Methods of Dendrochronology

Applications in the Environmental Sciences

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The second problem has been solved for the Maunder minimum by making high-precision yearly measurements of radiocarbon content in tree rings (Kocharov *et al.*, 1985; Kocharov, 1986 and references therein). As for the energy spectrum, it can be derived by simultaneous measurement of the content of several cosmogenic isotopes (^{10}Be, ^{14}C, ^{36}Cl) in dated samples (Kocharov, 1986). Our data on the evolution of radiocarbon content in the Earth's atmosphere during the Maunder minimum reveal considerable fluctuations against a generally rising ^{14}C content level, which implies that even during deep solar activity minima the mechanism of galactic cosmic ray modulation continues to operate. Fourier analysis reveals two peaks in the spectrum, with a confidence level above 80%, at the frequencies corresponding to periods of 11 and ~22 years. Note that a period close to 11 years is more clearly seen in the years preceding the Maunder minimum while during the minimum proper a 22-year oscillation is more manifest. Our analysis suggests that the 22-year modulation of cosmic rays found to have existed during the Maunder minimum is most probably related to a change of the solar polar magnetic field. One can thus conclude that the solar dynamo does not stop during deep minima of solar activity. The nature of the Maunder minimum is apparently associated with the existence of several long-period solar variations, the superposition of their minima having resulted in a dramatic drop of solar activity.

6.1.5. Conclusion

We have succeeded in analyzing only a fraction of the wealth of available information from studies of astrophysical, geophysical, and ecological phenomena making use of cosmogenic isotopes. We hope, however, that this report demonstrates the richness, uniqueness, and importance of the information on heliospherical processes recorded in tree rings, both in theory and in practice. This information can provide a basis for the reconstruction of past and the prognosis of future physical and chemical environmental changes.

6.2. Outline of Methods of Long-Range Prognosis on the Basis of Dendrochronological Information

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For the natural sciences, which deal with the study of uncontrollable or hardly controllable phenomena and processes (climatology, hydrology, ecology, etc.), prediction is the fundamental and frequently the only possible method of obtaining scientific results in the sphere of practical applications. In connection with working out long-term plans for the rational utilization and protection of natural resources in the last decades, there has been a sharply rising need to devise and elaborate long-term (from one year to several decades) ecological predictions. Such precautionary information is necessary to improve the effectiveness of adopted solutions.

Because dendrochronology is a scientific discipline in the ecological sphere, predictions based on the use of dendrochronological information could be placed in a separate class of ecological prognosis as dendrochronological predictions – particularly when one takes into account the fact that a tree-ring chronology contains information about the past that is unique in its duration and accuracy.

The basic task of dendrochronological prognosis is to forecast changes in the growth index of arboreal plants. Nevertheless, on the basis of knowledge about the functional and correlational ties between the growth index of trees and factors of the environment and with the course of various natural processes, it is also possible to provide qualitative and quantitative predictions of environmental factors themselves. The extensively practiced reconstruction of natural past conditions (climatic conditions in particular), on the basis of dendrochronological information, may also be given the name of prediction in the past or retrodiction.

The general methods of ecological prediction and the methods used in the prediction of dynamic systems are applicable to dendrochronological prognoses. In this case, it is necessary to take into account the specificity of the dendrochronological series, which are discrete time series reflecting principally the changes in external limiting factors, primarily of a climatic nature, that are common for a given aggregate of trees. The specific character of these series is also year-to-year persistence, i.e., the influence of the size and conditions of growth during the previous year on the size of the growth of the current year, and also the possibility for statistical evaluation of the growth indicators for the individual calendar years.

Although the problem of dendrochronological prediction had been studied as early as the end of the 19th century and the beginning of the 20th century by Shvedov (1892) and Douglass (1919, 1928, 1936), we cannot compliment ourselves on much success in this field. The attention of dendrochronologists has so far been focused mainly on reconstruction of the climatic conditions of the past, i.e., retrodiction.

The approaches used in making predictions in dendrochronology may be divided into two large groups: intersystemic and intrasystemic. The essence of the intersystemic approach lies in using the dynamics of an external system of variables (the predictors) to predict, with a certain probability, the change in a dependent system of causally linked tree-ring variables (the predictands). The intrasystemic approach is based on the existence of persistence or autocorrelation within the dendrochronological series, which also allows predictions to be made without the need for external predictor variables.

The intersystemic approach is the most promising one and is most frequently used in dendrochronological prognosis. It is necessary to link both systems to one another either functionally or correlatively, such that the response of the tree rings takes place after the occurrence of the predicting variable in time. The predicting systems are most frequently the chronological series of solar activity and the tide-forming forces of the Moon and Sun that influence growth-limiting factors of the environment on tree growth.

Interest in the establishment of the correlational ties between the growth of trees and solar activity has arisen from the very beginnings of the science of dendrochronology and has not diminished (Douglass, 1919, 1928, 1936; Erlandsson, 1936; Kostin, 1961; Kolischuk, 1966; Komin, 1969; Bitvinskas, 1974, 1986; Olenin, 1976; Mitchell *et al.*, 1987). This interest is far from accidental. The establishment of such a connection is additional evidence in favor of the hypothesis about the influence of solar activity on the course of geophysical and biological processes. For example, Currie (1980) found an 11-year cycle in temperature records from North America at locations east of the Rocky Mountains and north of 35°N, which he attributed to the 11-year sunspot cycle. Besides that, the series of indicators of solar activity (sunspots) possesses sufficient duration to enable cyclical fluctuations of various durations to be readily surveyed in it. We also have much experience in long-term prediction of solar activity (Vitinskiy, 1983).

An analysis of the literature on clarifying the correlation between the indicators of solar activity and the growth of trees shows that in certain regions the connections are fairly strong, in other regions they are weak, while in still other regions they are not evident at all. The nature and closeness of the connections differ for the different phases of solar activity. For example, Bitvinskas (1986) used solar activity (the Wolf sunspot numbers for hydrological years) as pointer years to which radial tree growth could be *attached* to forecast the ecoclimatic background fluctuations responsible for forest growth. Those areas with sufficiently stable connections in time between the variable quantities examined can be used fully for the purposes of dendrochronological prediction. But until we have discovered the physical mechanisms responsible for the influence of solar activity on natural process on the Earth, it would be difficult to expect any great successes in the utilization of this method of prediction.

A promising method for the prediction of tree growth from the biggest anomalies of hydrometeorological indicators derives from the distribution of the maxima of solar and lunar gravitational tidal forces on Earth. These tidal forces lead to the formation of blocking anticyclones and to changes in the character of the atmospheric circulation (Yavorskiy, 1977). Drought appears in the zone of such anticyclones, with considerably increased precipitation observed around its periphery. The width of the zone of maximum tidal effects amounts to 300–500 km in longitude. When the atmospheric tides are formed over regions of precipitation formation, e.g., above the North Atlantic, then the drought may be manifested over very large territories. The change in the amount of precipitation and in the air temperature can be observed on the growth of the trees, since there exist sufficiently strong connections between the growth indices, climate, and the intensity of the atmospheric tides. Long-term dendrochronological series are helpful in establishing such connections (Yavorskiy, 1977).

Calculations of the tide-forming forces of the Moon and of the Sun can be made for many years in advance. Using this method, it was possible to predict successfully the disastrous drought that occurred in the USSR in 1972 and 1975. In connection with the responsiveness of the atmosphere to the action of tide-forming forces, it is possible to explain the origin of a fairly large number of cyclic fluctuations in the growth of trees with the duration of two to several hundred years. The analysis of 102 recent tree-ring chronologies made by Currie (1984) confirms earlier evidence for 18.6-year tidal drought–flood induction (Currie 1981, 1984) and led to the discovery of the 11-year solar-induced drought–flood cycle for western North America. Bistable phasing in terms of geography was also found, with epochs of maxima in lunar nodal 18.6-year drought in western Canada out of phase with those in western United States and northern Mexico for the past two centuries. As for prognostical use, this approach awaits further studies because the climatic response of solar cyclicity is highly dependent on the atmospheric chemistry.

If we had at our disposal reliable predictions about the factors of the environment that determine tree growth, it would have been possible to make predictions of growth in a comparatively easy and reliable manner, particularly in those regions where the number of tree-growth limiting factors is low. Since long-term predictions of the hydroclimatic factors are unreliable, it is not possible to use them as predictors for the time being. Currently, on the basis of dendroclimatic models, a basic reconstruction, or retrodiction, is possible for the most important climatic factors, as well as an evaluation of the adequacy of the prediction models (Fritts, 1982; Fritts and Gordon, 1982). Self-organizing regression models (Ivaxenko, 1975; Rosenberg and Feklistov, 1982) can be of great help in developing hydroclimatic models, and they could also be useful for the purposes of long-term prediction. These models make it possible to evaluate both the contribution of the individual factors and the aggregate influence of a set of factors.

In the reconstruction of the environmental conditions of the past, the dendrochronological series appears in the capacity of predictors. The dendrochronological series could also be used as predictors of the future behavior of other time series if a stable and reliable connection exists between them, though with a shift in time. In this case, it would be useful to carry out a cross-correlation analysis.

In using the intrasystemic methodological approach, it is necessary to know the extent that the series can be represented by deterministic, stochastic, and purely random components. There is no unity of view on whether there is a deterministic component in dendrochronological series. Some authors believe that the cyclic components may be considered as deterministic. Others do not agree with this point of view and use methods from the theory of random stationary processes for analyzing the cyclical components. The theoretical prediction of the probability component must be made on the basis of the probability model of the process. Because no such models have yet been adequately worked out in dendrochronology, predictions make use of deterministic models in which the observable fluctuations are approximated and extrapolated by sinusoids. The purely random fluctuations in the dendrochronological series (white noise) are composed of random properties of the series and with methodological errors and, therefore, cannot be predicted. They determine the objective limit of predictability in the series.

The study of intraseries laws and principles of development and their utilization for the purposes of prediction are impossible without the availability of sufficiently continuous and homogeneous series. In this respect, the dendrochronological series are favorably different from the hydroclimatic series. Of great significance is the establishment of continuous fluctuations of the growth index, and in this connection, it is necessary to use appropriate methods of standardization of the tree-ring series. It is also necessary to account for the fact that the intrasystemic methods of prediction are not very appropriate in those cases when an essentially qualitative change occurs in the predicted system, for example, a change in the pattern of rhythmical fluctuation in tree-ring series (Kairiukstis and Dubinskaite, 1986).

The cyclical method of prediction is the one most frequently used in dendrochronology. It is based on the identification, approximation, and extrapolation of the most important cyclical components (Siren, 1963; Komin, 1978a, 1978b; Mazepa, 1985; Shiyatov, 1986). Several such cycles are usually identified in each series. We are now in possession of sufficiently powerful analytical methods and computing equipment to enable us to determine the necessary parameters of the cycles. Mention must be made of the promising nature of the joint utilization of maximum entropy spectral analysis and narrow-band digital filtering (Section 6.3).

The questions raised by Douglass (1919, 1928, 1936) about the reality of the cycles, about their stability in time, and about the mechanism of their formation are still topical. As long as the mechanism of cycle formation remains unknown, the reliability of such prognoses is restricted by the initial quantity of cycles more or less of one order, i.e., one type. With cycle change of the highest order, the type of cycles of the lowest order is changed as well. Then, the prognosis makes no sense. A paradoxical phenomenon occurs: the more accurate the prognosis, the less reliable it is (Kairiukstis, 1981). We come across such phenomena by processing tree-ring chronologies of many countries presented by different authors. Nevertheless, the only method of evaluating the reality of the cycles will be the analysis of their occurrence in sufficiently large numbers of continuous dendrochronological series obtained for one region or another. In any case, if the dendrochronological series contains well-expressed cycles that are stable in time, it could be fully utilized for the purposes of extrapolation. An attempt has also been made to establish and utilize the highest frequency cycles that are found by means of spectral decomposition. In this case, it is possible to give not only long-term climatic background predictions but also to predict short-term (seasonal) climatic fluctuations as well (Mazepa, 1985).

One of the methods of eliciting and using hidden periodicities for the purposes of long-term prediction was proposed by Berry *et al.* (1976). This method was tested on a sufficiently large number of dendrochronological series and produced fairly good results (Berry *et al.*, 1979; Kairiukstis, 1981; Kairiukstis and Dubinskaite, 1986). The essence of the method lies in that, by means of sorting out, the approximation of the series is carried out by single harmonics that are simple multiples of the sampling interval of the time series, and a selection is made of the most representative among them.

In dendrochronology, there is practically no use made of prediction based on the use of autoregressive functions. Since the dendrochronological series possesses a higher degree of autocorrelation compared with the climatic ones, it might be expected that autoregressive predictions for several years in advance could be effective in many instances.

Thus a definite, quantitative, and methodological basis exists for carrying out dendrochronological prediction. This is possible because of the knowledge of the laws of arboreal plant growth, the system analysis approach, and the theory of random stationary processes. With regard to the prediction of dendrochronological series, successes in this area are still modest.

Of great significance is the determination of the limits of predictability, i.e., an evaluation of how well and how far in the future it is possible to predict the change in the index of tree growth. In dendrochronological predictions such matters have not yet been studied extensively. Obviously, predictability must be higher in those series that have been obtained from extreme conditions of growth for arboreal vegetation. It is possible to expect higher predictability in regional average series, in comparison with single-site tree-ring chronologies. Nevertheless, experience gained in the Lithuanian SSR shows that indices of tree growth, as well as agricultural crops, forecast in the late 1970s (Kairiukstis, 1981) for normal growth conditions and boggy soils are still proving themselves. It is possible to expect higher predictability in regional average series, in comparison with single-site tree-ring chronologies.

The mathematical tools used today for the purposes of prediction are based on the assumption that the tree-ring series are stationary. But there are no purely stationary processes in nature. How is it possible to remove that apparent contradiction? It is possible that a theory will be developed for non-stationary random processes up to the level of practical application. At any rate, the probability approach to prediction is more promising than the deterministic one, although it is desirable for prediction to have a more concrete approach. Apparently, it will never be possible to eliminate completely the indeterminateness of prediction.

Finally, we wish to stress that it is desirable to use different methods of prediction. At least both of the intersystemic and intrasystemic approaches mentioned above must be linked to one another functionally or correlatively to improve our ability to make predictions. But what is most important to the successful development of prediction is the development of reliable, homogeneous, and continuous dendrochronological series, which would also contain continuous fluctuations of the growth indexes.

In connection with the increase in the anthropogenic load on forest ecosystems and with the appearance of new limiting factors (e.g., pollution of the air and soil), the problem of dendrochronological prediction is becoming more urgent and still more complex. We must no longer rely on the continuity of the properties of the data from the past to the future. It is necessary to adopt other methods to assess non-climatic influences and to use past cyclicity to predict the future. More advanced prognostic models must be worked out that would include anthropogenic factors. Promising approaches to solving this problem have been made using climatic response models (Cook, 1987; Eckstein *et al.*, 1984).

That is how dendrochronological prediction is both possible and necessary. The elaboration of predictions is not only of great practical significance, but of cognitive value as well, because it enables us to gain better insight into the mechanism of change in tree growth.