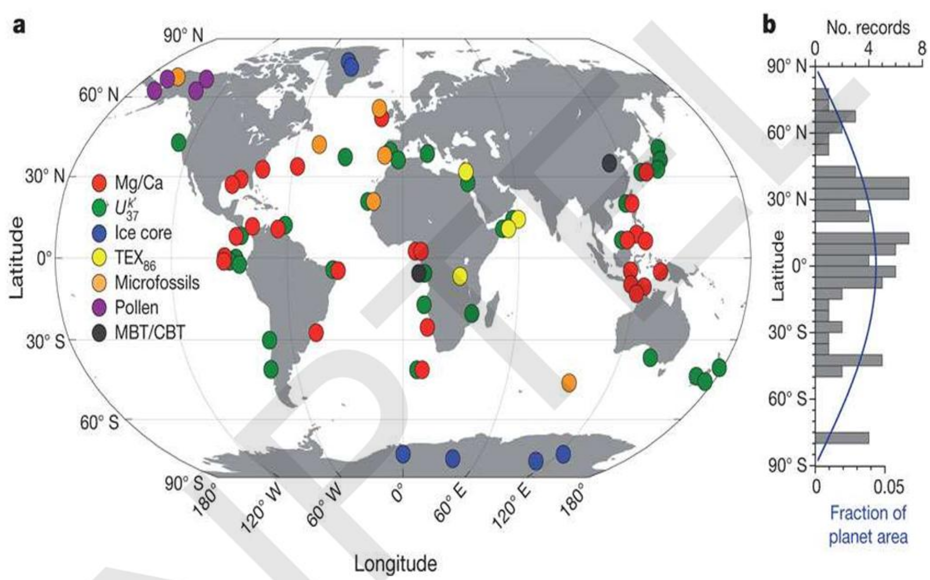
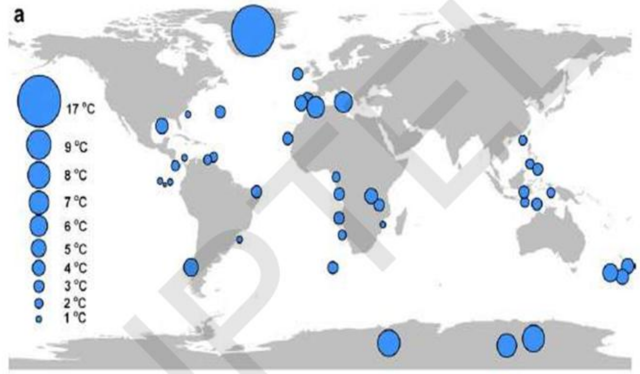
Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 36
Glacial to Interglacial transition

In the previous lecture, a key discussion centered on Jeremy Shakun's study that reconstructed global mean temperatures using proxy data from sources such as ice cores, ocean sediments, and other geological indicators. A significant challenge in such reconstructions arises from the uneven spatial distribution of proxy data, which tends to concentrate around coastlines, the Arctic, and the Antarctic, while leaving out vast continental interiors like much of Asia. This raises questions about the reliability of deriving a true global mean from such incomplete coverage. However, a major advantage in modern paleoclimate research is the availability of simulations from coupled ocean-atmosphere climate models. Notably, the NCAR (National Center for Atmospheric Research) has conducted simulations that span the last 20,000 years from the Last Glacial Maximum to the present. These models offer full global coverage through gridded data, allowing researchers to test how well the sparse proxy locations represent the global mean. By extracting model outputs at proxy-equivalent grid points and comparing the average to the model's true global mean, one can assess the representativeness of the proxy network. This issue will be further explored later in the lecture.



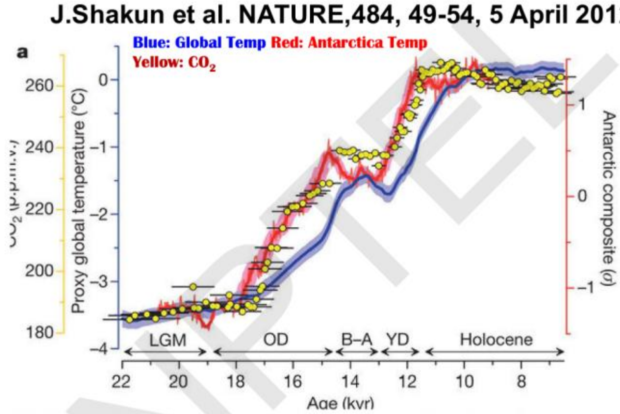
JD Shakun et al. Nature 484, 49-54 (2012)
doi:10.1038/nature10915



GLACIAL TO INTERGLACIAL TEMPERATURE RISE
Shakun and Carlson, Quaternary Science Review 2010

One important observation from proxy data is the pronounced spatial variation in warming between glacial and interglacial periods. These records indicate that polar regions, particularly the Arctic and Antarctic, experienced significantly greater temperature increases than the tropics during the transition from the last ice age to the present. For instance, Greenland is estimated to have warmed by as much as 17°C, whereas tropical regions showed a comparatively modest rise of only 1–2°C. This strong spatial gradient, consistently captured across various proxies, supports the credibility and reliability of proxy data in reconstructing past temperature changes.

J.Shakun et al. NATURE,484, 49-54, 5 April 2012

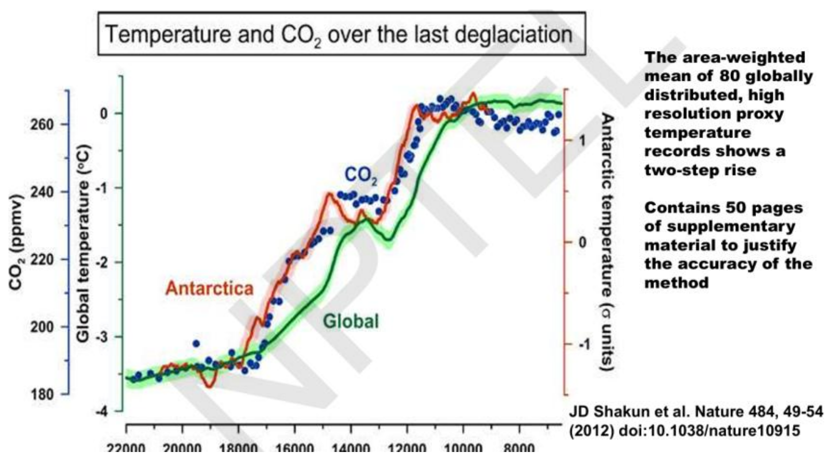


The global proxy temperature stack (blue) as deviations from the early Holocene (11.5–6.5 kyr ago) mean, an Antarctic ice-core composite temperature record[42] (red), and atmospheric CO_2 concentration (refs 12, 13; yellow dots).

A central finding of Shakun's study is the temporal relationship between Antarctic and global mean temperature changes during the deglaciation period. According to the proxy data, represented by a blue line for global temperature and a red line for Antarctic temperature, the Antarctic began to warm significantly around 18,000 years ago, preceding the global temperature rise by approximately 800 to 1,000 years. This key observation implies that Antarctic and global temperatures did not change synchronously during the transition from the last ice age to the Holocene.

The data also show that the Antarctic temperature rose rapidly at first, while the global mean temperature increased more gradually, underwent a brief cooling during the Younger Dryas period, and then rose sharply to reach interglacial conditions. A critical aspect of this sequence is the role of carbon dioxide (CO_2), which is uniformly mixed in the atmosphere regardless of its source. Proxy records (indicated by yellow dots on the graph) show that as Antarctic temperatures rose, surrounding oceans warmed and began releasing CO_2. This increase in atmospheric CO_2, from about 180 ppm to 200–220 ppm, enhanced the greenhouse effect globally, which subsequently triggered the rise in global mean temperature, again with a lag of about 800 years.

This phased response, with Antarctic warming leading the global temperature rise via a CO_2-mediated feedback, is a pivotal conclusion of Shakun's paper. Although the main paper is concise (about five pages), it generated significant debate regarding the methodology, particularly the approach used to combine data from over 80 proxy cores. The authors addressed these concerns extensively in the supplementary material, which spans about 50 pages and is publicly available. This supplementary documentation provides valuable insight into the process of scientific scrutiny and rigor, especially how peer-review comments and critiques are responded to in contemporary climate science. Such transparency, though not always available in earlier publications, is becoming more common in modern scientific journals.



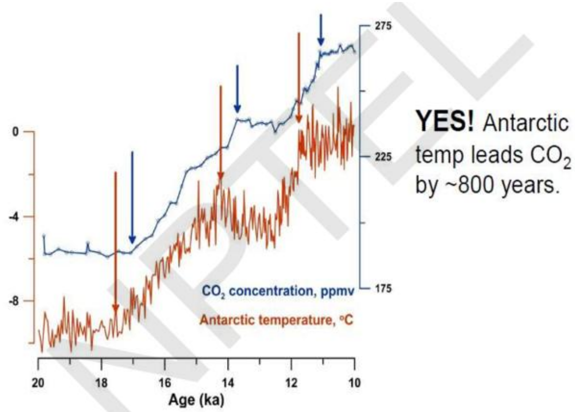
Shakun's study includes extensive supplementary material (about 50 pages) that addresses various concerns raised during peer review, particularly regarding the methods used to combine and interpret over 80 proxy records. A central result supported by this material is the sequence of events during the last deglaciation: Antarctic temperatures began to rise sharply around 18,000 years ago, leading to an increase in atmospheric carbon dioxide. Notably, this rise in CO_2 preceded any significant increase in the global mean temperature.

The timing of these changes is important. The data show that the initial increase in CO_2 began around 17,500 years ago, a point at which global mean temperature had not yet responded. This marks the beginning of a two-phase warming process. In the first phase, temperature rose gradually, driven primarily by increased solar radiation that peaked around 18,000 years ago. This radiation led to melting of glacial ice, particularly in the Northern Hemisphere, reducing Earth's albedo and contributing modestly to warming. However, the rate of warming from this effect alone was too slow to explain the full transition from glacial to interglacial conditions.

The second phase of warming was more rapid and was strongly amplified by greenhouse gas feedbacks, especially from CO_2 and later from methane. As the Southern Ocean warmed, it released CO_2 into the atmosphere. Since CO_2 mixes evenly across the globe, its greenhouse effect was felt worldwide, enhancing longwave radiation trapping and intensifying warming. Methane, another potent greenhouse gas, also began to increase, further amplifying the effect.

This combined feedback from albedo reduction and greenhouse gas increase led to a much faster rise in global temperatures. The Younger Dryas, a brief return to cooler conditions about 12,900 to 11,700 years ago, introduced a temporary disruption in the warming trend, but the overall pattern continued soon after.

The key conclusion from this part of the study is that ice melting alone was not sufficient to drive Earth out of the ice age. The initial warming, caused by orbital changes and solar insolation, triggered Antarctic warming. This in turn released CO_2, which acted as a global amplifier of warming. The feedback from CO_2 and methane was essential in accelerating the global temperature rise. The distinction in timing between Antarctic and global temperature changes highlights the leading role of Antarctic processes in triggering the deglacial CO_2 rise, which subsequently drove global warming.

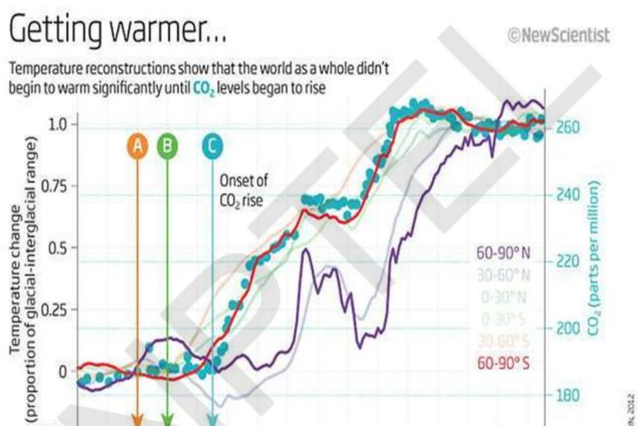


A closer examination of the proxy records reveals the detailed timing and relationship between Antarctic temperature and atmospheric CO_2 levels. In the above figure, Antarctic temperature is shown in red and CO_2 concentration in blue. While the data contains considerable short-term variability reflecting the inherent instability and natural fluctuations of the climate system in the polar regions an overall pattern is evident.

Antarctic temperatures began rising around 17,500 years ago, marked by a noticeable change in the slope of the temperature curve. Approximately 800 years after this initial warming began, atmospheric CO_2 levels also started to rise. This consistent lag of about 800 years highlights a key sequence: Antarctic warming occurred first, followed by a delayed but closely linked increase in global CO_2 levels.

This relationship persisted even through disruptions such as the Younger Dryas event. During the Younger Dryas, Antarctic warming stalled briefly, and a similar pause was observed in the rise of CO_2. However, once Antarctic temperatures resumed their upward trend, CO_2 concentrations followed with a similar 800-year delay. This repeated pattern reinforces the conclusion that Antarctic temperature changes were the primary trigger for CO_2 release, most likely from warming oceans in the Southern Hemisphere.

Importantly, while the initial trigger for CO_2 release was local, rooted in Antarctic and Southern Ocean warming, the effect of CO_2 increase was global. CO_2, being a well-mixed greenhouse gas, rapidly spreads throughout the atmosphere, influencing temperatures worldwide. The consistent sequence of Antarctic warming leading CO_2 rise by approximately 800 years is a central piece of evidence for understanding the feedback mechanisms that governed the transition from the last ice age to the present interglacial period.



A more complex version of the temperature timeseries graph above shows zonal temperature variations across different latitudes during the transition from the last glacial maximum to the Holocene. The graph particularly distinguishes between high-latitude regions: 60°–90° South (Southern Hemisphere polar zone) and 60°–90° North (Northern Hemisphere polar zone).

A clear contrast emerges between the behaviour of the two hemispheres. In the Southern Hemisphere, particularly over Antarctica, the temperature rise appears relatively smooth and gradual over the deglacial period. In contrast, the Northern Hemisphere high latitudes show pronounced fluctuations. The purple line representing the Arctic region displays sharp ups and downs, corresponding to well-known climatic events such as the Younger Dryas (a brief return to cold conditions) and the Bolling–Allerod (a warm interval prior to the Younger Dryas). These temperature oscillations are not observed in the Southern Hemisphere data, indicating that Antarctica experienced a more stable warming trajectory.

This hemispheric difference is attributed to geography and thermal properties of land and ocean. The Northern Hemisphere polar region (60°–90°N) contains extensive landmasses such as North America and Eurasia which respond quickly to climate forcings and exhibit larger temperature swings. In contrast, the Southern Hemisphere polar region (60°–90°S) is dominated by the Southern Ocean surrounding Antarctica. The ocean has a high thermal inertia, meaning it resists rapid temperature changes, resulting in smoother and more gradual warming.

Additionally, the above figure illustrates the concept of the bipolar see-saw, where the temperature trends in the Northern and Southern Hemispheres can move in opposite directions. For example, during the Younger Dryas cooling in the Northern Hemisphere, there was concurrent warming in the Southern Hemisphere. This anti-phase behaviour is linked to changes in the Atlantic Meridional Overturning Circulation (AMOC).

When large volumes of freshwater from melting ice sheets enter the North Atlantic, they reduce seawater salinity and density, weakening the AMOC. A slowed AMOC reduces the northward transport of heat, cooling the Northern Hemisphere. At the same time, less heat is extracted from the Southern Hemisphere, causing Antarctic temperatures to rise. This mechanism explains the warming observed in the Southern Hemisphere during periods of Northern Hemisphere cooling, highlighting the critical role of AMOC in interhemispheric climate dynamics.

Shakun’s paper provides a coherent explanation of the deglaciation process by linking orbital, oceanic, and atmospheric factors. The sequence begins with an increase in summer insolation in the Northern Hemisphere around 20,000 years ago. This increase in solar radiation, particularly over mid to high northern latitudes, initiated the melting of large ice sheets. The influx of freshwater from this melting disrupted the AMOC, a major component of the global ocean conveyor system.

The weakening or collapse of the AMOC had two major consequences: it reduced heat transport to the Northern Hemisphere, leading to regional cooling, and simultaneously caused warming in the Southern Hemisphere due to less heat being extracted from

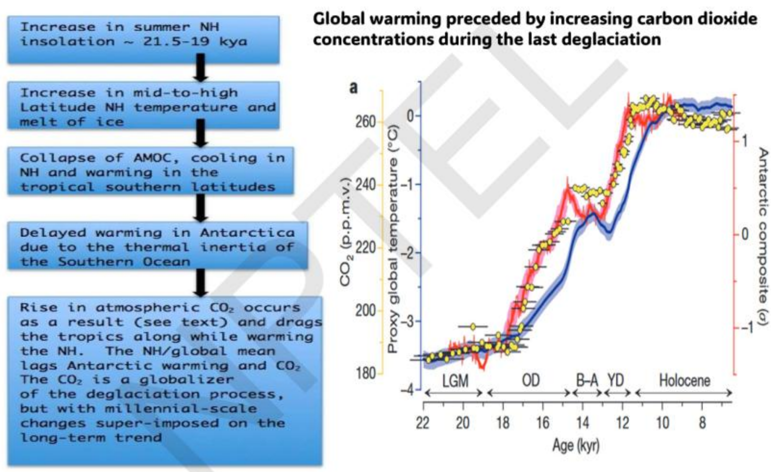
Southern Ocean waters. However, the warming in Antarctica did not happen immediately. The Southern Ocean, characterized by a deep and thick mixed layer, exhibits significant thermal inertia. This delays its response to changes in incoming solar radiation, leading to a lagged warming signal.

As Antarctic and Southern Ocean temperatures gradually increased, CO_2 was released from the ocean into the atmosphere. This increase in atmospheric CO_2, though triggered locally, had a global effect due to the well-mixed nature of greenhouse gases. Once CO_2 levels rose sufficiently, the greenhouse effect strengthened, and temperatures began to rise across the tropics and other regions, thus helping to globalize the deglaciation process.

Shakun's framework identifies two key linkages between the hemispheres:

1. **Atmospheric linkage**: CO_2 acts as a globally distributed agent of warming, connecting temperature changes in one hemisphere to the rest of the world.
2. **Oceanic linkage**: Changes in ocean circulation, especially the strength of the AMOC, directly influence the thermal state of both hemispheres. A slowdown in AMOC cools the North and warms the South.

In essence, while changes in ocean dynamics (via AMOC) initiate interhemispheric temperature contrasts, the rise in CO_2 integrates and amplifies the warming signal on a global scale. Ocean changes drive regional climate reorganization, whereas atmospheric CO_2 acts as a global amplifier of the deglaciation process.



To improve our understanding of past climate, researchers now make use of both proxy data and climate model simulations. Each data source has its strengths and limitations. Proxy records such as ice cores, sediment cores, and other geological indicators provide real evidence from the past, but they are often unevenly spaced in time and contain observational uncertainties. Climate models, on the other hand, offer continuous spatial and temporal coverage, but are based on theoretical formulations and assumptions that may not fully capture all real-world complexities.

To leverage the strengths of both, scientists employ a technique known as reanalysis. Reanalysis involves integrating observational data (in this case, proxy records) with model simulations to produce a more accurate and consistent reconstruction of past climate. The approach prioritizes proxy data where it is reliable and complements it with model outputs where direct observations are sparse or uncertain.

This method has been used to reconstruct the climate of the Last Glacial Maximum (LGM), which occurred roughly 24,000 years ago. In this reanalysis effort, all available proxy data from that period were combined with outputs from coupled climate models to create a coherent picture of global conditions. One of the outcomes was a more refined estimate of tropical temperatures during the LGM, which is otherwise challenging to determine due to limited and spatially biased proxy coverage.

Reanalysis therefore serves as a powerful tool to overcome the individual limitations of proxy data (such as gaps and measurement errors) and climate models (such as simplifications and parameterizations). The result is a hybrid dataset that enhances confidence in paleoclimate reconstructions and allows for better interpretation of Earth's climate system during critical transitions like deglaciation.

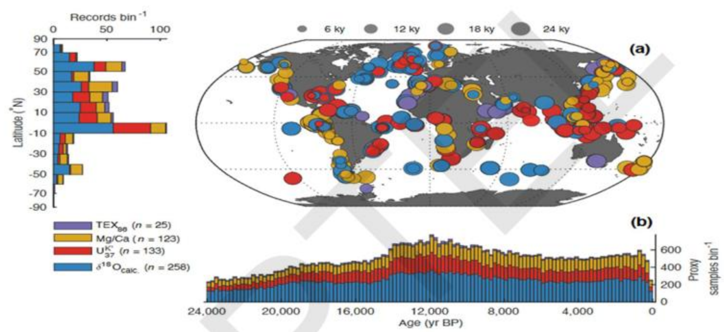


Fig. 1. Locations and temporal coverage of the SST proxies. (a) Site locations of TEX_{86}, Mg/Ca, $U^{K'}_{37}$ and $\delta^{18}O_{calc.}$ records (right), as well as their latitudinal distribution (left). (b) Temporal coverage of the proxies, binned at 200 yr intervals.

$$T = 16.9 - 4.38*\left(\delta^{18}O_c - \delta^{18}O_w\right) + 0.1*\left(\delta^{18}O_c - \delta^{18}O_w\right)^2$$

where T is the temperature in °C, $\delta O^{18}c$ is the δO^{18} of the carbonate of the shells, and $\delta O^{18}w$ is δO^{18} the of the ambient seawater.

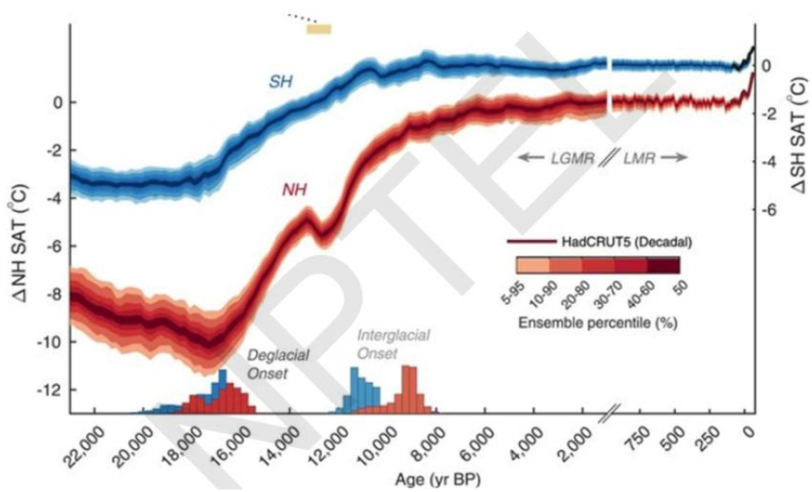
Nature | Vol 599 | 11 November 2021 |

Climate models, while powerful, have known limitations. One of the key issues is that they cannot resolve all spatial and temporal scales of variability. Fine-scale processes such as localized ocean mixing, regional convection, or sub-grid atmospheric turbulence are often approximated using simplified parameterizations. As a result, climate model outputs can have biases or fail to capture some observed patterns, especially at regional scales.

To overcome these limitations, climate model outputs are increasingly combined with observational datasets, particularly sea surface temperature (SST) proxies. Unlike ice cores, SST proxies are more plentiful. This is because ocean sediment cores can be extracted from many locations across the globe, especially in open oceans. In each latitude band, there are often between 50 and 100 data points available from SST proxies, making them highly valuable for reconstructing spatially detailed temperature fields.

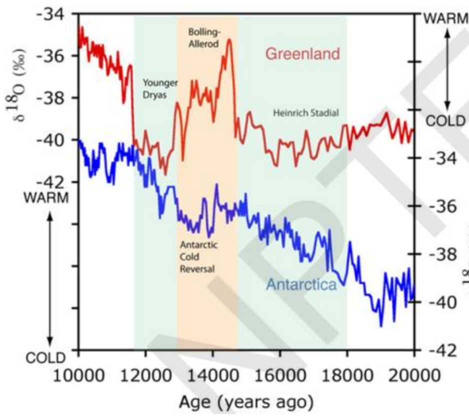
These proxies primarily rely on geochemical signals recorded in the shells of marine microorganisms, such as foraminifera. The calcium carbonate ($CaCO_3$) content in their shells and the ratio of oxygen isotopes (particularly $\delta^{18}O$) in seawater are both temperature-dependent. By analysing these chemical signatures, scientists can infer sea surface temperatures at the time the organisms lived. These records, when distributed across latitude bands and combined across sites, enable robust estimates of past SSTs.

To maximize the strengths of both proxy observations and model simulations, researchers use reanalysis techniques. Reanalysis is a method where observational data and climate model output are merged. In regions and time periods where observational proxy data is dense and reliable, the reanalysis relies more heavily on observations. In contrast, where data is sparse, it leans more on climate model output.



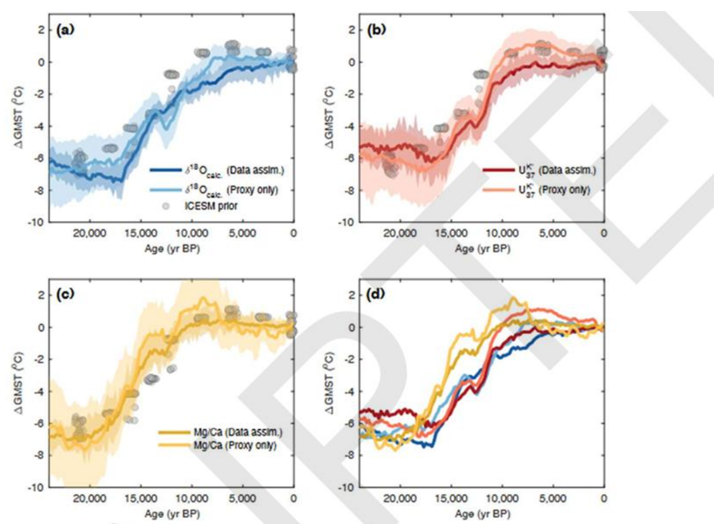
The resulting temperature timeseries from such reanalysis efforts covering both the Northern and Southern Hemispheres provides a clearer and more coherent picture of the past 22,000 years. These reconstructions capture key features of deglaciation, including the onset of the current interglacial period (the Holocene). One of the major advantages of this approach is the ability to validate and cross-check proxy-based reconstructions against climate model simulations.

Antarctic temperatures showed a gradual warming trend with some fluctuations due to glacial events. However, the pattern is different from that of the Arctic. The two poles respond on different time scales, and sometimes even in opposite directions. For instance, during a period when Greenland (Arctic) was warming, Antarctic temperatures declined. This apparent mismatch has raised questions, as it challenges the assumption that both poles should warm together. The differing behavior requires closer examination to understand the underlying mechanisms.

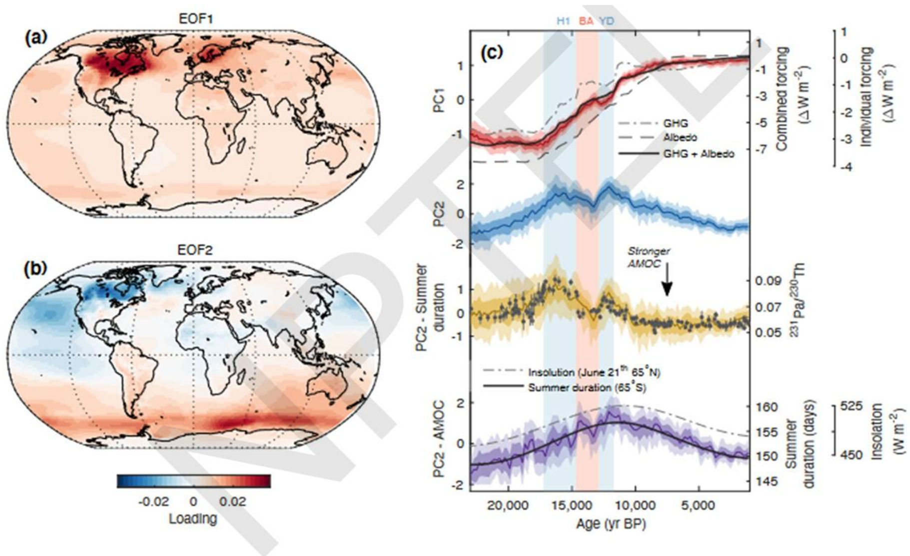


The δ O_{18} varies in large part due to temperature over the ice sheets. The figure shows that while Greenland was cold between 19,000 and 15,500 years ago, and during the Younger Dryas, Antarctica was warming. Likewise, when Greenland was warm during the so-called Bølling-Allerød period, Antarctica experienced a cold reversal. These records were put on the same time scale using the records of methane trapped in bubbles in the same ice cores - methane is mixed rapidly through the atmosphere and varies synchronously between hemisphere

Global mean temperature reconstructions shown below from different proxies show similar overall trends despite some differences. The blue, red, and yellow lines represent different proxies, with the yellow (Mg/Ca ratio) matching temperature well. While the proxies are not identical, they all show that global temperatures remained stable until around 17,500 years ago, then rose rapidly, peaked around 10,000 years ago, and slightly declined afterward. Although only 50 model ensemble members were used for assimilation, the timing of the sharp temperature rise is consistent across all proxies, supporting the reliability of the reconstruction.



Extended Data Figure 6. Proxy-specific GMST reconstructions. $\delta^{18}O_{calc}$ (a), $U_{37}^{K'}$ (b), and Mg/Ca (c). In (a-c), the shaded regions show the 95% confidence range across $n = 50$ ensemble members for the data assimilation derived GMST estimates, and $n = 10{,}000$ realizations for the proxy-only GMST estimates. All GMST curves from (a-c) are shown in (d) for side-by-side visualization.



An alternative method for understanding large-scale climate variations is Empirical Orthogonal Function (EOF) analysis, which is used to extract dominant patterns or modes of variability from complex spatial datasets. Unlike local proxy records, EOF analysis focuses on global patterns and helps isolate the major types of temperature changes over time.

In this context, two main modes of temperature variation were identified from the data. The first mode (EOF1) represents a global pattern of warming, evident across the European and North American continents as well as the Antarctic region. This mode reflects the broad, coherent temperature increase seen during deglaciation and is closely linked to greenhouse gas forcing.

The second mode (EOF2) shows a bipolar pattern, where the Southern Hemisphere warms while the Northern Hemisphere cools. This anti-phased behaviour between the hemispheres is a well-known phenomenon and is connected to disruptions in the AMOC. When large volumes of ice break off from ice sheets and enter the North Atlantic, they introduce freshwater into the ocean, reducing salinity and density, and weakening the AMOC. A weakened AMOC leads to less northward heat transport, causing cooling in the Northern Hemisphere. At the same time, the Southern Hemisphere, especially Antarctica, retains more heat and warms up.

This bipolar pattern highlights the interconnectedness of the hemispheres through the ocean. While the atmosphere is globally connected, allowing gases like CO_2, methane, and water vapor to spread and amplify warming, the ocean's circulation system links hemispheric temperature anomalies in more complex ways. Antarctic warming contributes to the release of CO_2 from the Southern Ocean, and this CO_2 spreads throughout the atmosphere, enhancing the greenhouse effect globally.

EOF1 captures the dominant global warming mode, largely driven by increased greenhouse gas concentrations. EOF2 captures the bipolar see-saw mode, reflecting how changes in ocean circulation can create opposite temperature responses in the two hemispheres. The time series associated with these modes, PC1 for EOF1 and PC2 for EOF2, demonstrate how these modes evolved over the last 22,000 years.

These findings help explain why the temperature transition from the last glacial period to the current interglacial was not smooth or uniform across the globe. Instead, it was shaped by the interaction of two overlapping processes: globally uniform warming from greenhouse gases and regional imbalances caused by ocean dynamics like AMOC.

To reconstruct a truly global mean temperature, like in Shakun's work, both EOF modes must be combined. Shakun's study essentially reflects the net result of these competing processes.