Method Article

The $\delta^{18}$O-inferred thermal reconstruction for the Pleistocene based on the modification of existing glacial and interglacial paleoclimatic models

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ABSTRACT

The determination of the climatic factors related to the Paleolithic archaeological, or fossils sites of the late Neogene and Quaternary periods would require the knowledge of all the fossil specimen's age-site-related paleoclimatic factors. Because the necessary high-temporal resolution georeferenced, paleoclimatic models do not exist for most of the periods of the Pliocene and Pleistocene epoch, at the first step, the former climatic conditions should be reconstructed according to the age-site pair data. The idea of the developed method is, that using the foraminiferal oxygen isotope ($\delta^{18}$O) ratio values, the available Pleistocene glacial and interglacial paleoclimatic model pairs can provide the bases for the reconstruction of the former thermal conditions for any period during the Pleistocene epoch. In a technical sense, the approach is based on the observation that the changes in the Cenozoic $\delta^{18}$O record can correspond with the global mean temperature alterations. Determining the cold and warm periods-related $\delta^{18}$O ratio values, new, georeferenced paleoclimatic models can be produced.

The main steps of the developed method are as follows:

- Determination of the oxygen isotope ratio ($\delta^{18}$O) which corresponds to the former thermal conditions of a site.
- Using a scaling technique to create new, approximate climate maps by changing glacial and interglacial maps.
- Reconstruction of the monthly mean temperature values based on the thermal conditions of the warmest and the coldest quarters.

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Specifications table

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Method details

The reconstruction of paleoclimatic values for a given period

The method to be used requires two existing paleoclimatic models, representing as far as possible one glacial and one interglacial state of the study period. For the Quaternary Period, the paleoclimatic reconstructions of the MIS19 Period or the Last Interglacial Period can be used as interglacial (‘warm climate phase’) models; the paleoclimatic reconstruction of the Last Glacial Maximum can serve as the general glacial (‘cold climate phase’) model. For the Pliocene epoch, the mid-Pliocene warm and cold periods-related paleoclimatic models can be used for the same purpose. The physical basis for reliable reconstruction of former global thermal conditions is the benthic foraminiferal δ^{18}O/δ^{16}O concentration (δ^{18}O) and Mg/Ca rate measurements [1]. In other words, it means that the basic consideration of the developed method is that the δ^{18}O-content of the benthic foraminifera of the North Atlantic sequences is closely related to the global mean temperatures.

It can be hypothesized according to the principle of Liu et al. (2009) [1] that:

1) The glacial phases can be characterized by high δ^{18}O values.
2) The interglacial phases exhibit low δ^{18}O values.

It formally implies that:

\[ |Δδ^{18}O| \sim |ΔT| \]

Accepting this assumption, the δ^{18}O concentration values can be utilized to reconstruct the global, and with certain restrictions, the local atmospheric palaeotemperature conditions or to determine the extent of previous ice sheets [3] due to the temperature-dependent carbon and oxygen isotopic disequilibria of deep-sea benthic foraminifera [2]. Although local temperature trends may differ somewhat from global ones, as an approximation, it can be assumed that thermal values are generally followed by fluctuations between the glacial and interglacial climatic states.

As a source of the paleoclimatic data, e.g., the PaleoClim.org database can be used [4].

The steps of the reconstruction of the paleothermal conditions for a given time are as follows:

1) The δ^{18}O-content values of the benthic foraminifera related to the selected glacial (G) and interglacial (IG) reference paleoclimatic models can be used as the lowest and highest temperature reference base in the determination of the former paleoclimatic conditions.
2) Then, the archaeological or the fossil site's age-related δ^{18}O-values should be determined.
3) Finally, a modifier factor can be calculated based on the δ^{18}O-values of the glacial and interglacial reference periods and the age of the archaeological or fossil sites.

The modifier factors were calculated using the formula below:

\[ m = 1 - \frac{d^{18}O_G - d^{18}O_N}{d^{18}O_G - d^{18}O_{IG}} \]

\[ m \] is a modifier factor,
\[ d^{18}O_G \] is the δ^{18}O concentration (%) of the selected general glacial Pliocene/Pleistocene paleoclimatic model,
\[ d^{18}O_N \] is the δ^{18}O concentration (%) of the Nth period,
\( \delta^{18}O_{IG} \) is the \( \delta^{18}O \) concentration (‰) of the selected general interglacial Pliocene/Pleistocene paleoclimatic model, and finally, based on the bioclimatic factors of the reference glacial and interglacial periods and modifier factor, the proportional paleoclimatic factor of the site in the given period was calculated according to the following formula:

\[
rf_{k,N} = f_{k,G} + m \times (f_{k,IG} - f_{k,G})
\]

where

- \( rf_{k,N} \) is the reconstructed paleoclimatic factor of the Nth period,
- \( f_{k,G} \) is the reconstructed paleoclimatic factor of the reference glacial period,
- \( m \) is a modifier factor,
- \( f_{k,IG} \) is the reconstructed paleoclimatic factor of the reference interglacial period.

The applicability of the developed method was illustrated via the example of reconstructed paleothermal values related to the Krapina Cave Neanderthal Archaeological Site (Croatia).

The basic data for the reconstruction process are as follows in this case:

1) The coordinates of the archaeological site: 46.164676 N, 15.863695 E for the determination of the present-day and the former climatic conditions.
2) The base reference paleoclimatic models were as follows: the LGM (Karger et al., 2021 [5]) and the LP (Fordham et al., 2017 [6]).
3) The age of the Krapina 3 Neanderthal skull is 113.5±13.5 kys [7]. The corresponding \( \delta^{18}O \) value is 3.575 ‰ [8].
4) The \( \delta^{18}O \) values for the LGM and the LIP are 4.990 and 3.735 ‰ [8]. The calculated \( m \) value is 1.1275.

Fig. 1 shows the reconstructed annual mean temperature values in 113.5 kya in the wider region of the Krapina Cave Neanderthal site.

Using the same method, other thermal values can also be calculated. Fig. 2 shows the reconstructed mean temperature of values of the warmest and the coldest quarters in 113.5 kya in the wider region of the Krapina Cave Neanderthal site.

The model also makes it possible for the long-term, near-continuous reconstruction of past climatic values of an archaeological site. The Middle Stone Age Krapina Cave Neanderthal site shows the changes in the annual mean temperature values over the last 130 kys (Fig. 3).

The reconstruction of monthly temperature values

In several cases, the monthly temperature values are needed for further modelling purposes. However, in several cases, climatic models contain the mean temperature of the warmest quarter \( (T_{mw}) \) and mean temperature of the coldest quarter \( (T_{mc}) \) values. The former monthly mean temperature values can be reconstructed based on the available archaeological/fossil sites - \( T_{mw} \) and \( T_{mc} \) values of the existing paleoclimatic models. The former monthly temperature value can be approximated using the normalized differences between the mean monthly temperature values and the differences between the present-day \( T_{mw} \) and \( T_{mc} \) values of certain sites. It is important to select the values of such a site which can be found close to the investigated archaeological/fossil site.

The normalization formula of monthly mean temperatures is as follows:

\[
dT_N = \frac{T^k_m - T_{mc}}{T_{mw} - T_{mc}}
\]

Where \( dT_N \) is normalized differences between the mean monthly temperatures, \( T^k_m \) is the mean temperature of the kth month of the year; \( T_{mw} \) is the mean temperature of the warmest quarter (°C), and \( T_{mc} \) is the mean temperature of the coldest quarter (°C).

After this process, using the reconstructed Pleistocene \( T_{mw} \) and \( T_{mc} \) values of the archaeological sites, the Pliocene/Pleistocene mean monthly temperatures were calculated according to the inverse formula of the above-described equation:

\[
T^k_m = dT_N \times (T_{mw} - T_{mc}) + T_{mc}
\]
Fig. 1. The mean annual temperature calculated from the reconstructed monthly mean temperatures in the Middle Stone Age Krapina Cave Neanderthal site in 1135. Green point: Krapina Cave Neanderthal Archaeological Site.
Fig. 2. The reconstructed mean temperature values of the warmest (A) and the coldest quarters (B) in the wider area of the Krapina Cave Neanderthal site in 113.5 kya. Green point: Krapina Cave Neanderthal Archaeological Site.
Fig. 3. The changes of the annual mean temperature values in the last 130 kys at the Middle Stone age Krapina Cave Neanderthal Archaeological Site in Croatia (small picture: the right front-side view picture of the Krapina 3 Neanderthal skull; A: Austria, BIH: Bosna and Herzegovina, CRO: Croatia, H: Hungary, SLO: Slovenia).
Fig. 4. The reconstructed mean temperatures values of January (A), February (B), March (C), April (D), May (E) and June (F) months in the wider area of the Krapina Cave Neanderthal Archaeological Site (green point) in 113.5 kya.
Fig. 5. The reconstructed mean temperature values of July (A), August (B), September (C), October (D), November (E) and December (F) months in the wider area of the Krapina Cave Neanderthal Archaeological Site (green point) in 113.5 kya.
Where $T_{km}$ is the mean temperature of the kth month of the year; $dT_{m}$ is normalized differences between the mean monthly temperatures, $T_{mwa}$ is the mean temperature of the warmest quarter ($^\circ$C), and $T_{mq}$ is the mean temperature of the coldest quarter ($^\circ$C).

The normalized values of present-day Krapina are as follows: -0.2 (January), 0 (February), 0.2 (March), 0.5 (April), 0.8 (May), 1 (June), 1.1 (July), 1.1 (August), 0.8 (September), 0.5 (October), 0.2 (November), -0.1 (December).

Fig. 4 shows the reconstructed monthly mean temperature values in the first half of the year at the Krapina Cave Neanderthal Archaeological Site in 113.5 kya.

Fig. 5 shows the reconstructed monthly mean temperature values in the second half of the year at the Krapina Cave Neanderthal Archaeological Site in 113.5 kya.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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