MONTHLY WEATHER REVIEW

Editor, ALFRED J. HENRY

VOL. 59, No. 3
W. B. No. 1041

MARCH, 1931

CLOSED MAY 2, 1931
ISSUED JUNE 5, 1931

NOTES ON LAKE LEVELS

By JESSE W. SHUMAN, C. E.

[Minneapolis, Minn., January 29, 1930]

In Chapter III of his book, Brückner (1) investigates the secular oscillations of lakes without outlets. He studied the Caspian Sea, Great Salt Lake, Lake George, and numerous others in various parts of the world. He sets up five general theses—

(1) Oscillations of lakes with complete outflow are small and follow without much lag, the oscillations of the various water supplies (inflows, springs, etc.)

(2) Oscillations of lakes without outlets are great, and show a very considerable lag in fluctuations, in comparison with the oscillations of their water supply. This lag may be so great that the maximum of the mean water level may not occur until the water supply has passed its peak and receded to its mean value.

(3) Lakes without outlets, whose inflowing rivers or water supplies have pronounced oscillations, show but little lag, and their oscillations are only a small per cent of those of the water supply. The same holds for lakes with level flat shores, in contrast with those having steep shores.

(4) Secondary oscillations of the water supplies, for a no-outlet lake, have no effect upon the latter as long as these oscillations are of small intensity and interfere in their flow with one another. The storage curve of the levels behaves similarily—the rise and fall is either accelerated or delayed.

(5) Lakes with partial, incomplete outlets stand in their behavior between complete outflow and no-outflow lakes.

Brückner now discusses the behavior of the various lakes, fortified with all the available data he could accumulate, both from recorded observations and indirectly obtained, and tabulates the results. Table 1, is a greatly abbreviated presentation of these results, and is given for the purposes of record. These data were assembled over 40 years ago, and with the accumulated observations since that time, should be of unique interest and assistance to a present-day investigator.

It will be noted that Brückner gives data on 7 lakes from 1600 to 1800 A. D. Their rise and fall being also compared to the advance and retreat of the Alpine glaciers. The rhymic swings seem to be well in step with one another. From 1800, the table gives data on 10 lakes in Europe, 11 in Asia, 2 in South America, 4 in North America, 6 in Africa, and 3 in Australia. All of these lakes are without outlets, the better known being: Caspian Sea; Lake George in Australia; Valencia in South America; Honey, Pyramid, and Great Salt Lake in North America.

At the end of Chapter III, Brückner closes with the following: "As the oscillations of the lake levels are of the same nature and occur at the same time, so must also the climatic changes for the countries of the world be similar and occur at the same time. This must be so. Is it possible that climatic oscillations can exist alone (with no effect upon anything else)? Which are the meteorological elements whose changes cause the variations in the lake levels? So far, we are completely in the dark, as the plotting of the meteorological observations alone will not determine it. At any events, it can only be the temperature that is active, which regulates the evaporation, or the rainfall, upon which the supply to the lake depends—perhaps it may be both at the same time. The influence of one oscillation in temperature is not to be underestimated; as first of all, it effects the evaporation from the surface of the lake, hence the level; then also the evaporation of the rain falling on the land, which influences the water supply. Also the effect of an oscillation in rainfall must be twofold—one direct in so far as the abundance of water is determined, which governs the inflow, and one indirect, inasmuch as hand to hand with the rainfall changes, the ratio of clouds vary, which in turn effects the evaporation. We do not know which alone of these factors to ascribe the principal work. We can only say the maximum of the lake levels seems to occur during a cool or wet to cool and wet, and the minimum of the levels to occur during a dry or warm to dry and warm, periods of weather. Quite definite is the conclusion that we can draw from the variation of the lake levels, relative to the position of the peak of the climatic oscillations. The former must not lag inconsiderably behind the latter. The peak of the latter must occur before the peak of the lake level oscillations. How great this lag of the lake is, we have not yet determined—and it must vary from lake to lake. Herein we have, perhaps, an explanation of the different behavior of the individual lakes from their neighbors. At any event, however, the periods of the lake level oscillations happen to occur, with respect to analogous portions of the curve of climatic oscillations, either at periods of maximum to (cold or wet) to (cold and wet), or at periods of minimum to (warm or dry), to (warm and dry)—certainly the same relationship continues to the end of the record. A general idea of lake-level oscillation is given in the following:

Dry or warm to dry and warm	Wet or cold to wet and cold
1720	1740
1760	1780
1800	1820
1835	1850
1865	1880

We know enough from what we have given above about the Caspian Sea, as well as for various lakes, whose meteorological data we have assembled and discussed (Table 1) in detail, to point out the reason for these oscillations. We will reserve this for later consideration. Sufficient here to say that all over the world, whereever there are lakes without outlets synchronous oscillation exists.

TABLE 1.—*Lakes without outlets up to 1800 A. D.*

[Condensed from the original]

	Alpine glaciers	Caspian Sea
Maximum about 1600	Increase 1595 to 1610	High 1838.
	Increase 1677 to 1681	
	Increase 1710 to 1716	
Minimum about 1720		Low 1715 to 1720.
Rising		Rising.
Maximum about 1740		Maximum 1742 to 1743.
Falling	Decrease 1750 to 1767	Falling.
Minimum about 1760		Minimum 1765 to 1766.
Rising	Increase 1760 to 1786	Rising.
Maximum about 1780		From 1780 (?) higher levels to 1809–1814.
Falling	Slight falling	

Lakes without outlets since 1800 A. D.

	North America			South America—Lake of Valencia	Australia—Lake George
	Honey Lake	Pyramid-Winnemucca	Great Salt Lake		
Minimum about 1800.				Low, 1800	Dry, about 1800.
Rising				Rising	Rising.
Maximum about 1820.				May, 1822, or a little later.	Maximum, 1822 or 1823.
Falling				Falling	Falling.
Minimum about 1835.				Minimum, 1835 (?)–1841.	Dry, 1838–1850.
Rising					Rising.
Maximum about 1850.			Moderate maximum, 1856.		Moderate maximum, 1852.
Falling			Falling		Falling.
Minimum about 1865.	Dry, 1859–1863.	Low, 1862	Minimum, 1861.		Dry, 1859.
Rising	Rising so that high in 1867.	Rising from 1867 on.	Rise before 1867.		Rising.
Maximum about 1880.		High in the 70's.	High in the 70's.	Maximum, 1873–1874; high until 1877.	Maximum, 1894.
Falling		Beginning in the 80's still higher than in 1862.	Falling until 1889.		Falling.

After discussing secular variation of rivers and lakes with outlets, rainfall, and barometric pressure Brückner deals, in Chapter VII, with secular variation in temperature, and certain relationships are disclosed in the following:

TABLE 2.—*Secular variation*

Lakes	Rainfall	Temperature
Minimum, 1720	Dry, 1716/25	
Maximum, 1740	Wet, 1736/55	Cold, 1731/45.
Minimum, 1760	Dry, 1756/70	Warm, 1746/55.
Maximum, 1780	Wet, 1771/80	Cold, 1756/90.
Minimum, 1800	Dry, 1781/05	Warm, 1791/05.
Maximum, 1820	Wet, 1806/25	Cold, 1806/20.
Minimum, 1835	Dry, 1826/40	Warm, 1821/35.
Maximum, 1850	Wet, 1841/55	Cold, 1836/50.
Minimum, 1865	Dry, 1856/70	Warm, 1851/70.
Maximum, 1880	Wet, 1871/85	Cold, 1871/85.

As is well known, Brückner determined from his studies that the length of the period of oscillation in our weather elements was about 36 years, and he points to the above table as indicating this in all three columns. He calls attention to the lag of rainfall behind temperature changes; also in further discussing temperature changes he makes the statement: "There is no doubt but that temperature oscillations are primary, and those of barometric pressure and rainfall are secondary."

Despite Brückner's classical and published studies regarding lakes, but little attention, if any, has been given them by American investigators. The rise and fall of the Great Lakes and Great Salt Lake, have received current newspaper comment from time to time, the oscillations of the former giving rise to some very expensive lawsuits; and while eminent engineers have dealt in their reports regarding the levels of the Great Lakes, and have ascribed climatic changes as the cause, it has been only in a decidedly vague manner.

Streiff (2) first pointed out that the Great Lakes and Great Salt Lake were oscillating in accordance with the cycle discovered by Brückner, and later (4) again referred to these lakes as well as Lake George in Australia. Inasmuch as public interests are much concerned with lake levels, and as so many of our smaller lakes are at extremely low levels, it is thought that these notes might throw additional light on the subject of their oscillations.

The various cycles referred to in these notes, have the following significance:

Secular cycle: The dictionary defines the word "secular," as brought about in the course of ages; occurring or observed once in an age or century. Brückner constantly refers to the secular variation in rainfall, temperature, lake levels, etc., and evidently means thereby the long swing in the climatic elements. Streiff (4) refers to secular cycle as being of variable periodicity, the last three periods being estimated at 70, 60, and 90 years in length, giving an average of about 73 years—the first period being estimated from Douglass's sequoia curve (1911, 11 trees). We adopt Streiff's nomenclature for the meaning of the secular cycle.

Wolf numbers or sunspot secular cycle: This is the long swing in the Wolf numbers; this cycle being low at 1816, high about 1856 and low again about 1906. From 1816 to 1906 is 90 years. This is the same cycle, evidently, as found in tree-ring growth.

Double secular cycle: It is shown in these notes that the secular variation of rainfall, temperature and lake levels appears to be such that there are two HIGHS for ONE of the Wolf numbers secular HIGH—giving rise to what is here called a double secular cycle (double the number of peaks, as in the Wolf numbers secular).

Wolf, solar cycle: By this is meant the cycle of approximately 11 years, the period from sun spot maximum to maximum. This is variable, also.

Double Wolf cycle: This is a cycle of half the solar or Wolf period; it has double the number of peaks as the Wolf. Again, this is Streiff's nomenclature.

Brückner cycle: This cycle is described by Streiff (4) as having twice the solar cycle period, or approximately 22.6 years. It is a variable, depending upon the actual length of two solar cycles. In his book, Brückner shows his cycle as having a variable periodicity, with an average of plus or minus 35 years. But as pointed out by Streiff (4), Brückner did not separate his cycle from what we now call the secular cycle.

HIGH, LOW: These terms in reference to cycles, herein, designate the periods of maximum and minimum values of the ordinates of the cycles.

Figure 3 shows the data on secular variation of rainfall, lake levels, and temperature, as found by Brückner, Table 2, plotted only to show the peaks and troughs at various times, without regard to vertical scale. We note the 30 to 45 year periods that are present in all three graphs. The lag of the lake levels behind the rainfall, and of the rainfall behind the temperature (wet after cold and dry after warm) is clearly indicated. Brückner's cycle, to him, consisted of twice the solar (4) cycle superimposed upon the Wolf numbers secular cycle, and this latter cycle has been traced in on one of the graphs of Figure 3. It will be noted that there are two HIGHS and two LOWS of the lake levels, for one of the Wolf numbers, secular cycle. Curves are also submitted, accompanying these notes, covering:

Figure 1, Rainfall at Padua, Italy.
Figure 2, Wolf numbers, mean annual smoothed.
Figure 4, Lake Ontario mean annual levels.
Figure 4, Mean annual temperature at Toronto, Canada.
Figure 4, Mean annual temperature at Detroit, Mich.
Figure 5, Mean annual temperature at Sidney, Australia.
Figure 5, Mean annual levels of Lake George, Australia.
Figure 5, Mean annual temperature at Bucharest, Rumania.
Figure 5, Mean annual departure of Caspian Sea levels.
Figure 5, Mean annual temperature at Salt Lake City.
Figure 5, Mean annual levels of Great Salt Lake.
Figure 6, Lake Ontario cycle analysis.

Considering the Padua rainfall, this is a graph of the annual values greatly reduced, or smoothed. Four reductions were first used to secure the double Wolf cycle, and the latter values were again reduced four times, giving the curve as plotted. The median line drawn through the loops of this curve, gives us the Brückner cycle, and a median line through the latter gives us the Wolf numbers, secular cycle, which was HIGH about 1780 and 1856, and LOW about 1815 and 1900. It will be noted that there is a *crest* of the Brückner cycle on *each* side of (before and after) the HIGH of the secular cycle, which gives rise to two periods of wetter than normal weather. These wet periods are reflected in lake levels, as will be shown later. This Padua rainfall record is one of the longest available, and is given here to show that while the Wolf numbers, secular cycle, affects the general swing up and down, the Brückner cycle also operates, and produces more HIGHS and LOWS than the former cycle. It seems probable that the same type of behavior may be expected all over the world, as in every record of rainfall examined by the writer, the Brückner and secular cycles are present. Sometimes they are very faint, but nevertheless present. Also because of the fact that lakes all over the world show certain synchronous swings, as found by Brückner, we may accept this as a fact, until it is disproved by bringing forward a series of raw data, which will fail to yield these cycles.

The curve of smoothed Wolf numbers, Figure 2, is submitted for comparison purposes, showing the Brückner cycle, superimposed on the secular cycle.

Taking up the lake levels, we refer first to curve No. 10, Figure 5, Lake George. Streiff's data (4) for this lake from 1852 to 1905 has been pieced out by data taken from Brückner's book, and the resulting graph gives a very good picture of how no-outlet lakes behave in the extreme. The sun-spot secular is shown in heavy smooth line, and the lake-level secular in dotted line. The Brückner cycle oscillates about the double or lake-levels secular, and the latter about the sun-spot numbers secular cycle. In October, 1929, Streiff (4) writes that this lake is already half full again. The curves indicate that a period of high levels is impending. A local Minneapolis newspaper, February 21, 1928, says, in a dispatch from Melbourne, Australia: "Fourteen persons are dead to-day and many are missing in what is believed to be the worst floods in the history of Australia—landslides were occurring at many points—damage to the town of

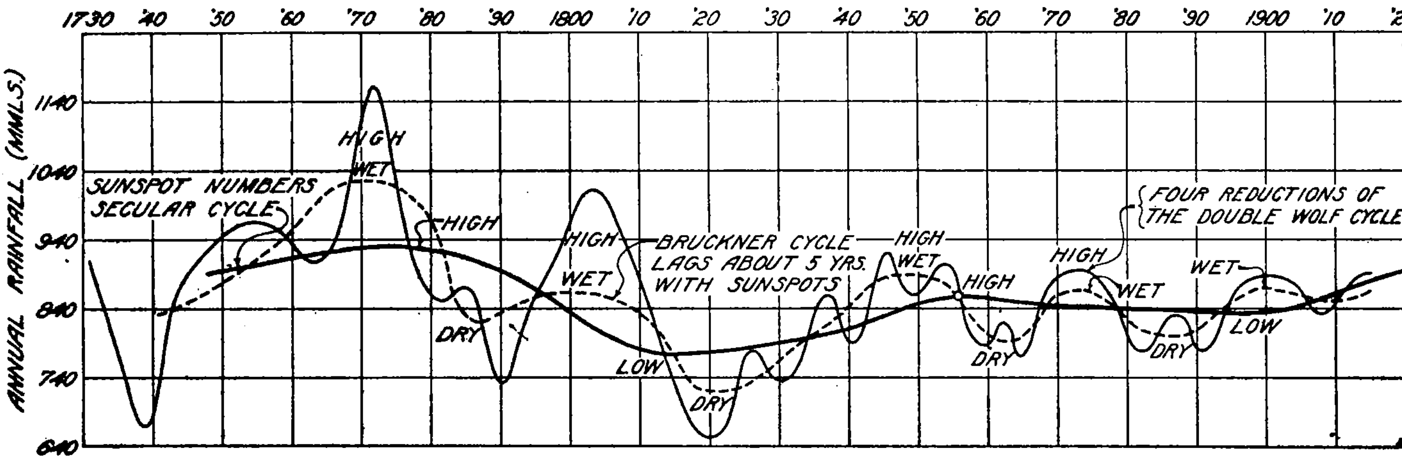

FIGURE 1.—Annual rainfall at Padua, Italy. Note a wet period occurs each side of sun-spot secular HIGH (the crests) of Brückner cycle

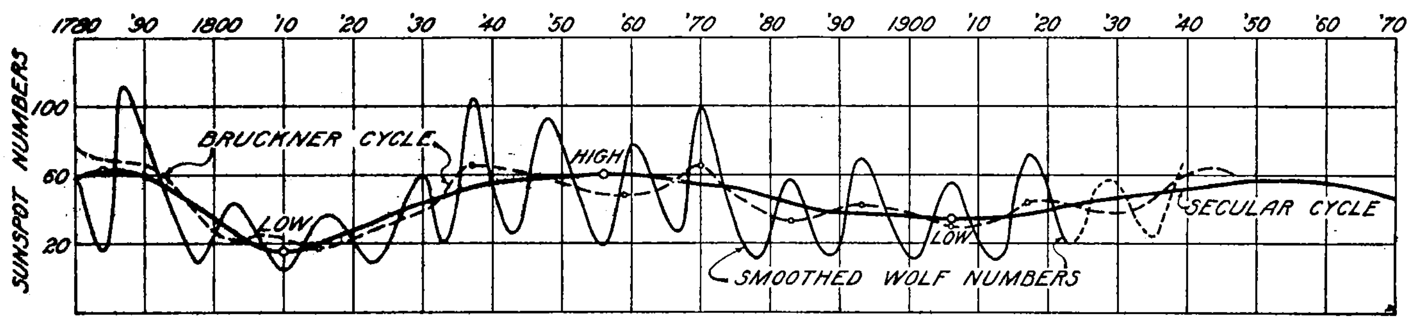

FIGURE 2.—Smoothed Wolf numbers

Grafton alone estimated at $3,750,000—water was 20 feet deep in some streets of Murwillumbah—the Brisbane River in Queensland district already is 26 feet above normal and is rising at the rate of 6 inches an hour." From the foregoing it is quite probable that Lake George will again attain the levels obtaining in the seventies to eighties.

Curve No. 9, Figure 5, is a graph of the mean annual temperature at Sidney, Australia. The solar, Brückner, and secular cycles have been traced in. Note the HIGH of the secular is about 1906, just opposite the LOW period of the Wolf numbers secular; and the LOW at 1875 is opposite the high period of lake levels, and about 19 years after 1856, the former HIGH of the Wolf numbers

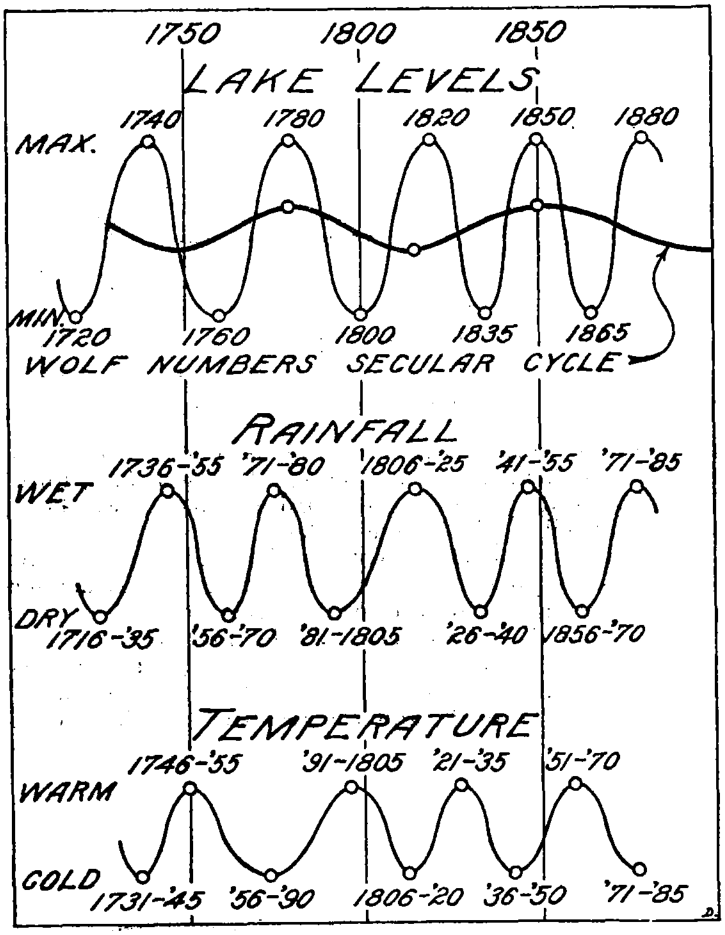

FIGURE 3.—Secular oscillation of lake levels, rainfall, and temperature. (From p. 236 of Brückner's Klimaschwankungen seit 1700.) Rainfall lags behind temperature, wet after cold, and lake levels behind rainfall

secular. It is self-evident, when we come to make these comparisons, as plotted, considering the cycles, that temperature alone must greatly affect lake levels, as at higher temperatures the evaporation must be greater, and vice versa. Thus, HIGH of the temperature secular is synchronous with low lake levels, and LOW of temperature secular with high lake levels.

Attention is directed to the HIGH of the temperature secular at about 1850 (see temperature curve No. 8, fig. 4, for Detroit, going back to 1940), close to Wolf numbers secular HIGH, as well as a HIGH about 1905, the LOW point of the Wolf numbers secular. It is known that the sun's heat output is slightly greater at sun-spot maxima, also this applies to high region of the sun-spot secular. Apparently also the mean temperature on the earth is higher at the LOW period of sun-spot numbers, i. e., 1905, as shown in all temperature graphs. Perhaps there is a decrease in the sun's heat output during sun-spot minima (and at LOW of its secular), but in any event there must be fewer clouds, with a net result of higher than normal temperature. This must be a fact, as examination of rainfall graphs everywhere indicate much less rain at the LOW periods of the Wolf numbers secular cycle. Thus the combined effect of rainfall and temperature on lake levels is to give a secular periodicity to the latter of approximately one-half of the period of the Wolf numbers secular, all as originally shown in Brückner's discussions and data.

Referring now to curves No. 11 and 12, Figure 5, temperature at Bucharest and mean annual departures of Caspian Sea levels, the same cycles as discussed above are present. While Bucharest is a long way from the Caspian Sea, it is still believed that the trends of temperature (all annual fluctuations ironed out) are very close to that of the actual contiguous area of the Caspian. Brückner's data on the Caspian stops at 1878, but there can be but little doubt as to the probable behavior of levels of the sea since that time. It must have been low about 1900 to 1910, and has undoubtedly been since rising, much as has Lake George. It may be noted that the HIGH levels of the 1870's accompanies the LOW period of the temperature secular; also that the annual peaks in the levels follow, by a few years, the LOWS of the temperature solar cycles.

Curves No. 13 and 14, Figure 5, give the temperature, at Salt Lake City, and the mean annual levels of Great Salt Lake (5). This lake has behaved identically with Lake George and the Caspian Sea. It has oscillated over 14 feet between 1873 and 1905. Note that the annual HIGH levels occur about the same time as the crests of the solar temperature cycles, and that these HIGH levels are really lagging behind the former LOWS of the temperature solar cycles. Streiff (4) has already pointed out the impending higher levels of this lake. The last LOW of the temperature solar cycle (curve No. 13) was about 1927–28; and judging from former behavior, the levels are about due to begin their rise (i. e., increased rainfall for the ensuing period is indicated). The Minneapolis Journal of July 1, 1930 states, in a dispatch from Tonapah, Nev.: "Nevada's forbidding desert *often* forsaken by its hardy horned toads and lizards, through a caprice of nature, has again become a haven for countless living things. Rain falling 19 successive days [1] recently transformed barren wastes into one brilliant flower bed. With abundant foliage to feed upon, insect life has multiplied until the great desert is alive with creeping creatures." The ensuing LOW of the temperature secular, about 1935 to 1940, will doubtless mark the culmination of these HIGH levels. Again, the Minneapolis Journal says, January 7, 1931: "Great Salt Lake, one of the saltiest lakes in the world, has succumbed to the cold. Ice was found on the lake yesterday for the first time in the history of the Weather Bureau."

The 19 days of successive rainfall and the formation of ice are simply climatic witnesses, in this region, to what is to follow. The word "often" italicized above by the writer, is significant in that it indicates in a general newspaper dispatch the fact that similar phenomena have occurred before. It is also interesting to note that this wet period at Tonapah came about at the same time as portions of the United States in the East were suffering from one of their worst droughts. This is

[1] This is not strictly accurate; the longest period of days with measurable rain in Nevada for May, 1930, was 11 and the total catch for the 11 days was 1.61 inches. The rainfall average for the State was 2.20 inches or 204 per cent of the May average.—Editor.

simply a concrete demonstration of the variation in phase of the Brückner cycles in weather elements in different parts of the country.

Inasmuch as Brückner, by his method of reduction of the raw or observational data did not separate the Brückner from the secular cycle, as we now understand the Brückner cycle (twice the solar cycle period), it appeared to him, just as shown in the examples above that the phase of this cycle plus or minus 35 years, was the same all over the world. If we separate the two, in meteorological data, we will find the phase of the secular cycle to be the same all over the world, and that of the Brückner cycle to vary, either leading, in phase with, or lagging behind the Brückner cycle in Wolf numbers. For the various lakes without outlet, here shown, the phase of the Brückner cycle is about the same, although this is not conclusive that it would be so for every no-outlet lake. For lakes with outflows, the phase of the Brückner cycle varies with the geographic location; viz, for Lake Ontario, the Brückner cycle seems to lead sun spots about 8 years. However, it is fairly easy to detect the Brückner cycle in any lake-level series, having a continuous fairly reliable record, and after levels data have been accumulated covering two complete Wolf numbers secular cycle swings, the behavior of lake levels will be more thoroughly understood.

Temperature oscillations do have a great effect upon the levels as shown by the examples given, and rainfall has not been considered here, because this element has generally been used as the basic active agent in affecting lake levels. More intimate knowledge, of course, can be gained regarding a lake's behavior in levels, by investigating rainfall and temperature together at the same time as levels. The purpose of these notes, however, is to show the reason for the double secular cycle, apparent in lake levels, and the effect of temperature. Securing the average rainfall and temperature (from all stations) surrounding a lake region will give slightly different results, in annual values, but the trends, cycles derived therefrom will not greatly differ from those of a single station in the vicinity if anomalies be taken into account. For quantitative studies, actual mean or average data on the basin should, of course, be taken.

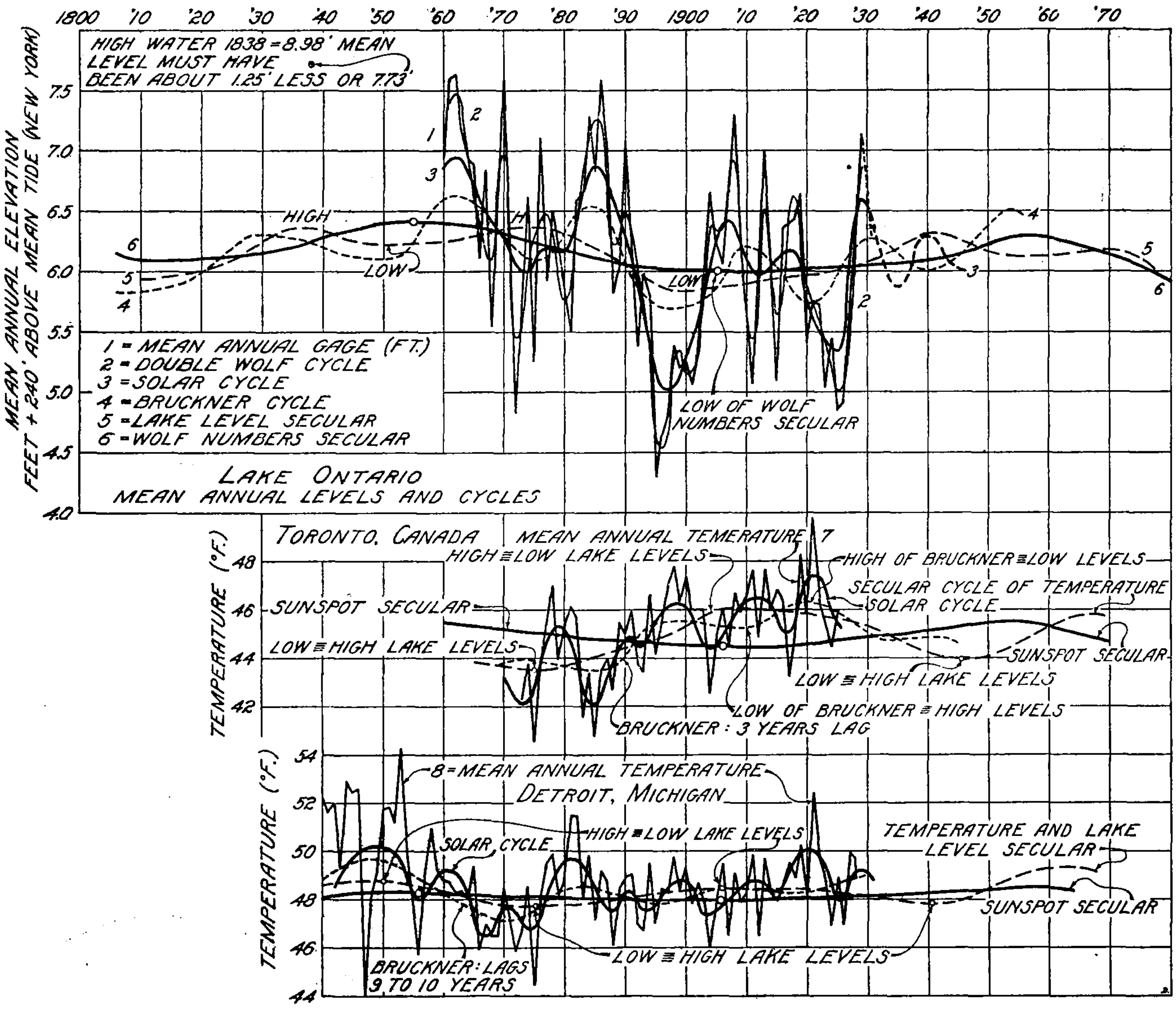

FIGURE 4.—Lake Ontario levels and cycles. Comparing the Toronto curve with that of Detroit, the Brückner cycle in former lags three years and in the latter lags nine years behind sun-spots trend, yet the secular cycle phases are identical

The fact that the phase of the Brückner cycle in both temperature and rainfall may differ in different parts of the country or world, explains very nicely just why

Brückner found, see his Table 1, some difficulty in matching up the periods of the lake oscillations; the HIGH lake levels, occurring as the LOWS of the temperature and the HIGHS of the rainfall secular cycles combined together, the occurrence of this event differing from place to place.

increased run-off and higher lake levels during wetter than normal weather is due, according to the opinion of the writer, to the effect of temperature. It is evident that as the secular trend of the temperature of a district reaches its LOW, the evaporation from the ground and the lakes therein must diminish, and this period is

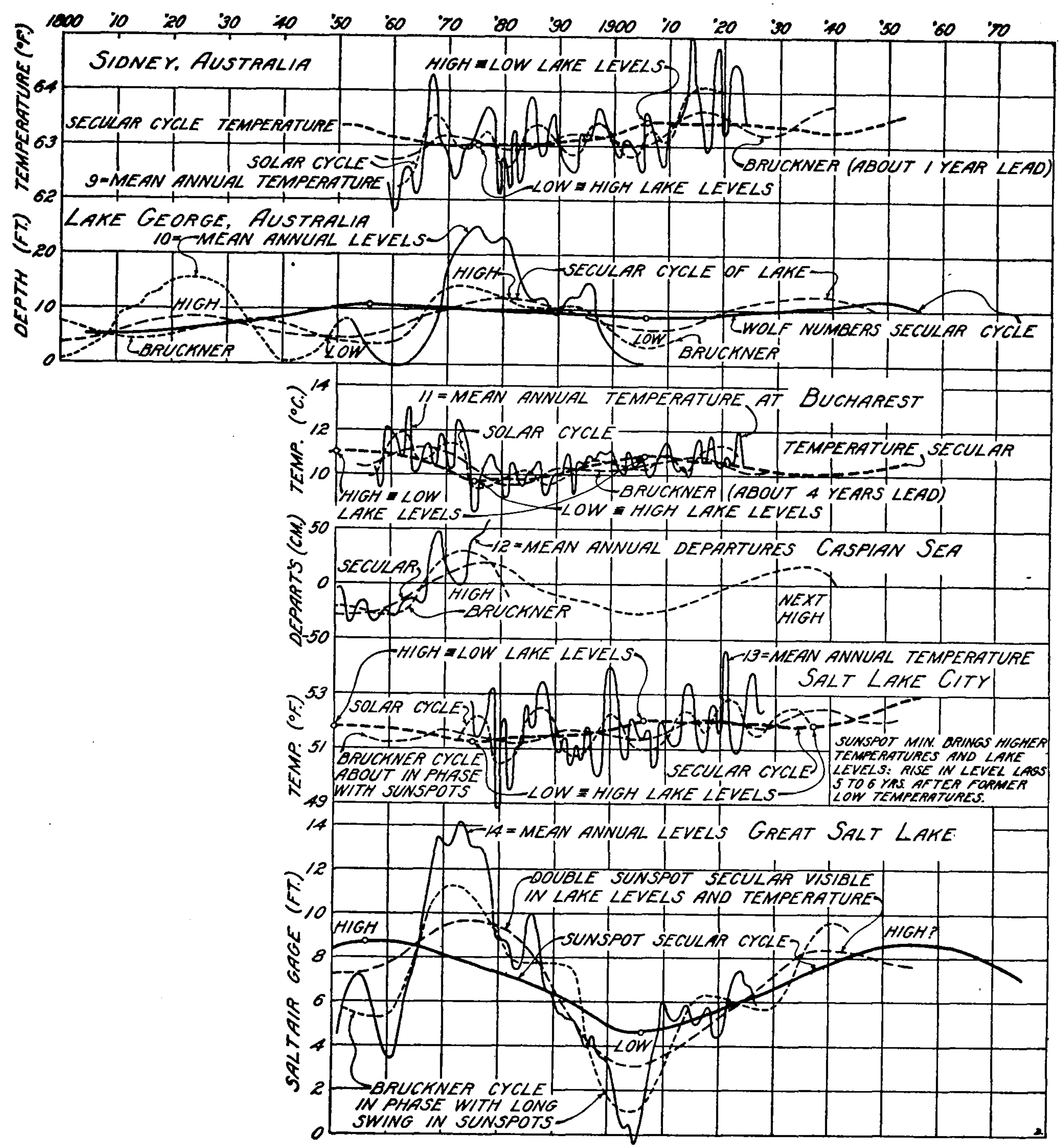

FIGURE 5.—Mean annual temperature, Sydney and Bucharest and levels of Lake George, Australia, Caspian Sea, and Great Salt Lake, Utah

Inasmuch as Streiff (2) has pointed out the correlation between Wolf numbers and the Brückner cycle, these cycles detected in lake levels, are no longer of uncertain periodicity. While the amplitudes of the cycles in rainfall and temperature are mostly of very small order their effect in lake levels is apparently greatly magnified, as already pointed out (4). The apparent results of promptly followed or accompanied by increased rainfall (see Brückner's data, fig. 3, or any other rainfall and temperature graphs for a certain place one wishes to make); the results being that the lake levels rise very much faster than they would had the evaporation continued at the same rate as in above normal temperature trends. The same applies to run-off. A simple analogy fits the case clearly—rainfall and temperature, in their causative effect in raising and lowering lake levels, are analogous to the motor and brakes of an automobile, the former tends to raise or drive forward, the latter tends to retard the action. It appears that at the time of increased rainfall, the "brakes" are taken off.

Knowing what to look for, in the matter of cycles, it is now comparatively easy to detect them in a record of levels, and the probable future extensions of the larger tions, with very hot summers. The return of this lake to its former size and depth is a matter of grave concern to the citizens of that part of the State. Beach marks of former greatly higher levels are in evidence around the lake. It is quite likely that this lake will again refill, but level records are insufficient to set up with certainty the cycles. However, at the eastern end of the lake, the desiccation has continued to the extent that petrified, or alkaline coated stumps of trees are now visible.

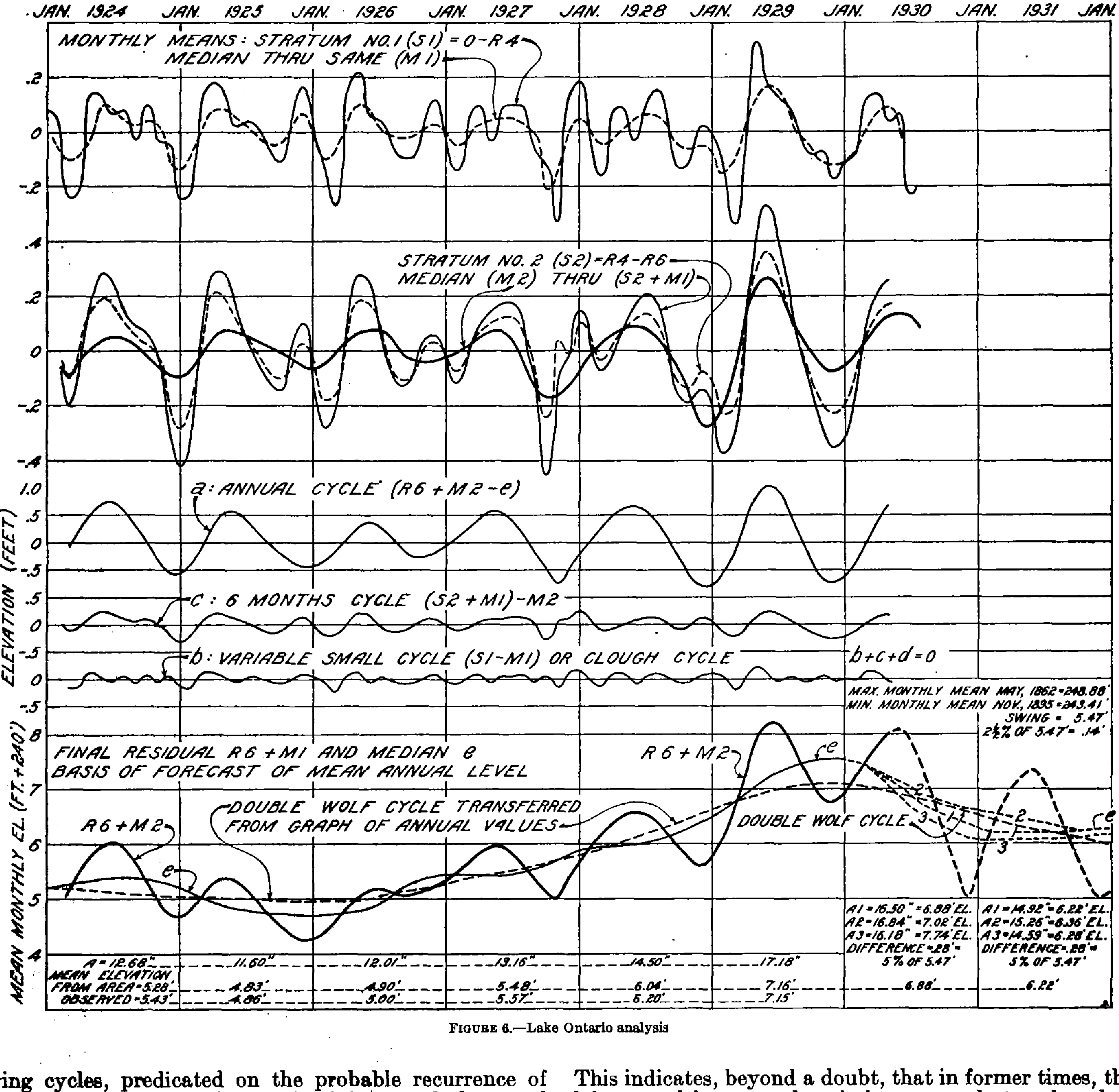

FIGURE 6.—Lake Ontario analysis

swing cycles, predicated on the probable recurrence of the Wolf numbers maxima and minima, and the trend of their secular cycle, enables us to set up a general picture of the future probable levels.

Devils Lake, N. Dak., is a no-outlet lake, and in 1867 was of considerable size and depth (111 square miles area). It has been steadily reduced in area and depth until in 1928 it has fallen 25 feet. The rainfall in this region varies from about 10.5 to 25.5 inches per year. This region is also subject to great temperature oscillations. This indicates, beyond a doubt, that in former times, this lake was drier even than it is now, and stayed so, long enough for a good sized tree to grow.

In the foregoing, we have pointed out, that the Brückner cycle in rainfall and temperature records follows, or is in step with, a similar cycle in Wolf numbers, and that as a HIGH or LOW point in the secular swing of the Wolf numbers necessarily entails two HIGHS of the Brückner cycle, one before and one after the secular cycle turning points, there results a "double" secular cycle, which is considerably mangified in lake levels; achieved apparently by the teamwork of rainfall and temperature, acting together at the temperature secular LOW, and against each other at the temperature secular HIGH.

The combined study of rainfall and temperature of a certain district will yield a good deal of information as to probable lake levels therein, even though no long continuous record of such is available, and each district must be studied separately. We are greatly indebted to Brückner for his work and discussions, pioneer in its nature. This investigation was undertaken after a hint from Mr. Strieff, who wrote in a personal letter to the writer, that he was convinced there was a double secular cycle in lake levels, after studying levels of several long records. Seeking for a cause, temperature records were investigated, as well as a search through Brückner's book, with the results as given herein.

For a lake with outflow, we take Lake Ontario. The mean annual levels are plotted in curve No. 1, Figure 4, with a greatly exaggerated vertical scale. Curve No. 2 is the double Wolf cycle, derived from No. 1. Curve No. 3 is the fourth residual of curve No. 2, and is approximately the solar cycle. Through the centers of the loops of this solar cycle is passed the curve No. 4, which is the Brückner cycle, and through the Brückner cycle loops are passed curve No. 5, the lake levels or double secular cycle; and finally through the swings of this last is passed the curve No. 6, the secular cycle of the Wolf numbers. Comparing the Brückner cycle in this graph with that of the sun spots, Figure 2, it will be noted that in Lake Ontario, the Brückner seems to lead by about eight years.

The continuous records of monthly mean levels of Ontario began in 1860, and there is also available, data as to high water in 1838 and low water in 1819. Two curves of temperature are given for comparison, Figure 4, one, curve No. 7 for Toronto, and curve No. 8 for Detroit, Mich. The Detroit temperature is given only to show the similarity of the secular cycles, to show the probable temperature trends of Toronto further back than its record goes, and also to point out the approximate phase coincidence of their solar cycles.

For a lake belonging in this class, comparing curves 1 with 7, it is apparent that temperature secular cycle has only a general effect, and that the temperature, Brückner, and solar cycles have a very pronounced effect, disregarding any consideration of rainfall. In the graph of curve No. 1, the extensions into the future of curves 3, 4, 5, and 6 are tentative only, predicated upon probable sun-spot numbers for the ensuing period, and the trend of the Wolf secular thereof. We do know, however, that the Wolf numbers secular cycle is rising toward a HIGH, and that this HIGH is likely to occur around 1950. Also, we can feel sure that there will be a HIGH of the double (lake) secular cycle prior to this HIGH of the Wolf secular. Also, the direction of trend of the Brückner cycle in the lake levels (curve No. 4) in the immediate future is somewhere near to the truth. If any reliance can be placed upon past behavior repeating itself, in a fashion, under similar conditions of cause, it would seem as though the mean annual levels of Lake Ontario were due for an oscillating reduction (first, high, then lower, but generally downward) for a few years, then an upward trend until about 1940; the values from 1930 to 1950 being perhaps a little less than for the 1870 to 1890 period.

With reference to levels prior to 1860, there is a record of high water in 1838, at 8.98 + 240 feet. The mean level for the year seems to average, in these records, about 1.25 feet less than the maximum level for the year, so that the probable mean annual level for Ontario in 1838 was about 7.73 + 240 feet. For the year 1819 there is a record of low water for Michigan, but not for Ontario. Lake Michigan was 6.6 feet lower in 1819 (584.3 − 577.7) than in 1838. This probably means the difference between the recorded maximum of 1838 and recorded minimum of 1819—not mean monthly levels. These greatly varying levels when plotted in the graph of curve No. 1, Figure 4, seem to check, with the cycle shown.

This lake, like the no-outlet lakes discussed, is rising and falling in step with certain well-known climatic cycles. Streiff (3) gives a method of analyzing river run-off data, which I have applied to lake levels here. I have taken the mean monthly levels, and treated them exactly like river run-off data. The results are shown in Figure 6. Four successive additions of consecutive monthly means were first made, R1, R2, R3, and R4. R4 was restored to scale by dividing by 16 and to phase by shifting results upward 2 months. R4, thus restored to scale and phase, was now subtracted from the original monthly means, giving Stratum No. 1 (=S1), shown in curve No. 1, at top of Figure 6. Next, two more reductions were made, taking every other value of R4 for addition, finally securing thus R6. After restoring to this scale by dividing by 4 and to phase by shifting upward 2 months, R6 was subtracted from R4, giving Stratum No. 2 (=S2), plotted in curve No. 2, just below curve No. 1. A median line is now drawn through S1, following the general contours of S2 (curve No. 2), and the ordinate values of this median, M1, are taken off and added to curve No. 2 values, giving curve No. 3. Next a median line M2 is drawn through curve No. 3, following the general swings of R6, (which may be tentatively plotted below for comparison temporarily) and the ordinate values of M2 are taken off and added to R6, giving curve No. 4. The median line "e" passed through the curve No. 4 is the final residual, whose mean ordinate for the 12 calendar months of the year, is approximately equal to the mean annual level. Subtracting M1 from S1 gives the (b) or Clough cycle; M2 from (S2 + M1) gives the (c), or 6 months' cycle; and "e" from (R6 + M2) gives the A = (a) or annual cycle. The algebraic sum, for a year, of these three cycles is equal to zero; also the algebraic sum of the three cycles, a, b, and c, and the residual "e," equals the original monthly means graph. Residual "e" is superimposed on the double Wolf cycle, also shown in curve No. 4. This is the same cycle as curve No. 2 in Figure 4, and its approximate path in the next ensuing year is shown. Residual "e" can also be extended a year or so into the future. The latest monthly mean levels data on hand at the time this study was completed, was for September, 1930. Note that the vertical scale in curve No. 4, Figure 6, is in feet from 4 to 8 feet, and that these values are to be added to the base elevation, 240 feet.

The highest recorded mean monthly level was in May, 1862 = 248.88; and the lowest was in November, 1895 = 243.41. This is total swing of 5.47 feet. Two and one-half per cent of this amount is equal to 0.14 feet. In extending residual "e" through to the end of 1930, I have shown three possible extensions; No. 1 is the base, for forecast values, No. 2 will give 2½ per cent greater elevation and No. 3 will give 2½ per cent less elevation, than for the base value. Residual "e" is shown plotted only from 1924 to date. The area, A, under the residual, and between January to January ordinates and zero below, is shown for each year; also the equivalent mean level, and the observed level. For all practical purposes, the computed and the observed values are the same.

For the year 1930, the extension No. 1, gives a mean elevation of 6.88 feet, for the year, or 240+6.88=246.88 feet. Extensions Nos. 2 and 3 are given simply to show that considerable error may be made in extending this residual "e," and yet influence the results only 5 per cent of the total maximum swing from highest to lowest mean monthly levels recorded. In order to forecast as closely as possible, one should secure the data to the end of the calendar year; as it is, the extension for the year 1931 indicates that the mean annual level will be about 6.22+240=246.22 feet, still lower than for 1930.

The accuracy of these forecasts depends a great deal in predetermining the path of the double Wolf cycle. In this record of lake levels, these double Wolf cycles do not emerge as perfectly as one could wish. If they were perfect, they would consistently appear in a certain relation to the sun spot maxima and minima. As it is, we can only tentatively extend them. If is self-evident, from a close inspection of curves Nos. 1 and 2, Figure 4, that the double Wolf cycle has reached its peak at 1929, and will trend downward to about 1932–33.

The same remarks apply to lakes with outflow, relative to investigating rainfall and temperature as for no-outlet lakes. It is most important to discover the lag of rainfall behind the temperature oscillations, and if possible the lag of the levels behind that of the rainfall. With lakes having data similar to Lake Ontario, one does not need necessarily to make these rainfall and temperature studies, only as indicated herein, to discover the epochs of the secular swings.

In his chapter headed "The Significance of Climatic Oscillations in Theory and Practise," Brückner says (p. 274).

Our climatic oscillations can also be modified due to different land conditions. Especially in arid districts, where there is little water, the hydrographic conditions alter greatly, in that they follow the oscillations of the rainfall. A map made during a dry period, will often present an entirely different picture, than if it were made during a wet period. Lakes vanish in dry periods and return in wet; viz, Lake George in Australia, which in 1820 and 1876 was an important lake 20 to 30 kilometers long, and an insignificant lake only in 1850. It was 10 kilometers wide and 5 to 8 meters deep, and in the dry periods, dwindled away completely down to the ground, so that grass grew in its basin. Likewise the neighboring lakes, Cowal and Bathurst, became depleted in the dry periods, and refilled in the wet periods. From a full consideration of these facts, it is clear that lakes Cowal and George behave somewhat like Lake Zurich. Very similar also is lake Hamun-Sumpf of Persia, although this does not completely dry up. Great, also, are the oscillations of Great Salt Lake, whose area changed from its minimum in 1850 to its maximum in 1870 a full 17 per cent, like that of Lake di Fucino, whose area decreased 19.2 per cent from 1816 to 1835. Relatively small, although very definite, are the larger oscillations of the Caspian Sea.

In an attempt to utilize Brückner's ideas, in the past, so many anomalies developed that his work has lain in obscurity. Brückner, himself, was unable to discover any correlation between his cycle and the sun spots. Great credit, therefore, should be given Streiff (2) for his discovery of this relationship, and why its existence had hithertofore escaped us; for until he made it, there was nothing to tie to—our climatic cycle was of a greatly varying period, and no one knew when it would change or end. With out present knowledge, we can turn back to Brückner's book, and use the information it contains to great advantage. Brückner calls attentoin in the extract given above to the difference that may exist in a map made in the dry period as against one made in the wet period. The last major climatic oscillation peak was about 1856, or 74 years ago. Practically all of our important railroad and public highway work has been done since that time. Most of our park systems driveways, and roads of all types for auto travel, in the various States, have been completed within the past 30 years, namely, beginning at the very lowest point of our climatic swing (1900 to 1910). There is every reason to believe, therefore, as the next 20 years comes on apace, we will witness considerable damage to work done during this past régime of weather.

(1) Klimaschankungen seit 1700, by Ed. Brückner, Vienna, 1890. This was also published as Heft II in Penck's Band IV, Geographische Abhandlungen.
(2) A. Streiff in Monthly Weather Review, July, 1926, Washington, D. C.
(3) A. Streiff in Monthly Weather Review, March, 1928, Washington, D. C.
(4) A. Streiff in Monthly Weather Review, October, 1929, Washington, D. C.
(5) United States Geological Survey data.

WEATHER AND CORN YIELDS

By W. A. MATTICE

[Weather Bureau, Washington, April, 1931]

Corn is one of the most widely grown crops of the United States; practically every State grows some corn, whether for grain or silage. The heaviest production is concentrated in nine States, comprising what is known as the "Corn Belt"; here is found about 60 per cent of the Nation's acreage and in 1925 this region produced 70 per cent of the total production. Figure 1 shows the area under consideration. The States outlined contain the Corn Belt proper, but the sections of heavy production do not include the entire region shown, as it is confined to the central parts of the Ohio Valley States, most of Iowa and Missouri, southeastern Minnesota and South Dakota, and eastern Kansas and Nebraska. The figures shown in the State boundaries are the percentages of the total crop area that is planted to corn in each State.

The weather data used in this study were obtained from the State Section Summaries and the original records of observations on file at the central office of the Weather Bureau. The precipitation and mean temperature data are State averages for all meteorological stations, but the maximum temperatures, percentage of possible sunshine, and p. m. relative humidity were obtained by averaging data of selected first-order stations.

As is usual in a study of this type, covering a relatively long period of years, it was necessary to adjust the records available to the several State boundaries, but every effort was made to keep the data representative and comparable. The yield data were obtained from the United States Department of Agriculture reports.

The method developed by Kincer (2) was applied to the several State data, using five weather elements covering the period April 1 to September 30, inclusive. In order to conserve space, and also as the method is familiar to most of the readers of this publication, the various data used in computation of the bases are omitted and only the final computed yields are given. By the expression "bases" is to be understood the computed yields used as a weather index for subsequent calculations. That expression is used for brevity and convenience in discussion. Table 1 shows the actual corn yields in bushels per acre and Table 2 the computed bases; the averages for the