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Mean global ocean temperatures during the last glacial transition

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Little is known about the ocean temperature's long-term response to climate perturbations owing to limited observations and a lack of robust reconstructions. Although most of the anthropogenic heat added to the climate system has been taken up by the ocean up until now, its role in a century and beyond is uncertain. Here, using noble gases trapped in ice cores, we show that the mean global ocean temperature increased by 2.57 ± 0.24 degrees Celsius over the last glacial transition (20,000 to 10,000 years ago). Our reconstruction provides unprecedented precision and temporal resolution for the integrated global ocean, in contrast to the depth-, region-, organism- and season-specific estimates provided by other methods. We find that the mean global ocean temperature is closely correlated with Antarctic temperature and has no lead or lag with atmospheric CO_2, thereby confirming the important role of Southern Hemisphere climate in global climate trends. We also reveal an enigmatic 700-year warming during the early Younger Dryas period (about 12,000 years ago) that surpasses estimates of modern ocean heat uptake.

Today, the global ocean takes up about 93% of the excess heat from anthropogenic activities[1], which dominates the current global radiation imbalance[2]. Owing to the heterogeneity and size of the global ocean it is difficult to measure its heat content and mean (global) ocean temperature (MOT) precisely. A large number of sensors are needed to track regional changes and derive global trends, as in the Argo float array project[3]. Nevertheless, this system does not yet cover much of the deep ocean (depth below 2,000 m), leaving uncertainty in the MOT estimates for the current warming. For changes in MOT before the Argo float system started (around AD 2,000), the data basis is much weaker, because the observations were much more sparse[1]. Considering that the slow overturning time of the global ocean (centuries to millennia) determines the responsiveness of MOT to changing climate, there is much interest in reconstructing ocean temperatures before the first observations (about AD 1872).

Marine proxies have produced such reconstructions on a variety of temporal and spatial scales[4–7]; however, the different proxies have strengths and weaknesses, leading to debate about the interpretation of the corresponding data (ref. 4 and references therein). The difficulty lies in separating temperature from other effects as well as assessing a precise proxy-to-temperature transfer function because of the complex biogeochemistry behind these proxies and potential regional as well as temporal differences[5,8]. Although trends in these proxies might be representative of the temperature trends, these issues are in particular problematic for the absolute accuracy of the corresponding temperature scale. The uncertainty of the absolute scale lies in the range[4,8] of ±1 °C, which poses a major limitation for the determination of the glacial–interglacial MOT change (about 3 °C)[4].

Here we use a proxy for MOT introduced in ref. 9 based on measurements of inert or noble gas mixing ratios (Kr/N_2, Xe/N_2, Xe/Kr) in ice core samples (see Methods and ref. 10 for analytical details). The data are used to reconstruct past MOT with unequalled accuracy, taking advantage of the following characteristics of the ocean–atmosphere system: (1) any heat and gas exchange takes place at the ocean–atmosphere interface; (2) there are no essential internal heat sources or sinks in the ocean[11]; (3) there are no essential sources or sinks of the measured gases in the combined ocean–atmosphere system; and (4) each gas species has a unique and well defined temperature-dependent solubility. Therefore, a change in MOT leads to a change of the dissolved noble gas inventory in the ocean, which is in turn mirrored by an opposing change in the atmosphere without any intrinsic temporal delay or filtering (see detailed discussion in Methods). Because the atmosphere is well mixed this method effectively integrates globally. Thus, as opposed to marine proxies, the atmospheric noble gas ratio is a purely physics-driven proxy for the global ocean heat content and MOT[9,11].

We analysed 78 ice samples (including ten partial to full sample rejections; see Methods) from the WAIS Divide ice core that cover the Last Glacial Maximum (LGM) to the pre-industrial period. For the period 22–8 kyr BP (thousands of years before 'present', that is, AD 1950)—which contains the last glacial transition (20–10 kyr BP)—a high temporal resolution of 250 yr on average was obtained. Together with the rich information available from the same ice core and the excellent age control in this climate archive, our record allows unprecedented insights into the interplay between climate and MOT during a period of major climate change.

Inferring MOT from noble gases

To derive the atmospheric ratios needed for the MOT reconstruction, the raw data has to be corrected for gravitational enrichment and thermal fractionation in the firn column[12]. As in refs 9 and 10, we use the measured argon isotope ratio $\delta^{40}Ar$ ($^{40}Ar/^{36}Ar$) to correct the elemental ratios for the gravitational fractionation. The correction we apply assumes that the firn air column is in full thermal–gravitational equilibrium, which might not have been the case, as indicated by the difference between the $\delta^{86}Kr$ ($^{86}Kr/^{82}Kr$) and $\delta^{40}Ar$ (see Methods). This anomaly in $\delta^{86}Kr$ is a phenomenon that needs to be investigated further; however, it is roughly constant over the entire record, suggesting that the potential bias is small on relative changes within the record (but might have an effect on the absolute scale of about 0.3 °C—see below and Methods for more details).

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