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Chronomics of Climatic Variations of Tree Ring Width

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Abstract—Variations in the average annual tree rings of 11 sequoia trees for 2189 years are studied. The power spectrum of tree ring variations, calculated by the Maximum Entropy Method (MEM), is power-law in character with the coefficient β close to –1.00, suggesting the fractal character of the considered time series. The calculations of the coefficient β in a 200-year sliding window showed that this coefficient rapidly drops to zero or very small positive values, indicating a break in the fractal structure in some intervals. We identified seven such episodes, two (the latest) of which correspond to Spörer and Maunder solar minima. The other five episodes, which occurred around 100 BC and 500, 700, 820, and 880 AD, i.e., before regular sunspot observations, may also correspond to climate changes. By combining methods aimed at identifying the specific spectral components, such as the Schwabe cycle and behavior of the 1/*f* dependence as a chaos characteristic, the chronobiologic (chronomics) approach can be used to study the global climatic processes—such as cycles of about 500 years—bearing on global warming.

Keywords: Chronoastrobiology, fractal scaling (1/*f* dependence), Spörer and Maunder minima of solar activity.

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INTRODUCTION

This work is an attempt to show how chronobilogy and chronomics may serve civilization and culture. Chronobiology began with the study of circadian (about 24-hour) rhythms and led researchers to identify photic (visible) and nonphotic (predominately invisible, except for aurorae) cycles. The photic cycles pertain to electromagnetic radiation in the visible spectral range; nonphotic cycles pertain to the electromagnetic effects in other spectral regions, such as solar, lunar and terrestrial magnetic fields, particle fluxes coming from Sun and outer space, gravity tides, and other (e.g., anthropogenic) effects.

Electromagnetically derived cyclic factors affect the human heart and brain and show up in electrocardiograms and electroencephalograms, as well as in encephalo- and cardio magnetograms. When sufficiently long data records can be obtained, they can be used to identify decadal-scale cycles, which are present not only in demographic data bases, but, very importantly, in heart-rate databases as well [Halberg et al., 2000].

Recently, statistical analyses have identified some new variates, namely, non-daily and nonannual, i.e., nonphotic cycles, among the geomagnetism cycles and the corresponding physiologic cycles of human beings and other organisms [Cornélissen et al., 2002; Halberg et al., 2000; Otsuka, 2001, 2002, 2003]. It has been evident that the invisible (nonphotic) cycles, predominately reflecting the effect of solar magnetic activity, affect life cycles on Earth and seem to imprint their chronobiologic structure on internal, environmentally driven physiological processes [Halberg et al., 2001].

Whenever the Sun is postulated as an overall origin in physics, economics, agriculture, and psychophysiology, we should seek the universal character of the solar effect, in particular, on us and the environment. Indeed, certain solar rhythms are as long as the cycles, known for biologic objects, and vice versa [Halberg et al., 2000]. However, not all rhythms of solar activity are amenable to direct study. For instance, records of aurorae and sunspots are too short to exhibit cycles with periods of 500 years or more.

DATA USED

For almost 100 years, tree rings have been considered indicators of climatic and other changes of environment, as well as of solar activity. An analysis of data on the ring width, which is considered an auxiliary indicator of solar activity, is of particular interest because there are data series for the last 2000 years or even longer time periods. This work uses data borrowed from the journal *Tree Ring Study*, which has a multiyear history.

The three-volume book by A.E. Douglass *Climatic Cycles and Tree-Growth* [Douglass, 1919, 1936] was republished in 1971 in the series *Historiae naturalis classica* [Douglass, 1971]. We analyzed the time series on the basis of annual rings of 11 sequoias from the flat west slopes of Sierra Nevada. We detected cycles with periodicities of about 6.51, 13.2, 38.3, 58.1, 98.6, 186, and 534 years [Nintcheu-Fata et al. 2003; Halberg

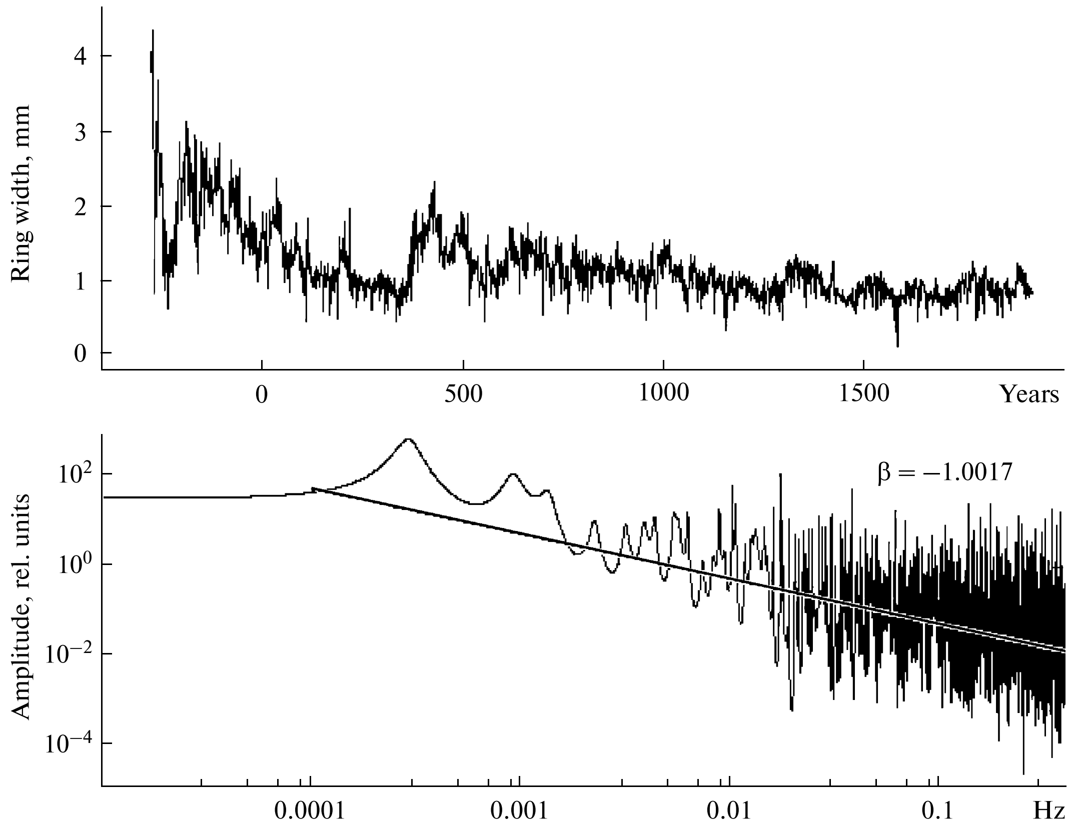

Fig. 1. Variations in the average tree-ring width of 11 sequoias for 2189 years [Douglass, 1971, p. 119–123] (upper panel) and MEM spectrum of this time series (lower panel). The spectral exponent $\beta = -1.0017$ is characteristic for fractal systems.

et al., 2004]. The last cycle corresponds well to the literature data [Halberg et al., 2004] on the 500-year variability cycle in the color of stalagmites, which, possibly, reflects changes in the near-surface of the Earth's temperature.

METHOD

Fractal dimension is one chaos (or complexity) characteristic. The concept of fractal dimension is most often associated with inhomogeneous geometric bodies possessing self-similarity. Fractal shapes split into fragments of different scalings, the structure of which is similar to the structure of the whole body [Mandelbrot, 1982]. In the ideal case, this property is scale-invariant. However, reality imposes lower and upper bounds within which such a scale-invariant representation can be assessed. Fractals account for many non-Euclidean structures in nature, such as tree branches, irregular coastlines, or rough mountain surfaces. Certain complex anatomic structures also have fractal geometry. The application of fractal analysis in biology and medicine may provide a new approach to risk assessment and predicting the sudden death of animals (including humans). At present, the most important scientific direction is to use fractal methods in physiologic studies and research branched signal systems.

Below, we analyze the measurements of the average tree-ring widths of 11 sequoias for 2189 years presented in [Douglass, 1971, p. 119–123]. The time dependence of this variable is plotted in Fig. 1 (upper panel). The fractal nature of the 2175-year time series of tree-ring widths was established by an analysis of its power spectrum calculated by the maximum entropy method (MEM). In the log–log coordinates, the regression between the frequency and spectral power is nearly linear; therefore, we can calculate the spectral exponent, i.e., the coefficient β, by the least squares method (a linear regression).

RESULTS

The coefficient of the power-law dependence β of the tree-ring width time series for 2189 years is −1.0017 (lower panel in Fig. 1). It is known that coefficient β values close to −1.00 are characteristic for fractal systems and memory processes. The future development of this process is not totally random, but it depends on the previous behavior of the time series.

The numbers of sunspots for 1700–2000 were also analyzed using MEM. The coefficient of the power-

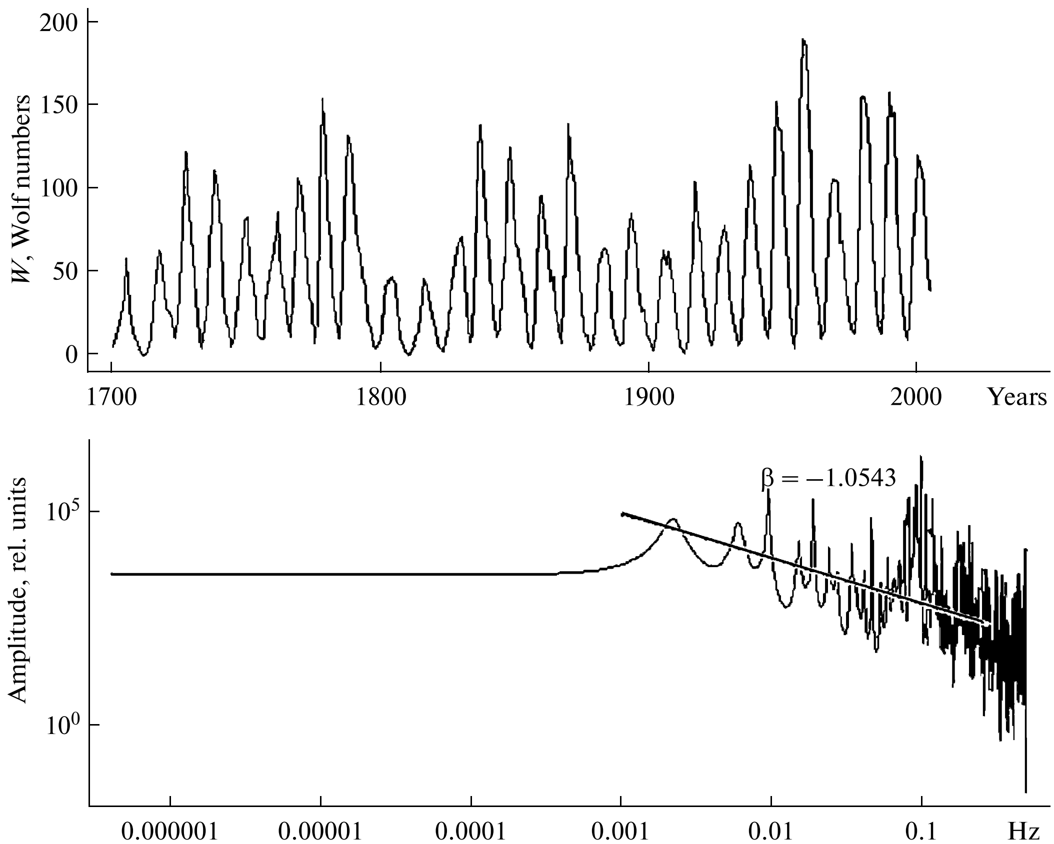

Fig. 2. Annually averaged sunspot numbers in the period from 1700 to 2000 (upper panel) and the MEM spectrum of this time series (lower panel). The coefficient of the power-law dependence $\beta = -1.0543$, indicating the fractal nature of the time series.

law dependence β was found to be equal to -1.0543, suggesting the fractal nature of the time series (Fig. 2).

Variations of the fractal properties of the tree-ring width time series were estimated using MEM in a 200-year running window with a successive 5-point shift in the time window. The left panel in Fig. 3 shows three examples of 200-year intervals, and the right panel in Fig. 3 shows the corresponding MEM spectra. An analysis of time variations of the coefficient β (lower panel in Fig. 4) reveals episodic breaks in the fractal nature. Seven episodes of these changes are indicated by arrows in Fig. 4. The two last episodes are time coincident with the Spörer and Maunder minima of solar activity.

These events, corresponding to first five disturbances of the fractal characteristics of tree-ring width time series, may also have been accompanied by global climate changes.

DISCUSSION

Chronomines are time structures consisting of multifrequency rhythms (covering a frequency range of over 10 orders of magnitude), chaos elements, trends in chaotic and rhythmic phenomena, and some other yet unknown variability effects. The word *chronoastrobiology* originates from *chronomics* (temporal structure) and *astrobiology* (the coupling of biologic and cosmic time structures).

The magnetic activity of the Sun affects terrestrial life by photic (visible light) and nonphotic mechanisms. In 1838, plants were found to be affected by nonphotic solar cycles. Later on, the nonphotic effects of solar–terrestrial interaction were recognized by economists and interdisciplinary scientists such as Brückner [Brückner, 1890] and Chizhevsky [Chizhevsky, 1971]. Recently, researchers became able to analyze the behavior of different processes flowing in living organisms; in particular, they analyzed data obtained for decades in self-observations. Statistical studies revealed new non-daily and nonannual (i.e., nonphotic) cycles in geophysics, including geomagnetism, and the corresponding physiologic cycles in human and other organisms [Cornélissen et al., 2002; Halberg et al., 2000, 2004; Otsuka, 2001, 2002, 2003]. In this context, it is interesting to analyze a tracer of solar activity such as tree-ring width, the study of which can cover a period of 2000 years or even longer. We analyzed a series of data for 11 sequoias and identified the 534-year period as the most expressive feature of the data [Nintcheu-Fata et al., 2003].

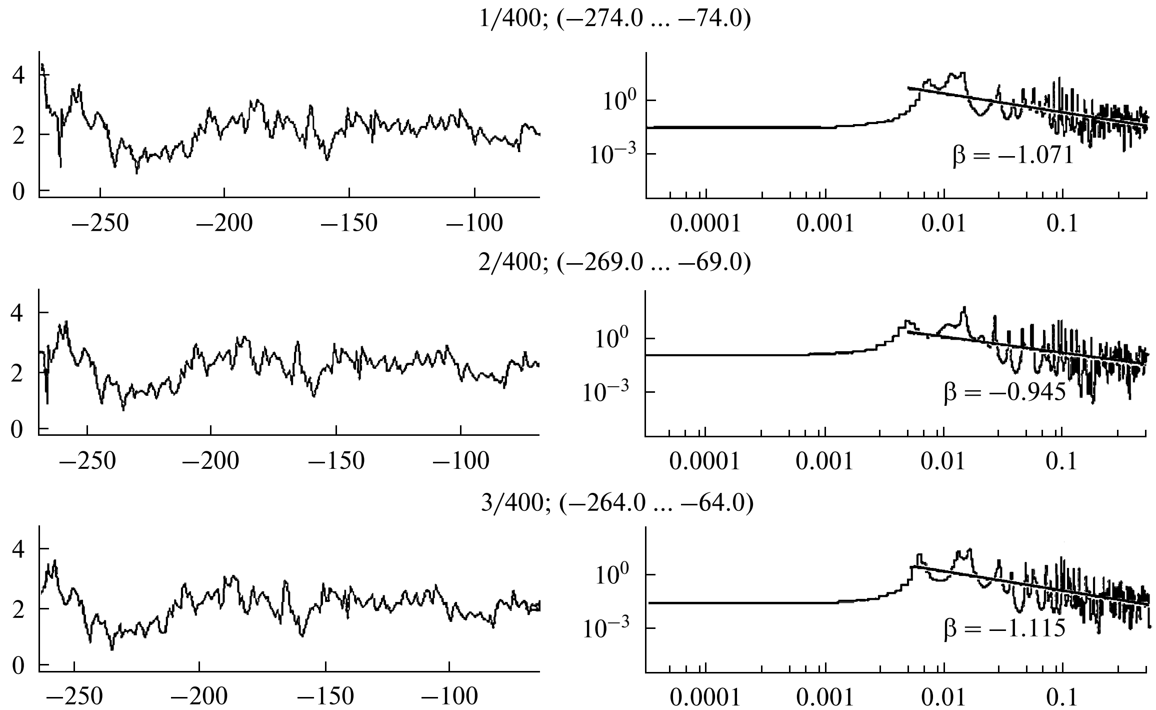

Fig. 3. Changes in the coefficient of the power-law dependence β, i.e., the fractal characteristic for the tree-ring-width time series. The initial data for three 200-year intervals (left panels) and the corresponding MEM spectra are shown. The vertical axes show the tree-ring widths (in millimeters, left panels) and amplitudes (in rel. units, right panels).

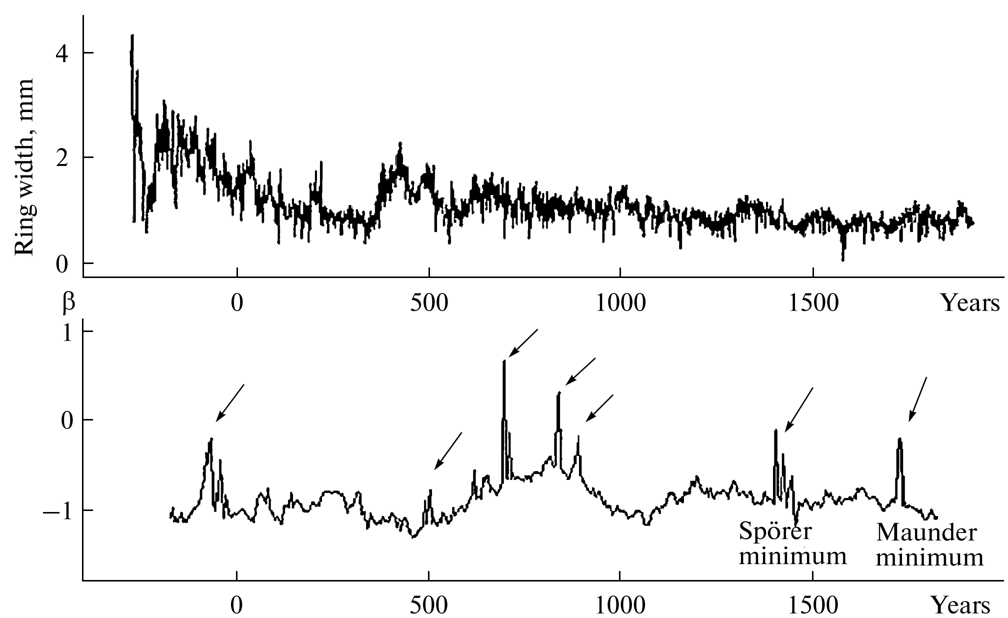

Fig. 4. Changes in the coefficient of the power-law dependence β for the tree-ring-width time series; an estimate of the 200-year running window is shown (lower panel). For ease of comparison, the upper panel shows the initial tree-ring width time series again.

It is quite evident that invisible (nonphotic) and, predominately, corpuscular and magnetic solar activity affects the processes occurring in the biosphere now [Gregori, 2002]. This activity seemingly also left a trace in the biologic record of the past. If variations in the $1/f$ structure of the tree-ring width time series do correspond to changes in the solar activity or climate, then observation time series of aurorae or other long-term records of reconstructed solar activity, such as data on the ^{10}Be concentration in polar icepacks [Usoskin et al., 2004], should be analyzed to identify these effects.

We found no changes in the fractal properties of tree-ring width time series in the vicinity of the Dalton/Hallström solar minimum (1790–1830) or Oort (about 1050) and Wolf (about 1300) solar minima. This may be because variations in the coefficient β were analyzed in a 200-year sliding window. Using such a large time window for the β estimation is necessary to calculate the spectrum in a wide enough frequency band. The window size is less than 10% of the entire time series and, hence, there are no distortions in the β estimates due to the long-term trend. Therefore, there is no need to detrend at the initial stage of analysis.

The data of oxygen isotopic composition in the V28-238 equatorial Pacific deep sea core were used to reconstruct the global climate changes over the last million years. In their description, it was shown that this time series could be compared with a low-dimensionality strange attractor. This means that long-term climatic evolution is governed by a small number of key variables [Nicolis and Nicolis, 1984]. However, this conclusion needs further verification. For instance, Grassberger studied global climate changes over last 1–2 million years (averages over about 5000-year spans) and local climate changes over last 7000 years and found no traces of this attractor [Grassberger, 1986]. Other researchers studied 13 time series of ring widths from the Verde and Salt river basins in Arizona and found no evidence of chaotic behavior in these data [Jeong and Rao, 1996]. They could model the time series by using a second-order stationary stochastic process.

Regardless of whether or not the tree-ring width time series considered here exhibits chaotic behavior, its time structure undergoes well-defined changes in accordance with the climatic conditions. This follows from an analysis of the time variations of the coefficient β in the 200-year running window. In any case, a fractal analysis can be regarded as a convenient tool for treating these processes.

Our earlier analysis of tree-ring data revealed a periodicity of about 534 years as the most distinct feature with a commensurate period around and inside us [Halberg et al., 2004]. By combining methods aimed at identifying the specific spectral components, such as Schwabe cycle and the behavior of the $1/f$ coefficient as a chaos characteristic, global climate changes can be described.

An analysis of the specific features of the time structure of different processes is of direct practical importance. For instance, in order to treat medical conditions such as myocardial infarctions or strokes, periods of increased risk should be foreseen. To the same degree of importance, this foresight may help resolve social problems and counteract criminal or military events. Chronomic studies are of basic importance because studying the identified cycles together with all their breaks may be a necessary condition for more clearly understanding the underlying mechanisms.

It should be stressed that our results characterize not local but rather global climate changes. This approach, based on a study of the time structure of the observed processes, such as different cycles and chaos may help (1) treat global warming (or cooling) and (2) identify the effects of cosmic weather on human health.

CONCLUSION AND ACKNOWLEDGMENTS

We thank three reviewers for their detailed and very valuable comments; it would be a pleasure to reveal their names if they would agree.

We are also very grateful to A. Sidorin, chief editor of the journal *Geophysical Processes and Biosphere*, who took part as another independent reviewer and organized a highly fruitful discussion between the authors and the reviewers. An extended and all-inclusive discussion of many questions concerning the methodologic problems of choosing and representing the initial data and identifying latent periodicities was very beneficial and will promote our future studies. In particular, we realize the need for a more careful study of the statistical properties of the analyzed time series at the stage of choosing analysis techniques. We took into account the reviewers' advice to use also some other methods of data analysis in the future and, in particular, wavelet analysis, which is now underway.

One important practical result of the discussion was its evolution into a collaborative study toward analyzing the time series under auspices of the Schmidt Institute of Terrestrial Physics, Russian Academy of Sciences (at a laboratory headed by A. Sidorin) and the Halberg Chronobiology Center, University of Minnesota, Minneapolis.

One of the reviewers indicated that large rings develop in young trees, giving rise to a trend in a newly formed time series. It was also stressed that the number of trees going into compiling the time series should be individually specified every time. One reviewer thinks that it is of utmost importance that the issue of the tentative effect of magnetism should be revisited. Guided by this, we used the term *nonphotic effect* instead of *magnetic effect*, which we used in earlier publications. It is noteworthy that the term *nonphotic* is defined to include the whole electromagnetic spectrum except for its visible part.

Lastly, one of the reviewers reasonably asked if million-year cycles have anything in common with the cycles over the last two millennia. Together with Sir Norman Lockyer, we claim "Surely in Meteorology, as in Astronomy, the thing to hunt down is a cycle, and if that is not to be found in the temperate zone, then go to the frigid zones or to the torrid zone to look for it, and if found, then above all things, and in whatever

manner, lay hold of, study it, record it and see what it means." Together with Sir Norman Lockyer, we had "hunted" for myriads of cycles, which is evident from the list of referred works in [Cornélissen et al., 2005; Rohde and Muller, 2005].

The authors are aware of our poor knowledge at this time; nonetheless, it is hoped that this paper will help give the chronomics to those dealing with geomagnetism, in particular [Persinger, 1991]. One of our main goals is to show that interdisciplinary barriers [Roederer, 1985] should be broken to get, at least, such valuable advice as the above-mentioned comments of our anonymous reviewers and A. Sidorin. Such advice and comments are necessary not so much to improve this paper, but rather to use it as a guidance in future research.

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