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THE ATMOSPHERE AND THE SUN

BY
H. HELM CLAYTON

(Publication 3062)

CITY OF WASHINGTON
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INTRODUCTION

This paper is the fifth of a series giving the results of investigations of the relation of solar activity to atmospheric changes. The earlier ones were published as Smithsonian Miscellaneous Collections, Vol. 68, No. 3; Vol. 71, No. 3; Vol. 77, No. 6; and Vol. 78, No. 4. The author has been stimulated to continue these researches because he believes in their great importance. The interest of Dr. C. G. Abbot and the sympathy and aid of Mr. John A. Roebling have encouraged him in the task and enabled him to undertake much work that otherwise would not have been possible. Miss M. I. Robinson has aided in the calculations needed for the discussion.

I. SOLAR CHANGES

It has long been known that spots appear on the surface of the sun and that the number and size of these spots varies from day to day, from month to month, and from year to year. More recently it has been discovered by Dr. C. G. Abbot and his associates that the radiation coming from the sun varies; so that, in general, it is known that the sun is hotter when there are many spots on its surface than when there are few or none.

There is also evidence that the heat of the sun varies from day to day and from week to week in short cycles of change. The most convincing evidence of this fact is the comparison of measurements of solar radiation made at observatories thousands of miles distant from each other, one in the northern hemisphere and the other in the southern hemisphere; so that the chance of both being affected by the same weather changes becomes very small. The solar radiation reaching the earth is measured in calories per square centimeter per minute, and averages about 1.940 calories. Table 1 shows a comparison of observations of solar radiation made simultaneously in northern Chile and in the United States (first in California and then in Arizona) during the years 1918 to 1924. The table shows the frequency of different values observed in the United States for each increase of .010 calorie in Chile.

TABLE 1.—*Comparison of Solar Radiation Values in Chile and the United States (Number of Cases)*

Values in United States	Values observed in Chile					
	1.910–9	1.920–9	1.930–9	1.940–9	1.950–9	1.960–9
1.890–9	1	6	6	6	0	0
1.900–9	11	11	1	0	0	0
1.910–9	**20**	25	11	5	4	0
1.920–9	18	**38**	21	5	4	2
1.930–9	7	23	**29**	11	11	0
1.940–9	4	6	12	**15**	**16**	4
1.950–9	0	4	10	10	13	**6**
1.960–9	0	1	3	4	7	5
1.970–9	0	1	0	1	3	2

If there were no relation between the measurements at the two stations, the observed values would be scattered through the different classes at random. The tabulation shows that a random distribution does not exist; but for each group of observations in Chile, there is a maximum near the same values in the observations in the United States. There is, therefore, a progressive displacement of the maximum frequency as the solar values increase from 1.910-9 to 1.960-9, or nearly three per cent of the mean value. The probable error of the measurements is ±.006 calorie; so that the solar variation during the interval covered by the observations was more than eight times the probable error of each group of observed values.

Since variability in solar radiation has been questioned by some investigators, it is well to state that the evidence of this variability rests on three fundamental and independent facts:

(1) The changes in radiation are alike when measured at two widely separated stations, allowing for variations from a middle value due to errors of observation.

(2) The changes both of short period and of long period in solar radiation are related to visible changes in the number and area of spots, faculae and flocculi seen on the sun.

(3) The changes in solar radiation are correlated with other phenomena such as certain changes in terrestrial magnetism, in radioreceptivity, and meteorological changes which are known by other evidence to be related to solar conditions.

The critics of solar variability have pointed out that the measured variations have decreased as the accuracy of the observations increased and that in the earlier observations the effects of water vapor in the air, of dust, of ozone, and of turbidity were not entirely eliminated; but they have in no manner destroyed or impaired these fundamental evidences of variability.

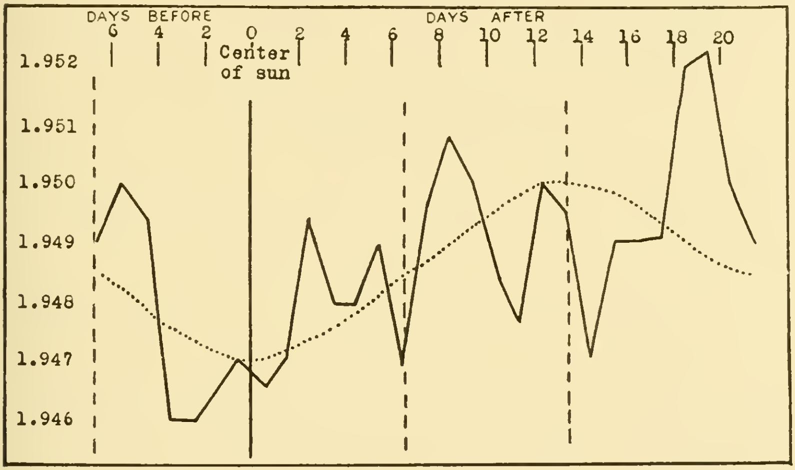

Fig. 1.—Calcium flocculi and solar radiation. The mean values of solar radiation received at the earth in calories per square centimeter per minute on days before and days after the passage of calcium flocculi across the central meridian of the sun. 1918-1920. Flocculi of 400 or more on the Ebro scale of values.

Abbot and his associates[1] have given evidence of the relation of solar radiation changes to solar contrast and to groups of spots on the sun, Fowle[2] has shown a relation to groups of flocculi, and I[3] have shown a relation to faculae. Bauer[4] has shown a relation to certain changes in terrestrial magnetism, and Austin[5] has found a

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[1] Smithsonian Misc. Coll., Vol. 66, No. 5, 1916.

[2] *Idem,* Vol. 77, No. 5, 1925.

[3] *Idem,* Vol. 77, No. 6, p. 53, 1925.

[4] Terr. Mag., Vol. 20, pp. 143-158, Dec., 1915.

[5] Smithsonian Misc. Coll., Vol. 80, No. 2, p. 13, 1927.

marked parallelism between radio-receptivity and changes in monthly values of solar radiation.

In order to study further the relation of clouds of calcium and hydrogen as seen in faculae and flocculi to solar radiation I took from the publication of the Ebro Observatory all days on which the area of observed clouds of flocculi exceeded 400 millionths on the Ebro scale. The day on which this area crossed the central meridian of the sun as seen from the earth was called zero day. Then, the solar radiation measured on that day and on each of the seven days preceding was averaged. The same was done for each of the following days up to 21 days later. The mean values for each day are shown plotted in figure 1. This plot shows that the radiation from the sun averaged lowest when the flocculi were near the center of the sun. This fact indicates changes of transparency in the sun's atmosphere and is interpreted to mean that the clouds of calcium and hydrogen in the flocculi cut off the radiation from the surface of the sun, just as water-vapor clouds cut off radiation from the surface of the earth beneath them. When near the limb of the sun, however, these clouds add to the total radiation.

II. LATITUDE EFFECT OF SOLAR CHANGES ON THE EARTH'S ATMOSPHERE

Studies of the relation of solar radiation changes to meteorological changes have been published in four preceding papers in this series. The results of recent researches and deductions drawn from the whole mass of data follow. Some readers may be inclined to think that the generalizations given are based on too small an amount of data, but in reality they are based on a large amount of data accumulated during 20 years of research. Where one example is given, many others might have been presented.

In the earlier papers of this series the first finding of importance was that there was a marked latitude effect of solar radiation changes on the pressure and temperature of the earth's atmosphere. Accompanying or immediately following short-period changes in radiation, there was an increase in temperature and a fall of pressure in equatorial regions, a rise of pressure and a fall of temperature between 40° and 60° latitude, while at latitudes above 70° the pressure fell and the temperature rose. These conditions hold true for both the northern and southern hemispheres. The chart illustrating this fact is reproduced in figure 2.

Figure 3 shows how, in the average of many cases, day to day changes of pressure at Honolulu are associated with simultaneous changes of pressure at Nome and also with day to day changes in solar radiation. During the interval covered by the data from which these curves were constructed, January to April, 1928, the pressure at Nome followed the solar radiation changes directly, and the pressure at Honolulu followed inversely. The changes are nearly simultaneous except that the solar minimum and maximum appear to occur slightly earlier.

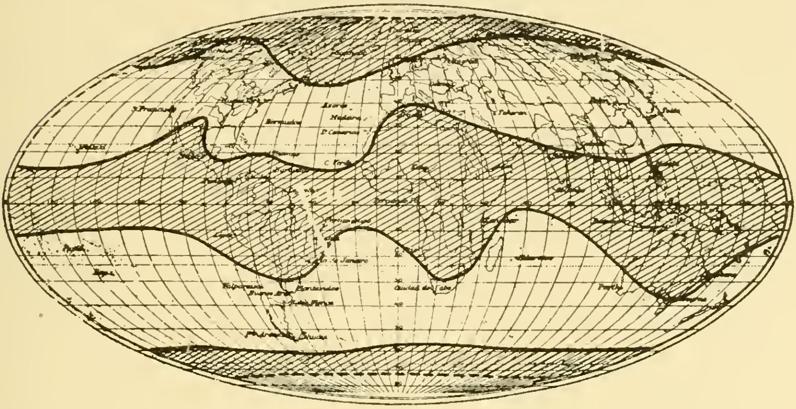

FIG. 2.—Zonal effect of increased solar activity. Shaded areas show regions where the pressure falls and the temperature rises with short period changes of solar radiation. Unshaded areas show regions where the reverse conditions occur.

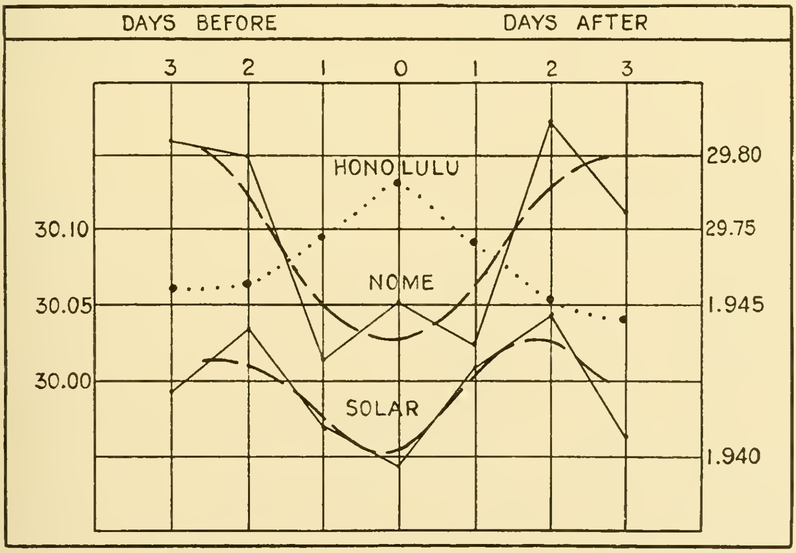

FIG. 3.—Maxima of pressure at Honolulu compared with pressure at Nome and with solar radiation.

A later investigation disclosed that there were also latitude differences in pressure correlated with changes in the monthly number of sun spots.[1] Using the data from about 200 stations, the average pressure when sun spots were near their maximum frequency was compared with the average pressure in the same latitudes when the sun spots were near a minimum of frequency and differences obtained. These differences are plotted in figure 4.

Figure 4, shows that when sun spots are more frequent in number, the pressure is lower in the equatorial region from about 30°N. to 30°S., while from about latitude 35° to 65° in both hemispheres, the pressure is higher when the sun spots are most numerous. This result is in good agreement with that found for short period changes of solar radiation and with the fact disclosed by the measurements of the Smithsonian Astrophysical Observatory that more radiation from the sun reaches the earth when sun spots are more frequent. A recent research by Ekhart[2] shows clearly the opposing oscillations of the pressure in high and in low latitudes. When the pressure falls in low latitudes, it rises in high latitudes and vice versa.

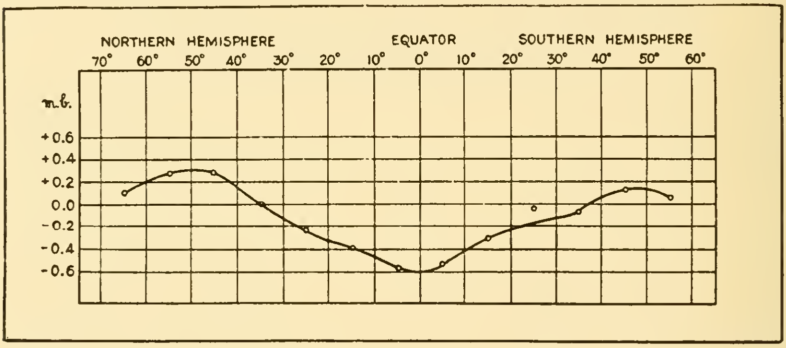

Fig. 4.—Mean difference of pressure at sun-spot maximum from that at sun-spot minimum.

In order to investigate this relation further with the data which appeared in "World Weather Records,"[3] 24 cases were selected in which solar activity was above normal as shown both by the Wolfer sun-spot numbers and by the Smithsonian values of solar radiation; and 24 cases where the opposite condition prevailed, namely, a small monthly sun-spot value and a low value of solar radiation. Where

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[1] Clayton, H. H., World Weather, p. 262. New York, Macmillan & Co., 1923.

[2] Ekhart, E., "Untersuchungen der jährlichen Schwankungen der atmosphärischen Zirkulation," Meteorologischen Zeitschrift, Heft 2, February, 1930.

[3] Smithsonian Misc. Coll., Vol. 79, 1927.

no values of solar radiation were available, only sun-spot numbers were used and an equivalent value of solar radiation was derived from Abbot's[1] plots of equivalent values and placed in parentheses.

Since both sun-spot numbers and increased solar radiation are considered in forming this table, the results derived from a comparison of the data in the table with meteorological conditions rest on increased solar activity, whether measured by sun spots, faculae and flocculi, or by an increase in solar radiation reaching the earth. Solar radiation values are missing for a number of the spring and winter months because no observations were made during these months in the earlier years. These months are included because it

TABLE 2.—*Relative Sun-spot Numbers and Average Values of Solar Radiation Used in Study*

High solar values			Low solar values		
Date summer	Sun-spot number	Solar radiation	Date summer	Sun-spot number	Solar radiation
Apr. 1916	72	(1.952)	Apr. 1912	4	(1.928)
" 1918	81	1.953	" 1913	1	(1.925)
May 1917	114	1.956	May 1910	22	1.916
" 1920	34	1.953	" 1913	0	(1.923)
June 1905	49	1.968	June 1909	23	1.930
" 1919	111	1.955	" 1912	4	1.930
July 1906	103	1.962	July 1910	14	1.913
" 1917	120	1.989	" 1911	3	1.917
Aug. 1917	154	1.956	Aug. 1909	23	1.926
" 1918	102	1.954	" 1910	11	1.912
Sept. 1917	129	1.948	Sept. 1909	39	1.908
" 1918	80	1.944	" 1910	26	1.915
Mean	95.7	1.958	Mean	8.3	1.917
Winter			Winter		
Oct. 1917	72	1.952	Oct. 1911	3	1.915
" 1918	85	1.939	" 1913	3	1.866
Nov. 1917	96	(1.954)	Nov. 1911	4	1.903
" 1919	42	(1.953)	" 1913	1	1.866
Dec. 1917	129	(1.957)	Dec. 1911	2	(1.926)
" 1920	40	1.955	" 1913	4	(1.928)
Jan. 1918	96	(1.954)	Jan. 1911	3	(1.927)
" 1920	59	1.964	" 1913	2	(1.925)
Feb. 1918	65	(1.951)	Feb. 1912	0	(1.923)
" 1920	51	1.956	" 1913	3	(1.927)
Mar. 1917	95	(1.954)	Mar. 1912	5	(1.929)
" 1920	72	1.945	" 1913	0	(1.923)
Mean	75.2	1.955	Mean	2.5	1.913

Values in parentheses are derived from sun-spot data and are taken from Abbot's curve of equivalent values, Smithsonian Misc. Coll., Vol. 80, No. 2.

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[1] A group of solar changes, Smithsonian, Misc. Coll., Vol. 80, No. 2, p. 8, 1927.

was desirable to have an equal distribution of the observations throughout the months in order to study and to eliminate seasonal influences. If, however, only those months had been used in which both values were present, the main conclusions which follow would

TABLE 3.—*Mean Departures of Pressure from Normal in Millibars with High Solar Activity*

Winter Half-Year

	180°–120° W.	120°–60° W.	60°–0° W.	0°–60° E.	60°–120° E.	120°–180° E.	Mean
80°–70° N.	(−0.5)	(+1.0)	+1.2	−1.7	(−1.0)	(0.0)	−0.2
70 –60	+1.2	(+1.6)	−0.6	−0.7	+0.5	+0.2	+0.4
60 –50	+0.6	+1.6	+1.4	+1.2	+0.6	+1.1	+1.1
50 –40	+1.6	+0.4	+1.0	+1.1	+0.7	+0.2	+0.8
40 –30	+0.5	+0.2	+1.5	+1.0	+0.1	+0.4	+0.6
30 –20	−0.8	+0.4	+0.2	+0.1	−0.1	+0.2	0.0
20 –10	(−0.4)	+0.4	+0.3	+0.2	−0.6	−0.6	−0.1
10 –0	(−0.3)	0.0	+0.3	0.0	−0.3	−0.6	−0.1
Summer Half-Year							
80°–70° N.	(−2.0)	0.0	+0.2	−0.6	+1.5	(−1.2)	−0.4
70 –60	−1.8	(+1.1)	+0.7	+3.8	+2.4	−1.4	+0.8
60 –50	+1.2	+.15	+1.1	+0.7	−0.1	+0.2	+0.8
50 –40	+0.6	+1.1	+0.5	+0.3	−0.7	−0.1	+0.3
40 –30	+0.1	+0.3	+0.4	0.0	−0.3	−0.2	+0.1
30 –20	−0.4	+0.2	−0.7	−0.2	0.0	−0.2	−0.2
20 –10	(−0.3)	+0.2	+0.1	−0.1	−0.2	−0.2	−0.1
10 –0	(−0.2)	+0.1	+0.7	0.0	−0.1	+0.1	+0.1
Year							
80°–70° N.	(−1.2)	(+0.5)	+0.7	−1.2	+0.2	(−0.6)	−0.3
70 –60	−0.3	(+1.3)	+0.1	+1.6	+1.4	−0.6	+0.6
60 –50	+0.9	+1.6	+1.3	+0.9	+0.3	+0.6	+0.9
50 –40	+1.1	+0.8	+0.8	+0.7	0.0	+0.1	+0.6
40 –30	+0.3	+0.3	+0.9	+0.5	−0.2	+0.1	+0.3
30 –20	−0.6	+0.3	−0.3	−0.1	−0.1	0.0	−0.1
20 –10	(−0.4)	+0.3	+0.2	0.0	−0.4	−0.4	−0.1
10 –0	(−0.2)	0.0	+0.8	0.0	−0.2	−0.3	0.0

Values in parentheses are interpolated from a synoptic chart (polar projection).

not have been greatly impaired, although the quantitative values would have been different.

The monthly values of pressure for the months when solar activity was above normal were separated into zones of 10° of latitude, namely all between 80° N. and 70° N., between 70° N. and 60° N., etc. Because the stations were not equally distributed, but were mostly land stations, a further selection was made by grouping the stations into areas of 20° of longitude and 10° of latitude and taking means for each group. Finally, the means for the different groups were obtained for each 10° of latitude. The average departures of the pressure from normal, in millibars, with high solar activity are shown in table 3, and the average departures from normal with low solar activity are shown in table 4.

Table 4.—*Mean Departures of Pressure from Normal in Millibars with Low Solar Activity*

	180°–120° W.	120°–60° W.	60°–0° W.	0°–60° E.	60°–120° E.	120°–180° E.	Mean
Winter Half-Year							
80°–70° N.	(+0.7)	(−0.5)	−3.9	−2.6	(−2.0)	(−1.2)	(−1.6)
70 –60	+1.2	(0.0)	−4.6	−2.3	−2.3	−1.6	−1.6
60 –50	+1.1	−0.2	−2.8	−1.3	−2.5	+0.4	−0.9
50 –40	+1.3	+0.8	−0.6	+0.5	−0.4	−0.1	+0.2
40 –30	+0.3	+0.9	+0.7	+1.3	0.0	+0.2	+0.6
30 –20	+0.7	+0.6	+1.0	+0.4	+1.7	+0.4	+0.8
20 –10	(+0.5)	+1.0	+0.7	+0.8	+0.4	+0.7	+0.7
10 –0	0.0	−0.2	+1.3	+0.7	−0.1	+0.6	+0.4
Summer Half-Year							
80°–70° N.	(+1.5)	(+1.0)	+0.1	+1.3	(−0.3)	(−1.0)	(+0.4)
70 –60	+1.0	(+0.6)	+0.6	+0.8	−0.6	−1.5	+0.1
60 –50	+0.5	+0.4	+1.1	+0.1	+0.6	−2.4	−0.1
50 –40	+0.4	+0.8	−0.5	−0.7	+0.4	−0.4	0.0
40 –30	+0.4	+0.8	+0.7	−0.2	−0.2	−0.7	+0.1
30 –20	+0.8	+0.6	−0.2	−0.2	−0.3	−0.7	0.0
20 –10	(+0.7)	+0.7	+0.4	+0.1	0.0	+0.2	+0.4
10 –0	+0.6	+0.2	+0.3	−0.3	−0.5	+0.3	+0.1
Year							
80°–70° N.	(+1.1)	+0.3	−1.9	−0.6	(−1.1)	(−1.1)	(−0.5)
70 –60	+1.1	+0.3	−2.0	−0.8	−1.5	−1.6	−0.7
60 –50	+0.8	+0.1	−0.9	−0.7	−1.0	−1.0	−0.5
50 –40	+0.8	+0.8	−0.6	−0.2	0.0	−0.3	+0.1
40 –30	+0.4	+0.8	+0.7	+0.5	−0.1	−0.2	+0.3
30 –20	+0.8	+0.6	+0.4	+0.1	+0.7	−0.1	+0.5
20 –10	+0.6	+0.8	+0.6	+0.5	+0.2	+0.5	+0.5
10 –0	+0.3	0.0	+0.8	+0.2	−0.3	+0.5	+0.3

Values in parentheses are interpolated from a synoptic chart (polar projection).

The means in the last columns of these two tables show clearly that with high solar radiation there is a defect of pressure in the equatorial belt from the Equator to 30°N. latitude, an excess of pressure from 40° to 70° N., and a defect in the vicinity of the pole, while the opposite signs are found in the same latitudes during low solar activity.

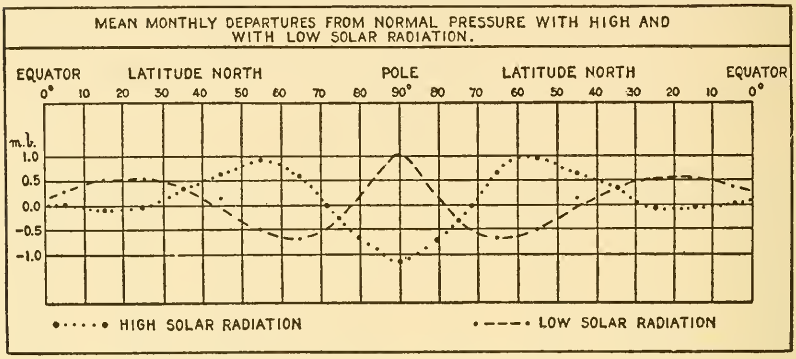

Fig. 5.—Mean monthly departures from normal pressure with high and with low solar radiation.

Figure 5 shows a plot across the pole of the means for the year in each case. The dotted line connects the values for high solar activity, and the broken line connects the values for low solar activity. Data are missing from points north of 80° so that the part of the curve near the pole is interpolated.

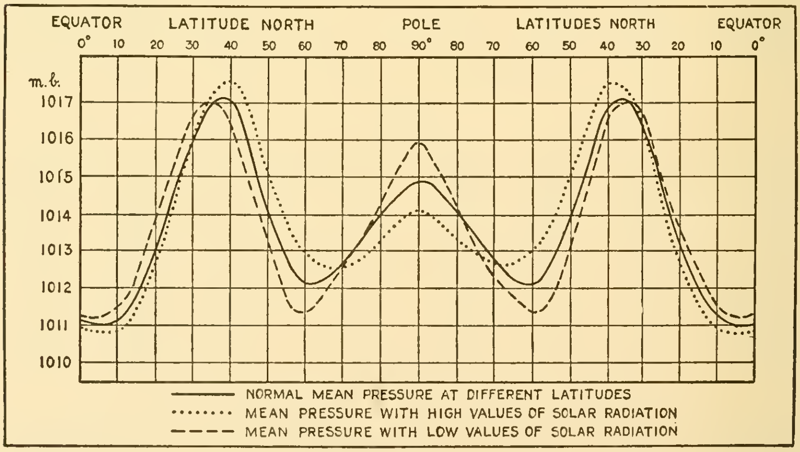

Fig. 6.—Mean pressure at different latitudes with different solar conditions.

This diagram brings out clearly the opposite oscillation of the pressure in latitude with high and with low solar activity.

Figure 6 shows how these departures appear when they are added to the normal distribution of pressure. In this figure the normal distribution of pressure with latitude is shown by a continuous line. The dotted line shows the distribution with high solar activity. With high solar activity the equatorial low pressure belt and the high pressure belts in middle latitudes are both intensified and the polar anticyclone diminished. This clearly means an intensification of the normal atmospheric circulation. The decrease in the polar anticyclone is attributed to the increased circulation around the pole, the centrifugal action developed in the circulating winds causing a fall of pressure in the polar basin. The effect of the earth's rotation on the wind increases with latitude, and for this reason the fall of pressure in the equatorial belt is greater at latitude 20° than at the Equator. (See fig. 5.) The broken line shows the distribution of pressure with

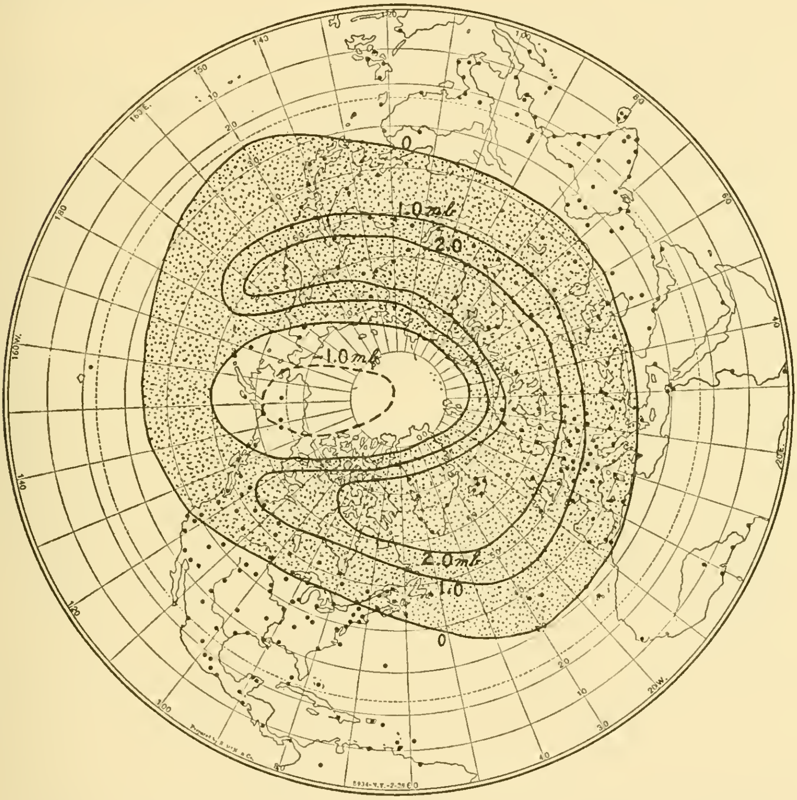

FIG. 7.—Differences in pressure with change from low to high solar activity. Shaded area shows increased pressure, unshaded areas decreased pressure. (Difference between yearly means in tables 3 and 4.)

low solar activity. The opposite conditions are here found; the pressure is higher in the tropics and near the pole, and lower in middle latitudes than the normal pressure.

Another fact to be noted is that the maximum of pressure between 30° and 40° latitude and the minimum of pressure between 60° and 70° latitude are nearer the pole when solar activity is high than when solar activity is low. This same condition prevails in both the northern and southern hemispheres.

The changes of pressure due to a change from low to high solar activity are shown in figure 7, where the changes for each 20° of longitude and 10° of latitude are plotted on a chart of the northern hemisphere with a polar projection. This map shows a decreased pressure all around the world in latitudes of 0° to 30° with increased solar activity. It shows increased pressure between latitudes 40° to 60° and diminished pressure in the polar basin. But there is evidently a longitude effect also. The excess of pressure in latitudes 40° to 70° is greatest over the Eurasian continent and least over the Pacific Ocean.

If the values in tables 3 and 4 are corrected for latitude effect by subtracting the mean values in the last column of the tables, there is seen to be a distinct tendency for the pressure in all latitudes to be low over the Pacific and high over Eurasia, with increased solar activity. Subtracting the yearly means in table 4 from those in table 3 and correcting for the latitude effect, the data were obtained from which figure 8 was drawn. The tabulated results are shown in table 5.

TABLE 5.—*Longitude Differences. Differences in Millibars between the Yearly Means in Tables 3 and 4 Corrected for Latitude*

	180°–120° W.	120°–60° W.	60°–0° W.	0°–60° E.	60°–120° E.	120°–180° E.
80°–70° N.	....	....	....	....	....	....
70 –60	−2.7	....	+0.8	+1.0	+1.6	−0.3
60 –50	−1.3	+0.1	+0.8	+0.2	+0.1	+0.2
50 –40	−0.2	−0.5	+0.9	+0.4	−0.5	−0.1
40 –30	−0.1	−0.5	+0.2	0.0	−0.1	+0.3
30 –20	−0.8	+0.3	−0.1	+0.4	−0.2	+0.7
20 –10	....	+0.1	+0.2	+0.1	0.0	−0.3
10 –0	....	+0.3	+0.3	−0.1	+0.4	−0.5

Figure 8 brings out clearly an excess of pressure over the Eurasian continent with increased solar activity, the maximum being in latitude 50° to 80° N.; while a defect is evident over the Pacific Ocean and North America, the greatest depression being in high latitudes over the North Pacific. This longitude distribution is apparently another effect of centrifugal action developed by increased atmospheric circulation with increased solar activity. In regions where the air flows more freely, as over the great expanse of the Pacific, the centrifugal force developed tends to lower the pressure, especially in high latitudes, more over the water surfaces than over the land areas.

Fig. 8.—Longitude differences between high and low solar activity.

The primary cause of the general atmospheric circulation is believed to be the contrast in temperature between equator and pole. This circulation and all its attendant phenomena changes in unison with changes in the amount of solar radiation received by the earth, just as the regulator on a steam engine varies with the amount of heat received by the boiler.

Once in operation there are at least four modifying forces of importance acting on the general atmospheric circulation:

The first of these modifying forces is the earth's rotation. The effect of this rotation is to cause a high pressure belt in middle latitudes and a diminished pressure in the polar basin, although it cannot entirely destroy the central high pressure at the pole due to increased cold without stopping the circulation. Hence, any increase in solar radiation should intensify the pressure belt in middle latitudes and lower the pressure in the polar basin, and the reverse with decreased solar radiation. This is exactly what happens.

A second modifying force is the change in cloudiness caused by increased or decreased atmospheric circulation. Clouds and water vapor[1] have an important influence on incoming and outgoing radiation, so that the belts of cloudiness near the Equator and near 60° of latitude have an important influence on the temperature and pressure and thus should aid materially in maintaining the latitude effects of changes in solar radiation reaching the atmosphere of the earth.

A third modifying force is the movement of ocean water under the influence of wind. An increase in the general circulation should cause an increased flow of ocean waters, with all the modifications in weather which such an increase implies.

A fourth modifying force is the distribution of land and water.

The influence of all these modifying causes can be seen in the latitude and seasonal effects, with differences in solar activity.

III. SEASONAL INFLUENCES

When the influences of solar changes on the pressure are worked out separately for each month of the year for different places, it is found that the effect is different at different seasons of the year.

At continental stations in high latitudes, such as Dawson, the pressure increases much more in mid-winter with increased solar radiation than at other seasons, and at mid-summer the effect may even be the reverse of that in mid-winter. Figure 9 shows the annual period in the effect of increased solar activity at Dawson. At other stations such as Stykkisholm in the North Atlantic and Nome in the North Pacific there is a dominant semi-annual period in the solar influence. (See fig. 9.) The dotted curves in figure 9 are sine curves derived from the first and second terms of the harmonic formula in a

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[1] Simpson, G. C., Further studies in terrestrial radiation. Mem. Roy. Meteor. Soc., Vol. 3, No. 21, 1928. Manson, M., The evolution of climates, Baltimore, Md., 1922. Ångström, A. K., On radiation and climate, Geogr. An., Vol. 7, p. 122, Stockholm, 1925. Brooks, C. E. P., Climate through the ages, p. 138, London, 1926. Abbot, C. G., The radiation of the planet earth to space, Smithsonian Misc. Coll., Vol. 82, No. 5, 1929.

12-month period. The 6-month period and the annual period in pressure were computed in this way for stations all over the northern hemisphere from the data in "World Weather Records" for the

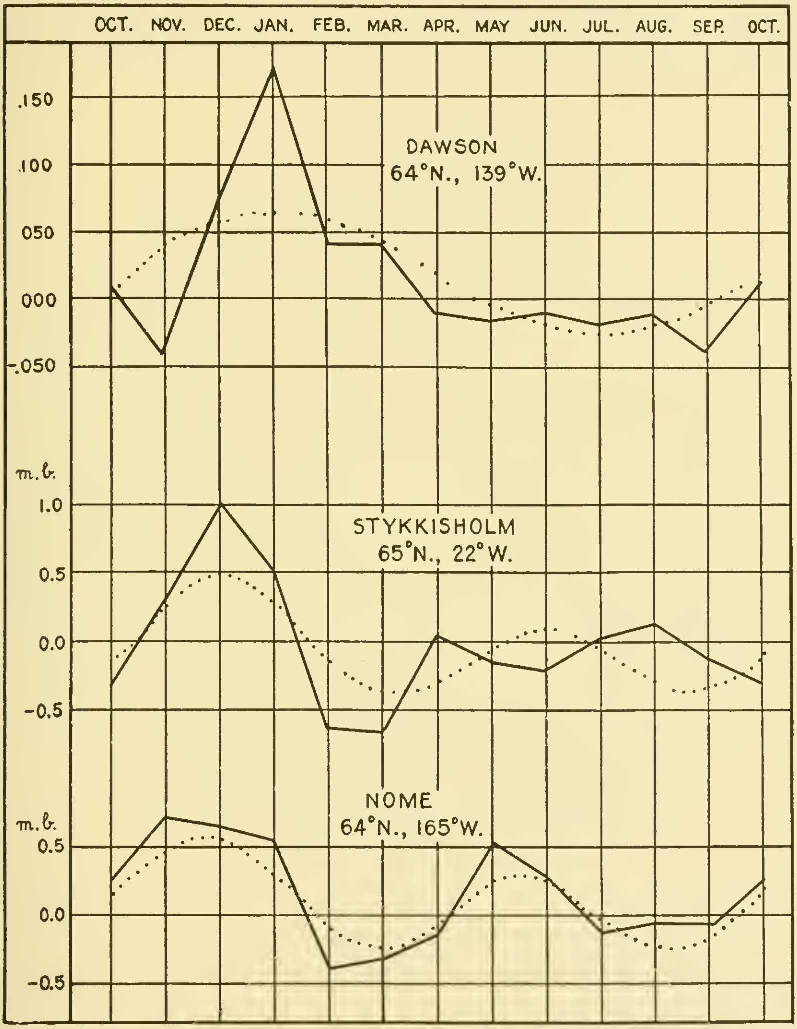

FIG. 9.—Departure from normal pressure by months with high solar activity.

months when solar activity was high and for the months when solar activity was low as given in table 2. The results for the 6-month period when solar activity was high at the epochs April and October are shown in figure 10 plotted on a map of the northern hemisphere.

It is seen from this map that the latitude effect as pictured in figure 7 is increased twice a year when the sun crosses the Equator in March and October. At that time the effect of high solar activity on the pressure is accentuated. The decreased pressure at the Equator, the increased pressure in middle latitudes and the decreased pressure at the poles are greater than at other times of the year.

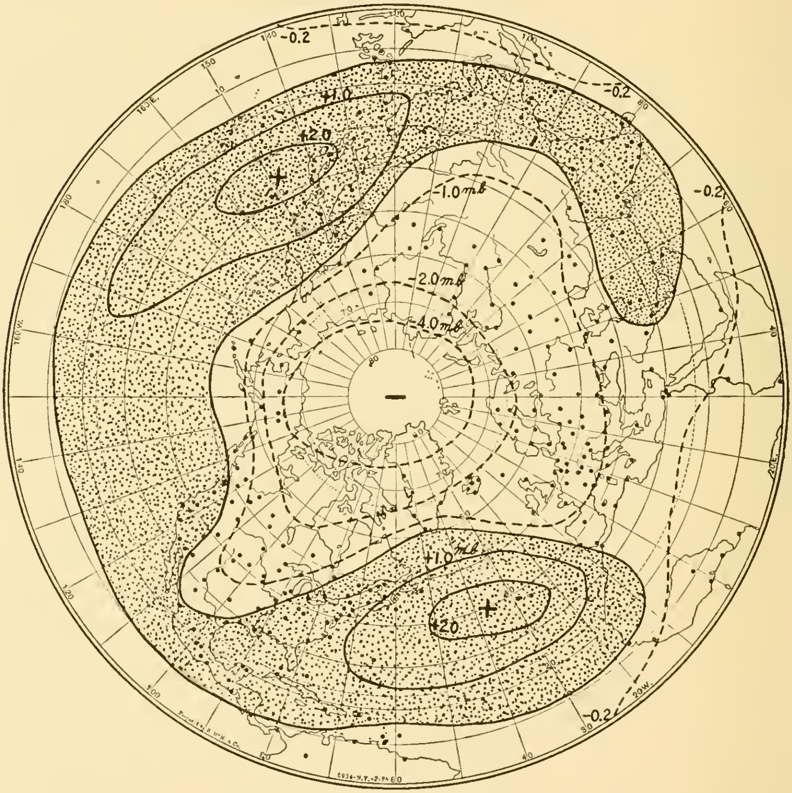

Fig. 10.—Excess or defect of pressure at the Equinoxes (March and September) with increased solar activity.

On the other hand, when the sun is at the solstices in June and December the latitude differences are diminished and effects due to contrasts between land and water are accentuated. The greatest increase of pressure with increased solar activity is over the continents in winter and over the oceans in summer. This is an annual change in contrast to the semi-annual period in latitude effects. The annual effect is shown in figure 11.

This chart is derived from the annual period in pressure as computed from the data by harmonic analysis. The areas outlined on the chart show where the maximum increase of pressure occurs at different seasons when solar activity is greater than normal. In mid-winter the excess of pressure is greatest over the continents in high latitudes. There is a defect in the same regions in summer.

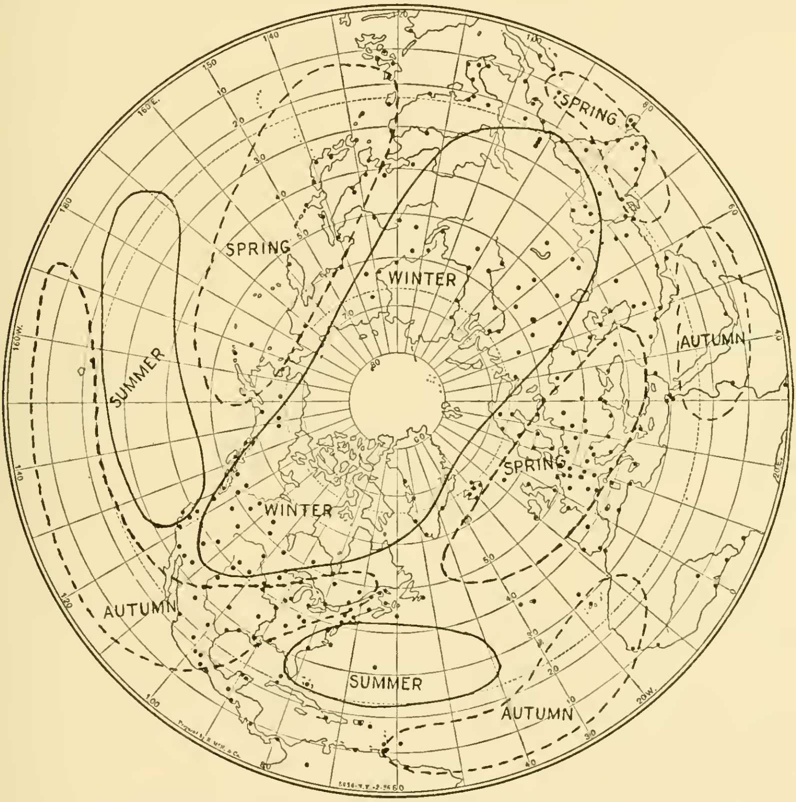

FIG. 11.—Regions in which highest pressure occurs at different seasons with increased solar activity. Annual period.

In spring the greatest excess occurs over the North Atlantic and North Pacific, and there is a defect in autumn. In autumn there is an excess in middle latitudes and a defect in spring.

The results both for the semi-annual period and for the annual period were checked by an analysis of the data during periods of low solar radiation which give in general the opposite effect.

The shifting in position of maximum effect on the atmosphere in the annual period is clearly related to surface conditions and may be explained by changes in the balance between incoming and outgoing radiation. In summer the land masses in high latitudes absorb solar heat and this absorption increases with increased solar radiation. There is also an increase of cloudiness at that time which should play an important rôle in determining the effect of increased solar radiation on the atmosphere. In autumn an increased atmospheric circulation causes an excess of warm water and of cloudiness in the North Atlantic and North Pacific with an accompanying diminution of pressure. The same increase in atmospheric circulation determines an increased flow of cold water along the north coast of Africa and of Western Mexico and thus determines the opposite annual period in these regions to that in the northern part of the same oceans.

The seasonal shifting in the centers of maximum solar action in the atmosphere are thus plausibly related to changing physical conditions in the atmosphere and in the surface conditions of the earth.

IV. ATMOSPHERIC WAVES

When atmospheric changes, whether of pressure, temperature, or wind movement are analyzed into oscillations of different lengths they are usually found not to be stationary but to progress from point to point. The short oscillations move fastest and the longer oscillations progress more and more slowly with increasing length. They thus have some analogy to ocean waves and are frequently called waves.

Meteorological data may be analyzed into longer and shorter oscillations by means of smoothing, by means of using changes of successively greater length, by means of sine curves derived from individual periods, or by the process of averaging successive periods, using trial periods of different length. These processes are described and illustrations given in "World Weather."[1]

The method adopted for the present research was to select from plotted curves the cases where an oscillation of some particular length was unusually strong and then to get the average of several successive oscillations, so as to eliminate oscillations of longer period. This process was repeated successively for each particular oscillation selected, dropping one and adding another later in time. An example of the method is shown in table 6 for St. Paul, Minnesota. The data were obtained from the Washington 8 a. m. weather map.

The consecutive means of four successive periods, obtained as shown in table 6 for the months of November and December, 1927, are plotted in figure 12 for a series of stations running from Nome,

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[1] Clayton, H. H., World Weather, p. 114. New York, Macmillan & Co., 1923.

TABLE 6.—*Means of 4 Periods of 7 Days Each, St. Paul, Minnesota*

	Observed pressure, 29.00 + inches							Consecutive means of 4 periods, 29.00 + inches						
Day	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Nov. 4	.68*	1.02	1.32	1.24	1.16	1.26	.86							
11	.66*	1.42	1.26	1.14	.92*	1.38	1.28	.88	1.12	1.18	.98	.86*	1.29	1.13
18	1.30	1.28	.94	.84*	.94	1.26	1.02	1.06	1.24	1.17	.87	.81*	1.18	1.22
25	.88	.76	1.18	.70	.42*	1.26	1.36	.98	1.20	1.15	.79	.76*	1.12	1.04
Dec. 2	1.40	1.48	1.30	.78*	.96	.82	1.20	1.02	1.10	1.22	.94	.89*	1.13	1.14
9	1.34	1.28	1.18	.84	.70*	1.14	.58	1.16	1.26	1.26	1.10	1.05	.93*	.97
16	.46*	.88	1.20	1.46	1.48	1.32	1.40	etc.						
23	1.46	1.42	1.38	1.32	1.08	.42*	.68							

* Minimum.

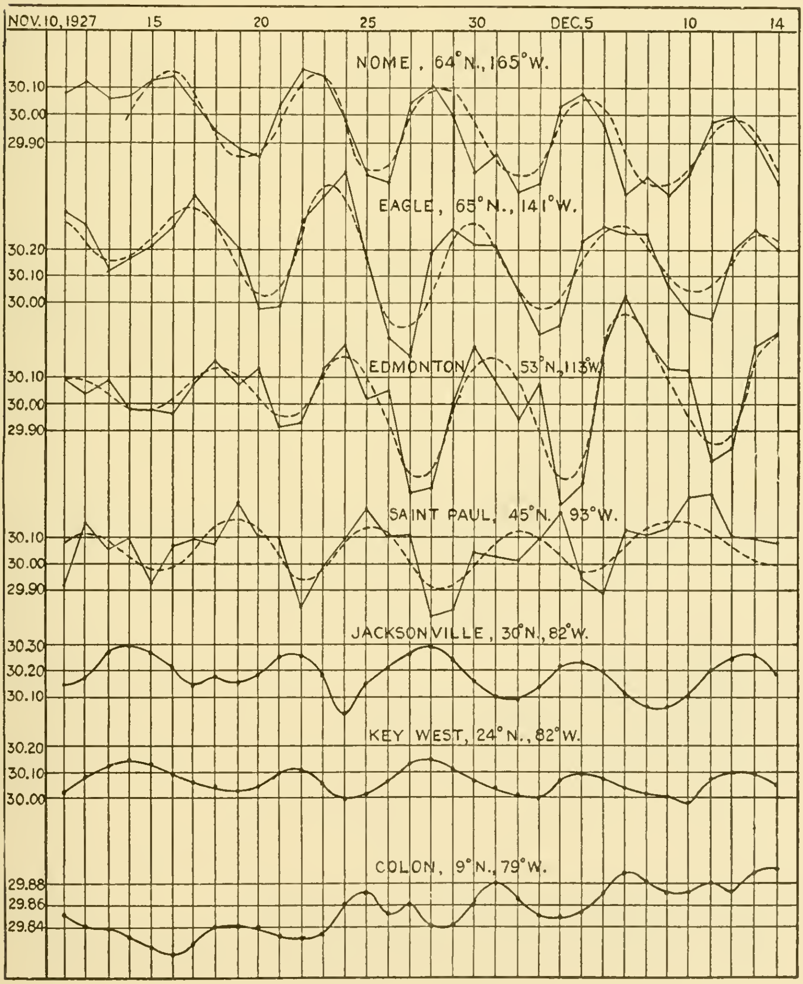

FIG. 12.—7-day pressure wave.

Alaska, southeastward to Key West, Florida, and to Colon, Panama. It is evident from the plot that the maxima and minima occur later at southern stations, so that at Williston, North Dakota (not shown in fig. 12), the oscillations are opposite in phase to those at Nome; but further southward at Key West they are in the same phase as at Nome, although much diminished in intensity.

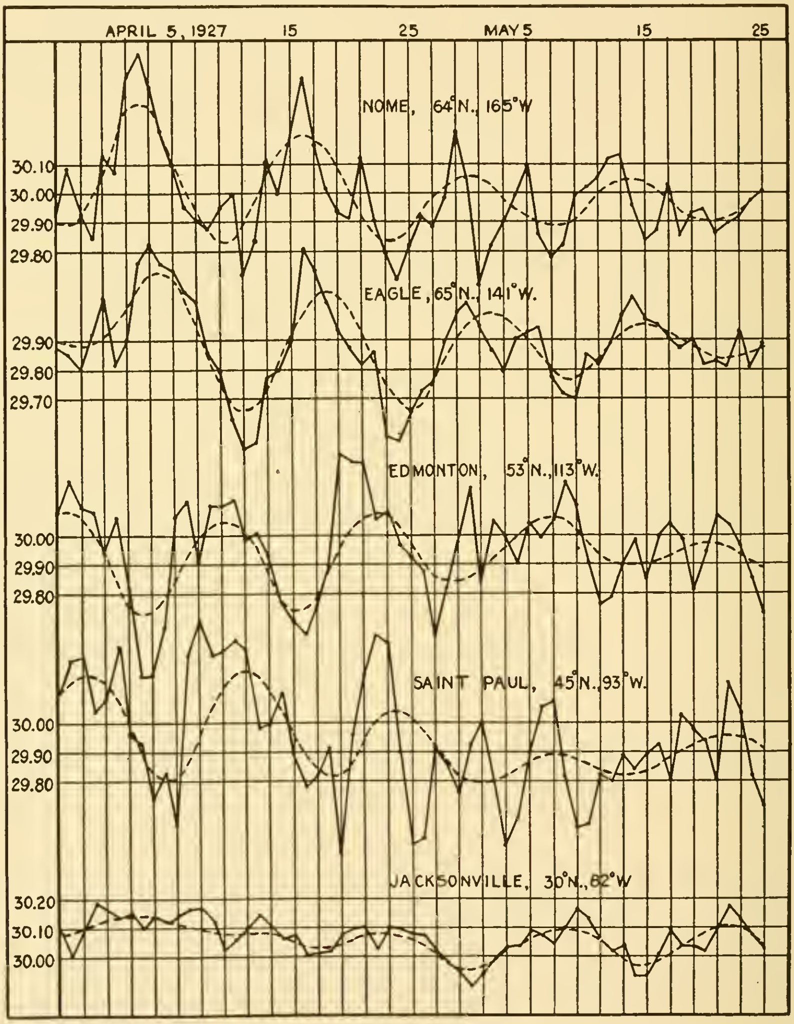

FIG. 13.—14-day pressure wave.

Figure 13 shows an oscillation of 13.6 days averaged in overlapping two-period intervals. The continuous lines were plotted from the averages; sine curves computed from the data by harmonic analysis are shown by dotted lines. Here, again, it is found that the maxima and minima of the oscillations occur later at the more southern stations and the phase is inverted at St. Paul, showing that the progressive movement is only about one half as rapid as the 7-day period. In other words the ratio, rate of progress divided by length of period, is the same for both periods and apparently for all periods, as will be shown later.

That atmospheric pressure and temperature may be analysed into waves or oscillations which move at different speeds inversely proportional to their wave length was advanced by me in the monthly Weather Review, April, 1907, and has been confirmed by a number of research workers, Defant, Vercelli, Danilow,[1] Clough,[2] Weickmann,[3] and others. These waves do not always move from the same direction, as Danilow and Weickmann have pointed out; but the dominant direction of motion is from northwest to southeast in the northern hemisphere and from southwest to northeast in the southern hemisphere.[4]

The rate of progress for all classes of moving atmospheric waves appears to follow a very simple law. This may be illustrated by the progress of the 7-day wave. Using the data from about 16 stations, the progress of the wave from Alaska is illustrated in figure 14 by a series of heavy lines giving the wave front on successive days as it passed across the North American Continent. Small circles show the positions of the stations used. It is seen that the wave moved from about 180° W. longitude at a rate which would carry it half around the world in one period of oscillation, namely in seven days, and hence entirely around in two periods. At the same time the wave front advanced from the Arctic Circle near Nome to the Tropic of Cancer near Key West also in a period of seven days or at a rate which would carry it, from pole to Equator in the time of two periods of oscillation.

If, however, the rate of progress is taken not along the wave front but along a meridian—in this case the 90th meridian west is a good example—the rate of progress southward from the Arctic Circle to the Tropic of Cancer takes place in $3\frac{1}{2}$ days, or at a rate

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[1] Wetterwellen, Podoleschen Abtheilung des Ukrainischen Meteorologiches Dientes, 1926.

[2] Monthly Weather Review, Vol. 52, No. 9, p. 436, Sept. 1924.

[3] Weickmann, L., Das Wellenproblem der Atmosphäre. Meteor. Zeitschr., S. 241, 1927.

[4] Clayton, H. H., World Weather, p. 111. New York, Macmillan & Co., 1923.

which would carry it from pole to Equator in one period of oscillation. This is evidently a law which applies to wavelike changes of all lengths.

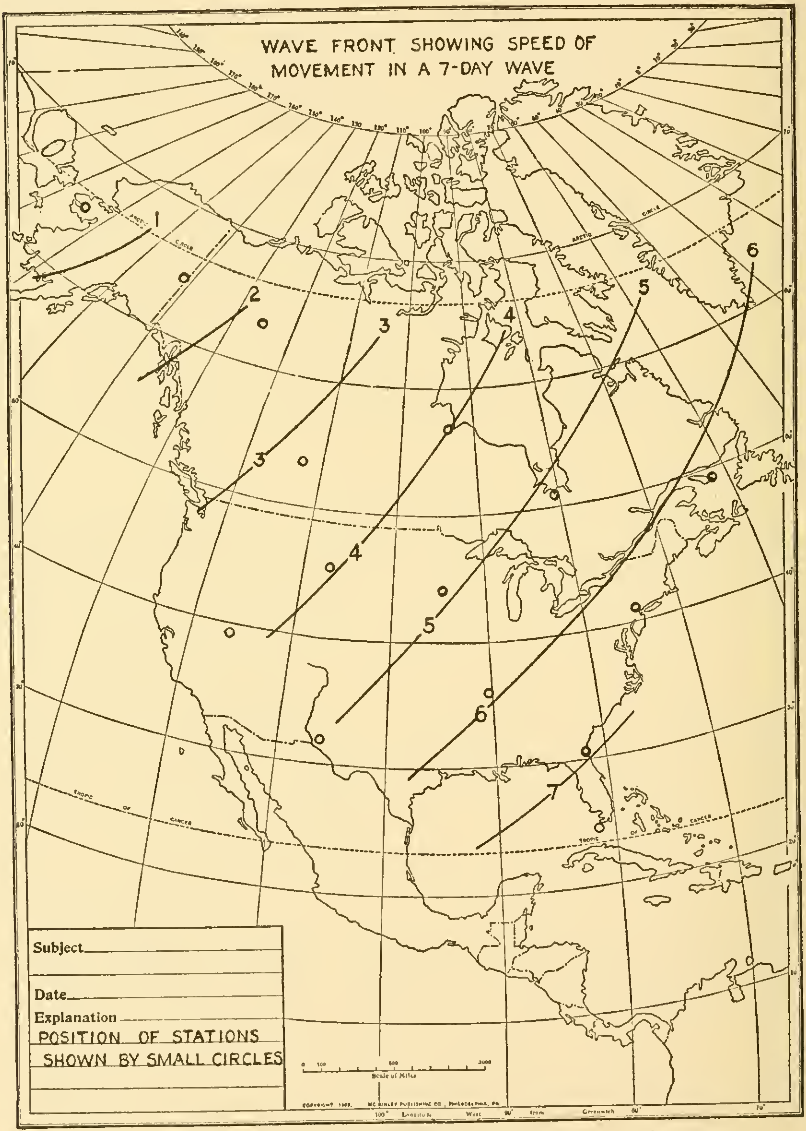

FIG. 14.—Wave front showing speed of movement in a 7-day wave.

In Dr. Weickmann's[1] able analysis of the 24-day wave of pressure of the winter of 1923-24, it is shown that the wave originated

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[1] Petermanns Mitteilungen, Ergänzungsheft No. 191, 1927.

in the polar basin and spread southward toward the Equator. Figure 15 is derived from a plot made by Dr. Weickmann. The plot is made to show the wave at successive dates along the meridian of 45° E. longitude. The dotted curve No. 1 in figure 15 shows that on December 10 there was a minimum of pressure in the arctic basin north of Spitzbergen and a high pressure over Central Asia about 60° N. Six days later, on December 16, as shown by the broken curve No. 2, the low pressure was about 70° N. and a high pressure about 45° N. Twelve days later on December 22, as shown by the continuous curve No. 3, the period was in opposite phase and the low pressure is found at 60° N. with a high pressure south of 30° latitude and also in the polar basin. Eighteen days later, on December 28, as shown by the dotted curve, No. 4, the low pressure is at 45° and a high pressure is advancing southward.

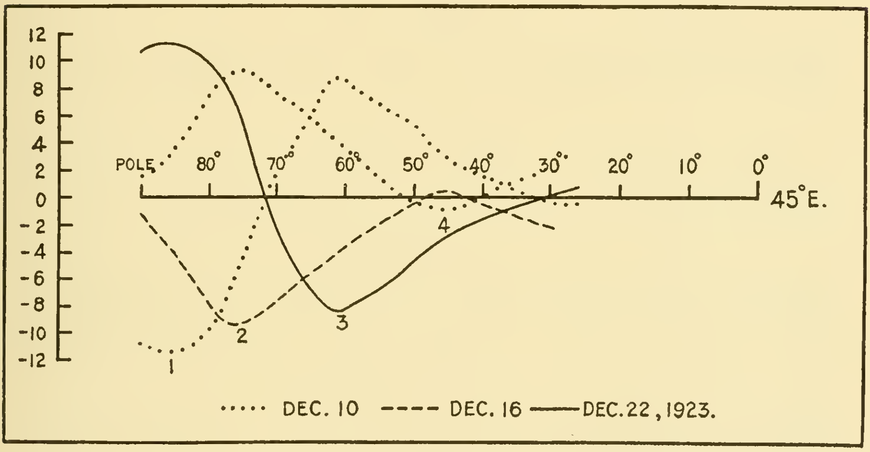

FIG. 15.—Pressure departures in 24-day period (data derived from diagram by Weickmann).

The plot brings out clearly the decrease in amplitude of the oscillations with decreasing latitude. Owing to the decrease of amplitude with latitude the velocity of progress of the wave is best obtained from the points where the curve crosses the zero line. The first zero point is at 72° latitude and the second about 30° latitude. This is the distance traversed by the wave in 12 days, a rate which would carry it from pole to Equator in about one period of 24 days.

In Mr. Clough's[1] study of a period of about 2½ years in pressure he says: "The epochs of the short period for St. Paul, St. Louis,

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[1] Monthly Weather Review, Vol. 52, No. 9, p. 436, Sept., 1924.

Memphis, Vicksburg and New Orleans have been derived and it is found that there is an average lag of 0.19 year from St. Paul to St. Louis and a lag of 0.37 year between St. Paul and New Orleans." The distance from St. Paul to New Orleans is 15° of latitude and 0.37 year is about one-sixth of the period, so that the rate of progress here indicated would carry the wave from pole to Equator in one period.

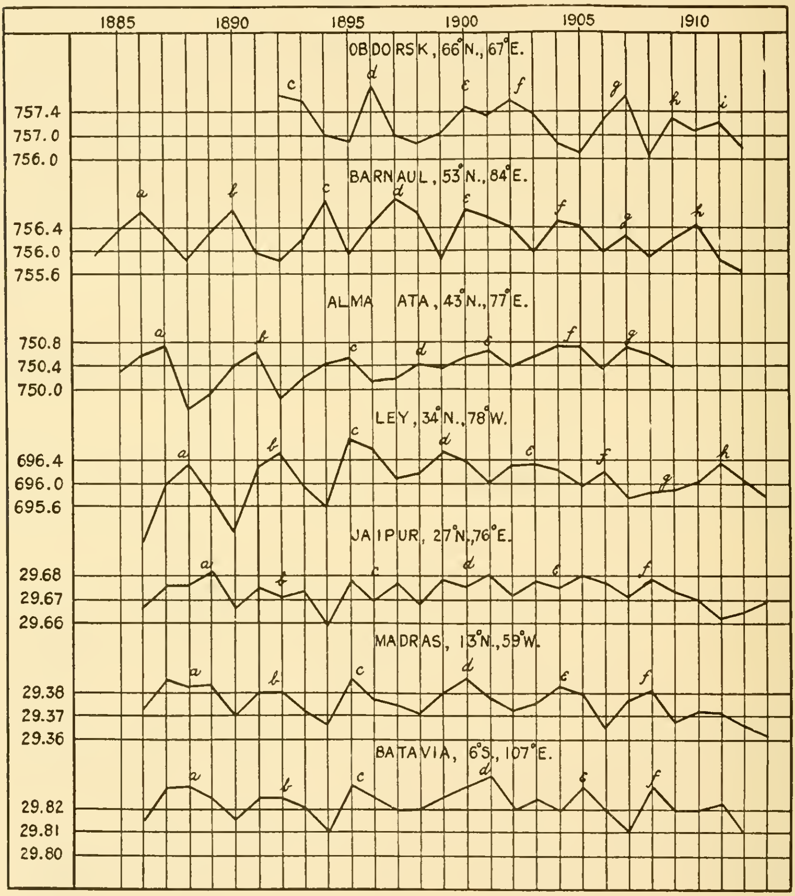

FIG. 16.—Pressure in 3.77-year period.

In figure 16 is found a period in which the unit of time is years instead of days. The period of oscillation in pressure is about four years. It was taken to be 3.75 years, or one-third of a sun-spot period of 11.3 years, and averages were made for each three successive oscillations of 3.75 years. The continuous curves show the averages. The letters a, b, c, etc., show successive maxima. The data were derived from "World Weather Records" and cover the continent of Asia where the data are more complete for different latitudes than in North America.

It is seen from the plot that the maxima and minima of the period occur first in high latitudes and successively later at stations nearer the Equator, at least down to about 30° latitude, taking about three years to move from Obdorsk, 66° N., 66° E., to Ley, 34° N., 77° E. In the equatorial belt between 20° N. and 20° S. the maxima and minima occur simultaneously at all stations as shown by the results for Madras and Batavia. However, from figure 16 it is seen that the pressures at Alma Ata, 43° N., and at Batavia, near the Equator, are opposite in phase, which is further evidence that this wave traversed 90° of latitude in one period of about 3.75 years.

A recent study of 2- and 3½-year waves in temperature by Ernest Rietschel[1] shows a rather complex movement indicating a combination of standing and moving waves.

That the law of wave progress quoted above holds true in the Southern Hemisphere as well as in the northern is shown by the rate of progress of a temperature wave of about 18 days shown plotted on page 223 of "World Weather."[14] This wave progressed from Santa Cruz, 50° S., to Cuyaba, 16° S., in seven days, a rate which would carry it from pole to Equator along a meridian in one period of 18 days.

The rate of progress of a 7.5-year wave is indicated in figure 22 where the maxima and minima of the waves occur successively later at Stykkisholm, Rome, and Calcutta, the minima and maxima at Calcutta being about 7 years later than at Stykkisholm.

These facts render it evident that the rate of latitude displacement is a general law for periodic oscillations of all lengths. This law may be stated as follows:

Law of latitude displacement of periodic waves.—Periodic oscillations in atmospheric conditions progress in latitude from point to point along a meridian at a rate that would carry the wave from pole to Equator in one period, whatever the period of oscillation.

It is probable that the law of displacement in longitude is equally simple. Figure 14 shows that the 7-day wave progressed in longitude about 180°, or half around the world, in seven days.

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[1] Die 3-3½ jährige und die 2 jährige Temperaturschwankung, von Ernst Rietschel. Geographical Institute of the University of Leipzig, Vol. IV, No. 1, 1929.

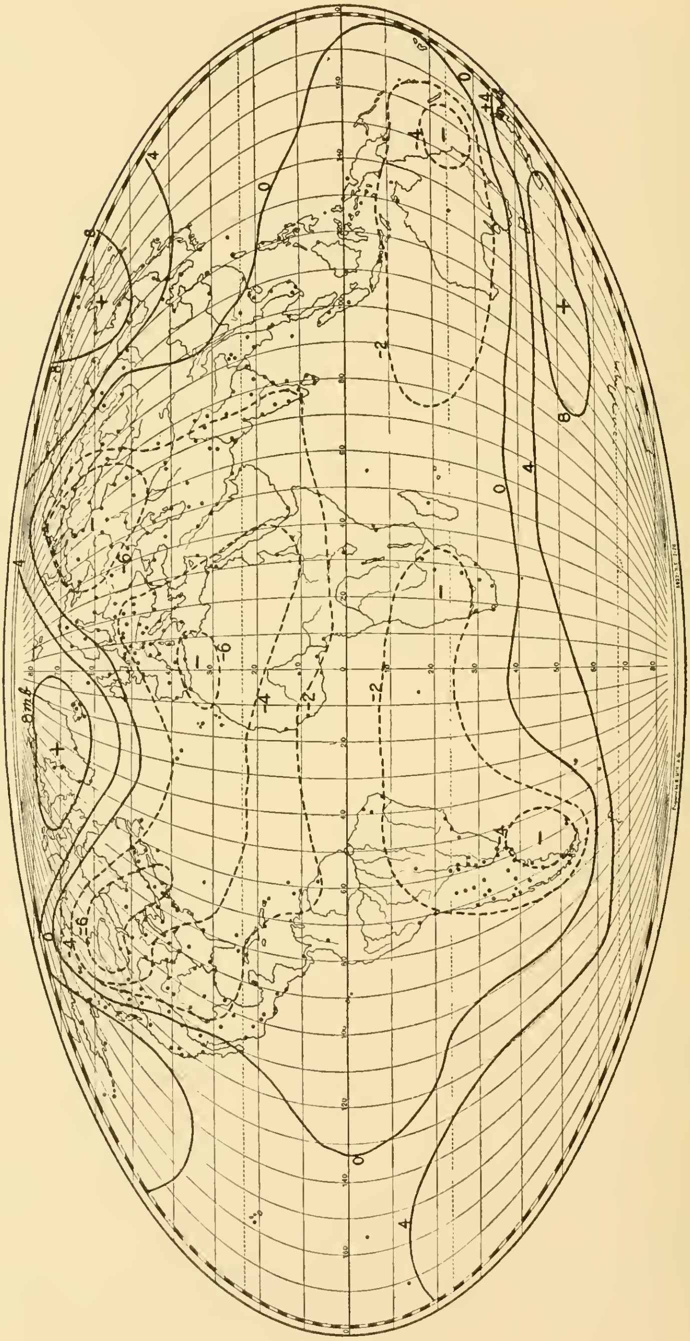

Fig. 17.—Departures of pressure from mean in 7.5-year period. Epochs 1885, 1893, 1900.

A proportional rate of progress appears to occur in the periodic wave of about 7.5 years. Figure 17 shows the centers of oscillation in a 7.5-year wave on a world map. This map is derived from harmonic values computed from groups of three periods between 1883 and 1913 at 117 stations scattered over the world. It shows the centers of oscillations at the epochs, 1885, 1893, 1900, etc. Continuous lines show equal values above normal and broken lines show equal values below normal. It is not possible with available data to follow the progressive movement of all the centers, but the center over Greenland shows a distinct progress from west to east. This progress will be evident from figure 18 which shows the centers of oscillation in the area between 50° W. and 120° E. north of the Equator when the epochs are taken successively two years later. The results in figure 18 are derived from the data of 48 stations taken from " World Weather Records."

In 1885 there was a marked excess of pressure over Greenland (see fig. 17) ; in 1887 this center of excess pressure is displaced to Norway; in 1889 this center is over the northern part of central Siberia; two years later, in 1891, it is over the northern part of western Siberia. The progress of the centers is shown by small circles in the upper chart of figure 18. The circles show that the center was displaced eastward about 180° in a period of 7.5 years or at a rate which would carry it around the world in two oscillations of this period.

In his study of the 2½-year period Mr. Clough[1] found that the epochs at Portland, Oregon, preceded those at Toronto by about 0.75 year. The difference in longitude is 43°. At that rate the epoch would move about 150° of longitude in one period, or approximately around the world in two periods.

The charts given by Dr. Weickmann in his study of the 24-day period referred to previously do not show the drift in longitude so clearly as the drift in latitude. However, in his charts there are found centers of maximum departure which show a drift in longitude. A center in the Aleutian Islands on December 10, 1923, moved eastward across Canada to Labrador in 11 days, which is at the rate of about one period for 180° of longitude; but a center near Greenland moved eastward to northern Siberia and then retreated.

The longitude drift of the waves is, hence, not so clearly defined as the latitude drift; but there is undoubtedly a trend which may be stated as follows:

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[1] Monthly Weather Review, Vol. 52, No. 1, p. 39, Jan., 1924.

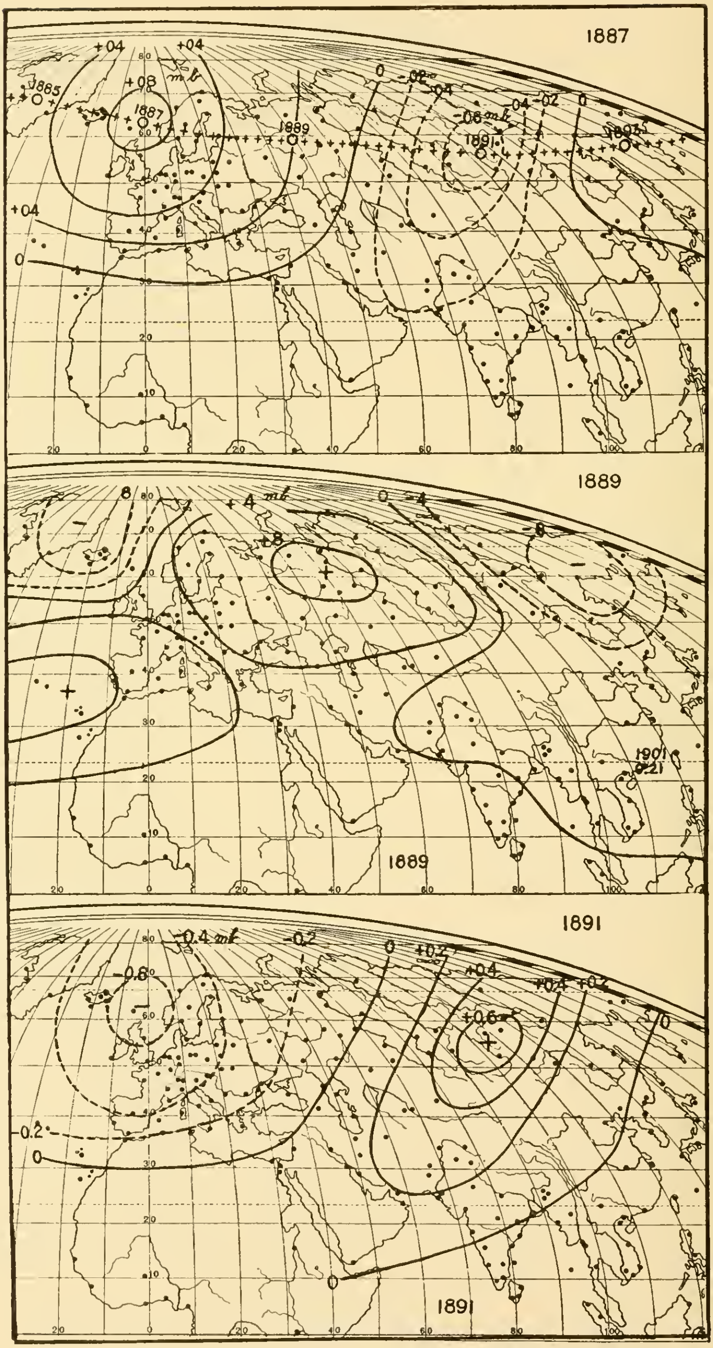

Fig. 18.—Departures of pressure in 7.5-year period, epochs 1887, 1889, 1891.

Law of longitude displacement of periodic waves.—Periodic waves tend to drift eastward at a rate of 180° of longitude in one period, whatever the length of the period. The centers of greatest departure are found in high latitudes, 60° to 80° from the Equator.

There are several factors which make this drift toward the east difficult to follow. First there are the factors depending on solar changes described in the latitude effect and which are nearly instantaneous with solar changes. There are also seasonal factors and probably others which influence the results.

Examining the successive charts in figure 18 it is found that the magnitude of the departures in the 7.5-year period decreased rapidly as the central areas passed into Siberia and increased again over Kamchatka. This enhanced intensity in the departures coincided with a maximum of solar activity as will be seen later.

Another disturbing factor is the formation of centers of disturbance moving at right angles to the normal waves. When waves of high pressure and low temperature are advancing from the northwest, low pressure areas form in front of them and advance from southwest to northeast. These disturbances advancing toward the northeast are particularly frequent over the warm ocean waters to the east of Asia and of North America. These cross currents greatly complicate the normal movement of atmospheric waves and make analysis of the data difficult.

V. RELATION OF THE WEATHER WAVES TO SOLAR CHANGES

If the values of solar radiation observed by the Smithsonian Astrophysical Observatory simultaneously with the pressure waves are treated in the manner just described they show in each case wavelike changes of the same length as the pressure waves.

Figure 19 shows the successive means of four periods of seven days in solar radiation during November and December, 1927, compared with the atmospheric pressure observed at the same time at Eagle, Alaska, and treated in the same manner as in table 6. The dotted curves in each case show the harmonic values of the 7-day wave computed from the data. Compare this diagram with the plots in figure 12.

Figure 20 shows the means of successive values of a period of 13.6 days in solar radiation and in pressure derived from the means of two periods. This diagram may be compared with the plots in figure 13. The dotted curves in figure 20 show harmonic curves computed from the data.

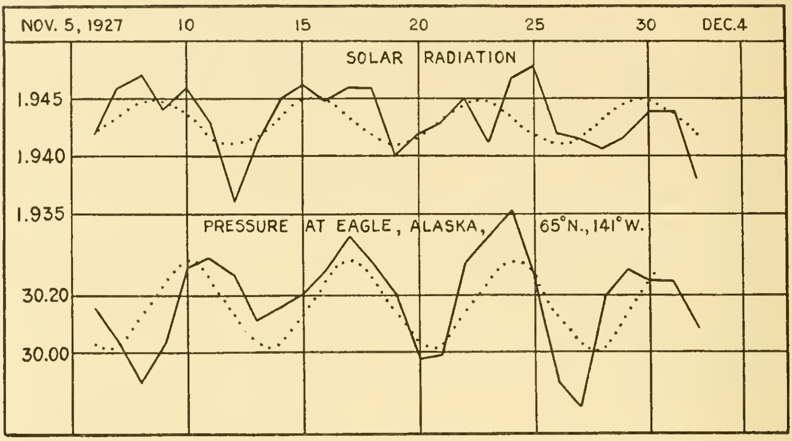

FIG. 19.—7-day period in solar radiation and pressure.

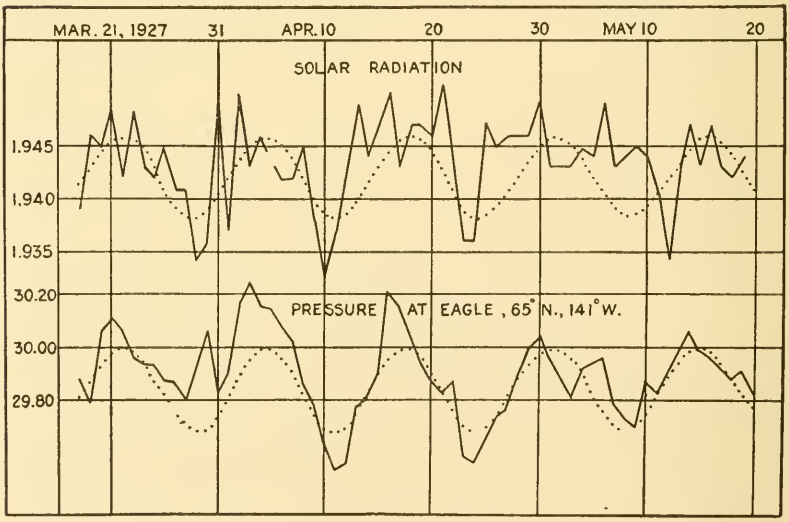

FIG. 20.—13.6-day period in solar radiation and pressure.

Figure 21 shows the observed values of solar radiation during December, 1923, and January and February, 1924. These values are compared with the observed values of pressure at Spitzbergen and at Hamburg. A 24-day period of oscillation is evident in each case and this oscillation is shown by the dotted curves computed from the data in each case by harmonic analysis. Pressure data from all over the northern hemisphere were treated in this way for a period of 24 days by Dr. Weickmann and showed a systematic wave movement from the polar basin southward.

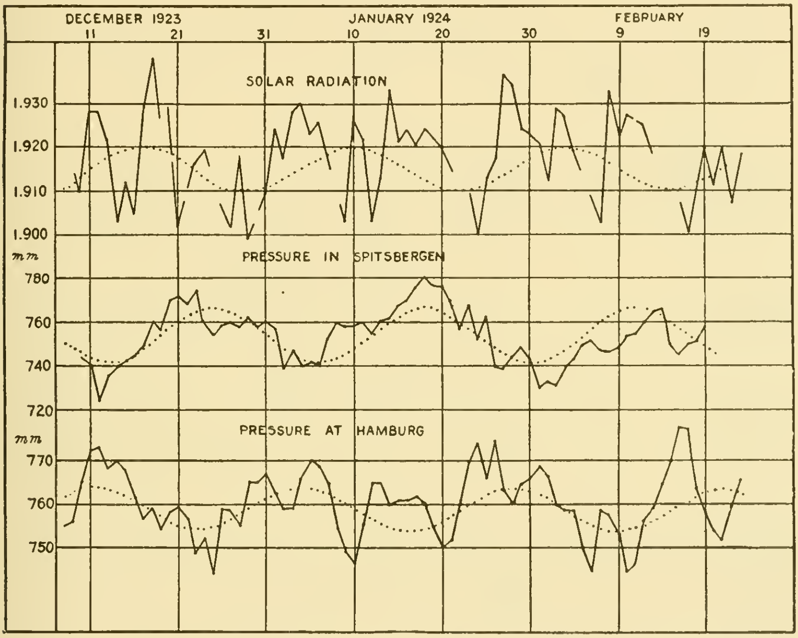

FIG. 21.—24-day period in solar radiation and pressure.

For the study of long periods, no values of solar radiation are available; but the 7.5-year period shows a distinct relation to sun-spot changes. Figure 22 shows a plot of consecutive means of three periods of 7.5 years. This period is one-third of Hale's sun-spot period of 22.5 years, and the mean of the three periods eliminates the 11.3-year sun-spot period which is one-half of Hale's period.

Pressure curves are plotted for five widely separated stations. These plots show distinctly an oscillation in the atmosphere of the length of 7.5 years and a progress southward from high latitudes.

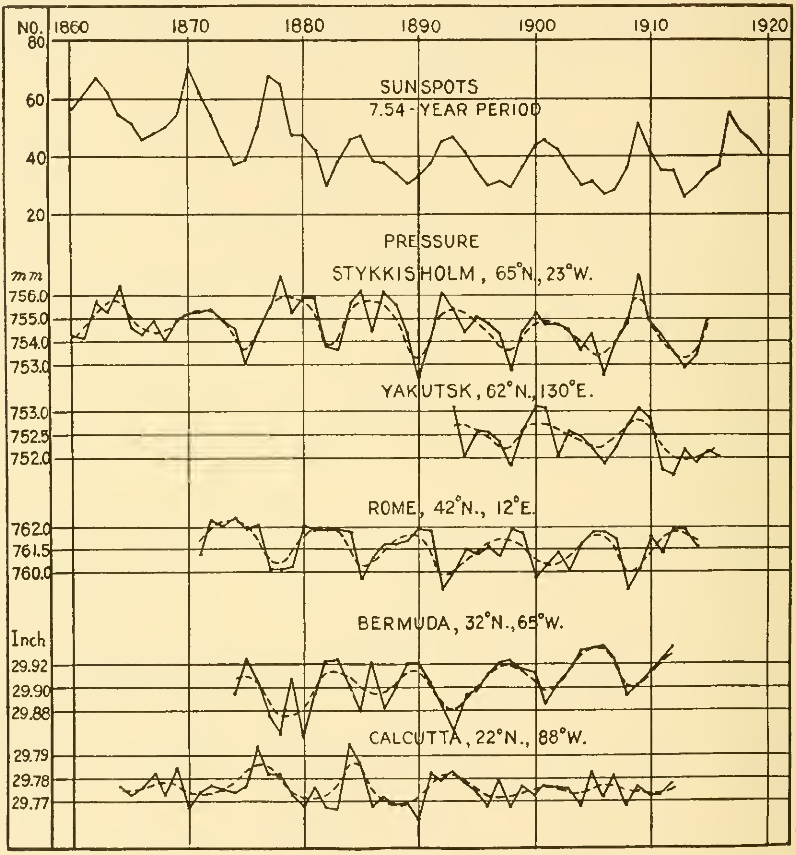

FIG. 22.—7.54-year period in sun spots and pressure means of 3 periods.

VI. SOLAR CYCLES AND WEATHER CYCLES

From the preceding investigation it is evident that atmospheric and solar conditions show wavelike changes of a periodic nature. The question has long been a challenge to investigators, as to whether there are fixed and regular cycles in weather and in solar changes. If such regular cycles could be found, it would greatly assist in unraveling the complexities of the weather and in forecasting future occurrences. There is a dominating period of about 11 years in sunspot numbers, and many efforts have been made to find this same dominating period in weather changes. Such a relation has not been found and the reason appears to be that weather changes follow changes in solar radiation more closely than they do sun-spot numbers, and solar radiation is more variable and shows a more complex periodicity than do sun spots.

When the 11-year period 1917 to 1928 is analysed harmonically for sun spots and solar radiation, the results in table 7 are obtained.

TABLE 7.—*Harmonic Terms for 11¼-Year Period in Sun Spots and Solar Radiation*

Sun-spot numbers		Solar radiation	
Epoch 1917.5	Amplitude in numbers	Epoch 1917.5	Amplitude in calories
$A_1 = 104°$	$a_1 = 35.3$	$A_1 = 64°$	$a_1 = .009$
$A_2 = 274°$	$a_2 = 7.9$	$A_2 = 238°$	$a_2 = .004$
$A_3 = 305°$	$a_3 = 10.6$	$A_3 = 50°$	$a_3 = .008$
$A_4 = 333°$	$a_4 = 6.0$	$A_4 = 339°$	$a_4 = .005$

These results show that in a general way the oscillation in the number of sun spots and in the intensity of solar radiation are in the same phase—that is, when one increases the other increases; but the amplitudes of the changes are very different. The amplitude of the primary oscillation, a_1, in the sun spots (the $11\frac{1}{4}$-year period) is decidedly predominant while in the solar radiations the amplitudes of the harmonics of $\frac{1}{2}$, $\frac{1}{3}$, and $\frac{1}{4}$ of 11.3 years, a_2, a_3, and a_4 are almost as large as the primary a_1. The pressure data for tropical stations for the 11 years 1917 to 1928 are not available at present, so that a computation of pressure changes was made by going back two periods of $11\frac{1}{4}$ years to January, 1890, and computing the harmonic terms from the mean pressure of nine equatorial stations extending from Quixeramobim in Brazil eastward across Africa and the Indian Ocean to Malden Island in the Pacific. The data covered two 11-year periods, 1890-1913, and the epochs were taken at 1895.0 = 1917.5.

TABLE 8.—*Harmonic Terms for 11¼-Year Period in Pressure, 1890-1913*
Mean Pressure of 9 Equatorial Stations
Epoch 1895.0 = 1917.5

$A_1 = 325°$	$a_1 = 0.36$ mb.
$A_2 = 29°$	$a_2 = 0.32$ mb.
$A_3 = 265°$	$a_3 = 0.25$ mb.
$A_4 = 150°$	$a_4 = 0.35$ mb.

This comparison indicates that in the $11\frac{1}{4}$-year period in pressure in the Tropics, the phase is in general terms opposite to that of sun spots and solar radiation, and hence when these increase the pressure decreases. This fact is also made very apparent by comparing the individual periods in sun spots with pressure from 1870 to 1920. It is also evident that the amplitude a_1 of the 11-year period is not dominant as in the sun-spot period; but as in the case of solar radiation the subharmonic terms a_2, a_3, and a_4, are almost as large as the primary a_1.

In order to compare the harmonic terms of the $11\frac{1}{4}$-year period in pressure in equatorial regions with those in other latitudes, the mean pressure was obtained for each 10° of latitude in the northern hemisphere for each year from 1890 to 1913. A period of 23 years was taken because from Hale's observations of magnetism in sun spots the complete period of the sun spots is about 22.6, so that 11.3 years becomes the second harmonic of this period. From the data thus obtained harmonic terms were computed for each zone of latitude and are given in table 9. The phases of the periods varied for each latitude as it was evident they must do from the preceding investigation of wave movement. The striking facts brought out are: (1) The amplitudes of the periods increase greatly in high latitudes where they are much greater than in low latitudes and, (2) the amplitudes of the smaller subharmonics in high latitudes are much greater than that of the period of 11.3 years.

TABLE 9.—*Amplitudes of the Harmonics of a 22.6-Year Period in Pressure*

Zones of latitude	No. of sta.	a_2 11.3 yr.	a_3 7.54 yr.	a_4 5.65 yr.	a_6 3.77 yr.	a_8 2.83 yr.	a_{24} 11.3 mo.	a_{48} 5.7 mo.	a_{72} 3.8 mo.
70°–80° N.	2	0.60 mb.	0.65 mb.	0.94 mb.	0.92 mb.	1.12 mb.	2.40 mb.	2.50 mb.	3.75 mb.
60°–70°	14	0.59	0.61	0.77	0.88	0.86	2.09	2.78	2.31
50°–60°	21	0.34	0.38	0.46	0.61	0.76	1.32	1.60	1.28
40°–50°	25	0.32	0.42	0.43	0.45	0.51	1.22	1.10	1.23
30°–40°	30	0.24	0.33	0.40	0.31	0.31	0.67	1.02	0.88
20°–30°	13	0.36	0.21	0.29	0.24	0.23	0.62	0.63	0.53
10°–20°	15	0.42	0.25	0.35	0.21	0.33	0.42	0.45	0.40
0°–10°	6	0.36	0.27	0.32	0.25	0.35	0.39	0.25	0.38

NOTE.—In computing the harmonics in Table 9 the means of three or of four periods were used in each case except the case of a_2 where two periods were used. The observed values from which a_2 were computed covered the entire interval of 22.6 years, while the values from which a_{72} were computed covered only one twenty-fourth of this interval.

This last finding is of the utmost importance to meteorology, because it shows that the shorter periods are of much more importance in the meteorology of high latitudes than the longer periods of 11 years or more. These meteorological and solar periods are all believed to be harmonics of longer solar periods.

Clough found solar periods of 300, 11.3, 7, and 2.5 years, and an analysis of the sun-spot data by Schuster disclosed a number of other periods besides the 11-year period. Turner found evidences of a period of 260-280 years from a study of tree rings, Nile floods, Chinese earthquakes, and sun spots. (Mon. Not. Roy. Astron. Soc., 1919 and 1920.) According to a recent analysis of the Wolfer sun-spot data made by Dinsmore Alter, published in the Monthly Weather Review of October, 1928, there are solar periods of more than 200 years in length, and the 11-year sun-spot period is a subharmonic of much longer periods. This view agrees with that put forward by Ellsworth Huntington and S. S. Visher in "Climatic Changes," 1922, p. 45. My own investigations are in accord with this view, except that recently the longer periods seems somewhat greater than that given by Alter.

Beginning with a period of 90 years, instead of 84 as given by Alter, I find periods of approximately the following length: *Length of solar periods in years:* 90, 56, 45, 35, 30, 28, 22.5, 18, 15, 12.9, $11\frac{1}{4}$, 10, 9, 8.2, $7\frac{1}{2}$, etc. All of these shorter periods are subharmonics of 90 years, except 56, 35, and 28, which are harmonics of a longer period.

They agree very well with meteorological cycles found by Prof. A. E. Douglass[1] from rings indicating the annual growth of trees in the southwestern part of the United States where rainfall is the most essential factor in growth. The periods found by Professor Douglass are: 35, 31, 28, 22.5-24.0, 20.5, 17.2, 14.2, 11.2-11.7, 10.2, 8.6, 7.6, 6.8 years.

A study of periodicities in the Nile floods by C. E. P. Brooks[2] leads him to pick out the following periods in years: 76.8, 64.6-67.4, 39.85, 33.49, 24.43, 21.81-22.43, 18.32, 16.68, 14.87, 12.50, 10.86-11.36, 8.33, 7.33, 6.83, 5.52, 3.66, 2.86. It is pointed out that 11 out of 16 of these periods are multiples or submultiples of a period of 22.12 years. This period is somewhat shorter than Hale's period of 22.6 years; but the difference may be due to the fact that the period actually was shorter during the intervals covered by Brook's data which go back to the year 641. His data indicate a systematic variation in the phase of this period, so that at the end of about 200 years the phase is inverted as regards epochs 200 years earlier.

The researches of D. Brunt[3] also indicate that there are a great many meteorological cycles, or else there are none. His periods in years derived from the Greenwich temperatures are: 23, 17.5, 15, 8.17,

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[1] Climatic cycles and tree growth, Vol. 2, p. 123. Carnegie Inst. of Washington, 1928.

[2] Mem. Roy. Meteorol. Soc., Vol. II, No. 12, 1928.

[3] Quart. Journ. Roy. Meteorol. Soc., Vol. 53, No. 221, Jan., 1927.

7.34; and in months, 64, 60, 42, 37, 26, 25, $21\frac{1}{3}$, 19.3-19.5, 14.5-14.7, 13, $12\frac{1}{3}$. The researches of Dinsmore Alter[1] published in the Monthly Weather Review also bear testimony to the multiplicity of meteorological cycles.

My own researches have dealt largely with shorter periods of days and months rather than years, principally because there was a much larger mass of data available for discussion. In my earlier studies of pressure and temperature data in the United States.[2] I found the following periods in days: 3, 3.6, 4.6, 5.45, 6.14, 7.24, 9.1, 11, 18, 22, 29, 44, 58, etc. My recent studies indicate that there are many more cycles and that all are probably harmonics of the sun-spot cycle.

A. Defant[3] in a world-wide study in 1912 found the following periods in days: 4.4, 7.9-8.7, 12.0-13.0, 16.8, 24.5, 31.2-31.5. Arctowski, Turner, Simpson, Wallén, Myrback, Wasserfall, Schostakowitsch, and Kidson have all found short meteorological cycles of various lengths Even the short period cycles of a few days are probably submultiples of much longer solar cycles, the most prominent of which is the 11-year sun-spot cycle, or its double value, the 22.5-year cycle.

In most cycles the subharmonics of small length are not important, but it has been shown in table 9 that in high latitudes the subharmonics of the 11-year period in meteorological cycles are of greater amplitude than the primary period of 11 years and that the amplitude increases with decreasing length of the harmonic. The sequence has not been followed through for the entire Northern Hemisphere beyond the period of about four months, but the amplitudes of meteorological cycles at stations in the northern United States and Canada apparently increase down to a length of about three days. These shorter periods determine the origin and movement of the ordinary cyclones and anticyclones seen on the weather map.

Most investigators of meteorological cycles assume at the beginning of their work that any cycle which may exist is constant in amplitude and phase and may by repetition be separated from other changes by which it is masked. This belief is the basic assumption underlying the analysis by the Fourier series or the Schuster periodogram. Prolonged investigation usually convinces the research worker that this assumption cannot be maintained. I early became

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[1] Monthly Weather Review, Vol. 54, p. 44, and Vol. 55, pp. 60 and 263.

[2] Amer. Meteorol. Journ., Feb., 1895, p. 376; also Amer. Journ. Sci., March, 1894.

[3] Sitzungberichte d. Wiener Akad., Bd. 121, Heft 3.

convinced that meteorological cycles change both in amplitude and phase. (Science, 1898, p. 243.)

Figure 23 shows an analysis of the Wolfer sun-spot numbers between 1890 and 1913 into a period of 22.6 years and its harmonics. It is seen that the chief period is one of 11.3 years, but some of the other periods show a fairly large amplitude of oscillation.

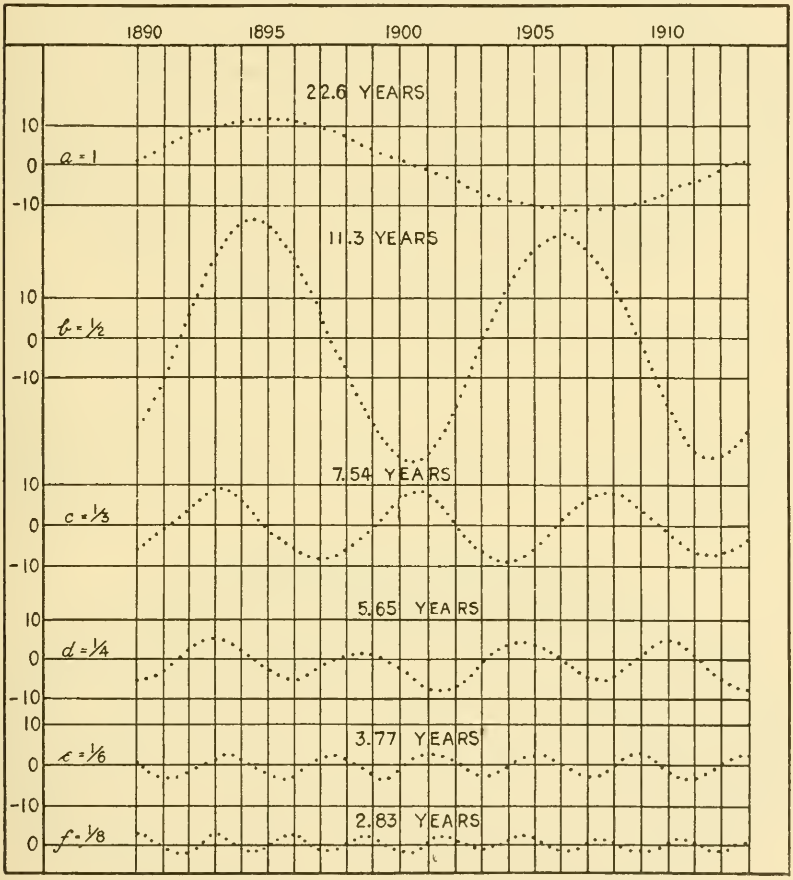

FIG. 23.—Harmonic analysis of 22.6-year sun-spot period, 1890-1913.

The meteorological data at more than a hundred stations in various parts of the world were analyzed in the same manner. Figures 24, 25, 26, and 27 show lines of equal departure of pressure for the various periods at the time of maxima of the solar periods of the same length. A chart showing the departures at the time of the solar maxima of the 7.5 year period is given in figure 17.

Certain common features stand out clearly in all these charts. First, in the equatorial belt, except possibly over parts of the Pacific Ocean, the pressure is lower than normal at the time of maximum solar activity in each period. Second, in middle latitudes of the Southern Hemisphere there is a tendency to a belt of pressure above normal which cannot be well outlined on account of insufficient observations. Third, in the Northern Hemisphere in high latitudes there is a tendency for the departures to form centers of positive and negative departures, usually two centers of positive departure, and

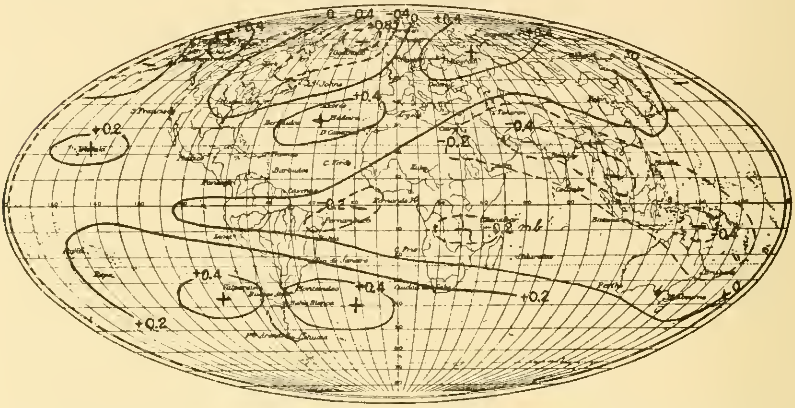

FIG. 24.—11.3-year period in pressure = $\frac{1}{2}$ of 22.6 years. Departures at time of maximum of solar period of same length.

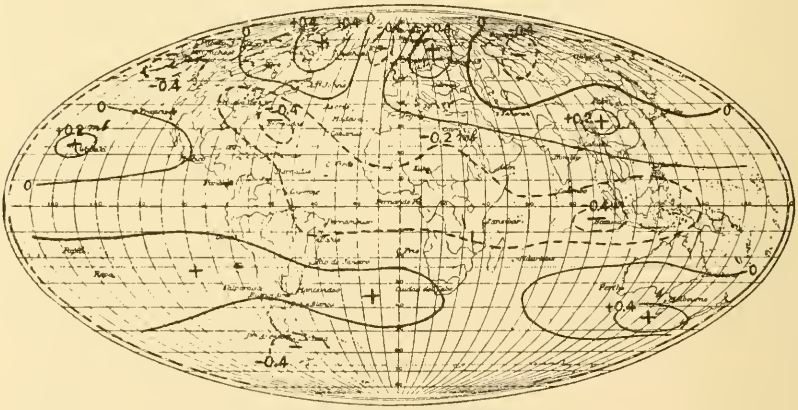

FIG. 25.—5.65-period in pressure = $\frac{1}{4}$ of 22.6 years. Departures at time of maximum of solar period of same length.

two centers of negative departure. Fourth, these centers are not in the same geographical position for the different periods and do not remain fixed for successive epochs of the same period. The reasons for these shifting centers are not clear. They are associated with changes in the phase and amplitude of the cycles.

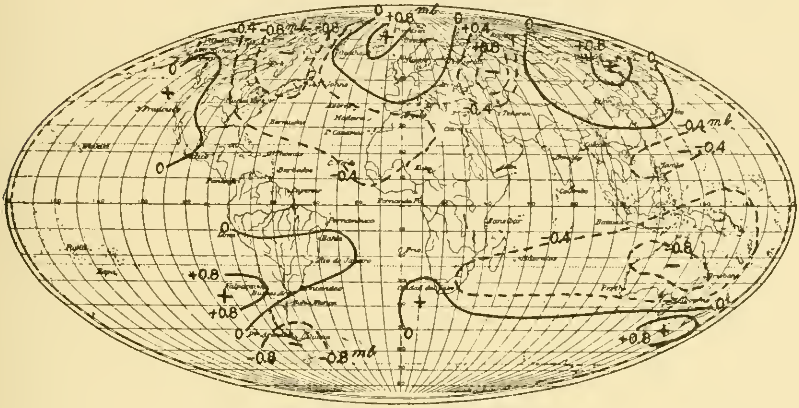

FIG. 26.—3.77-year period in pressure = $\frac{1}{6}$ of 22.6 years. Departures at time of maxima of solar period of same length.

Changes in amplitude are both apparent and real. Apparent changes occur where two periods of nearly the same length first strengthen each other when they are in the same phase and then weaken each other when they are opposed in phase. This change will be familiar to most readers from diagrams to illustrate beats in sound

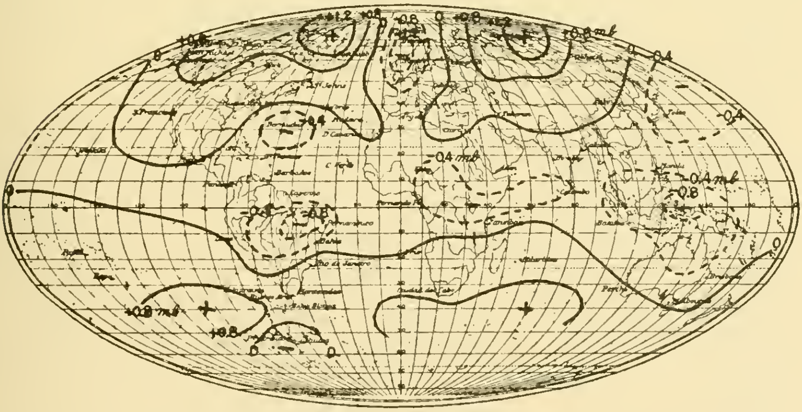

FIG. 27.—2.82-year period in pressure = $\frac{1}{8}$ of 22.6 years. Departures at time of maxima of solar period of same length.

waves. The beats are even more complicated when there are three or more periods of nearly the same length. In such a case there may be an apparent change of phase in one of the periods.

Real changes in amplitude are brought about by the influence of longer periods on shorter periods. An example of this is the influence of the annual period on shorter weather cycles. All weather changes are most intense in winter, because then the contrasts in temperature between Equator and pole, between ocean and continent, and between adjacent bodies of land and water are at a maximum intensity and the general atmospheric circulation is increased.

Also all periodic changes in the atmosphere are more intense when solar activity increases. The reason for this increased intensity will be clear, first from the fact shown in the early part of this paper that increased contrasts of temperature and pressure in the atmosphere result from increased solar activity, and second from the fact that the amplitude of the solar cycles increases with increased solar activity.

An example of the increased amplitude of solar periods with increased solar activity is shown in figure 22 where the amplitudes of the 7.5-year sun-spot period is distinctly greater during the interval 1865 to 1875, when the general level of solar activity was higher, than during the interval 1885 to 1895, when it was lower. The increase of amplitude during the first of these intervals and decrease during the second was also evident in the sun-spot cycle and in its harmonics of 5.65, 3.75, 2.82 years, etc.

An example of increased amplitude of meteorological cycles with increased solar activity is shown in figure 28 where a period of $7\frac{1}{2}$ months in pressure at Chicago shows a marked increase in amplitude at the time of maximum of sun spots in 1917 and a diminished amplitude during the intervals of minima of sun spots in 1913 and 1923-1924. The data for this curve are the means of 10 overlapping periods of $7\frac{1}{2}$ months obtained in the manner indicated in table 6. The dotted curves are sine values computed for each individual period.

That meteorological cycles change in phase as well as in intensity is also evident. These changes of phase appear to arise from several different causes. First, the solar periods themselves change phase. In most cases this change occurs suddenly and appears to be about 180°

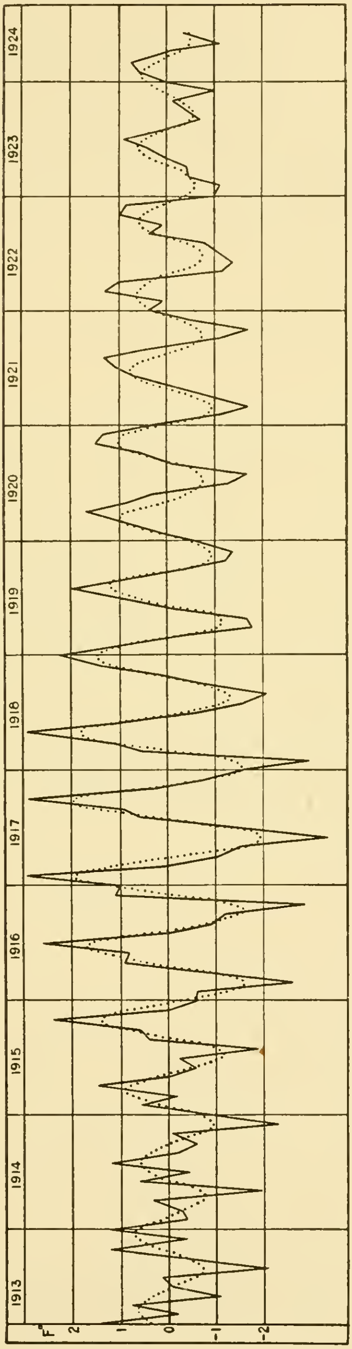

Fig. 28.—7½-months period in temperature in Chicago (showing increase of amplitude near sun-spot maximum).

or a complete reversal in phase. Figure 29 shows what appears to be a reversal in phase in the sun-spot cycle. The average length of this cycle is about 11 years, so that two cycles occur in 22.5 years. If the cycles are plotted in 22-year periods as in figure 29 it is seen that in the period 1770 to 1792 the cycle is nearly inverted in phase to the cycles occurring 22 years earlier and 22 years later. It is, however, quite possible that this result is due either to interference of periods of different lengths, or to lack of accuracy in the early observations. No such apparent inversion has occurred since 1800.

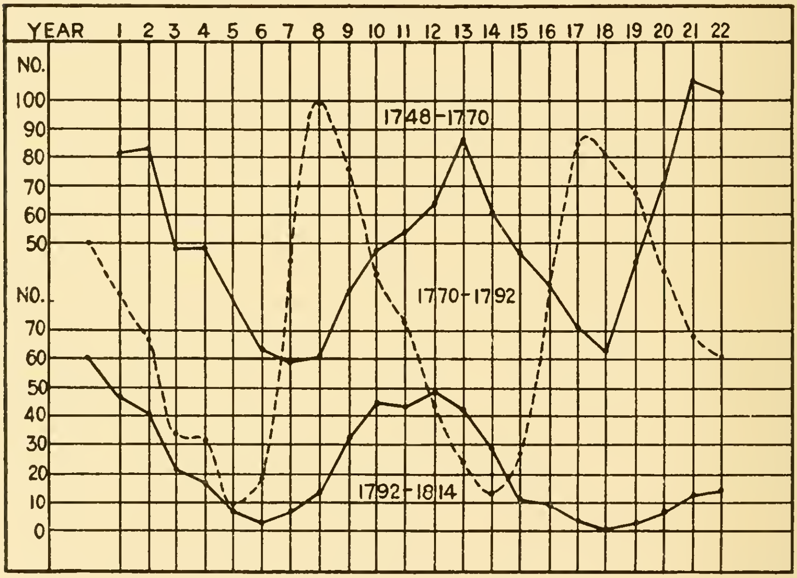

FIG. 29.—11-year sun-spot cycle, showing apparent inversion of phase.

In figure 30 is given what appears to be a reversal of phase in the $7\frac{1}{2}$-year period. This cycle was in one phase from 1848 to 1870, as shown by the broken curve in figure 30, but appears to have been in an opposite phase from 1825 to 1847, as will be seen by the continuous curve in figure 30. This type of change is found in every solar and meteorological period. Brooks and Clough seem to think that shiftings of phase are gradual; but my own researches lead me to the opinion of Professor H. H. Turner that the changes are sudden and of the nature of discontinuities.

The change of phase in meteorological cycles is not brought about entirely by changes in phase of solar cycles; but is in part, at least, due to shifting of centers of action in the atmosphere. In the case of pressure, when it rises in one part of the world, there is an equivalent fall in other parts. These centers of rise and fall are not fixed in position, but shift their position to some extent as illustrated in the case of a 25-month period in a preceding paper of this series.[1]

The variations in intensity and phase of solar and meteorological cycles makes the investigations of the separate cycles difficult. The use of the Fourier series and of the Schuster periodogram are not well adapted to such work. In order to meet these difficulties I devised the correlation periodogram[2] which is to a considerable extent independent of variations in intensity of the periods; but does not overcome the difficulty of shifting of phase. The best method appears to be to use trial periods of successively greater and greater length and harmonic analysis for each individual oscillation[3]; then to combine the results for each period into groups of 3, 5, 10 or more. By this method the curve in figure 28 was obtained. This method of research, using groups of 10, has made it possible to analyze and to follow the changes of a great number of meteorological periods and to recombine them by synthesis for a trial in practical forecasting. Such analyses of more than 100 cycles have convinced me that these cycles follow solar cycles of the same length and that they are, mostly at least, harmonics of long solar cycles.

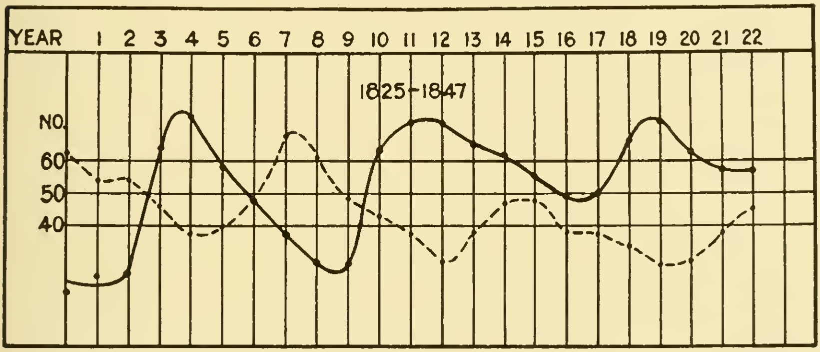

FIG. 30.—$7\frac{1}{2}$-year sun-spot cycle. Means of 3 cycles, showing apparent inversion.

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[1] Smithsonian Misc. Coll., Vol. 78, No. 4, p. 48, 1926.

[2] Smithsonian Misc. Coll., Vol. 71, No. 3, p. 15, 1920.

[3] Clayton, H. H., World Weather, p. 376, New York, Macmillan & Co., 1923.

VII. THE USE OF WEATHER CYCLES IN FORECASTING

Having developed methods of separating and studying various conditions which make up the weather, it seemed important that a test be made of the possibility of using them in practical forecasting. Forecasting future weather conditions in the present state of knowledge may be undertaken in at least three different ways: (1) By tracing out the results which follow the increase or decrease in the general circulation of the air with changes in solar activity. (2) By analyzing and following weather waves of different classes. (3) By computing the amplitudes and phases of different cycles found in solar and weather changes and projecting these forward into the future.

In regard to the use of the first method, since increased solar activity is attended by a fall of pressure in equatorial regions and by increased contrasts of pressure in higher latitudes, there is brought about an increased atmospheric circulation and certain general conditions follow:

(1) The cloudy and clear belts of the world are intensified and thus alter the incoming and outgoing radiation.

(2) The increased air circulation means an increased flow of ocean waters which brings an increased northward flow of warm water along the east coast of the United States and Japan and an accumulation of warmer water in the North Atlantic and North Pacific. The accumulation of warmer waters in these regions especially in autumn brings increased cloudiness and increased rainfall. The increased cloudiness reacts by diminishing radiation losses from the earth and thus further modifying weather conditions. On the other hand the increased oceanic circulation brings increased cold water to the shores of North Africa and southern California, and produces a chain of atmospheric conditions which affect the northern shores of South America and the West Indies and extend well out into the Pacific. A parallel set of changes is produced in the Southern Hemisphere in an opposite way on the east and west sides of the continents. When solar activity diminishes the reverse conditions prevail.

(3) Increased solar activity brings also an increased flow of air over the continents and with it an increased rainfall in certain regions and a decreased rainfall in other regions. The distribution of pressure and attendant conditions is to a large degree influenced by the seasons.

Hence, to follow the sequences of weather resulting from increased solar activity it is necessary to consider the month or seasons separately and to work out expected conditions for different intensities of solar activity.

In regard to the use of the second method, forecasting weather as ordinarily practiced at the present time depends on anticipating for a day or two at a time the drift of weather conditions. Such forecasts can be improved and extended in time by analyzing weather into waves of different lengths and forecasting the progress of the stronger waves. Even long range forecasts can be made on this basis, as I have demonstrated by actual tests.

The third method of forecasting is by means of the periodic vibrations in the sun and atmosphere. Any pulsation in solar condition will be attended by similar pulsations in the earth's atmosphere. The shorter pulsations will be felt relatively more in high latitudes of the earth and the longer pulsations relatively more at low latitudes, but all will be repeated to some extent in every part of the atmosphere. An analysis of the periodic terms in the weather at any point on the earth would make it possible to project the periodic terms ahead to any length of time desired, were there no variations in the amplitude and phase of the periods. But there are variations and for this reason it is necessary to redetermine the periodic terms at short intervals and to limit the time in advance which they are made to cover. When these variations in the periodic terms become calculable, this method of forecasting will probably replace all others. Already considerable progress has been made along this line.

In practical forecasting at present it is desirable to consider all of the three methods mentioned and to use them as checks on each other. Forecasting in words has but little meaning to the average expert, because the meanings of words can be interpreted in various senses and there are no accepted rules for verifying such cases. Quantitative forecasts can, however, be verified by accepted standards; so that from the beginning of my experiments in forecasting, both verbal and quantitative forecasts were made. These quantitative forecasts were made first for about a week in advance, then for longer intervals up to a month. Figure 31 gives one of the more recent of these forecasts of pressure made on November 24, 1929, for 27 days in advance beginning on November 26 and ending on December 21. The forecast was made up from a combination of cycles varying in length from 3 days to 13 days. The correlation of the forecasted with the observed pressure is 0.64 ± 0.06.

By computing pressure in this way for a network of stations, weather maps bearing unmistakable resemblance to observed weather maps may be computed in advance. In March, 1929, values of pressure were computed for one week in advance for 23 selected stations forming a net over the United States and from these computed values lines of equal pressure departures were drawn. The maps thus forecasted are compared with the observed pressure distribution in figure 32. The close resemblance of the two sets of maps is apparent. This degree of accuracy can be obtained, however, only when the meteorological cycles are comparatively steady. It is nevertheless the goal toward which research is leading and to which it will undoubtedly attain.

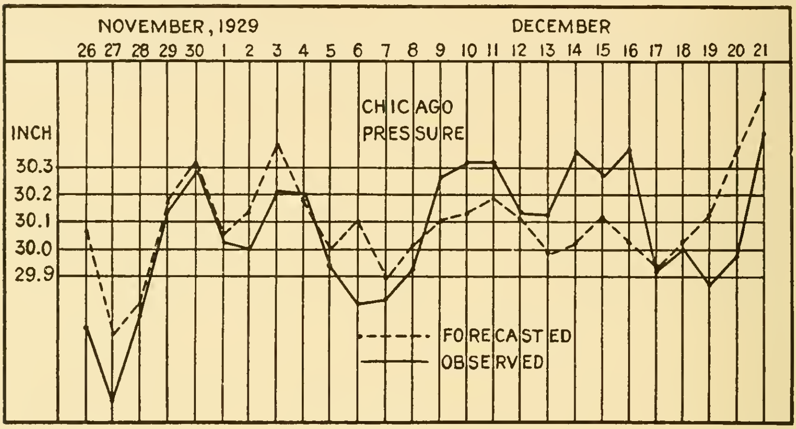

Fig. 31.—8 a. m. pressure.

In April, 1929, a diagram was sent to a number of persons, including the Secretary of the Smithsonian Institution, giving a forecast of departures from normal temperature by weeks from April 2 to September 3 for New York City and for two other stations. Figure 33 gives a copy of this plot for New York City. The broken curve shows the forecast and the continuous curve shows the observed departures from normal. The correlation coefficient for the 23 weeks is 0.37 ± 0.12. This correlation taken alone is inconclusive as to the possibility of such forecasts, except in the light of other data indicating its possibility. It is believed that forecasts by months and years are feasible on the same basis and by the same methods, but no prolonged test is yet available.

If the conclusions presented in this paper are verified and accepted by other research workers, as I feel they must be in time, it will

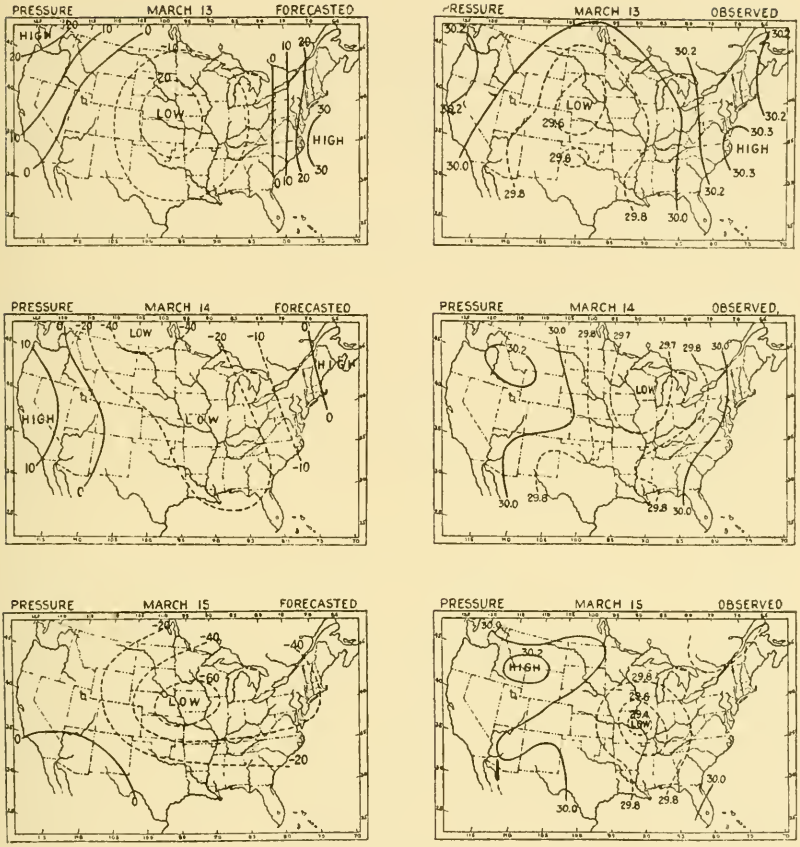

FIG. 32.—Pressure forecasted from a combination of meteorological cycles.

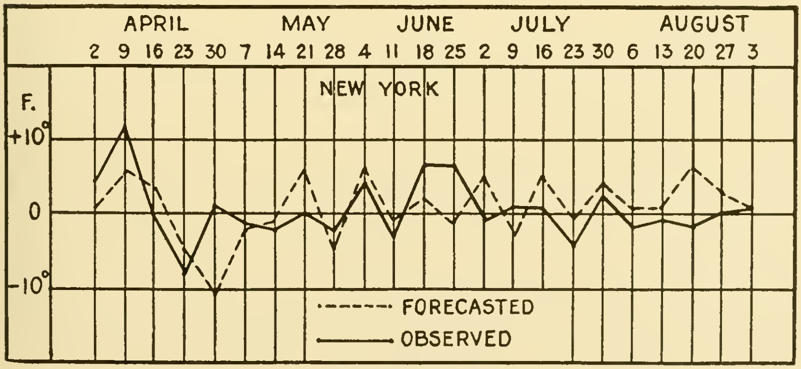

FIG. 33.—Weekly temperatures 1929.

mean a revolution in present methods of weather forecasting. The forecasting of pressure and temperature will be made in much the same way that ocean tides are now predicted, except that the periods used will be solar periods rather than lunar periods and will need to be treated in a special way owing to changes in phase and amplitude.

Such a successful forecast as that shown in figure 31 seems conclusive evidence that day to day weather is not a haphazard occurrence as many persons believe, but is subject to calculation. It is evident that changes of pressure are calculable to some extent now, and the calculations will, no doubt, in the future be made with increasing accuracy for weeks and perhaps months in advance. Processes will be simplified and machinery like the tidal machines will be introduced in order to handle the immense amount of data which will be needed for world-wide forecasts, or even for forecasts over a large area like the United States.

SUMMARY

This paper contains evidence pointing to the following conclusions: Solar activity varies in complicated pulses. These pulses or variations in intensity are attended by variations of pressure in the earth's atmosphere. When solar activity, as indicated by spots and radiation values, increases, the latitude contrasts of pressure in the earth's atmosphere are increased and atmospheric circulation speeded up. The pressure falls in the equatorial belt, rises in middle latitudes and falls in the polar regions. When solar activity decreases the reverse conditions occur. The zonal regularity of these changes is interfered with by the distribution of land and water and by seasonal changes.

Immediately following the decrease of pressure in the polar region with increased solar activity, a wave of decreased pressure moves toward the Equator. With decreased solar activity the pressure in polar latitudes increases and a wave of increased pressure travels towards the Equator. These waves move with a speed proportional to the length of the solar pulse or period causing them. If the period of oscillation is seven days the wave moves from pole to Equator, when measured along a meridian, in seven days. If the length of the oscillation is 27 months, or 2¼ years, the time of the wave movement from pole to Equator is 27 months and if the length of the period is 7½ years the time of movement from pole to Equator is 7½ years, or one period of oscillation in each case.

There are also east to west movements of the waves, and there are probably returning waves toward the poles of less intensity; so that the observed phenomena are extremely complex. The analyzed wave movements are subject however to apparently simple laws, and can, therefore, probably be computed and combined to produce observed conditions.

The observed data of sun-spot numbers and solar radiation values when subjected to harmonic analysis for the 11-year period 1917 to 1928 show that the dominating period of about 11 years in sun spots is no more marked in solar radiation values than the subharmonics of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, etc., of the 11-year period which have amplitudes nearly as large as the 11-year period itself.

When the pressure observations in the Tropics are subjected to harmonic analysis they show periods resembling in amplitude those of solar radiation values and not those of sun spots. The analyses of the data in higher latitudes show that the amplitudes of the subharmonics increase with latitude, so that in high latitudes in the neighborhood of the pole the subharmonics become vastly more important than the primary period.

A study of the possibility of analyzing the data at each particular part of the earth with the view to discovering fixed periodic cycles indicates that if such cycles exist, the amplitudes are subject to wide variations and even to inversion of phase from time to time. However, when the complex cycles are analyzed individually and averages taken for a small number of successive cycles, it is possible to project them into the future and combine and plot them in a curve which at times has a striking resemblance to observed data. As knowledge of methods and laws of change progress, this kind of forecasting will undoubtedly be done with increasing accuracy.