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A METHOD OF ESTIMATING RAINFALL BY THE GROWTH OF TREES*

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In the great northern plateau of Arizona, lying at an average altitude of 6,000 feet above the sea, the higher elevations are covered with forests of yellow pine (*Pinus ponderosa*), a fine timber tree with heavy cylindrical trunk and bushy top. The trees are scattered gracefully over the plains and hills, and, with the remarkable absence of undergrowth, render travel through their midst attractive and delightful. For centuries these magnificent pines have stood there, enduring the vicissitudes of heat and cold, flood and drought. The possibility that they might serve as indices of the climate of the past led the author to begin the investigation of the matter in 1901. His line of reasoning was as follows: (1) The rings of a tree measure its food supply; (2) food supply depends largely upon the amount of moisture, especially in this dry climate where the quantity is limited and the life struggle of the tree is against drought rather than against competing vegetation; (3) in such countries, therefore, the rings are likely to form a measure of the precipitation. In planning the work three fundamental steps were anticipated. First, to prepare a curve of tree growth; second, to find if there exists in this any connection with precipitation; third, by carrying this back through long periods to find whether meteorological variations, if discovered, show association with astro-

*Portions of a chapter from a forthcoming volume to be published by the Carnegie Institution of Washington, under the title "The Climatic Factor as Illustrated in Arid America," by Ellsworth Huntington, with contributions by Chas. Schuchert, A. E. Douglass and C. J. Kullmer.

nomical phenomena. A fourth step has been added by Dr. Ellsworth Huntington, namely, the application of such tree records to the investigation of historical conditions and events.

Advantages of Location. The pine tree of northern Arizona lends itself peculiarly well to the investigation here contemplated. Not only is its situation favorable climatically, and because of the absence of other vegetation and of pests which might seriously alter the growth of the tree, but the soil is of such a nature that variations in precipitation are quickly felt in the tree. The tree itself is favorable, because of its conspicuous annual rings. The difference between the soft, rapidly growing white tissues of the summer, and the slow-growing reddish layer formed in the fall, is much less conspicuous in most of the common trees than in the pine. The sharp, outer edge where the growth of the red layer is checked by the cold of winter, gives a precise point from which to measure.

Meteorological records in northern Arizona are necessarily meager, yet not so deficient as might be expected. The record at Whipple Barracks, near Prescott, which was begun in 1867, is the longest continuous record in the pine forest, and is therefore made use of below.

The Collection and Measurement of Sections. At the beginning of the investigation it was foreseen that enough trees would have to be measured to give a real average. The trees would have to be spread over enough country, and be sufficiently numerous to eliminate accidents of grouping and other minutely local conditions, and yet they must not extend beyond a single meteorological region. They must be numerous enough to be susceptible of division into groups, which, by showing common characteristics, would testify to the genuineness of whatever variations appeared. Accordingly in the first series of measurements twenty-five trees from near Flagstaff were made use of. They were divided into three groups: A, six trees from three miles south of Flagstaff; B, nine trees from about eleven miles southwest of Flagstaff; C, ten trees a mile west of the last. The method of measurement consisted of determining the thickness of each annual ring in millimeters along some typical radial line. The average age of the trees was 348 years, with two extending to 520 years, more than a hundred years before the discovery of America. The total number of individual measurements reached over ten thousand. A comparison of the three groups clearly reveals the general character of the variations hereafter to be discussed.

Other interesting facts also came to light. It was especially noticeable that years of marked peculiarities could be identified in different trees with surprising ease. Perhaps the most characteristic feature was a group of narrow rings about the years 1879-1884. These could be identified in practically every tree, and an examination of stumps scattered about the country showed that it was easy to pick them out wherever one chose. In the case of one stump near town, which had been cut some twenty years previously, this group of rings enabled the writer to name the year in which the tree was felled, and the date was verified exactly by the owner of the land. In the more recent work this same group shows conspicuously among Prescott trees, and in general 95 per cent. of these trees have rings so characteristically marked that the identification of the same series can be made with little doubt whether at Flagstaff or at Prescott.

As a rule, the thickness of a given ring is not uniform on all sides of the tree. It varies slightly for accidental reasons, and also according to the points of the compass. The maximum growth occurs a little to the east of north. The average variation between the maximum growth in the northerly direction and minimum growth to the south is 12 per cent. The relative width of rings in different radii of a tree is wonderfully constant in these Arizona pines. This is not so of all trees.

The Dating of Rings. In comparing the growth of trees and the rainfall over long periods of years, it is essential that the date of formation of any individual ring shall be certain. As a rule, each annual ring is extremely well marked, and there is no doubt as to its purely annual or seasonal character. In some cases, however, rings die out completely, while in others they are double. Such defects tend to cause errors in dating the earlier rings. In the first investigation of the trees at Flagstaff, it was thought that the final result was subject to an error of 2 per cent., most of which occurred near the center of the tree from doubling. The more rigorous methods subsequently employed, however, proved that the error of unchecked counting in those trees was 4 per cent., and lay almost entirely in the recent years. It was due chiefly to the omission of rings. Such errors can only be guarded against by a process of cross identification which will be described shortly. The common effect of errors of omission or doubling of rings is to lessen the intensity of the variations in the curve of growth. After cross identification, however, I find the remaining errors may be divided into two classes, first, local errors of identity in small groups of rings in a few individual trees, which simply flatten the curve in one small part, without affecting other portions at all; and, second, cases in which a given ring, in spite of all attempts at cross identification, is still in doubt. This error does not flatten the curve at all but does lend the same doubt to the date of all earlier rings.

The Trees of Prescott. The problem of cross identification is well illustrated in the trees of Prescott. These were measured in 1911 for the purpose of testing the conclusions derived from the Flagstaff trees some years earlier. About 3,500 measures were made upon 64 cuttings selected in five groups depending on their nearness to town. The farthest group was 10 miles southeast and the nearest one mile south. It was apparent that the agreement between growth and precipitation increased as the location of the actual rainfall station was approached. The nearest group, containing ten trees, shows so much greater agreement than do the others that it has been used alone in drawing final conclusions.

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The chief feature of the Prescott series which places its results on a firmer basis than any previous work is the cross identification of rings between trees. The extent and accuracy of this identification came as a surprise to me. After measuring the first eighteen sections it became apparent that much the same succession of rings occurred in each, and, thereupon, the other sections were examined and the general appearance of some sixty or seventy rings memorized. All the sections were then reviewed and identification marks placed in the wood against certain rings. Some conspicuous characteristics were noted, such as that the red ring of 1896 is nearly always double; the rings of 1884 and 1885 are wider than their neighbors. The most pronounced feature was a series of compressed rings from 1878 to 1883 (as noted at Flagstaff), preceded by a very faint 1877 and then a wider series. Out of 67 sections averaging fifty rings each, only two proved puzzling, and they are mentioned here because they were the worst cases of defective ring systems observed in this entire investigation. After minute examination it finally appeared fairly certain that one of them had the rings from 1879 to 1887 merged into one, and the rings from 1890 to 1895 merged into one. The other had the rings from 1890 to 1895 in one and 1898 to 1900 in one. Previous to those dates the rings were entirely normal, showing perfect agreement with the other trees.

The cross identification of trees from the Prescott region was limited to a district only ten miles long. It was a surprise then to find that rings in the Flagstaff sections could be identified at once in terms of the rings at Prescott. The process appears to be applicable to areas still farther removed from one another. Two trees out of three which were tested from the Santa Rita Mountains in southeastern Arizona, 200 miles from Prescott, were found to have rings which could readily be identified in terms of the Prescott series.

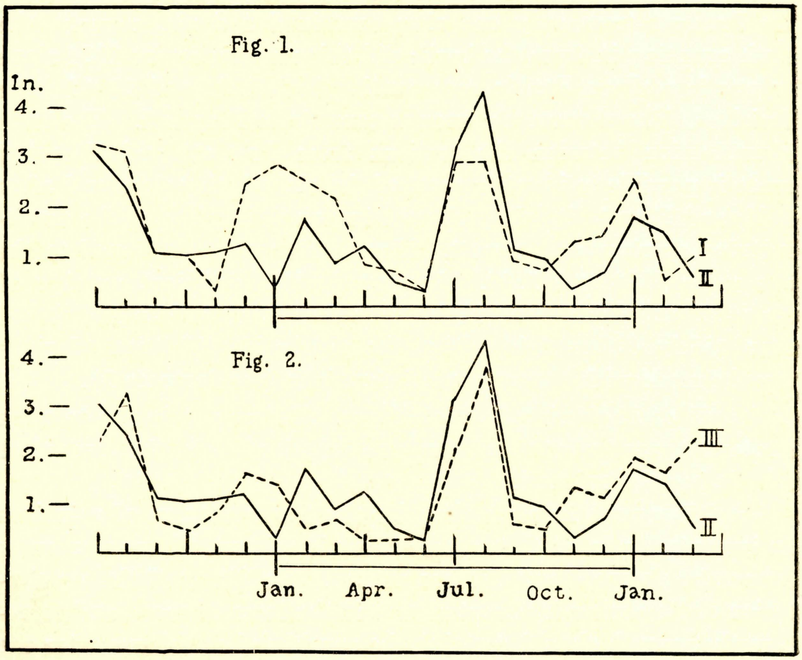
Yearly Identification. Upon the complete comparison between the Prescott trees only one ring contained a doubt, namely, the sixth counting in from the bark: did this ring represent 1904 alone or was it really a double representing both 1903 and 1904? The decisive evidence strangely enough came from Flagstaff. The cross identification between the sections from Prescott and Flagstaff made it possible to identify most of the rings both before and after 1903, and Flagstaff plainly showed two rings in place of the doubtful ring or rings at Prescott. Hence this was apportioned to the two years 1903 and 1904. Apparently if a sufficient number of comparisons be made and if the trees thus compared be distributed over widely different localities, the yearly identification of rings may be made with almost perfect certainty (see footnote 1).

Month of Beginning Annual Means. Before passing on to other matters, a word of explanation must be added as to the method of calculating the rainfall.

That it must take some time for the transmutation of rain into an important part of the organic tissue is evident. Moreover, snow cannot be absorbed until it has melted. At Flagstaff the precipitation of November is almost always in the form of snow, and therefore that month should certainly be considered as falling after the arboreal new year. Hence for purposes of comparison with tree growth, the month of beginning annual means would fall some time in the autumn. This matter has been tested empirically. Annual means have been formed beginning at various months from July 1st of the previous year to March 1st of the current year. These were compared with the tree growth, and it was found that the years beginning November 1st at Flagstaff and September 1st at Prescott give the closest agreement. These dates therefore are used.

The Time of Year of Ring Formation. Among the problems connected with the relation of the growth of trees and the amount of rainfall, one of the most interesting was suggested by Mr. R. H.

Forbes of the Arizona Experiment Station. The problem is to determine the time of formation of the red or autumn portion of the rings, and the causes of the doubling. This study is the more necessary because many rings in the Prescott series, although very few at Flagstaff, show a faint, preliminary red ring, forming a double. The first test was designed to determine the distribution and character of the rainfall in the years producing such double rings. The half-dozen most persistent years of doubling were



FIGS. 1 and 2—Rainfall and Doubling of Rings.

I. Monthly rainfall in years producing large single rings.
II. Monthly rainfall in years producing large double rings.
III. Monthly rainfall in years producing small single rings.

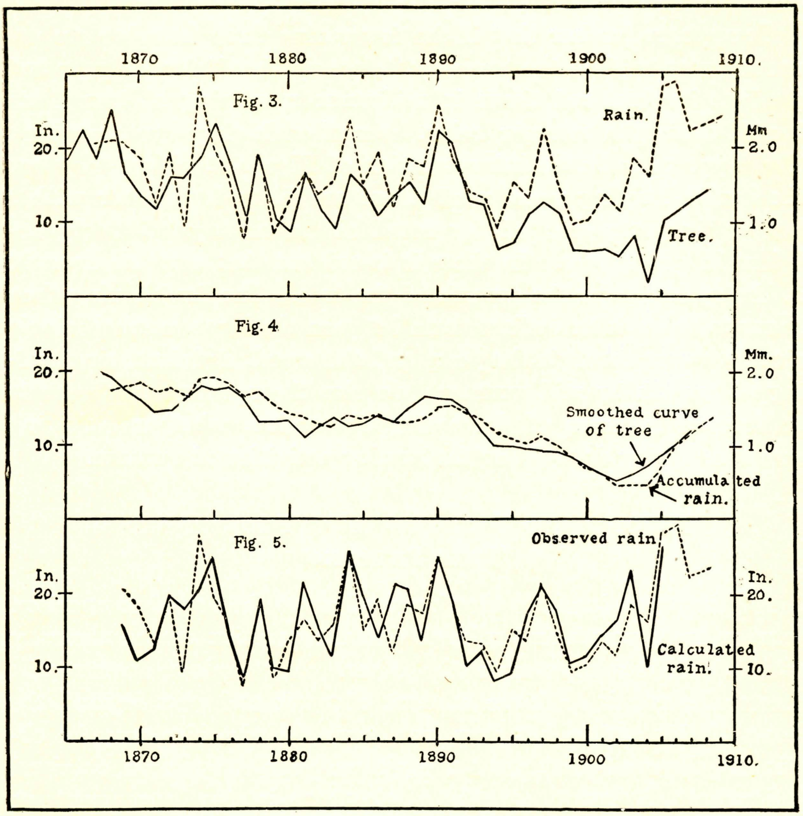
selected and their mean rainfall plotted month by month. This forms the solid line in Figure 1. Six other years averaging the same growth, 1.55 mm., but producing single red rings, were then selected and the monthly rainfall plotted as before. This forms the dotted line in the same figure. The curves seem to indicate clearly that the chief cause of doubling is a deficiency of snowfall in the winter months, December to March. This means that if the winter precipitation is sufficient to bridge over the usual spring drought, the growth continues through the year, giving a large single ring which ends only in the usual red layer as the severity of winter comes on. If, however, the preceding winter precipitation has not been entirely adequate, the spring drought taxes the resources of the tree, and some red tissue of deficient absorption comes on in summer.

It appears further that if the few spring drought rains are unusually scanty, then the tree may "close up shop" for the year and produce its final red tissue in midsummer, gaining no immediate benefit from the summer rains, even though they are abundant. This appears to be the interpretation of Figure 2. Here the same six double-forming years used above are plotted, together with a list of six years selected for small single rings particularly deficient in red tissues. In these it is evident that extreme drought in the spring stops the growth of the tree. The double ring then seems to be an intermediate form between the large, normal, single ring, growing through the year, and the small, deficient, ring ending its growth by mid-summer. So also the red tissue appears to be formed in times of decreasing absorption, whether following excessive spring drought or the waning activities of autumn.

Rainfall and Tree Growth at Prescott and Their Relation

All the preceding investigations lead up to the actual comparison between tree growth and rainfall and the question of the accuracy with which one represents the other. A complete answer will necessarily require a large amount of work and pass beyond the scope of this article but even now some definite idea may be obtained. Figure 3 displays a forty-three year comparison obtained at Prescott, Arizona. On the whole there is close agreement, as may be seen by matching the crests and troughs of one with those of the other. These curves, then, support the idea of a proportional relation between annual rainfall and annual growth.

In order to obtain a still more accurate idea of this relationship, an effort has been made to construct formulas for reducing one to the other. Without entering into details, it is sufficient to say that the result gave an agreement of over 80 per cent. This is shown in Figure 5, whose slight errors might fairly be expected considering the mile or more of distance separating the trees from the rainfall station. Figure 4 shows the main basis of transition from Figure 3 to Figure 5, namely that the mean growth of the tree is proportional to the accumulated rain. Regarding any formula, however, it should be emphasized that one found to apply in dry climate conditions, such as exist in Arizona, is likely to be very different from one operating in moist climates and perpetually water-soaked ground.



FIGS. 3 to 5—Rainfall and Tree Growth at Prescott, Arizona, 1865–1908.

Fig. 3. Tree growth and rainfall, uncorrected.
Fig. 4. Accumulated rainfall and smoothed curve of tree growth.
Fig. 5. Observed rainfall and computed rainfall.

THE FLAGSTAFF 500-YEAR CURVES

In the preceding portions of this article, we have endeavored to determine the exact relation between growth and rainfall, and to ascertain the most accurate method of obtaining results. We shall now apply these conclusions and methods to the oldest available trees. For this purpose 19 of the Flagstaff sections were selected, and were subjected to minute examination and cross identification, in order, as far as possible, to eliminate all errors due to the omission or doubling of rings. For convenience in handling the sections, each one was reduced to a strip of wood extending from center to bark. The best of these was adopted as a standard. It was then compared with each of the others, ring for ring. In the entire period only one ring was held as doubtful, that of 1822, which was often merged with that for 1821. The two rings appear as one in ten sections, and as two in only nine, but in many or most of the cases where it appeared as two, they were so distinctly separate that they were finally so regarded. This is not absolutely certain, however, and thus there may be an error of one year in the portions of the growth before 1822. So far as known, there is no probability of any other error.[1]

Test of Accuracy of Record in Small Groups. In studies like the present, it is manifestly desirable to carry the curves of growth as far back as possible. Inasmuch as only a few trees go back to an age of over 300 or 400 years, the curves for earlier centuries may be less accurate than those for later. In order to test the degree of accuracy to be obtained from a small number of trees, a comparison was made between large groups and small. After the entire number of rings, some 6,300 in all, had been identified and numbered, their measures were tabulated in overlapping groups, and in a convenient manner averages were obtained of the oldest five reaching back 400 years; the oldest ten (including the preceding five) reaching back 350 years; the oldest fifteen (including the ten) reaching 300 years, and the entire nineteen reaching only 200 years. Finally at the ancient end of the first group, the oldest two were carried back to fully 500 years. On plotting these various groups, it was immediately evident that five trees gave almost the same record as ten or fifteen, even to small details. So in the work discussed below, the five are used to give the record from about 1503 to 1906. In a similar manner, the comparison between these five and the oldest two taken by themselves gave an agreement not quite so perfect, yet so close that errors thus introduced will not at all affect the curves referred to below. However, the oldest two were

[1] Some months after writing the above, I reviewed H. H. Bancroft's "History of Arizona and New Mexico" with special reference to climatic records. Some fourteen cases of agreement with the Arizona tree record as thus identified were found, to one doubtful case of disagreement, and the identification here used was considered as confirmed, having no likelihood of error in any part. Regarding this particular case Bancroft says, on page 302: "Irrigation generally protected the inhabitants against drought, as in 1803 and in 1820-2"; and on page 309, note 8, he states that in 1823 the Indians claimed to be dying of hunger. The trees show poor growth in 1820 and 1823 and *very* poor in 1822, thus forming a group of poor years corresponding well with his description of drought and famine from 1820 to 1823.

very slow-growing trees and they required on the average an increase of about 30 per cent. in order to make their curve continuous with the whole five. Thus the tree record is made to begin at 1392. In the recent years of the record also, between 1891 and

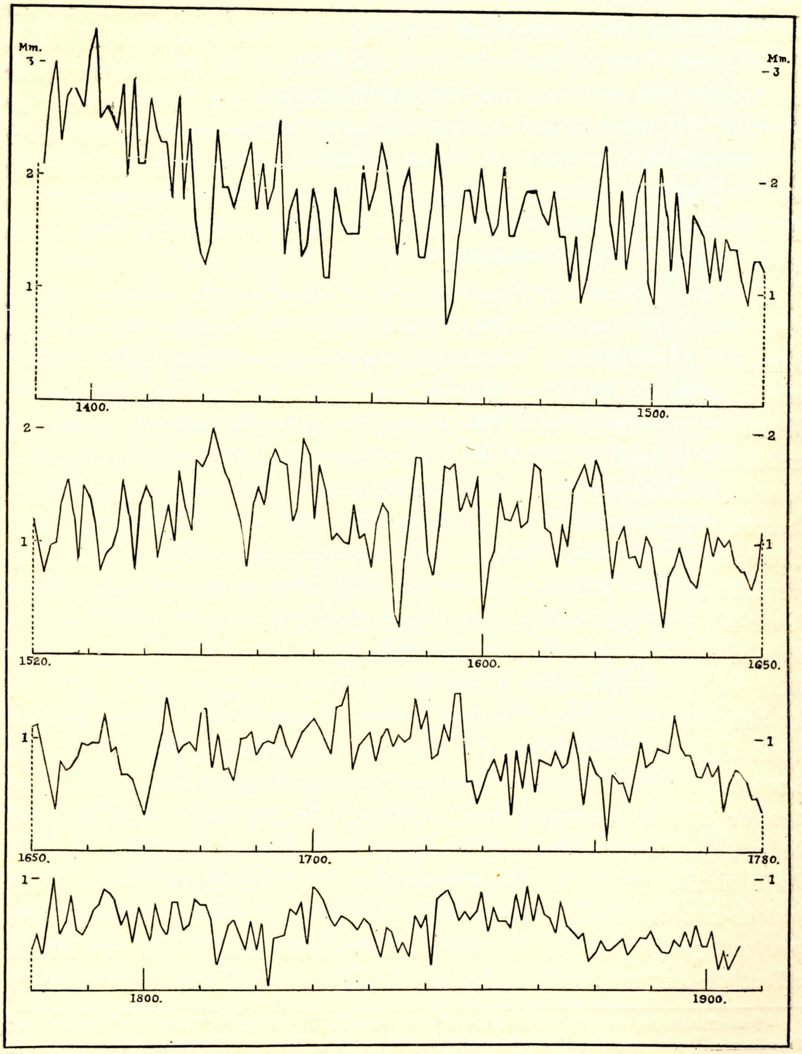


FIG. 6—Tree Record in Northern Arizona, 1392–1906.

1896, a slight correction was made for omitted rings, the complete omission of a ring being an exaggeration that introduces error. Thus Figure 6 gives the tree record for northern Arizona from 1392 to 1906, inclusive, a period of 515 years.

Climatic Cycles. Investigations of rainfall are undertaken for the purpose of predicting the future. The basis of daily or short distance prediction is found in the conditions existing about the country at a given moment and a knowledge of the usual movement of storm areas. A basis for long distance prediction is now generally sought in climatic cycles. Such cycles may or may not be permanent. Perhaps they are nothing more enduring than a series of wave systems on a water surface. Yet for the navigator a knowledge of the existing system is important, and so for the purpose of weather prediction we need to know the nature of the pulsations actually operating, and each one should be studied minutely. For this purpose the very long tree record and its presumable fair accuracy seem especially advantageous, since it gives us a range in centuries which the meteorological records with few exceptions give only in decades. In order to adapt it properly for this purpose it has been corrected empirically for age by drawing a long, sloping, nearly straight line through it from end to end, averaging its growth and then calculating the percentage of departure of each year from this line.

The 33-Year and Longer Variations. In order to bring out the longer variations the curve was smoothed by 20-year overlapping means. The result gives four conspicuous crests about the years 1400, more or less, 1560, 1710 and 1865, suggesting a very long period. A period of 33.8 years fits very well since 1730, with a total amplitude of some 25 per cent., and very poorly before that, yet without entire discordance. The last crest came in 1900. This we readily identify as the well-known Brückner period.[2]

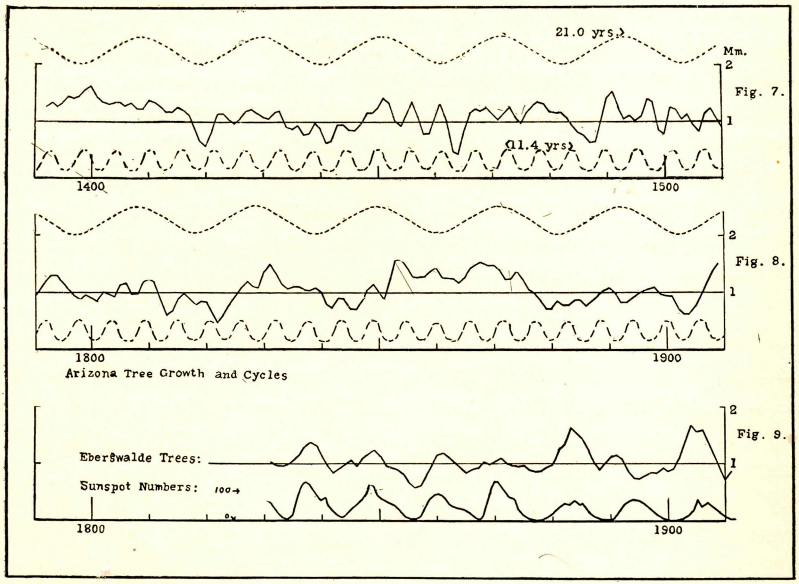
A 21-Year Period. The most persistent of the longer periods seems to be approximately 21 years in length with an average amplitude of 20 per cent. (10 per cent. from the mean), and its last crest in 1892. This pulsation is well marked from 1410 to 1520; then in the next hundred years it has three or four glaring discrepancies; finally from 1610 to the present time it is again strongly marked and very regular. Dr. W. J. S. Lockyer, in his "Discussion of Australian Meteorology"[3] finds a pronounced 19-year cycle in barometric pressures in Australia and South America. The 21-year period was worked out independently in 1907 and 1908, from an early and crude tree record of 200 years. It seems quite possible that these two periods are the same. If so, and if my inter-

[2] "Klimaschwankungen seit 1790"; see also H. W. Clough, *Astrophysical Journ.*, Vol. 22, 1905, July, p. 42, and many others.

[3] South Kensington Solar Physics Observatory, 1909.

pretation of the tree curves is correct, the real value is likely to be closer to 21 years since the time interval here investigated is about ten times as long as his. Something of this 21-year variation is shown in the dotted lines of Figures 7 and 8. The application becomes more evident when the minor variations are smoothed.

The 11-Year Cycle. The last cycle to be considered is that of eleven years. In the sixty years during which the eleven-year sunspot and magnetic cycles have been accepted, this period has been of the greatest interest, for, if found to be terrestrial, it must signify a connection between the sun and the earth other than



FIGS. 7 and 8—Arizona Tree Growth and Cycles, 1390-1510 and 1790-1910 (21-year period, dotted; tree growth, solid; 11.4-year double cycles, broken line).

FIG. 9—Eberswalde (Germany) Trees and Sunspot Numbers, 1830-1910.

gravity which holds the earth in place, and the mere constant heat energy which sustains all life. Since 1873 numerous writers (Koeppen, Bigelow, Lockyer, Abbott, Buchan, Hann, Hellmann, Arctowski and others) have found variations in the ordinary meteorological elements, rainfall, temperature, pressure, etc., corresponding to this period. But so much disagreement appeared at the same time between different workers, and the periods of time used were so short, that much doubt has remained. Hence it is of peculiar interest to see whether the trees which carry the rainfall record back so far with a comparatively high degree of accuracy, show the same cycle. In nearly all parts of the long, 500-year curve, there are plain suggestions of an eleven-year variation. By tracing these throughout the record, the most satisfactory period is found to have a length of very nearly 11.4 years, which is practically the sunspot cycle. (The sunspot cycle is sufficiently variable to render almost any period between 11.0 and 11.8 equally applicable, since 1755. This will be discussed and illustrated in another place.) The average double amplitude of the tree period is 16 per cent. The average form of this cycle during different portions of the last five centuries has been ascertained, from which it appears that it is not uniform throughout (see Figure 10). In general the curve shows two maxima and two minima: from 1400 to 1670, the second is the deeper and its recurrence most regular, as shown in Figure 7; from then to 1790 the curve flattens out and has less marked cyclic character, or the period of the cycle is varying; from that time to the present, there are again two minima, but the first is more conspicuous.

Something of this may be seen in Figures 7, 8 and 10. In Figures 7 and 8 the first and last centuries of the tree record are respectively shown, smoothed in each case by Hann's formula. Hann's formula is usually given $T^1_n = \frac{1}{4}(T_{n-1} + 2T_n + T_{n+1})$ but is better described and obtained as the *second* set of intermediate values, that is, the second set of means of successive, overlapping, pairs. With each are plotted the corresponding sections of a double-crested 11.4-year cycle cast to the best advantage upon the whole five hundred years. By comparing the crests of this cycle with the respective crests in the tree curve, one can see to what degree the tree varies on that particular cycle. Throughout Figure 7 the growth varies closely on the double-crested 11-year period and less perfectly on the 21-year. In Figure 8 the case seems to be partially reversed.

Correlation between tree growth and sunspot variation is not confined to the American region here investigated. A series of measures on thirteen tree sections (*Pinus sylvestris*) from the forest of Eberswalde, near Berlin, Germany, the first of a number of series to be made on North European pine trees, discloses a striking time relation of similar character. Figure 9 exhibits the results on this group. The mean curve for the whole thirteen was corrected for age and smoothed by three-year means. This smoothed curve is given in the figure and below it is the sunspot curve. The similarity may be traced without further comment.

The 11-Year Tree Cycle Compared with Solar and Some Meteorological Elements. A final comparison of the 11-year cycle with the mean sunspot curve and with two meteorological elements, temperature and rainfall, on the adjacent California coast, gives a significant series of curves. Figure 10 has on its upper line the average of all the 11.4-year periods in the whole five hundred years.

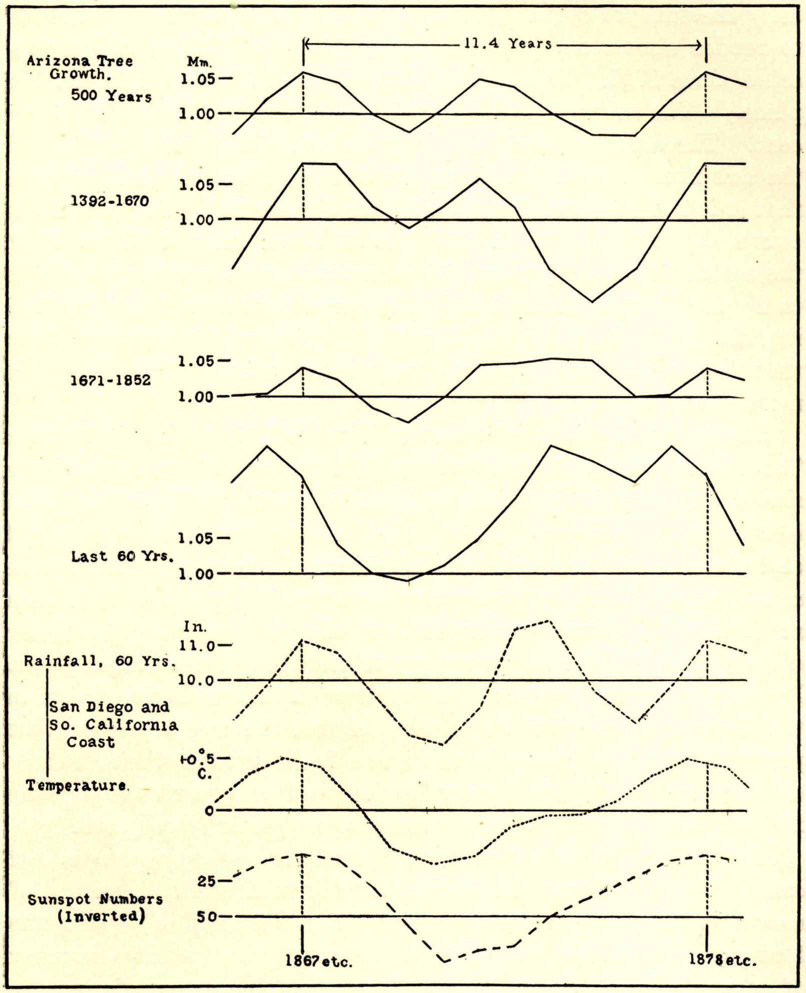


FIG. 10—Study of an 11.4-year Period. First four curves: Arizona tree growth: (1) average for the 500 years covered by the period of investigation; (2 to 4) curves for the periods 1392–1670, 1671–1852 and 1850–1911, respectively. Last three curves: rainfall and temperature on the coast of southern California and inverted sunspot numbers for the period 1850–1911.

Below this is a partial analysis of the same in different intervals in three curves which show variations in this cycle. The last of the three is taken for sixty years only, in order to give an exact comparison with the curves which follow. The first dotted curve is the coast rainfall for sixty years arranged on identical periods. Although this coast is five hundred miles distant from the Arizona trees, and lies beyond the mountains, yet the crests and troughs of the tree growth in Arizona match those of the rainfall in California. This is not surprising, for while the summer rains of northern Arizona have no relation to those on the coast, the winter precipitation in the two regions varies in harmony. Below the rainfall curve is placed another, showing the average temperature at San Diego during the 11-year periods since 1850. Shorter curves of temperature and rainfall of other coast towns show the same characteristics as those of San Diego. The lowest curve shows the sunspot numbers (inverted) for the same interval from 1850 to the present time.

There appears to be a marked similarity between these curves. Even the subordinate crest which sometimes shows in the change from maximum to minimum sunspots, matches the suppressed second crest of temperature and the full second crests of rainfall and tree growth. This would seem impossible in the absence of a real relationship between them.

Conclusion. Further research will probably show other, and perhaps still more important, relationship between the growth of vegetation, meteorological elements and changes in the sun. Meanwhile, the methods of computing rainfall from tree growth must be still further perfected. Already, however, the original purpose of the work here outlined has been accomplished. A connection has been found between tree growth and rainfall, a curve of tree growth has been made for at least one locality, apparent climatic cycles have been observed and indications of association between meteorological and astronomical phenomena have been found. But the most important part of all, I hope, has been the origin and development of a method of estimating rainfall, capable of extension to other regions, and of adaptation to other branches of science.