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RESEARCHES IN DENDROCHRONOLOGY

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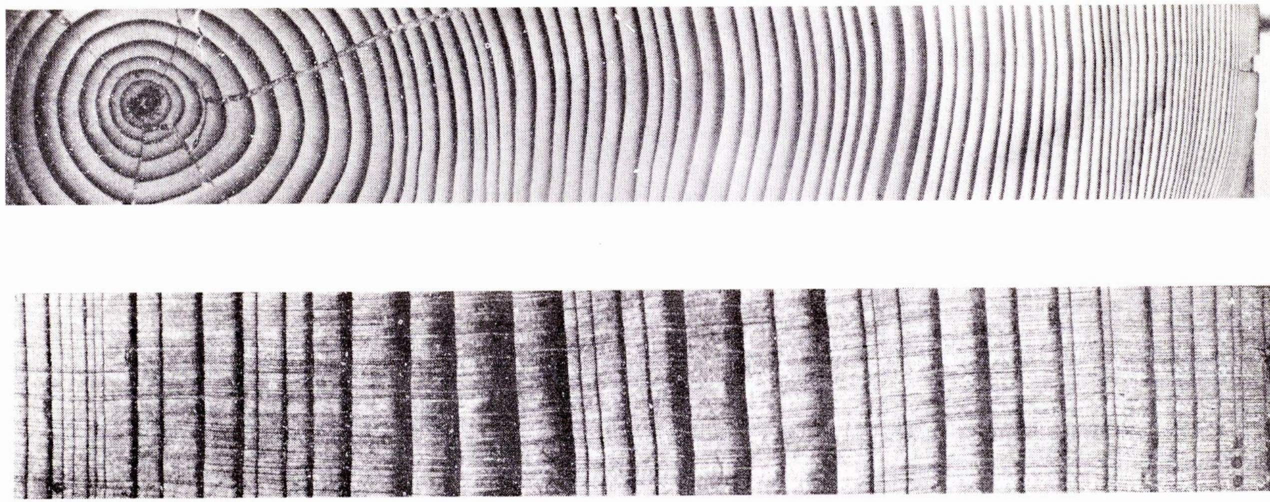

Fig. 1. Complacent and Sensitive Rings.

Above MLK-142, complacent and undatable; below M-179, highly sensitive and dated with precision. See year 700 marked by three dots near right end. The group of 5 small rings near left end, dated A.D. 660-664 is easily found near the "late" (right) end of Fig. 9.

From "Tree Rings and Chronology," University of Arizona.

RESEARCHES IN DENDROCHRONOLOGY*

By A. E. Douglass
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The Laboratory of Tree-Ring Research of the University of Arizona has developed a new source of climatic data in the rings of properly located trees and a new method of cyclic analysis specially adapted to handling climatic changes. These two features seem to the writer to open a gateway through which perhaps long-range forecasting may advance.

The purpose of this paper, therefore, is to give: First, the climatic basis of our tree-ring records which makes them proper material in the study of climate; second, the extent of these records in time and space, and third, a survey of the methods and advantages of our cyclic analysis. It is still too early to give the results of our tests.

I. Tree-Ring Basis of Our Climatic Data**

Assured many years ago that crossdating by ring patterns (that is, finding the same chronological placement of deficient rings in different trees) is in most of our cases entirely correct and reliable, the search was undertaken to find why it seems to fail in some cases. We were pointed clearly to the environment of the individual trees. So we examined minutely the surroundings of great numbers of modern trees as we bored them and studied their rings. We found that the best ring records came from sites of limited and discontinuous water supply and that the identity of climatic trees was established by definite crossdating. Thus crossdating between many trees is itself the evidence of the climatic origin of the dating features.

Fig. 1. In our dry country, complacent ring sequences, as in the upper picture, indicate that the tree is getting sufficient water and does not respond to changes from year to year. The lower photograph shows highly sensitive rings; these indicate a climatic stress, and in this dry country are associated with the limited moisture supply. If similar ring patterns are found in many trees, the tree-ring records are said to crossdate.

Fig. 2. Such agreement shows crossdating and identifies the common variations as climatic. Hence, a real climatic ring record is based not on a single record, but on a crossdated group of records from several trees.

Fig. 3. The upper pair of curves gives rainfall in the dotted line and tree growth in the solid line, 1867 to 1910. Below is shown the rainfall in the dotted line and a rainfall record calculated from tree growth by applying in reverse a conservation of the accumulated moisture type.

*Lecture given in the program of the American Meteorological Society, Pacific Division, A.A.A.S., Salt Lake City, June 17, 1942. Under the present date of February, 1946, a slight revision has been made to bring it up to date; the changes are very slight, chiefly an increased confidence in the results here presented.

**For highly important portions of this work, including several illustrations, my thanks are due to the Carnegie Institution of Washington, the National Geographic Society, the University of Arizona, the Museum of Northern Arizona, and other institutions and friends.

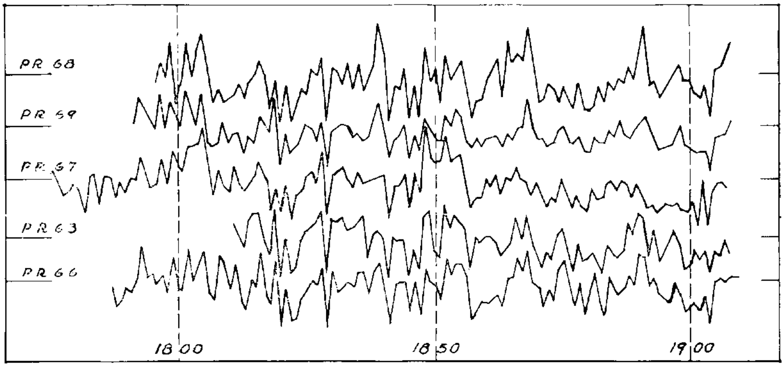

FIG. 2. Five Prescott Curves of Ring Growth in Separate Trees.

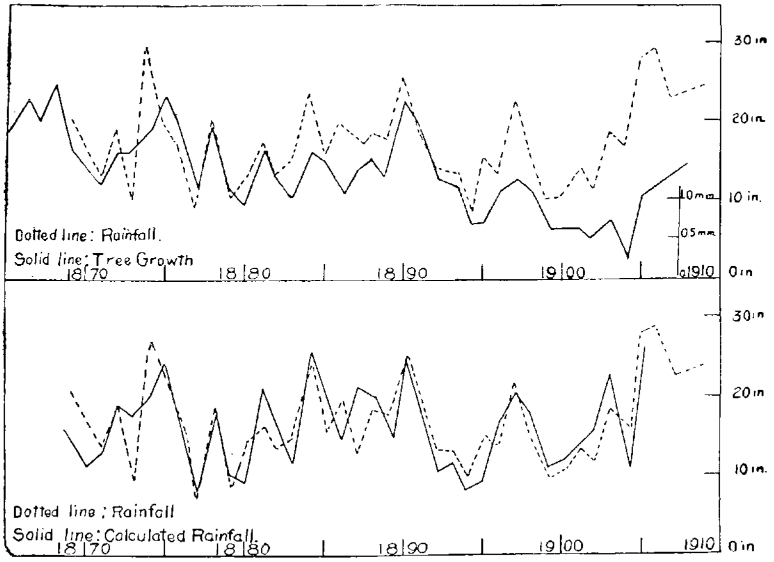

FIG. 3. Prescott Rain and Tree Growth.

FIG. 4. This grove of Douglas firs in Fewkes' Canyon, Mesa Verde National Park, is on steep northerly exposure, shallow soil, cliffs above and below, sedimentary rocks (upper right) slope away from this grove. These conditions compel these trees to depend on precipitation in their own area. They give highly similar ring records; two of them appear in curves 3 and 4 in the next figure.

FIG. 5. Ring records collected by Schulman in the type site and in similar groves near Mesa Verde National Park Headquarters 1 and 2 miles away. This crossdating indicates climatic effects and gives a near record of precipitation in that region.

FIG. 4. Type Site, Mesa Verde National Park; showing highly significant location of trees giving high quality crossdating.

FIG. 6. Schulman's researches near Monterey and Carmel showed that Monterey pines must be carefully selected as to their sites; the good trees are found in shallow soils and on steep slopes. In poor locations they sometimes give extra rings from rains in the autumn. These rings, relatively very few in number, must be carefully identified by comparisons among many trees. If sufficient tree records from different sites are secured, these non-annual rings may be shown in different stages from apparent strength to complete absence, other rings being unchanged. This shows the non-annual character of these extras. No conservation is used in this case.

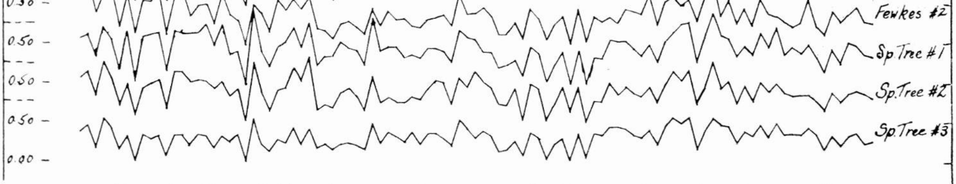

FIG. 5. Crossdating in growth curves of 500-year Douglas Firs in Type Site and Neighboring Canyons, Mesa Verde National Park. By E. Schulman. (in Bull. Am. Met. Soc. May, 1942).

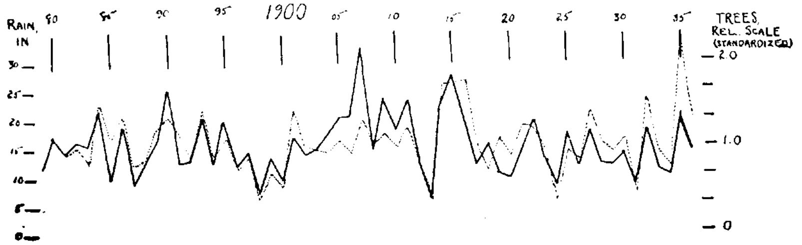

FIG. 6. Monterey Rainfall and Pine Ring Growth after Schulman.

II. Length of Our Near-Climatic Records

By a happy circumstance, the Indians found this region adapted to their form of agriculture and made settlements along the lower margins of the forest zones, where they could combine irrigable land with water supply for their crops and logs for their housebuilding. These logs carry in their rings such an accurate climatic chronology that they have made possible the exact dating of those prehistoric ruins. In the process of building chronologies back to prehistoric times we use the ring patterns as "bridges" that carry our dates from the early parts of a recent beam to the late parts of an older one. So we have called this the bridge method. Our identified ring patterns extend into the past nearly 2000 years.

FIG. 7. Chronology building commonly begins with easily dated modern ring records, and from them matches and dates overlapping ring records from older and older prehistoric ruins. However, we sometimes encounter groups of logs of unknown date whose rings crossdate and form perfectly good relative or floating sequences. Such floating chronology is immensely aided by placing an imaginary or relative date on a particular ring. For example, in the picture herewith, the left middle connecting line between A and B joins rings that were used as the zero year for a temporary, floating chronology called "M-179D" in specimen C. This "M-179D," therefore, served to express the ring relations in a considerable group until the time relation of that group to a still larger one, JCD, was obtained; these rings were then expressed in the JCD series until they were joined finally to our AD series.

FIG. 8. This picture contains the story of bridging a difficult gap near 700 A. D. The pattern 700-4-6-7-9-12, and especially 704-9, had been found in M200, whose center was, in 1931, found to be A.D. 475. Finally, in 1933 and 1935, the ring record here presented showed the connection between long chronologies before and after 700.

FIG. 9. The five small rings forming a group near the outside may be found in Fig. 1, M-179, close to the early end (left).

A chronology of more than 300 years may be traced in the ring photographs herewith. It begins with the small ring near the center of Fig. 7, A, 526 A.D., thence to Fig. 7, B and C; on 640 it transfers from C to Fig. 9; then at 660 it goes to the left end of Fig. 1, lower photo, and thence at 700 moves to Fig. 8, and extends to 840 A.D.

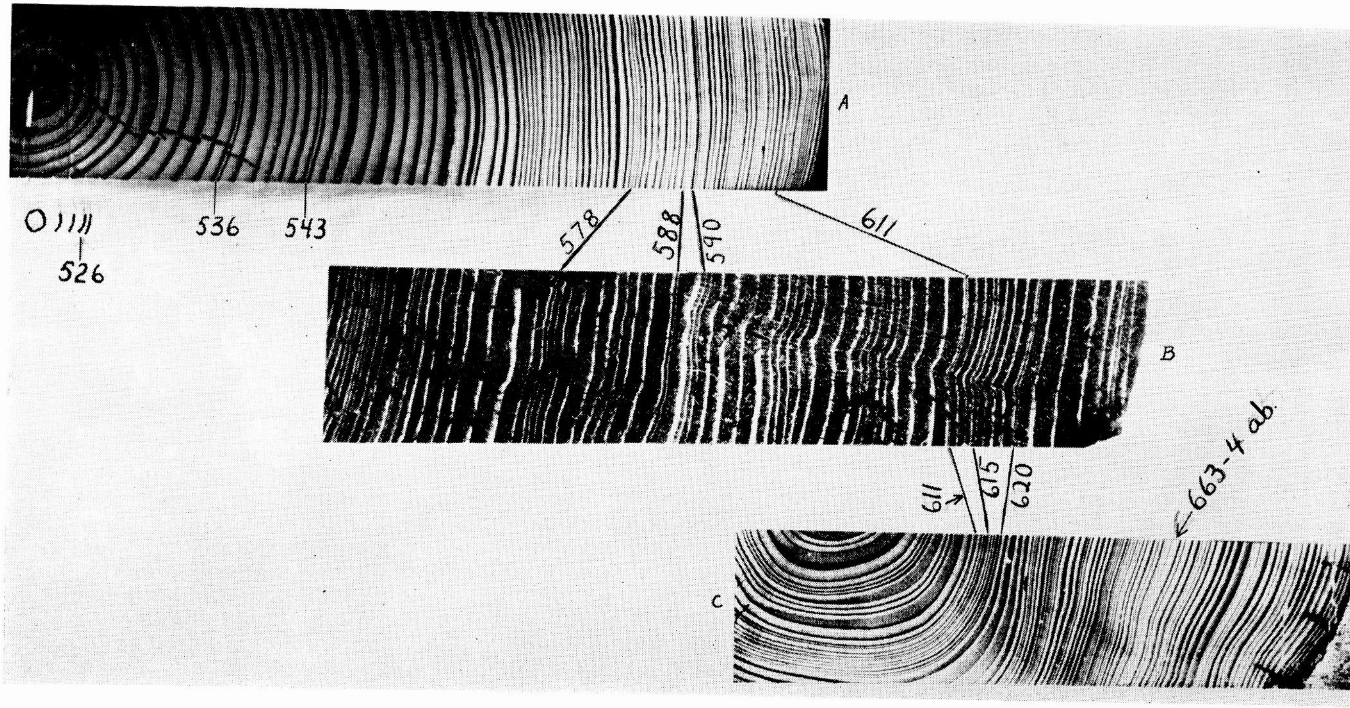

FIG. 7. Bridge Method of Chronology Building A. MLK-127, B. MLK-36, C, M-179 (from Carn. Inst. Pub. 486, Plate 7, slightly modified).

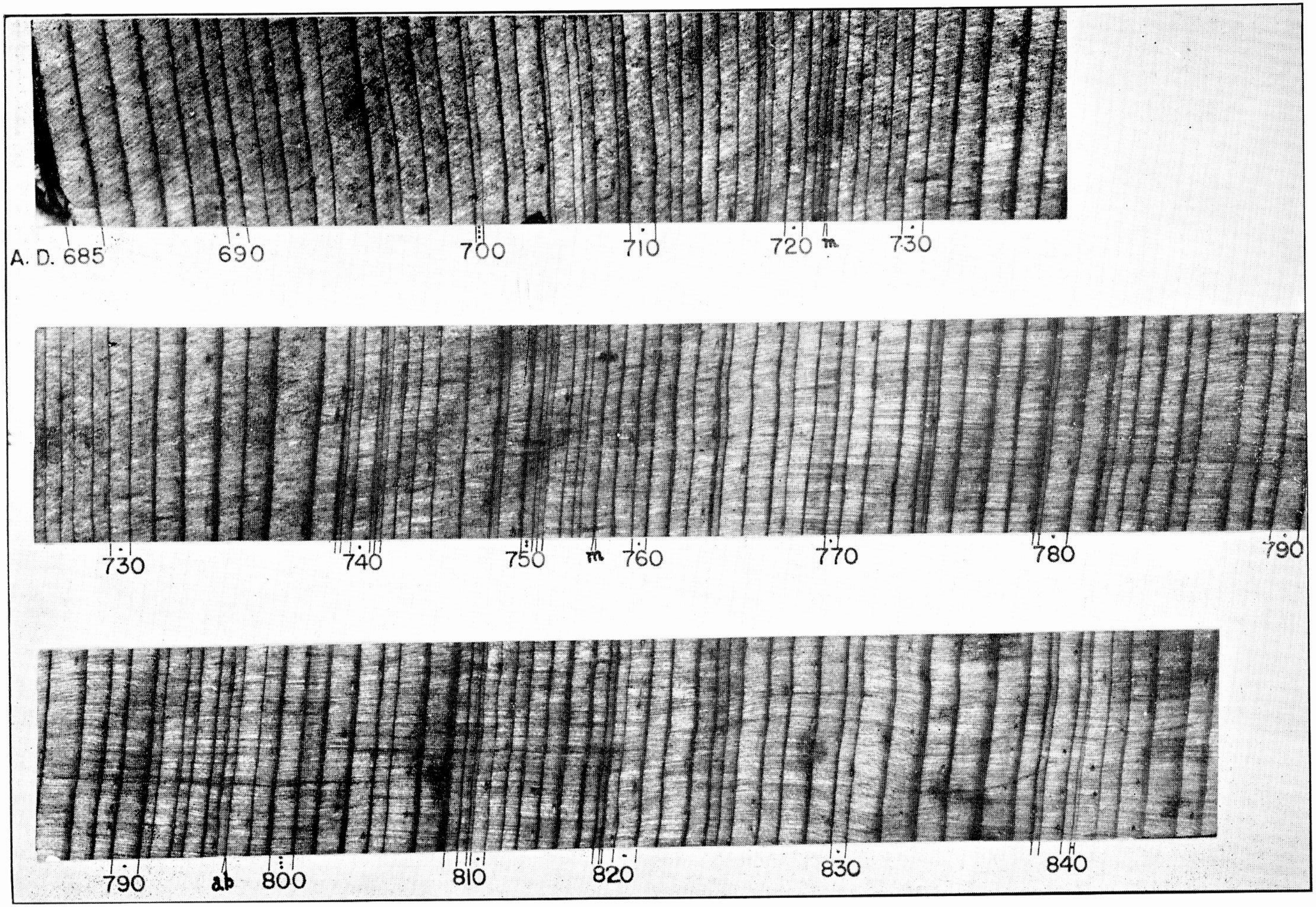

Fig. 8. CK-331. 685-845 Tree-Ring Bulletin, Jan. '37.

FIG. 10. The rings from A.D. 175 to 203 (incomplete) have exceedingly good climatic quality. They came from a ruin, Ignacio 7:101, Floor 1, Beam 9, and were collected by Mr. E. H. Morris and I. F. Flora. A.D. 176 and 181, 189 and 190, are very small—also 199 and 201.

Building a Chronology into Past Climates

Our first ring chronology was made in 1913, when crossdating was introduced. It was 500 years long and consisted of pine tree records of the Flagstaff area. Our collections increased rapidly after 1919, with large groups of archæological specimens from Aztec and Pueblo Bonito, both in New Mexico. At that time the chronology was carried back to 700 A.D.*

In 1931 a large section found by Morris, showing 356 rings, helped bind together several isolated or floating chronologies, and its series from A.D. 475 to 831 was temporarily called the JCD—Johnson Canyon dating. These early floating chronologies were then joined to the known chronology in early 1932 by a Chettro Ketl piece that gave a fine record from near 650 to about 800. This was confirmed by specimens from Allentown and Flagstaff in Arizona in 1933 and 1935.

By these means the superb collections of Mr. Morris at Mummy Cave and Obelisk and Broken Flute Caves in northeastern Arizona were dated. These specimens had formed a floating chronology first distinguished in 1927 and temporarily called EPD—early Pueblo dating. Its connection to JCD close to 500 A. D. was established in 1933. Dating of the best quality was carried back to about 250 A.D. In Obolisk Cave an immense Douglass fir log was found whose rather complacent ring series extended back to 11 A.D. This gave the earliest dated rings in the Pueblo area, but its climatic record was poor. In the last few years specimens from near Durango, Colorado, have given superb records through the 200's and back to 175 A.D. Also confirmatory pine ring records over the same interval have come from Bluff Ruin at Forestdale, near Showlow, Arizona.

Finally a good pinyon log from a cave near Kanab, Utah, found years ago by Mr. Jesse Nusbaum of the National Park Service, was dated recently by W. S. Stallings as cut in A.D. 217, with center going back to about 90 A.D. This stands almost alone as a good record between 105 A.D. and 175 A.D. except one assumed absence in the 150's.

Five prehistoric ruins have contributed to these early ring records, whose dates are within the 300's or preceding them. The locations are of interest and can be described with reference to the "Four Corners" of Arizona, New Mexico, Colorado and Utah. Taking that spot as a reference point, Durango, Colorado, is 75 miles east-north-east; the caves in Red Rock Valley on the southern edge of the Carizzo Mountains are 20 miles southwest; Mummy Cave in Canyon del Muerto is 50 miles south-southwest; Bluff Ruin, 10 miles south of Showlow, Arizona, is 175 miles south-southwest; and Kanab or the duPont Cave is 200 miles due west.

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*See Dating Pueblo Bonito and other Prehistoric Ruins of the Southwest. Paper No. 1 Pueblo Bonito Series, 1936, National Geographic Society.

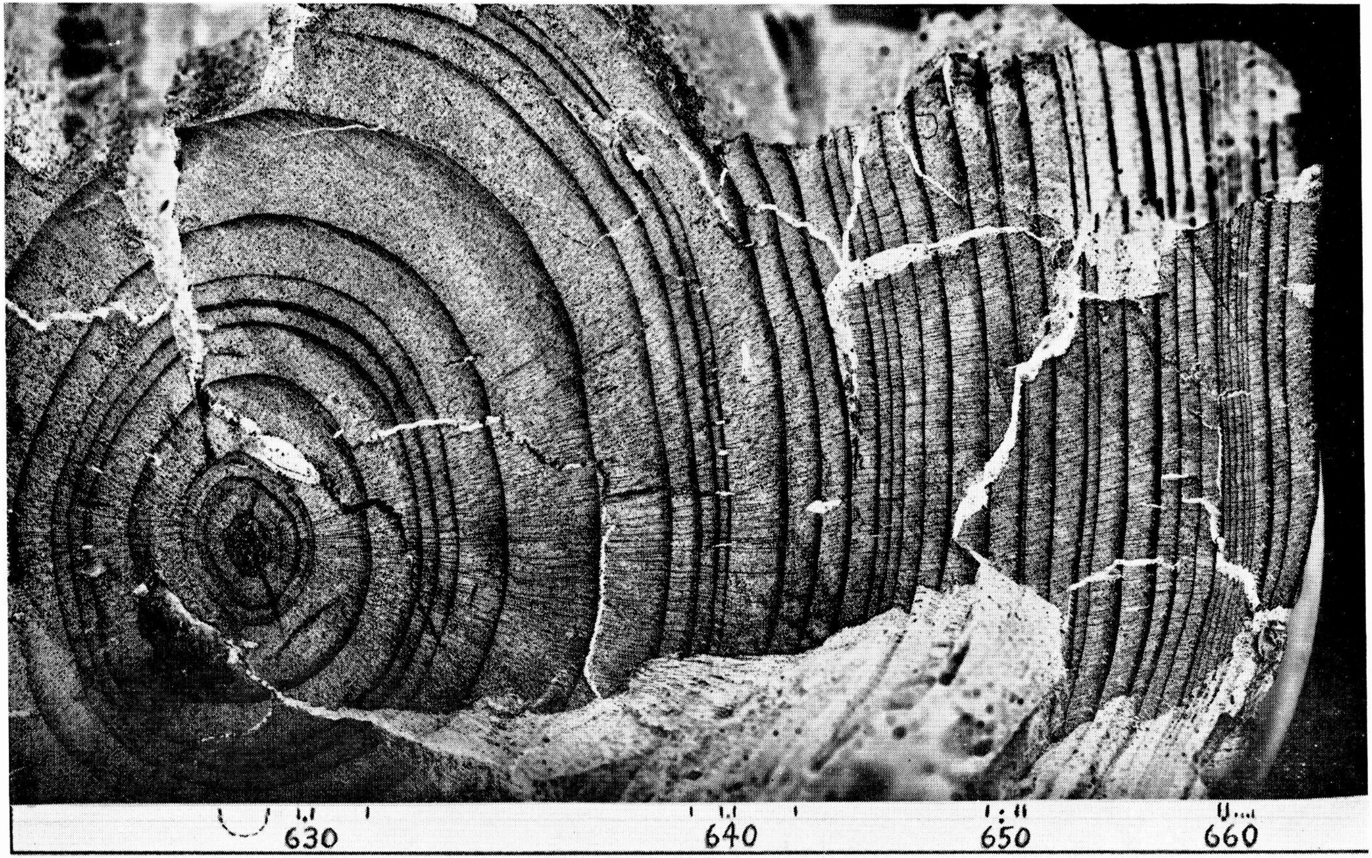

FIG. 9. MLK-17, Charcoal negative.

The dates at lower edge apply to a horizontal line from the tree center (at left) to right edge. Ring 651 is very small and shows best near its upper end. Photographed by H. Faurest Davis.

III. Geographical Areas of Our Near-Climatic Records

The preceding section dealing with the prehistoric records derived by tree-ring methods has been somewhat detailed, because it was the writer's fortune to contribute much time to its development. But the extension of tree-ring records into different parts of the world, which we hope for, is a large undertaking. All meteorological students know only too well the complexity of their records about the earth. For that very reason the highest efforts are needed to find, if possible, a real key to the distribution process about the earth. The attempt to untangle these data is imperative. Happily the early approaches to this difficult problem become valuable in themselves, to fill an engineering need.

The increasing use of hydro-electric power and the vast constructions for water storage and water use by increasing populations in semi-arid countries are at or near the time when deficiency of water becomes a strong controlling factor. Its forecasting would be of unbelievable value. But right now, the precise history of the water supply of the last several centuries can be of the greatest importance, because it gives an idea of what amount of construction will be necessary to meet future demands.

That is decidedly something to which tree-ring work can make a contribution and has done so already. My colleague, Dr. Schulman, has made careful studies by tree-ring methods of the history of the water supply of Coolidge Dam in southeastern Arizona, and more extensive studies of the drainage area of the Colorado River, to develop 500-year indices of the runoff of that river, which supplies Boulder Dam and Lake Mead. For the same purpose he has made special studies of large areas in Colorado, New Mexico and Washington (state), California, with exploratory studies in Canada and Mexico and many southern and eastern states. We may be perfectly confident that the extension of this work is destined to be worldwide.

Two important pieces of work have been done by two laboratory associates who have worked with us. One was by Mr. W. S. Stallings, who built a full Rio Grande ring chronology extending from modern trees back a thousand years. The other is by Mr. J. Louis Giddings, Jr., of the University of Alaska, Fairbanks, Alaska, who brought back here the results of some two or three years field work there and a group of specimens and spent a year in preparing a report which has been published jointly by the Universities of Alaska and Arizona under the title "Dendrochronology in

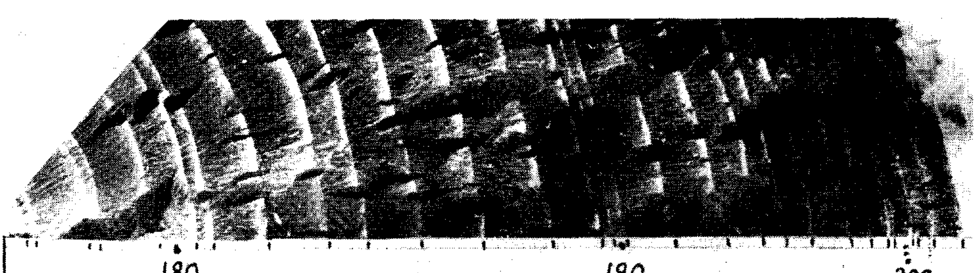

FIG. 10. Earliest Dated Douglas Fir Record, from Durango; Charcoal.

Northern Alaska." He found the distribution of crossdating in latitude as the forests fade out to the north. He proved that crossdating qualities in his spruce rings are at their best near timberline, which is the upper forest border, and depend upon temperature stresses. Such extensions of our ring records are important contributions to a world picture and are therefore basically important.

The growth curves derived from tree-ring series as described provide a substantial basis for investigations of climatic changes. They supplement the observed meteorological data by providing (1) a length of record many times that of the longest meteorological series, (2) records in mountainous areas and on sites where meteorological data are rarely obtained; such sites are, perhaps, more representative of general conditions than those in large citeis; and (3) series which are homogeneous throughout many centuries, in contrast to the striking heterogeneity of the longer meteorological series.

IV. Cyclic Analysis of Climatic Records

A study of cycles is a serious subject to include in a non-technical paper. But its inclusion is much desired now for two reasons. The first one is personal. Years, ago the relation of terrestrial climate to the sun, to be tested by cycles in the rings of trees, due to weather influence, was the idea that started this study of the rings.*

The second reason is this: We are sorely in need of the kind of forecasting that will help power and reclamation projects. Our tree-ring laboratory for more than 30 years has been gathering historical climatic data in the rings of trees of unique length and precision and has been subjecting these data to a special kind of analysis that seems very helpful in climatic studies, because it easily handles the unstable recurrences (cyclics) that constitute a large part of climatic changes.

Nature makes use of two kinds of cyclic phenomena; one can be called the planetary type, in which the planetary returns are so well formulated that they can be predicted with precision. The other can be called the climatic type; it may be exemplified by a hypothetical geyser whose subterranean reservoir needs to fill to a certain point before spouting takes place. Let us attribute the filling time to the wetness of the season, for which we do not yet have a formula. At the moment we may include in this type cyclonic motions in fluids that fade out and thus are unstable. These introduce variables that we know too little about, but while they do not necessarily mean random occurrence, they do eliminate the regularity of planetary motions and change the word "prediction" to the word "forecast." Our offering to the problem is two-fold: The first part is theory, namely, that recurrences originating in the fluid sun, or taking place in the earth's fluid atmosphere, cannot be stable or permanent and must belong to the second or climatic type of recurrence; they, therefore, are not

*That idea took form in 1901 when, after visiting Kanab in Utah, I went down the precipitous east side of the Kaibab Plateau and noted the climatic change from Jacob Lake in the pine forest at 8000 feet altitude to the dry desert at 4000 feet. The question naturally followed: why should not similar changes from year to year enter the rings of trees. And if such rainfall changes are influenced by solar activity, we could perhaps secure a history of the sun.

proper subjects for harmonic analysis; and, second, we have produced a practical form of analysis, adapted to unstable recurrences. By applying this to tree-ring material, we are obtaining the distribution of unstable terrestrial periodicities in time and space.

Once recognizing these cyclics that are so prominent in cycloscope analysis, many phenomena can be much more clearly described, for example, sunspot data. As will appear below, the pattern or cyclogram of sunspot data shows at once that sunspot recurrence is not merely a series of random points about a mean, but rather a series of two or more cyclics in succession. These successive near-means are Bartels' quasi-persistences which he regarded (1935) only as obstacles, because they were not permanent. We recognize them as important features in the sunspot cycle.

This led us to consider what a proper analysis must do in examining the significant, but apparently unstable, recurrences in climate and sun. Evidently we need to see at once the time of beginning and time of ending of each cyclic, and, of course, its phase, or time of maximum, and the presence of harmonics. Most of all, we need the main periodic cycle length and its steadiness in that length. Its amtitude is less important than its cyclic length, because much more variable—(one recalls the "spotty" character of the amounts of rain in this dry region.)*

The cyclic details named can be found with difficulty by expensive and slow computations, and are often overlooked. We, therefore, worked out, in 1913, and 1914, our highly rapid visual and photographic method of analysis, which we call cycloscope, or cyclic analysis.**

This analysis consists of an instantaneous, automatic three-dimensional, multiple pattern of maxima (or minima if desired) from 5 time units of cyclic length to about 28 of the same. It analyzes 450 to 500 terms at once and can be changed in one second to a different set of data.

Our method depends on interference between 2 sets of parallel lines at a small angle to each other (15° to 17°); one set is commonly vertical and spaced directly from the maxima in the observed data; the other set, slightly inclined, has narrow transparent lines spaced in a true periodic series. The bright vertical lines of the observed maxima pass through the equally spaced, inclined narrow transparent lines of the grating and are cut up into fragments which are strewn about in a pattern, but which inevitably have this character: that any set of maximal fragments that form a straight line must have occurred originally in true periodic order; the pattern is called a cyclogram. Great range of cycle length is secured by changing relative size of either one of the sets of parallel lines. We find that changing the scale of the data gives a stronger instrument than changing the gratings, because the harmonics are made easily recognizable.

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*Our winter rains cover a great area in any one storm—thus for either storm or season, the time of the storm or time of the phase of the rain curve is the important common element. But the amount of rain or the amplitude of the rain curve in any one place, even when expressed as relative to its own normal, is less constant for many reasons. Hence an analysis based on amplitude is much less practical than one based on cyclic length.

**See Astrophysical Journal, October 1914, "A Photographic Periodogram of the Sunspot Numbers"; and April 1915, "An Optical Periodograph". Also Climatic Cycles and Tree Growth, Vol. III. Carn. Inst. Wash. Pub. 289, 1936, Appendix by Schulman.

FIG. 11. Showing mirror box on track to right: its movement gives great range of cycle length by changing the horizontal length of the image of the observed data as it falls upon and through the grating; comparator (upright frame at left) enables us to compare different sets of data in rapid succession; the observing eyepiece is at left center, see next figure. This instrument uses a variable image and constant grating, and harmonics are easily seen and described.

FIG. 12. Note that from the illuminated cycleplot at left in the comparator, fourth from bottom, light passes to the movable mirrors outside on the right, then back through cylindrical lens and grating in center of picture, where the analyzing image is formed.

FIG. 13. Cyclograms have the time scale advancing from left to right, and an enlarged time scale, from above downwards. In the cyclic row conspicuous at the left center, the cycle length reads closely 10 years, as in trees. From 1788 to 1829 the cyclic is 14 years closely; between 1837 and 1928 the average is 11.4. Thus we find several cyclic readings. The best straight line through the data since 1610 is close to 11.2 years, which is near Newcomb's result. But a general value like that is obviously a very defective way of stating the facts. The cyclics are prominent in this form of analysis, and one can readily locate the dates of beginning or ending, or change in them.

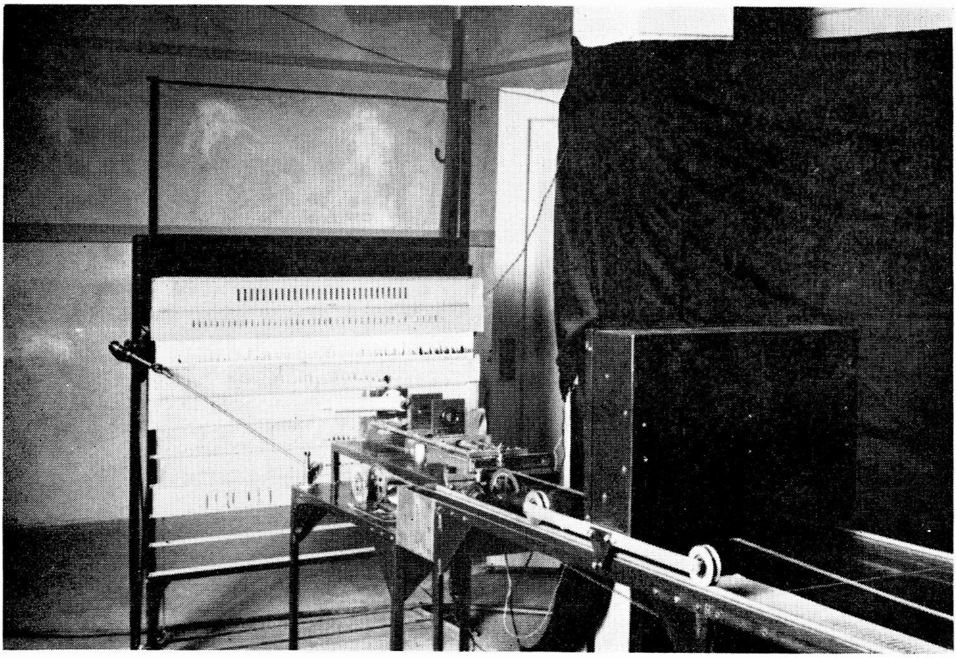

FIG. 11. Cycloscope Built by Aid of the Carnegie Institution in 1936.

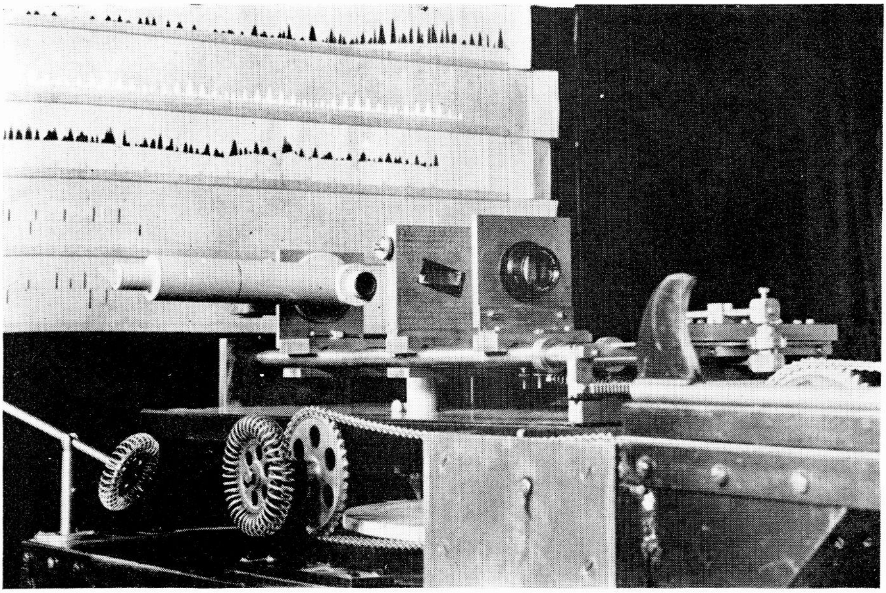

FIG. 12. Cycloscope Close-up: Observing End.

FIG. 14. There are 4 of the longer identical horizontal lines giving (left to right) the first maximum at 1816; the periodicity is an 11.6-year cycle with maxima usually 2 years after sunspot maxima; the last one in that line came in 1909; the intermediate (shorter) horizontal lines indicate a submultiple, which is 5.8 years. In this secondary line, the horizontal spacing shows maxima occurring some time after sunspot minima, with the last

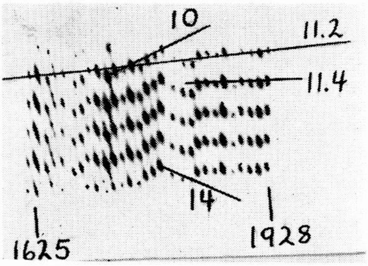

FIG. 13. Cyclogram of Sunspot Maxima (Negative) 1610-1930, to show cyclics as they begin and end; their cyclic lengths indicated by the direction of the alignment are given in years in the diagram.

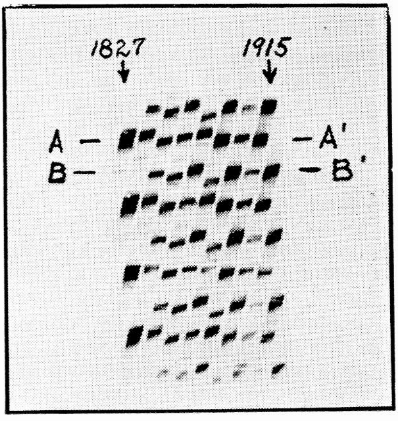

FIG. 14. Cyclogram of Ring Record in Grand Canyon Trees; Centralized Maxima to Show Harmonies.

(The enlarged time scale advances upward in this diagram.)

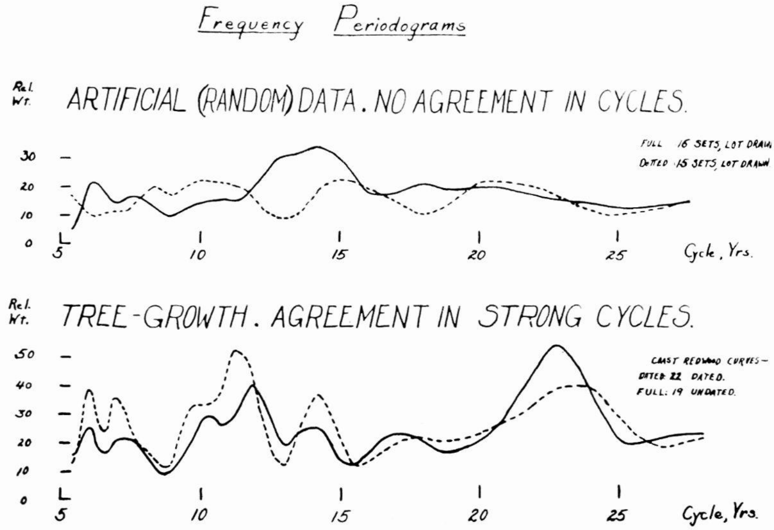

FIG. 15. Frequency Periodogram Shows the Difference between Natural and Lot-Drawn Data: Prepared by Schulman. From Tree-Rings and Chronology, 1937.

one in 1915. There is some evidence of a 23-year cycle. These Grand Canyon specimens came from close to the Canyon's edge, about 14 miles east of El Tovar.

As a very efficient tool in our study of cyclics by the rapid cycloscope analysis described above, we have developed and used extensively the "frequency periodogram" giving the frequency of occurrences of a series of cyclic lengths in a group or groups of data. This takes the form of Shuster's periodogram, with cyclic length in the abscissæ and frequency in the ordinates. The different occurrences may even be given weights. The result in Fig. 15 is a good sample of great numbers of cases.

The upper curves are made each from independent sets of 15 trees each, values being drawn by lot. There is no agreement. The lower pair of curves shows the agreement between the same sets of data when taken in the natural order. Hundreds of cases have given us these results in natural data averages and nothing in random data averages. Coast Redwoods were used in this case. Hence we feel that unquestionably we have

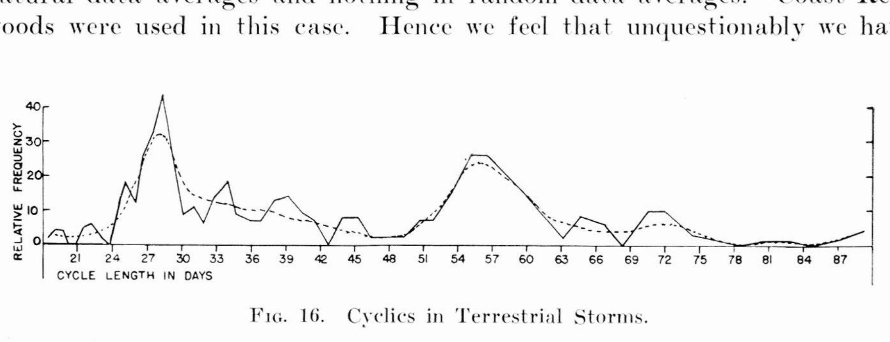

FIG. 16. Cyclics in Terrestrial Storms.

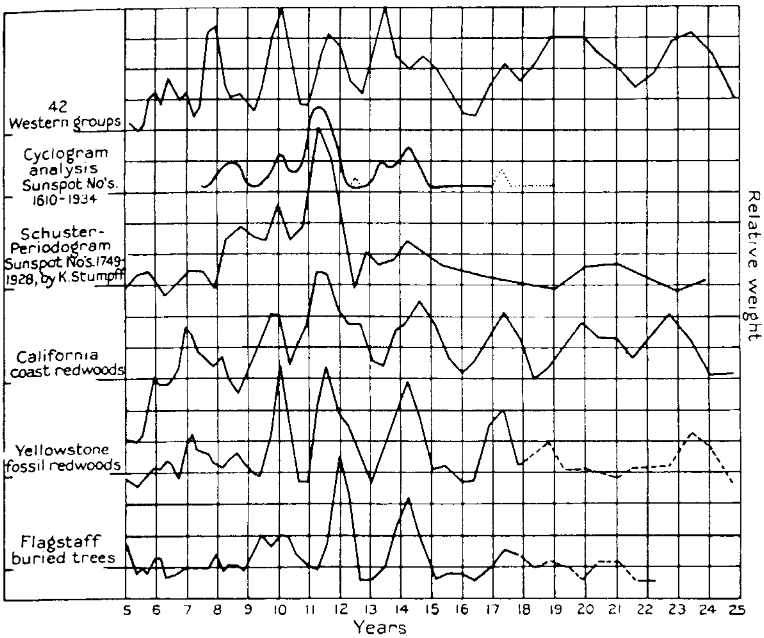

FIG. 17. Cyclic Complex in Trees, Climate, and Sun.

some real facts in regard to these cyclics. Thus we try storm recurrence during the sunspot minimum of 1932, 1933 and 1934, and find that storms came on a periodic timing similar in length to solar rotation. (See Fig. 16.)

FIG. 16. Data from some 750 stations, mostly in the United States, upon the occurrence of storms in 1932-3-4 (a sunspot minimum). Note the relation to the equatorial solar rotation of closely 27 days (synodic). Prepared by Schulman.

FIG. 17. When the frequency periodogram is applied to ring records and solar records, there is wide agreement in the preferential cyclic length. The 11-year cyclic in tree-ring records is often double-crested, and in that case is now being called the "Hellmann" cycle. These cyclics, with their relation to rainfall, offer a method of analyzing climatic changes.

Tree Rings and Forecasting

There are two types of forecasting, statistical and cyclic, to which tree-ring data may give some aid. *Statistical Forecasting*—When tree-ring measurements receive their best treatment they give factual materials regarding rainfall which can be used at once for historical information upon the durations of drouth and wet periods in the last 500 years. This is vital information in estimating the size of dam needed to withstand the strains and demands of centuries. That perhaps would simply be classed as engineers' estimates of what is needed. Tree-ring data gives 5 or 10 times the usual historical background set up.

If the management of the reservoir seeks to know what will be the situation in the next 3 years, then the statistician with 500 years of tree-ring records can tell how many 3-year drouths per century have happened in the last 500 years and can give some ideas of the probabilities, considering what drouths have occurred in the recent past. He may go a little farther and treat his 500-year curve to cycloscope analysis. If he finds some short period cyclic operating he may project it into the future and assume that it will have one more maximum such as it has been showing and he will have a good chance of being right. After all even that procedure will remain statistical until he knows the cause of any particular cycle length having a dominance at any particular time.

Cyclic Forecasting. Two processes are available in the use of cyclic values in forecasting: one is the application of pure recurrence cyclics with full regard for their unstable or non-permanent character, and the other is the solar relationship method for anticipating terrestrial conditions because of a presumed effect of solar conditions on terrestrial weather. Our part in the former is obviously the determination of the best form and character of climatic cyclics. Our part in the solar relationship method is in the search for terrestrial cyclics that correspond to these in solar phenomena.

This double use of cyclics might seem to be a very complicated task, but the writer feels that nature has simplified it by emphasizing climatic cyclics that appear in solar phenomena. These cyclics, though more fluid than permanent periods, easily show relationships that cannot appear when we insist on cycles and periods that are permanent. This looks as if we were getting some light on the nature of climatic changes.

We have traced certain patterns of cyclic lengths over wide geographical areas and into past climates over 2000 years ago and even into geological climates and have found a resemblance in them to cyclic lengths in the sunspot cycle, but with very little prominence at 11+ years. This cyclic in southwestern ring records, usually has two crests. It was recognized in 1909 in FL-13. We now feel that it should be distinguished from the sunspot cycle and we call it the Hellmann cycle. It does not extend back through the last thousand years or two except under the assumption of decided changes in length—which are not impossible. The double values, about 23 years, was chiefly noted by us years ago because of its persistence in the long-lived sequoias. It has been strong generally in the California trees, and Schulman has found it well marked in his recent carefully collected specimens in this inter-mountain area. Besides these lengths, there are others near 10, 13-14, 20, and so forth in some cases, with half values. This display was first recognized in 1926 and in 1928 described as a group of simple harmonics of 1, 2, or 3 times the length of the sunspot cycle. These cyclics are found in wide geographic areas, as, for instance in the western third of the United States, but seem subject to emphasis on different harmonics.

They may last through 5 to 20 repetitions or more, individually, and then change. It is probable that they do not all change at once, and it is also possible that preferred times of change will be anticipated. It may prove possible to develop forecasting by the direct application of these cyclics.

Perhaps this is one of the first attempts to describe generally the unstable periodicities or cyclics that make up our climatic changes. It is but a beginning, but it may be on the right track. The writer feels that in these cyclics there may be found a real basis for forecasting.