we present here it might be possible to better constrain such estimates in the future and narrow down some of the uncertainties related to the LGM GAST.

It is interesting to note that since the LGM about the same amount of energy has gone into MOT as into melting grounded ice (Fig. 3b). This is not contradicting the understanding that most of the current anthropogenic warming has been taken up by the ocean even though only about 10 cm of sea-level rise (about half of the total rise of 19 cm since 1900) is attributed to melting of grounded ice[2], whose latent heat equivalent is only about 3% of the total energy taken up by the ocean[1]. The response of melting land ice to global warming is very much dependent on the geometry/configuration/sensitivity of the global ice sheets at a specific point in time[27]. Therefore, the 1:1 ratio of energy going into the ocean and melting grounded ice has to be regarded as an average over the whole last glacial transition and cannot be expected to hold for the anthropogenic warming. However, as a recent study has shown[28], including ice melting is important to close also the current global energy budget and can provide new insights into the mechanism behind recent decadal global temperature variabilities.

Climate–MOT interplay

There is no temporal uncertainty between the MOT and CH_4 records (Fig. 3g) because they were obtained from trapped air in the same ice core. Atmospheric CH_4 reacts quickly to changes in the northern and tropical regions (within decades) and has been measured with very high resolution and precision[29]. Therefore, it is an excellent time marker for the abrupt changes in Northern Hemisphere climate (dashed lines in Figs 2 and 3) related to variations in the Atlantic Meridional Overturning Circulation (AMOC), that separate the climate periods Heinrich Stadial 1 (HS1), the Antarctic Cold Reversal and the Younger Dryas from each other[30]. This allows a precise comparison between MOT and the changing climate and ocean circulations that are associated with the climate periods mentioned above (Fig. 3).

First, the comparison of the inflection points of MOT and abrupt changes in the CH_4 record shows no lead or lag of MOT relative to these events (with the exception of the end of the Younger Dryas; see below). In particular for the transition from the HS1 to the Antarctic Cold Reversal, the temporal constraints are strong owing to the high resolution of both the MOT and the CH_4 records. For this event we estimate the MOT inflection point to occur at $14{,}780 \pm 390$ yr BP. This is indistinguishable from the occurrence of the corresponding CH_4 change at $14{,}580 \pm 80$ yr BP. This constrains any possible phase shift between CH_4/AMOC change and MOT to be within a couple of centuries, at least for this point in time.

Second, the trends in the MOT record we present here are strikingly similar to those of Antarctic temperature (AAT) during the last glacial transition (Fig. 3). AAT and MOT show the same general evolution of stable temperatures during the LGM, followed by a moderate warming during HS1 (17,690–14,580 yr BP), a cooling during the Antarctic Cold Reversal (14,580–12,750 yr BP), a strong warming during the Younger Dryas (12,750–11,550 yr BP) before reaching stable Holocene values. In fact, the Younger Dryas MOT warming finished about 500 yr before the rapid CH_4 rise at 11,550 yr BP that marks the end of the Younger Dryas. The end of the Younger Dryas is an anomaly to the otherwise close relationship of MOT and AAT during the last glacial transition.

During the HS1 period, MOT changes at a rate of 0.67 ± 0.11 mK yr^{-1}, which corresponds to an energy uptake by the ocean of $(3.6 \pm 0.52) \times 10^{21}$ J yr^{-1} (all errors given in this paragraph are 1σ). This is about 30% of what is estimated[1] for the ocean heat uptake between 1997 and 2015 ($(12.4 \pm 5.0) \times 10^{21}$ J yr^{-1}). The Antarctic Cold Reversal period is characterized by a statistically significant cooling of the global ocean of -0.29 ± 0.13 mK yr^{-1}, which translates into an energy loss of $(-1.4 \pm 0.66) \times 10^{21}$ J yr^{-1}. The warming from 12,750 yr BP to 12,050 yr BP (referred to as YD1) within the Younger Dryas represents the strongest global ocean warming phase within our record. The MOT change rate is 2.5 ± 0.53 mK yr^{-1} and the corresponding energy uptake $(13.8 \pm 2.9) \times 10^{21}$ J yr^{-1}. This unprecedented natural MOT warming rate is comparable to the strong warming since 1997 estimated in ref. 1, but clearly surpasses the estimate therein for the multidecadal trend from 1971 to 2005 (see below). The close relation between our MOT record and AAT/AMOC changes as well as the strong warming during the YD1 are two intriguing features of our record and are discussed here in more detail.

The synchronicity of MOT and AAT during the last glacial transition is somewhat surprising because AAT (and atmospheric CO_2) seems to lead global averaged surface temperatures (GAST) by several centuries[6] (Fig. 3f). However, this is not a contradiction because the lag of GAST relative to AAT/CO_2 is explained by a lag of the Northern Hemisphere temperatures (N-GAST) while the Southern Hemisphere temperatures (S-GAST) are synchronous with (or even lead) AAT/CO_2. MOT is a S-GAST-biased parameter owing to the larger volume of the ocean ventilated in the Southern Hemisphere[20,22], so the synchronicity of MOT and AAT/CO_2 is consistent with GAST lagging AAT/CO_2, as found in ref. 6. The general picture arising from this is that MOT, CO_2 and S-GAST are changing synchronously (within the given uncertainties) and N-GAST is lagging during the last glacial transition. With the glacial atmospheric CO_2 rise attributed to the release of CO_2 from the Southern Ocean[31], this suggests that (at least for this transition) the Southern Hemisphere climate was driving the global climate out of the glacial period and not the Northern Hemisphere. The similarity between AAT/AMOC and MOT could be explained such that only the waters ventilated at the high southern latitudes have a net effect on MOT. Through the well known AMOC-related meridional surface heat transport mechanism known as the bipolar seesaw[32], the Southern Ocean surface temperatures increase when the AMOC is in a weak state and vice versa. These surface temperature changes may have reached the southern deep-water formation areas and subsequently changed the temperatures of the AABW, which comprises a large portion of the global ocean volume. Changes in other regions might not necessarily have a net effect on MOT. This simple explanation suggests that the current ocean heat uptake could indeed be underestimated or undersampled given that AABW forms in the Southern Ocean and fills the bottom part of the ocean below 2,000 m, areas which are inadequately covered by observation systems such as the Argo floats[3].

However, this purely Southern-Ocean-driven explanation for the AMOC–MOT relation might be too simplistic. The basic behaviour of MOT increase during a weak AMOC and vice versa is seen in two model experiments[11,33], but it is explained by changes in the low-latitudinal ocean. The change in AMOC affects the heat capacity of the low-latitudinal Atlantic, which leads to accumulation of heat in this region after a switch from a strong to weak AMOC (such as from LGM to HS1) and a release of heat in the opposite case (such as from HS1 to the Bølling–Allerød period)[33]. This mechanism produces very similar MOT patterns and rates of change in the experiments of ref. 33 to what we find for the HS1 and Bølling–Allerød periods, providing some support for this underlying mechanism. However, this mechanism is not sufficient to explain the MOT pattern and rates of change during the Younger Dryas, where we find a much stronger warming in the first phase (about 700 yr), followed by temperature stabilization. In fact, this pattern is more comparable to what ref. 11 simulate in their AMOC disturbance experiments, though the magnitude of change in these experiments is quite different. In summary, the relationship between AMOC strength and MOT is a consistent feature in the few model studies that investigate the tie between these parameters, but neither study replicates the temporal pattern or magnitude of MOT change observed in this record.

So far we have looked into the ways that changes in AMOC could affect MOT. The causality, however, may be flipped: MOT may affect the AMOC. As shown in ref. 34, changes in Southern Ocean surface heat flux can affect the stability of the AMOC. If southern heat fluxes are high, the AMOC is stronger, and vice versa, because a warmer/colder Southern Ocean is associated with a warmer/colder AABW,