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GEOGRAPHY

Symmetry of Late Pleistocene Glacial Cycles in Records of the Antarctic Vostok and Dome C Stations

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Drilling in the Antarctic ice sheet at the Vostok Station by Soviet scientists revealed a unique clear pattern of alternation of glacial and interglacial epochs for the past 400 ka [2, 5]. The European Project of Ice Coring in Antarctica (EPICA), now under implementation, is intended to further develop this achievement. Analyses of ice cores from one of the EPICA stations, Dome Concordia (Dome C) have recently been published. The station is located only 560 km away from the Vostok Station. However, the core of the Dome C Station yielded information about glacial cycles for a 800-ka-long time interval, thanks to lower rates of snow accumulation in its vicinity.

The present work compares deuterium records (proxy of the surface air temperature) from the Vostok and Dome C stations. We detected some symmetry in the shapes of Late Pleistocene glacial cycles, relative to the warming (the so-called marine isotope stage 11 [3]), observed approximately 400 ka BP (this symmetry was not noted by previous researchers). Wavelet transform of these records into three components corresponding to the precession, obliquity, and eccentricity time scales in the Earth's orbital rotation around the Sun suggests that the symmetry of the cycles is related to the amplitude and frequency modulations of climate responses to orbital insolation variations.

Figure 1 demonstrates both compared records. Numbers denote moments of the achievement of peaks of major warming in each record (ka BP): Holocene peaks (12 and 11), Mikulinian/Riss–Würm interglacial peaks (129 and 130), and peaks that preceded the Riss, Okaian/Mindel, and Günz glaciations (243 and 238; 336 and 324; and 408 and 410, respectively). Due to the geographical proximity of the stations, the moments of peaks should apparently coincide accurate to the time resolution of records (1 and 3 ka at the Vostok and Dome C stations, respectively). However, discrepancy is greater between the two peaks of interglacials bounding the Okaian/Mindel glaciations. Therefore, boundaries of this glaciation should be recognized as unreliable. Peaks of interglacials (474, 585, and 690 ka BP) separating older (Danube/pre-Günz) glaciations are also shown in the Dome C record. Peaks of secondary warming events revealed in almost all the glacial cycles are shown in parentheses. The most intense secondary warming happened during the Riss and the cycle that took place ~600 ka BP. Secondary warming of four (Günz, Okaian/Mindel, Riss, and Mikulinian/Würm) glacial cycles followed the major warming events. Both records demonstrate a saw-tooth curve noted in [2], owing to sharp warming and a consequent prolonged and nonmonotonous cooling. However, the Dome C record shows that secondary warming episodes preceded the major events in the Danube/pre-Günz glacial cycles; i.e., these cycles began with prolonged and nonmonotonous warming followed by drastic cooling episodes. Their saw-tooth curve shape is apparently time-reversed.

The major warming (the so-called marine isotope stage 11 [3]), the extremum of which in the Vostok and Dome C records took place 410 and 408 ka BP, respectively, was not followed by a second warming either before nor after the event. It lacked the saw-tooth variation and can be regarded as a center of symmetry for the previously or subsequently saw-tooth curves in both groups of glacial cycles (Fig. 1). Taking into consideration the aforementioned inaccuracy of boundaries of the Okaian/Mindel Glaciation, the central symmetry is also evident in the systematic variation of glacial cycle duration. The duration of cycles shows a direct correlation with the lag relative to the isotope stage 11. The Okaian/Mindel and Günz glaciations directly adjoining the isotope stage 11 have a duration of only 70–90 ka,

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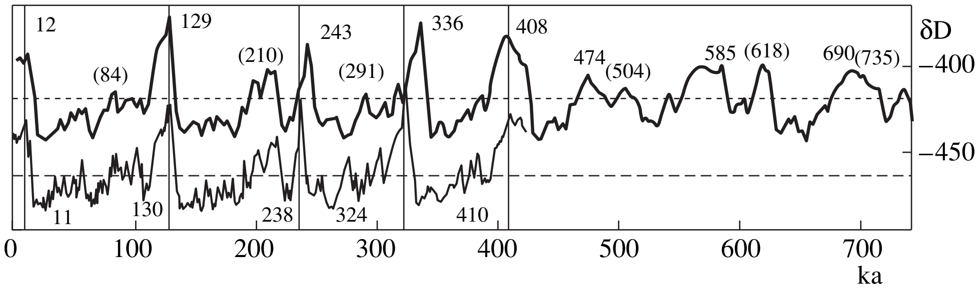

Fig. 1. Time series of the deuterium content in ice cores from Dome C (top) and Vostok (bottom) stations. Time intervals (ka BP) are given for major maximums achieved in each ~100-ka-long glacial cycles. Thin vertical lines are drawn across the maximums in the Vostok deuterium record for an easy recognition of discordant pairs of these maximums in both records. For the Dome C record, times of secondary maximums are shown in parentheses.

whereas the Mikulinian/Würm interglacial and the oldest cycle (among the cycles recorded at the Dome C Station) are ~120 ka long. The transitional Riss interglacial and ~600 ka BP cycle with intense secondary warming episodes had durations of ~100 ka.

To reveal causes of the symmetry, we performed direct and inverse wavelet transform (WT) of the deuterium record for the Dome C Station using the Morlet wavelet function, which is particularly convenient for studying time variations in the spectral composition of fluctuations in the transformed record. To reduce WT sensitivity to boundary distortions, the record was preliminarily normalized so as to obtain a zero mean and a unit variance. The normalized record is shown at the top of Fig. 2. Shown at the bottom are three components of this record reconstructed from a WT real component by means of its inverse transformations within the range of fluctuations of precession (4–26 ka), obliquity (26–57 ka), and eccentricity (57–125 ka) in the Earth's orbital motion around the Sun. The spectral estimates (omitted here for the sake of brevity) show that the harmonic with the period of 23 ka, which corresponds to the known principal fluctuation of precession, makes the major contribution to variations in the reconstructed component within the range of 4–26 ka. The harmonic with the period of 41 ka of the obliquity cycle is the principal contributor within the range of 26–57 ka. The harmonic with the period of about 92 ka, which is similar to one of the main fluctuations of eccentricity, is substantial within the range of 57–125 ka. Hence, contributions of the corresponding orbital variations of insolation were really essential for the dynamics of the Late Pleistocene climate, as was assumed by Milankovich's theory. The bottom of Fig. 2 shows residual records obtained by subtracting all the three reconstructed components from the initial record shown at the top.

Vertical continuous and dotted lines are drawn across peaks of major and secondary warming events of all the glacial cycles, thus facilitating the estimation of contributions of individual components to these peaks and emphasizing the distinction in saw-tooth configuration of glacial cycles in two periods of the Late Pleistocene scenario. Contributions of three reconstructed components to the total variation in the Dome C record are nearly similar, whereas contribution of the residual record is half as great as contribution of each component taken separately. Therefore, components of ranges 4–26 and 26–57 ka BP describe more than one-half of the total variation in the record and thus allow one to show well the saw-tooth configuration of the curve and the average 100-ka-long duration of Late Pleistocene glacial cycles, as has already been demonstrated by the corresponding wavelet analysis of the Vostok Station record in [1]. This can be accounted for the amplitude modulation of the climatic response to orbital variations of insolation. Especially clear is the amplitude modulation during the Günz, Okaian/Mindel, Riss, and Mikulinian/Würm glacial cycles. Within the range of 4–26 ka BP, the fourth modulation in the Günz and Okaian/Mindel cycles had an especially great contribution ($4 \cdot 23 = 92$ ka) to the aforementioned, relatively small (70–90 ka) duration of these cycles. In the Riss and Mikulinian/Würm cycles, the fifth modulation yielded a similar amplitude ($5 \cdot 23 = 115$ ka). Effects of amplitude modulation within the range of 26–57 ka BP were similar. In the Günz and Okaian/Mindel cycles, the second modulation had a great amplitude ($2 \cdot 41 = 82$ ka yielded shorter cycles). In the Riss and Mikulinian/Würm cycles, the third modulation had a great amplitude ($3 \cdot 41 = 123$ ka yielded longer cycles). Continuous vertical lines drawn across the major interglacials of all the listed four cycles coincide well with peaks achieved by amplitudes of both ranges. This defines the contribution of amplitude modulation of climate responses to variations in precession and obliquity into the saw-tooth configuration of glacial cycles.

Fluctuation periods of the reconstructed component within the range of 57–125 ka BP decrease from margins to the center of the component record, indicating the frequency modulation of climate fluctuations within the range of variations in the Earth's orbit eccentricity. Continuous vertical lines rather precisely pass across four out of five major maximums of these fluctuations in the time interval from 400 ka BP to the present day.

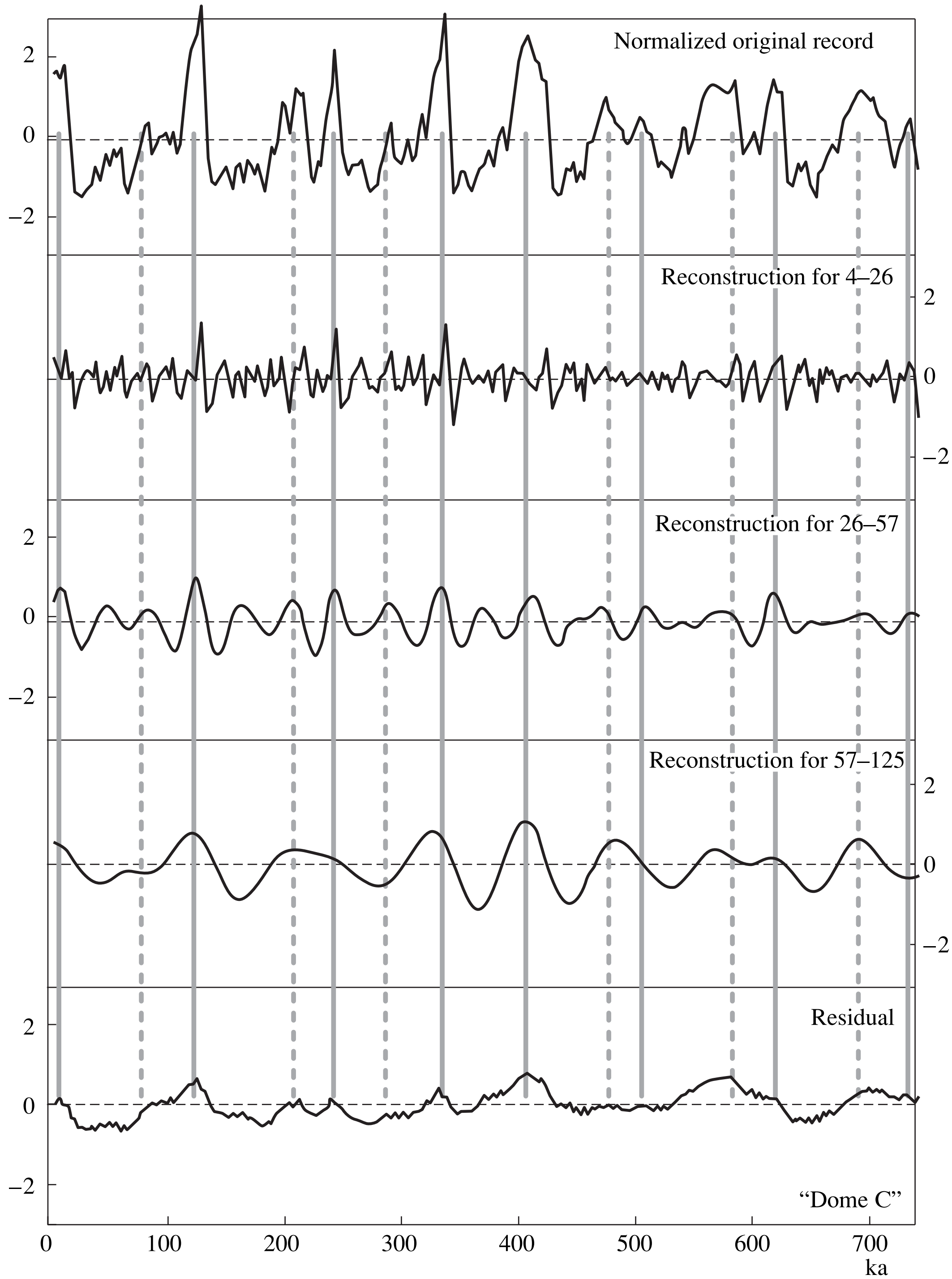

Fig. 2. Results of the splitting of fluctuations in the deuterium record of Dome C Station into three time scales according to possible climate responses to variations of precession, obliquity, and eccentricity in the Earth's orbital motion around the Sun. The top plot shows normalized original deuterium record. The intermediate plot shows series of record reconstruction by inverse wavelet transform at time scales of precession (4–26 ka), obliquity (26–57 ka), and eccentricity (57–125 ka). The bottom plot shows residual series obtained by subtracting the sum of three reconstructed series from the original record. Vertical lines are drawn across points of major and secondary maximums achieved in the original record.

The vertical dotted line corresponding to a second powerful warming episode in the Riss cycle crosses the fifth maximum. Dotted vertical lines cross the major maximums of the discussed component in the record corresponding to the period from 800 to 400 ka BP. All this determines the principal role of the component in the origin of the central symmetry of the Late Pleistocene glacial cycles relative to isotope stage 11.

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