the 2 years 1936 and 1941. The fall is distinctly shown both in 1936 and 1941, being greater in 1936 when sunspot changes were greater.

The most reasonable explanation of the foregoing results is that increased radiation is absorbed by the air in and around cyclones. Whether this increased absorption is due to ozone which is found in greater amount above cyclones or whether it is due to water dust in the form of haze and cloud particles remains to be determined. The increased temperature resulting from this absorption causes the air to expand, so that the pressure falls within the area of the cyclones and rises in other regions, principally farther north where the air is colder.

New outbreaks of sunspots are closely related to clouds of flocculi. When seen on the limb of the sun they are usually associated with faculae.

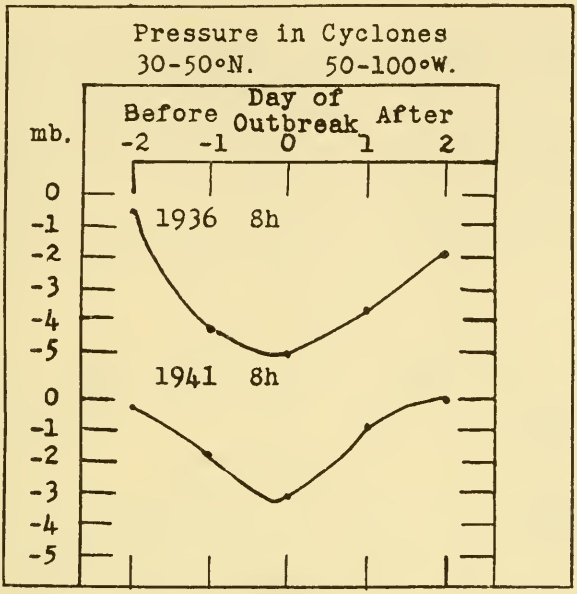

FIG. 9.—Fall of pressure in the central area of cyclones over the Gulf of Mexico and eastern United States in relation to fresh outbreaks of sunspots of 10 or more (Zurich).

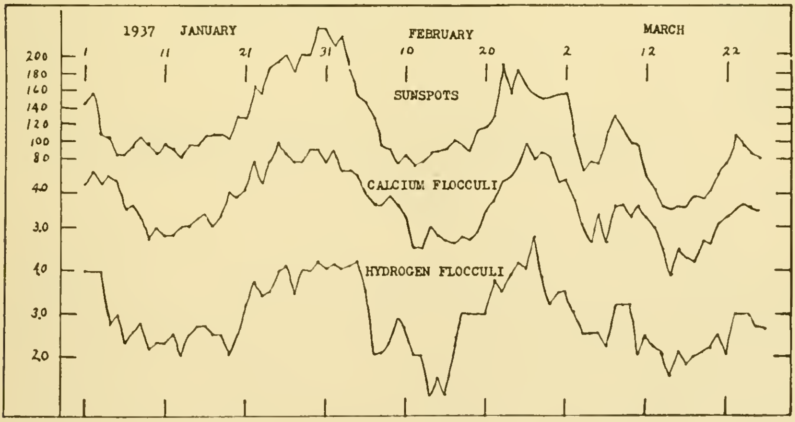

FIG. 10.—Comparison of day-to-day observations of sunspots, calcium flocculi, and hydrogen flocculi.

Figure 10 shows a plot of daily relative sunspot numbers for the early part of 1937 as published at Zurich by W. Brunner and also plots of areas of calcium and hydrogen flocculi observed on the same days by the International Astronomical Union. It is seen from these plots that almost every detail of the changes in sunspot numbers is reflected in the changes in flocculi.[2] The correlation between the

[2] NOTE BY C. G. ABBOT.—The relationship between solar appearance and solar radiation output is puzzling and requires further study. L. B. Aldrich (Smithsonian Misc. Coll., vol. 104, No. 12, 1945) separates the sunspot cycles 1923 to 1933 and 1933 to 1944, and finds, by comparison of identical days between sunspot numbers and the values of the solar constant of radiation, dependencies involving considerable fractions of the range of the solar constant, but squarely opposite marches for the two cycles. Aldrich's graph is here reproduced. His

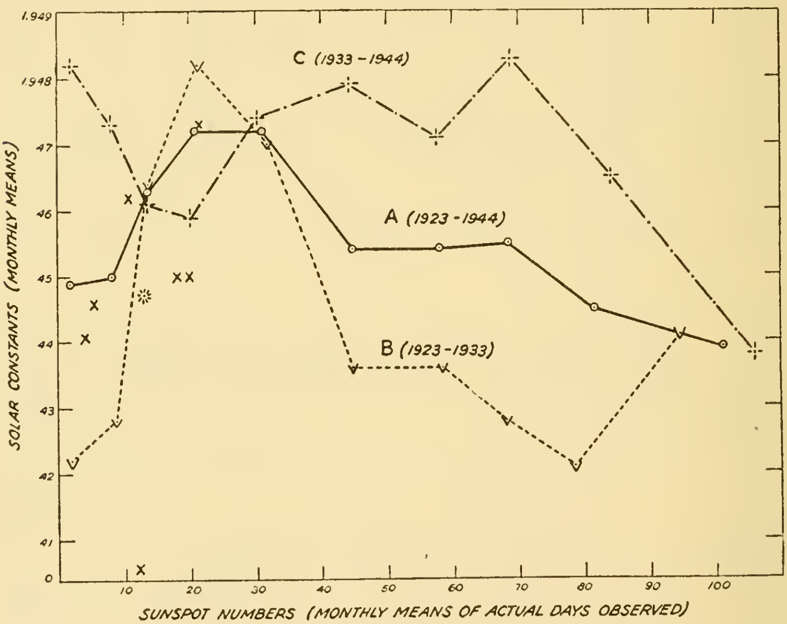

FIG. 1.

(From Aldrich, Smithsonian Misc. Coll., vol. 104, No. 12, 1945.)

results imply that the sunspot cycle should be considered not as 11⅓ years, but 22⅔ years. He gives the indications by crosses on the diagram for 7 months subsequent to the interval 1933 to 1944, and these tend to follow the curve for 1923 to 1933 as would be expected.

A cycle of 22⅔ years was discovered by G. E. Hale in the magnetism of sunspots. He found that the polarities of pairs of spot groups in both solar hemispheres reverse at the beginning of each new 11⅓-year sunspot cycle. I point out (Abbot, C. G., Smithsonian Misc. Coll., vol. 94, No. 10, p. 20, fig. 10, 1935) that the total area included under sunspot-number graphs is alternately smaller and larger, also indicating a 22⅔-year cycle. It has also been found by meteorologists in many researches.

sunspots and flocculi is more than 0.80. Spectroscopic observations show that these clouds of flocculi are at a much higher temperature than the sun. Deslandres estimates the temperatures at 20,000° C. or

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As regards day-to-day changes in solar activity, I report (Abbot, C. G., Proc. Nat. Acad. Sci., vol. 9, No. 10, pp. 355-357, 1923) comparisons of solar-constant changes with appearances of sunspots, faculae, and flocculi photographed at Mount Wilson Observatory. I state:

"I believe the four following general principles will be found to hold for almost all cases:

"1. When sunspots form or grow, or are brought by rotation into view on the visible disk, higher radiation values occur on the same day.

"2. When sunspots transit across the central diameter of the visible disk, lower radiation values occur, and usually reach a minimum on the day following the transit.

"3. When the direct photographs and Hα spectroheliograms show a much disturbed solar surface, the radiation values run high.

"4. When a period of quiescence in solar activity occurs, the radiation values tend to fall continually lower and lower until some new outbreak of activity is observed."

This is harmonious with Clayton's statements in this present paper.

I have also showed that the rise and the fall of solar-constant values are associated with definite, long-continuing, and large fluctuations of temperature and of precipitation. These same weather effects are associated, as I show, with rise and fall of the areas of flocculi on the sun's surface, and also with the rise and fall of "critical frequencies" in the "E layer" of the ionosphere (Abbot, C. G., Smithsonian Misc. Coll., vol. 101, No. 1, 1941; vol. 104, No. 5, 1944, and No. 13, 1945). Identical meteorological changes are associated, as I have indicated, with all three of these independent solar phenomena. But the percentage magnitudes of fluctuations of these three types of solar phenomena are very different. The average changes referred to in the solar constant are but 0.7 percent. In the areas of flocculi they range from 0 to 3,000 on the scale of observation. In the critical frequency, even after removing the average yearly range and the average sunspot range, the day-to-day fluctuations exceed 10 percent.

In volume 6 of the Annals of the Astrophysical Observatory it is shown, in figure 11, that the variation of solar radiation is very small in the infrared spectrum, and rises rapidly for shorter wave lengths till at 3500 A. it is about six times as great as the variation of the solar constant. Several scientists have adduced reasons to suppose that the variation of the sun in the extreme ultraviolet spectrum is very great indeed. Values as high as 500 percent have been put forward. It is known that variations of ultraviolet radiation are apt to produce variations of atmospheric ozone, which has important functions in regard to weather. Cloudiness, also, is another variable apt to be influenced by solar changes, not only of the intensity of radiation, but of atmospheric ionization.

In view of all this it is my thought that Clayton perhaps takes too simple and direct a view of the causes of the correlations of sunspots and weather. He inclines to attribute them to changes in the intensity of solar radiation. I suggest that they may be indirect results produced by alterations of ionization, ozone concentration, and cloudiness, all induced by solar changes.

more. Recently, Dr. D. H. Mensel has published estimates of the temperatures of faculae in the higher atmosphere of the sun which he places at approximately 2,000,000° C. (Time, June 16, 1941, p. 69; Science News Letter, June 14, 1941, p. 374).

These faculae are believed to be associated with protons ejected by eruptions from the interior of the sun which, cooled by adiabatic expansion, combine with free electrons in the outer atmosphere of the sun, liberating an enormous amount of subatomic energy and forming fiery clouds of matter at very high temperatures. Sunspot changes are also closely related to terrestrial magnetic changes [3] and to ionic changes in the earth's atmosphere.

The measurements of astrophysicists show that there is a marked depletion of solar radiation by the atmosphere when dust, haze, or clouds are present in the lower atmosphere. On densely cloudy days a very small percentage of the solar radiation reaches the earth. Even a small increase in haze in the lower atmosphere noticeably depletes the solar rays.

In some comparisons of the amount of solar radiation received at the summit and base of Mount Washington on 2 very clear days, October 2 and 3, 1942, Irving F. Hand found a decrease of visibility in the lower atmosphere due to increasing haze coinciding with an increased depletion of radiation in the stratum of air beneath the summit. He says,[4] "On the 3rd the readings at the Half Way House were only 4 percent higher than those at the base, while the readings on the summit ranged from 11 to 14 percent higher than those at the base." Mr. Hand further finds that a thin layer of smoky air above cities almost completely eliminates the radiation near the blue end of the spectrum, more especially the ultraviolet.

The physical observations are lacking which would enable us to compute how much the atmosphere is heated by this depleted radiation, but the statistical evidence presented above indicates that this may be an important factor in weather changes.

The next step in the investigation was to find what relation existed, if any, between monthly changes in sunspots and changes in atmospheric pressure. The data available for this study were the mean monthly pressures at 10° intersections of the lines of latitude and longitude derived from daily weather maps by the Weather Bureau [5] for the years 1929-1938.

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[3] Terrestrial Magnetism and Atmospheric Electricity, March 1942.

[4] Monthly Weather Review, May 1943, p. 67.

[5] World Weather Records, 1931-1940, to be published by the Smithsonian Institution (in press).

The monthly changes in these means were tabulated and averaged for the months when sunspot numbers increased 10 or more. The means for the winter half-year and for the summer half-year separately along the fiftieth parallel of north latitude are shown graphically in curves A in figure 11; while curves B show the normal distribution of pressure along the fiftieth parallel of north latitude in midwinter and midsummer. However, the vertical scale in the two sets of curves is not the same. Curves B show that in midwinter the pres-

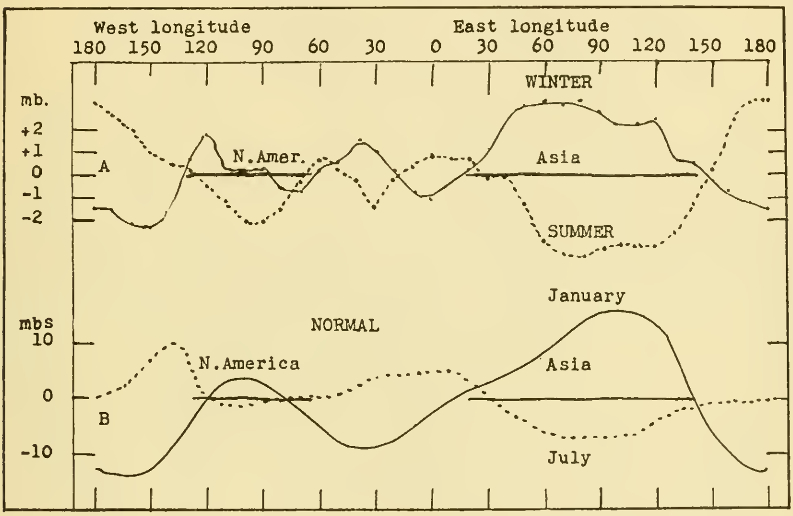

FIG. 11.—A, mean monthly changes in pressure at 50° N. latitude for the winter half-year and for the summer half-year accompanying sunspot changes of 10 or more in relative sunspot numbers; B, normal monthly pressure in January and July at 50° N. latitude in different longitudes.

sure is high over the continental land surfaces of Eurasia and of North America and low over the oceans. In summer the reverse conditions prevail—the pressure in middle latitudes is low over the continental masses and high over the oceans.

In the case of curves A, the normal annual period is eliminated by reason of the fact that months of normally rising pressure are equally balanced by months of normally falling pressure; so that the seasonal effect is annulled. Notwithstanding this elimination of seasonal change, the winter and summer effects of monthly increase in sunspots produce the same effect as do the annual changes in the sun's position. This fact is brought out even more graphically by plots of the averages of pressure at all the intersections of the Northern Hemisphere, shown in figures 12 and 13.

These maps show the distribution of pressure for the winter and summer half-year separately accompanying monthly increases in sunspots. They show a decreased pressure over the continents in summer and an increased pressure in middle latitudes over the oceans. These

FIG. 12.—Monthly changes in pressure accompanying monthly increases in sunspots, summer half-year.

conditions are reversed in winter, except that over the oceans the low pressure near Iceland and the high pressure to the south and southeast in mid-Atlantic and mid-Pacific are intensified in both seasons by increased solar activity.

This transfer of air mass takes place rapidly as is shown by the daily change in pressure. If the semidiurnal change of pressure is eliminated by subtraction from the 24-hourly change, there remains a diurnal pressure change which is closely related to the diurnal change of temperature. At noon Greenwich time, which is afternoon over most of Asia and early morning over most of the Americas, the pressure is below normal over most of Eurasia and Africa and above normal over North and South America. At 22^h and 24^h Greenwich time the condition is reversed—the pressure is low over the Americas and high over Eurasia. ("World Weather," by H. H.

Fig. 13.—Monthly changes in pressure accompanying monthly increases in sunspots, winter half-year.

Clayton, pp. 65 and 67, 1923.) This exchange of air mass between the continents could hardly be the result of overflow from the warmer to the colder continent. It suggests direct lateral expansion of the air by heating as well as vertical expansion which is known to take place because of increased pressure on mountain summits.

The next step in the inquiry concerns the relation between atmospheric pressure and the 11-year sunspot period. The short-term oscillations in pressure are relatively larger than short-term oscillations in sunspots, so that some process of smoothing is necessary to bring out the relations to longer pressure changes like the 11-year sunspot period. In my earliest investigations a latitude effect was discovered in the difference of pressure between sunspot maximum and sunspot minimum. In periods of marked solar activity the pressure is lower than normal in the equatorial belt and higher

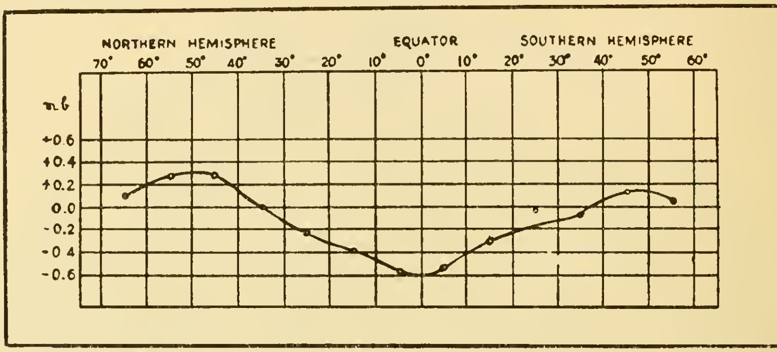

FIG. 14.—Mean difference of pressure at sunspot maximum from that at sunspot minimum.

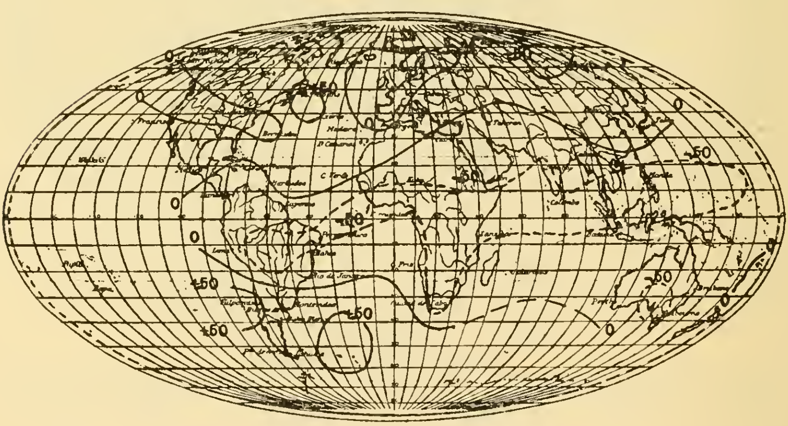

FIG. 15.—Correlation between sunspots and 3-year means of pressure.

than normal in high latitudes, as will be seen in figure 14 taken from "World Weather," 1923. This figure shows the difference between the mean pressure at each 10° of latitude during periods of sunspot maxima as compared with sunspot minima. In the mean the pressure falls in the zone between about 35° N. and 35° S. and rises at higher latitudes. However, the width of this belt varies at different longitudes under the influence of local conditions. Figure 15 shows the correlation between 3-year means of atmospheric pressure and sunspots. This figure includes observations down to 1920.[6] It would be somewhat altered by the inclusion of later data, but these later data continue to show a high negative correlation of sunspots with the smoothed values of pressure between Malaya and northern South America. This region of high negative correlation with sunspots is a region of high water temperature and of clouds. It is also a region where rainfall increases during periods of increased solar activity as shown by figure 16.

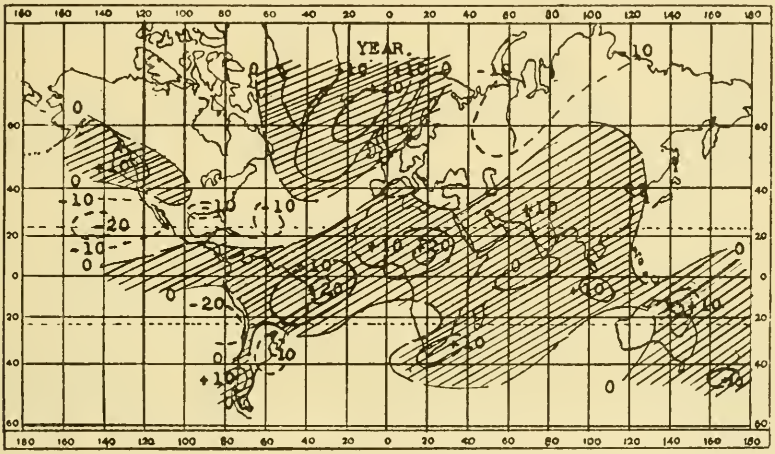

FIG. 16.—Distribution of differences of precipitation between sunspot maximum and sunspot minimum. Shaded areas show greater rainfall at sunspot maximum. Figures indicate percentages of normal.

There is also a region in the North Atlantic south of Greenland and Iceland where the pressure falls and rainfall increases with increased solar activity. This region is also one where the pressure is normally low throughout the year and there is much cloudiness and rainfall. The close relation of sunspot changes to changes of pressure at certain tropical stations is shown in figure 17, where the mean annual pressures at two tropical stations corrected for long-time trend are compared with the inverted sunspot curve. The full line in the upper curve connects the annual values, while a dotted line shows the overlapping means of 5 years.

The latitude effect of sunspot changes was recently investigated by Irving I. Shell,[7] whose data covered the period 1902-1944. He

[6] Smithsonian Misc. Coll., vol. 77, No. 4, 1926.

[7] Bull. Amer. Meteorol. Soc., vol. 24, pp. 85-93, March 1943.

used a chain of stations between 60° and 70° N. for comparison with a chain of stations near the Equator and used the standard deviation as a unit of measure. The results show that in this unit the variations are as large in the Tropics as in high latitudes. With high sunspot numbers the pressure was below normal in the Tropics and above normal in high latitudes. Furthermore, the largest deviations in pressure occurred in the periods of largest deviations of sunspots from their mean values.

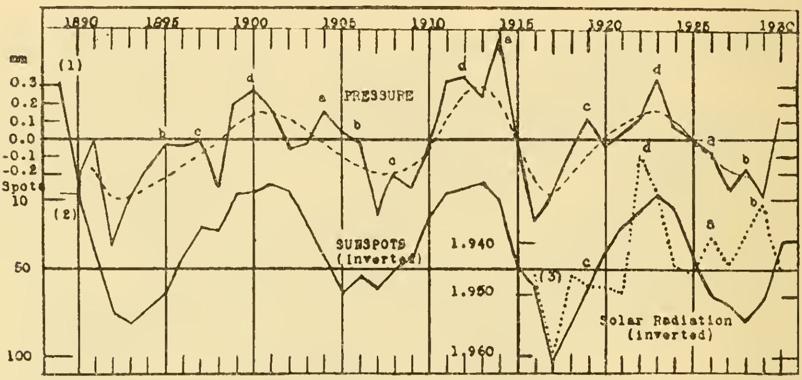

FIG. 17.—Comparison of mean pressures in the Tropics with sunspots and solar radiation. (1) mean annual pressures at Quixeramobim and Antananarivo, corrected for trend; (2) mean annual number of sunspots, inverted; (3) mean annual values of solar radiation, in calories per minute, inverted.

The average amount of the deviation of pressure from the normal for each year of the sunspot period, covering from five to seven sunspot periods of 11 years, 1867-1940, is shown in table 5 for three widely separated tropical stations.

TABLE 5.—*Average deviation from normal of pressure at tropical stations for each year of the sunspot period, in millibars*

		Years before			Max. spots	Years after		Years before			Min. spots	Years after	
		−3	−2	−1	0	+1	+2	−3	−2	−1	0	+1	+2
Quixeramobim, Brazil,	988.0..	+.6	−.1	−.4	−.5	−.6	.0	−.2	+.7	+.3	+.2	+.3	.0
Zanzibar, East Africa,	1013.2..	.0	−.3	−.3	−.2	+.2	+.2	−.1	+.1	+.2	.0	.0	+.2
Colombo, Ceylon,	1008.8..	+.2	−.1	−.0	−.1	+.2	+.4	−.1	+.1	+.4	.0	.0	+.4
Mean..................		+.3	−.2	−.2	−.3	−.1	+.2	−.1	+.3	+.3	+.1	+.1	+.2
Mean of three............		...	.0	−.2	−.2	−.1	.0	+.1	+.2	+.2	+.2	+.1	...

The 3-year means of the three stations is plotted in figure 18.

This arrangement of the data shows that *the maximum effect of the sunspots comes 1 year earlier than the maximum number of spots.* At that time spots are increasing rapidly, so that rate of increase in

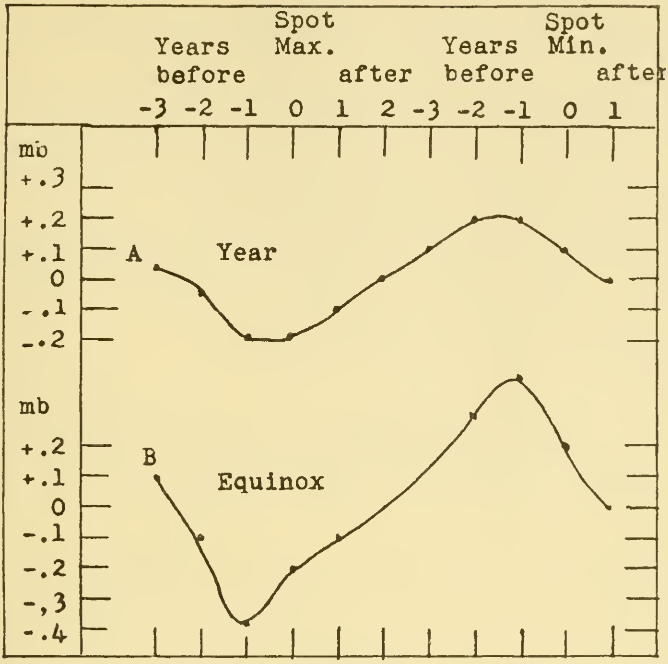

FIG. 18.—Pressure changes at tropical stations during sunspot period of 11 years. A, smoothed values of yearly means; B, unsmoothed means for March and September.

spots is one of the factors in determining the effect. The persistency of this influence on the pressure throughout the year is shown in table 6.

TABLE 6.—*Mean differences in millibars between the pressure near maximum and minimum sunspots (Max. minus Min.) for each month of the year, from the means of three tropical stations (Quixeramobim, Zanzibar, and Colombo) for each year of the sunspot period*

	Years before			Max. spots	Years after	
	−3	−2	−1	0	+1	+2
January	.0	+.4	−.6	−.6	−.4	+.1
February	+1.2	−.2	−.4*	−.4	−.6*	−.3
March	+.6	.0	−.6*	−.3	−.4	+.1
April	+.2	−.3	−.9*	.0	−.3	.0
May	+.4	−.2	−.5*	+.3	−.4	+.6
June	.0	−.7*	−.4	−.7*	+.4	+.7
Mar. and September	+.4	−.5	−.8*	−.4	−.1	+.1

	Years before			Max. spots	Years after	
	−3	−2	−1	0	+1	+2
July	+.3	−.5	−.5*	−.1	+.2	+.5
August	+.2	−.1	+.1	−.6*	+.3	+.3
September	+.2	−.9	−1.0*	−.4	+.2	.0
October	+.1	−1.2*	−.5	−.2	−.2	+.3
November	.0	−.3*	−.2	.0	−.3	.0
December	−.1	−.5	−.8*	−.3	−.3	+.4
Year	+.3	−.3	−.5*	−.3	−.2	+.2

* Minima.

This table shows not only that there is a decreased pressure near sunspot maximum throughout the year in the Tropics, but shows also that the decrease is greatest near the equinoxes.

It is universally accepted by meteorologists that the lower atmospheric pressure found in the Tropics is due to the greater heating of the atmosphere near the Equator by the sun. If one knew how much this observed pressure differed from the normal pressure at the Equator of a rotating earth at uniform temperature, it would be possible to compute the relative amount of decrease in pressure between sunspot minimum and sunspot maximum.

With proper assumptions this normal could be calculated, but for the present, at least, I have determined it graphically in figure 19, where the average observed pressure is plotted and a mean curve drawn through it, as shown by the dotted line.

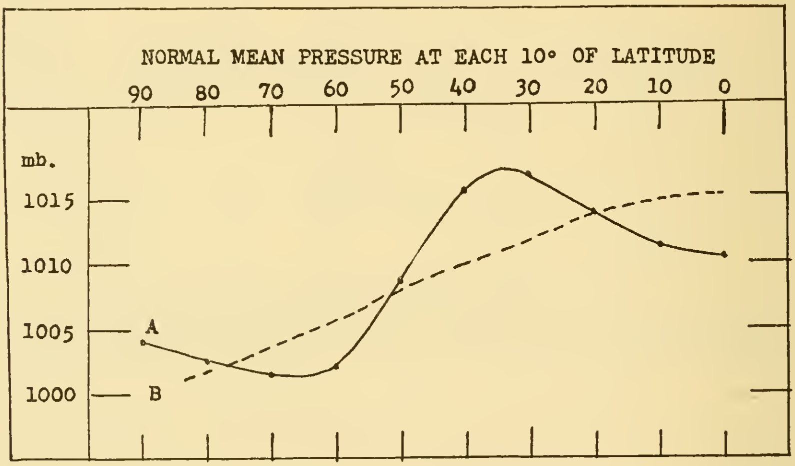

FIG. 19.—A, normal mean pressure at each 10° latitude of earth; B, estimated normal pressure on earth of uniform temperature.

The average observed pressure is taken from "World Weather," p. 29, as follows:

TABLE 7.—*Average observed pressure in millibars*

	Equator									Pole
Latitude	0	10	20	30	40	50	60	70	80	90
Mean pressure north	1011	1011	1013	1016	1017	1014	1012	1013	1014	1015
Mean pressure south	1011	1012	1015	1018	1014	1003	992	990	991	....

From figure 19 the estimated pressure at the Equator on a rotating earth of uniform temperature is estimated at 1015.5 mb., while the normal pressure at the Equator is 1011.0 mb. The difference between the observed and estimated pressure is 4.5 mb. Near sunspot maximum the pressure at the equinoxes averages 0.8 mb. lower at sunspot maximum than at sunspot minimum, which, divided by 4.5 mb., gives a percentage increase of 18 percent.

Another method of approach was the change in the annual oscillation in pressure which was found to average greater during the years near sunspot maxima than during the years of sunspot minima. The annual period in pressure was separated from the semiannual period by harmonic analysis of each year separately. The computed values for Quixeramobim are plotted in figure 20 for the years 1897 to 1906. The variations in amplitude are distinctly visible in the plot. The amplitudes diminished to 1901 when a minimum in sunspots occurred, then increased until near the sunspot maximum in 1905.

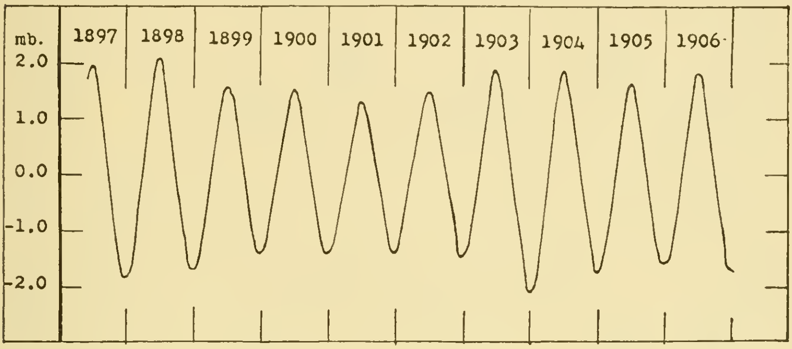

FIG. 20.—Amplitude of annual range of pressure at Quixeramobim, Brazil, for each year, 1897-1906, computed by harmonic analysis.

The mean annual ranges of pressure in relation to the sunspot period were computed for three tropical stations, Quixeramobim, Lagos, and Colombo, for the interval 1890 to 1940. The results are given in millibars in table 8.

TABLE 8.—*Mean annual ranges of pressure at three tropical stations*

	Years before			Max. spots	Years after		Years before			Min. spots	Years after	
	−3	−2	−1	0	+1	+2	−3	−2	−1	0	+1	+2
Mean.......	1.9	1.9	2.1	2.2	2.1	2.0	2.0	2.0	2.0	1.9	2.0	1.9
Max. − min.	−.1	−.1	+.1	+.3	+.1	+.1	....	....	....	....	....	....

The ranges were also computed for one station in the Southern Hemisphere outside the Tropics, namely, Santiago, Chile. The results are given in millibars in table 9.

TABLE 9.—*Mean annual ranges of pressure at Santiago, Chile*

	Years before			Max. spots	Years after		Years before			Min. spots	Years after	
	−3	−2	−1	0	+1	+2	−3	−2	−1	0	+1	2+
Mean.......	5.2	5.6	6.3	6.4	5.7	5.5	5.7	5.3	5.2	5.5	5.7	5.7
Max. − min.	−.5	+.3	+1.1	+.9	.0	−.2	....	....	....	....	....	....

The annual ranges outside the Tropics are larger than in the Tropics, but it is interesting to note that the changes in range between sunspot maximum and sunspot minimum have the same percentage ratios to each other. Thus the mean range at the tropical stations is 2.0 mb. and the increased range between sunspot maximum and sunspot minimum is 0.3 mb. or 15 percent. At Santiago the mean range is 5.7 mb. and the increased range at sunspot maximum is 1.1 mb. or 16 percent.

An even more interesting comparison is with stations in central Asia. The variation in pressure between summer and winter in this region is the largest in the world. The pressure is lowest in summer shortly after the summer solstices, when the sun is farthest north and the days are long. It is highest in winter, closely following the time when the sun is farthest south and the daylight is short. The only data available for that region at the moment of writing cover the interval from about 1880 to 1930. I have selected two typical stations for study, namely, Irkutsk, 52° N., 104° E., and Tashkent, 41° N., 69° E. The mean pressures for the summer half-year and the winter half-year were computed separately and departures from the normal values for the two seasons were obtained for each station. These were then averaged for each year of the sunspot period. The results are given in table 10.

TABLE 10.—*Mean departures from normal pressure at Irkutsk and at Tashkent, Siberia, in millibars for each year of the sunspot period*

	Years before			Max. spots	Years after		Years before			Min. spots	Years after	
	−3	−2	−1	0	+1	+2	−3	−2	−1	0	1	2
						Winter half-year						
Irkutsk	−.6	+.3	+.1	+.7	+.6	+.6	−.1	−.3	+.2	+.2	−1.7	−.7
Tashkent	+.4	.0	.0	+.2	+.5	.0	+.5	−1.4	−.7	+.5	.0	+.5
Mean	−.1	+.2	+.1	+.5	+.5	+.3	+.2	−.8	−.3	+.3	−.8	−.1
Mean of three	....	+.1	+.3	+.4	+.4	+.3	−.1	−.3	−.3	−.3	−.2	....
						Summer half-year						
Irkutsk	+.2	−.4	−.2	−.7	−.6	−.3	+.5	+.5	+.6	+.4	+.2	+.4
Tashkent	−.2	−.3	−.3	−.3	.0	.0	+.1	+.9	+.2	.0	−.6	−.3
Mean	.0	−.3	−.2	−.5	−.3	−.1	+.3	+.7	+.4	+.2	−.2	.0
Mean of three	....	−.2	−.3	−.3	−.2	.0	+.3	+.5	+.4	+.1	.0	....

The smoothed 3-year means in table 10 for the stations are plotted in figure 21. This plot shows that the departures are reversed between summer and winter. In summer in central Asia the pressure averages lower than normal near sunspot maximum. In winter it is higher. Also the departures in winter appear to lag behind those of summer. This lag may be due to accumulations of snow and ice in high latitudes which take time to melt. In summer the greatest departures occur about 1 year before maxima and minima of sunspots, whereas in winter they occur at nearly the same time as the maximum and minimum of spots. The summer effect appears to be more nearly a direct effect of solar changes.

The changes of pressure from month to month are so great that it is necessary to deal with 3-year means in order to get smooth results. For the summer half-year at Irkutsk and at Tashkent the following differences are found for the 3 years immediately preceding and including sunspot maximum and sunspot minimum: At Irkutsk, −.9 mb. lower at sunspot maximum; at Tashkent, −.7 mb. lower. The normal departure of pressure from the mean of the year for the

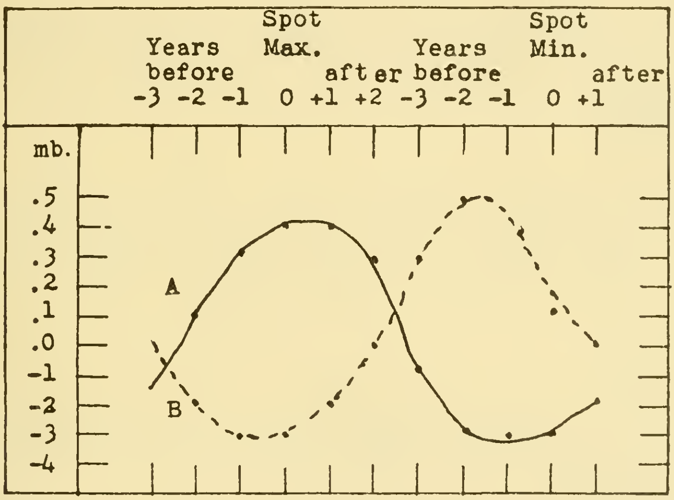

FIG. 21.—Average departures of smoothed means of pressure from normal at Irkutsk and Tashkent, Siberia, during sunspot period. A, winter half-year; B, summer half-year.

summer half-year is 5.1 mb. at Irkutsk, and 4.8 mb. at Tashkent. Hence, the influence of the sunspots is to increase the fall between minimum and maximum spots by 17 percent at Irkutsk, and 15 percent at Tashkent, or a mean of 16 percent for the two stations.

In three widely separated regions of the earth, that is, in the equatorial belt, in central Chile, and in central Asia, the annual changes in pressure were increased by about 16 percent between sunspot maxima and sunspot minima in the average of five sunspot periods. Furthermore, there is evidence, from figure 17, that pressure in the Tropics varies with the intensity of the solar activity, showing the 11-year and 22-year changes which characterize sunspots. Such a variation is also evident in higher latitudes. At Tashkent and at

Irkutsk there are unbroken records of pressure available from 1881 to 1930. When the average pressure for the 6 summer months, April to September, are obtained for each year at Tashkent and Irkutsk from 1881 to 1930 and analyzed harmonically for overlapping 12-year periods,[8] the results show periodic changes closely correlated with 3-year changes in sunspots, as will be seen in figure 22. The maxima and minima of the 3-year changes in sunspots between 1893 and 1917 come in the same years as the maximum yearly number of spots, but the minima come 1 to 2 years earlier than the yearly minimum of spots.

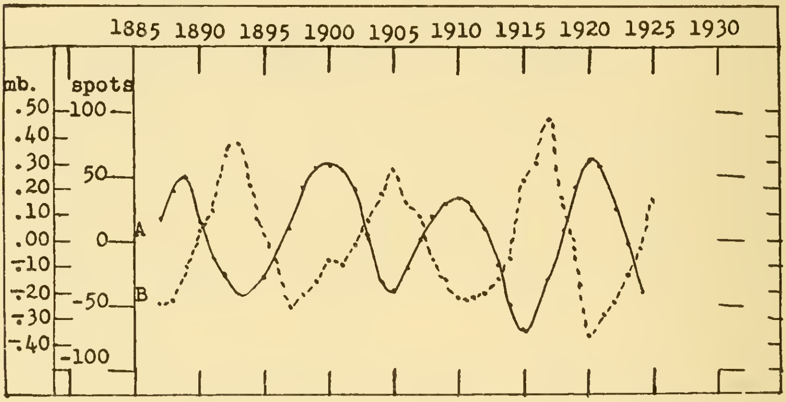

FIG. 22.—A, harmonically smoothed values of the mean pressure for the summer half-year at Irkutsk and Tashkent, Siberia, 1881-1930; B, 3-year changes in sunspot numbers.

The search for the relation between solar changes and weather changes has been complicated by the following factors:

(1) A latitude effect due to difference between Pole and Equator.

(2) A longitude effect due to the different compositions of the earth's surface, more especially the difference between land and water surfaces.

(3) A diurnal effect due to a change in the sun's position during the course of a day.

(4) A seasonal effect due to a change in the sun's position during the course of a year.

[8] For the method of harmonic smoothing see The atmosphere and the sun, Smithsonian Misc. Coll., vol. 82, No. 7, p. 4, 1930, or Solar relations to weather, by H. H. Clayton, vol. 2, p. 336, 1943.

(5) Wavelike movements in the atmosphere which tend to move from west to east with a trend southward, except near the Equator.

(6) Oscillations in the atmosphere where air mass moves back and forth between opposing centers of oscillation. These oscillations are semiperiodic and may be analyzed into many periods varying in length from a few days to many years. They are difficult of analysis, however, for the reasons that the periods vary in amplitude and the centers of oscillation shift in position, rendering futile the efforts to resolve them by the usual mathematical methods.

(7) These terrestrial oscillations are closely related to similar oscillations in solar changes.

(8) The absorption and loss in the earth's asmosphere of radiant energy coming from the sun needs further investigation.

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