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Commentary

The temperature record of the Holocene: progress and controversies

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The pattern of temperature variation during the Holocene, the most recent geological epoch, has been studied intensively, partly because of its significance for the development of human civilization. Prior to the 1980s, based on ice core records in Greenland and Antarctica, the climate of the Holocene was thought to have been rather stable [1]. However, this view was challenged by the discovery of a substantial amount of contrary evidence, such as the sequence of ice-rafted events in the high latitude North Atlantic which clearly reflects significant dynamic regional climate variations. In the 1980s, COHMAP (the Cooperative Holocene Mapping Project) aimed to compare well-dated paleoclimate records and model simulations [2]. Later, the Holocene Thermal Maximum (HTM), a relatively warm climate phase between 11 and 5 ka, was confirmed by various proxy records and was attributed to the strengthening of summer insolation [3]. With the availability of improved analytical techniques and the development and refinement of temperature proxies, an increasing number of quantitative reconstructions have revealed substantial Holocene temperature variability, suggesting a relatively warm early- to mid-Holocene followed by a cool late Holocene. Marcott et al. [4] compiled 73 quantitative temperature records worldwide and confirmed a pattern of early Holocene (10–5 ka) warmth followed by ~0.7 °C of cooling through the middle to late Holocene (<5 ka), and a temperature increase caused by the rapid accumulation of atmospheric greenhouse gases [5]. However, Liu et al. [6] questioned the reliability of global temperature reconstructions; their conclusion was based on three coupled ocean-atmosphere models [the Community Climate System Model 3 (CCSM3), the Fast Met Office/UK Universities Simulator (FAMOUS), and the Loch-Vecode-Ecbilt-Clio-Agism Model (LOVECLIM)] forced by well-known climate forcings, including orbitally-driven insolation variations, greenhouse gases, continental ice sheets and the associated meltwater fluxes. In contrast to proxy-reconstructed global temperature records, all simulations forced by Holocene boundary conditions show a gradual Holocene warming with an absence of late Holocene cooling. This result is called the "Holocene Temperature Conundrum" [6] and it highlights discrepancies between paleoclimate records and model simulations, despite the fact that both have been investigated intensively for decades. A discrepancy between proxy records and modeling results was also reported earlier in China. Jiang et al. [7], using 36 Paleoclimate Modeling Intercomparison Project (PMIP) models, found that during the mid-Holocene the annual temperature was 0.4 °C colder over China compared with the preindustrial era, which could be attributed to much colder winter and spring seasons and a relatively mild summer. Liu et al. [6] suggested that the conundrum could result from the seasonality of the current temperature proxies and the inadequacy of current climate models.

Climate proxy indicators are interpreted using physical or biophysical principles to represent specific combinations of climate-related variations. For example, alkenones likely reflect the temperature of the growing season of haptophytes, via its influence on the ratios of the unsaturated compounds; thus, U_{37}^{K} reflects warm season temperatures at high altitudes and cool season temperatures at low latitudes [8]. Seasonal biases in the alkenones have been reported in several investigations worldwide, as well as in culture experiments [9]. Foraminifera Mg/Ca ratios have been suggested to be less affected by seasonality than the alkenone proxy $U_{37}^{K'}$ since the foraminifera integrate a climate signal over a longer time interval [8]. We carefully assessed the 73 temperature records in Marcott et al. [4], which include 31 alkenone records, 19 foraminifera Mg/Ca records, and several records of chironomids, diatoms, pollen and glycerol dialkyl glycerol tetraethers (GDGTs). The temperature stack of $U_{37}^{K'}$ records indicates a warm early to mid-Holocene, and then a gradual decrease since 6 ka. However, the stack of foraminiferal Mg/Ca records shows a nearly constant temperature throughout the Holocene (Fig. 1a). Moreover, only the regional stack for middle to high latitudes of the Northern Hemisphere (90°–30°N) (including 16 alkenone records, 3 foraminifera Mg/Ca records and 10 other records) is consistent with the claimed global temperature reconstruction. By contrast, the temperature stacks from the tropics (30°S–30°N) (10 alkenone records, 16 foraminifera Mg/Ca records and 6 other records) and the Southern Hemisphere (90°–30°S) (5 alkenone records and 7 other records) are not consistent with global reconstructions (Fig. 1b). This is likely caused by the complexity of the seasonality effects on the proxies, which requires more detailed investigation in the future.

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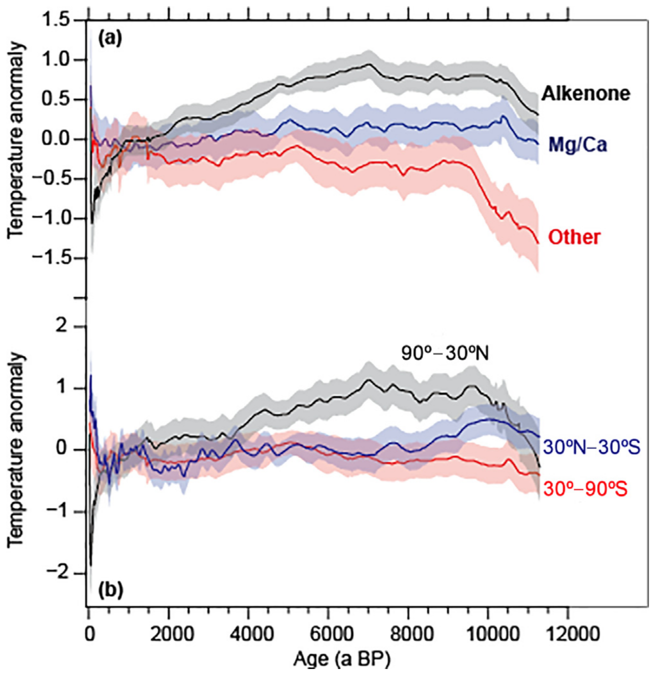

Fig. 1. Temperature records used in global temperature reconstructions [4]. (a) Stacks for various proxies; black: alkenones, blue: foraminifera Mg/Ca, red: other records. (b) Stacks for records at different latitudes, black: 90°–30°N, blue: 30°N–30°S, red: 30°–90°S.

A recent study [10] claimed that a cooling trend throughout the Holocene was largely a feature of marine and costal records, which were mainly used in Marcott et al. [4]. Marsicek et al. [10] further demonstrated that early Holocene temperatures in North America and Europe were 2 °C lower than during the past two millennia, based on pollen records, which is consistent with the CCSM3 simulation. This further confirms the influence of seasonality on pollen records.

It is generally accepted that summer temperatures were high during the early to mid-Holocene and then declined in the late Holocene. However, it remains unclear how annual and winter temperatures varied during the Holocene, due to the fact that most temperature proxies reflect the climate of the growing season. For those proxy indicators that are suggested to record annual temperature, such as pollen, the transfer functions are mostly based on an empirical function without an in-depth understanding of their physiological basis [11]. Therefore, we urgently need to develop proxies which reflect annual temperature or winter temperature. Wang et al. [12] proposed that combinations of diatoms could reflect winter temperature as well as winter monsoon intensity in China, which would be helpful for resolving the "Holocene temperature conundrum". In addition, the recently proposed "winter limnology", which mainly focuses on modern limnological processes in winter lake and then seeks appropriate proxies to reconstruct the climate in cold seasons, may provide new opportunities to resolve the issue.

Without a comprehensive understanding of ecological effects on land surface processes, climate models may either under- or over-estimate energy fluxes, thus producing biased results. For example, the CCSM3 simulation does not consider several physical mechanisms, such as the climate impacts of volcanic activity, dust and vegetation, which may affect climate simulations. By fully considering climate forcings, climate modeling can also provide a powerful approach for deciphering the mechanisms and climate forcing response on various temporal and spatial scales [13].

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.02.012.

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