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TREE-RING RESEARCH IN EUROPE

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ABSTRACT

In the last ten years tree-ring analysis in Europe and its application has been extended considerably. By varied methods, a number of chronologies have been established for conifers and deciduous trees from different climatic regions that partly reach back to periods before the birth of Christ. The focus of dendrochronological research is usually dating and climatological studies are carried on only sporadically.

INTRODUCTION

It is not known exactly who first recognized that trees grow in annual layers. A summary of the early history of crossdating was done by Studhalter (1955). In North America Douglass (1919) was probably the first to do systematic research in dendrochronology. In Europe Švedov (1892) and Kapteyn (1914) independently had similar ideas. Whereas in the U.S.A. a central laboratory was established, dendrochronological work was done somewhat randomly in Europe, mainly in Scandinavia, Russia, and Germany.

According to Kolčin (1965), there are two main reasons for the slow development of European dendrochronology. First, in Europe trees do not grow to as old ages as in America. Second, climatic relationships are much more complex. Some developments were bound to reach a dead-end; for example E. H. De Geer's attempt to synchronize European tree-ring series with the American sequoia ring sequence. In 1956 she was still advancing her theory of a worldwide teleconnection. Huber (1941), on the other hand, made an essential contribution to European dendrochronology which will be looked into more closely in this study.

In the course of time a substantial body of literature has developed in numerous periodicals and various languages. An extensive survey was made by Glock (1955) with 359 references, while hardly considering the European studies.

In addition, a short summary was done by Huber, Merz, and Fürst (1961) in Germany. Another survey by Kolčin (1965), written in Russian, deals with eastern European dendrochronology. Other surveys were published for Norway and Finland by Høeg (1956) and Mikola (1956).

The present contribution deals solely with the dating of the annual growth layers and the exploitation of the information they contain. The numerous papers on tree-ring analysis done in forestry and wood research are not taken into consideration. Although these papers analyze the annual increment, dating to the precise year is not necessary. The literature of the last decade will be included, the most recent of an individual's studies often standing as examples for the whole of his work. I regret not being able to mention extensively enough all the studies on the subject in question. This is due in part to a necessarily subjective selection and partly to the fact that information was not available to me.

METHODICAL ASPECTS

Dendrochronological dating is based on the same principle everywhere and has been described extensively by Bannister (1963) and Stokes and Smiley (1968). On the basis of this principle, different methods have been developed in different laboratories. In the following the dendrochronological methods presently in use will be briefly explained. A description of the numerous possibilities of climatological calculation would, however, exceed the scope of this study.

The samples for a tree-ring analysis are taken as cross-sections or beam sections or in form of cores. The measuring of the tree-ring widths is done with an eye piece micrometer, a microscope, or a semi-automatic tree-ring measuring equipment which registers the measurements and punches them on a paper tape at the same time. With a plotter the tree-ring diagrams can then be drawn mechanically (Eckstein and Bauch 1969). Whereas in North America the tree-ring sequences can be synchronized with the skeleton-plot method (Stokes and Smiley 1968), in Europe the whole length of a tree-ring curve has to be taken into consideration because of the more balanced climatic conditions.

The dating method introduced by Huber (1941, 1942) and commonly used in central, southern and western Europe is based on a semi-logarithmic scale. On this scale the same percentage of change in growth results in the same slope and the same length of the curve independent from the absolute tree-ring widths. In addition, the maxima of a curve are smoothed and the minima emphasized. This fact makes the visual comparison of two diagrams easier. Lately the synchronization has been rationalized by the use of computers (Eckstein and Bauch 1969) but the semi-logarithmic paper continues to be in use, since the results still have to be checked visually. Huber's method does not eliminate the age trend of the ring series which is not very marked in the oak. As a measure for the similarity of two tree-ring curves the value of agreement ('Gleichläufigkeitswert') is accepted. It is defined as the percentage of parallel intervals in two different curves, not taking into account the absolute tree-ring widths. The percentage of parallel intervals of non-synchronous curves averages 50. The single values vary more around this mean the less two curves overlap. In the same way the values of agreement between synchronous pairs of curves vary about a mean value (>50) depending on the length of their overlap. Both distributions (the variations around the two means of 50 and >50, respectively) cover each other considerably when the overlap of two curves is short. When the length of the overlap increases, this covering decreases.

A reliable chronological synchronization of tree-ring curves using only the value of agreement is often not possible. On the contrary, from a number of equally useful positions reported by computer, the best one has to be selected visually. A valuable help are the significant years of a curve. These are years where the single curves that have been included in a mean curve have the same trend. However, of several single curves in a synchronous position more than 50 percent may rise or fall in a certain year by chance. How many curves of a mean curve must show the same trend in a year in order to be acknowledged as significant depends on the number of single curves. Whereas there must be 90 percent with the same trend in a group of 20 curves, 65 percent will be sufficient in a group of 100 curves.

Eastern European dendrochronologists also do not eliminate the age trend when the aim of the research is the dating of an object. Mostly several methods are combined. For example, a ring width diagram with a semi-logarithmic scale is used together with the depression diagram (Vichrov and Kolčin 1962). The value of agreement is used to measure the similarity (Kolčin and Bitvinskas 1972). If the objects are very difficult, tree-ring indices are calculated on the basis of 20-year-moving-averages with 5-year intervals.

In northern Europe, where dendrochronology developed from tree-ring analysis in forestry, methods to eliminate the age trend were used at an early date (Ording 1941). The similarity between such index series is tested with the simple coefficient of correlation, which has recently been rationalized through the use of computers (Brandt 1969). The coefficient of correlation itself is in its significance dependent on the overlap of the two curves.

Other possible ways of making a statistic comparison of tree-ring series have been suggested by Munaut (1966), Brandt (1969), and Alestalo (1971).

EUROPEAN TREE-RING CHRONOLOGIES

Figure 1 indicates the dendrochronological laboratories presently at work. By means of the different methods discussed above, numerous tree-ring chronologies have been established which are summarized in Table 1. The short chronologies that exist occasionally, for example for yew, lime, alder, ash, and other tree species have not been dealt with, as they seem to be of no further importance at the moment.

In eastern Europe there are three chief chronologies of pine and spruce, covering the whole of the Russian plain. These chronologies show considerable resemblance to each other. Because of the strong partitioning of the Scandinavian countries by mountains, it is necessary to establish several independent chronologies there for pine and spruce. There are also separate chronologies for the different species of conifers in the southern German area and the Alpine region. In central and western Europe, however, the chronologies for deciduous wood become more prevalent. Whereas the oak chronology that has been established for south and southwest Germany is valid from Czechoslovakia in the east to Normandy and, partly, to the south of England in the west, the northern and northwestern area of Germany must be divided into small regional sections together with Denmark and the Netherlands.

APPLICATION

Architectural History

In the examination and preservation of historical buildings a major problem is often precise dating. Archival information frequently does not allow reliable conclusions about the architectural history of a research object. The application of art-historical criteria in the dating of an object does not always lead to precise results, either. Not even the radiocarbon method reaches the required degree of accuracy when it is applied to the period of the past 1000 years; the period most in question. For these reasons, dendrochronology, which is in the most favorable cases able to date the very year of origin of an object, meets with special attention in the research of architectural history.

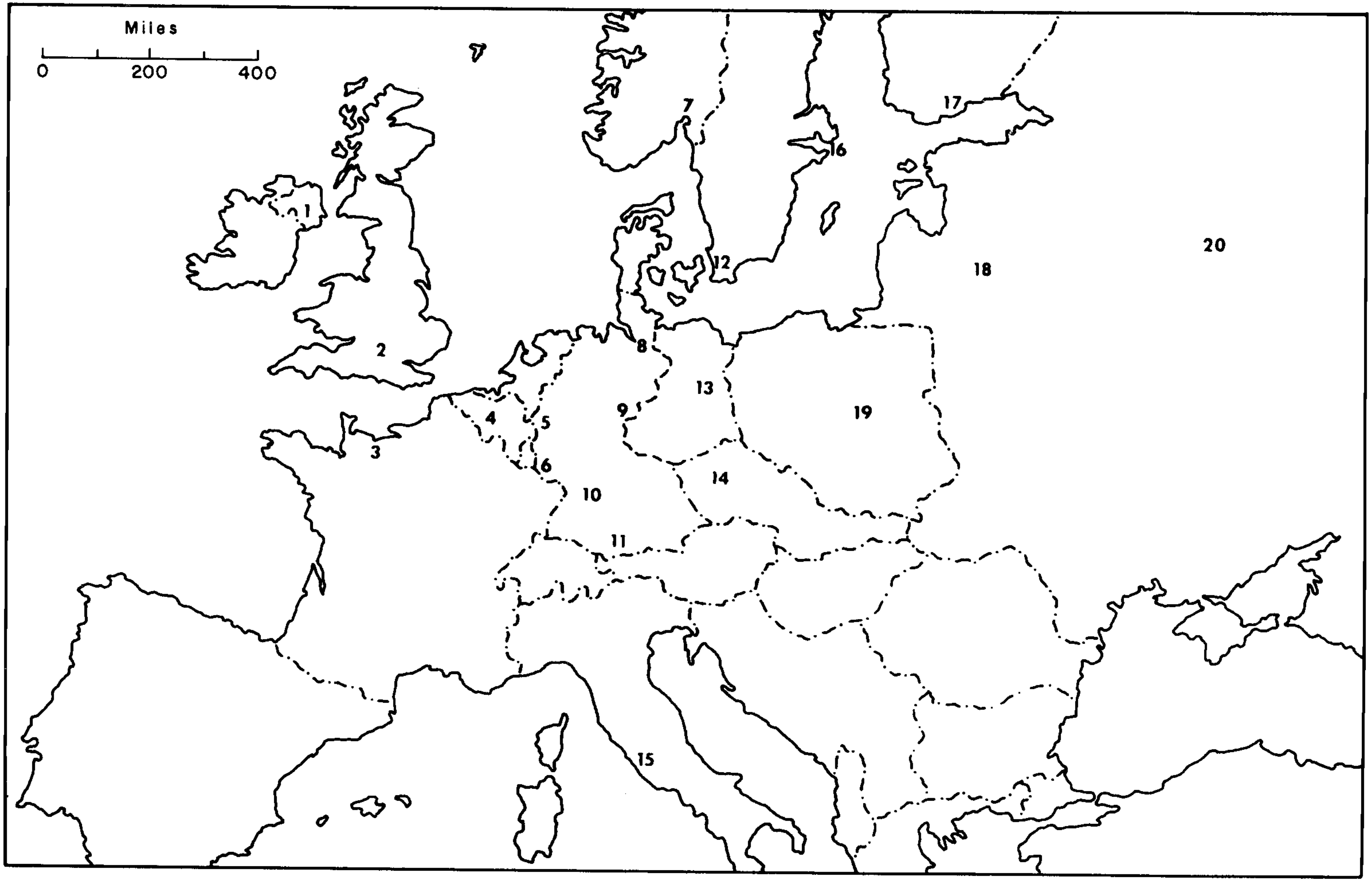

Figure 1. Dendrochronological laboratories in Europe. 1, Belfast; 2, Oxford; 3, Caen; 4, Louvain; 5, Cologne; 6, Trier; 7, Oslo; 8, Hamburg; 9, Göttingen; 10, Stuttgart; 11, Munich; 12, Lund; 13, East Berlin; 14, Zbraslav; 15, Rome; 16, Stockholm; 17, Helsinki; 18, Kaunas; 19, Warsaw; 20, Moscow.

Table 1. European chronologies.

Region	Species[1]	Period	Source
Ireland	oak	AD 1970-1381	Baillie 1973
Southern England	oak	AD 1550-0850	Fletcher, unpublished
Netherlands	oak	AD 1970-1680	Brongers, unpublished
Netherlands	oak	AD 1613-1140	Bauch, Eckstein, and Meier-Siem 1972
Belgium	pine	2300-2500 BC[2]	Munaut and Casparie 1971
Northern France	oak	AD 1610-1280	Giertz, unpublished
Eastern Norway	spruce	AD 1937-1690	Ording 1941
Eastern Norway	pine	AD 1937-1639	Ording 1941
Eastern Norway	pine	AD 1940-1556	Aanstad 1960
Eastern Norway	pine	AD 1950-1687	Slåstad 1957
Eastern Norway	pine	AD 1954-1383	Eidem 1959
Western Norway	pine	AD 1959-1535	Brandt, unpublished
Central Norway	spruce	AD 1937-1460	Eidem 1953
Central Norway	pine	AD 1938-1424	Eidem 1953
Northern Norway	pine	AD 1936-1396	Ording 1941
Denmark	oak	AD 1971-1630	Bartholin 1973
Northern Germany	oak	AD 1970-1266	Eckstein, Bauch, and Liese 1970
Northern Germany	oak	AD 1100-0500[3]	Eckstein and Liese 1971
Northern Germany	oak	AD 1967-1338	Eckstein, Mathieu, and Bauch 1972
Weserbergland	oak	AD 1970-1004	Delorme 1972
NW Germany	oak	0500-6000 BC[2]	Schmidt 1973
South, SW Germany	oak	AD 0200-6700 BC[2]	Becker 1972a, b
South, SW Germany	oak	AD 0339-0717 BC	Hollstein 1965 and unpubl.
South, SW Germany	oak	AD 1973-0383	Hollstein 1965 and unpubl.
South, SW Germany	oak	AD 1960-0832	Huber and Giertz-Siebenlist 1969
South, SW Germany	beech	AD 1948-1320	Jazewitsch 1953; Hollstein 1973
South, SW Germany	fir	AD 1965-0820	Becker and Giertz-Siebenlist 1970
South, SW Germany	spruce	AD 1961-1583	Fürst 1963
Switzerland	oak	2400-3000 BC[2]	Huber 1967; Giertz, unpubl.
Switzerland	oak	0952-1282 BC[2]	Huber 1967; Giertz, unpubl.
Austria	stone pine	AD 1971-1468	Giertz, unpublished
Austria	larch	AD 1971-1333	Brehme 1951; Giertz, unpubl.
Finland	pine	AD 1960-1181	Sirén 1961
Sweden	pine	AD 1973-1530	Jonsson, unpublished
Northern Russia	pine, spruce	AD 1970-0884	Kolčin and Bitvinskas 1972
Northern Russia	pine, spruce	AD 0800-0600[3]	Kolčin and Bitvinskas 1972
Northern Russia	oak	AD 1420-0900	Kolčin, unpublished
Northern Russia	larch	AD 1969-1103	Šijatov 1972
Western Russia	pine, spruce	AD 1970-1050	Černych 1972
Eastern Russia	pine, spruce	AD 1970-0980	Černych 1972

Note 1. Oak = *Quercus petrea, Q. robur*; Beech = *Fagus sylvatica*; Pine = *Pinus sylvestris*; Spruce = *Picea abies*; Fir = *Abies alba*; Stone pine = *Pinus cembra*; Larch = *Larix decidua, L. sibirica.*

Note 2. Discontinuous chronologies, placed by radiocarbon.

Note 3. Relative chronologies, placed by archaeological context.

In northern Europe, especially in Norway, farm buildings, storehouses, and stave-churches from the 18th and 19th centuries, made out of pine and spruce, are of interest (Slåstad 1957). To date the exact year of origin is difficult, since the timber for a certain building project was not necessarily all cut at the same time. On farms the timber would be felled during the short periods between the seasons and stored for future building purposes. Frequently old timber was re-used.

These problems do not arise in Germany. Numerous dendrochronological datings of objects whose time of origin is known precisely, have shown that, as a rule, the timbers were cut immediately for the purpose of building and that the construction was done without delay after the cutting. Hollstein (1966) was able to prove that the wood, mainly oak, was even used in green condition. According to his observations, building timbers often show a characteristic curvature due to the shrinkage that occurred after it had been used. The pores are still clearly visible on the cross-cut ends, which is only possible, if the wood was in green condition when shaped with an axe.

An impressive example of dendrochronological dating of historical buildings is the dating of the Trier and Speyer Cathedrals (Hollstein 1968). Square and round poles of a former scaffold appeared in the stone walls of the Trier Cathedral after the removal of recently applied plaster. These poles had been in green condition when they were used in the construction. Together with lining boards and other building timber, an exact and differentiated sequence of the different stages of the construction was found. The phases of A.D. 1042 to 1047, 1054 to 1056, and 1074 are laid open as in a diary. Two scaffolding poles of the Speyer Cathedral from the year A.D. 1045 prove that the construction had at that point reached a height of 18.30 m.

In other cases tree-ring chronology has contradicted already existing dating results. The dating of foundation poles made of fir in the church of St. Martin's at Landshut (south of Munich) established A.D. 1441 as the date of cutting (Becker and Giertz-Siebenlist 1970), which is nine years later than the death of the supposed mason. The present dating of the completion of the main entrance based on the date of A.D. 1432 in the tympanon cannot be maintained any longer.

New knowledge in architectural research and in folklore has also been achieved in Northern Germany by dendrochronological means (Eckstein, Bauch, and Mathieu 1972). Isolated areas of rural culture can be found with buildings whose construction can only be dated to a 100 years at the closest. The focus of the present research is the farm house typical of the 16th century. Numerous buildings have been discovered which have outlasted the Thirty Years' War. In several instances, evidence could be found that the house inscriptions that had been taken for the dates of construction had been added as much as 150 years later and only referred to minor additions to the buildings.

Other objects of German frame-work architecture were dated in the southern part of Lower Saxonia (Delorme 1972). The first results of historical examination of buildings were published in East Germany (GDR) on a 16th century castle (Jährig 1972) which was dated by means of the west German master curve.

Dendrochronological examinations of 15th century market halls and barns in the north of France (V. Giertz, personal communication) have shown, besides new information about the dates of origin, that the southern German master curve is applicable even to those distant areas as a basis for the dating.

Similar examinations have been conducted on several large barns in England (V. Giertz, personal communication). However, the results are not as unequivocal as the one gained in France. Some specimens show a good resemblance to the southern German oak curve, but most of the wood samples are of a strongly local character as to their tree-ring structure. For these reasons a regional chronology is required for the dating of such specimens, which is being worked on at present (J. M. Fletcher, personal communication).

In southern Europe, above all in Italy, several kinds of wood were frequently used in a building. Beside oak, they also took chestnut, pine, larch, and other species.

Therefore it is difficult to obtain sufficient material for comparisons from one and the same object. In addition, no regional chronologies of Italy have been established yet. As an example, the dating of the Roman church of St. Antimo's at Montalcino (Siena) may be mentioned (Corona 1971). The approximately 60 year tree-ring sequence of five oak beams have been dated with the southern German master curve to cover the time between A.D. 1067 and 1127.

Historical monuments have of course been examined dendrochronologically in the USSR as well. Buildings with a well-known architectural history are often examined to establish an absolute chronology.

Art History

The problems of placing an object chronologically is often of major interest to the art historians. It proves difficult to find objective criteria for individual creative works of art, when, for example, changes in style are to be recognized, or, when the original work of art is to be distinguished from a copy. To solve these problems various scientific methods, such as the x-ray method, infra-red photography, and others have been developed, and, most recently, the method of dendrochronology (Bauch and Eckstein 1970).

So far this method has almost exclusively been applied to paintings of Dutch painters of the 16th, 17th, and 18th centuries that were painted on oak panels. As these boards were usually formed radially because of the better technical quality, they can contain as many as 300 tree-rings that are measured directly on the object without any specimens being taken. Frequently sapwood remainders are found which make the precise dating of the cutting year possible. The aim of such a dendrochronological examination is the establishment of a "terminus post" for the year of origin of a painting. To that purpose, the earliest possible cutting time of the tree that provided the board of the painting is determined. The analysis of 300 paintings of 30 old masters proved that only eight years had passed on the average between the cutting time of the tree and the execution of the painting (Bauch, Eckstein, and Meier-Siem 1972). Recently, further paintings of English galleries, particularly Tudor portraits, have been evaluated (J. M. Fletcher, personal communication).

Dendrochronology is also used to date sculptures carved out of wood (Bauch, Eckstein, and Brauner 1974). Hollstein (1970) examined a medieval oak carving whose authenticity is very much debated. Its origin has been dated by dendrochronological means to be between the year A.D. 1222 and 1330, so that the period most likely for an imitation must be excluded.

In the area of art forgery belongs also the imitation of string instruments of the Italian masters of the 17th and 18th centuries. The tree-ring analysis of violin bodies which in most cases were made of fir, sometimes provides additional criteria for a decision (Lottermoser and Meyer 1958). As a basis for comparison, tree-ring curves of several violins of one and the same master that are doubtless genuine are used.

Archaeology

In the science of archaeology relative chronologies have been established for almost all past civilizations by means of stratigraphic and typologic methods. Criteria for the dating are the thickness of refuse layers and the rate of the development of various new techniques, respectively. As there are no historical sources for these periods, there is not a great amount of evidence for the time-scales thus obtained. Therefore dating methods of the natural sciences are used more and more. For the dating of wood, dendrochronology has proved very useful because of its great accuracy.

In the southern part of central Europe, the research done in the past decade relates to the Stone and Bronze Ages. In the Bronze Age settlement of Zug-Sumpf (Switzerland), the dendrochronological analysis of oak, ash, and alder samples showed that the settlement had been occupied over almost 200 years (Huber and Merz 1962). The oak tree-ring curve comprises 269 years and reaches from 1282 to 1014 B.C. according to placement by radiocarbon. It has been extended to 952 B.C. by the inclusion of additional material.

The neolithic Swiss lake settlements of Thayngen-Weier (near Schaffhausen) and south and southwest of Burgäschisee (near Bern) were inhabited only a few years or decades according to the dendrochronological results (Huber and Merz 1963; Huber 1967). An explanation for the relative short period of occupation is not yet possible. Chronologically the settlements follow in this sequence: Thayngen-Weier (lower settlement), south and southwest Burgäschisee, Thayngen-Weier (middle settlement). The time-span is approximately 35 years. On the whole, an oak chronology of 312 years was the result. The settlements had been built in the 38th century B.C. according to radiocarbon dating (Ferguson, Huber, and Suess 1966).

For the Rhine, Moselle, and Maas area an oak chronology has been established that covers wood specimens of the Latène, Roman, and Merowingian periods (Hollstein 1967). The tree-ring curves crossdate so well despite the great distances, for example between Aachen in the north and Avenches (Switzerland) in the south, that even wood samples from other sites can be placed correctly by means of this chronology. The wood samples come mainly from poles and beams of Celtic and Roman bridges, houses, wells, and fortifications in Cologne, Mayence, Trier and other historical centers. Because the connection to the medieval oak tree-ring curve is lacking, the years of the chronology from 717 B.C. to A.D. 339 are based on the time of the building of the Roman Bridge in Cologne, which is known to be around A.D. 310. After the closing of the gap between A.D. 339 and 383, the chronology will comprise 2690 years.

In northern Germany and Denmark archaeological research is presently concerned with the settling of the country between A.D. 800 and 1200. Of great importance in our knowledge about medieval urban development are the excavations of Haithabu. This former settlement is situated about 150 km north of Hamburg and belonged to the largest trading center in northern Europe at the time of the Vikings. Dendrochronology is of particular importance in the case of Haithabu because of the extremely unfortunate stratigraphic conditions. For that reason, an exact relative chronology is being established from the evidence of 4000 oak samples from houses, pavements, wells, and fences. At the moment it comprises 205 years and provides a mean-curve of 550 years (Eckstein and Liese 1971).

Of further interest are the remnants of Slavonic settlements in the eastern part of Schleswig-Holstein. In the centers of the political and economic life of that time, ramparts of wood and earth were erected. From such mounds, for example in the old part of Lübeck, samples are taken for dendrochronological analyses. An absolute dating is not yet possible, since no wood specimens before the year 1300 have been preserved above the ground in this region. Therefore, it is necessary to use exclusively the wood found during excavations.

In the harbor of Bremen, a trading ship, the so-called 'Hanse-Kogge' built at the time of Hanseatic navigation has been found. The cutting of the timber could be dated precisely at A.D. 1378 with the dendrochronological method (Liese and Bauch 1965). Since the tree-ring curves harmonize with the southern German master curve, it can be assumed that the timber came from the Weserbergland area and had been floated on the Weser down to Bremen. Generally, the dating of ships proves most difficult, because the origin of the timber is most frequently unknown.

The focus of dendrochronological work in Russian archaeology is the excavation in Novgorod (Kolčin 1972). The material consists of approximately 3000 pine and spruce samples from houses and roads from the period between the 10th and 15th centuries. During that time, 32 wooden pavement layers had been laid down, each on the top of the other, the oldest of which dates from the year A.D. 953. With these samples, containing up to 200 rings, a precise chronological sequence could be established for the different layers. Apart from the roads, numerous buildings were excavated, but the timbers were not so suitable for a tree-ring analysis since most contained less than 100 rings. Frequently the dates of origin of new street layers or buildings correlated with historically verified fires. The quantity of the specimens shows here as well that the timber had been cut immediately before the construction began.

A major point of interest is also the exploitation of timber discovered in the course of excavations of medieval towns in the eastern European plain (Černych 1972). A number of objects have already been dated precisely. From Smolensk (12th through 16th centuries) and Belosersk (12th and 13th centuries), there are sufficient wood specimens with enough tree-rings, whereas other excavations yielded only a few samples with a small number of tree-rings. These, in addition, belonged to a very long period of time. The timber consists of pine and spruce which makes absolute dating with the Novgorod master curve possible. In Smolensk, 76 buildings could be dated from 405 wood samples with 31 to 260 tree-rings. The entire tree-ring series comprises 635 years, the youngest of which is A.D. 1605.

In the ruined polar city of Mangazeja, between the tundra and the taiga, excavations brought forth remains of the timbers of former buildings (Šijatov 1972). Siberian spruce and larch are the predominant species. The establishment of an absolute chronology with recent trees from the northern Ural showed that within a range of about 700 km along the northern timber line synchronous fluctuations of tree-ring widths occur. On the whole, a chronology has been established for this region that covers 867 years from A.D. 1103 to 1969.

Dendrochronological research in British archaeology centers on Roman and Saxon remains (Schove and Lowther 1957). Relative chronologies have been developed for the period between the 2nd century B.C. and the 4th century A.D., and for the 8th and 9th centuries, respectively. The statements made about the absolute dates of this material result from a correlation with archaeological finds such as coins and pottery, and meteorological records. However, a dating of that kind cannot be accepted as strictly absolute as long as there is no extension of those relative chronologies to the present time, nor a synchronization with already existing master curves of adjoining regions. Recent British analyses have been dealing with a Middle Saxon cistern whose planks had been cut out of a 240-year old oak tree. That tree had been felled in A.D. 832±30 according to radiocarbon (Fletcher and Switzur 1973).

All the research programs mentioned require intensive co-operation with archaeologists. But apart from those studies, there are also several single examples of dating work. Molski (1965) reports on the relative dating of the vegetable market of Szczecin (Poland) which was, however, based on only short tree-ring curves and which, moreover, belong to different species of deciduous trees. The same applies to the study of Jährig (1971) of wood samples from a Slavonic settlement near Neubrandenburg, East Germany (GDR). From ten oak samples with 32 to 95 tree-rings, a relative sequence was established for seven stages of construction. Finally, Dabrowski and Ciuk (1972) described the dating of samples from Ostrówek in southern Poland using the Novgorod chronology over a distance of about 1200 km.

Geomorphology of the Postglacial Period

The geomorphological changes that have taken place in Europe during the past 10,000 years, simultaneously with the development of the flora and fauna, have been dated previously by means of varve chronology, the C-14 method, and pollen analysis. In the future, however, more precise chronological information will be required.

Dendrochronological investigations of subfossil trunks of oak trees in the southern part of central Europe which are buried under gravel and sand along the rivers have been started to develop a complete Holocene tree-ring chronology. The purpose is to study the paleogeographical changes of the river systems – most of all of the rivers Danube, Main, and Rhine (Becker 1972 a,b). Analyses of about 850 cross-sections developed 15 floating chronologies with tree-ring series up to 650 rings. According to radiocarbon, they cover a period from 6700 B.C. to A.D. 200. Three main horizons of subfossil oak trunks have been found in a wide distribution along the rivers examined, showing simultaneous periods of gravel-accumulations. During these phases series of big floods that lasted up to 500 years destroyed the riverine oak forests. They date from the Bronze, Iron, and Roman Ages. A comparison of the growth ages of the buried trunks shows that they never reached their possible natural age – each oak forest within the valleys studied must have been destroyed by floods or by the meandering river itself two or three times within one millenium. According to radiocarbon, the floating chronologies show a good overlap within the period of the years A.D. 200 to 2500 B.C. Thus the conditions for establishing a complete tree-ring series up to Neolithic times seem to be favorable.

As the growing conditions in the southern part of central Europe differ from those in northern Germany, suitable oak tree-ring chronologies ought to be set up for this area (Schmidt 1973). Further relative chronologies covering several hundreds or thousands of years B.C. exist for the Dutch coastal area for pine stubs (Munaut and Casparie 1971) and for oak from northern Ireland (Baillie 1973).

The chronological placement of geomorphological changes by means of dendrochronology has also been the aim of Alestalo (1971), who has named this method "dendrogeomorphology." Research of this kind is based not only on tree-ring analysis. Studies of form growth of trees and roots as well as studies of changes in tree communities will be used to establish further criteria. Then a dendrogeomorphological analysis will allow statements about the rising or lowering of water levels, about volcanic processes, mass movements – most of all on river banks – cryopedological processes that are the results of the freezing and thawing of the ground, and fluvial processes such as degradation of slopes through the influence of the rain. Moreover, it will provide information about degradation and aggradation caused by waves and ice thrusting, about aeolian processes that led to erosion, about the burial of trees, advance of dunes, and organogenic processes such as those occurring in moors.

The term "dendrogeomorphology" can also be applied to the studies of LaMarche and Fritts (1971). A good agreement has been found between the ring widths of recent stone pines (*Pinus cembra*) and the advances of the glaciers in the Austrian and Swiss Alps. If chronologies reaching back a great number of years were established, the history of the glaciers of the Alps could be traced back even further.

Dendroclimatology

Dendroclimatology is dendrochronological analysis that uses climatic information in dated growth layers to study variability in present and past climates (Fritts 1971). Dendroclimatological analyses in Europe have been restricted to regions where a single climatic factor dominates. Under northern conditions, it is the temperature of the growing season that masks the other possible factors exerting an influence. The effect of summer temperature increases from the south to the north and is most prominent at the northern timber line (Mikola 1962). Finnish studies confirm the results of Swedish and Norwegian research (Eklund 1957; Høeg 1956).

The northern European studies mentioned mainly deal with Scots pine and Norway spruce, which show slight differences in their reactions to temperature. Whereas low winter temperatures are favorable for the growth of spruce, high temperatures in March and April favor the growth of pine (Jonsson 1969). In addition, growth accelerates with increasing rainfall in summer up to a certain amount, and diminishes afterwards.

According to the connection between growth and climate, there is also a close correlation between the northern timber line and the weather. Thus a climatic amelioration between the turn of the century and the 1930s led to increased natural reproduction and temporary reforestation as well as to an expansion of the wood-working industries in Lapland (Mikola 1971). The climatic improvement included a lengthening of the growing season and an increase of the temperature during the vegetation period (Jonsson 1969). From the 1930s onward temperatures have been falling again. According to Sirén (1961), this trend can be expected to continue until the end of the 20th century. In future planning of forest management, this prediction will have to be considered.

Kärenlampi's examinations of Scots pine (1972) have for the first time shown a significant influence of rainfall on the growth of trees close to the timber line. This is assumed to be the case because temperature determines the general range within which the growth will vary, and the water supply causes a considerable part of the variation within this range; a tendency more pronounced on drier sites.

Further south, for example in Denmark, rainfall proved to be a dominant factor for most tree species (Holmsgaard 1955). In the temperate regions of central Europe, the ring width cannot be correlated closely with any single climatic factor. According to Elling (1966), temperature affected the growth of alder in a southern German site before the growing season and rainfall during it. On some northern German sites only half of the tree-ring variations of oak trees could be explained by the influence of climatic fluctuations; the influence of the temperatures dominating somewhat (Eckstein and Schmidt 1974).

Dendroclimatological studies on spruce in the Tatra mountains in Poland show a strong positive correlation of growth with high temperatures in the vegetation period from June to August. The correlation with precipitation is negative. On the other hand, the growth in the year following a very favorable year seems to decrease. This deterioration is perhaps a result of the faster aging and falling of the needles (Feliksik 1972).

According to von Jazewitsch (1961), sites with a predominant single weather factor can also be found in central Europe. To examine the correlation between the tree-ring growth and the temperature she chose a larch forest on the alpine timber line and found a positive correlation for the months May to July. To study the correlation with precipitation she selected a pine wood near Würzburg which was extremely warm and dry for central European conditions. The result of this study was a positive correlation with the amount of rainfall in the months April to July.

Russian scientists are searching for a solution of paleo-climatological problems, mainly of the past 1000 years (Adamenko and Lovelius 1968). Furthermore, the possibility of longterm forecasts of the productivity of forests, climatic forecasts in order to evaluate the probability of catastrophic conditions for agriculture, and other issues of that kind are being discussed.

Fürst (1963) tried to interpret the tree-ring width of fir, spruce, beech, and oak of various proveniences and different periods of time concerning their climatological evidence. The mean sensitivity served as a parameter. Thus the mean sensitivity increases in central Europe from west to east, probably because of the increasingly continental climate. The comparison of the mean sensitivities of samples from the present time, the Middle Ages, the Bronze, and Neolithic Ages, taken in Switzerland, demonstrated that the climate of the Neolithic Ages was more continental than today. In the Bronze Ages, however, it was more temperate. In the Middle Ages a period of higher variation from 1650 onwards ("little ice age") followed after a period of low mean sensitivity. Ermich (1960) suggested using trees as living meteorological stations in order to divide forest areas into uniform climatic spaces and exploit them for forestal purposes.

The need for dendroclimatological analyses is being realized in Europe more and more. In the course of the next years further results are to be expected from this field of research.

Radiocarbon Analysis

Dendrochronology is also respected in other than the above mentioned fields of applications. It has, for example, provided a means to check radiocarbon dating. The accuracy of a C14 dating depends mainly on the knowledge of the variations of C14 content in the atmosphere in past times. Ferguson (1970) succeeded in establishing a tree-ring sequence for bristlecone pine (*Pinus aristata*) which reaches an age of about 4600 years in the White Mountains of California. He included fallen trees and large remnants, and by overlapping, extended the sequence to the year 5142 B.C., and thus provide a series of organic substance, including every single year, as a gauge.

Using these exactly dated samples Suess (1969) obtained a calibration for the C14 values. This calibration has been compared with European wood samples (Ferguson, Huber, and Suess 1966; Vogel, Casparie, and Munaut 1969; Suess and Strahm 1970). In addition, the establishment of absolute oak chronologies ranging over several thousand years is in progress for southern and northwest Germany, as mentioned above (Becker 1972 a,b; Schmidt 1973), after whose conclusion a C14 comparison between America and Europe will be possible.

Environmental Control

Dendrochronology has become a special discipline of environmental control. Industrialization has very much expanded during the last decades and caused increasing emissions of industrial fumes which have done considerable damage to the surrounding forests. Smog and salt in towns also pollute the trees, which are necessary for climatic and esthetic reasons.

Dendrochronology can aid greatly to the solution of these problems together with air, leaf, and soil analyses. With the analysis of the tree-rings the beginning of the damage can be determined and the decrease in growth can be calculated (Vinš 1965; Pollanschütz 1971; Jonsson and Sundberg 1972; Havas and Huttonen 1972). As soon as it is known when the damage began, important evidence can be given concerning the specific cause of the damage and possible measures suggested to prevent it.

Legal Matters

Occasionally dendrochronology is also used in detective and legal matters. Examples for this are given by Rozanov (1968) and Liese and Eckstein (1971).

CONCLUSIONS

The present survey shows that European dendrochronology has constantly extended its range of application during the last decade. Almost all European countries possess dendrochronological laboratories or use laboratories in adjoining countries for the evaluation of their research.

The establishment of chronologies alone has lessened in importance. Of major interest today is the solution of archaeological and art-historical problems and questions of architectural history on the basis of the existing chronologies.

Stimulated by the recent discussions of environmental problems, the climatological and ecological aspects of dendrochronology will become more and more important in the near future. In the United States research of that kind has been done for many years (Fritts 1971). Komin and Šijatov (1968) discussed the necessity of analyses of that kind for the Asiatic part of the U.S.S.R., as the conditions there are very favorable because of the 2000-year juniper species and the larch species which are up to 1200 years old. Some results have come from Lovelius (1971) concerning the mountain regions and the northern timber line of Siberia.

Still, dating work will maintain the same position in Europe where, from prehistoric times to the late Middle Ages, a vast amount of timber was used in the construction of a great number of buildings.

REFERENCES

Aandstad, S.
1960 Daterte årringer i furu fra Solør. *Blyttia*, Vol. 18, No. 8, pp. 49-67.
Adamenko, V. N. and N. V. Lovelius
1968 Ispol'zovanie dendrohronologičeskih dannyh dlja izučenija mnogoletnej izmenčivosti meteorologičeskih uslovij poslednego tysjačiletija (Use of dendrochronological data for the study of long-term variability of meteorological conditions for the last thousand years). In "Materialy Vsesujuznogo soveščanijanaučnoj konferencii po voprosam dendrohronologii i dendroklimatologii," Fiz-Teh. Inst. Akad. Nauk SSSR; Inst. Botan. Akad. Nauk Litov. SSR; Litov. Nauč.-Issted. Inst. Les. Hoz., pp. 30-35.
Alestalo, J.
1971 Dendrochronological interpretation of geomorphic processes. *Fennia*, No. 105, pp. 1-140.
Baillie, M. G. L.
1973 A dendrochronological study in Ireland with reference to the dating of medieval and post medieval timbers. Doctoral dissertation, The Queen's University of Belfast.
Bannister, B.
1963 Dendrochronology. In *Science in Archaeology*, edited by Don Brothwell and Eric Higgs, pp. 162-176. Thames and Hudson, London.
Bartholin, T. S.
1973 Undersøgelse af muligheden for dendrokronologisk datering af egetrae i Danmark, specielt Sønderjylland. *Det forstlige Forsøgsvaesen i Danmark*, Vol. 33, No. 3, pp. 217-241.
Bauch, J. and D. Eckstein
1970 Dendrochronological dating of oak panels of Dutch seventeenth-century paintings. *Studies in Conservation*, Vol. 15, pp. 45-50.
Bauch, J., D. Eckstein, and M. Meier-Siem
1972 Dating the wood of panels by a dendrochronological analysis of the tree-rings. *Nederlands Kunsthistorisch Jaarboek*, Vol. 23, pp. 485-496.
Bauch, J., D. Eckstein, and G. Brauner
1974 Dendrochronologische Untersuchungen an Gemäldetafeln und Plastiken. *Maltechnik*, Vol. 4.
Becker, B.
1972a Möglichkeiten für den Aufbau einer absoluten Jahrringschronologie des Postglazials anhand subfossiler Eichen aus Donauschottern. *Berichte der Deutschen Botanischen Gesellschaft*, Vol. 85, Nos. 1-4, pp. 29-45.
1972b Absolute Chronologie der Nacheiszeit (Holozän) mit Hilfe der Dendrochronologie. *Jahrbuch der Akademie der Wissenschaften und Literatur*, pp. 143-145.
Becker, B. and V. Giertz-Siebenlist
1970 Eine über 1100 jährige mitteleuropäische Tannenchronologie. *Flora*, Vol. 159, pp. 310-346.
Brandt, N.
1969 Årringundersökelser på furu (*Pinus silvestris*), metode og anvendelse. *Universitetsforlagets trykningssentral*, pp. 1-120.
Brehme, K.
1951 Jahrringchronologische und -klimatologische Untersuchungen am Hochgebirgslärchen des Berchtesgadener Landes. *Zeitschrift für Weltforstwirtschaft*, Vol. 14, pp. 65-80.
Černych, N. B.
1972 Dendrohronologija srednevekovyh pamjatnikov Vostočnoj Evropy (Dendrochronology of medieval monuments in eastern Europe). In "Problemy absoljutnogo datirovanija v arheologii," Akademija nauk SSSR, Izdatel' stvo "Nauka," Moskva, pp. 93-112.
Corona, E.
1971 Studi dendrocronologici su S. Antimo di Montalcino (Siena). *L'Italia Forestale e Montana*, Vol. 26, pp. 208-210.
Dabrowski, M. J. and K. Cuik
1972 Materialy do dendrochronologicznej stratigrafii osady na Ostrówku w Opolu. *Archeologia Polski*, Vol. 17, pp. 445-462.
De Geer, E. H.
1956 Planetary geochronology. Vth Congrès International de Chronométrie, Procès-Verbaux et Mémoires, Besançon, Vol. 2, pp. 455-488.
Delorme, A.
1972 Dendrochronologische Untersuchungen an Eichen des südlichen Weser- and Leineberglandes. Dissertation, Forstl. Fak. Univ. Göttingen.
Douglass, A. E.
1919 Climatic cycles and tree-growth. Vol. 1. *Carnegie Institution of Washington Publication*, No. 289.

Eckstein, D. and J. Bauch
1969 Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwiss. Centralblatt*, Vol. 88, pp. 230-250.

Eckstein, D. and W. Liese
1971 Jahrringchronologische Untersuchungen zur Altersbestimmungen von Holzbauten der Siedlung Haithabu. *Germania*, Vol. 49, pp. 155-168.

Eckstein, D. and W. A. van Es
1972 Dendrochronologische Untersuchungen von Daubenbrunnen aus der frühmittelalterlichen Siedlung Dorestad, Holland. *Kunde*, Vol. 23, pp. 220-226.

Eckstein, D. and B. Schmidt
1974 Dendroklimatologische Untersuchungen im maritimen Klimagebiet Schleswig-Holsteins. *Angew. Bot.*, Vol. 48.

Eckstein, D., J. Bauch, and W. Liese
1970 Aufbau einer Jahrringchronologie von Eichenholz für die Datierung historischer Bauten in Norddeutschland. *Holz-Zentralblatt*, Vol. 96, pp. 674-676.

Eckstein, D., K. Mathieu, and J. Bauch
1972 Jahrringanalyse und Baugeschichtsforschung – Aufbau einer Jahrringchronologie für die Vier – und Marschlande bei Hamburg. *Abhandlungen und Verhandlungen des naturwiss. Vereins Hamburg*, Vol. 16, pp. 73-100.

Eidem, P.
1953 Om svingninger i tykkelsestilveksten hos gran (*Picea abies*) og furu (*Pinus silvestris*) i Trøndelag. *Medd. Norske Skogforsøksvesen*, Vol. 12, No. 41, pp. 1-155.
1959 En grunnskala til tidfesting av trevirke fra Flesberg i Numedal. *Blyttia*, Vol. 17, No. 7, pp. 69-84.

Eklund, B.
1957 Om granens årsringsvariationer inom mellersta Norrland och deras samband med klimatet. *Meddelanden från Statens Skogsforskningsinstitut*, Vol. 47, No. 1, pp. 1-63.

Elling, W.
1966 Untersuchungen über das Jahrringverhalten der Schwarzerle. *Flora*, Vol. 156, pp. 155-201.

Ermich, K.
1960 Zagadnienie telekonekcji w dendrochronologii na przykladzie debu bezszypulkowego w Bawarii i w Polsce (Problems of teleconnection in dendrochronology on the example of the sessile oak in Bavaria and in Poland). *Rocznik Sekcji Dendrologicznej Polskiego Towarzystwa Botanicznego*, Vol. 14, pp. 31-43.

Feliksik, E.
1972 Studia dendroklimatologiczne nad Świerkiem (*Picea excelsa* L.) (Dendroclimatic studies of spruce (*Picea excelsa* L.). *Acta Agraria et Silvestra*, Vol. 12, pp. 41-70.

Ferguson, C. W.
1970 Dendrochronology of bristlecone pine, *Pinus aristata*. Establishment of a 7484-year chronology in the White Mountains of eastern-central California, U.S.A. In *Radiocarbon variations and absolute chronology*, edited by I. U. Olsson, pp. 237-259. Almquist & Wiksell, Stockholm.

Ferguson, C. W., B. Huber, and H. E. Suess
1966 Determination of the age of Swiss lake dwellings as an example of dendrochronologically-calibrated radiocarbon dating. *Zeitschrift für Naturforschung*, Vol. 21a, No. 7, pp. 1173-1177.

Fletcher, J. M. and R. Switzur
1973 North Elmham; the dating. *Current Archaeology*, Vol. 4, No. 1, pp. 25-28.

Fritts, H. C.
1971 Dendroclimatology and dendroecology. *Quaternary Research*, Vol. 1, No. 4, pp. 419-449.

Fürst, O.
1963 Vergleichende Untersuchungen über räumliche und zeitliche Unterschiede interannueller Jahrringbreitenschwankungen und ihre klimatologische Auswertung. *Flora*, Vol. 153, pp. 469-508.

Glock, W. S.
1955 Growths rings and climate. *Botanical Review*, Vol. 21, pp. 74-188.

Havas, P. and S. Huttonen
1972 The effect of air pollution on the radial growth of Scots pine (*Pinus sylvestris* L.). *Biological Conservation*, Vol. 4, No. 5, pp. 361-368.

Høeg, O. A.
1956 Growth-ring research in Norway. *Tree-Ring Bulletin*, Vol. 21, Nos. 1-4, pp. 2-15.

Hollstein, E.
1965 Jahrringchronologische Datierung von Eichenhölzern ohne Waldkante. *Bonner Jahrbuch*, Vol. 165, pp. 12-27.
1966 Jahrringchronologien aus dem romanischen Haus in Münstereifel. *Jahrbuch der Rheinischen Denkmalpflege*, Vol. 26, pp. 149-151.
1968 Dendrochronologische Untersuchungen an den Domen von Trier und Speyer. *Kunstchronik*, Vol. 21, No. 6, pp. 168-181.
1967 Jahrringchronologien aus vorrömischer und römischer Zeit. *Germania*, Vol. 45, pp. 70-83.
1970 Jahrringchronologie der "Luxuria." *Berliner Museen*, Vol. 20, No. 1, pp. 16-23.
Holmsgaard, E.
1955 Arringsanalyser af Danske skovtraer. *Det forstlige Forsøgsvaesen i Danmark*, Vol. 22, No. 1, pp. 1-246.
Huber, B.
1941 Aufbau einer mitteleuropäischen Jahrring-Chronologie. *Mitteilung Akad. Dtsch. Forstwiss.*, Vol. 1, pp. 110-125.
1942 Über die Sicherheit jahrringchronologischer Datierung. *Holz als Roh- und Werkstoff*, Vol. 6, pp. 263-268.
1967 Seeberg, Burgäschisee-Süd - Dendrochronologie. *Acta Bernensia*, Vol. 2, pp. 145-156.
1962 Jahrringchronologische Untersuchungen zur Baugeschichte der urnenfelderzeitlichen Siedlung Zug-Sumpf. *Germania*, Vol. 40, pp. 44-56.
Huber, B. and W. Merz
1963 Jahrringchronologische Synchronisierungen der jungsteinzeitlichen Siedlungen Thayngen-Weier und Burgäschisee-Süd und -Südwest. *Germania*, Vol. 41, pp. 1-9.
Huber, B. and V. Giertz-Siebenlist
1969 Unsere tausendjährige Eichenchronologie durchschnittlich 57 (10-150) fach belegt. *Sitz. Ber. Österr. Akad. Wiss.*, Mathem. naturwiss. Kl. Abtlg. 1, Vol. 178, Nos. 1-4, pp. 37-42.
Huber, B., W. Merz, and O. Fürst
1961 Dendrochronologie in Europa. Report of the VIth International Congress on Quaternary, Vol. 1, pp. 677-685.
Jährig, M.
1971 Dendrochronologische Untersuchungen von Holzproben aus der jungslawischen Siedlung auf der Fischerinsel bei Neubrandenburg. *Zeitschrift für Archäologie*, Vol. 5, pp. 134-140.
1972 Dendrochronologische Untersuchungen an Deckenbalken des Güstrower Schlosses als Beitrag zu einer Dendrochronologie des nördlichen Raumes der Deutschen Demokratischen Republik. *Bodendenkmalpflege in Mecklenburg*, Jahrbuch 1971, pp. 333-341.
Jazewitsch, W. von
1953 Jahrringchronologie der Spessart-Buchen. *Forstwiss. Centralblatt*, Vol. 72, Nos. 7/8. pp. 234-247.
1961 Zur klimatologischen Auswertung von Jahrringkurven. *Forstwiss. Centralblatt*, Vol. 80, pp. 175-190.
Jonsson, B.
1969 Studier över den av väderleken orsakade variationen i årsringsbredderna hos tall och gran i Sverige. *Institutionen för Skogsproduktion, Rapporter och Uppsatser*, No. 16, pp. 1-297.
Jonsson, B. and R. Sundberg
1972 Has the acidification by atmospheric pollution caused a growth reduction in Swedish forests? *Institutionen för Skogsproduktion, Rapporter och Uppsatser*, No. 20, pp. 1-48.
Kärenlampi, L.
1972 On the relationships of the Scots pine annual ring width and some climatic variables at the Kevo Subarctic Station. *Rep. Kevo Subarctic Res. Stat.*, Vol. 9, pp. 78-81.
Kapteyn, J. C.
1914 Tree growth and meteorological factors. *Rec. Trav. Bot. Néerl.*, Vol. 11, pp. 70-93.
Kolčin, B. A.
1965 Dendrohronologija Vostočnoj Evropy (Dendrochronology in Eastern Europe). Akademija nauk SSSR- Institut arheologii, Izdatel'stvo "Nauka," Moskva, pp. 62-85.
1972 Dendrohronologija Novgoroda 1970 g. In "Problemy absoljutnogo datirovanija v arheologii," Akademija nauk SSSR, Izdatel'stvo "Nauka," Moskva, pp. 113-118.
Kolčin, B. A. and T. T. Bitvinskas
1972 Sovremennye problemy dendrohronologii (Contemporary problems of dendrochronology). In "Problemy absoljutnogo datirovanija v arheologii," Akademija nauk SSSR, Izdatel'stvo "Nauka," Moskva, pp. 80-92.

Komin, G. E. and S. G. Šijatov
1968 Itogi i zadači dendrohronologičeskih issledovanij v vostočnyh rajonah strany (Results and problems of dendrochronological research in the eastern regions of the country). In "Materialy Vsesojuznogo soveščanijanaučnoj konferencii po voprosam dendrohronologii i dendroklimatologii," Fiz-Teh. Inst. Akad. Nauk SSSR; Inst. Botan. Akad. Nauk Litov. SSR; Litov. Nauč.-Issted. Inst. Les. Hoz., pp. 19-22.

LaMarche, V. C. and H. C. Fritts
1971 Tree rings, glacial advance, and climate in the Alps. *Zeitschrift für Gletscherkunde und Glazialgeologie*, Vol. 7, Nos. 1-2, pp. 125-131.

Liese, W. and J. Bauch
1965 Das Alter der Bremer Kogge. *Bremisches Jahrbuch*, Vol. 50, pp. 14-19.

Liese, W. and D. Eckstein
1971 Die Jahrringchronologie in der Kriminalstik. In "*Die Grundlagen der Kriminalistik*," Vol. 7, pp. 395-422.

Lottermoser, W. and F. J. Meyer
1958 Über die Möglichkeiten einer Dendrochronologie von altitalienischen Geigen. *Instrumenten-Zeitschrift*, Vol. 12, pp. 295-296.

Lovelius, N. V.
1971 Reconstruction of the course of meteorological processes on the basis of the annual tree rings along the northern and altitudinal forest boundaries. Proceedings IV. International Meeting on the Biological Productivity of Tundra, Leningrad, pp. 248-260.

Mikola, P.
1956 Tree-ring research in Finland. *Tree-Ring Bulletin*, Vol. 21, Nos. 1-4, pp. 16-20.
1962 Temperature and tree growth near the northern timber line. In *Tree Growth*, edited by T. T. Kozlowski, pp. 265-274. Ronald Press, New York.
1971 Reflexion of climatic fluctuation in the forestry practices of Northern Finland. *Rep. Kevo Subarctic Res. Stat.*, Vol. 8, pp. 116-121.

Molski, B.
1965 Preliminary dendrochronological investigation in archaeological stand on "vegetable market" in Szczecin (Poland). *Archaeologia Polona*, Vol. 8, pp. 190-207.

Munaut, A. V.
1966 Recherches dendrochronologiques sur *Pinus silvestris*, I. Etude de 45 sylvestres récents originaires de Belgiques. *Agricultura*, Vol. 14, No. 2, pp. 193-232.

Munaut, A. V. and W. A. Casparie
1971 Étude dendrochronologique des *Pinus sylvestris* L. subfossiles provenant de la tourbière d'Emmen (Drenthe, Pays-Bas). *Rev. Palaeobot. Palynol.*, Vol. 11, pp. 201-226.

Ording, A.
1941 Årringanalyser på gran og furu. *Meddelelser fra det Norske Skogforsøksvesen*, Vol. 7, No. 2, pp. 105-354.

Pollanschütz, J.
1971 Die ertragskundlichen Meßmethoden zur Erkennung und Beurteilung von forstlichen Rauchschäden. In "Methoden zur Erkennung und Beurteilung forstschädlicher Luftverunreinigungen." *Mitteilungen Forstl. Bundesversuchsanstalt Wien*, No. 92, pp. 155-206.

Rozanov, M. I.
1968 Predmet sudebnoj dendrohronologii (Dendrochronology and forensic expert's reports). In "Materialy Vsesojuznogo soveščanijanaučnoj konferencii po voprosam dendrohronologii i dendroklimatologii," Fiz-Teh. Inst. Akad. Nauk SSSR; Inst. Botan. Akad. Nauk Litov. SSR; Litov. Nauč.-Issted. Inst. Les. Hoz., pp. 23-29.

Schmidt, B.
1973 Dendrochronologische Untersuchungen an Eichen aus der Kölner Bucht und dem Werre-Weser-Gebiet. *Archäologisches Korrespondenzblatt*, Vol. 3, No. 1, pp. 155-158.

Schove, D. J. and A. W. G. Lowther
1957 Tree-rings and medieval archaeology. *Medieval Archaeology*, Vol. 1, pp. 78-95.

Šijatov, S. G.
1972 Dendrohronologija Mengazei. In "Problemy absolutnogo datirovanija v arheologii," Akademija nauk SSSR, Izdatel'stvo "Nauka," Moskva, pp. 119-121.

Slåstad, T.
1957 Årringundersøkelser i Gudbrandsdalen. *Medd. Norske Skogforsøksvesen*, Vol. 14, No. 48, pp. 571-620.

Stokes, M. A. and T. L. Smiley
1968 *An introduction to tree-ring dating*. University of Chicago Press, Chicago.

Studhalter, R. A.
1955 Tree growth. I. Some historical chapters. *Botanical Review*, Vol. 21, pp. 1-72.
Sirén, G.
1961 Skogsgränstallen som indikator för klimafluktuationerna i norra Fennoskandien under historisk tid. *Communicationes Instituti Forestalis Fennia*, Vol. 53, pp. 1-66.
Švedov, O.
1892 Derevo, kak letopis zasuh (Tree as chronicles for dry periods). *Meteorologičeskij vestnik*, No. 5, pp. 163-178.
Suess, H. E.
1970 Bristlecone pine calibration of the radiocarbon time-scale 5200 B.P. to present. In *Radiocarbon variations and absolute chronology*, edited by I. U. Olsson, pp. 303-311. Almquist & Wiksell, Stockholm.
Suess, H. E. and C. Strahm
1970 The Neolithic of Auvernier, Switzerland. *Antiquity*, Vol. 44, pp. 91-99.
Vichrov, V. E. and B. A. Kolčin
1962 Osnovy i metod dendrohronologii (Principles and methods of dendrochronology). *Sovetskaja Archeologia*, Vol. 6, pp. 95-112.
Vinš, B.
1965 A method of smoke injury evaluation – determination on increment decrease. *Communicationes Inst. For. Čechosl.*, No. 4, pp. 235-245.
Vogel, J. C., W. A. Casparie, and A. V. Munaut
1969 Carbon-14 trends in subfossil pine stubs. *Science*, Vol. 166, pp. 1143-1145.

TREE-RINGS AND SUNSPOT NUMBERS

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ABSTRACT

Tree-ring series that record climatic variation have long been of interest for study of possible effects of solar variability on terrestrial phenomena. Spectral analysis, harmonic dial analysis, digital filtering, cross-correlation and principal component analysis were used separately and in combination in an attempt to detect relationships between the annual Wolf sunspot numbers and ring-width indices, primarily from western North America. The results show no evidence of significant, consistent relationships between tree-ring data and sunspot numbers.

INTRODUCTION

This report gives the results of a study of possible relationships between sunspot numbers and tree-ring indices. It was undertaken because longer series of annual sunspot numbers were needed to test certain models for prediction of future solar activity. We felt that tree-ring and sunspot data might be sufficiently correlated to permit the estimation of sunspot numbers from tree-ring data for a long period prior to the beginning of the oldest continuous sunspot records.

The search for periodicities or trends in tree-ring series which might be related to the behavior of the sun is based on the hypothesis that solar variation causes variations in climate, which in turn affect the growth of trees (Douglass 1919, 1928, 1936). It has been amply demonstrated that the variation in widths of annual rings of certain trees from environmentally limiting sites contain long records of climatic fluctuations. In southwestern North America a number of dry-site trees (those which are frequently limited by drought) are usually selected from within a particular area. Their rings are dated and the ring widths are measured and standardized. The data are then pooled in such a way as to maximize the climatic "signal" and minimize the non-climatic "noise" (Fritts 1969). If such data from such a stratified sample of trees are properly treated (Fritts 1969), the resultant tree-ring chronology of wide and narrow growth rings is highly related to climate (Fritts 1965; Julian and Fritts 1968).

There is a long history of the tree-ring and sunspot studies. The possibility of using long records of tree growth to extend sunspot records intrigued the astronomer A. E. Douglass (1919, 1928, 1936). He devoted a major part of his life to the development of the science of dendrochronology and to the search for cycles in tree-ring data. Although a voluminous literature has grown up around this topic since the turn of the century, the evidence for a relationship has not been conclusive, and many have remained skeptical.

In this investigation, several different methods of time series analysis were applied to test for possible associations between variations in sunspot numbers and fluctuations in tree growth. Power spectrum and cross-spectrum analyses were used to search for possible short period cycles or oscillations in tree-ring data which might be related to the well known 11-year sunspot rhythm, or to the 22-year "Hale cycle." The harmonic dial was used in conjunction with a series of digital filtering functions to test for both short and long period cyclic behavior in tree-ring series. The possibility of associations between the very long period or non-periodic variation in sunspot numbers and in that the tree-ring data were further tested by simple linear cross-correlation of the smoothed records.

The various tests were applied not only to tree-ring chronologies for individual sites, but also to the amplitude series derived by principal component analysis of chronologies from throughout western North America (LaMarche and Fritts 1971). The most important series expresses the large-scale changes in ring widths referred to as the characteristic tree-growth anomaly patterns. They are less subject to error than single site chronologies and represent the variation of climatic patterns on a regional scale.

Most of the tree-ring chronologies used in the early phases of this investigation were selected from a set of 26 chronologies from Canada, the United States, and Mexico which were previously used in a study of climatic changes in western North America (Fritts 1965). However, some of these chronologies ended as early as 1930, some combined data from more than one species, and others were based on comparatively small samples. While this particular investigation was under way, there was a major effort by the Laboratory of Tree-Ring Research to increase the number and improve the quality of representative North American tree-ring chronologies, as well as bring them more nearly up to date. As these chronologies became available, they were incorporated into a new data set, making a total of 49 chronologies (Stokes and others 1973), which provided the basis for certain later analyses. In a few cases, other chronologies were used for particular tests. The published or unpublished sources are cited where these results are given.

The sunspot data used were the annual values of the Zurich relative sunspot numbers (Wolf sunspot numbers) as given by Waldemier (1961) for the period A.D. 1700-1960. This record is thought to be highly reliable back to about 1830, less reliable back to 1749, and rather crude to 1700 (Allen 1964).

SUMMARY OF TECHNIQUES

Power Spectrum Analysis

A high proportion of the variance in sunspot numbers is associated with a quasi-periodic rhythm having an average frequency of about 1/11 cycles per year (cpy) (Figure 1). Power spectrum analysis is designed for the study of such rhythmic behavior in a time series. To obtain a power spectrum of an annual series, the autocorrelation coefficient is computed for a lag of one year, two years, three years, and so forth up to a predetermined maximum number of lags. Harmonic analysis of the autocorrelation function yields estimates of the relative spectral density at each of a number of frequencies. These "raw" spectral estimates are then smoothed using a moving-average filter. Several types of filter weights are in common use (Jenkins and Watts 1968). The resulting smoothed spectrum will contain sharp peaks at frequencies corresponding to exact periodicities in the original series, and broad humps where the variation in the series is less regular. In addition, the power spectrum of a time series containing persistence will show noticeable trend upon which the spectral peaks are superimposed.

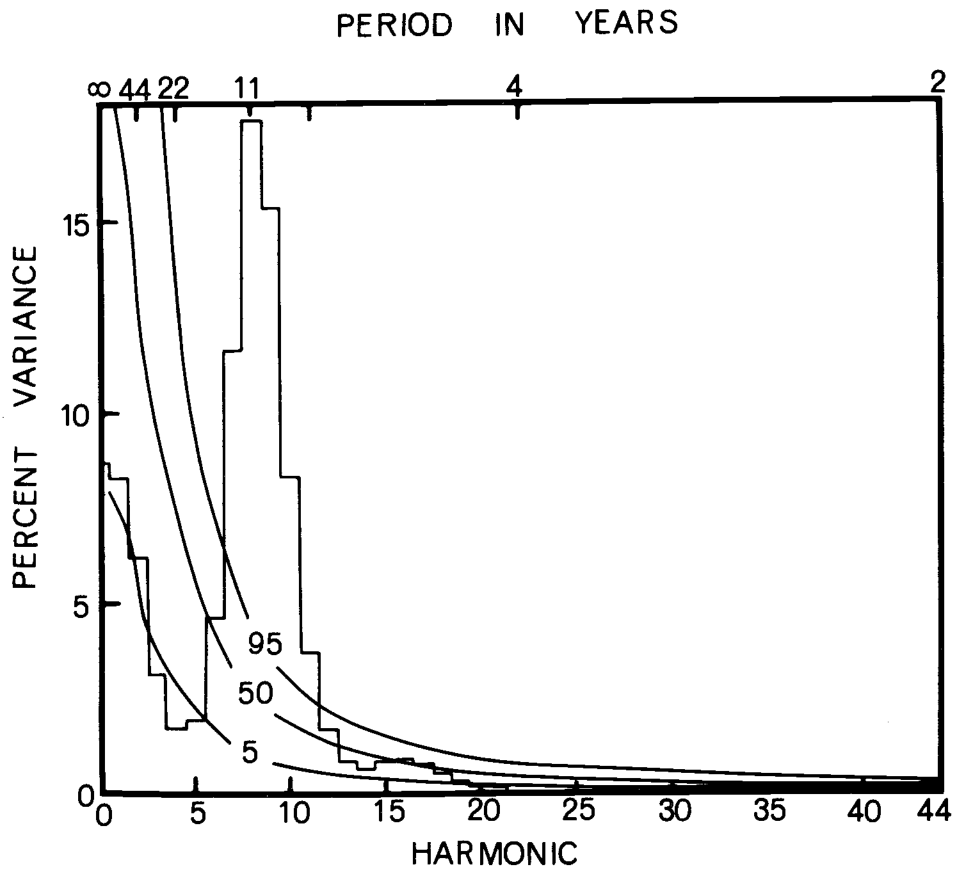

Figure 1. Power spectrum of annual sunspot numbers, based on 44-lag analysis using Parzen weights. Smooth lines give 5 percent, 50 percent, and 90 percent confidence limits for spectral estimates from a Markov process having a first-order autocorrelation coefficient equal to that observed for the time series (Mitchell and others 1966).

The total number and particular frequencies at which spectral estimates are obtained is determined by the maximum number of lags for which the autocorrelation coefficient is computed. In general, increasing the maximum number of lags improves the spectral resolution, but also increases the possibility of obtaining a high spectral density at some frequency by chance alone. In this study, most analyses were carried out to 44 lags, but in no case did the number of lags exceed 1/4 the number of observations in the series. Using a number of lags equal to a multiple of 11 years ensured that one spectral estimate would be centered in the frequency range of particular interest, in this case that of the 11-year sunspot rhythm.

A peak in the power spectrum of a time series cannot be accepted as proof of an underlying periodicity unless it can be shown that this result is unlikely to have been obtained by chance alone. A procedure for testing the statistical significance of peaks in power spectra has been outlined by Mitchell and others (1966) and was followed in this work. It is known that tree-ring series normally exhibit relatively high first-order autocorrelation (Matalas 1962). The effect of this autocorrelation is to inflate the spectral densities in the low-frequency range. Using the observed first-order autocorrelation coefficient for the series, a null continuum is calculated which represents the theoretical power spectrum for a series containing only first-order Markov persistence in addition to random variation. Statistically significant peaks in the power spectrum are those lying outside the confidence limits which parallel the calculated null continuum (see Figure 1).

Digital Filtering

Filtering and smoothing functions are used in order to emphasize variation in a time series within particular frequency ranges. The justification for filtering is the assumption that variation at other frequencies is either random error, or is of no significance to the particular type of evaluation being carried out. The filtered value of an observation in a time series is thus an estimate of what the value would have been if variation at the other frequencies had not been present. Recent developments, made possible by high speed computers, have eliminated many of the objectionable features associated with simple moving averages. Filters can now be designed which will preserve the phase and amplitude characteristics of the original series, within any desired frequency range.

The filtered value of any observation x_t is calculated according to the equation

$$\hat{x}_t = \sum_{k=-n}^{m} W_k X_{t+k}$$

$$= W_{-n} X_{t-n} + \ldots + W_0 X_t + \ldots W_m X_{t-m}$$

where W_k is a particular weight in the smoothing function, and W_0 is termed the central or principal weight. An important characteristic of any filtering function is its frequency response curve, defined by the ratio of the amplitude of a sine wave before filtering to its amplitude after filtering, at each frequency. Techniques for the selection of filter weights giving a desired frequency response are presented by Holloway (1958).

Four digital filters were used in this study. The filter weights are listed in Table 1 and their frequency response curves are shown in Figure 2. The "high-pass" filter removes most of the variation at frequencies lower than 1/8 cpy. The "low-A" filter is the reciprocal of the high pass filter, and removes most of the variation at frequencies higher than 1/8 cpy. The "11-year band-pass" filter, as given by Brier (1961), retains variation with periods of 6 to 15 years and suppresses variation outside this range. The "low-B" filter eliminates most of the short-period oscillations while retaining long-term periodicities and trends. The effects of filtering are illustrated in Figure 3, which shows the Wolf sunspot numbers from 1700 to 1960 plotted in their original form, and after filtering with the 11-year band pass filter and with the low-B filter, respectively.

Harmonic Dial

One type of analysis that utilizes time series which have been smoothed by a digital filtering operation is the construction of a harmonic dial. Prefiltering of the two series to be compared emphasizes oscillatory movements within the frequency range of interest, without modifying the original phase relationships. To construct a harmonic dial, the dates of maxima in one series are converted into indices representing their occurrence

Table 1. Weights for four digital filters.

M	HIGH-PASS	LOW-A	11-YEAR BAND PASS	LOW-B
0	.7744	.2256	.1360	.0798
±1	-.1933	.1933	.1070	.0782
2	-.1208	.1208	.0340	.0737
3	-.0537	.0537	-.0460	.0667
4	-.0161	.0161	-.0950	.0581
5	-.0030	.0030	-.0980	.0486
6	-.0003	.0003	-.0620	.0390
7			-.0190	.0301
8			-.0230	.0223
9			.0380	.0159
10			.0340	.0109
11			.0230	.0071
12			.0130	.0045
13			.0070	.0027
14			.0030	.0016
15			-.0010	.0007
16			-.0060	
17			-.0080	
18			-.0090	
19			-.0060	
20			-.0040	
21			-.0010	

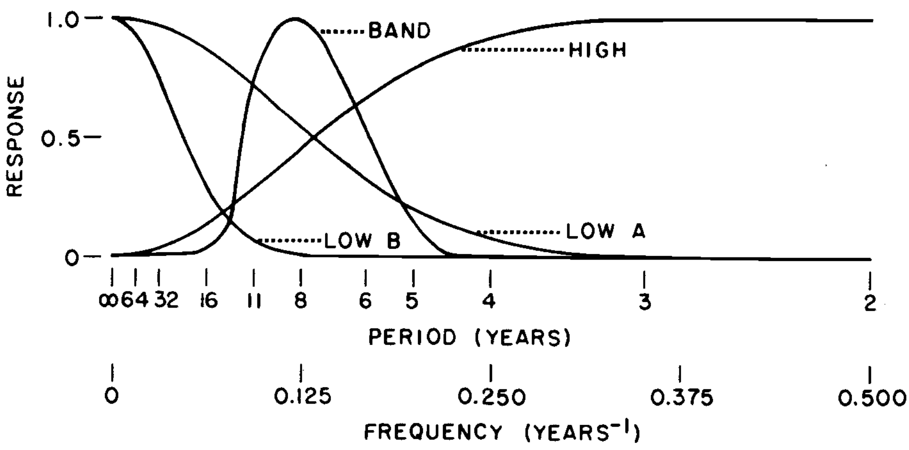

Figure 2. Frequency response functions for four digital filters.

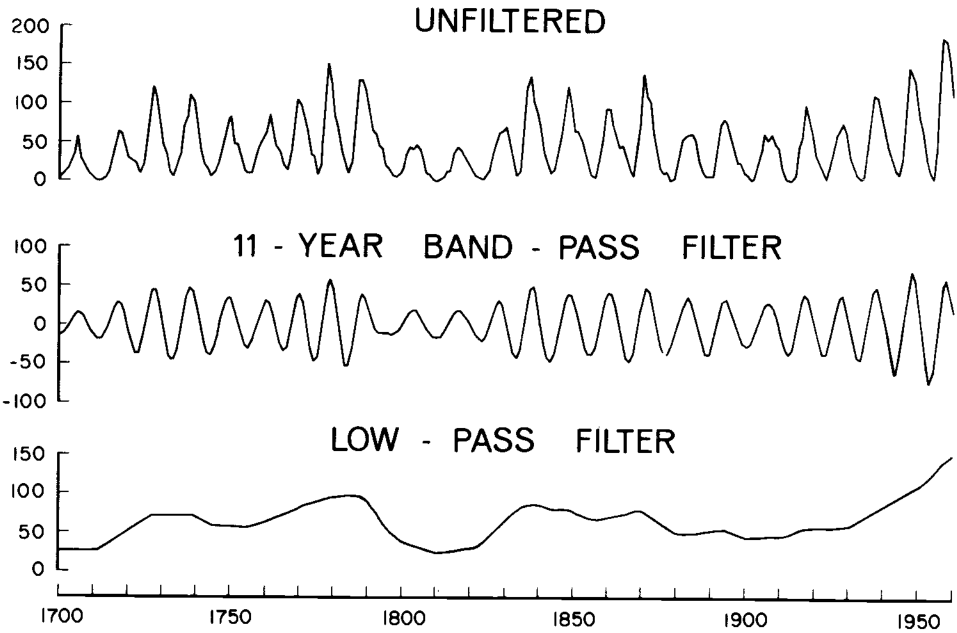

Figure 3. Annual sunspot numbers plotted in original form, and after smoothing with 11-year band-pass and low-B filters, respectively.

relative to peaks in another cyclical series, where $\theta_s = 0$ indicates the beginning of the cycle, $\theta_s = 90°$ indicates 25 percent of the way through the cycle, $\theta_s = 180°$ indicates half way through the cycle, etc. The values of θ_s and the magnitude of the maxima in the first series are then plotted on a circular diagram on which radial distance represents amplitude and angular distance represents phase (Brier 1961).

Correlation and Regression

The simple linear correlation coefficient can be used to test the association between two time series. In this work, individual tree-ring chronologies, as well as amplitude series derived by principal component analysis of tree-ring data, were compared with the series of annual Wolf sunspot numbers. Testing the significance of the correlation coefficients obtained from comparison of these time series is complicated by the fact that each normally contains significant persistence. Although techniques exist which enable one to correct for the effect of persistence, this was not found to be necessary because very few of the correlation coefficients obtained exceeded the limits expected for completely uncorrelated time series.

Correlation was also made after smoothing both the sunspot and tree-ring series, using the two low-pass digital filters described above. In this case, the effective number of observations in each series is greatly reduced, with a corresponding increase in the absolute value of the correlation coefficient required to demonstrate a statistically significant correlation (Rodriguez-Iturbé and Yevdjevich 1968). A conservative estimate of the effective number of observations in the filtered series was obtained according to the formula

$$N' = N/k$$

where N is the number of observations in the original series and k is the number of filter weights used.

Principal Component Analysis

Principal component analysis – also termed the "eigenvector" or "empirical orthogonal function" approach – was used in this investigation to determine whether large scale patterns of tree-growth variation show any demonstrable response to changing levels of solar activity. This method of analysis was introduced into meteorology by Lorenz (1956), and is being increasingly applied to problems in this field (Grimmer 1963; Stidd 1967; Kutzbach 1967; Fritts and others 1971). Basically, it is a method for reducing the number of variables that need to be specified in order to "explain" a major proportion of the total variance in a set of data, by taking advantage of the intercorrelations that exist in the original data field.

The underlying theory and a procedure which closely parallels that used in this study are discussed in detail by Sellers (1968). In our application, the data field consists of a two-dimensional array of observation points (tree-ring collection sites). The observations are the time series of annual tree-ring indices at each point after normalization by subtracting the chronology mean and dividing by the chronology standard deviation. A contour map of the components of each eigenvector resulting from the analysis represents a characteristic tree-growth anomaly pattern (LaMarche and Fritts 1971). The amplitude of the eigenvector, computed from the normalized tree-ring indices, is a function which shows how the relative importance of each characteristic pattern changes through time. An important attribute of these amplitude series is that they are statistically uncorrelated.

RESULTS

Short Period Oscillations

The power spectrum of sunspot numbers (Figure 1) shows that most of the variance is concentrated in a frequency range of 1/15 to 1/8 cpy, with a peak at 1/11 cpy. If there is variation in tree-ring growth associated with this short period solar variation, the power spectra of tree-ring series would be expected to show corresponding peaks, and there would be clustering of points in a certain quadrant of the harmonic dial. In Figures 4 and 5 power spectra of two long tree-ring series illustrate typical results. In both cases, significant spectral peaks occur, corresponding to long-period variation in the series. However, in neither spectrum is there any suggestion of an 11-year oscillation. Also there was no significant clustering in the harmonic dial.

Another solar rhythm, with an average period of about 22 years, has been thought to be reflected in some terrestrial time series. This is the Hale or "double-sunspot" cycle, based on the observation that the magnetic polarity of sunspot groups reverses between

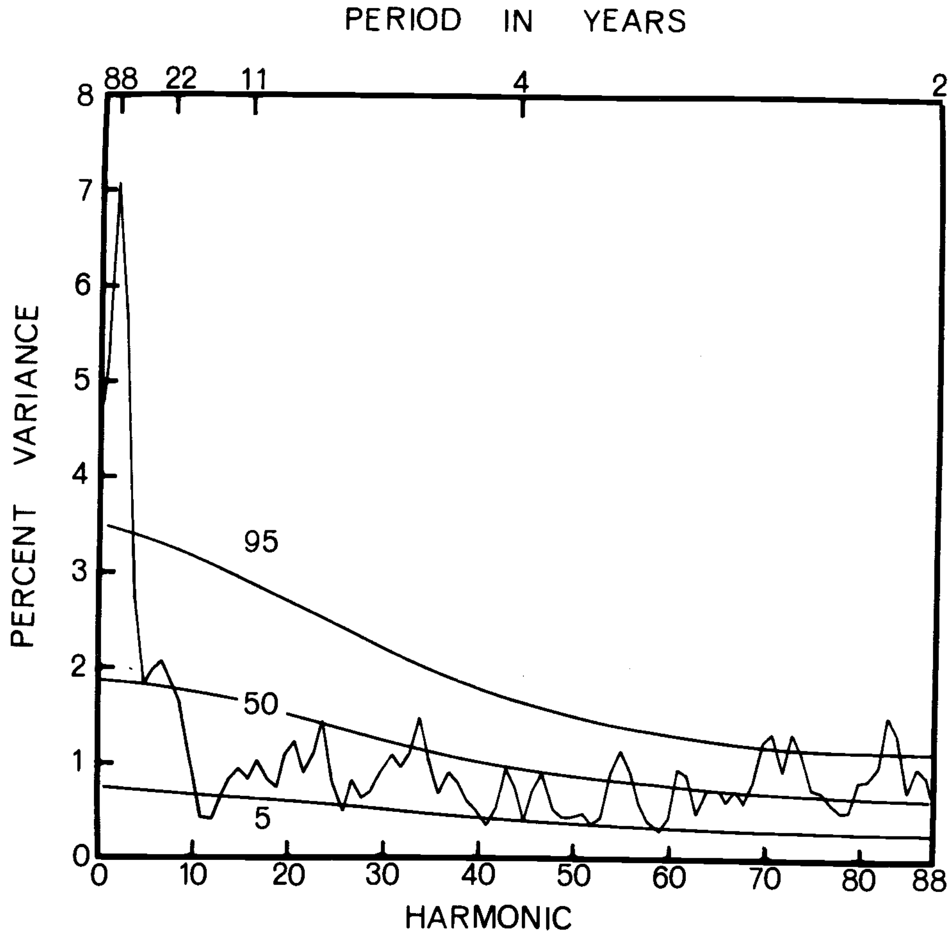

Figure 4. Power spectrum of tree-ring indices from 464 year-old Douglas-fir, Mesa Verde National Park, Colorado. Period is A.D. 1400 to 1963. Analysis carried out to 88 lags with Tukey-Hanning weights.

successive maxima (Bray and Loughead 1967). Neither of the power spectra show significant spectral peaks at this frequency.

Power spectra were also obtained from analysis of shorter tree-ring series. A set of 17 were analyzed – nine from the Rocky Mountain region and eight from areas along the Pacific Coast. The distribution of normalized spectral densities at frequencies of 1/11 cpy and 1/22 cpy is shown in Figure 6. None are significant, as all of the spectral estimates fall within the range expected for series containing only first-order Markov persistence in addition to random "noise."

The harmonic dial was also used to test for relationship between the sunspot rhythm and the variations in tree-growth indices. A number of tree-ring chronologies from western North America, including several published series from the Arctic (Giddings 1947; Sirén 1961), were smoothed using the 11-year band-pass filter (Table 1 and Figure 2). The maxima in the plotted, smoothed series were compared with those of the similarly filtered sunspot series (Figure 3), following the method of Brier (1961). In none

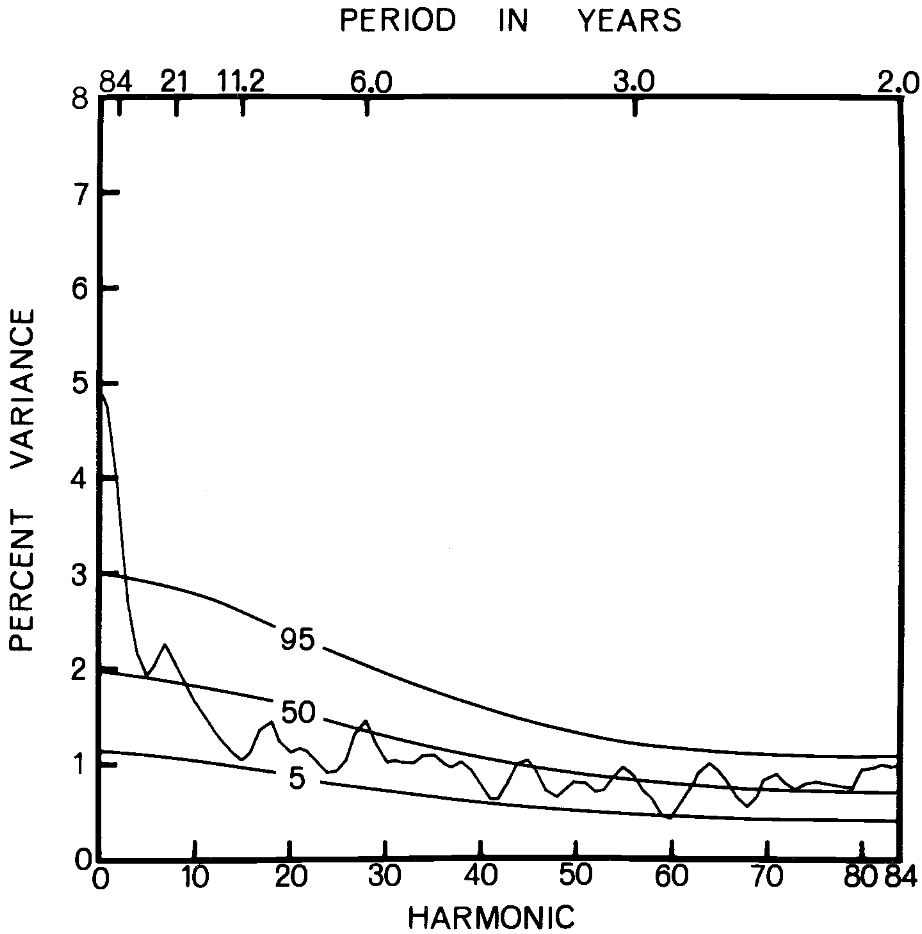

Figure 5. Power spectrum of ring-width index chronology for bristlecone pine, White Mountains, California. Period A.D. 801 to 1954 (Stokes and others 1973). Analysis carried out to 84 lags with Tukey-Hanning weights.

of the analyses was there any significant clustering of points which might indicate a consistent phase relationship between peaks of the 11-year sunspot rhythm and the peaks of the smoothed tree-ring series. The peaks would sometimes coincide for a few cycles but would shift to other phase angles so the long records which give adequate replication turned out to exhibit no consistent relationship. Spectral analysis of the long tree-ring record from northern Sweden (Sirén 1961) also fails to indicate an 11-year periodicity, although spectral peaks at other frequencies could be related to solar variation (Sirén and Hari 1971).

Regional Growth Anomaly Patterns

Power spectrum analysis was used to test the possibility that patterns of tree-growth anomalies on a continent-wide scale might show variations associated with changes in sunspot numbers. For the initial study, 23 of the original set of 26

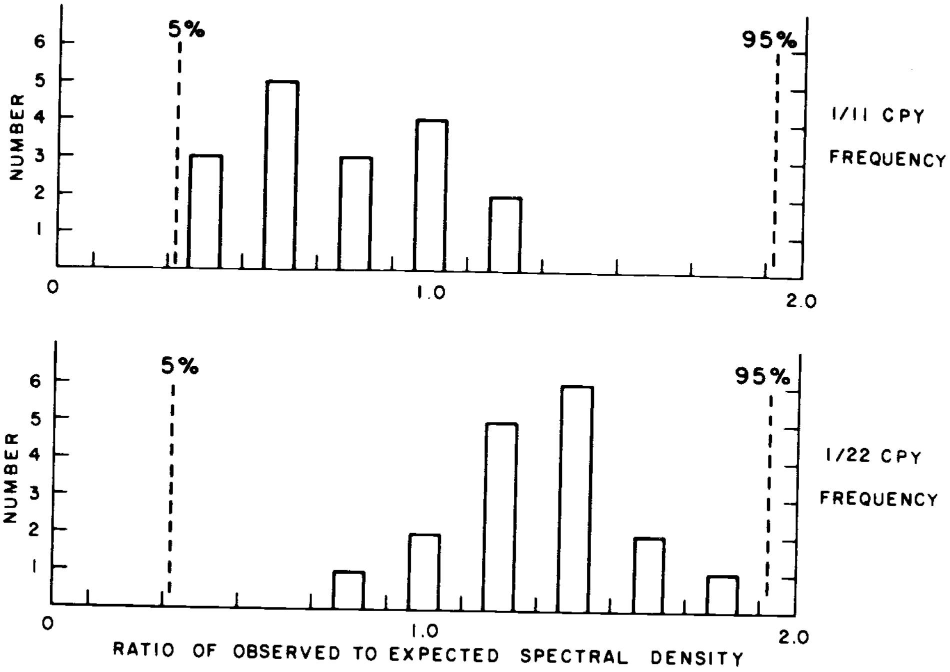

Figure 6. Distribution of spectral estimates at 1/11 cpy and 1/22 cpy for 17 North American tree-ring chronologies expressed as the ratio between observed spectral density and density expected for a Gauss-Markov process having the same first-order autocorrelation coefficient. 5 percent and 95 percent confidence limits calculated according to Mitchell and others 1966.

chronologies were selected for their greater length. Using tree-ring indices for the period 1541-1930, principal component analysis yielded 23 eigenvectors. The seven most important accounted for about 65 percent of the total variance in the original 23 series. Power spectrum analysis of the amplitude functions of these seven eigenvectors, to a maximum of 44 lags, produced results of potential significance to this study. The power spectrum of the amplitudes of the first eigenvector contained a pair of peaks corresponding to frequencies of 22.0 and 29.2 years. Following the procedure outlined by Mitchell and others (1966) the joint occurrence of these two peaks was found to be significant at the 99 percent confidence level, under the hypothesis that variation in this frequency range might be expected *a priori* from knowledge of similar variation in the sunspot series.

Two alternative schemes were used to convert the Zurich yearly mean sunspot numbers into a series reflecting the 22-year magnetic polarity cycle. First, the sunspot numbers were given negative signs in alternate cycles, with the sign of the 1957 maximum considered positive. Then, the method proposed by Jose (1965) was used, in which certain minor maxima are considered to be parts of longer cycles. The series have very similar power spectra, but differ in phase between 1797 and 1876. The amplitude of the first eigenvector is plotted for comparison with the modified sunspot record in Figure 7.

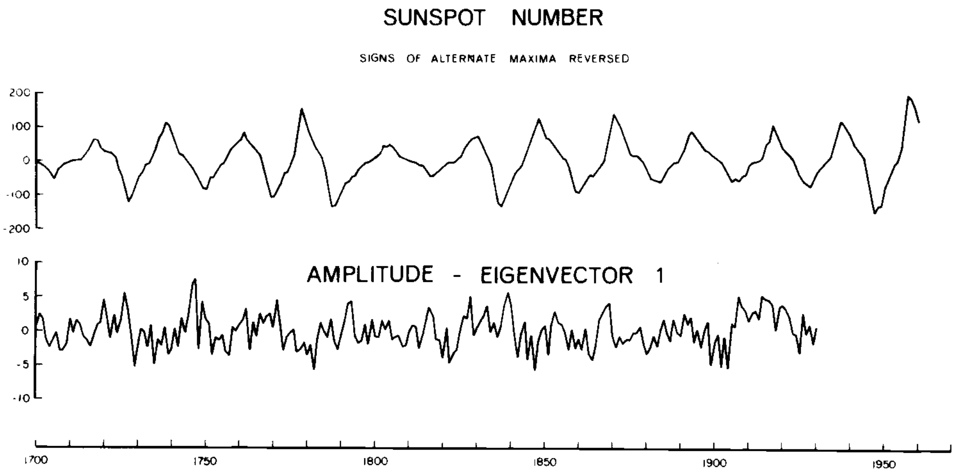

Figure 7. Amplitude of first eigenvector of tree growth, 1700-1930, plotted for comparison with the modified sunspot record (signs of alternate maxima reversed). There is a recognizable oscillation of the amplitude series with a period of 20 to 30 years, but it appears unrelated to the "double sunspot cycle."

To test the possibility that the 20 to 29 year peak in the spectrum of the first amplitude series might be related to the "double sunspot cycle," the coherence (Jenkins and Watts 1968) between the amplitude series and each of the converted sunspot series was computed. There proved to be no significant coherence. Therefore, the 22-29 year oscillation in the first eigenvector amplitude is apparently unrelated to solar variability. It may, however, reflect other extraterrestrial influences. Brier (1968) has presented evidence for a 27-year repeat pattern in the value of the zonal index. He tentatively attributes this to the seasonal modulation of an 11.6-month cycle in the solar-lunar gravitational tide.

Long Period Variation

Much of the variance in sunspot numbers is due to variations over periods much longer than that of the 11-year rhythm. A graph of the yearly mean sunspot numbers (Figure 3) shows that, although the minimum sunspot numbers remain nearly constant from one cycle to the next, the maximum numbers tend to increase or decrease regularly for several consecutive cycles. Removal of the 11-year component through use of a low-pass filter emphasizes this feature.

As shown by their power spectra, many tree-ring series also contain significant low-frequency variance. It is thus conceivable that general trends in the level of solar activity might be reflected in tree-ring growth. The first method that we used to test this possibility was simple correlation after pre-filtering to remove all or part of the 11-year periodicity from the sunspot series, and to remove high-frequency "noise" from the tree-ring series. Both the low-A and low-B filters were used. The distribution of the resulting simple correlation coefficients is shown in Figure 8. In 26 trials using the low-A filter (with a 50 percent response at 8 years) none of the correlation coefficients was

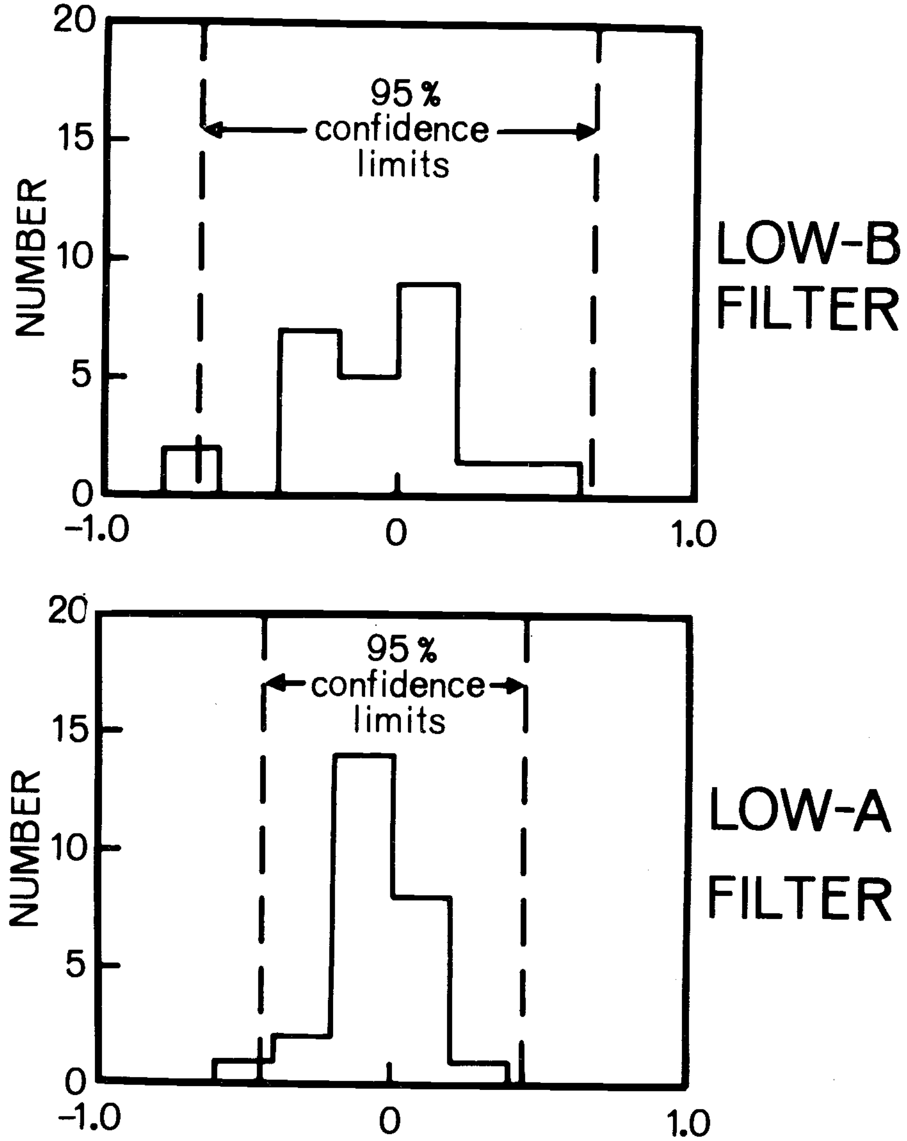

Figure 8. Distribution of correlation coefficients between smoothed ring-width index series and the record of annual sunspot numbers. High-frequency variation was removed from the series using the low-A and low-B filters, respectively, prior to correlation. Confidence limits were calculated using the estimated effective number of observations, N′, described in the text.

found to be significant. Using the low-B filter (with a 50 percent response at 28 years) only one result exceeded the confidence limit, an expectable result in a large number of trials. It must be concluded that there is no evidence from these calculations of an in-phase relationship between individual tree-ring chronologies and the smoothed sunspot record.

The harmonic dial was again used to search for possible out-of-phase relationships of tree growth and long period solar variation. The maxima from five long tree-ring series from bristlecone pine (*Pinus longaeva*), sequoia (*Sequoia gigantea*), limber pine (*Pinus flexilis*), and Douglas-fir (*Pseudotsuga menziesii*), after smoothing with the low-B filter, were converted to indices representing the locations relative to maximum in the 179-year cycle of Jose (1965), where θ_j represents the phasing within each 179-year cycle analogous to the phasing of the 11-year cycle described previously. If there is any significant association of tree-ring maxima with the particular cycle in question, the plots on the harmonic dial will show a clustering of values at a particular quadrant of the dial (see Brier 1961, Figures 9 and 10). However, the plotted tree-ring maxima were scattered randomly around the dial. These results show no evidence for phase relationships between these tree-ring series and a 179-year solar cycle.

CONCLUSIONS

The results of our investigation offer no convincing evidence of consistent relationships between ring width and solar variation. The absence of significant peaks in power spectra or of phasing in the harmonic dial corresponding to the 11-year sunspot rhythm or the 22-year "double cycle" indicate that no persistent relationship with the Zurich sunspot numbers exists in any of the tree-ring series studied. Furthermore, the power spectra of the amplitude series, reflecting variations in major regional growth-anomaly patterns in western North America, show no significant spectral peaks at the 1/11 cpy frequency. However, the results of the power spectrum analyses do not rule out the possibility of solar-related oscillations in tree-ring series which undergo frequent phase shifts or reversals. Neither do these results completely exclude the possibility that longer period variation in the level of solar activity is reflected in tree-growth variation. However, the results of correlation tests comparing smoothed sunspot data with tree-ring series and with eigenvector amplitude series gave essentially negative results.

From the results of this investigation and from the similar results of other studies (Bryson and Dutton 1961; Rodriguez-Iturbé and Yevdjevich 1968), we conclude that a continued search for empirical associations between terrestrial time series, such as tree-ring indices, and the record of sunspot numbers is likely to prove unrewarding. However, long tree-ring records are available or are being developed for many species over a large part of the globe. The expanding data base, the improved understanding of the relationships between climatic variables and tree-ring growth, coupled with more powerful analytical techniques, may permit testing of geophysical hypotheses linking solar variations to climate over time periods longer than those encompassed by climatic or sunspot records.

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REFERENCES

Allen, C. W.
1964 The influence of the sunspot cycle on phenomena at the bottom of the atmosphere. *Planetary and Space Science* 12: 327-331.
Bray, R. J. and R. E. Loughead
1967 *Sunspots.* The International Astrophysics Series, Vol. 7, edited by Sir Bernard Lovell and Zdenek Kopal. Chapman and Hall Ltd., London.
Brier, G. W.
1961 Some statistical aspects of long-term fluctuations in solar and atmospheric phenomena. *Annals of the New York Academy of Science* 95: 173-187.
1968 Long range prediction of the zonal westerlies and some problems in data analysis. *Reviews of Geophysics* 6: 525-551.
Bryson, R. A. and A. Dutton
1961 Some aspects of the variance spectra of tree rings and varves. *Annals of the New York Academy of Science* 95: 580-604.
Douglass, A. E.
1919 Climatic cycles and tree-growth. A study of the annual rings of trees in relation to climate and solar activity. Vol. I. *Carnegie Institution of Washington Publication* 289.
1928 Climatic cycles and tree-growth. A study of the annual rings of trees in relation to climate and solar activity. Vol. II. *Carnegie Institution of Washington Publication* 289.
1936 Climatic cycles and tree growth. A study of cycles. Vol. III. *Carnegie Institution of Washington Publication* 289.
Fritts, H. C.
1965 Tree-ring evidence for climatic change in western North America. *Monthly Weather Review* 93: 421-443.
1969 Tree-ring analysis: a tool for water resources research. *Transactions, American Geophysical Union* 50: 22-29.
Fritts, H. C., T. J. Blasing, B. P. Hayden, and J. E. Kutzbach
1971 Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *Journal of Applied Meteorology* 10: 845-864.
Giddings, J. L.
1947 Mackenzie River Delta chronology. *Tree-Ring Bulletin* 13: 26-29.
Grimmer, M.
1963 The space-filtering of monthly surface temperature data in terms of pattern using empirical orthogonal functions. *Quarterly Journal of the Royal Meteorological Society* 39: 395-408.
Holloway, Leith
1958 Smoothing and filtering of meteorological time series and space fields. In *Advances in Geophysics*, Vol. 4, edited by H. E. Landsberg. Academic Press, N.Y.
Jenkins, G. M. and D. M. Watts
1968 *Spectral analysis and its applications.* Holden Day, San Francisco.
Jose, P. D.
1965 Sun's motion and sunspots. *The Astronomical Journal* 70: 193-200.
Julian, P. R. and H. C. Fritts
1968 On the possibility of quantitatively extending climatic records by means of dendroclimatological analysis. *Proceedings of the First Statistical Meteorological Conference, American Meteorological Society*, pp. 76-82.
Kutzbach, J. E.
1967 Empirical eigenvectors of sea level pressure, surface temperature and precipitation complexes over North America. *Journal of Applied Meteorology* 6: 791-802.
LaMarche, V. C., Jr. and H. C. Fritts
1971 Anomaly patterns of climate over the western United States, 1700-1930, derived from principal component analysis of tree-ring data. *Monthly Weather Review* 99: 138-142.
Lorenz, E. N.
1956 Empirical orthogonal functions and statistical weather prediction. *Massachusetts Institute of Technology, Department of Meteorology, Scientific Report 1.*
Matalas, N. C.
1962 Statistical properties of tree-ring data. *Bulletin of the International Association of Scientific Hydrology* 7: 39-47.
Mitchell, J. M. with B. B. Dzerdzeeoskii, H. Flohn, W. L. Hofmeyr, H. H. Lamb, K. N. Rao and C. C. Wallen
1966 Climatic change. *World Meteorological Organization Technical Note* 79.

Rodriguez-Iturbé, Ignacio and Vujica Yevdjevich
1968 The investigation of relationship between hydrologic time series and sunspot numbers. *Hydrology Papers* 26, *Colorado State University.*
Sellers, W. D.
1968 Climatology of monthly precipitation patterns in the western United States, 1931-1966. *Monthly Weather Review* 96: 585-595.
Sirén, Gustaf
1961 Skogsgränstallen Som Indikator för Klimatfluktuationerna i norra Fennoskandienunder Historisk Tid: Metsantutkimuslaitoksen Julkaisuga 54.2; *Communicationes Instituti Forestalis Fenniae* 54.2.
Sirén, Gustaf and P. Hari
1971 Coinciding periodicity in recent tree rings and glacial clay sediments. *Report of the Kevo Subarctic Research Station* 8: 155-157.
Stidd, C. K.
1967 The use of eigenvectors for climatic estimates. *Journal of Applied Meteorology* 6: 255-264.
Stokes, M. A., L. G. Drew, and C. W. Stockton, editors
1973 Tree-ring chronologies of western America. I. Selected tree-ring stations. *Chronology Series* 1, Laboratory of Tree-Ring Research, The University of Arizona.
Waldemier, M.
1961 *The sunspot activity in the years 1610-1960.* Zurich Schulthess and Co.

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