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Our frozen past: Ice-core insights into Earth's climate history

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Ice cores provide a unique window into Earth's climate history. This article explores the various climate indicators stored in ice cores and some of the scientific insights that have resulted from studying them.

Climate indicators

Ice cores contain an invaluable record of Earth's past climate. The climate information stored in ice cores, or climate indicators, can be broadly divided into three categories: (1) atmospheric composition, (2) regional atmospheric circulation, and (3) local temperature and snowfall. Past atmospheric composition is determined by directly sampling ancient air which was trapped during the transformation of snow to ice (McCrimmon et al. p. 112). As overburdened snow layers compact, the interconnected pores within old snow (firn) close and trap atmospheric gases (e.g. O_2, N_2, Ar, CO_2, CH_4) within the newly formed bubbles (Banerjee et al. p. 104). Analyzing the isotopes of atmospheric gases provides insight into their potential sources and sinks.

Past changes in regional atmospheric circulation (i.e. transport pathways) are inferred by examining mineral dust, volcanic ash, and ions in ice cores. The distribution of dust grain size indicates transport strength, and the geochemical composition of dust and ash reveals potential source areas. Dust concentrations can also provide insight into global aridity, while variations in ions (e.g. Na^+, Cl^-, Ca^{2+}, Mg^{2+}, NH_4^+) and organic compounds are used to infer regional changes, such as sea-ice extent and marine productivity.

Past changes in local air temperature are inferred from the analysis of oxygen ($\delta^{18}O$) and hydrogen ($\delta D = \delta^2H$) stable isotope ratios in the water molecules of ice. Air temperatures influence the degree of mass fractionation of water isotopes during the vapor condensation process inside clouds. Isotopic ratios of $\delta^{18}O$ and δD are translated to past temperatures using an empirical relationship derived from, for example, a spatial network of modern snowfall analysis or temperature–depth profiles within the ice sheet. During periods of rapid warming, a vertical temperature gradient within the porous firn column can form, causing gases to thermally fractionate. As a result, deviations in $^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$ provide an additional proxy for rapid temperature changes. Changes in temperature and snowfall accumulation influences the rate of ice formation, which provides further information about local climate conditions.

Long-term climate change

In the 1960s, glaciologists at Byrd Station (Antarctica) drilled an ice core that dated back to the last glacial period (Martin et al. p. 100). Their pioneering work revealed that cooler temperatures during the last glaciation coincided with lower greenhouse gas concentrations (Berner et al. 1980). This discovery led to a fundamental understanding of the link between global temperature and greenhouse gas concentrations.

Over the last five decades, a multinational effort to collect several deep ice cores from the East Antarctic Plateau has resulted in the now iconic 800-thousand-year (kyr) climate

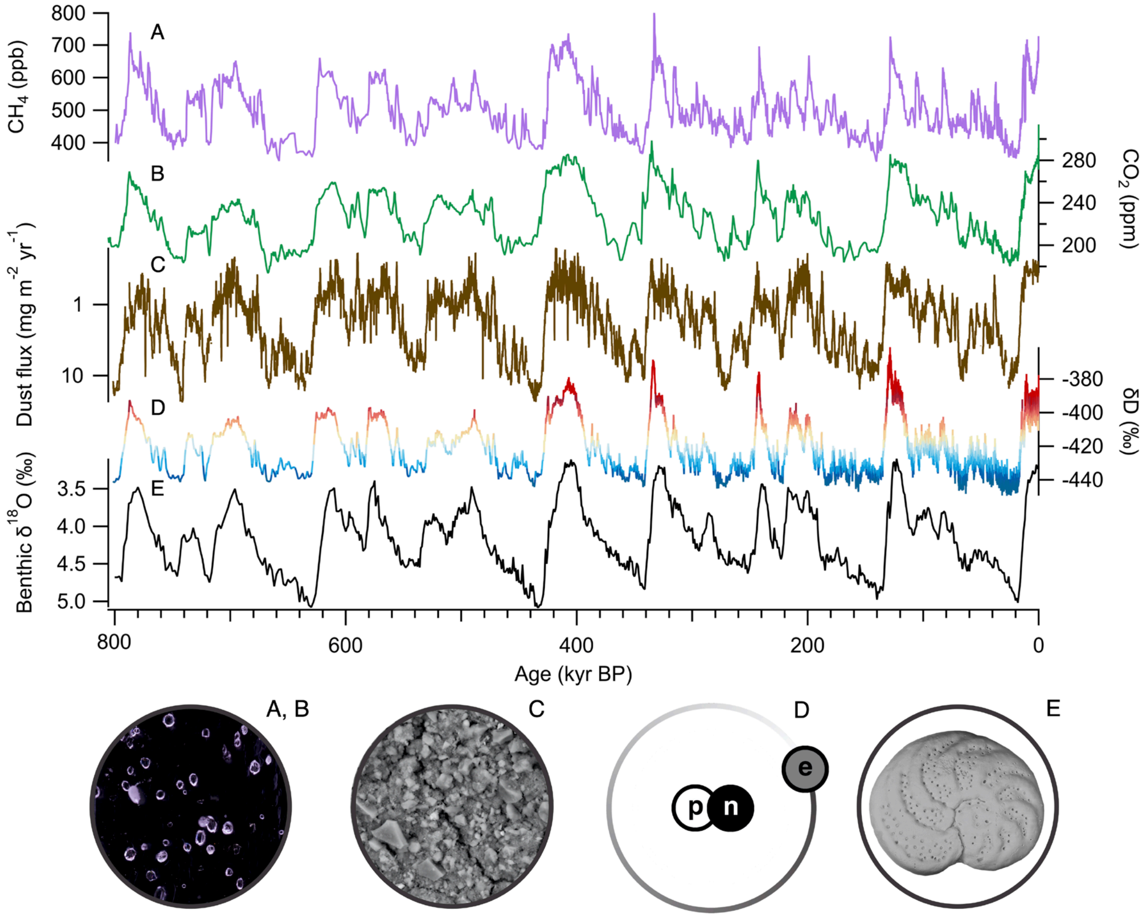

Figure 1: Climate indicators in Antarctic ice **(A-D)** and marine sediments **(E)** reveal climate change over the last 800 kyr. From top: **(A-B)** Atmospheric methane (purple, Loulergue et al. 2008) and carbon dioxide (green, Bereiter et al. 2015); **(C)** 250-year smoothed dust flux plotted on a reversed logarithmic scale (brown, Lambert et al. 2012); **(D)** Variations in δD (rainbow, Jouzel et al. 2007) which reflect Antarctic temperatures (red indicating warmer and blue indicating cooler); and **(E)** Variations in the $\delta^{18}O$ of benthic foraminifera in marine sediments (black, Lisiecki and Raymo 2005).

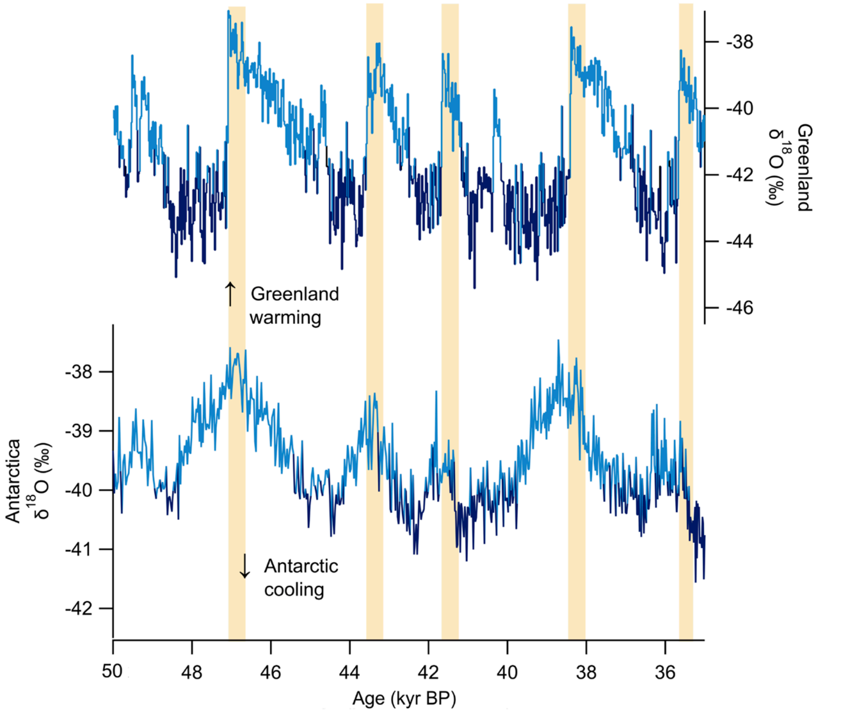

Figure 2: Example of abrupt climate change during the last glacial period. Top panel shows ice $\delta^{18}O$ from North Greenland (NGRIP Members 2004) plotted on the adjusted GICC05 chronology. Bottom panel shows ice $\delta^{18}O$ from West Antarctica (WAIS Divide Project Members 2015) plotted on the WD2014 chronology. Yellow bars indicate the timing of D-O events, during which Greenland warms rapidly. Shades of blue illustrate how relatively cold atmospheric temperatures were at each location, with darker blues showing colder temperatures.

record (Fig. 1). The compiled record offers a window into past greenhouse gas concentrations, Antarctic temperatures, and atmospheric transport properties over the last eight glacial cycles. Climate indicators within the ice reveal major synchronous variations on glacial–interglacial timescales (Fig. 1). The recorded variations resemble the blade of a jagged saw with the troughs representing glacial periods. When compared to warm interglacial periods, glacials are characterized by cooler Antarctic temperatures, lower greenhouse gas concentrations, and dustier winds blowing over Antarctica (Fig. 1a-d). For example, Antarctic temperatures were between 4 and 10°C cooler (e.g. Buizert et al. 2021) and atmospheric CO_2 concentrations were over 100 ppm lower (Lüthi et al. 2008) during the Last Glacial Maximum (20 kyr ago) relative to pre-industrial conditions.

The 800-kyr ice-core record shows remarkable similarities to other paleoclimate records worldwide. Most notable is the $\delta^{18}O$ of benthic foraminifera in deep ocean sediments (Fig. 1e), which is widely used as an index for global ice volume (Lisiecki and Raymo 2005; Christ et al. p. 116). Examining synchronous variations provides a complete picture of the global changes that occur on glacial–interglacial timescales and, most importantly, what drives them. The study of ice cores and other long-term climate records have contributed to the understanding that glacial cycles are paced by Earth's orbital configuration. Climate changes caused by variations in incoming solar radiation are further amplified by a cascade of feedbacks within the climate system. This is best observed during a glacial termination, when climate records worldwide show a systematic and rapid transition to interglacial conditions (Fig. 1). Ice cores have been instrumental in revealing the order, timing, and magnitude of these key climate shifts.

Abrupt climate change

Ice cores also provide unique insight into past periods of abrupt climate change (Alley 2000). Evidence from ice cores suggests that Greenland experienced large swings in temperatures at millennial-scale intervals throughout the last glaciation (Fig. 2; Dansgaard et al. 1993). Abrupt warming periods, known as Dansgaard-Oeschger (D-O) events, are defined by a ~10°C increase in Greenland temperatures over the short period of a few decades (Severinghaus and Brook 1999). Approximately 200 years after an abrupt warming in Greenland, Antarctic temperatures begin to cool (WAIS Divide Project Members 2015; Fig. 2). Similarly, abrupt cooling in Greenland ultimately gives way to Antarctic warming. This phenomenon is known as the thermal bipolar seesaw (Stocker and Johnsen 2003). It can be explained by perturbations in the northward heat transport via the Atlantic Ocean, which exert opposite temperature effects on both hemispheres. The 200-year delay in Antarctic temperatures is the result of a north-to-south propagation of the climate signal through oceanic processes that operate on centennial timescales.

Recent work on high-resolution Antarctic ice cores have revealed variations in CH_4, CO_2, and the relationship between $\delta^{18}O$ and δD that are near-synchronous with Northern Hemisphere D-O events (e.g. Bauska et al. 2021). The timing of these coeval changes suggests a rapid atmospheric response that is uncoupled from ocean circulation. Shifts in the distribution of tropical precipitation or the meridional position of midlatitude westerlies could rapidly propagate signals between hemispheres. These interhemispheric mechanisms are the focus of ongoing research. Resolving these finer-scale changes shed important light on fast-acting feedbacks within Earth's climate system.

Climate sensitivity

Ice cores support our understanding of past climatic changes and play a critical role in future climate projections. Since Eunice Foote's discovery of CO_2's warming properties in 1856 (Foote 1856), the study of greenhouse gases and their influence on Earth's radiative balance has remained a cornerstone of climate sciences. The study of past atmospheric greenhouse gas concentrations drastically improved our understanding of their role in amplifying climate changes that result from variations in incoming solar radiation due to rhythms in Earth's orbit. For example, approximately 40% of the radiative forcing associated with the last glacial termination has been attributed to changes in atmospheric CO_2 and CH_4 (Lorius et al. 1990). Greenhouse gas records from ice cores can also be used in conjunction with reconstructions of global temperature to quantify equilibrium climate sensitivity (i.e. the magnitude of temperature change associated with a given change in greenhouse gas concentration). Future climate projections that aim to quantify the global temperature response to fossil-fuel emissions require accurate estimates of climate sensitivity. If not for the ancient atmosphere encapsulated in ice cores, predicting future climate change would be far more uncertain.

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