SYNCHRONOUS VARIATIONS IN SOLAR AND TERRESTRIAL PHENOMENA

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I. THE THIRTY-SIX-YEAR CYCLE IN TERRESTRIAL PHENOMENA

Numerous attempts have been made to discover definite periods of recurrence of meteorological phenomena, and many so-called weather cycles have been announced, ranging in length from a few days to a hundred or more years. The cycle discovered by Dr. Brückner is, however, the only one which has gained general acceptance among meteorologists. Brückner in 1890 published an elaborate monograph[1] in which he seemed to demonstrate the existence of a cycle of about 35 years in terrestrial climates, utilizing not only all available meteorological observations from about 1700, but in addition a vast amount of material affording indirect indications of climatic changes, including records of the advance and retreat of glaciers, the time of grape harvest, the opening and closing of navigation by ice, and the occurrence of severe winters, by which he was enabled to trace back the period nearly 1000 years. Briefly, his conclusion is that the whole Earth undergoes climatic variations or oscillations, cold and wet periods alternating with warm and dry periods. The mean dates or epochs of the former are 1700, 1740, 1780, 1815, 1850, and 1880; and of the latter, 1720, 1760, 1795, 1830, and 1860.

A careful examination has been made of Brückner's results, and where the author has given in general terms intervals of time, 10 to 20 years in length, embracing periods during which the values of the meteorological elements were above or below the average, I have attempted to assign in place of these relatively long periods single lustrums or years, representing as nearly as possible the average date or the epoch of each extreme. Comparison of the epochs of the meteorological elements as regards their sequence is thus facilitated. Besides utilizing the data which Brückner published, exten-

[1] *Klimaschwankungen seit 1700*, Vienna, 1890.

sive use has been made of data derived from other sources, and corresponding epochs have been determined in like manner for several additional meteorological phenomena.

Table I contains the meteorological epochs. The series of epochs for barometric pressure from 1740 to 1830, pressure-gradient, variability of temperature, frequency of easterly winds, frequency of West Indian hurricanes, frequency of thunderstorms, and grain prices are my own additions to Brückner's data. The remaining portions of the table are reproduced in all essential respects from Brückner's work, the main difference being, as above stated, that the mean epochs have been more accurately determined.

1. Temperature

Instrumental records of temperature are available from about 1730 in Europe, and from about 1780 in the United States. Brückner regarded this element as the one upon which all other elements depend, either directly or indirectly, and I also find that the epochs of temperature almost invariably precede those of precipitation and pressure. He concluded that the variations in temperature in his 35-year cycle are synchronous over the entire globe, but a careful examination of his lustrum means leads me to the conclusion that a slight retardation of the epochs occurs in southern as compared with northern Europe. This retardation is quite clearly shown by a comparison of the lustrum means of Scandinavia and northwestern Russia with those of southern Europe (p. 227).

The fluctuations are more regular and of greater amplitude in high latitudes, the extreme range of variation, considering the unsmoothed lustrum means, being $1^{\circ}.0$ to $1^{\circ}.5$ C. in northern Europe. In the tropics the fluctuations are somewhat irregular and of small amplitude.

The retardation and decreased amplitude of the oscillations in low latitudes is probably due to the fact that the circulatory activity of the atmosphere decreases toward the tropics, and the waves of high and low pressure, with their attendant temperature variations, which traverse the atmosphere in middle and high latitudes, penetrate into low latitudes slowly and with diminished intensity. These conditions are shown on the daily weather map in winter, the cold waves appearing first in high latitudes and gradually extending southward with a diminution of intensity. By analogy we infer that the long-period atmospheric oscillations appear earliest in high latitudes, and ultimately extend into low latitudes with diminished intensity.

2. Precipitation

European rainfall records extend back to 1688, when observations were begun at Paris. From 1725 they are sufficiently numerous for accurate determination of epochs. In the United States, although isolated and fragmentary records date from 1738, it is not until about 1810 that sufficient records are available, and accordingly historical accounts of great floods in the Mississippi and Ohio Rivers were utilized to determine the epochs in the eighteenth century. The epochs in the table refer to the interior of Europe and the United States, and the variations in these two regions appear to be synchronous. Brückner finds that, unlike temperature, the epochs of precipitation are not synchronous over the whole globe, but that there are oceanic regions where the variations are the reverse of those over the interior of the continents. These regions he characterizes as "temporary" and "permanent" exceptions. Examples of these exceptional regions are found along the Atlantic coast of the United States, the coast of Ireland, and on some of the islands of the Atlantic Ocean. He considers that the oceanic areas experience rainfall variations opposite to those of the continental areas, so that a compensatory relation between continent and ocean seems to exist as regards rainfall. He also shows that the amplitude of the oscillation increases with the continentality of the region, the greatest range being in western Siberia, where 2.3 times as much rain falls in the rainy period as in the dry period.

While Brückner inferred that no progressive retardation in the epochs of rainfall occurs, with change either of longitude or latitude, yet a careful inspection of his rainfall data seems to lead to the conclusion that, as with temperature, the extremes occur earlier in high latitudes, the retardation averaging probably five years at the tropics. In the equatorial regions the epochs of rainfall are probably synchronous with those in high latitudes. This is shown by the fluctuations of the Nile, which synchronize closely with those of rainfall in northern

Europe. Brückner's curves of rainfall variations (pp. 181, 182), showing the changes of the secular oscillations from north to south in the Old and New Worlds, illustrate this fact of retardation in low latitudes.

Comparison of the epochs of temperature and precipitation shows that cold periods are attended by an excess and warm periods by a deficiency of precipitation over the continental areas. A tendency, however, toward a retardation in the epochs of precipitation is clearly evident, the average amount being about six years.

3. Height of Water Surface of Lakes and Rivers

Supplementing and confirming the series of rainfall epochs are those obtained from records of fluctuations of the water surface of inland seas, lakes, and rivers. One series of epochs in the table refers to the oscillations of lakes without outlets in various regions of the globe, the data being largely derived from historical and traditional accounts of high and low water. Another series comprises epochs derived mainly from records of mean stages of European rivers and lakes in river courses. Both series are reproduced without change from Brückner. The general agreement of these epochs with those of rainfall is readily apparent.

4*a*. Barometric Pressure

The records which Brückner employed in his investigation of pressure variations in Europe and surrounding regions were those compiled by Dr. Hann in his work on the pressure distribution in Europe.[1] These records begin in 1826, and the epochs in the table, beginning with 1831–1835, are those determined by Brückner. The epochs prior to 1825 were determined by me from the records compiled by Buys-Ballot,[2] and the entire series of epochs relate to pressure variations in Europe only.

Correlation of pressure and rainfall variations.—Brückner found that the curves of rainfall and pressure for Europe are nearly exact counterparts of each other as regards synchronism of phase and amplitude of variation, excessive rainfall and low pressure being coincident. This relation between pressure and rainfall which he

[1] *Die Vertheilung des Luftdruckes über Mittel-und Süd-Europa,* Vienna, 1887.

[2] *Met. Jahrbuch,* 1870.

found for Europe during the period from 1826 to 1885 is confirmed by the epochs of pressure from 1740 to 1825. He did not investigate pressure variations in America, but it is found that a relation, the reverse of that for Europe, prevails in the northeastern portion of the United States, particularly in winter. In this region relatively high pressure and excessive precipitation prevailed about 1850 and 1882, and low pressure and deficient precipitation prevailed about 1835, 1865, and 1900. This relation was derived from investigation of rainfall variations in the upper Ohio valley and pressure variations at Toronto. A similar relation exists for the region of low pressure about Iceland, as will be shown below. The explanation of this inversion in pressure between Europe and northeastern United States evidently lies in the fact that the belt of maximum storm frequency attains its most southerly position in America, extending over the region of the Great Lakes and the St. Lawrence valley; while in Europe the path of greatest frequency lies far to the northwestward, being traced over the Atlantic midway between Iceland and the Faroe Islands, thence over extreme northern Scandinavia.

In his investigation of pressure and rainfall variations over the whole Earth, Brückner discovered that during the continental wet periods relatively high pressure, or pressure above the normal, prevails over the North Atlantic Ocean in the vicinity of Iceland and the Faroe Islands, also over the equatorial belt of low pressure in the northern part of the Indian Ocean and the China Sea. At the same time the pressure is below the normal throughout the permanent belt of high pressure which extends from the Azores northeastward through central Europe to the interior of Russia and in winter over Siberia. The reverse is true for the dry period. The pressure variations in winter and summer for the wet and dry periods are shown in the following table by Brückner, presenting variations from the normal for the season:

Period	North Atlantic		Western and Central Europe		Eastern Europe and Siberia	
	Winter	Summer	Winter	Summer	Winter	Summer
Wet	Above	Below	Below	Below	Below	Above
Dry	Below	Above	Above	Above	Above	Below

From the foregoing facts Brückner deduced the generalization that wet periods are characterized by a diminution of local and seasonal differences of air-pressure, or a weakening of sea-level gradients. This implies a decrease in the annual pressure-gradient over middle latitudes, a decrease in the seasonal gradient between continent and ocean, and a decrease in the amplitude of the seasonal variation at any given locality. In other words, the gradient between the North Atlantic Low at Iceland and the North Atlantic High at the Azores is less during the wet periods than during the dry periods. The gradient between Iceland and central Europe also varies in like manner. Furthermore, the pressure over the interior of the continents during the wet periods is lower in winter and higher in summer than during the dry periods.

Variation in the activity of the general circulation.—In his discussion of these relations Brückner concluded that the increase in pressure in the polar and equatorial regions, the simultaneous decrease over middle latitudes, and the decrease in the amplitude of the seasonal variation, during cold, wet periods, imply a decreased activity of the general circulation. He attributed the cold periods to a decrease in solar radiation, and accordingly assumed that during such periods the temperature-gradient between equator and pole should be less than during warm periods, resulting in a diminished circulatory activity. Since, however, his table of temperature fluctuations for different latitudes showed that greater amplitudes prevailed in high latitudes, he concluded, in order to account for this discrepancy between theory and fact, that the slight fluctuations in the tropics were caused by discontinuity in the records and to a masking effect of the eleven-year period of Köppen. It will be shown below, however, that a weakened pressure-gradient in middle latitudes, as between Iceland and the Azores, and a decreased amplitude of the seasonal variation—conditions occurring during the cold, wet periods—probably denote greater circulatory activity. *A priori*, a decrease in solar radiation would result in a diminished temperature-gradient between equator and pole, so that a paradox is apparently involved in attributing the cold periods to a decrease in solar radiation.

From a consideration of some phenomena of the general circulation it appears probable that changes in pressure, similar to those which characterize cold periods, result from an increase in circulatory activity. The distribution of air-pressure over the surface of the Earth, considered as a rotating globe, is mainly the resultant of two factors. The first factor is the temperature-gradient between the equator and the poles caused by their varying insolation. The resulting circulation tends to form a belt of relatively low pressure in the equatorial region, a belt of high pressure near latitude 35°, a belt of low pressure near latitude 65°, and a region of relatively high pressure around the poles. This is the pressure distribution resulting from the circulation of the atmosphere over an ideal water surface. The second factor is the distribution of land surface over the Earth which distorts the ideal courses of the isotherms parallel with the equator, resulting in a seasonal temperature-gradient between continent and ocean. The effect of this factor is to modify the ideal distribution by the formation of high-pressure areas during winter over the continents in the northern hemisphere, and of corresponding low-pressure areas during summer. This interaction of land and water, summer and winter, results in large seasonal inequalities of pressure. The seasonal charts of pressure in the northern hemisphere, therefore, show isobars greatly distorted from the ideal courses, parallel with the equator, which largely prevail in high latitudes in the southern hemisphere with their preponderance of water surface, and in the free air above the irregularities of land surface that offer great resistance to pressure readjustments in the lower atmosphere.

If the general atmospheric circulation be accelerated, thereby overcoming to a greater extent the inertia of the lower atmosphere, we should expect, in the first place, the influence of the second factor, which distorts the ideal isobars, to be weakened and the resulting distribution to be more uniform over the Earth, the differences between the pressure on land and water being thereby lessened. This tendency toward more uniform pressure distribution with increased circulatory activity implies a decrease in pressure over the regions of high pressure which prevail in winter over the continents and in summer over the oceans, and a corresponding increase over the regions of low pressure, or a general diminution of the seasonal control which results from the interaction of land and water. A further result of an acceleration of the general circulation is an increased centrifugal force of the great circumpolar whirls, crowding the subtropical belts of high pressure nearer the equator and causing the belt of average storm-tracks to descend to lower latitudes. The pressure over middle latitudes to the southward of the path of average storm tracks will therefore decrease, while that over the polar and equatorial regions will increase. These changes in pressure caused by greater circulatory activity are apparently the same as those found by Brückner to prevail during the wet periods as compared with the dry periods. The conclusion, therefore, is that the cold, wet periods are characterized by an increase in the rapidity of the atmospheric circulation, attended by greater decrease in the temperature of the polar as compared with the equatorial regions, and consequently an increase in the temperature-gradient between pole and equator.

Dr. Hann in a recent paper[1] discussed the abnormal variations in the pressure-gradient between the Azores and Iceland, and concluded that an increase in the gradient is a consequence of an increased intensity of the atmospheric circulation. But it is possible that even with increased gradients at sea-level the gradients in the upper atmosphere may at the same time be diminished, so that the intensity of the general circulation is decreased. In this investigation the instances of abnormal variations during certain months may be misleading, since the mean distribution of pressure over the Earth in any given month may be the result of so many factors that the effect of variations in the intensity of the general circulation is largely masked. It is conceivable that there may be other causes, aside from the thermal gradients between pole and equator, continent and ocean, that bring about pressure variations. Hence only annual or lustrum means in which the effect of other factors is probably eliminated, should be considered. By reducing upward, we obtain the pressure distribution in the upper atmosphere which is immediately related to the general circulation. It may easily be shown

[1] "Die Anomalien der Witterung auf Island in dem Zeitraume 1851 bis 1900 und deren Beziehungen zu den gleichzeitigen Witterungsanomalien in Nordwesteuropa," *Sitzungsberichte der Akad. der Wiss. in Wien.*, Jan. 1904.

that the higher the level to which the reduction is made, the less becomes the influence of variations in the sea-level pressure, so that at great heights the pressure is almost entirely a function of the surface temperatures and the direction of the isobars approximates closely to that of the isotherms at sea-level. For example, at 30,000 feet a variation of 0.01 inch in the sea-level pressure becomes a variation of 0.003 inch, while a variation of 1° F. becomes a variation of 0.04 inch, showing that variations in the sea-level pressure become almost negligible at this elevation. During the cold periods, therefore, the diminished pressure-gradient at sea-level will have but slight effect on the pressure-gradient at high levels, while the increased temperature-gradient will be reflected in an increased pressure-gradient; consequently an increase in the intensity of the general circulation will result.

4*b*. Pressure-Gradient

A series of epochs which confirm the relation above stated is afforded by the variations in the annual pressure-gradient over the region from the high-pressure belt of central and western Europe northwestward to Iceland. They are: maximum gradient in 1790, 1831–35, 1860, and 1895; minimum gradient in 1815, 1840, and 1875. During cold periods, therefore, a decrease in the pressure-gradient occurs over western Europe. This is true also for the gradient between the Azores and Iceland.

5. Frequency of Easterly Winds

Since the direction of the pressure-gradient over western Europe implies a prevailing southwesterly surface current, a weakening of the average gradient would seem to indicate an increase in the frequency of easterly to northerly winds; and observations show this to be the case. Numerous records of wind-direction frequency have been examined, and at stations north of the permanent high-pressure belt a variation in the frequency of easterly winds was disclosed, corresponding with the variations of pressure-gradient, such that a decrease in the gradient and an increase in the frequency of easterly winds coincide. This relation is found to exist also in the United States, and is probably universally true over the northern hemisphere where the gradient involves a maximum frequency of westerly winds.

Tracks of storm-centers.—Since the main track of low-pressure areas over the North Atlantic is from mid-ocean northeastward, skirting the coast of Norway, the prevailing winds over Europe, north of the ridge of high pressure, are westerly to southerly. Hence an increase in the frequency of easterly winds at any point would imply that more storm-centers pass to the southward of the locality. In other words, the average latitude of storm-tracks is lower than usual. A diminished pressure-gradient likewise implies a lower average latitude of storm-tracks. The conclusion therefore is that in cold periods the storm-tracks lie farther south than in warm periods. This shifting to the southward of the belt of average storm-tracks was shown above to be a probable result of the increased circulatory activity which was assumed to characterize cold periods.

Additional confirmation of this relation results from a count of storms passing north and south of Chicago during the period 1873–1900, disclosing a maximum ratio of southern to northern storms about 1878, the center of a cold period, and a minimum ratio about 1895, the center of a warm period. The number of storms passing north and south for each year, with the ratio of southern to northern storms, is shown in the following table:

Year	N.	S.	Ratio S.:N.	Date	N.	S.	Ratio S.:N.
1873.......	80	40	0.50	1887......	68	34	0.50
1874.......	73	38	0.52	1888......	61	32	0.52
1875.......	66	44	0.67	1889......	74	31	0.42
1876.......	70	35	0.50	1890......	80	36	0.45
1877.......	68	40	0.59	1891......	72	35	0.49
1878.......	55	43	0.78	1892......	81	25	0.31
1879.......	70	38	0.54	1893......	76	33	0.43
1880.......	85	32	0.38	1894......	77	26	0.34
1881.......	53	31	0.58	1895......	73	30	0.41
1882.......	64	26	0.41	1896......	75	27	0.36
1883.......	62	38	0.61	1897......	62	28	0.46
1884.......	67	35	0.52	1898......	71	26	0.37
1885.......	56	32	0.57	1899......	72	25	0.35
1886.......	65	42	0.65	1900.....	81	36	0.44

6. Variability of Temperature

An important deduction has been drawn from a study of the variability of mean daily temperature, or the average change in mean temperature from one day to the next, considered without regard to sign. The variations of the annual means of this quantity from year to year at any place are due to varying meteorological conditions, such as amount of cloudiness, distance from storm-centers passing north or south, intensity of storm-development, velocity of storm-movement, etc. It is found, however, that the latter element chiefly influences the variability, so that at stations situated within or near the belt of average storm-tracks, girdling the Earth north of the forty-fifth parallel, the changes in this element are an index to the varying velocity of movement of storm-centers. This relation is based upon a study of the variations in the two phenomena in the United States. Yearly values of this element are available for several Russian stations,[1] enabling the variations to be traced from about 1750, and show a tendency to fluctuate with mean epochs as given in the table. The close synchronism of these epochs with those of temperature is readily apparent.

The inference drawn from this series of epochs is that cold periods are characterized by increased variability of temperature, which probably implies an increase in the velocity of storm-movement, and consequently an increase in the circulatory activity of the atmosphere during these periods.

Velocity of storm-movement.—Further confirmation of this deduction has resulted from an investigation of the average velocity of movement of storms in the United States. The average velocity for each year from 1872 to 1901 has been computed from the monthly means given in the *Monthly Weather Review*, and the resulting values, when smoothed, show a decrease from a maximum about 1882 to a minimum about 1895. The average yearly velocities are shown in the following table:

1872...	26.2	1878...	22.4	1884...	32.7	1890...	30.8	1896...	26.7
1873...	25.2	1879...	31.7	1885...	28.7	1891...	27.1	1897...	25.8
1874...	26.8	1880...	30.5	1886...	27.7	1892...	29.6	1898...	26.0
1875...	28.2	1881...	33.6	1887...	28.6	1893...	29.8	1899...	27.1
1876...	27.2	1882...	28.8	1888...	30.0	1894...	24.2	1900...	29.5
1877...	25.7	1883...	32.2	1889...	28.2	1895...	26.1	1901...	27.8

Thus the conclusion derived from a consideration of the general atmospheric circulation, that an increase in activity occurs during the cold periods, is confirmed by two independent investigations.

[1] Wahlen, *Tägliche Variation der Temperatur an 18 Stationen des Russischen Reiches.* St. Petersburg, 1886.

7. Frequency of West Indian Hurricanes

The frequency of tropical hurricanes has been shown by Poëy and Meldrum to vary in a period approximately 11 years, or that of the solar spots, and it appears to be fairly well established that they reach a maximum frequency shortly after the sun-spot maximum. An examination of Poëy's table of West Indian hurricanes from 1750 to 1873[1] discloses in addition a long-period variation with well-defined maxima in 1786, 1817, and 1838, and minima in 1762, 1798, 1823, and 1864. The remaining epochs in this series were derived from his catalogue of hurricanes from 1493 to 1855, and from the records of the Weather Bureau, beginning with 1873. The epochs of maximum frequency coincide with the wet periods of the Brückner cycle, particularly with the corresponding epochs of precipitation in the United States.

The conditions favorable to the development of tropical hurricanes are thus probably connected with the general circulation, and cannot be regarded as of purely local origin. Years in which the movement of storms of middle latitudes is most rapid and their paths extend far southward, indicating an increased activity of the general circulation, are signalized by frequent hurricanes in low latitudes. Furthermore, observation of the daily weather map shows that the development of West Indian hurricanes is usually coincident with an increase in the velocity of movement of high- and low-pressure areas in the United States.

8. Frequency of Thunderstorms

Von Bezold,[2] in his investigation of thunderstorm frequency, arrived at the conclusion that periods of maximum thunderstorm frequency are conditioned upon high temperature as well as a solar surface free from spots. His table of relative numbers for Europe yields epochs approximately as follows: maxima in 1768, 1797, 1822, and 1852; minima in 1783, 1814, and 1837. Comparison of these epochs with those of temperature in Europe shows that thunderstorms are least frequent during cold periods, thus confirming v. Bezold's conclusion in regard to temperature conditions.

[1] *Comptes Rendus*, **77**, 1223, 1873.

[2] "Ueber gesetzmässige Schwankungen in der Häufigkeit der Gewitter," *Sitzungsberichte der math.-phys. Klasse der B. Akad.*, **4**, 1874.

9. Frequency of Severe Winters

Pilgram's catalogue of severe winters was used by Brückner to extend his cycle back nearly 1000 years, and confirmatory evidence is at hand to prove the validity of the method he employed. For every fifth year, as 800, 805, 810, etc., he gives a number which represents the total number of severe winters recorded in the 20-year period of which it is the center. The epochs in the table were derived by me from Brückner's table (p. 268), and are intended to represent as nearly as possible the centers of periods of maximum and minimum frequency of severe winters. They approximately coincide with the general epochs of low and high temperature. These variations in temperature are shown graphically on Chart 2, the epochs being plotted with a uniform amplitude of variation.

This series of epochs is the result of careful consideration of all data available and comparison with the mean epochs derived from other climatic records; it departs from Brückner's table of warm and cold periods from 1020 to 1890, and omits in the sixteenth century one oscillation which should be regarded as secondary. The third and fourth columns give the intervals, derived from the epochs of maximum and minimum frequency of severe winters, embracing each three successive periods. Thus in column 3, the first number, 120, is the interval between the two epochs 1000 and 1120. The longest three-period interval in the series is 125, and the shortest is 90. If there is an additional oscillation in the sixteenth century, the three-period intervals in that century would be reduced to 75 years, which is highly improbable, since the latter interval is the length of two average periods, and there is no other three-period interval less than 90 years in the entire series.

The average length of this cycle was computed by Brückner from his table of cold and warm periods derived from his table of the frequency of severe winters. He writes (p. 270): "The table embraces the years 1020 to 1890. Within this period of time of 870 years we enumerate twenty-five cold periods and twenty-five warm periods, hence twenty-five complete oscillations. We find therefore the average length of one oscillation to be 34.8 years." But, as shown above, the number of complete oscillations should be reduced by one, making the length of the cycle 36.25 years.

10. Duration of the Season of Navigation

The dates of the opening and closing of navigation on rivers, lakes, and harbors in Russia have been recorded for 150 years at many localities and in the vicinity of St. Petersburg from the middle of the sixteenth century. Brückner derived his data from Rykatschef's memoir on ice conditions in Russian waters.[1] The epochs of this series were derived from Brückner's tables and are well defined, affording a most valuable indirect method of exhibiting climatic variations. They average about 6 years later than those of severe winters.

11. Time of Grape Harvest

The time of beginning of the grape harvest in France and southern Germany has been recorded in some localities for many hundred years, and these records were utilized by Brückner to determine secular climatic variations. In this series of epochs, as with that of the frequency of severe winters, a rearrangement of dates in the sixteenth century was necessary in order to eliminate one oscillation in Brückner's table. The epochs synchronize well with those of the severity of winters, occurring on the average five years later. Late harvests, therefore, characterize periods of excessive precipitation.

12. Grain Prices

In his discussion of climatic oscillations, Brückner did not refer to fluctuations in grain prices as an index to these changes, but in a later paper[2] he compares prices and climatic variations in Europe during the past 200 years, and finds a relation such that high prices occur during or shortly after periods of maximum rainfall.

In order to confirm this relation and extend the comparison as far back as possible, Rogers' *History of Prices and Agriculture in England* was consulted. These volumes contain an exceedingly valuable collection of prices of grain and commodities, beginning with 1265. Rogers incidentally mentioned the possibility of a seasonal cycle being discovered in the fluctuations of grain prices. He writes:[3]

[1] *Ueber den Auf- und Zugang der Gewässer des Russischen Reiches.* St. Petersburg, 1887.

[2] "Der Einfluss der Klimaschwankungen auf der Ernteerträge und Getreidepreise in Europa," *Geographische Zeitschrift*, 1895.

[3] Vol. I, Pref., p. xi.

"Lastly, as there were no regular means for supplying deficiencies in the produce of the home market by foreign importation, the prices of necessaries such as corn give no small insight into the course of the seasons, if, as I do not dare to assert, such a cycle can yet be found."

Examination of Rogers' statistics of grain prices discloses fluctuations in the prices of wheat, rye, barley, etc., corresponding with those of temperature, periods of high prices occurring shortly after periods of low temperature, with an average retardation of about seven years. Thus the series of epochs of grain prices serve to confirm the epochs of severe winters. This is especially the case in the earlier centuries. In the last two centuries disturbing influences have contributed to mask the fluctuations, and accordingly from about 1700 onward, grain prices in continental countries were also used in determining the epochs.

These epochs synchronize very well with the epochs of the time of grape harvest, and the conclusion is that the same stress of weather which tended to retard the maturity of the vine in France caused deficient grain harvests in England.

II. THE THIRTY-SIX-YEAR CYCLE IN SOLAR PHENOMENA

Brückner discussed at considerable length the origin of the secular climatic variations which he discovered, and concluded that it must be referred to a cosmical source. He examined the sun-spot relative-numbers of Wolf, but found no evidence of his 35-year cycle in their variations. Nevertheless, he stated it as his conviction that such a variation must exist in solar phenomena, and that the climatic oscillations on the Earth point to a solar cycle, to be discovered later. He thought it probable that the cycle would be shown in the variations in the intensity of solar radiation.

Dr. W. J. S. Lockyer[1] pointed out that a cycle of about 35 years exists in the variations of the interval from one sun-spot minimum to the succeeding maximum. He writes: "There is some law at work which introduces a secular variation by retarding the sun-spot maxima in relation to the preceding minima." He considers this as the source of the Brückner cycle.

[1] "The Solar Activity, 1833–1900," *Proc. R. S.*, **68**, 285, 1901.

Professor A. Wolfer,[1] on the other hand, discusses Dr. Lockyer's results, and concludes from examination of the relative-numbers and epochs from 1750 that no regular periodicity exists, and that "the continued existence of a 35-year cycle is not yet demonstrated." It will be shown, however, in this paper that a 36-year cycle in the variations of solar phenomena undoubtedly exists, and also that a much longer cycle exists, underlying the 11 and 36-year cycles.

Variations in the length of the eleven-year cycle.—In Table II, "Sun-Spot Epochs" (Wolfer), the epochs of sun-spot maxima and minima, determined by Wolf and revised by Wolfer, are shown in the first two columns. The third and fourth columns contain the successive intervals, maximum to maximum and minimum to minimum. It is well known that the so-called 11-year cycle is only an average of these varying intervals. Uniting these intervals into one column, and smoothing them by the formula $\frac{1}{3}(a+b+c)$, we have a series of numbers, column 5, which vary more or less regularly. These numbers are plotted to form the first curve in Chart 1. By inspection of the data in this and in the preceding columns, the dates in columns 6 and 7 are obtained. These epochs represent the centers of periods of maximum and minimum intensity of the processes which result in the 11-year cycle of solar activity, a rapid completion of this cycle indicating a maximum intensity of solar activity, as will be shown below. The mean length of this cycle of variation in the length of the 11-year period, based on the epochs from 1615 to 1880, is 35.7 years. This cycle of solar activity is thus derived from nearly 300 years' observations of sun-spots, since the invention of the telescope, during which period the successive 11-year epochs of maxima and minima can be relied upon as approximately correct.

Fritz[2] has compiled a list of all recorded observations of sun-spots previous to 1610, when their regular observation by the telescope began. Nearly all of these observations are derived from ancient

[1] "Revision of Wolf's Sun-Spot Relative-Numbers," *Monthly Weather Review*, **30**, 171, 1902.

[2] "Die Perioden solarer und terrestrischer Erscheinungen," *Vierteljahrsschrift der Naturforschenden Gesellschaft*, Zürich, 1893.

Chinese annals, beginning about 300 A. D.; a few records are from European sources. From this list Fritz deduced approximate epochs of sun-spot maxima, where sufficient observations were available, and showed that a period averaging about eleven years has existed during the entire interval. In the same paper he gives a list of years during which auroras have been recorded, with the number of displays observed each year, and derives therefrom a series of probable epochs of auroral maxima. From these two independently determined series, supplemented by early records of great hailfalls, he deduces a series of probable sun-spot maxima from 301 A. D. to 1616, there being only twenty-seven epochs missing for which no adequate data exist. From 1057 to 1616 there are only six epochs missing from his list, which is reproduced in column 1 of Table III —"Epochs of Sun-Spot Maxima" (Fritz). The required epochs have been supplied and are designated by an asterisk. One change was made in the epochs, namely that of 1603, which is obviously too early, and in the table 1605 was substituted. The second column of the table contains the intervals between these epochs of maxima. From the data in these two columns the epochs in columns 3 and 4 were derived, being a continuation backward of the epochs in columns 6 and 7 in Table II. They are less exact, however, having been derived from epochs of maxima only, which are subject to considerable uncertainty. Nevertheless, the mean interval between these epochs during the period 1050 to 1600 is 36.6 years, which is very nearly identical with that obtained from the table of Wolfer's epochs, thus confirming in a remarkable manner the general accuracy of these "probable maxima" of Fritz.

The epochs of maxima and minima of the 36-year solar cycle from 1000 to 1900 are shown graphically on Chart 2.

The missing epochs of Fritz's list of "probable maxima" from 301 A. D. to 1057 have been approximately determined, and probable epochs of the 36-year cycle derived. Table III contains the 36-year epochs from 295 to 1100. The average length of the 11-year cycle from 301 to 1104 is 11.00 years, while from 1104 to 1894 it is 11.13 years. The mean length, therefore, during 144 periods from 301 to 1894 is 11.063 years. The average length of the 36-year cycle from 300 to 1900 is 36.5 years, the mean from 300 to 1100 being practically the same as from 1100 to 1900.

The sun may therefore be regarded as a variable star, whose mean period of variation undergoes a cyclical variation in length. Chandler has shown that this phenomenon is characteristic of many variable stars.

Lockyer's conclusion that a 35-year period exists which alters the time of occurrence of the maxima in relation to the preceding minima, is evidently only partially true, since the interval maximum to minimum likewise undergoes a similar variation. The solar-spot activity is periodically accelerated and retarded, and this action is primarily manifest in the varying length of the 11-year spot cycle, since it operates continuously throughout the entire interval to accelerate or retard the occurrence of the two phases.

Variations of the relative-numbers.—In Table II, column 8, are given the relative-numbers at the time of each maximum, beginning with 1685. Prior to 1750 the average relative-number for the year in which the phase occurred is

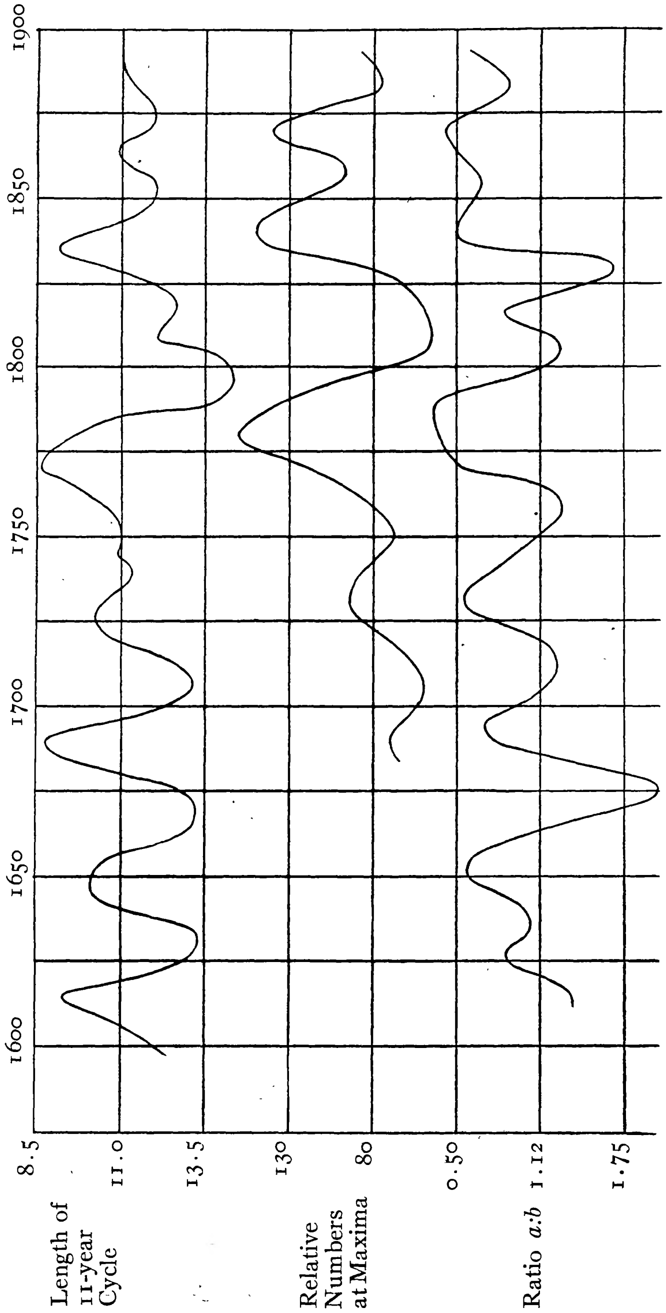

CHART 1.—The 36-Year Solar Cycle.

given; subsequently, the highest value contained in Wolfer's table of smoothed numbers is placed opposite the corresponding epoch. Comparing the variations in these numbers with the variations of the 11-year period, shown in column 5, the conclusion is evident that periods of rapid development of the cycle of changes averaging 11 years are also those of increased intensity of solar activity, as evidenced by the increased frequency of spots. That is to say, when the period is shorter the sun-spot number is larger. The second curve on Chart 1 displays graphically these variations in the relative-numbers.

Wolf[1] showed that the shortest periods brought the most acute crises. This relation for the 11-year period, first stated by Wolf, was confirmed by Dr. Halm,[2] who also found that "in the individual spot-periods the maximum occurs earlier in proportion as the development of the spots is more rapid." This inverse relation between the intensity at a maximum and the interval from the preceding minimum follows as a deduction from the general law, which may be expressed as follows: The solar spottedness varies inversely with the length of the cycle of activity. It will be shown below that this law applies to the 36-year cycle as well as to the 11-year cycle.

One oscillation in the series of relative-numbers at maxima, column 8, is absent, although existing in the variations of the 11-year interval, thus resulting in a 59-year interval from the maximum of 1778 to that of 1837. The abnormally low numbers for the maxima of 1805 and 1816 correspond with the unusually long sun-spot periods between 1788 and 1830.

The average relative-number for each 11-year period, minimum to minimum, is shown in column 9, opposite the corresponding maximum epoch. These numbers are from the paper by Fritz quoted above. The variations of this series are synchronous with those of the maximum relative-numbers in the preceding column.

Comparing the variations in the length of the 11-year cycle with those of the relative-numbers, a retardation of the epochs of the latter is evident, averaging 5 years.

Variations of the ratio a:b.—In columns 10 and 11 of Table II are given the intervals of the 11-year cycle, minimum to maximum and maximum to minimum. Representing the former by *a* and the latter by *b*, the successive ratios *a:b* were computed and are shown

[1] Wolf, *Astronomische Mittheilungen*, No. 12, 1861. [2] *A. N.*, **156**, 33, 1901.

in column 12, opposite the corresponding maximum epochs. Chart 1 exhibits in graphical form the variations of these ratios. Inspection of this series of ratios discloses variations parallel with the 36-year variation in the length of the 11-year period; the ratio varies directly with the length of the period. The epochs of these variations of the ratio occur about 7 years later than the corresponding epochs of the variations of the length of the period.

Comparison of the variations of the relative-numbers with the variations of the ratios *a:b* shows that the two series of numbers vary inversely, with epochs of variation nearly coincident.

Column 13 of the table contains the ratios *a:b*, smoothed by taking the mean of each five successive values. These smoothed ratios disclose a long-period variation, with a maximum about 1685, and a minimum about 1865. In other words, the sun-spot curve flattens out about 1685, so that the intervals *a* and *b* approach equality, or *a* is even greater than *b*.

Referring to the series of epochs of the 36-year cycle, columns 6 and 7, it is apparent that the intervals between the epochs are not uniform in length, being relatively long about 1700 and short about 1850. Thus the long-period variation in the ratio *a:b* corresponds with a similar long-period variation in the length of the 36-year interval, the ratio varying directly with the length of the period. Hence the ratio *a:b* varies directly with the length both of the 11- and the 36-year cycles.

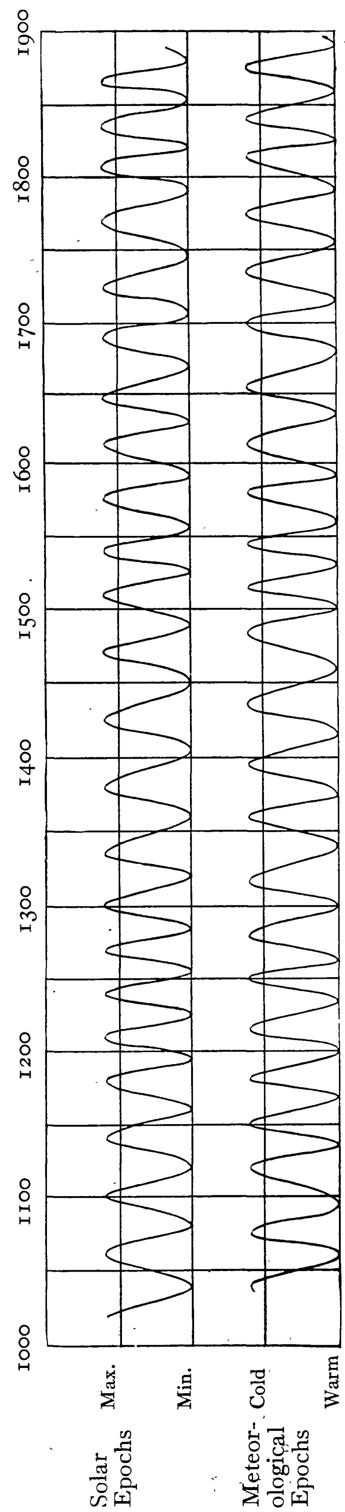

CHART 2.—Epochs of the Thirty-six-Year Cycle.

The long-period variations in the ratio $a:b$ are generally synchronous with the secular variations of spottedness, columns 8 and 9, varying inversely with the latter, in conformity with a similar relation shown above to exist in connection with the 36-year cycle.

Reliability of Wolfer's epochs.—The accuracy of the sun-spot epochs in the seventeenth and eighteenth centuries, particularly those from 1788 to 1805, has been questioned by some investigators. It has been assumed that a uniform period exists, and that the irregularities which are shown by Wolfer's epochs arise from imperfections of the records. But the records of magnetic declination which are available from about 1780 show that variations in the range exist with epochs practically coinciding with Wolfer's epochs. The epochs of auroral frequency from 1700 also confirm the sun-spot epochs. Furthermore, the evidence for the 36-year cycle, cited above, proves that variations in the length of the 11-year period really exist and are of a periodic nature. The normal period is eleven years, subject to alternate acceleration and retardation during a cycle averaging 36 years. The synchronism between the variations of the ratio $a:b$ and the variations of the 11-year interval furnishes additional evidence of the substantial accuracy of the epochs of Wolfer.

Epochs of magnetic declination range.—These epochs, given in Table IV, columns 1 and 2, were derived from the table of smoothed means of declination range in a paper by Fritz,[1] with the exception of those subsequent to 1878, which are those determined by Ellis in his discussion of the Greenwich magnetic observations. The epochs of the 36-year cycle, columns 6 and 7, were derived in the same manner as those of the sun-spots in Table II, and the two series of epochs are almost exactly synchronous. The table is particularly instructive as affording indirect confirmation of the accuracy of the sun-spot epochs of Wolfer, especially those in the latter part of the eighteenth century.

The average range at each epoch of maximum and minimum is given in columns 8 and 9.

Epochs of auroral frequency.—The 11-year auroral epochs, given in Table V, columns 1 and 2, are those determined by Fritz,[2] and

[1] *Viertel. d. Natur. Gesell.*, Zürich, 1884.

[2] *Die Beziehungen der Sonnenflecken zu den magnetischen und meteorologischen Erscheinungen der Erde*, Haarlem, 1878.

have been treated similarly to the sun-spot epochs. The resulting 36-year epochs, columns 6 and 7, seem to occur about 5 years later than the corresponding 36-year sun-spot epochs.

The secular epochs of maximum and minimum visibility of the aurora are given in columns 8 and 9 of the table, and apparently occur about 8 years later than the epochs in columns 6 and 7. The variations in the visibility of the aurora are thus shown to lag behind the variations in solar activity in the 36-year period by about 10 or 15 years. This probably indicates a dependence upon terrestrial as well as solar conditions. The belt of maximum frequency of auroras descends to lower latitudes during increasing solar activity in the 11-year and the 36-year cycles. It was shown in the first part of this paper that a similar change of position occurs in the belt of maximum storm-frequency during cold periods, which will be shown to follow closely periods of maximum solar activity. The intimate relation between auroral and meteorological phenomena is thus apparent.

Correlation of solar and terrestrial variations.—As shown above, terrestrial and solar phenomena undergo cyclical variations in recurring intervals of about 36 years, and these variations have been traced back to about 1050 A. D. in each instance. The epochs of maximum and minimum severity of winters, Table I, series 9, which are practically coincident with those of temperature, will be considered as the primary series of meteorological epochs. Comparing these epochs with those of solar activity, Table II, columns 6 and 7, it is readily apparent that the two series synchronize closely, with an average retardation of about 7 years in the meteorological epochs.

When the two series of epochs, previous to 1610, are compared, the synchronism is less exact, as might be expected. It seems remarkable that from the epochs of sun-spot maxima, determined by Fritz, the epochs of the 36-year cycle should be derived in such a regular sequence, considering the source and character of the data he utilized. Although the lag of the meteorological epochs is somewhat greater and more variable than that since 1610, still the correspondence is much closer than one would anticipate. The great number of coincidences shown in the comparison of the two series of epochs from 1050 to 1895 makes the conclusion irresistible that our meteorological variations are conditioned upon variations in solar activity. (Compare Chart 2.)

It was stated above that the epochs of maximum and minimum spottedness in the 36-year cycle show a slight retardation when compared with the epochs with which the meteorological epochs were compared. Hence the latter differ by less than 5 years from the epochs of variation of solar spottedness.

Summarizing, therefore, the foregoing results, we conclude that periods of maximum solar activity, characterized by a minimum length of the 11-year cycle, are followed 7 to 10 years later by terrestrial temperature minima, and 6 years thereafter by rainfall maxima; and that, coincidently with the low temperature, the activity of the general circulation reaches a maximum, and storm-centers move with increased velocity and in lower latitudes.

III. SHORT CYCLES OF SOLAR AND METEOROLOGICAL PHENOMENA

A brief reference will now be made to the shorter cycles of solar activity and the corresponding meteorological variations.

The evidence for the existence of an 11-year variation in meteorological phenomena is very conflicting and inconclusive, but on the whole it points to greater activity of atmospheric circulation, lower temperature, and excessive precipitation shortly after the sun-spot maximum.

A study of the short cycle of solar activity, evidenced by variations in the frequency of solar prominences, yields far more satisfactory results. Sir Norman Lockyer and Dr. W. J. S. Lockyer[1] first announced a period of about $3\frac{1}{2}$ years in the prominence frequency, and traced synchronous variations in pressure and rainfall. Professor F. H. Bigelow[2] previously had shown that a 3-year variation existed in meteorological phenomena in the United States and found similar fluctuations in the terrestrial magnetic field. In a recent paper[3] he showed that the pressure over the Indo-Oceanic and

[1] "On Some Phenomena which Suggest a Short Period of Solar and Meteorological Changes," *Proc. R. S.*, **70**, 500, June, 1902.

[2] "Inversion of Temperatures in the 26.68-Day Solar Magnetic Period," *Am. Jour. Science* (4), **18**, Dec., 1894.

[3] "Synchronism of the Variations of the Solar Prominences with the Terrestrial Barometric Pressures and the Temperatures," *Monthly Weather Review*, **31**, 509, 1903.

Arctic regions varies directly with the prominence frequency, while over the Azores and Hawaii it varies inversely; also that the temperature over Iceland, northern Europe, and the northern United States varies inversely with the prominence frequency

In order to trace synchronous variations in the $3\frac{1}{2}$-year cycle, analogous to those shown above to exist in the 36-year cycle, I have made a careful comparison of the variations in the prominence frequency with those of various meteorological phenomena during the period 1873–1903, and the following conclusions appear to be justified. Coinciding with the maxima of the prominence curve, indicating secondary maxima of solar activity, are:

1. Increased activity of atmospheric circulation, shown by—
   a) Greater velocity of storm movement in longitude.
   b) Lower latitude of storm-tracks.
2. Higher pressure over arctic and tropical regions.
3. Lower pressure over middle latitudes, shown most clearly by the pressure at the Azores and Hawaii.
4. Weaker gradient between the Azores and Iceland.
5. Lower temperature in Iceland, northern Europe, and the northern United States.

These conditions, prevailing at or shortly after the secondary maxima of solar activity in the $3\frac{1}{2}$-year cycle are identical with those shown to exist in connection with the solar maxima of the 36-year cycle, and the two results are mutually confirmatory.

The effect of an increase in solar activity upon the Earth's atmosphere, shown by both short- and long-period variations, is immediate, and results in increased activity of the polar whirls, forcing equatorward masses of cold air, and causing both highs and lows to traverse paths in lower latitudes and with increased velocity.

Speculation as to the manner in which the solar influence is exerted seems unprofitable in the light of our present knowledge of the manifestations of solar energy. Whether variations in solar radiation exist, sufficient to produce such variations in climate, is a problem still undetermined. The paradox involved in attributing the cold periods to diminished solar radiation, apparently precludes variations in the latter as the efficient cause, or at least renders it probable that they are of secondary importance. The fact that our meteorological variations are greater and occur earlier in high latitudes seems to indicate that the polar and not the equatorial regions are mainly influenced by the varying manifestation of solar energy, in which case some action involving variations in the magnetic field of the earth must be taken into consideration.

IV. THE THREE-HUNDRED-YEAR CYCLE

The tendency of the ratio $a:b$ to decrease from about 1685 to 1860 suggests a long-period variation in solar activity, since, as shown above, this ratio varies inversely with the relative-numbers in the 36-year cycle. Furthermore, the length of the 36-year interval is not uniform, but is least about 1850, averaging 30 years, greatest during the early part of the eighteenth century, averaging 40 years, and decreases again in the early part of the seventeenth century.

Regarding variations in solar activity since 1600, the records indicate that a chief minimum occurred in the latter part of the seventeenth century and a maximum about the middle of the nineteenth century. Miss Clerke[1] writes: "Spoerer's researches showed that the law of zones was in abeyance during some 70 years previous to 1716, during which period sun-spots remained persistently scarce, and auroral displays were feeble and infrequent even in high latitudes. An unaccountable suspension of solar activity is, in fact, indicated." Young[2] writes: "From 1672 to 1704 absolutely no spots were recorded in the northern hemisphere."

Thus considering the period 1600 to 1900, a minimum of solar activity prevailed about 1680, associated with a maximum value of the ratio $a:b$ and a maximum length of the 36-year interval; the reverse conditions prevailed about 1860. The maximum of 1778 and the minimum of 1810 appear to be phases of a secondary variation.

For the centuries previous to 1600 we have the catalogue of early observations of sun-spots and auroras, compiled by Fritz, which enable us to trace this secular variation back for nearly 1500 years. The following table gives for each hundred-year interval the number of years when sun-spots and auroras were recorded.

[1] *History of Astronomy,* p. 148.

[2] *The Sun,* p. 149.

Interval, A. D.	Sun-Spots	Auroras
100– 200	1	1
200– 300	1	0
300– 400	24	2
400– 500	3	8
500– 600	8	25
600– 700	1	11
700– 800	1	12
800– 900	10	19
900–1000	1	21
1000–1100	6	13
1100–1200	19	36
1200–1300	7	12
1300–1400	10	18
1400–1500	0	6
1500–1600	7	56

Curves showing this secular variation in the frequency of sun-spots and auroras may be found on Chart 3.

Fritz[1] asserts that the sixth, ninth, twelfth, sixteenth, and nineteenth centuries have been distinguished by great and frequent auroral displays; the above table of frequency of auroras in each century serves to illustrate this statement. The table of sun-spot frequency shows that sun-spots have also been more frequently observed in these centuries. It was shown above that the periods of maximum visibility of the aurora during the last 200 years have been preceded by periods of increased solar activity, and it may therefore be considered as probable that unusual outbursts of solar energy occurred during the centuries above mentioned.

Approximate epochs for these long-period variations of solar activity and auroral frequency are given in Table VI, from which the average length of this cycle is found to be about 300 years.

Since the length of the 36-year cycle has varied parallel with variations of solar activity during the last 300 years, a similar relation would be expected to prevail in the preceding centuries. The series of 36-year epochs in Table III show that variations in the length of this cycle have indeed occurred. The epochs of maxima and minima with the mean length at each epoch are given in Table VI, columns 5 and 6. These epochs correspond very well with the epochs of sun-spot and auroral maxima and minima. The conclusion is that

[1] *Die Beziehungen der Sonnenflecken zu den magnetischen und meteorologischen Erscheinungen der Erde*, p. 41.

variations in solar activity in the 300-year cycle are associated with variations in the length of the 36-year solar cycle, ranging from 30 to 45 years, the period-length decreasing with increasing solar activity. A smoothed curve of these variations in the length of the 36-year solar cycle is shown in Chart 3. Similar variations in the length of the 11-year cycle exist, and the approximate epochs of minimum and maximum length with the average interval at each epoch are shown in Table VI, columns 11 and 12.

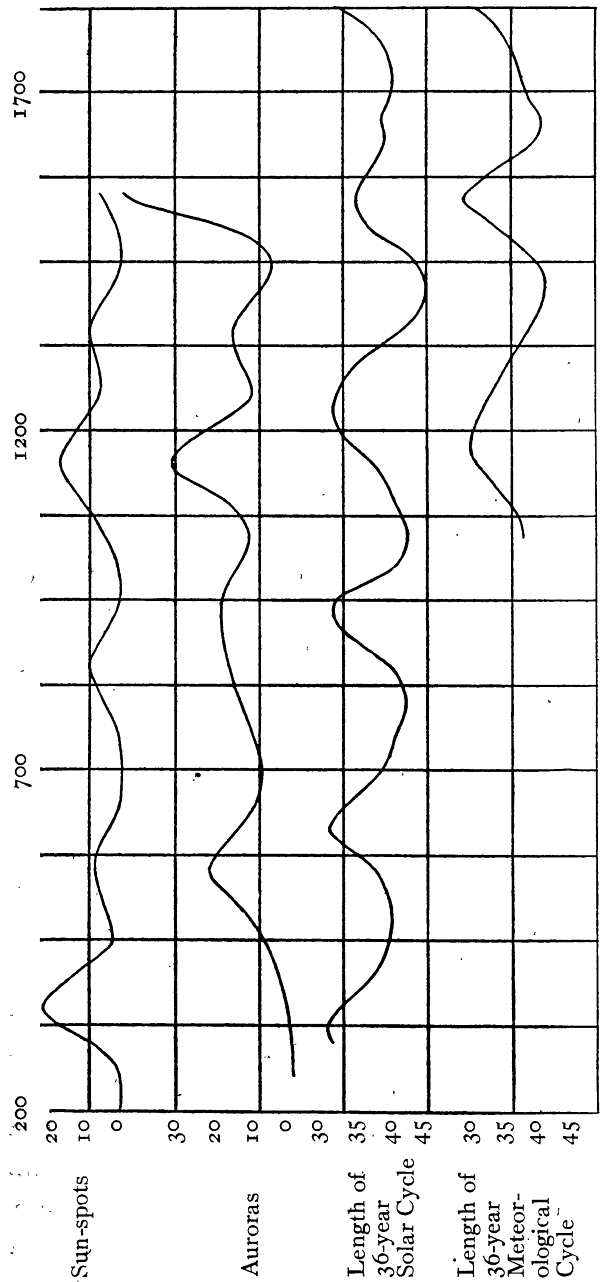

CHART 3.—The 300-Year Cycle.

With regard to meteorological variations in a cycle of 300 years, the best evidence at hand is the nearly continuous record of the time of grape harvest at Dijon, France, since 1400. The average date of beginning of the harvest for each half-century is shown in the following table:

Period	Average Date	Period	Average Date
1400–1450	September 24	1650–1700	September 23
1450–1500	September 28	1700–1750	September 27
1500–1550	September 27	1750–1800	September 30
1550–1600	September 29	1800–1850	October 2
1600–1650	September 26		

There is clear evidence of periods of high temperature about 1425 and 1675, while low temperatures prevailed about 1550 and 1825.

The average date of opening of navigation at Riga has varied as follows:

1530–1623	March 28.2	1751–1802	March 25.3
1626–1750	March 24.4	1803–1852	March 27.5

The variations in temperature shown by this table accord very well with those shown by the average time of grape harvest.

Referring to the series of epochs of the severity of winters, Table I, series 9, an inspection of columns 3 and 4 discloses variations in the length of the 36-year interval, minima occurring about 1200, 1525, and 1850, and maxima about 1050, 1415, and 1675. Chart 3 contains a smoothed curve of these variations. The secular variations in the time of grape harvest at Dijon agree closely with these variations in the length of the 36-year cycle, periods of low temperature corresponding with periods during which the average length of the cycle is 30 to 32 years, while periods of high temperature coincide with an average length of 40 to 42 years.

These epochs of maxima and minima in the length of the 36-year cycle in meteorological phenomena correspond closely with those found above for the 36-year solar cycle, thus furnishing additional evidence of a close connection between the two phenomena.

Chart 2 exhibits graphically this 300-year variation in the length of the 36-year solar and meteorological cycles.

NOTE.—The increased retardation of the meteorological epochs at the minima of the 300-year solar cycle, shown by these curves, is significant as indicating that the relation between the two phenomena is one of cause and effect.

TABLE I

METEOROLOGICAL EPOCHS

1						2				3			
TEMPERATURE						PRECIPITATION				HEIGHT OF WATER-SURFACE			
EUROPE		UNITED STATES		WHOLE EARTH		EUROPE		UNITED STATES		(a) CLOSED LAKES		(b) RIVERS	
Cold	Warm	Cold	Warm	Cold	W'rm	Wet	Dry	Wet	Dry	High	Low	High	Low
1736–40	1750	1784?	1796	1738	1750	1701–05	1726–30	1740	1762?	1600	1656?	1740	1760
1766–70	1786–90	1815	1826	1770	1790	1741–45	1761–65	1775	1795	1638?	1683?	1775	1795
1811–15	1821–25	1837	1860	1813	1825	1771–75	1796–00	1815	1836	1674?	1720	1820	1831–35
1836–40	1860	1880	1892	1838	1860	1811–15	1831–35	1848	1864	1710	1760	1850	1861–65
1876–80	1895			1878		1846–50	1861–65	1882	1895	1740	1800	1876–80	1895
						1880	1898			1780	1835		
										1820	1865		
										1850			
										1880			

4				5		6		7		8	
BAROMETRIC PRESSURE (a)		PRESSURE-GRADIENT (b)		FREQUENCY OF EASTERLY WINDS		VARIABILITY OF TEMPERATURE		FREQ'CY OF WEST INDIAN HURRICANES		FREQUENCY OF THUNDERSTORMS	
Low	High	Min.	Max.	Max.	Min.	Max.	Min.	Max.	Min.	Min.	Max.
1741–45	1760	1815	1790	1775	1755	1780	1755	1590?	1685	1783	1768
1771–75	1795	1840	1831–35	1815	1790	1810	1795	1625?	1725	1814	1797
1811–15	1831–35	1875	1860	1845	1830	1836–40	1821–25	1655	1762	1837	1822
1846–50	1861–65		1895	1880	1865	1876–80	1855	1710	1798		1852
1876–80	1895				1895		1895	1745	1823		
								1786	1864		
								1817	1895		
								1838			
								1885			

1905ApJ....22...42C

TABLE I—*Continued*

9				10		11		12	
FREQUENCY OF SEVERE WINTERS				SEASON OF NAVIGATION		TIME OF GRAPE HARVEST		GRAIN PRICES	
Max. or Cold	Min. or Warm	Interval of Three Periods: Max. to Max.	Interval of Three Periods: Min. to Min.	Short	Long	Late	Early	High	Low
1000									
	1025								
1045									
	1060	120							
1075			110						
	1095	105							
1120			110						
	1135	105							
1150			100						
	1170	95							
1180			100						
	1195	100							
1215			90						
	1235	100							
1250			105						
	1260	100							1265
1280			105					1290	
	1300	110							1305
1315			115					1320	
	1340	115							1340
1360			115					1370	
	1375	120							1385
1395			120			1405		1405	
	1415	125					1421–25		1420
1435			125			1446–50		1438	
	1460	120					1466–70		1465
1485			115			1481–85		1482	
	1500	110					1501–05		1500
1515			95			1511–15		1527	
	1530	95					1526–30		1540
1545			90	1560		1545		1555	
	1555	100			1570		1556–60		1570
1580			105	1591–95		1585		1596	
	1590	110			1611–15		1601–05		1603
1615			125	1621–25		1621–25		1640	
	1635	120			1645		1636–40		1654
1655			125	1660		1660		1662	
	1680	120			1690		1681–85		1688
1700			120	1710		1701–05		1700	
	1715	120			1726–30		1726–30		1730
1735			110	1741–45		1741–45		1740	
	1755	115			1761–65		1756–60		1753
1775			110	1781–85		1766–70		1772	
	1790	105			1791–95		1786–90		1785
1815			105	1811–15		1815		1812	
	1825	100			1821–25		1831–35		1835
1840			100	1841–45		1846–50		1855	
	1860				1861–65		1865		1864
1875				1876–80		1881–85		1873	
	1890								1895
1910?									

TABLE II

Sun-Spot Epochs (Wolfer)

Epochs of 11-Year Cycle		Interval			Epochs of 36-Year Cycle		Relative-Numbers		Interval		Ratio	
Max.	Min.	Max. to Max.	Min. to Min.	Smooth'd Means	Max.	Min.	At Maxima	Av'ge Min. to Min.	Min. to Max. *a*	Max. to Min. *b*	*a*:*b*	*a*:*b* Smooth'd
1	2	3	4	5	6	7	8	9	10	11	12	13
	1610.8											
1615.5			8.2	9.4	1615				4.7		1.34	
	1619.0	10.5		11.2						3.5		
1626.0			15.0	13.0					7.0		0.87	
	1634.0	13.5		13.2		1630				8.0		
1639.5			11.0	11.3					5.5		1.00	0.94
	1645.0	9.5		10.2						5.5		
1649.0			10.0	10.2	1647				4.0		0.66	1.07
	1655.0	11.0		10.7						6.0		
1660.0			11.0	12.3					5.0		0.83	1.14
	1666.0	15.0		13.2		1670				6.0		
1675.0			13.5	12.8					9.0		2.00	1.08
	1679.5	10.0		11.2						4.5		
1685.0			10.0	9.3			67		5.5		1.22	1.18
	1689.5	8.0		8.8	1690					4.5		
1693.0			8.5	9.7			68		3.5		0.70	1.25
	1698.0	12.5		11.7						5.0		
1705.5			14.0	13.1		1707	50	17	7.5		1.15	0.97
	1712.0	12.7		12.7						6.5		
1718.2			11.5	11.2			67	27	6.2		1.17	0.87
	1723.5	9.3		10.4						5.3		
1727.5			10.5	10.3	1725		92	43	4.0		0.61	0.95
	1734.0	11.2		10.9						6.5		
1738.7			11.0	11.3			88	41	4.7		0.74	0.97
	1745.0	11.6		10.9		1745				6.3		
1750.3			10.2	11.0			68	33	5.3		1.08	0.85
	1755.2	11.2		10.9						4.9		
1761.5			11.3	10.2			86	52	6.3		1.26	0.82
	1766.5	8.2		9.5						5.0		
1769.7			9.0	8.6	1770		116	63	3.2		0.55	0.74
	1775.5	8.7		9.0						5.8		
1778.4			9.2	9.2			158	69	2.9		0.46	0.78
	1784.7	9.7		10.8						6.3		
1788.1			13.6	13.5		1790	141	50	3.4		0.33	0.69
	1798.3	17.1		14.3						10.2		
1805.2			12.3	13.5	1807		49	30	6.9		1.28	0.91
	1810.6	11.2		12.1						5.4		
1816.4			12.7	12.5			49	19	5.8		0.84	0.92
	1823.3	13.5		12.3		1820				6.9		
1829.9			10.6	10.5			72	40	6.6		1.65	0.97
	1833.9	7.3		9.2	1835					4.0		
1837.2			9.6	9.3			147	65	3.3		0.52	0.83
	1843.5	10.9		11.0						6.3		
1848.1			12.5	11.8			132	52	4.6		0.58	0.75
	1856.0	12.0		11.9		1853				7.9		
1860.1			11.2	11.2			98	50	4.1		0.58	0.59
	1867.2	10.5		11.1	1865					7.1		
1870.6			11.7	11.8			140	57	3.4		0.41	0.61
	1878.9	13.3		11.9						8.3		
1883.9			10.7	11.4		1880	75	32	5.0		0.88	
	1889.6	10.2		11.0						5.7		
1894.1			12.1				88	36	4.5		0.61	
	1901.7									7.6		

TABLE III

EPOCHS OF SUN-SPOT MAXIMA (FRITZ)

EPOCHS OF MAXIMA	INTERVAL MAX. TO MAX.	EPOCHS OF 36-YEAR CYCLE		EPOCHS OF MAXIMA	INTERVAL MAX. TO MAX.	EPOCHS OF 36-YEAR CYCLE	
		Max.	Min.			Max.	Min.
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
1057		1060		1324			
	12				10		
1069				1334		1335	
	12				14		
1081			1080	1348			
	15				12		1360
1096				1360			
	8	1100			12		
1104				1372			
	13				8		
1117			1120	1380		1380	
	13				8		
1130				1388			
	8				13		
1138		1140		1401			1405
	10				14		
1148				1415*			
	13				10		
1161			1160	1425*		1425	
	16				10		
1177				1435			
	8	1180			13		
1185				1448*			1450
	8				14		
1193				1462			
	10		1195		10		
1203				1472		1470	
	9	1205			11		
1212*				1483			
	13				16		1490
1225			1225	1499*			
	13				12		
1238		1240		1511		1510	
	9				7		
1247				1518			
	13		1255		11		1525
1260				1529			
	10				9		
1270		1270		1538		1540	
	8				11		
1278				1549			
	13		1285		11		1555
1291				1560			
	9				12		
1300*		1300		1572			
	8				8	1575	
1308				1580			
	16		1320		11		
1324				1501			1590
					14		
				1605			

TABLE III—*Continued*

APPROXIMATE EPOCHS OF THIRTY-SIX-YEAR SOLAR CYCLE, 295 A. D. TO 1100 A. D

Maxima	Minima	Maxima	Minima	Maxima	Minima
295			570	845	
	315	585			865
325			600	880	
	345	615			900
355			630	915	
	375	645			930
390			665	045	
	415	680			960
430			700	975	
	455	720			995
470			740	1015	
	490	760			1040
510			780	1060	
	530	800			1080
550			825	1100	

TABLE IV

EPOCHS OF MAGNETIC DECLINATION RANGE (FRITZ)

EPOCHS		INTERVAL			EPOCHS OF 36-YEAR CYCLE		AVERAGE RANGE AT EPOCHS	
Maximum	Minimum	Max. to Max.	Min. to Min.	Smoothed Means	Max.	Min.	Max.	Min.
1	2	3	4	5	6	7	8	9
1778.0							14.5	
	1784.8	9.4						9.8
1787.4			15.6	13.7		1792	15.1	
	1800.4	16.1		14.4+				7.0
1803.5			11.5	13.7	1805		9.2	
	1811.9	13.6		12.5−				6.6
1817.1			12.3	12.9+		1820	9.2	
	1824.2	12.8		11.8				6.6
1829.9			10.4	10.1			12.4	
	1834.6	7.0		9.1−	1835			9.2
1836.9			9.8	9.3			14.1	
	1844.4	11.2		11.3				8.6
1848.1			12.9	12.2+		1852	12.5	
	1857.3	12.6		11.9				6.5
1860.7			10.2	11.0			11.4	
	1867.5	10.2		10.5−	1864			7.9
1870.9			11.0	11.4			12.8	
	1878.5	13.0		11.8+				6.7
1883.9			11.3	11.4		1880		
	1889.8	9.9						
1893.8								

TABLE V

EPOCHS OF AURORAL FREQUENCY (FRITZ)

EPOCHS		INTERVAL			EPOCHS OF 36-YEAR CYCLE		EPOCHS OF VISIBILITY	
Max.	Min.	Max. to Max.	Min. to Min.	Smoothed Means	Max.	Min.	Max.	Min.
1	2	3	4	5	6	7	8	9
1692								
	1700	15.4						
1707.4			12.4	13.4+		1700		
	1712.4	12.3		12.1				1710
1719.7			11.6	11.4				
	1724.0	10.4		10.3				
1730.1			8.8	9.1−	1730			
	1732.8	8.2		9.6				
1738.3			11.8	10.2			1738	
	1744.6	10.5		10.7				
1748.8			9.8	10.4				
	1754.4	10.8		10.4				
1759.6			10.7	11.5+		1760		
	1765.1	13.1		11.6				1765
1772.7			11.1	10.6				
	1776.2	7.6		8.3				
1780.3			6.2	7.1−	1780			
	1782.4	7.6		10.1				
1787.9			16.4	13.6			1788	
	1798.8	16.8		15.1+		1800		
1804.7			12.1	14.2				
	1810.9	13.7		12.4				1810
1818.4			11.3	12.1				
	1822.2	11.2		11.5				
1829.6			12.1	11.3				
	1834.3	10.7		10.8				
1840.3			9.6	10.0−	1840			
	1843.9	9.6		10.5				
1849.9			12.4	10.9			1848	
	1856.3	10.7		11.0+		1855		
1860.6			10.0	10.2				1860
	1866.3	9.9		10.7	1865			
1870.5			12.2	11.9			1870	
	1878.5	13.5						
1883.5								

TABLE VI

EPOCHS OF THE THREE-HUNDRED-YEAR CYCLE

SOLAR SPOTTEDNESS		AURORAL FREQUENCY		LENGTH OF 36-YEAR CYCLE				TEMPERATURE SHOWN BY TIME OF GRAPE HARVEST		LENGTH OF 11-YEAR CYCLE	
				SOLAR		METEOROLOGICAL					
Max.	Min.	Max.	Min.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
1	2	3	4	5	6	7	8	9	10	11	12
350				325–30						325–10.40	
	450				475–39						440–11.55
550		575		600–30						575–10.20	
	700		750		800–42						750–11.40
850		900		925–30						975–10.37	
	1000		1050		1050–42		1050–40				1100–11.73
1150		1175		1225–31		1200–32				1225–10.50	
	1450		1450		1410–45		1415–41		1425		1450–11.90
1550		1550		1550–32		1525–32		1550		1550–10.63	
	1680		1700		1700–41		1675–41		1675		1650–11.37
1850		1860		1850–30		1850–32		1825		1750–10.55	

WASHINGTON, D. C.,
December, 1904.