

Ice core evidence for past climates and glaciation

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Introduction: Ice cores contain an abundance of climate information --more so than any other natural recorder of climate such as tree rings or sediment layers. An ice core from the right site can contain an uninterrupted, detailed climate record extending back hundreds of thousands of years. This record can include temperature, precipitation, chemistry and gas composition of the lower atmosphere, volcanic eruptions, solar variability, sea-surface productivity and a variety of other climate indicators. It is the simultaneity of these properties recorded in the ice that makes ice cores such a powerful tool in palaeoclimate research. (4)

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Long ice cores from Greenland and Antarctica and shorter cores from minor ice caps and glaciers have documented annual and decadal climate change through time. As snow and ice accumulates on polar and alpine ice caps and sheets as a response to winter accumulation and ablation, it lays down a record of the environmental conditions at the time of its formation. Near the glacier surface the winter layer are normally light in colour, while summer layer darker due

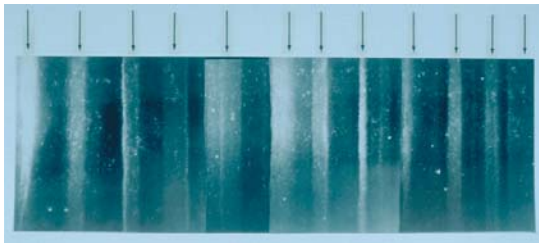


Fig 1. 19 cm long section of GISP2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.

to partial melting and impurities as shown in fig.1. Deeper in the ice mass, however, the annual layers are difficult to detect due to thinning and distortion through pressure from the ice above and flow deformation. Analyses of ice cores from high altitude and high latitudes, where

little or no surface melting takes place during the ablation season, have demonstrated that these contain a great deal of palaeoenvironmental information. For example, annual layer thickness provides information about winter snowfall and degree of melting (determined by summer temperature). Aerosol and dust particles give information about the history of volcanic activity and dust storms in desert regions. Trace gases in the atmosphere are recorded in the composition of carbon dioxide and methane trapped in the englacial air bubbles. Stable isotopes (mainly oxygen isotopes) are proxies for climate change and act as correlation tools between terrestrial and marine records. Natural and artificial radioactive isotopes provide the possibility of dating ice cores. The wide range of data obtained from ice cores therefore makes them one of the most important archives of Late Cenozoic palaeoenvironmental data. (1)

Stable isotope analysis

The basis for palaeoclimatic interpretations of variations in the stable

isotope† content of water molecules is that the vapour pressure of H_2^{16}O is higher than that of H_2^{18}O . Evaporation from a water body thus results in a vapour which is poorer in ^{18}O than the initial water; conversely, the remaining water is enriched in ^{18}O . During condensation, the lower vapour pressure of the H_2^{18}O ensures that it passes more readily into the liquid state than water vapour made up of the lighter oxygen isotope (Dansgaard, 1961). During the poleward transportation of water vapour, such isotope fractionation continues this preferential removal of the heavier isotope, leaving the water vapour increasingly depleted in H_2^{18}O . Because condensation is the result of cooling, the greater the fall in temperature, the lower the heavy isotope concentration will be. Isotope concentration in the condensate can thus be considered as a function of the temperature at which condensation occurs. Water from polar snow will thus be found to be most depleted in H_2^{18}O . This temperature dependency allows the oxygen isotope content of an ice core to provide a proxy climate record. Similar palaeoclimatic studies can be carried out using isotopes of hydrogen (^1H and ^2H (Deuterium)), but these are rarer in nature and the laboratory techniques involved are more complex. (2)

Dating ice cores

One of the biggest problems in any ice core study is determining the age-depth relationship. Many different approaches have been used and it is now clear that fairly accurate time scales can be developed for the last 10,000 years where sufficient snow falls each year to form recognizable annual layers, marked by seasonal variations in physical, chemical, electrical, and isotopic properties. These

can be counted to determine ages. Accuracy can be assessed by comparison to the chemically identified fallout of historically dated volcanoes and in other ways (3)

Prior to that, there is increasing uncertainty about ice age. The problem lies with the fact that the age-depth is highly exponential, and ice flow models (e.g. Dansgaard & Johnson, 1969) are often needed to determine the ages of the deepest sections of ice cores. For example, the upper 1000m of a core may represent 50,000 years, whilst the next 50m may span another 100,000 year time period, due to the severe compaction, deformation and flow of the ice sheet in question. It seems possible to count annual layers into the glacial period (>10,000 years ago) and possibly down to 110,000 years, or for about 90 per cent of the core lengths.

Radio isotope dating†, using ^{210}Pb (lead) (Crozas & Langway, 1966), ^{32}Si (silicon), ^{39}Ar (argon) (Oeschger *et al.*, 1977) and ^{14}C (carbon) (Paterson *et al.*, 1977) have all been used with varying degrees of success, over different time scales, to determine the age of ice cores. (1,2)

Aerosols

Anything in the atmosphere eventually can end up in an ice core. Some materials are reversibly deposited, but most remain in the ice unchanged. The details of the air-snow transfer process are very complex but are being elucidated. Careful statistical and physical analyses are needed to make sense of small, short-lived changes, but large changes in concentrations of most materials in ice reflect changes in their atmospheric loading, with high confidence. Isotopic composition of dust allows “fingerprinting” of source regions.

Major ions provide information on sea salt, continental dust, and biogenic contributions; pollen tracks productivity on land nearby; methane sulfonate responds to oceanic productivity; and other insights are possible. Cosmogenic and extraterrestrial indicators also are of interest for some studies.

Gases

Trapped gases in ice-core bubbles are highly reliable records of atmospheric composition, as shown by intercomparisons among cores from different ice sheets and intercomparison with instrumental records and the air in firn above the bubble-trapping depth. The slight differences between bubble and air composition caused by gravitational and thermal effects are well understood and recognizable. Chemical reactions in impure ice can produce anomalous compositions for some gases. However, the ice chemistry warns of trouble, and the close association of the gas and ice-chemistry anomalies, rather than being offset by the age difference between gas records and ice records of a climate change, is a clear indicator. Methane is of particular interest in studying abrupt changes. It was primarily “swamp gas” in pre-industrial times and thus gives an indication of global wetland area. Methane destruction occurs globally, but sources may be localized. The residence time in the atmosphere is short enough that when methane sources are predominantly in the Northern Hemisphere, Greenland ice shows significantly higher methane concentrations than similar-age samples from the Antarctic; hence, changes in the concentration difference between Greenland and Antarctica record changes

in the latitudinal distribution of methane sources.

Climate records from ice cores

Deep cores from Greenland and Antarctica and shorter cores from minor ice caps and glaciers have documented annual and decadal climate change beyond the last interglacial. The first ice cores were obtained from Camp Century (NW Greenland) in 1966, Dye 3 (south Greenland) in 1981, Renland (east Greenland) in 1988, and from Devon Island (North West Territories) in 1976. On the Antarctic ice sheet, cores were retrieved from Byrd Station (1985), Dome C (1979) and Vostok Station (1985). In the early 1990s, two cores were obtained from the summit of the Greenland ice sheet. The GRIP (Greenland Ice Core Project) reached bedrock at 3029 m in 1992, while the North American GISP2 (Greenland Ice Sheet Project Two) drilled c. 30 km away from the GRIP location, and reached bedrock at a depth of 3053 m in 1993.

The initial interpretation of the GRIP ice core indicated a rapid climate shifts (fig

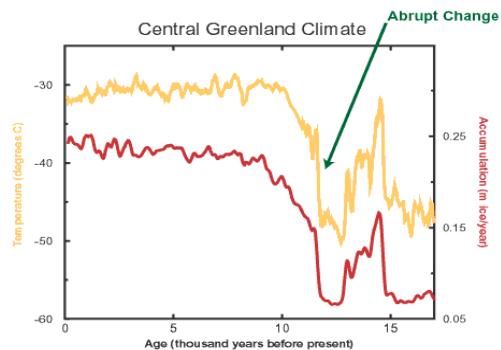


Fig 2. Rapid changes in the past climate shown by the ice cores. The Holocene we live has been the most stable in the last 200,000 years.

2) present during the last ice age that persisted through the previous interglacial (the Eemian, Sangamonian). The GISP2

ice core also showed significant oscillations through the same period. The timing and character of the fluctuations were, however, different. The Greenland records show that climate changes have been very large, rapid, and widespread. Coolings were achieved in a series of steep ramps or steps and warmings in single steps. The more dramatic of the warmings have involved 8°C warming and 2X increases in snow accumulation, several-fold or larger drops in windblown materials, and 50% increase in methane, indicating large changes in global wetland area. Between 80,000 and 20,000 yr BP, some 20 interstadial events are recorded. These so-called Dansgaard-Oeschger events lasted for about 500-2000 years and therefore cannot be explained by orbital forcing mechanisms. Instead, they are interpreted to reflect feedback mechanisms involving ice sheet/glacier fluctuations, variations in the ocean system and atmospheric circulation fluctuation. (1,3)

The completion of the ice drilling at the Vostok station in east Antarctica in January 1998 (length of ice core 3623 m) has allowed the extension of the ice core record of atmospheric composition and climate to the past four glacial-interglacial cycles. The records from the Vostok ice core indicate that climate, within certain bounds, has almost always been in a state of changes for the last 420,000 years (fig 4). Features of the last glacial-interglacial cycle are also seen in previous cycles. During each of the last four glacial terminations, properties change in the following sequence: the temperature and atmospheric concentrations of CO₂ and CH₄ rise steadily, whereas the dust input decreases. During the last half of the temperature rise, CH₄ increases rapidly.

The results from the Vostok ice core suggest climate forcing from orbital parameters followed by greenhouse gases and an albedo effect. The temperatures in Antarctica were higher during interglacial 5.5 and 9.3 than during the Holocene or interglacial 7.5. (1)

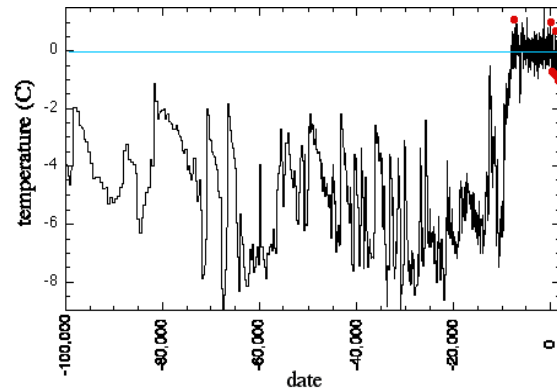


Fig 3. Greenlandic ice core record.

The ice-core record of abrupt climate changes is clearest in Greenland. (fig 3) Several of these variations have also been identified in deep-sea sediments from the North Atlantic. No other record is available that spans the same time interval with equally high time resolution, complicating interpretations. It appears, however, that ice cores from the Canadian arctic islands, high mountains in South America, and Antarctica contain indications of the abrupt changes. Dating is secure for some of the Antarctic cores. The Canadian arctic cores show a sharp cold reversal during the deglaciation that is probably the Younger Dryas event. Ice cores from the high peaks of Huascaran and Sajama in the Andes also show a deglacial reversal in the ice isotopes that may be correlative with the Younger Dryas. However, for various reasons, the exact timing and abruptness of the changes are difficult to ascertain in these records, and records of older abrupt changes are even less secure. (3)

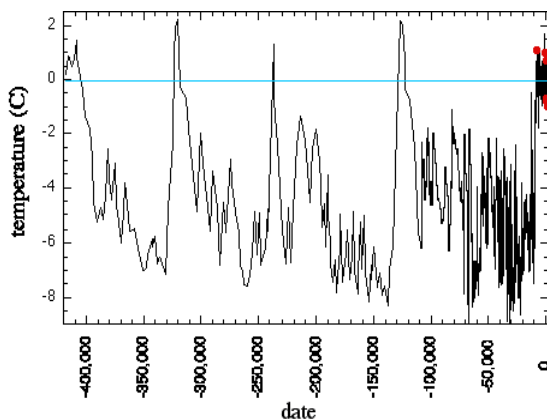


Fig 4. Ice core from Vostok, Antarctica, showing abrupt climate changing spanning the last 400,000 years.

The question still remains, what are the causes of this abrupt climate changes? Deep ocean currents are important components of the planetary meridional heat transport. Commonly known as the "thermohaline circulation," these currents are driven by the sinking of cold water in the North Atlantic Ocean and as shown by gas bubbles trapped in the ice cores that this thermohaline circulations can slowdown or completely shut-down causing great effects on the climate.

The greenhouse gases, especially CO₂, N₂O and CH₄, have shown variations which parallel past global average temperatures, and closely reproduce the glacial/interglacial cycles and probably related to the ocean chemistry (CO₂), the extension of wetlands (CH₄), and the

Pictures

Fig 3,4 http://muller.lbl.gov/pages/IceAgeBook/history_of_climate.html

Fig 1. <http://www.ngdc.noaa.gov/paleo/icecore/greenland/summit/document/gripinfo.htm>

marine biological activity (N₂O). Other causes are related the albedo feedback of solar radiation, volcanic eruptions releasing aerosol to the atmosphere and major effects as the Milankovitch orbital cyclisity. (6,7)

The mechanisms of these relationships are poorly understood (7), and it is not known with any certainty which is the drag force of a climate change, especially when talking about an abrupt climate change as testified by the ice cores.

References

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