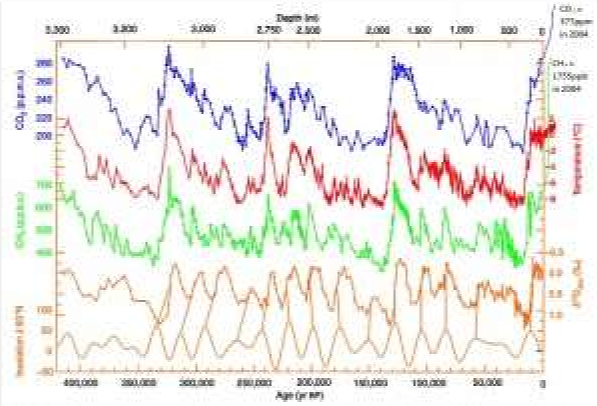
Ice core basics

By Bethan Davies – Last updated 09/01/2015

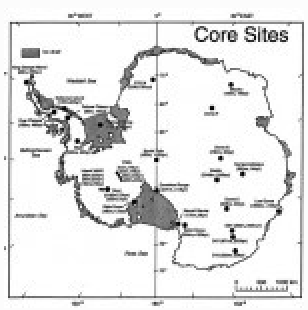
Why use ice cores?



420,000 years of ice core data from Vostok, Antarctica research station. Current period is at right. From bottom to top: * Solar variation at 65°N due to en:Milankovitch cycles (connected to 18O). * 18O isotope of oxygen. * Levels of methane (CH4). * Relative temperature. * Levels of carbon dioxide (CO2). From top to bottom: * Levels of carbon dioxide (CO2). * Relative temperature. * Levels of methane (CH4). * 18O isotope of oxygen. * Solar variation at 65°N due to en:Milankovitch cycles (connected to 18O). Wikimedia Commons.

Ice sheets have one particularly special property. They allow us to go back in time and to sample accumulation, air temperature and air chemistry from another time[1]. Ice core records allow us to generate continuous reconstructions of past climate, going back at least 800,000 years[2]. By looking at past concentrations of greenhouse gasses in layers in ice cores, scientists can calculate how modern amounts of carbon dioxide and methane compare to those of the past, and, essentially, compare past concentrations of greenhouse gasses to temperature.

Ice coring has been around since the 1950s. Ice cores have been drilled in ice sheets worldwide, but notably in Greenland[3] and Antarctica[4, 5]. High rates of snow accumulation provide excellent time resolution, and bubbles in the ice core preserve actual samples of the world's ancient atmosphere[6]. Through analysis of ice cores, scientists learn about glacial-interglacial cycles, changing atmospheric carbon dioxide levels, and climate stability over the last 10,000 years. Many ice cores have been drilled in Antarctica.

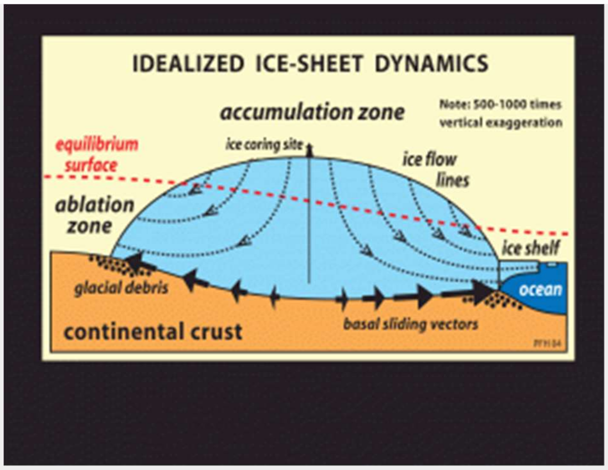


Antarctic ice core drill sites with depth and record duration. From the US ITASE project.

This photograph shows an ice core sample being taken from a drill. Photo by Lonnie Thompson, Byrd Polar Research Centre, Ohio State University. From Wikimedia Commons.

This picture shows a traversing field camp from December 2010. The team were travelling across the West Antarctic Ice Sheet to study snow accumulation. They spent two nights at each site, first collecting radar data and secondly collecting a 15 m shallow ice core. From Wikimedia Commons.

How do ice cores work?



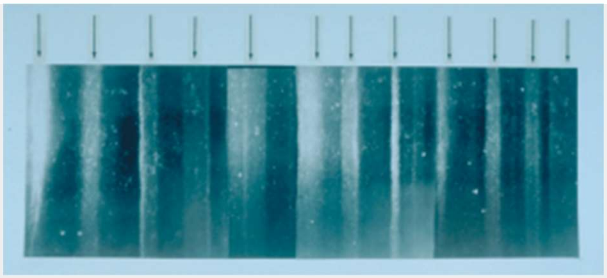
This schematic cross section of an ice sheet shows an ideal drilling site at the centre of the polar plateau near the ice divide, with ice flowing away from the ice divide in all direction. From: [Snowball Earth.]

The large Greenland and Antarctic ice sheets have huge, high plateaux where snow accumulates in an ordered fashion. Slow ice flow at the centre of these ice sheets (near the ice divide) means that the stratigraphy of the snow and ice is preserved. Drilling a vertical hole through this ice involves a serious effort involving many scientists and technicians, and usually involves a static field camp for a prolonged period of time.

Shallow ice cores (100-200 m long) are easier to collect and can cover up to a few hundred years of accumulation, depending on accumulation rates. Deeper cores require more equipment, and the borehole must be filled with drill fluid to keep it open. The drill fluid used is normally a petroleum-derived liquid like kerosene. It must have a suitable freezing point and viscosity. Collecting the deepest ice cores (up to 3000 m) requires a (semi)permanent scientific camp and a long, multi-year campaign[6].

Layers in the ice

If we want to reconstruct past air temperatures, one of the most critical parameters is the age of the ice being analysed. Fortunately, ice cores preserve annual layers, making it simple to date the ice. Seasonal differences in the snow properties create layers – just like rings in trees. Unfortunately, annual layers become harder to see deeper in the ice core. Other ways of dating ice cores include geochemisty, layers of ash (tephra), electrical conductivity, and using numerical flow models to understand age-depth relationships.



This 19 cm long of GISP2 ice core from 1855 m depth shows annual layers in the ice. This section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers. From the US National Oceanic and Atmospheric Administration, Wikimedia Commons.

Although radiometric dating of ice cores has been difficult, Uranium has been used to date the Dome C ice core from Antarctica. Dust is present in ice cores, and it contains Uranium. The decay of ^{238}U to ^{234}U from dust in the ice matrix can be used to provide an additional core chronology[7].

Information from ice cores

Accumulation rate

The thickness of the annual layers in ice cores can be used to derive a precipitation rate (after correcting for thinning by glacier flow). Past precipitation rates are an important palaeoenvironmental indicator, often correlated to climate change, and it's an essential parameter for many past climate studies or numerical glacier simulations.

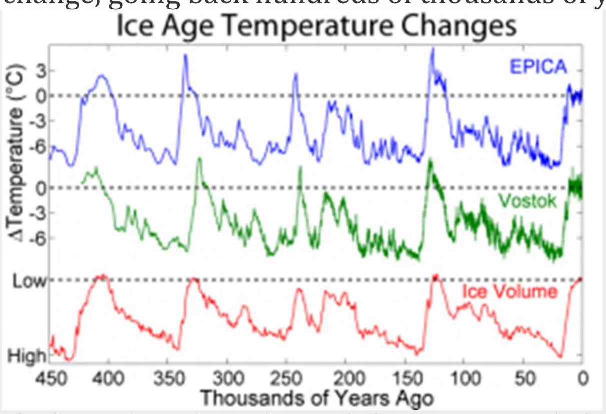
Melt layers

Ice cores provide us with lots of information beyond bubbles of gas in the ice. For example, melt layers are related to summer temperatures. More melt layers indicate warmer summer air temperatures. Melt layers are formed when the surface snow melts, releasing water to percolate down through the snow pack. They form bubble-free ice layers, visible in the ice core. The distribution of melt layers through time is a function of the past climate, and has been used, for example, to show increased melting in the Twentieth Century around the NE Antarctic Peninsula[8].

Past air temperatures

It is possible to discern past air temperatures from ice cores. This can be related directly to concentrations of carbon dioxide, methane and other greenhouse gasses preserved in the ice. Snow precipitation over Antarctica is made mostly of $H_2{}^{16}O$ molecules (99.7%). There are also rarer stable isotopes: $H_2{}^{18}O$ (0.2%) and $HD^{16}O$ (0.03%) (D is Deuterium, or ^2H)[9]. Isotopic concentrations are expressed in per mil δ units (δD and $\delta^{18}O$) with respect to Vienna Standard Mean Ocean Water (V-SMOW). Past precipitation can be used to reconstruct past palaeoclimatic temperatures. δD and $\delta^{18}O$ is related to surface temperature at middle and high latitudes. The relationship is consistent and linear over Antarctica[9].

Snow falls over Antarctica and is slowly converted to ice. Stable isotopes of oxygen (Oxygen [^{16}O, ^{18}O] and hydrogen [D/H]) are trapped in the ice in ice cores. The stable isotopes are measured in ice through a mass spectrometer. Measuring changing concentrations of δD and $\delta^{18}O$ through time in layers through an ice core provides a detailed record of temperature change, going back hundreds of thousands of years.



The figure above shows changes in ice temperature during the last several glacial-interglacial cycles and comparison to changes in global ice volume. The local temperature changes are from two sites in Antarctica and are derived from deuterium isotopic measurements. The bottom plot shows global ice volume derived from δ18O measurements on marine microfossils (benthic foraminifera) from a composite of globally distributed marine sediment cores. From Wikimedia Commons.

An example of using stable isotopes to reconstruct past air temperatures is a shallow ice core drilled in East Antarctica[10]. The presence of a "Little Ice Age", a cooler period ending ~100 to 150 years ago, is contested in Antarctica. Disparate records often provide conflicting evidence. This ice core attempted to investigate the evidence for cooler temperatures during this period.

A 180 m deep ice core from the Ross Sea, Antarctica, was drilled by a team led by Nancy Bertler in 2001/2002[10]. The top 50 m of the ice core was analysed at 2.5 cm resolution using a continuous melting system. Ice core samples were analysed for stable isotope ratios, major ions and trace elements. An age model was extrapolated to the ice core using a firm decompaction model[10]. Deuterium data (δD) were used to reconstruct changes in summer temperature in the McMurdo Dry Valleys over the last 900 years. The study showed that there were three distinct periods: the Medieval Warm Period (1140 to 1287 AD), the Little Ice Age (1288 to 1807 AD) and the Modern Era (1808 to 2000 AD).

These data indicate that surface temperatures were around 2°C cooler during the Little Ice Age[10], with colder sea surface temperatures and possibly increased sea ice extent, stronger katabatic winds and decreased snow accumulation. The area was cooler and stormier.

Past greenhouse gasses

This photograph shows me (Bethan Davies) visiting Nancy Bertler and others in her ice core laboratory at GNS, New Zealand. The ice core is continuously melted and analysed by numerous automatic machines.

The most important property of ice cores is that they are a direct archive of past atmospheric gasses. Air is trapped at the base of the firn layer, and when the compacted snow turns to ice, the air is trapped in bubbles. This transition normally occurs 50-100 m below the surface[6]. The offset between the age of the air and the age of the ice is accounted for with well-understood models of firn densification and gas trapping. The air bubbles are extracted by melting, crushing or grating the ice in a vacuum.

This method provides detailed records of carbon dioxide, methane and nitrous oxide going back over 650,000 years[6]. Ice core records globally agree on these levels, and they match instrumented measurements from the 1950s onwards, confirming their reliability. Carbon dioxide measurements from older ice in Greenland is less reliable, as meltwater layers have elevated carbon dioxide (CO_2 is highly soluble in water). Older records of carbon dioxide are therefore best taken from Antarctic ice cores.
Other complexities in ice core science include thermal diffusion. Prior to becoming trapped in ice, air diffuses to the surface and back. There are two important fractionation processes: thermal diffusion and gravitational settling[11]. Thermal diffusion occurs if the surface is warmer or colder than the bottom boundary (the close-off depth). This temperature gradient occurs from climate change, which affects the surface first. The heavier components of the air (like stable isotopes) also tend to settle down (gravitational settling).

Thermal diffusion and gravitational settling can be measured and analysed because the fractionation of air follows well understood principles and relationships between different stable isotopes (namely, nitrogen and argon).

Other gasses

Other major gases trapped in ice cores (O_2, N_2 and Ar) are also interesting. The stable isotope concentration ($\delta^{18}O$) in ice core records mirrors that of the ocean. Oceanic $\delta^{18}O$ is related to global ice volume. Variations of $\delta^{18}O$ in O_2 in ice core gasses are constant globally, making it a useful chronostratigraphic marker. It's another way to relate ice-core chronologies.

Other ice-core uses

The vertical profile of an ice core gives information on the past surface temperature at that location[6]. In Greenland, glass shard layers from volcanic eruptions (tephra) are preserved in ice cores. The tephra ejected in each volcanic eruption has a unique geochemical signature, and large eruptions projecting tephra high into the atmosphere results in a very wide distribution of ash. These tephra layers are therefore **independent maker horizons**; geochemically identical tephra in two different ice cores indicate a time-synchronous event. They both relate to a single volcanic eruption. Tephra is therefore essential for correlating between ice cores, peat bogs, marine sediment cores, and anywhere else where tephra is preserved[12, 13].

Changes in sea ice concentrations can also be reconstructed from polar ice cores[14]. Ice core records of sea salt concentration reveal patterns of sea ice extent over longer (glacial-interglacial) timescales. Methane sulphonic acid in near-coastal ice cores can be used to reconstruct changes and interannual variability in ice cores.

Mineral dust accumulates in ice cores, and changing concentrations of dust and the source (provenance) of the dust can be used to estimate changes in atmospheric circulation[15]. The two EPICA ice cores (European Project for Ice Coring in Antarctica) contain a mineral dust flux record, showing dust emission changes from the dust source (glacial Patagonia). Changes in the dust emission is related to environmental changes in Patagonia.

Further reading

- IPICS (International Partnerships in Ice Core Sciences)
- Ice cores and climate change (British Antarctic Survey)
- NSIDC: Ice cores in Antarctica and Greenland
- Ice core research at Victoria University of Wellington, New Zealand
- James Ross Island ice core