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II. *EVIDENCES OF CYCLES IN TREE RING RECORDS*

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This paper describes some preliminary results in a search for a theory of climatic change, based on cycles. The search has been warranted by two possible advantages in approaching the subject: first, tree ring records, climatic in character, reaching a maximum length of three thousand years and accurately dated, whose climatic interpretation is based on ecological considerations and a limited number of actual tests; second, a cyclogram method of analysis of plotted curves, whose flexibility and speed of operation has made these studies possible. It is not intended in this paper to deal with the interpretation of these cycles beyond pointing out their apparent relationship to solar variations.

The cyclogram is a pattern in which simple cycles are automatically separated from one another by a process which causes them to appear as rows of dots pointing in different directions. Each cyclogram includes the complete series of data and the cycle may appear anywhere within it. Thus it is independent of the beginning and ending of the sequence. Its character is denoted by the regularity and conspicuousness of the alignment of dots. We are therefore free to detect a cycle whether it is simple or composite, constant or variable in length, long or short in length, long or short in duration, subject to reversals of phase or subject to fractionizing. The method also gives a first approximation to amplitude, often sufficient. By the use of some simple light-sensitive instrument the amplitudes can be measured quantitatively, or after the cycle is well delineated, its various elements may be determined by simple mathematical means. Thus in comparison with other methods the length of a cycle is determined in a few minutes with a precision approximating a least square solution (this was found in a test on variable stars reported to the American Astronomical Society in 1919); the beginning and ending of a cycle and composition and possible variations appear at once, as never possible in previous methods: the amplitude, however, is less precise, having been estimated on a scale of four, yet nearly every maximum must be present and there must be enough of them to give the impression of a straight line in the pattern.

The capacity of this method may be seen in figure 1, which shows a multiple standard for calibration and its cyclogram. We can easily detect four of the five cycles of the original; in the analyzing instrument the fifth is seen as easily as these four.

Discontinuities in a cycle become at once apparent as illustrated in figure 2 which shows the first cyclogram of sun-spot numbers, made in 1914. The bending of the horizontal fringes points out the discontinuities listed by Turner in 1913. It is evident that the solar cycle is not a precise and invariable period, yet we call it a cycle. Therefore a cycle may be defined as the recurrence of similar conditions at similar intervals. The beginning and end of duration of a cycle may be observed with precision, which is sometimes of first importance, as will be illustrated in connection with the Hellmann cycle. (Figure 2 originally appeared in Astrophysical Journal, Vol. XLI, page 174, April, 1915.)

Reliability Tests.—Natural sequences shown in tree growth may be distinguished from accidental or "scrambled" sequences using the same values, if the sequence is long enough. In attempting to select the genuine out of three curves, two of which were accidental—this is called the "triangle" test—curves of 60 to 75 years in length could not be distinguished. Curves of 125 or more years met with better success. Some eighteen tests have been made on group curves of trees averaging about 175 years in length. Successful selection was made in every case. Over eighty per cent were easy. Two methods of selection were used; namely, smoothed curves and cyclogram analysis. Smoothing an accidental curve tends to reduce it to a straight line, while the natural sequence retains its larger variation. This is shown in figure 3.

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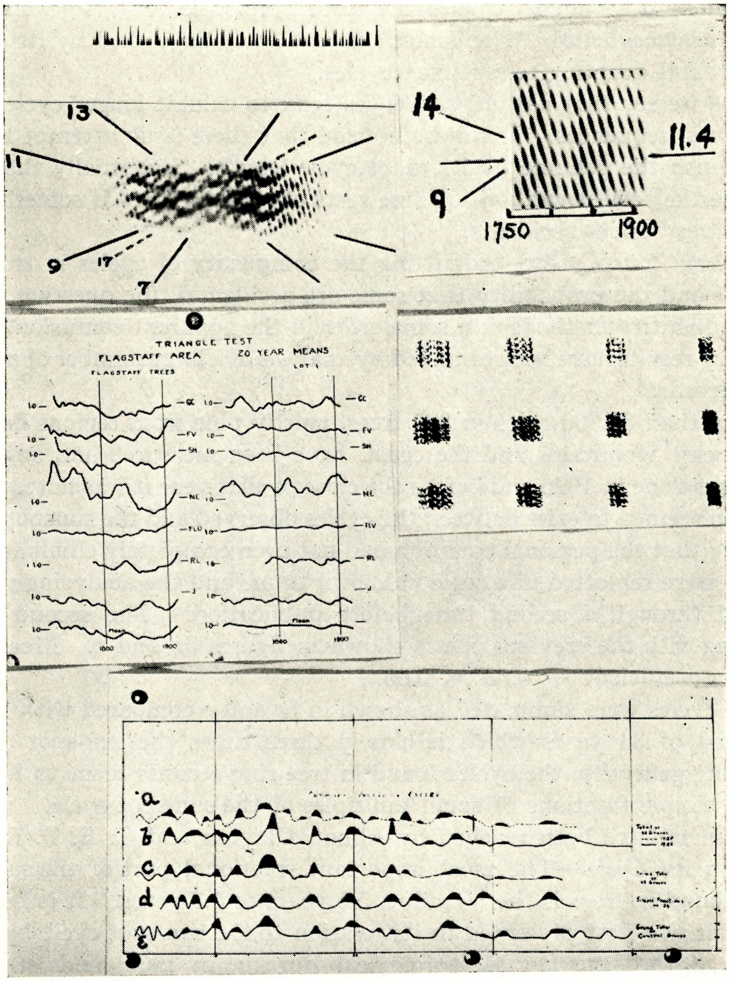

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PLATE 1

1. Calibration curve (negative) and its cyclogram (cyclograms best seen by slanting view).
2. Cyclogram of sun-spot numbers 1755–1914.
3. Triangle test by smoothing: natural sequences on left, accidental sequences on right.
4. Triangle test by cyclograms: natural sequence top row, others accidental.
5. Independent cycle analyses of western pine records (*a* and *b*), mean (*c* and *e*), sun-spot cycle ratios (*d*).

The cyclogram test as shown in figure 4 consists of three cyclograms in four different settings. One of the three horizontal rows is genuine, the others are accidental. The genuine is readily distinguished by its clearer background denoting fewer short cycles.

Thus we see that natural sequences tend to exhibit longer cycles than accidental sequences. It will be noticed that there is no attempt here to distinguish the genuine by its exact cycle length. Eventually that may become the easiest method. These tests show that there is something in the curves besides accidents.

Western Zone Cycles.—Admitting the complexity of cycles in tree ring records and the probability that some are accidental, the question is, can we by quantity methods find some order in the apparent confusion. Preliminary results have been obtained by analysis of a large number of western tree records.

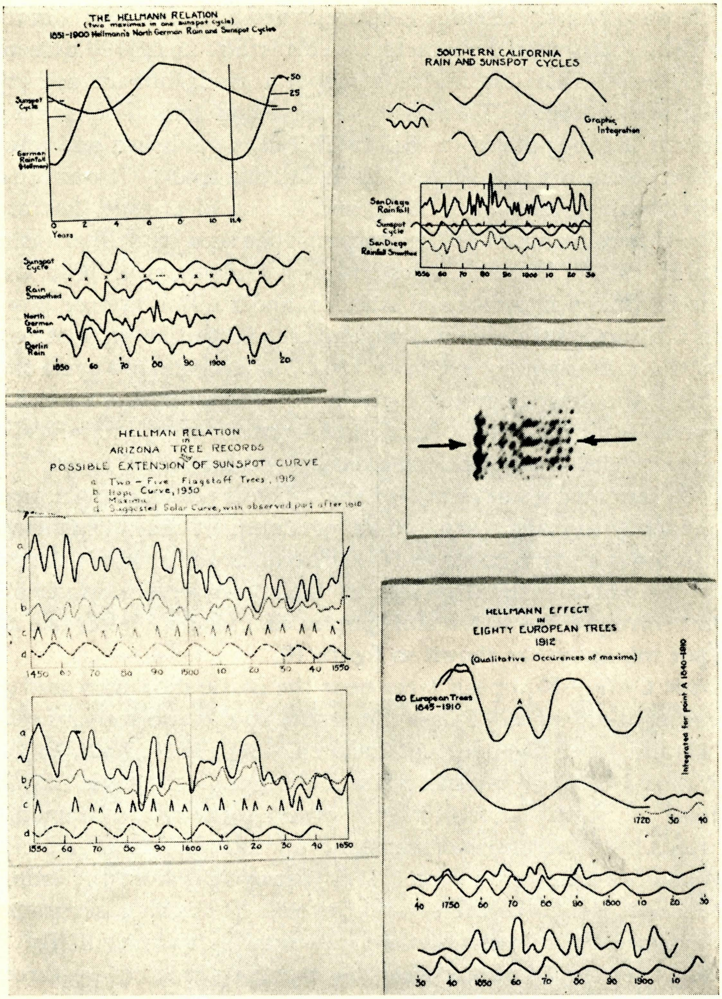
More than 52,000 rings in 305 trees, mostly pine from regions between the Rocky Mountains and the coast, have been measured and analyzed. This was done in 1926 and before the close of that year it was noted that a relation seemed to exist between the cycles observed and the sunspot cycle. Fearing that the personal equation had not been completely eliminated, 84 curves were replotted in a scale unknown to me and the analyzing process carried through a second time before publication. The second result agreeing with the previous one is shown in figures 5*a* and *b*. Mean correlation coefficient $+ 0.53 \pm 0.06$.

The cycles were summated as shown in 5*c* and *e* compared with simple fractions of 34 years which is closely three times the sun-spot cycled. Speaking generally, the cycles found in tree ring records seem to be very nearly simple fractions of small multiples of the sun-spot cycle. Similar expressions have been reached by Abbot, Clayton and C. E. P. Brooks.

Hellmann Cycle.—The most important fractional part of the sun-spot cycle found in trees is the $^1/_2$ value, 5.5 years to 5.7 years. It is believed that this was first presented in its relation to the sun-spot cycle by Hellmann, of the Prussian Meteorological Bureau, in 1906, in a study of North German rainfall. It is therefore called by his name. His curve is shown in figure 6.

It is readily found at other places. A California rainfall curve expressly presented by an author to show the absence of cycles is shown in figure 7. On being smoothed it seems to show this Hellmann cycle. Horton in 1903 mentions this short cycle in California rain. Its length and association with the sun-spot cycle was published by the present writer in 1909. It has been plotted recently by Nicholson, who, however, does not attach any special significance to it. It is in use by Gorton at the Scripps Institution of Oceanography. It appears in many centuries of sequoia growth.

About 1914 the Hellmann cycle was recognized as a marked character-



6 7 8 9 10

PLATE 2

6. The Hellmann relation.
7. Similar relation in San Diego rainfall.
8. Hellmann cycle in early Arizona trees.
9. Same in Grand Canyon trees, 1700–1920, isolated maxima.
10. Hellmann effect in 80 European trees.

istic of Arizona trees in the fifteenth century. Two different curves of tree growth are shown in figure 8; the maxima are marked to bring out the Hellmann cycle and a suggested position of the sun-spot cycle is placed below. This cycle was readily seen in the cyclograph in early analytical work. It was further noticed that from 1650 to near 1725 the elevenyear cycle was absent. About 1725 it returned and after 1800 began again to show the double crested character. This failure near 1700 caused much doubt of the possible relation to sun-spot records but an account of it was published in 1919. Three years later Maunder's description of the great dearth of sun-spots from 1645 to 1715 was published and offered an explanation of the absence of the cycle in Arizona trees. It was the ability of the cyclogram to show beginning and ending of a cycle that drew attention to this coincidence. The story may be seen in ordinary curves as published in 1919 (Climatic Cycles and Tree Growth, page 103; Carnegie Institution. The relationship of Arizona and California tree growth to southern California rainfall and temperature and to the sun-spot cycle was given in the same volume on page 104). The Hellmann cycle shows in the means of the Arizona groups including 58 trees, but it is necessary first to remove a 19-year cycle. The Grand Canyon group, however, shows the cycle very clearly in "isolated maxima" cyclogram of figure 9.

In north Europe certain groups of trees show an excellent sun-spot cycle with a tendency to introduce an added maximum at time of sun-spot minimum. In a qualitative result in 80 European trees in which the number of occurrences of maximum growth in each year were plotted, a strong maximum corresponded to the sun-spot maximum and a lesser one appears at sun-spot minimum, as shown in figure 10.

Sun-Spot Cycle.—European trees near the Baltic show increased growth during sun-spot maxima. This is illustrated in the two sections shown in figures 11 and 12 The sun-spot maxima, 1830, 1837, 1848, 1860, 1871, 1884, 1895 and 1905 are marked with dots. On plotting the ring growth of 57 trees of north Europe, mostly pines, a curve is obtained which closely resembles the curve of sun-spot numbers as shown in figure 13.* Integration of this tree growth on a 11.4-year cycle is almost identical with the similar integration of the sun-spot cycle. It has been suggested that these effects are due to thinning the forest with German regularity. On a recent visit there I was assured that the forest is thinned every three years or so for instruction purposes in the University.

The Arizona trees have a tendency to give a cycle of about 14 years. The cyclogram of these trees in figure 14 shows the Hellmann relation in the left quarter, which is the early 125 years of its length. In the central part, near 1700, it shows an approximate 10-year cycle during the dearth of sun-spots, and in the right-hand third something close to 21 years.

Early analysis of the Flagstaff 500-year tree records (1909) gave a cycle of about 21 years since 1700. This has remained very prominent in the last 200 years of Arizona tree growth. In various curves of cycle inten-

* Figure 10 has appeared in Climatic Cycles and Tree Growth (Carnegie Institution: I, 1919; II, 1928) I, page 78: Figure 11, *Ibid.*, I, Plate 8A: figure 12, II, Plate 8: figure 13, I, page 77: figure 14, II, Plate 9, no. 7.

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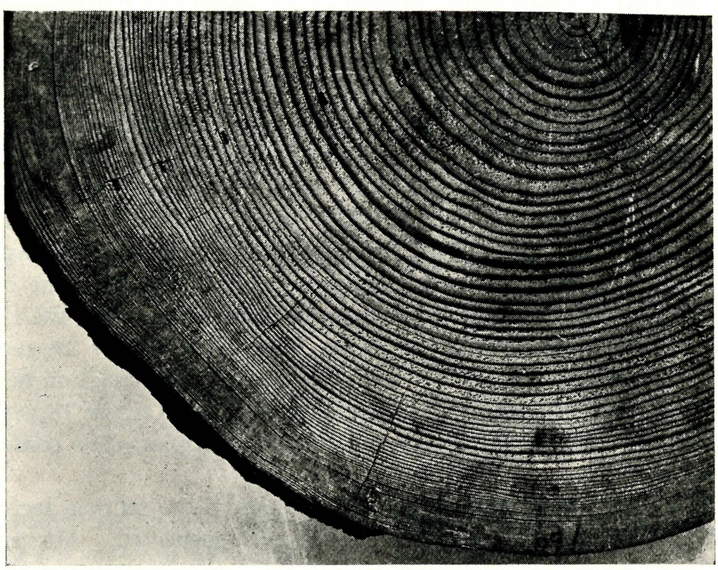

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PLATE 3

11. Eberswalde (German) pine showing large growth at sun-spot maxima
12. Swedish spruce showing same.

sity (periodograms) a considerable crest from 19 to 22 has been evident. There has always been uncertainty regarding the real length of this cycle. A series of integrations at 18, 19, 20, 21 and 22 years in figure 15 give 20 years as a good average value of this cycle. The best mean values from 1700 to 1920 were recently sent to Dinsmore Alter, who subjected them to periodogram analysis in a rapid and skilful mathematical attack. His correlation periodogram of this sequence is given in figure 16, which shows a strong crest at something over 20 years, with further conspicuous crests of about 40 and 80 and 120. A cyclogram made of the same data is represented in figure 17, which shows at once that this 20-year cycle is composite during this 220-year interval. Through the first one-third, a cycle of about 23 years is prominent and in the remainder a strong 19-year cycle appears. One recalls that 19 is approximately one-third of five times the sun-spot cycle. Thus this puzzling but strong cycle proves to be a composite of two taken in succession.

A curve of Arizona tree growth plotted at $^1/_5$ horizontal scale for 1200 years shows approximately five times the sun-spot cycle from 1168 to 1512 A. D.

I have illustrated above a number of cycles but it will be seen that each one is a simple fraction of a small multiple of the 11-year sun-spot cycle.

Sequoia Integrations.—The difficulty with the study of cycles in climate has been the limited lifetime or duration of any one cycle. One thinks he has a cycle well tied down only to find that it has vanished and another has taken its place. The possibility of finding a definite succession of cycles has long been recognized and the great sequoias have seemed the most promising location for the search. We have in our laboratory 50 radials of these trees, of which about half show 2000 rings or more, and four extend back 3100 years; one reaches 3237 years, to 1305 B. C. They fall into two groups, the Grant Park sequoias and the Springville sequoias, some forty miles apart. It was discovered about 1921 that the double sun-spot cycle 22 or 23 years is more common in these trees than the 11-year cycle. The pine tree curve of the Sierra Nevadas resembles the sequoias in giving prominence to a cycle of about 23 years. A correlation periodogram of this series of data by Dr. Alter, reproduced in figure 18, shows a pronounced crest at about $22^1/_2$ years and its multiples, thus confirming these results.

In 1927 a study was made of certain portions of the sequoia records in which the presence of the 11-year cycle had been suspected. Integrations on a basis of 23 years gave immediate results in the form of a recurrence cycle of 260 to 280 years, in which 23/5 or 4.5 years repeated itself. At the present time the same form of integration has been extended so that now we have a series of curves each 23 years long, that are consecutive

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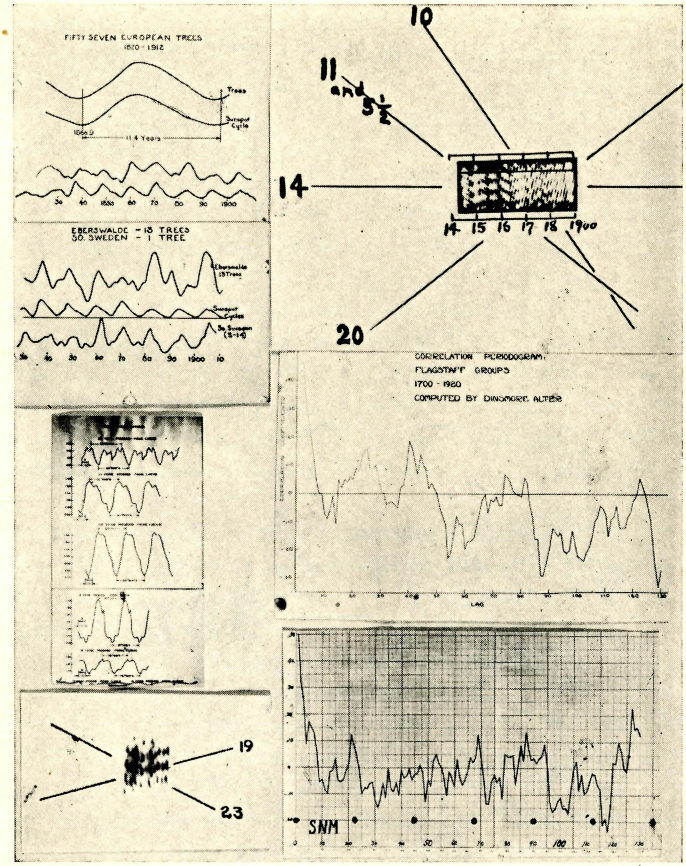

PLATE 4

13. Fifty-seven European trees and sun-spot cycle. Below: 13 Eberswalde pines and 1 Swedish spruce.
14. Cyclogram of Arizona tree record showing succession of cycles.
15. Arizona 20-year cycle by integration at 18, 19, 20, 21 and 22 years.
16. Alter's correlation periodogram of same, 0 to 130 years.
17. Cyclogram of same showing succession of 23- and 19-year cycles.
18. Alter's correlation periodogram of Sierra Nevada pines showing 22.5-year cycle at dots and its subdivision.

and continuous through nearly 3000 years and each curve is a running or overlapping mean of three successive 23-year intervals.

A large percentage of these 130 curves show clearly a 23-year cycle or some subdivision of it up to five equal parts. The division into 4 parts is illustrated in figure 19. Of course this work is far from finished but these

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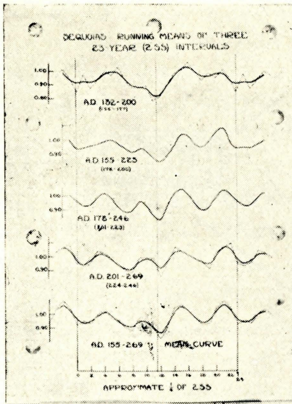

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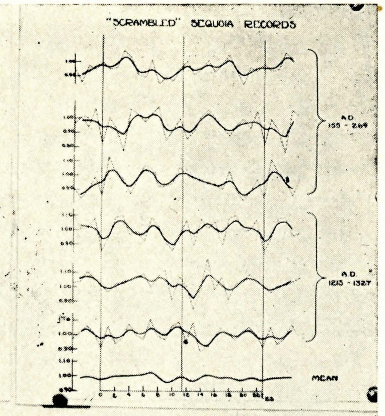

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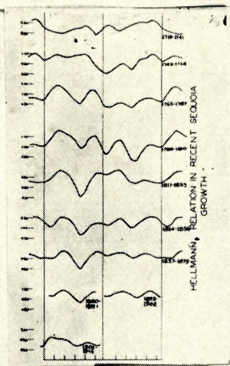

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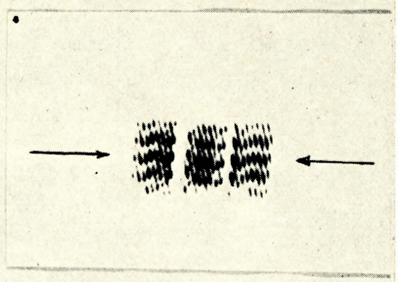

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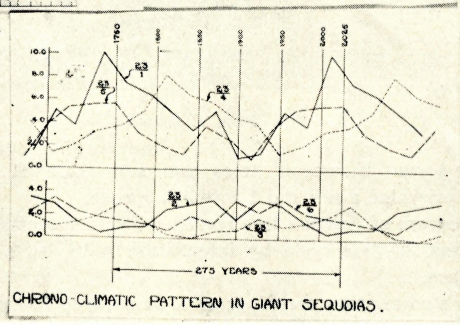

PLATE 5

19. Hellmann cycle, (a quarter of 23 years) in California sequoias, by integration method, A. D. 155 to 146.
20. Similar values drawn by lot and treated in same manner.
21. Hellmann cycle in sequoias by same method, 1719 to 1914.
22. Possible 275-year recurrence cycle in 2100 years of sequoia records (indicated in horizontal alignment).
23. Average cycle succession in Grant Park sequoias in 2100 years.

results apparently agree in the two separated sequoia groves. Limited checking has also been carried successfully to other sequoia groupings that for various reasons have been segregated. As a matter of safety a couple of hundred years of sequoia values were "scrambled" and then treated by the same integration method, as shown in figure 20. This brought out the fact that the manner of smoothing eliminates two-year cycles which in turn leaves 3-year cycles, or 8 crests in the curve, most numerous, 7 crests in the next and so on. One scrambled curve has five crests, and one has four, showing that some of the fractionizing in the real curve is accidental, especially in isolated cases. In the scrambled curves the same fraction does not occur twice in succession. But in the natural curves the same occurs three to five or more times in succession and the chances are greatly against accident. As the length of the fraction increases, for example from $4^1/_2$ to $7^1/_2$ years, accident becomes less and less likely. So even three curves in succession showing triple subdivision, $7^1/_2$ years, are very probably real.

The Hellmann relation is fairly evident in upland sequoias for the same time, as appears in figure 21, which was developed like those above. It is interesting to note that in the large groups of sequoias it seems to extend back to about 1750.

In these 130 curves, covering the age of the sequoias, a recurrence cycle of about 275 years seems to be a common character as shown in this preliminary study, three examples of which are given in the horizontal bands in figure 22. A cycle about 100 years long is common to them all and something near 220 years is also there. All these are mentioned by Turner. Something near 300 years is discussed by Clough. Dr. Alter mentions 250 years. The double value near 560 years also appears and it is possible that it will prove important. In order to visualize the possibilities, the 275-year length is taken as a workable solution for the time being. A provisional pattern based on this 275-year succession is shown in figure 23. This diagram shows the sequence of different short cycles in the 275-year pattern derived from 2000 years of the Grant Park sequoias and is perhaps the most promising sign at the present time. In it we find that the persistence of the Hellmann relation since 1750 agrees with previous recurrences of that cycle. If the various cycles continue as they have done we have some reason to expect that through the next 70 years this Hellmann relation should be less conspicuous or absent, with a probability of replacement by a 23-year cycle or the same divided into five equal parts.

This pattern therefore encourages us to hope that from the giant sequoias, checked by historical material, we shall obtain in some form of cycle succession a real step forward toward a theory of climatic change and long range prediction.