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TREE RINGS AND CHRONOLOGY

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BY
A. E. DOUGLASS

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TREE RINGS AND CHRONOLOGY

By A. E. Douglass

Director of Steward Observatory, University of Arizona; Research Associate, Carnegie Institution of Washington

Twenty-Five Cents

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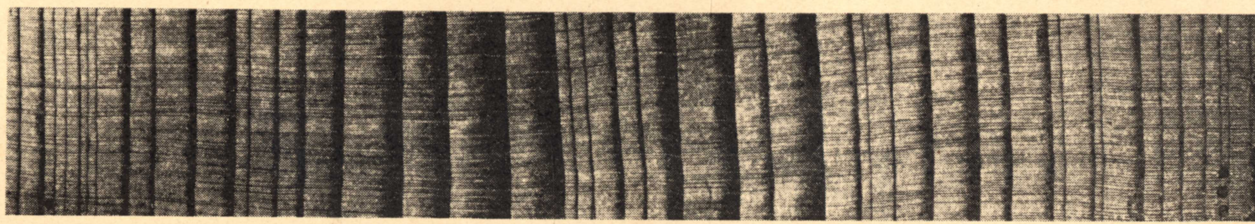
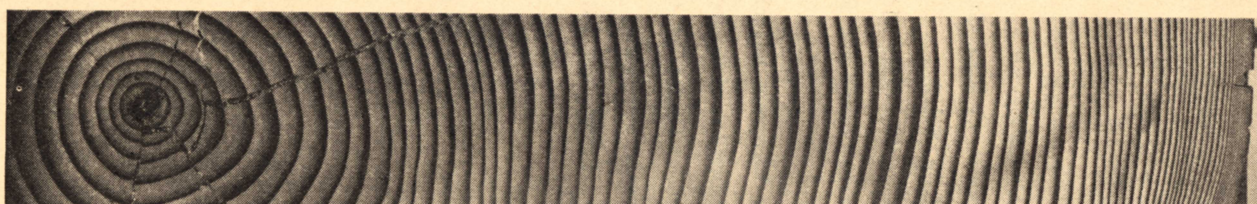


CLIMATIC EFFECTS IN TREES

The irregularities in the widths of the rings are the climatic effects; they make strong dating characters. Specimen M-179, Douglas fir, Chin Lee area; dot (left end) dates 660 A.D.;three dots (right end) date 700 A.D.



ABSENCE OF CLIMATIC EFFECTS

Absence of irregularities in the ring pattern makes dating impossible; associated beams have dates near 600 A.D. Specimen MLK-142, Douglas fir, Red Rock Valley, northeastern Arizona. (Specimens collected by Earl H. Morris; photographed by H. F. Davis.)

TREE RINGS AND CHRONOLOGY*

INTRODUCTION

The tree-ring work described in the following pages began as a co-operative search for nature's secrets along the paths of astronomy, botany, and climate. Combining these three sciences in a common cause might seem a day's work but the very nature of the case introduced a new factor—namely, thousands of years of historical changes in climatic conditions revealed by the long ring chronologies whose annual changes were accurately dated. This added enormously to the extent and interest of the investigation, making the whole study dynamic rather than static. These chronologies were seized at once as offering a rare opportunity for a historical study of climate, and so a new method was devised for the cyclic analysis of tree-ring and climatic records. This has, I believe, revised the approach to one of our great economic problems, estimation or prediction of future conditions. And then a fascinating human element entered in the dating of prehistoric ruins. This brought about a co-operative research between tree rings and anthropology in which by supplying multitudes of superb beam specimens, the anthropologists secure the exact construction dates of their prehistoric buildings, and hence, in part, history of migrations and other activities of the prehistoric people.

The ring of a tree is an annual affair—it is the layer of wood put on each year all about the tree structure. In tropical woods it is not easy to tell one ring from the next, but in temperate climates, with snow in winter, the succession of seasons during the year produces different characters in sequence in each ring, a large-celled, soft growth in the spring, turning commonly to a hard, reddish growth in the late season, which like fur coats for us enables the tree to endure the rigors of winter and be ready to grow again in the coming spring.

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*John Wesley Powell Lecture: Southwestern Division, American Association for the Advancement of Science, Denver, Colorado, June 24, 1937.

One can see these rings in the end of a beam or in attractive, artistic distortion on furniture, but the best way is on the tops of stumps out in the pine forest and in the logging camps where trees are freshly cut. Rings are easy to see in pine and cone-bearing trees. Their value for chronology building is best observed by tracing a line with the finger from the center of the tree section slowly out to the bark and noting the varying thicknesses of the rings on the way. The pine trees of Arizona produce wide rings at the center, the thickness gradually decreasing to the outside or bark ring. This gradual decrease is known as the age curve and does not carry the important message that trees can give us. But if in moving the finger from center to bark we encounter departures from the gradual and regular change and especially if we encounter sudden and marked changes in thickness then we are reading the wireless code of the trees. (See frontispiece.)

For to some extent the speech of the trees is like wireless, whose occasional long unbroken sounds in the earphones do not talk, nor do sounds talk if they vary continuously in pitch or loudness in one direction (like trees without rings, or with merely the age curve); nor do we get a message from a long series of dashes (like a long series of rings of the same size in the tree). But when we break up our wireless signals into dots and dashes, we can make letters and the letters form words and the message comes over the air. So the trees talk their message by the sudden changes which form, as it were, dots and dashes of ring thickness.

The writer's first thought that these rings could be turned to some special purpose came in 1901 when seven years' residence in the dry country in and around the pine and juniper forests of northern Arizona had impressed upon him the vital dependence of these trees upon each year's precipitation; and since in a general way it is the sun's heat that evaporates the ocean water and causes winds to bring that water over the continents to fall as rain, it seemed possible or even likely that we would find in the variation of ring thickness some traces of variation in the sun, perhaps some indications of the eleven-year sunspot cycle. The characters in any sort of climatic changes which could most easily be identified with a solar source would be cycle length and similar time of coming of the maxima.

Any attempt to trace relationship between tree rings and the sun would obviously need the approximate and if possible the exact dating of individual rings. It had been known for centuries that one could count back from the bark and assign dates to the rings if the rings were alike and easy to count. But our wireless simile showed us that rings all alike gave no message that interested us. And so began the dating of unlike rings or ring groups or patterns. This occurred in 1904, while measuring the rings in six tree sections, as the first tangible step in the proposed work. Counting was done inwards from the bark, and it was noticed that at twenty-one years in, there was in each tree a group of small rings which made a similar pattern. A stump near Flagstaff, evidently cut some years before, aroused a desire to see whether the same ring group could be recognized. That was easily done, but surprisingly it was only eleven years in from the outside, instead of twenty-one; hence ten years had passed since the tree had been cut and its date of cutting must have been 1894. The owner of the land in answer to a question as to when his timber had been cut replied that it was done in 1894, verifying exactly our tree-ring dating.

This was our first definite use of ring patterns and by them we had obtained the date of cutting of a tree whose outer rings were of unknown date. This showed the possibility of dating ancient specimens by a method depending only upon cross-dating or cross-identifying the interior ring groups or patterns, and, excepting one modern tree at the start, quite independent of any dated exterior rings. But it was seven years before the highly fundamental character of these facts was realized.

That realization came in 1911 while studying three score pines from near Prescott, Arizona. As piece after piece passed under the lens, the same long and definite pattern of rings was found. This was cross-dating, and its nearly universal application to the pine trees of that region and its essential value in establishing any chronology were finally realized. This milestone, passed in 1911, led the way directly to the formation of long ring chronologies, to the dating of prehistoric ruins, to the climatic meaning in rings, and other developments that will be told. By the present time we have dated and measured about a half million rings and have studied twice that number with care.

Before entering upon this list of results, it is a pleasure to mention those who gave aid in this long investigation. They are: the United States Weather Bureau, the Elizabeth Thompson Science Fund through Harvard College Observatory, the American Association for the Advancement of Science, Mr. T. J. Riordan of Flagstaff, Mr. Clarence G. White of Redlands, the Carnegie Institution of Washington, the National Geographic Society, the Research Corporation of New York, the American Museum of Natural History, the Museum of Northern Arizona, and the University of Arizona; besides these, many individuals have aided generously. And certainly I include with pride the skillful and enthusiastic students of tree rings, whose ready learning of the technique and whose highly successful applications of it have been one of the highest tributes to its genuineness.

RING CHRONOLOGIES

We insist upon a tremendous difference between a ring *count* and a ring *chronology*. This may be illustrated by our first work upon the big sequoias. In 1915 we collected fifteen V cuts from stumps in the high Sierras near General Grant Park; the youngest of these had only 700 rings and many had over 2,000. No. 1 was carefully counted and every ten years indicated by a pinprick, all in one evening. No. 2 took the same time, but when it was compared with No. 1 there seemed no resemblance between them in ring patterns except in the last century or so. How was one to know that in the last 700 years No. 1 had six or eight absences and No. 2 had three, and who could tell us where each absence occurred? The process of bringing the larger part of the fifteen specimens into agreement by finding the exact location of their errors took practically a year. Finally after two additional trips to the Sierras and four years of study a real chronology had been secured, 3,000 years long.

What then is the character of a ring chronology as we use the word? It means a precise sequence of rings, so checked and corrected by cross-dating that each ring means one year. In the case of the sequoias this meant that each ring was correctly dated, but in the pines and firs of the Pueblo area, trees that mostly reach ages under 200 years, we build scraps of real chronology that are not dated at all. But their relative dating is correct and the first long one was called "RD" or Relative Dating. When others came into use we needed a more specific term and so used some name like EPD (Early Pueblo Dating) or JCD (Johnson Canyon Dating). These were floating chronologies and to the writer remain under their special names to this day even though now the real dating of each is know. Thus one can understand what a chronology really is.

Two major ring chronologies have been developed—namely, a 1,900-year composite chronology in yellow pines, Douglas firs, piñons, and faintly in junipers, in the central Pueblo area of Arizona, New Mexico, Colorado, and Utah; and second, a giant sequoia chronology of more than 3,200 years complete in individual trees in the high levels of the Sierra Nevada of California. Of these two chronologies, the Arizona or Pueblo sequence interests us more because of its close resemblance to the winter rainfall record in that country.

The Pueblo chronology took a long time in its establishment. In January, 1920, cross-dating between Aztec and Pueblo Bonito, 50 miles apart, in northwestern New Mexico, was found. Neither of these ruins was dated, but it was proved that the building time of Aztec was forty to fifty years after the major building time at Pueblo Bonito. These ancient ruins therefore were dated relatively, not absolutely in our chronology. A common floating chronology was needed, and in 1919 a system of relative dating had been adopted by calling a certain large ring RD (Relative Date) 500, and the problem of finding the real date of this ring and hence the age of the pueblos was then in full swing. Its solution took nearly ten years and was largely carried through by the interest of Mr. Neil M. Judd who was excavating Pueblo Bonito for the National Geographic Society. To them it became the problem of dating an immense old ruin, the largest in the United States; to me it was also the establishment of a ring chronology, useful for many purposes.

Three beam expeditions into the Pueblo area were financed by the National Geographic Society, 1923, 1928, and 1929. The first was a reconnaissance trip and brought back about 100 specimens, borings, and sections from scattered locations in the Pueblo area. Serious work was begun on these and other prehistoric groups in the spring and summer of 1927. Floating chronologies were built up and attached to the Aztec-Pueblo Bonito series till the prehistoric sequence was 585 years long and still unattached to the historic ring series, which by 1928 went back in many specimens to 1300 A.D. and on one specimen to 1260.

Between this prehistoric and the modern sequence there was a gap that needed to be closed. To this end attention first went strongly to Oraibi and the Hopi villages. Search was made in the kivas for large logs of Spanish origin. These failing to reach back far enough, stone-ax-cut logs antedating the coming of the Spanish were tried and found to fail. Then search was made for the abandoned villages whence the inhabitants of the Hopi villages originally came; and in one of these, Kawaika near Jeddito, north of Holbrook, small bits of wood were found by Mr. Hargrave, and in August, 1928, it was provisionally dated in the 1400's. This was completely verified in the course of a couple of months, and thus the first prehistoric date by the tree-ring method was obtained. One or two other late-prehistoric ruins were dated, but the gap problem was not solved.

By the beginning of 1929 more than thirty ruins had contributed to the Relative Dating chronology and thus would be dated as soon as the gap could be closed. The problem still was to find beams of the proper age to close the gap by supplying sequences in the 1200's or before. For this, we must pick ruins of the right age. Two considerations were important: by study of the pottery types as related to historic or prehistoric cultures, it was easy to see that an orange color was much used at about the time of the gap, and we should select ruins where this sort of pottery appeared. In the second place, we recognized that the wood

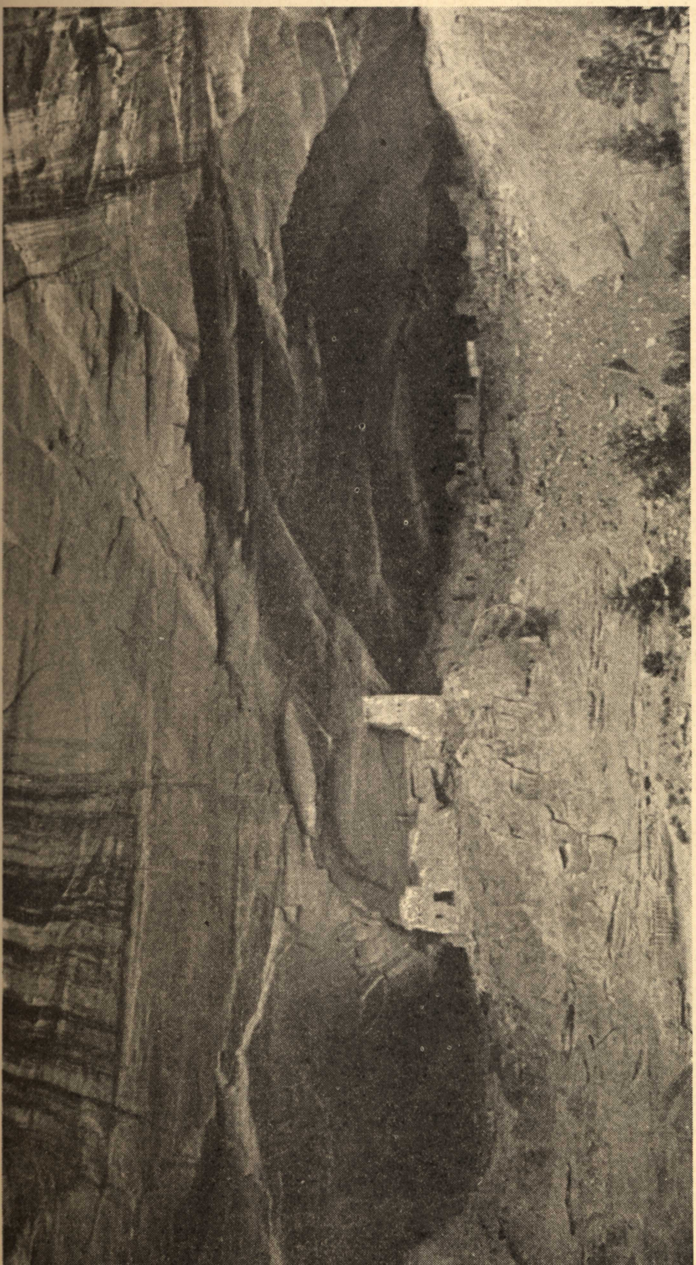

Plate I.—Mummy cave, Canyon de Chelly National Monument, northeastern Arizona. The large tower in the center was built about 1280 A.D. The structures in the cave to the right of the tower were built at various periods from 600 A.D. on. The structures beneath them were much earlier, the oldest dated log having been cut in 348 A.D.

specimens desired would be entirely decayed unless turned to charcoal. Abundance of charcoal was more likely to be encountered in or close to the pine forests. The best ruins to fulfill these two conditions were Showlow and Pinedale, some 50 miles south of Holbrook, Arizona, and there we did our first work in May, 1929.

On June 22, a fragmentary, hollow, charred cone that once had been the burnt end of a log was found. That night its early rings supplied a cross-dating between the known historic sequence and the late end of the relatively dated prehistoric sequence. Thus, all at once, more than thirty prehistoric ruins were given real dates, and the ring chronology was extended to 700 A.D. Now the list of dated ruins is approaching 200. It will reach the thousands.

Extensive initial work was done on the chronology preceding 700 A.D. in the spring of 1931. Two independent floating chronologies were developed, called EPD and JCD. (Plate II). In March, 1933, the two floating chronologies were joined, and EPD was shown to be the earlier; finally, in July, 1934, the joint near 700 A.D. to the earliest previously dated rings (suspected since January, 1932) was verified, and dated ruins were established as early as 348 A.D. and dated ring sequences extended back to 11 A.D. One wonders what climatic significance lies in the distribution of early building dates, a number between 348 and 380, another group in the early 400's, another group between 475 and 490, very few in the 500's, great numbers in the 600's, fewer in the 700's followed by great numbers from 800 on.

SEQUOIA CHRONOLOGIES

The sequoia chronologies were begun in 1915 as described above. In 1918 a special trip was made to the General Grant Park and King's River region to get the oldest trees mentioned by Ellsworth Huntington in his report of his measures on sequoia stumps in 1911-12 (see Climatic Factor: Carnegie Pub. 192). These trees included D 21 near Converse Hoist, whose innermost ring proved to be 1305 B.C., and two other 3,000-year trees from Enterprise Mill site, south of Sequoia National Park and radials from five different trees between

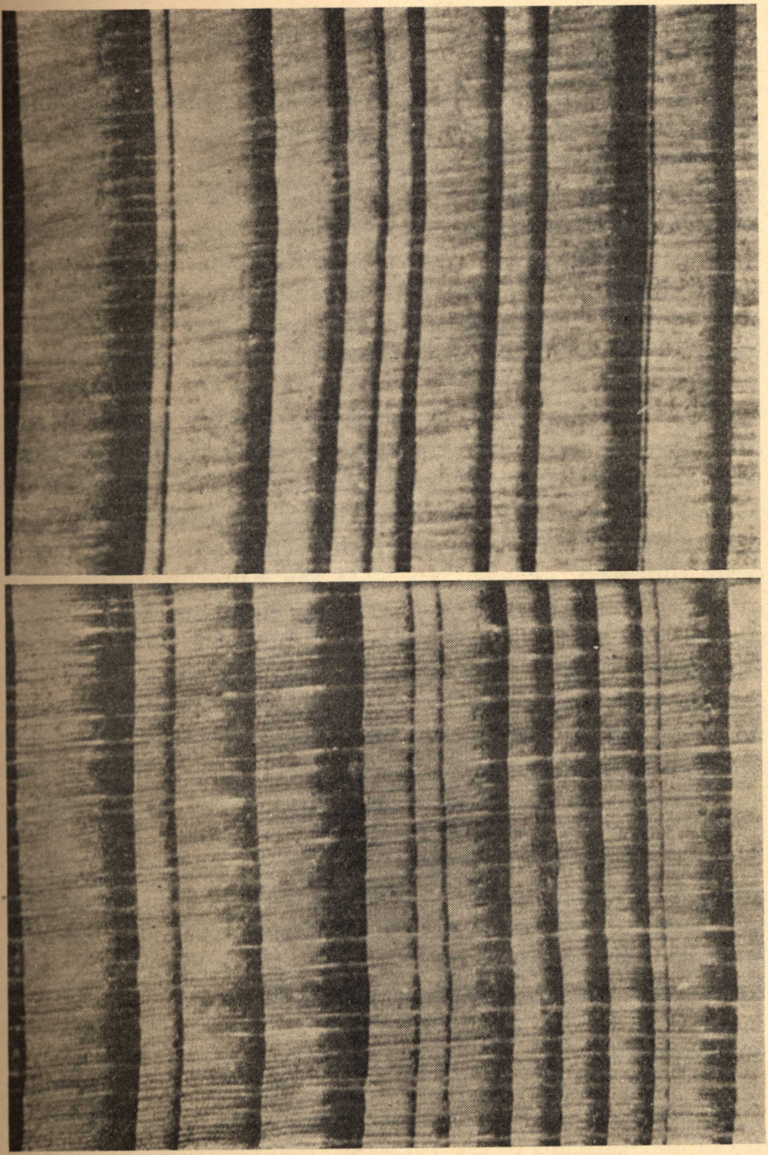

Plate II.—Two "signatures" or ring patterns that played an important part in the early southwestern ring chronology. Above is the EPD (Early Pueblo Dating) signature, 423-31 A.D., containing nine rings including the first and last small ones; below, the JCD (Johnson Canyon Dating) signature containing ten rings including the first and last small rings, dated 611-20 A.D. The unavoidable difference of one ring between these two patterns so similar in appearance necessitated two years of active search for the real relation between them and resulted eventually in an addition of five centuries of early chronology.

2,000 and 3,000 years in age from beyond the Hume Lake in the King's River country.

These were readily dated, but doubt was left regarding a possible annual ring which if genuine would be 1580 A.D. So another visit was made in 1919 to the same region, near the lake and lumber mill, beyond General Grant Park. Twelve more partial radials, averaging about 700 years each, were cut by the writer, largely in Redwood Gulch, locally called Camp 6. These showed the suspected ring to be genuine and the immense tables and dating marks on the wood had to be changed one year for all dates previous to 1580 A.D.

In 1924 Calaveras Grove of big trees was visited and cuttings obtained. The ring records were easily cross-dated with the records in the southerly groves. There were no very old ring records obtained, and their general sensitivity with respect to yearly changes was sensibly less than in the more southerly groves. In 1925 the Enterprise site, south of Sequoia Park, was revisited and numbers D 36 to 49 secured, of which D 43 had just 3,000 years but lacked a foot at the center. This central record was obtained in 1931 and showed a total age of 3,100 years for that tree. This then was the fourth 3,000-year tree. At this time also Sequoia National Park was visited to secure borings in living trees for checking the basic dating of the whole sequoia series. It was found to be correct.

It was specially noted that the dry winter of 1923-24 produced a small ring in 1924. This is quite worth mentioning to correct a published statement that the giant sequoias made large growth that year due to the lengthened growing season following the early disappearance of the snow.

CLIMATIC MEANING OF RING GROWTH

After our long and careful tests showing rainfall effects in our dry-climate trees, after our years of residence in this climate and observing such effects on every side, after dating prehistoric ruins by these very moisture-supply effects on the rings, it has been an interesting experience to encounter the reluctance of many biologists to admit that such effects can be found. No such hesitation appeared among the archaeologists in reference to dating prehistoric ruins by a method depending on climatic effects in the trees, for they had at hand immediate checks and could see that we corroborated what they had learned and then added a precision that was entirely new. The archaeologists met us halfway by learning at once the new method of dating prehistoric ruins and becoming highly proficient in it.

But there is obviously a background to the biologists' reluctance which has had a great influence. One meets it repeatedly; it is a matter of what we might call "home climate." An illustration or so will suffice. An editor of an eastern agricultural magazine wrote me that he could not accept Lynch's Rainfall Indices, 1790 to 1930, in southern California, because they were based largely on crop reports—the larger the crop, the greater the rainfall in the preceding winter; while in fact, he said, the reverse had been shown to be true by some investigations in England. Now of course those who have lived both in southern California and in England know that the climatic stress in the former is lack of rain, which is certainly not the case in England. England in fact seems near the other extreme—namely, a need of clear skies and favorable temperatures for the betterment of crops. The critic had not realized the effect of these climatic differences. The viewpoint of our dry-climate people was voiced by a young man in Tonto Basin (Arizona) to me many years ago when he refused to believe that people could safely travel about New England without carrying canteens of water. He had never seen it done at home.

All this illustrates what I have sometimes called climatic blindness. One understands perfectly that there is a momentum in the human spirit that makes a person interpret a new fact in terms of his past experience. Much of the authoritative biological work on tree and plant growth has been done in moist climates; and compared with northeastern Arizona even the coast regions of California, where some fine work has been accomplished, are highly moist. It has sometimes been impossible for me to convince eastern scientists of the inexorable dryness of the conditions under which we find tree growth here in the lower levels of the forest

at some seasons of the year

5043 Buchanan St, Highland Park

Frank C. Reid 835 El Molino, Pasadena in Feb. 1943 told me this with more detail than I remembered. L.D.

zones on the mountain slopes. It may be, as MacDougal once said in conversation, that our region where this tree-ring study started, is one of the most favorable in the world for it.

Our first tests for rainfall effects in tree-ring growth were made as early as 1906, long before correct dating had been reached. In 1914 an excellent agreement was found in yearly values of rain (November to October) and tree-growth at Prescott, Arizona, since 1867, and this was improved if a conservation factor was introduced to account for an apparent delay in the coming of the full effect in trees.

Local effects at Flagstaff were less satisfactory because in part I am sure the early Flagstaff trees were not so well selected topographically, many of them coming from relatively moist spots. But later selections of trees from near the lower forest border gave excellent agreement and then gave very fine agreement if some two years' lag was allowed in smoothed fluctuations. To people accustomed to the region there seems no manner of doubt that the trees properly selected in the matter of topographic environment contain important records of rainfall.

Experience with the rings in our trees and their relation to climate has given us a set of principles adapted to our region as follows:

1. *Uniformity.*—Trees that show good sensitivity (obvious differences in thickness between successive rings) and at the same time good circuit uniformity (many individual rings traceable about the circuit of the tree) are highly likely to cross-date with other trees; and conversely where cross-dating between trees is found the uniformity within each tree is likely to be of high order.

We have dissected Flagstaff pine trees to the core and found remarkable uniformity practically everywhere in the main stem of the tree, including its tip growth. The branches were datable but somewhat erratic; a root was datable but very erratic. All this agrees entirely with an enormous experience including multitudes of incidental tests of these points.

2. *Cross-Dating Principle.*—When many trees in an area are found to cross-date by common agreement in ring patterns over considerable periods of time, the variations in thickness

from ring to ring are indicating climatic changes because climate is the changing environment continuously common to all the trees.

It is rather self-evident that a tree showing these cross-dating characters does so because it is growing under a climatic stress, and good sense must be used in the selection of trees for climatic tests by choosing those that by their topographic environment are emphasizing the particular stress in that region.

3. *Latitude Effect.*—Since it is a climatic stress that impresses itself on the rings of a tree, we recognize that the stress in the lower forest border of the Pueblo area is lack of moisture from the fact that the trees there have all the warmth they can use in the heat of the adjacent deserts, and moisture is obviously so grievously lacking at lower levels that the forest area has come to a stop. A conspicuous fact of the environment of our trees is the great dryness of the soil during substantial parts of the year, a condition usually quite unrealized by the visitor used to moist climates and wet soils. Since these desert areas are a latitude character, it is possible that similar reaction will be found in trees at about this latitude, north and south about the world.

On the other hand, at high latitudes where the ground is frozen much of the year it is only good sense to expect that warm summers and increased length of time when the soil is thawed will give larger ring growth. Thus a resident of Alaska has reported to me that this really happens in his country. A relationship between the ring record in north Sweden and the temperatures has been reported.

4. *Topographic Influence.*—In any climatic stress, full advantage must be taken of topographic features that increase or otherwise alter the general climatic effect. Here in Arizona it is folly to expect a rainfall record from trees that get a permanent water supply from a stream near by: rather one finds the desired record in trees on a steep hillside or over a thin dry soil, and in this country we really mean dry soil when we say it (Plate III).

In the central part of the pine zone (remember that in this dry country the pine zone is limited to, and means, a certain range in altitude above the sea) the trees get a more favorable

Plate III.—Pine trees giving good climatic records; these grow in a dry wash at the top of Black Mesa, northern Arizona.

supply of moisture and give "complacent" series of rings; this of course is modified by local topography. The trees on steep slopes and on isolated hills and on sandstones and limestones, which are often cracked and permit moisture to pass away easily, develop better responses to yearly changes in moisture supply. Such records are called sensitive, because they depend more exclusively on the rainfall of the immediately preceding winter.

Trees near the lower forest border have diminished rain and are struggling very hard to maintain themselves. At the border itself they obviously fail to maintain themselves, and near there, we get the other extreme, many rings are lost: the rings that do appear may be microscopic, especially as the tree gets too large for its original soil. In such cases so many rings may be missing that it becomes impossible to identify the series, and the tree is of no value in climatic studies. The sheepherders find these border areas excellent for grazing; these trees are convenient for campfires, and the forest edges are retreating.

5. *Absolute Rainfall Indications in Tree Rings.*—Our earliest direct test of rainfall and ring growth was made in 1919 in connection with Prescott trees. A strong correlation was present and grew stronger with some conservation of the moisture; even a better relation was found when we used very large areas such as northern Arizona and northern New Mexico together. It seemed advisable to find, if we could, the type of ring record that gave the best rainfall information.

Upon examining about 700 large dated specimens, a distinct classification as to ring type was evident. We found that the quality characterizing the best recorders of rainfall was high mean sensitivity which is our technical name for strong cross-dating characters (irregular changes in ring size; see Plate IV). Some of them even exaggerate, making the big-ring years appear too wet and the small-ring years too dry. Evidently it is possible to find the type of record that most nearly represents rainfall variations. Prehistoric beams come from so many different places that it will almost certainly be possible to identify a number of locations giving ring growth that can be correlated satisfactorily with modern rain-

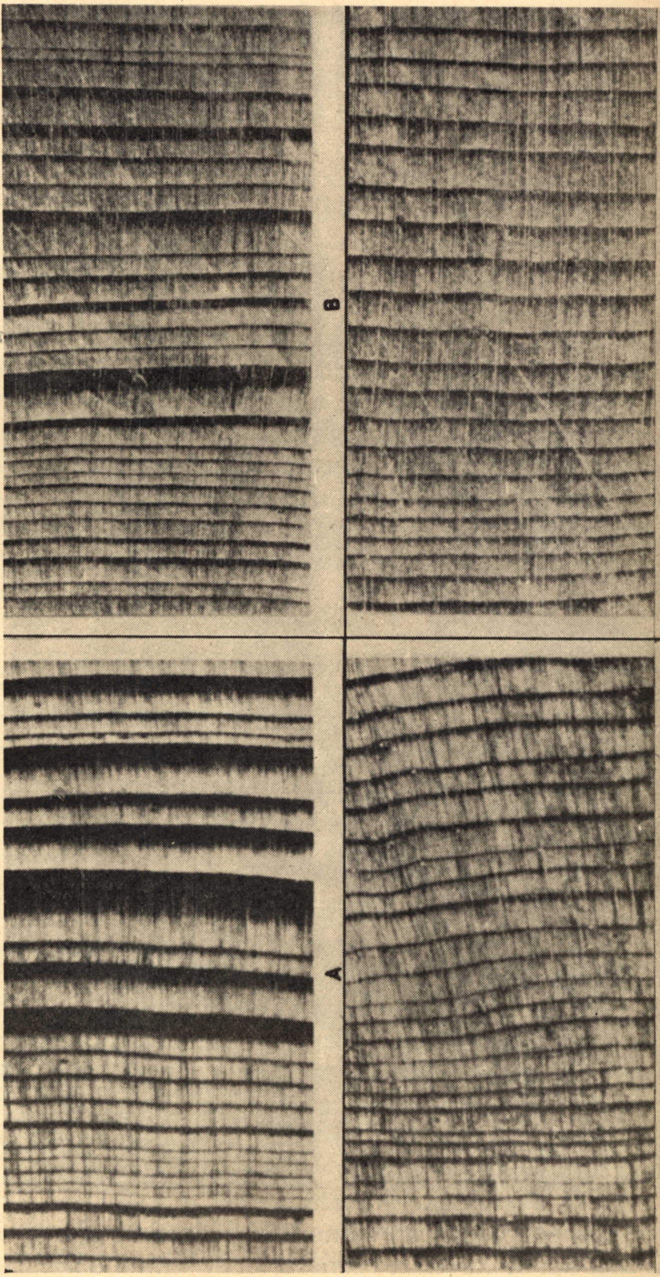

Plate IV.—The four types of climatic ring records; *A*, highest quality, very "sensitive" record; *D*, low climatic quality, very complacent.

Checked 5-13-40

1F-20 DF CN 208 1883

513 MV-23 DF CN-214

FL-19 Pine CN 207 1800 ?

BE-133 Pine CN 213 from 1400 ? P

fall and hence with ancient rainfall. This, so far, refers to winter rain. Douglas firs, which give superb records, practically do not have double rings, while the pines have them. The extra ring is due to summer rain and is easily identified. Thus the comparisons between these two species in different locations offer a means of estimating the total amount of winter rain and even the distribution of rain in the year. One can say with confidence that here is a definite method of estimating past rainfall amounts—a better method than any heretofore used—and that it can be tested on modern trees.

SEQUOIA RAIN RELATION

Judging from experience in getting the exact dating of about 100,000 giant sequoia rings and knowing the site of each tree, one becomes sure that the trees that grew in the uplands and on the ridges give ring records sensibly resembling rainfall records; those that grew in the wet basins average several times as large in mean ring thickness as the former and are very complacent and without doubt are more subject to surges of large rings whose meaning is questionable. Thus for the more detailed climatic work we much prefer at present only the upland trees.[1]

EXTENSION OF TREE-RING METHODS TO OTHER REGIONS

The situation in northern Arizona is so favorable that here if anywhere we might have expected a beginning of this kind of work. The forest region in Arizona is exceedingly dry both in atmosphere and soil. The Arizona trees have 200 to 500 rings, while the Monterey pines for example are apt rarely to go over 100 years. The longer sequences make

[1] Adverse comment has been made on our suggested climatic interpretation of the big tree-ring records because a study of Huntington's measures showed differences between his basin and upland trees. In my opinion a judgment based on such comparison would have little value, for while Huntington's dating was sufficiently good for his purpose, his upland trees with their small rings were subject to many errors of dating, mostly under fifty years; a few were practically without error but a single error of 300 years was found. The freedom of the basin trees from these errors of counting creates an inevitable difference between the two groups in his material, quite apart from the natural differences between them.

cross-dating much easier. And again the age curve of the normal yellow pine of Flagstaff is far less than in the coastal pine. This is the rate of diminution of ring thickness on passing from the center out to the bark. Such rapid change in the coastal trees interferes with good judgment of ring size. And lastly the double rings are very different in the two localities. Arizona has two well defined rainy seasons, winter and summer, with a dry spring and autumn. The main spring growth of the ring comes from the winter rains and begins in mid-June. There seem to be two extremes. If winter rain is very abundant, the growth in pine trees probably continues into the summer and uses the summer rainfall without break: if winter precipitation is very scant, the tree puts on only a very small growth and does not seem to absorb the summer rain at all. But there is an occasional middle condition in which the tree begins to form late wood after the spring growth, then succeeds in reaching the summer rains and returns gradually to the spring type of growth and later, perhaps in September, puts on the normal late wood. This produces a false (nonannual) red ring of late wood which is practically never mistaken for the real annual ring because it is hazy and ill-defined on the outside, while the real late wood has a sharp outside edge where the following year's growth begins. This enables us at a glance to give the correct interpretation of any ring under question. This type of double ring does not necessarily occur in other places.

CARMEL TREE GROWTH AND RAIN

An excellent study of ring growth in Monterey pine and of rainfall was made at Carmel, California, by Mr. Edmund Schulman. Carmel has no summer rain; the spring growth passes on into late wood, and the ring comes to a sharp outer edge. But it appears that once in many years (averaging the last hundred) this locality has very heavy rains in September and October that cause many trees to form a new small ring that also comes to a sharp outer edge as it closes for the winter. Thus it is not so easily distinguished from an annual ring, and doubtless many mistakes have been made in ring counting. These extra rings can be identified by comparison with the monthly rainfall record but otherwise have to be identified by cross-dating the ring patterns with other trees.

There were not many of the September-October rings in the last hundred years according to Mr. Schulman. At Carmel they appeared at 1844 (?), 1889, 1899, 1904, 1907, and 1918, several being grouped in or near the last great drought period in Arizona, 1896-1904.

Taking this into account he finds the correlation coefficient between Monterey rain and tree-growth 1900-36 to be $.75 \pm .05$ and the coefficient between Lynch's Rainfall Indices 1821-1930 for southern California and Monterey tree-growth to be $.62 \pm .025$. These give tremendous probabilities of real relation.

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CYCLE ANALYSIS

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CYCLE ANALYSIS

The urge to get into cycle analysis in connection with tree rings was more than mere curiosity or the desire to test out bioclimatic ring records of such extraordinary length merely because we had them; the original thought on which tree-ring work had been based was the evidence it might give on the solar-terrestrial relation discussed below in more detail. One realized, too, that the ultimate practical value in this relation is a better knowledge of past or future climates and weather.

So 1913 saw the development of a 500-year sequence in the pines of Arizona, accurately dated (an error of one year at 1464 was corrected in 1919) and showing a strong climatic interpretation in rainfall. Here was a golden opportunity of testing carefully for the presence of an eleven-year cycle, provided adequate means of making such test were available. I had made previous attempts at cycle study; each method used was a direct test of cycle length and not an indirect test by way of amplitude and phase. An instrument was therefore devised that used this direct method of showing cycle length first of all, and it proved to be able to give hitherto unexplored details about the temporary and unstable fragments of periods in climatic changes. The cyclograph (or cycloscope, for it is both) produces automatically a pattern that photometrically represents a cycle summation (or integration) table from which the cycle form is commonly obtained. This process becomes very easy if the summation is done in light values as was actually done in 1913 by using solid plots cut out in white paper mounted on a black background (Fig. 1).

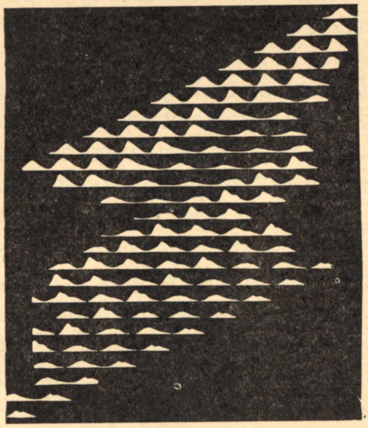

Figure 1.—The multiple plot, presenting the basis of cyclogram analysis; the "cycle" alignments of maxima are best seen by looking along the pattern at a low angle, from below upward.

This diagram, called a multiple plot,[2] became an epitome of cyclograph development. First, it reminds us how the

[2] Mechanism of the cyclograph partly shown in Plate V.

In order to make a multiple plot by an automatic process, the curve on a scale of 2 millimeters to the year is transferred to heavy brown paper cycle was found by numerical summation in one vertical direction; second, it visualizes to a slight degree how the pattern can be added by light values in many directions to make a periodogram; and third, it shows how the final most advantageous use is to leave the pattern without summation and observe the cycle fragments as straight lines of maxima, sometimes beginning or ending within it. These can be seen in Figure 1 especially by looking across the pattern at a low angle in what is here the vertical direction. These fragments gave rise to our usage of the word "cycle." They are exactly what we observe today in the cyclograph. For increased convenience the pattern is now turned on its side so that these cycle alignments take place more or less horizontally.

In its present form the cyclograph may be described as an optical instrument that automatically produces a three-dimensional plot in which time moves from left to right; differential time is up or down; and amplitude is in light

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and the maxima cut out. This gives us a cycle plot. It is placed in front of a brightly lighted background. This light passes through a cylindrical lens, so arranged that in the image produced the maxima are extended in vertical bands, while horizontally they represent time distribution as before. Finally this series of vertical, parallel bands falls upon an analyzing plate consisting of a bank of equally-spaced, narrow, transparent, parallel lines, tipped to the cylindrical lines at an angle of some 17 degrees. The pattern that comes through is called the cyclogram, for the equal spacing on the analyzing plate picks out the periodic characters in the data and throws good periods into straight alignments of bright dots whose direction is different for different cycle lengths. Thus different cycle lengths are automatically separated.

To increase the range, a most satisfactory method was devised of changing the size of the cylindrical pattern that falls on the parallel transparent lines of the analyzing plate. This was done by passing the light from the illuminated curve (cycle plot) through movable mirrors before bringing it to the analyzing plate. As the mirrors move and the image changes size, each alignment of dots representing a cycle appears to rotate in position angle, that is, direction. A place may be found where the alignment becomes horizontal. The size of this image then depends on the position of the mirrors, and so the mirrors' place on a scale becomes a direct measure of cycle length. In the latest model this scale reading is thrown directly into the eyepiece along with the final cyclograph pattern or cyclogram.

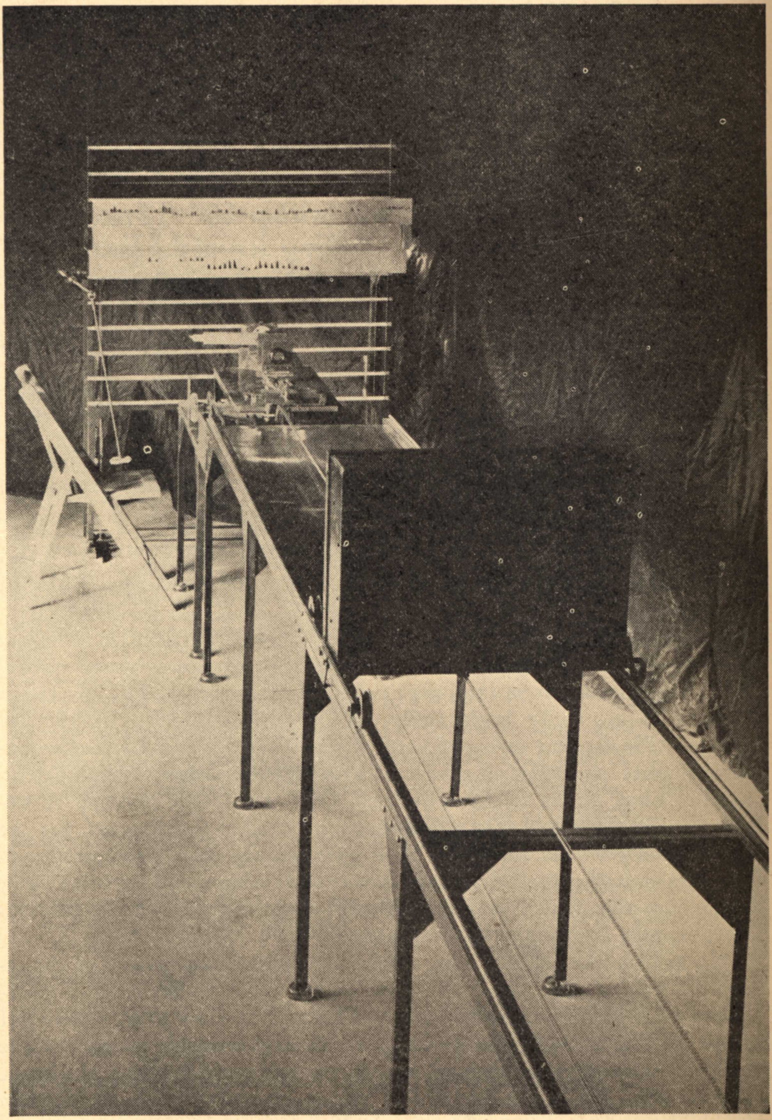

Plate V.—The cyclograph. At the back is the illuminator with the comparator frame showing three cycle plots ready for analysis (the middle plot is lighted); attached to the farther end of the track is the table carrying the optical parts; on the track is the movable box holding the mirrors.

intensity. It is instantly adjustable over a wide range of cycle length and has a comparator device for passing from one set of data to another in about one second's time interval. This gives very unusual facility in comparing the cyclic qualities of different sets of data. Its general appearance is shown in Plate V.

Since the pattern of the whole sequence of data is visible at all times, and the various cycles if present point in different directions according to their lengths and the setting of the mirror, it follows that any cycle alignment that does not last through the data may have its beginning or ending or other changes identified immediately as to date. The cyclograph separates coexistent cycles so that each may be studied by itself, an important operation that other methods do with greatest difficulty if at all. And lastly, it has the virtue of being incredibly more rapid than other forms of analysis.

CHANGING VIEWPOINT REGARDING CYCLES

Twenty years ago the accepted view about temporary or apparently unstable cycles was that they appeared to begin or end because of interference of "real" (that is, permanent) continuous periods. The ever-present hope of the cycle student was to find one of these permanent periods. In the ten years from 1918 to 1927, some 500 cycle plots (curves ready for analysis) were carefully analyzed, and there was never an impression of a reviving cycle that might have caused a disappearance by interference.

This use of the cyclograph brought about a fundamental change in the writer's viewpoint as to cycles. It amounted to a complete discarding of any idea of permanent periods in climatic data, other than the day, the month, or the year or their variants (lunar day, etc.). This was accompanied by a redefining of the words cycle and period, by which cycle becomes a general term meaning obvious or significant recurrence, such as seen in the cyclograph, and period becomes the special case where the repetition is approximately exact and permanent. In this definition the word cycle is directly applicable to the changes we see in climatic data, and therefore, if accepted, becomes highly useful.[3]

This usage has been suggested by Dr. F. E. Clements and Dr. E. B. Wilson. It lies in a medium position between two extremes, on the one hand the precision idea of a suspected period, held by the astronomers and their followers, and on the other hand the less exact view of the biologists and geologists that a cycle is a rather indefinite succession of conditions or states that is repeated from time to time. The strongest argument for the definition here proposed is that it constitutes an "operational" definition—namely, it is what we see in the cyclograph—thus anyone may get a perfectly clear idea of it.

To those who look upon the cycle as a suspected period it becomes a real period only when it is proved to be permanent and accurate. To them the climatic changes which are not permanent are random and cannot be admitted because they are not measurable by their methods. Now that we have an efficient method, it is proper and worth while to measure and study these temporary cycle effects. One ventures to hope that the word "cycle" will come into great usefulness by being accepted as the general term for apparently significant repetition.

It is further evident that the probability methods applicable to permanent periods cannot apply to cycles as here defined. In our cycle work, significance is judged by number of repetitions (or duration), amplitude, and regularity of recurrence. As to repetitions, five are usually regarded as a minimum number. Our amplitude is slightly different from the idea of amplitude in harmonic analysis. Here other cycles are visible at the same time as such and do not necessarily constitute the random background that reduces the amplitude in numerical computations. In addition there is no assumption at all as to the exact form the cycle should take. The assurance of exactness in cycle length in cyclograph analysis

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[3] It has been suggested that to avoid confusion the word "cyclic" be tried as a substitute for the word "cycle" when used in this more generic sense.

because only those are taken as cycles that do form approximately straight lines

is the assurance one has in passing a straight line through a series of dots that practically form a straight line anyway. The final assurance of physical reality comes from the similarity in many frequency periodograms, just as a cycle emerges after averaging several "sets." (For the frequency periodogram, see Figures 2 and 3.)

SOME APPLICATIONS OF CYCLOGRAPH ANALYSIS

A new form of cycle analysis is hard to understand without the instrument itself and difficult to appreciate without fairly extensive use of it. Hence two applications besides its use in tree-ring work are worth a brief description.

Cyclograph determinations of periods of variable stars illustrated the special method of applying that instrument to interrupted sequences of data, which is practically always the case with variable stars. The method as worked out in 1918 consisted of plotting observed light departures from a mean (which is not our usual method) and then placing a tinted glass or film behind all plotted values below the mean.

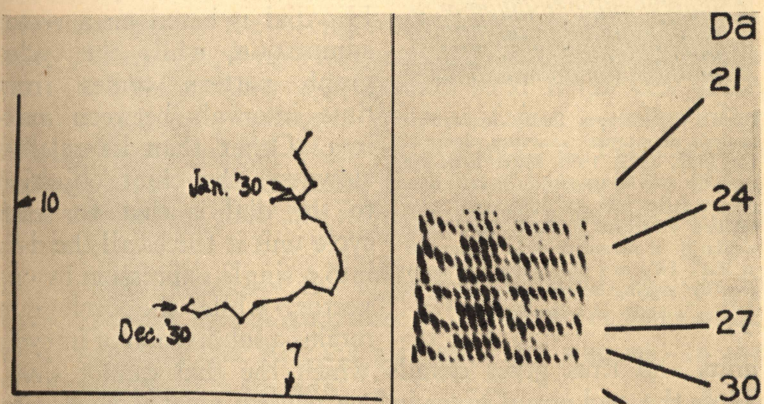

Plate VI.—A comparison between dial (left) and cyclogram (right) in cycle analysis of identical values (1930) of the magnetic character figure C; in the dial time moves along the bent lines, and each solar rotation is expressed in totality by the direction and length of a single line. In the cyclogram time moves from left to right, and solar rotation becomes expressed from above downward. Four rotations are shown to permit other cycle alignments than twenty-seven days to be recognized.

It is evident at once that opposite sides of the rotating sun act differently.

This gave a pattern made up of white maxima and colored minima. Then a scale reading was located that brought satisfactory analysis to the easily distinguished maxima and minima separately at the same time; thus they form alternating horizontal lines of white and colored dots in the pattern. It was estimated after tests that least-square solutions were reached in five or ten minutes after the cycle plot was made.

More extended mention should be made of the tests for solar rotation in various records because such tests offer a very promising means of searching for solar influence in terrestrial weather. Solar rotation (synodic) takes twenty-seven days at the solar equator, up to thirty days or more at higher latitudes on the sun. These different rotation rates are coexistent on the sun and are visible in sunspot motions, magnetic fluctuations (on the earth), and in other ways. The tests originated in the need for a comparison between Bartels' dial method of anaylsis and the cyclograph method applied to the same data. Use was made of the magnetic character figure C for the year 1930. His dial is based on a vector summation, while the cyclograph pattern comes from time intervals between maxima. Other than its relative slowness, the chief objection to the dial is that for each cycle unit it forces all the data into a single expression by one vector, while the cyclogram retains a subdivision of its cycle units and thus gives details which the dial cannot show. Thus the cyclogram gives in one pattern what is happening on the opposite longitudes of the sun and at different latitudes. Plate VI shows this comparison applied to magnetic character figure C for 1930.

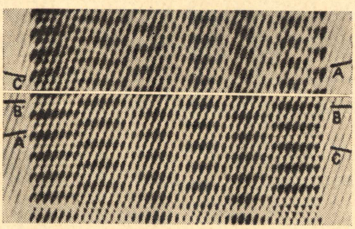

Plate VII.—Upper half, cyclograph analysis of magnetic character, figure C for 1932, 1933, 1934, lower half, the analysis of a synthetic curve; time moves from left to right, and solar rotation progresses upward. Note their similarity in secondary cycle alignments at AA', BB', and CC'; these are easily seen by looking across the paper horizontally at a low angle.

The most intriguing result was obtained in October, 1935, after a few minutes' application of the cyclograph to the

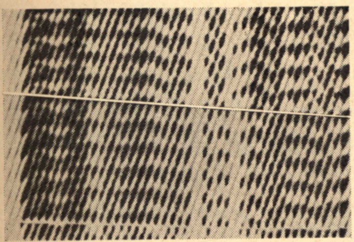

Plate VIII.—Upper half, cyclograph analysis of sunspot data, central disk 1932, 1933, 1934; lower half, similar analysis of calcium flocculus data for the same time. Note correspondence, especially the heavy horizontal alignments that denote long persistence in solar longitudes on a twenty-seven-day rotation; time moves from left to right, and solar rotation advances upward. Cycle alignments are best seen by looking at a low angle across the pattern horizontally.

magnetic character figure C, using data observed during the last sunspot minimum, 1932-34, though the same effect was noted as present at many other times. There are plain indications that the well-known, six-months' maxima alternate in opposite solar longitudes, even though at the same time Bartels finds them influenced to some extent by terrestrial conditions (that is, the relation of the sun to the earth's equator). (See Plate VII.) More details of this will be given elsewhere.

Most interesting is a rotational comparison between three-day sunspot means applying to the sun's "central" zone, 1932-34, and similar means of the calcium flocculi for the same area and the same interval of time (Plate VIII). One notes not merely the strong resemblance between these two solar phenomena, long recognized by astronomers, but also their obvious persistence in definite solar longitudes which has not been fully realized. We have found a similar effect of solar rotation, 1932-34, in ultraviolet light. This comes to us from all parts of the solar disk, but the absorption of the solar atmosphere probably emphasizes the radiation from the central zone.

The resemblance of the ultraviolet radiation analysis to that of sunspot and calcium flocculi is noticeable; and similar resemblance of the Arizona rainfall (101 stations) to the solar phenomena is evident.

APPLICATION OF CYCLOGRAPH TO TREE-RING WORK

In 1918 the first rapid and efficient instrument was made. During the following ten years or so, some 500 tree-ring curves were analyzed from one to five times. In 1925 a large collection of pines and firs from the western states was fully measured, condensed to forty-two groups, and these groups analyzed in various forms for checking purposes. The results were grouped in December, 1926, and the first frequency periodogram was made, giving the frequency of occurrence of the different cycle lengths.

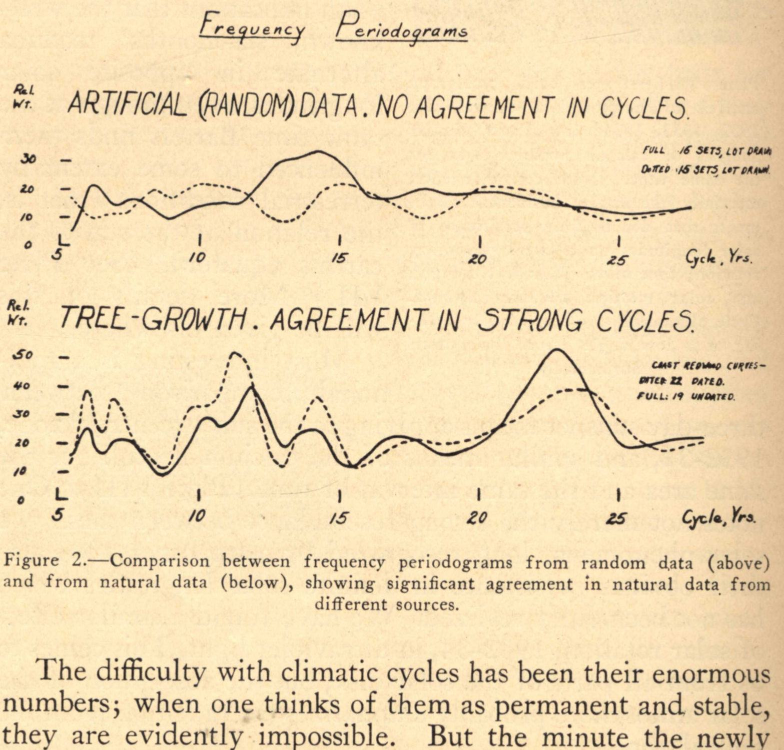

Figure 2.—Comparison between frequency periodograms from random data (above) and from natural data (below), showing significant agreement in natural data from different sources.

The difficulty with climatic cycles has been their enormous numbers; when one thinks of them as permanent and stable, they are evidently impossible. But the minute the newly suggested idea of cycle gets in mind, then all these sequences of recurrence are cycles (of our type), and it is quite in order to recognize that some are more important than others and some are purely accidental. Hence we see the advantage in grouping a large number from some one source in order to form a periodogram of the frequency of different cycle lengths. If the cycles in natural data were really random, we would almost never get frequency periodograms twice alike, and averages of many would approach straight lines; but we get many alike, showing that there is a tendency for certain cycle lengths to occur far more widely over the earth and in past and present centuries. This is shown in Figure 2.

In 1934 Mr. Edmund Schulman began doing extensive analysis. Probably we have each several times analyzed the larger part of the thousand plots of 150 to 500 years. Each plot probably had four or five cycles. So the number of cycle measures must run toward 15,000.

no ¶ ~~Thus,~~ the frequency periodogram representing a mass result from this vast amount of data establishes for us a cycle complex or group of preferred cycles in climate, as in Figure 3, top line. This group is usually the one operating in the last 200 years. In our long tree-ring chronologies there were differences with the passage of centuries. We use the name "chrono-periodogram" for a plot or pattern that shows such changes.

SOLAR-TERRESTRIAL RELATION

While a solar relation was sought since the earliest work on tree rings, it was taken more seriously in 1912 after finding an eleven-year cycle in German and Swedish trees. Near 1914 we found an eleven-year cycle in Arizona trees from the early 1400's on, except for some seventy-five years covering 1650 to beyond 1700. After this was published with misgivings about its reception by others, E. W. Maunder, unaware of these results, published his description of the great dearth of sunspots from 1645 to 1715, thus showing a striking agreement between tree-ring cycles and the sunspot cycle. An important feature of this tree-ring cycle as it occurs in many locations is that it has two crests in the eleven years, often very unequal; this double-crested cycle has been called the Hellmann cycle.

It is ten years since the frequency periodogram from western pines and firs and its resemblance to the periodogram of the sunspot numbers were first found. From the start it seemed important enough to withhold from publication until it was verified. So the forty-two curves were copied at a scale unknown to me and analyzed, the corrections were applied, and the result confirmed the cycle complex already noted above. Since that time Mr. Schulman has found the same complex of frequent cycles in the coast redwoods; we have confirmed them in the Yellowstone fossil redwoods and in the buried trees of the recent terrace at Flagstaff.

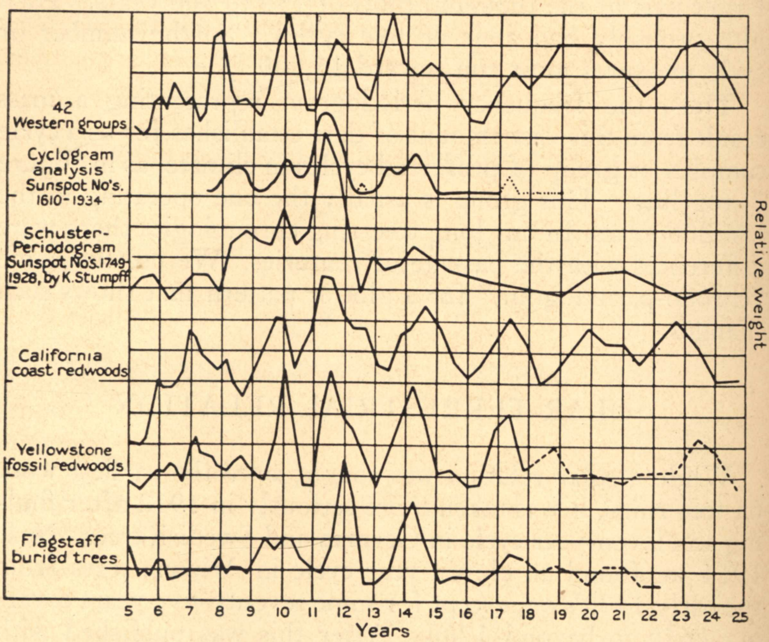

Figure 3.—Frequency periodograms from various sources, showing relation between terrestrial and solar activity when measured in cycles; second and third from top are from sunspot data; rest from tree-ring records.

In the periodograms of all these sources of data there is an obvious resemblance to a periodogram of the annual sunspot numbers made in the same way (Fig. 3). This we regard as a high order of evidence of a relationship between sun and terrestrial weather because of the enormous mass of terrestrial data that it represents.

THE CLIMATIC PREDICTION PROBLEM

We shall not deal now with prediction itself in the least—we desire to take advantage of this unique opportunity to present a brief note upon the problem in the light of our new analytical method and a clearer idea of the climatic material we have to work with.

Heretofore climatic-cycle investigators have been looking for something that is not there—namely, the permanent cycle or period (except the day, month, and year). Very few have searched for something that is there, for example, terrestrial uniformity, that is, the delineation of areas over which meteorological effects expressed in temporary and variable cycles are uniform. Some students using statistics have recently discarded conservation or sequential similarity in data in order to use a completely independent variable. In this they are discarding the very climatic features we are trying to investigate. These older analytical methods so beautiful and marvelous in their place, it seems to the writer, are preventing the advance of climatic studies, and the matter of definition is playing a far too important part.

Climatic students should discard the confusing word "random," which has its own meaning in a different sphere and should forget the word "real" that in its technical meaning is always the joyful challenge of the statisticians.

Since we have measured 15,000 cycles of the variable type, it would greatly help us to feel that our usage of the word is acceptable. But after all, the idea is more important than the word.

In the line of cause and effect from sun to weather, solar activity, solar radiation, terrestrial reactions, and terrestrial distribution follow one after the other. Each is complex, especially the last, and in fact we probably know least of all about this last one. However, solar activity and radiation to the earth are now being recorded in the most skillful manner; and we believe we have added great strength to the solar-terrestrial relation by the frequency periodogram.

The next step then on a large-scale operation toward long-range prediction finds its suggestion in the frequency periodogram giving a cycle complex, and its relation to the sun and in the difficulties of terrestrial distribution just mentioned. The indication is that we should analyze all available meteorological records that are long enough and develop every possible long tree-ring record having climatic interpretation in order to lengthen enormously the meteorological knowledge in many locations by ring records that are scattered at innumerable points over thousands of square miles. We can perhaps use as a geographical guide evidence of solar rotation effects in daily meteorological data. Then combining the work of the astronomer on all apparent changes in the sun, the physicist on all forms of radiation, the tree-ring and cyclograph man on the cycles past and present, and the meteorologist with his practical knowledge of weather changes about the world, we shall have a co-operative group that can look into the future.

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