which reduces/increases the density differences between NADW and AABW and, hence, increases the pull/push onto the AMOC. In fact, the two causal relations mentioned here (effect of the AMOC onto MOT and vice versa) could provide a feedback loop that explains the fluctuations of the AMOC characteristic of the glacial periods[23]: during a weak AMOC state, the Southern Ocean/AABW warms[33], which decreases the density differences between NADW and AABW, continuously increasing the 'pull' onto the AMOC. Once the 'pull' becomes too large, the AMOC switches to its strong state, which in turn starts cooling AABW, making it again harder for the AMOC to sustain its strength as AABW becomes denser again. In other words, the bipolar seesaw and the teleconnection between Southern Ocean and AMOC together would make up a density oscillator which could—depending on the background ocean temperatures or stratification[34]—be self-sustaining and not necessarily triggered by a North Atlantic surface perturbation, often thought to be the cause behind the glacial AMOC fluctuations. This density oscillator is probably not only temperature-driven but also involves salinity changes. As outlined in ref. 22, Southern Ocean temperatures also affect the sea ice extent and the associated effect of brine rejection on the salinity/density of the Southern Ocean waters potentially exceeds the temperature effect on AABW density by up to a factor of five. The idea described here needs thorough testing with ocean models, and does not explain, for example, the abruptness of the AMOC changes that are characteristic to these AMOC changes in glacial times. However, it provides an alternative to the otherwise North-Atlantic-focused explanations for these oscillations and is in line with the MOT record presented here.

Younger Dryas warming

The strong YD1 MOT warming is a striking element of our record and represents a clear anomaly to the otherwise strong link between MOT, AAT and AMOC, respectively. The event starts at the same time as the corresponding warming events seen in the AAT and GAST records, but MOT shows a clearly higher warming rate and reaches its Holocene level considerably earlier. The correction of our data for the firn fractionation processes is critical, but neither do the stable isotope data used to derive this correction show any inconstancy nor does the uncertainty in the thermal correction have enough leverage to explain this event (see Methods).

There is an unexpected change in the accumulation rate in the WAIS Divide ice core from 12,000 yr BP to 11,600 yr BP[35], which could cause weakly understood dynamic firn fractionation processes, but this event had no effect on the YD1 part of the noble gas record because the air was already trapped in the ice before the accumulation event started (the uncertainty[36] in gas age versus ice age is only $\pm$50 yr). Therefore, the YD1 noble gas changes found here seem to be truly atmospheric. We cannot exclude the possibility that the ocean circulation pattern has shifted rapidly from its potential glacial state[22] to its modern state during the YD1, which could cause a dampening of the YD1 MOT change by up to 0.35 °C (the sum of the Kr and Xe saturation state and the AABW volume biases; see Methods) because we currently assume a gradual change. There is no evidence that such a change happened specifically at this point in time, for which reason we continue with the gradual change assumption. Nevertheless, this 22% leverage with which to dampen the YD1 MOT event still leaves the YD1 as an extreme event in terms of MOT warming.

The YD1 phase is associated with a strong ocean heat uptake of 1.1 ± 0.23 W m^{-2} (1σ), but the greenhouse gas forcing is basically stable, the orbital forcing change is negligible, the sea-level record does not indicate any major losses of land ice or albedo[14] (Fig. 3b), and other processes tend rather to a slight negative radiative forcing[37]. This suggests that the YD1 MOT warming is driven by ocean dynamics rather than by radiative forcing changes. The drainage of Lake Agassiz probably drove the AMOC changes during the Younger Dryas[37]; however, AMOC-disturbance experiments using intermediate complexity climate models either do not reproduce the high MOT warming rate of YD1 (1.6 °C in about 700 yr)[33], or fail to sustain this high rate over the observed period[11]. This suggests that AMOC changes can explain only part of the YD1 MOT warming. In experiments using state-of-the-art global climate models forced by anthropogenic greenhouse gas emissions[1], none of the 15 models (individually averaged over all realizations) reaches the warming rate of YD1 averaged over 1971–2005 (35 yr). The mean rate over all models is about a third of the YD1 warming rate, even though the greenhouse-gas radiative forcing is at least ten times stronger than during YD1[38]. In summary, this shows that the YD1 MOT warming is challenging the current understanding of global ocean temperature regulation and suggests that either current climate models generally underestimate the ability of the ocean to take up heat, or that climate conditions/drivers during the YD1 have been substantially different from the model experiments mentioned here in a way that allows much stronger heat uptake. Two ideas about possible conditions/drivers behind the YD1 warming are further discussed in Methods and are related to the strong insulation in high latitudes during YD1 (see Fig. 3d) and an isolated water mass combined with a drastic change in the global ocean overturning circulation, respectively.

In summary, the MOT reconstruction for the last glacial transition we present here constrains MOT with unprecedented accuracy from a novel proxy based on noble gases in the atmosphere. The record provides unique insights into the energy budget of the currently largest energy buffer in the climate system—the ocean—and its interplay with changing climate and ocean circulation. The insights we gain here raise questions about how the ocean regulates its temperature under variable conditions—a topic very important for future climate change—but have not yet been studied extensively owing to a lack of long-term reconstructions. We describe here the general features of the data and possible explanations for them, but further work is needed using global climate models to test our hypotheses.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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