
GEOGRAPHY

Synchronism of Late Pleistocene Glacial Cycles with Insolation Variations on the Equator

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We show that Late Pleistocene glacial cycles were synchronous with frequency-modulated insolation variations on the equator related to changes in the Earth's orbit eccentricity. The glacial stages of these cycles coincided with periods of a synchronous decrease in insolation of Polar regions in both hemispheres. Interglacials coincided with periods of a simultaneous increase in insolation due to changes in the Earth's obliquity.

The modern theory of alternating glacial and interglacial epochs in the history of the Earth's climates is based on the hypothesis of M. Milankovitch. According to this hypothesis, the growth of ice sheets is promoted by cool humid warm seasons, which can take place if summer insolation decreases in Polar regions at a certain phase of the precession cycle in the Earth's orbital motion around the Sun. However, the reconstruction of the four last glacial cycles in the Late Pleistocene based on data of the Vostok Station in Antarctica showed [2] that glaciations in the Southern and Northern hemispheres proceeded synchronously, although precession insolation oscillations are antiphase processes and, hence, the Antarctic ice sheet formed under conditions of enhanced summer insolation. This fact is inconsistent with the Milankovitch hypothesis and compels us to search for another explanation of glacial cycles.

Figures 1 and 2 (upper panel) demonstrate series of variations for the past 800 ka in the deuterium content (an indirect characteristic of the surface air temperature) in the ice core, which was recovered at the Dome C Station of the European Project of Ice Coring in Antarctica (EPICA) [5], as well as synchronous insolation variations at 65° N (diurnal insolation in mid-July) and 65° S (diurnal insolation in mid-January). For the sake of convenience, all the series were preliminarily nor-

malized so that their average values and dispersion became equal to zero and 1, respectively. The lower panels of Figs. 1 and 2 show the splitting of these series (based on wavelet transforms, see [1] for detail) into components for ranges 4–26 (precession), 26–57 (obliquity), and 57–125 (eccentricity) ka B.P., as well as residues left after the subtraction of these components from the initial series. The existence of the residue is related to the following reasons: (i) the presence of >125-ka-long oscillations related, in particular, to the ~412-ka cycle of eccentricity in insolation series; (ii) unavoidable proximity of numerical realization of direct and inverse wavelet transforms. It is evident that the share of each component of the deuterium series (including the residue) in the general variation is nearly equal (i.e., about a quarter). Taking into account that the residue series is mainly composed of relatively long-period oscillations, the contribution of the component from the eccentricity range can be estimated at nearly half of the general variation of the deuterium series. For the sake of convenience in the comparison of positions of extremums in the time path of all deuterium series, the first and second maximums in each glacial cycle are separated by solid and dashed vertical lines, respectively.

Figure 1 shows that the precession component of the July insolation at 65° N oscillated nearly synchronously with analogous oscillations of the deuterium content with a certain physically reasonable advance in phase. This relationship is well known, and it could have been accepted as evidence in favor of the Milankovitch hypothesis had it been found when comparing deuterium oscillations with the precession component of insolation oscillations in the Southern (as in Fig. 2) rather than the Northern (as in Fig. 1) Hemisphere. However, Fig. 2 demonstrates the opposite relationship; i.e., precession oscillations of deuterium and insolation in the Late Pleistocene were generally antiphase processes. Modern followers of Milankovitch explain this situation in the following way: due to the relatively small volume of glaciers in the Northern Hemisphere compared to the Antarctica ice sheet, their dynamics played a leading role in the global synchronization of

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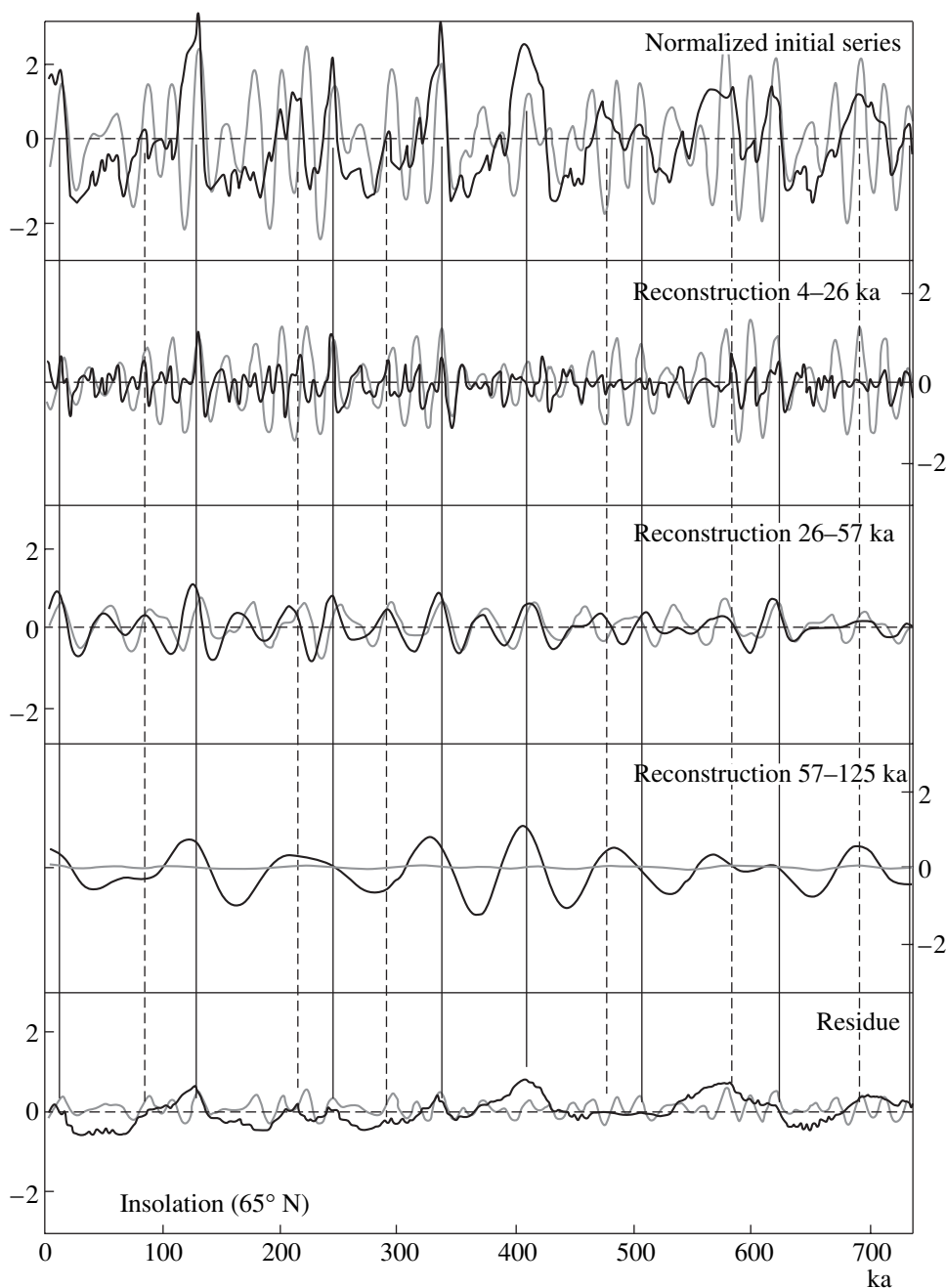


Fig. 1. Results of oscillation splitting in the deuterium series at the Antarctic Station Dome C (shown in black lines) and in the series of diurnal insolation at 65° N in mid-July (shown in gray lines) for three ranges: 4–26 ka B.P. (precession), 26–57 ka B.P. (obliquity), and 57–125 ka B.P. (eccentricity). Solid and dashed vertical lines mark moments of the first and second warming events in each glacial cycle. The first warming event was the major one in cycles 1–4; the second warming event, in cycles 5–7. The symmetry of glacial cycle patterns (relative to the moment of 400 ka B.P.) mentioned for the first time in [1] is related to this specific feature.

glacial cycles with summer insolation of the northern Polar area. However, the mathematical theory of dynamic systems indicates that the locking phase of the dynamic system of interacting subsystems is usually determined by a more inertial subsystem in the case of synchronization with the external periodic action. For instance, a seasonal trend of the surface air temperature lags just slightly behind the annual trend of insolation

in continental climates. In marine climates, this lag is much more substantial due to heat exchange of the surface air layer with the sea surface, the annual temperature trend of which lags strongly due to high heat capacity.

As is well known and confirmed in Figs. 1 and 2, precession oscillations of insolation at 65° N and 65° S were in antiphase. Their amplitudes simultaneously

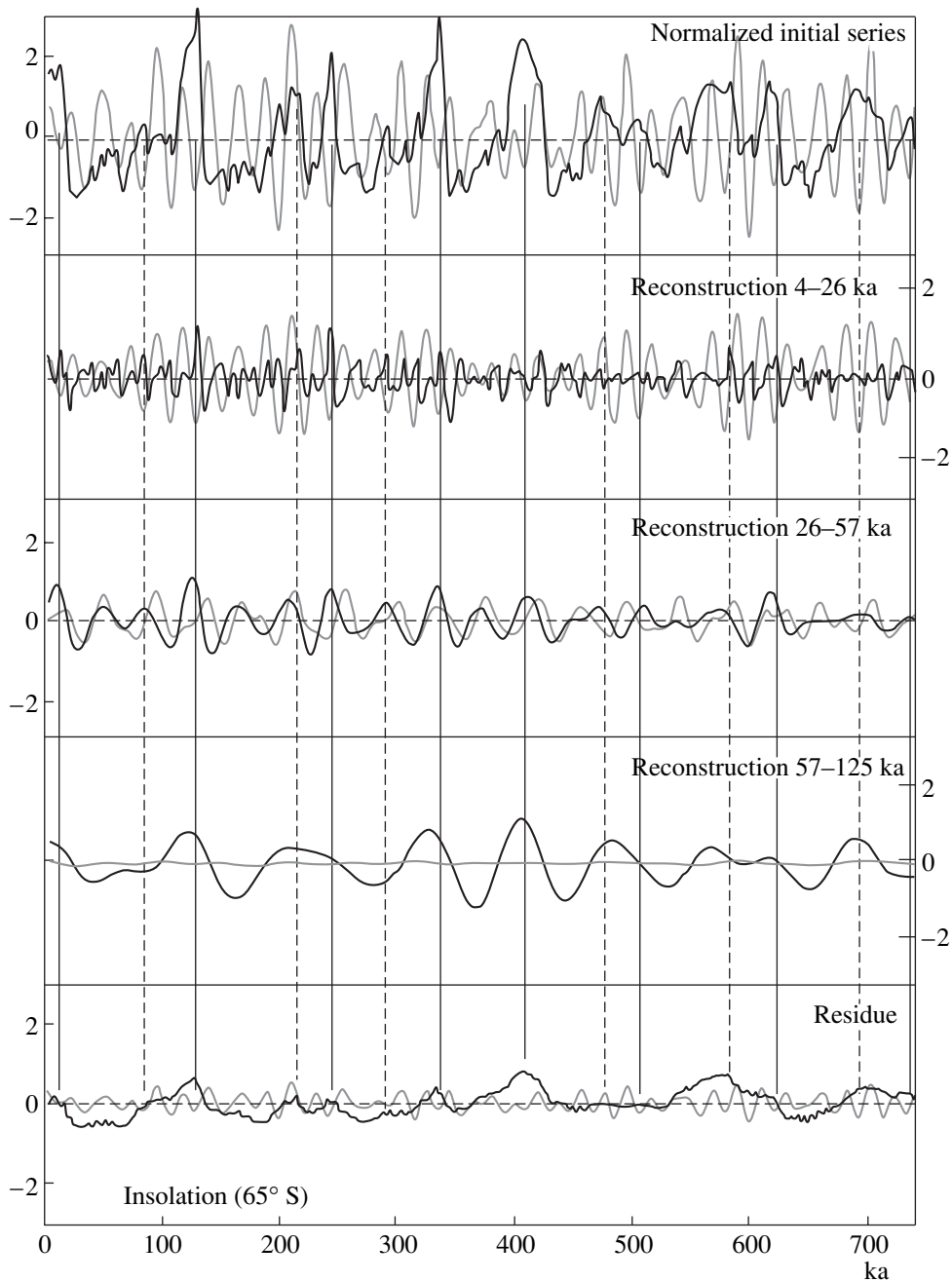


Fig. 2. The same as in Fig. 1, but the deuterium series is compared to the diurnal insolation series in mid-January at 65° S.

(and more or less gradually) increased, decreased, again increased, and so on with an average period of ~ 100 ka. The precession component of variations in the deuterium content also shows a ~ 100 -ka cycle. However, as was reported for the first time in our paper [1], the amplitudes of oscillations of the discussed scale range were uniformly small at glacial stages of glacial cycles 1–4 and nearly twice as large during the major warming events. In the case of earlier glacial cycles 5–7, it is rather difficult to note the amplitude jumps, but the pattern does not appear as gradual amplitude changes in

insolation oscillations. Therefore, it is reasonable to seek the cause of deuterium content oscillations at 4–26 ka B.P. not in the response of the climatic system to insolation oscillations but in some inner processes. Hence, there is no need for Milankovitch's hypothesis. This certainly does not mean a complete negation of the influence of insolation variations on Late Pleistocene glacial cycles.

Let us consider in Figs. 1 and 2 the components of insolation oscillations for the range of 26–57 ka B.P. due to changes in the Earth's obliquity. Such oscilla-

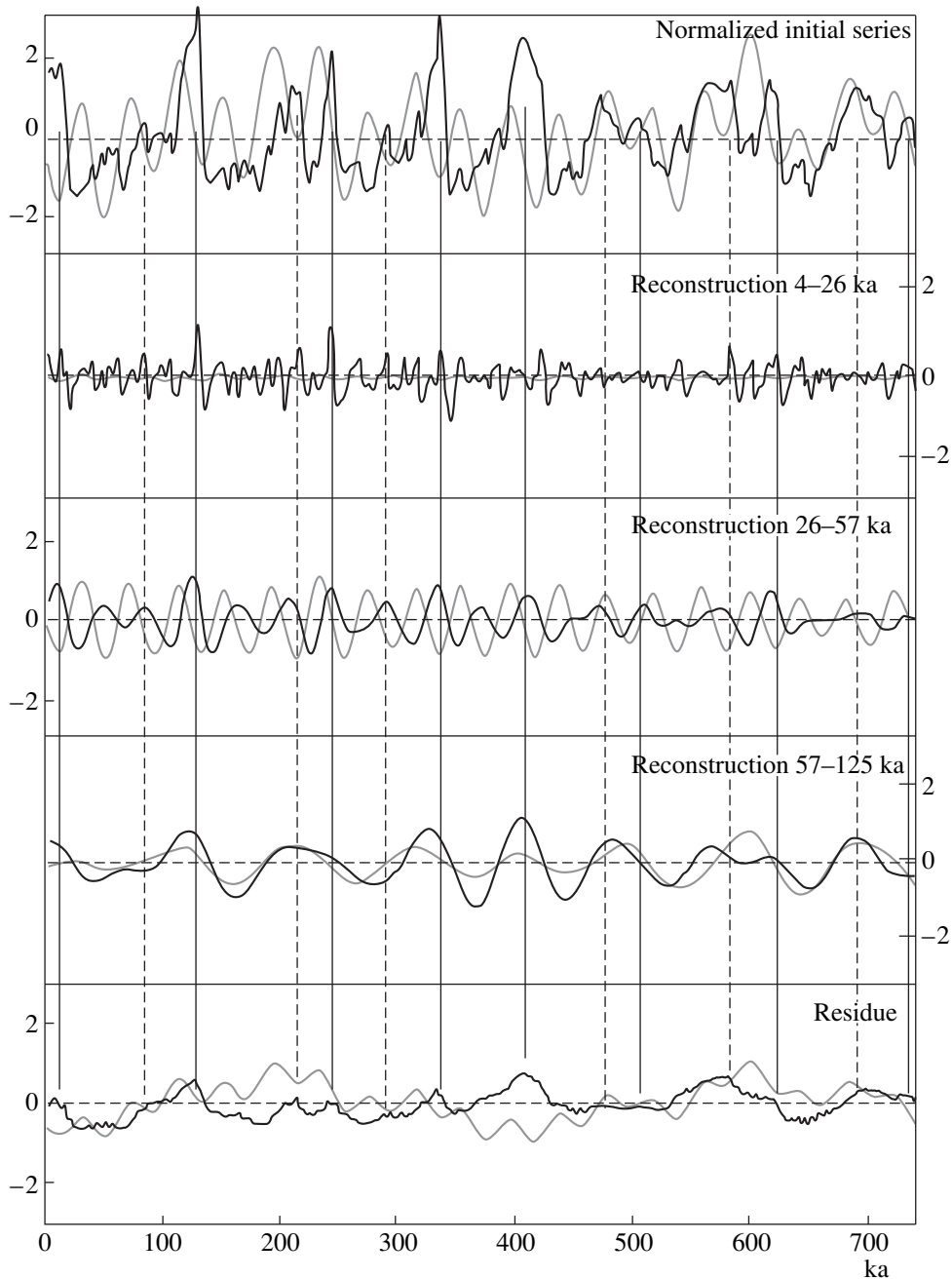


Fig. 3. The same as in Fig. 1, but the deuterium series is compared to the diurnal insolation series averaged for all the months on the equator.

tions are known to redistribute simultaneously insolation between low and high latitudes in both hemispheres. Therefore, it is not surprising that the diagrams of these oscillations are nearly identical in Figs. 1 and 2, and Fig. 3 represents their mirror image. It is significant that the oscillations were nearly synchronous with oscillations of the corresponding deuterium component. Moreover, insolation maximums in Polar regions (insolation minimums on the equator) were only a few thousand years ahead of the main maximums of the deuterium content (interglacials). Insolation minimums

in Polar regions (insolation maximums on the equator) correlate rather well with deuterium minimums. The imperfection of the time scale of the deuterium series may be responsible for some violations observed in the latter relationship. Disregarding these violations, we can support the recent opinion of some paleoclimatologists (see, for example, [4]) that simultaneous alternation of glacial and interglacial epochs is caused by the response of the climatic system to latitudinal redistribution of insolation in both hemispheres.

This is, however, insufficient for complete explanation of the dynamics of Late Pleistocene glacial cycles, because, as was above mentioned, the contribution of the 26–57 ka component to the total variation of the deuterium content made up only a quarter in the Late Pleistocene, whereas nearly half of the deuterium content variation in the Late Pleistocene fell on the 57–125 ka component in the range of oscillations of the Earth's orbit eccentricity. However, Figs. 1 and 2 confirm the well-known thesis that the share of the latter component in insolation oscillations at 65° N was negligible. In contrast, Fig. 3 shows that its share on the equator was approximately one-third (the remaining two-thirds fell on the 26–57 ka and residue components). Moreover, like the duration of glacial epochs, the duration of equatorial insolation oscillations of the 57–125-ka range varied from 70 ka in the mid-Late Pleistocene to 120 ka at the end of this period. In other words, frequency modulation of deuterium content oscillations in the eccentricity range, which is identified in [1] (see also [6]) as the principle property responsible for specific (symmetric relative to the moment of ~400 ka B.P.) changes in the duration of Late Pleistocene glacial cycles, already exists in the external influence on the equatorial zone of the climatic system. It should also be noted that the residue series is dominated by oscillation with the 412-ka period, the minimum of which falls just on the center of symmetry at ~400 ka B.P. As follows

from [1], the origin of these peculiarities in the insolation pattern is related to the disturbing influence of large planets on the Earth's orbit.

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