Global warming has reached the top of the Greenland ice sheet

Air temperatures at the Greenland ice sheet have been reconstructed with unprecedented quality from an array of ice cores. The analysis shows that modern temperatures are 1.5 °C warmer than those of the twentieth century, and that this warming has been accompanied by increased run-off of Greenland meltwater.

The problem

The growing contribution of the Greenland ice sheet to sea-level rise as it melts is of serious concern. The problem is aggravated because warming can be amplified by positive feedback effects that accelerate the loss of mass[1]. Mounting evidence[2] suggests that climate change has also reached the high-elevation, cold and remote areas of the central Greenland ice sheet. However, if we are to attribute drivers to recent change, and better determine the sensitivity of the ice sheet's climate to anthropogenic forcing, we must know how temperature varied before industrialization — that is, the natural climate variability.

Stable water isotopes in ice cores enable the reconstruction of past temperatures. Single ice-core records are noisy[3], so arrays of ice cores are used to improve the climate signal. Numerous ice cores have been drilled in the past, but many of these do not provide a record of the past two decades.

Different proxy records — from other climate archives, such as tree rings or sediment cores, and recent measurements from weather stations — can be combined statistically to reconstruct past temperatures. However, such a technique might underestimate natural climate variability[4].

The solution

By re-drilling and thus updating existing ice-core records, and combining a total of 21 records from central and north Greenland, we reconstructed temperatures from the pre-industrial era 1,000 years ago to 2011 (Fig. 1). We analysed statistical relationships between the records, as well as between our reconstruction and data from coastal weather stations, climate models and reanalyses. Our reconstruction represents a robust temperature record for central and north Greenland that includes the pre-industrial time periods. The simplicity of our approach — relying on an array of a single proxy-type measure that spans the full time period — means our reconstruction robustly preserves both modern and past climate variability. This enables us to study temperature trends and infer natural temperature variability from the pre-industrial era, and thus to put recent temperature trends into a long-term context.

We find the decade from 2001 to 2011 in Greenland to be the warmest of the past millennium, being 1.5 °C warmer than the twentieth-century average. The likelihood of such temperatures occurring by chance within natural variability (that is, in the pre-industrial era) is almost zero. This implies that anthropogenic global warming has reached the high-elevation areas of central and north Greenland.

Our temperature reconstruction has a strong statistical relationship with Greenland-wide meltwater run-off over the instrumental period (beginning in the nineteenth century). This link might be attributable to an atmospheric-circulation pattern that leads to the flow of warm air across the ice sheet. This statistical relationship enabled us to reconstruct the pre-industrial meltwater run-off record for Greenland, providing an important data set for investigating the relationship between meltwater run-off and ocean-climate variability. It further shows that modern meltwater run-off is also outside the range of natural variability.

The implications

Our findings provide evidence that anthropogenic warming has reached the high-elevation areas of the Greenland ice sheet, one of the most remote places in the world. The strong link between temperature and meltwater run-off implies that further warming will lead to increased meltwater run-off and thus accelerate sea-level rise.

There are two main limitations to our approach. First, our record ends in 2011, and so lacks data for the decade from 2011 to 2021, when several Greenland-wide melt events were observed. Second, owing to remaining uncertainties in our reconstruction, we restricted our interpretation to decadal timescales and did not reconstruct spatial maps of the temperature changes.

We want to extend our record further into the twenty-first century. Moreover, we plan to increase reconstruction quality and resolution through further replication and use of our continually improving understanding of how ice cores record climate variations. This should enable us to perform spatially resolved temperature reconstructions so that we can better disentangle the links between temperature, atmospheric circulation and meltwater run-off.

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EXPERT OPINION

"It has been difficult to use ice cores to evaluate climate variability over recent decades, owing to a lack of up-to-date cores. This is especially true in Greenland and Antarctica, where natural climate variability is fundamentally extreme. This work sheds light on climate evolution across the Greenland ice sheet, including a human-caused warming signal that is of dire consequence for the future mass balance of the ice sheet." (CC BY 4.0)

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FIGURE

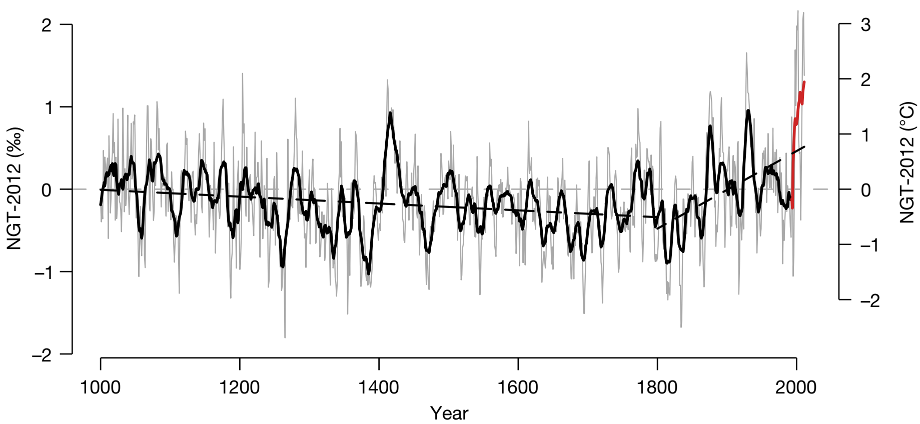

Figure 1 | Reconstruction of the temperature record from central and north Greenland. A composite record of the air temperature in central and north Greenland – called NGT-2012 – was derived from ice cores. The black line shows the 11-year running mean of the ratio ($\delta^{18}O$, parts per thousand) of the abundances of the stable oxygen isotopes oxygen-18 and oxygen-16 in the water molecules that make up the ice (left axis) and the inferred temperature time series (right axis) in the years between 1000 and 2011. The grey line shows annual mean values. The red line highlights the extension of existing ice-core records from 1995 to 2011 by ice-core re-drillings performed as part of this study. Estimated linear trends over the period 1000–1800 (pre-industrial) and 1800–2011 are shown as dashed lines. Hörhold, M. *et al.*/*Nature* (CC BY 4.0).

BEHIND THE PAPER

In the 1990s, researchers travelled across the northern Greenland ice sheet, collected numerous ice cores, and then spent years analysing them. Strikingly, no warming signatures could be detected in these records, prompting discussion of a 'warming hiatus' — a delay of, or pause in, global warming, or even the lack of it, as announced by climate-change sceptics. In the meantime, researchers better deciphered how the climate signal is recorded in ice cores and studied how these cores present a faithful, yet noisy, thermometer for ancient climate. Now, through extension of some of the old drill sites and careful statistical analysis, we understand: the ice cores show strong natural variability on top of ongoing global warming. Ultimately, we need the work laid out by our pioneering colleagues almost 30 years ago, and an ever-improving understanding of the climate-proxy signal, along with knowing how best to retrieve information about past climate from the ice.

M.H. and **T.L.**

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FROM THE EDITOR

Even with the old, there is an obsession with the new. That is, scientists would normally seek to obtain a new record of past climate variability, rather than revisit previously explored sites. But Hörhold and colleagues have done just that, re-drilling the site of previously obtained ice cores. Their work enables the most recent patterns of climate variability to be contextualized against the deeper time variability usually seen in ice-core research.

Michael White, Senior Editor, *Nature*