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GEOGRAPHY

The Key Role of Precession Cycle Modulation in the Alternation of Late Pleistocene Glacial and Interglacial Epochs

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The works of the Russian glaciologists and climatologists at the station *Vostok* headed by V.M. Kotlyakov made a fundamental contribution to the knowledge of paleoclimates. Among other achievements, they provided a more reliable basis for critical consideration of the theory published more than 80 years ago by the Yugoslavian scientist M. Milankovitch. According to this theory, alternation of glacial and interglacial epochs in the Earth's climate is attributed to changes in the quantity of solar radiation influx [1]. The Milankovitch theory implicitly assumes that the climatic system has a linear correlation with quasiperiodic insolation changes. Therefore, maxima and minima of paleoclimatic variations should lag relative to extremes in the insolation. The glaciation history inferred from the study of ice cores from the station *Vostok* and other data is not fully consistent with the Milankovitch theory. It has been established that the highest peak in the energy spectrum of paleoclimatic variations corresponds to the approximately 100-ka-long periodicity of the Earth's eccentricity cycle, which is very weak from the energy standpoint (its contribution is approximately 1/1000 of the average insolation variability). Alternation of 100-ka-long glacial and interglacial epochs in the Pleistocene became noticeable less than 1Ma ago, when the amplitude of the 100-ka-long eccentricity cycle was particularly low. Prior to this time, glacial epochs alternated with a period close to the 41-ka-long cycle of the Earth's obliquity, which only governs the seasonal redistribution of solar radiation. The response to the 400-ka-long eccentricity cycle, whose amplitude is much greater, is not reflected in Pleistocene climate reconstructions at all. These and other contradictions in the Milankovitch theory remain to be solved [2].

This paper shows that the 100-ka-long periodicity in the alteration of Late Pleistocene glacial and interglacial epochs was mainly controlled by the precession cycle modulation (related to the 100-ka-long eccentricity cycle) supplemented with a contribution from the obliquity cycle modulation.

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Let us first consider the energy spectrum of deuterium series in the ice core obtained at the station *Vostok*. According to [3], this series adequately describes the fourfold alteration (with an average ~100-ka-long period) of glacial and interglacial epochs during the Late Pleistocene (Fig. 1). This spectrum has an almost white noise base and numerous statistically significant peaks, including peaks with periods at 103 and 41 ka that fit orbital eccentricity and obliquity cycles. The peak at 103 ka provides the largest contribution (more than 10%) to the general variability of the studied series. At first glance, this is responsible for the 100-ka-long cycle in alternation of glacial and interglacial epochs. The contribution of the peak at 41 ka is also significant (7%), although it is not distinct in alternation of epochs. An additional peak (periodicity ~29 ka, contribution to general variability ~3%) corresponds to the lateral harmonic of the obliquity cycle. As was recently established [4], this harmonic is produced by the amplitude and frequency modulation of the obliquity cycle. According to [5], however, contributions of the amplitude and obliquity cycle modulations to insolation variability are almost negligible. Nevertheless, the presence of a significant peak in the energy spectrum of the deuterium series confirms the assumption proposed in [6, 7] that the obliquity cycle modulation influences the climate. Peaks with periods corresponding to harmonics of the precession cycle (18 and 24 ka) can also be seen in the the higher-frequency spectral region. The contribution of the highest of these peaks (with a period of 21.7 ka) is approximately 5%, i.e., is more than two times lower than that of the peak with a 100-ka-long period. The highest-frequency spectral region shows peaks of superharmonics and combination harmonics of the precession cycle as well. Formally, these peaks are statistically insignificant. However, as was shown in [7], the influence of the precession cycle on solar radiation influx is such that the duration of this cycle is apparently two times shorter. It can be assumed that teleconnections between climates in equatorial and polar zones of the Earth are so significant that superharmonics of the precession cycle are also manifested in the deuterium series.

The table presents 10 main peaks in the energy spectrum of the deuterium series arranged in order of decreasing duration of corresponding periods. It is seen

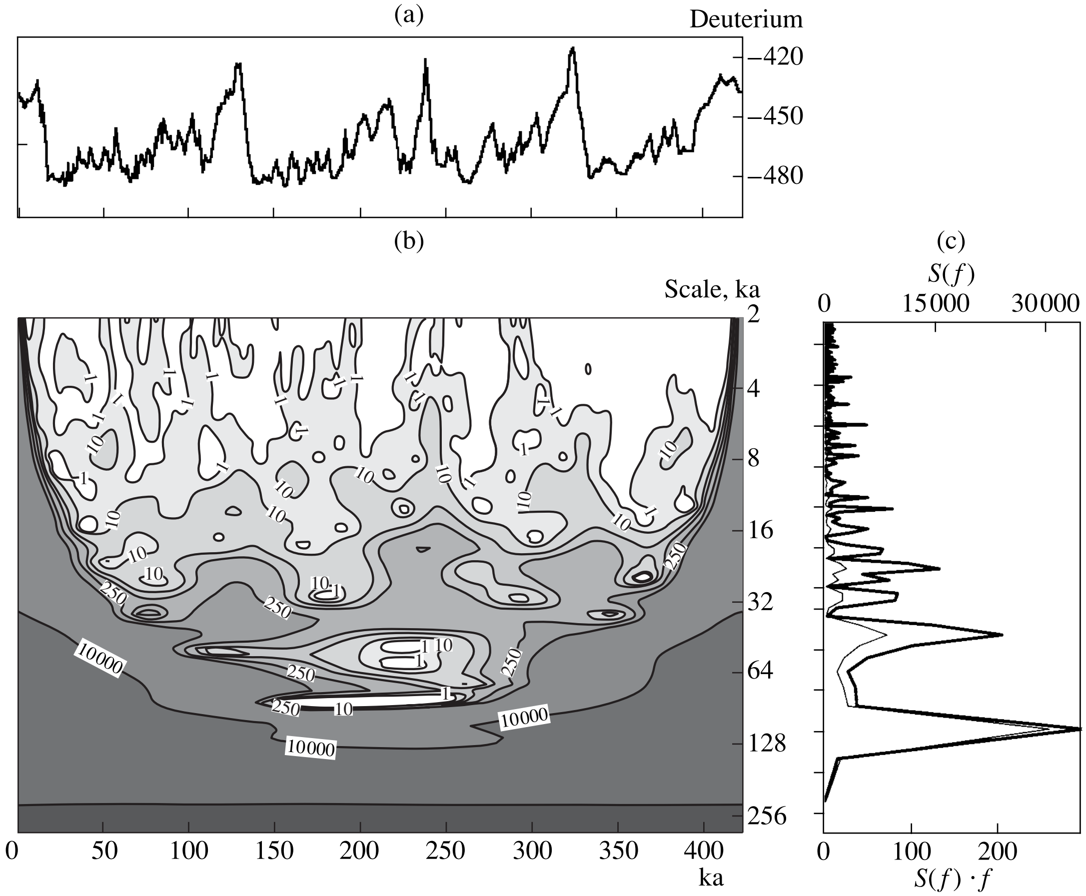

Fig. 1. (a) Time series of the deuterium content in ice core from station *Vostok* (Late Pleistocene); (b) amplitudes of its wavelet transformation (areas with elevated amplitude values are shaded); (c) Fourier spectrum $S(f)$ (thin line) and contribution of Fourier spectrum harmonics to general variability of the series $S(f)$ (thick line).

that peak amplitudes shown as their ratio to the height of the first (main) peak at 103 ka decrease with reduction of the period duration approximately according to the "–2" power law. The peculiar property of this law indicated in every manual of harmonic analysis is the fact that the sawlike time function, i.e., function whose current value periodically increases in a jumpwise manner and then gradually diminishes, can be expanded into the Fourier series

$$D(t) = \sum_{m=1}^{\infty} \frac{1}{m} \sin(m\omega t), \qquad (1)$$

where the period of the first harmonic $l = 2\pi/\omega$ is equal to the "saw" period (approximately 100 ka in our case). The deuterium series has this characteristic, although far from being ideal, sawlike form, which was repeatedly emphasized by V.M. Kotlyakov. Hence, the deuterium series can be approximated by the type (1) series. For instance, one can select truncation (1), which includes all harmonics of the precession cycle because their total contribution to the general variability of the deuterium series reaches 17%. Many paleoclimatologists assumed long ago that precisely a precession harmonic rhythm controls the alternation of glacial and interglacial epochs with a period of 100 ka. The rhythms do not result, however, in the peak with a 100-ka-long period in the spectrum. Therefore, the first harmonic (with the saw period) should be undoubtedly included into a finite-dimensional approximation (1) in order to describe the observed alternation of glacial and interglacial epochs. It is impossible to define in the context of harmonic analysis (1) whether or not this harmonic with a period of 100 ka relates to the precession cycle rhythms.

In order to solve this problem, we carried out the wavelet transformation (WT) of the deuterium series using the Morley wavelet function particularly convenient for the analysis of rhythms. Figure 1 demonstrates the distribution of WT amplitude values on the half plane (time–scale). It is seen that areas with high and low WT values located within a scale interval of 16–32 ka alternate in time. This indicates the amplitude modulation of corresponding harmonics (in the considered case, precession cycle harmonics), which is well known from the wavelet theory. The average modulation

Peaks of spectral density of the deuterium series arranged in decreasing order of the corresponding period

Peak (ord. no.)	1	2	3	4	5	6	7	8	9	10
Peak period, ka	103	41	29.4	24.2	21.7	17.8	14.7	12.1	10.8	9.4
100-ka period/period of peak	1.0	2.5	3.5	4.2	4.7	5.8	7.0	8.5	9.5	10.9
(Period of peak/100 ka)^2	$\frac{1}{1.}$	$\frac{1}{6.2}$	$\frac{1}{12.2}$	$\frac{1}{18.1}$	$\frac{1}{22.6}$	$\frac{1}{33.5}$	$\frac{1}{49.0}$	$\frac{1}{72.2}$	$\frac{1}{91.0}$	$\frac{1}{120.1}$
Peak amplitude/peak amplitude with 100-ka period	$\frac{1}{1}$	$\frac{1}{3.6}$	$\frac{1}{12.8}$	$\frac{1}{16.9}$	$\frac{1}{10.7}$	$\frac{1}{25.3}$	$\frac{1}{41.6}$	$\frac{1}{32.3}$	$\frac{1}{56.5}$	$\frac{1}{138.7}$
	$\left(\frac{1}{1}\right)$	$\left(\frac{1}{4}\right)$	$\left(\frac{1}{9}\right)$	$\left(\frac{1}{16}\right)$	$\left(\frac{1}{25}\right)$	$\left(\frac{1}{36}\right)$	$\left(\frac{1}{49}\right)$	$\left(\frac{1}{64}\right)$	$\left(\frac{1}{81}\right)$	$\left(\frac{1}{100}\right)$

Note: Peaks are ratios between their periods and amplitudes relative to the period and amplitude of the first peak (with period of 103 ka). Ratios between peak amplitudes and the peak amplitude with period of 103 ka in the case of an ideal saw are given in brackets.

period is approximately 100 ka, which almost coincides in phase with similar alternation of areas with high and low WT amplitudes. This is evident from the WT amplitude pattern of the precession cycle demonstrated by Fig. 2c in [6]. The lower zone of the figure shows a band (scales 32 ka and slightly larger) characterized by an almost constant WT amplitude. Hence, the obliquity cycle modulation is subordinate for climate dynamics at the major period of 41 ka, as was suggested in [5]. The lateral harmonic of this cycle (period ~29 ka) occurs, however, within the aforementioned scale band with amplitude modulation. The amplitude modulation is also observed in the second lateral harmonic of the obliquity cycle (period ~54 ka). The occurrence of amplitude modulations in both lateral harmonics indicates frequency modulation of the obliquity cycle [6]. In addition, the series under consideration is too short for defining any variations in the amplitude of the 100-ka-long eccentricity cycle harmonic during the analysis of its wavelet transformations. The last harmonic is represented by a band with a high WT amplitude in the middle of the lowest (undistorted by side effects) segment of Fig. 1.

Let us now construct an approximation of the deuterium series using harmonics of the precession cycle and inverse wavelet transformation within scale limits from 2 to 32 ka characterized by modulation. It should be noted that, because of the finiteness of the deuterium series, the wavelet transformation results in significant side distortions (distorted lateral and lower parts of the WT pattern in Fig. 1 are characterized by extremely high amplitudes). Therefore, the initial and terminal parts of the series cannot be reliably reconstructed using the inverse WT procedure. Moreover, wavelet transformation is insensitive to the constant component of the transformed series. Therefore, the inverse WT is determined with a constant accuracy, which is of no importance for our purposes. The time series reconstructed for the indicated scale interval reproduces in the smoothed form all main features of the original deuterium series (Fig. 2b). Therefore, the residual series (Fig. 2c) obtained by subtracting the reconstructed series from the original one contains only those features of the original series that are characterized by the highest frequency and are indefinable by the Morley wavelet function even at a scale of 2 ka. The most important point is that the reconstructed series reproduces, although with reduced amplitude (approximately by one-third in the second and fourth warming peaks and approximately by one-half in the third peak), alternation of glacial and interglacial epochs with a period of 100 ka. The fact that the 100-ka-long cycle is reproduced with reduced amplitude can partly be related to imperfection of the applied calculation procedure. Its optimization can slightly refine reconstruction. On the other hand, the direct influence of the 100-ka-long eccentricity cycle or other factors not related to precession cycle rhythms on the climate is probable. Therefore, the ratio between the reconstructed part of the

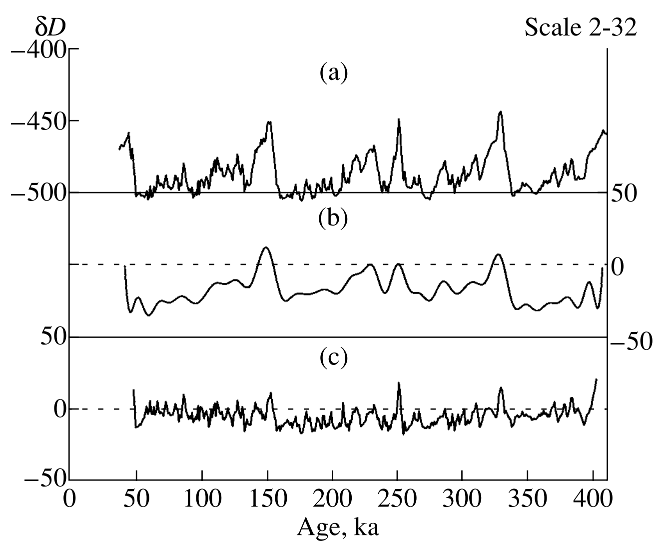

Fig. 2. (a) Time series of the deuterium content in ice core from station *Vostok* (Late Pleistocene); (b) series based on the inverse wavelet transformation in a scale interval of 2–32 ka; (c) residual series obtained by subtracting the reconstructed series from the original one.

100-ka-long cycle and its amplitude in the residual series (approximately 2 : 1) can be considered a rough indicator of the significance of precession rhythms in climatic changes as compared to other factors.

Thus, alternation of glacial and interglacial epochs during the Late Pleistocene were mainly controlled by the amplitude modulation of precession cycle, as well as its superharmonics and combination harmonics with a lateral harmonic of the obliquity cycle. Excitation of such a wide combination spectrum in response to the Milankovitch orbital cycles can be explained only by the nonlinear nature of the climatic system. Construction of an adequate mathematical model describing the nonlinear response represents one of the most pressing issues in the refinement of the Milankovitch theory.

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