I

ICE CORE METHODS

Contents

Overview

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Introduction

Cores through the polar ice sheets provide a remarkable record of past environmental conditions, on time scales of thousands of millennia to the last few decades. Ice-core records are unique in paleoclimatology, primarily because of very high ice accumulation rates (providing excellent time resolution), the preservation of multiple proxies of past environmental conditions, and the fact that small samples of the ancient atmosphere are entombed in bubbles.

Ice coring evolved as a science in the 1950s and 1960s (*see* History of Research, Greenland and Antarctica) through the pioneering efforts of scientists from several nations, and is now conducted by a variety of national and international research teams, in the Arctic, Antarctic, and glaciated mountain regions of the world. Existing ice-core data inform us about human impacts on the polar regions and the global atmosphere, the long march of glacial-interglacial climate changes over the last 800,000 years, and provide spectacular, if only partly understood, data about abrupt climate change during the last ice age and the stability of climate over the last 10,000 years. Future ice cores will take the records further back in time, and also provide more detailed spatio-temporal information about the evolution of climate and environmental change. Summaries of a number of specific areas of ice-core research are provided (*see* History of Research, Greenland and Antarctica–Africa).

Ice-Core Basics

Snow accumulating on the polar plateaus of Antarctic and Greenland, and at high elevations in lower latitude mountain regions, accumulates in a regularly ordered fashion that preserves a stratigraphic sequence accessible by drilling vertical borings in the ice. Collecting these cores is a specialized engineering challenge. The drilling equipment used for ice coring was developed in the late 1950s/early 1960s, and has continuously improved since (*see* History of Research, Greenland and Antarctica). Because ice is a deformable material, and flows, ice coring locations must be chosen carefully to extract the most reliable paleoclimate information. The best drilling sites are generally on or near ice divides (**Fig. 1**), where ice deposited at or near the same elevation as the current surface elevation can be obtained, and the distortion of the age versus depth curve due to thinning can be reliably modeled.

Ice cores of various lengths are collected for different purposes. Shallow cores (generally less than 100–200 m) can be collected relatively easily with

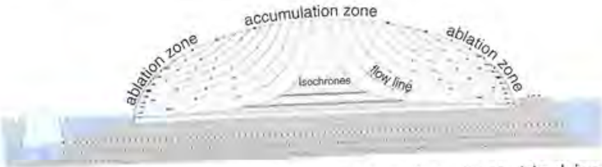

Figure 1 Schematic cross-section of an ice sheet. Ideal ice-core drilling sites are at or near the 'ice divide' at the center of the ice sheet where a core recovers ice deposited at approximately the same location on the surface.

lightweight equipment and generally cover a few hundred years of history, depending on accumulation rates. Networks of shallow cores have been collected to study spatial variations in climate on these time scales (for example, the Program for Arctic Regional Climate Assessment (PARCA) and International Trans-Antarctic Scientific Expedition (ITASE) programs in Greenland and Antarctica, respectively). Deeper cores require larger equipment, and fluid-filled boreholes to avoid collapse of the hole. Drilling fluids are typically petroleum-derived fluids like refined kerosene, but other organic liquids (for example butyl acetate) have been used. The physical characteristics of the fluid, particularly freezing point and viscosity (and viscosity-temperature characteristics) are critical parameters and can make choosing appropriate fluids a challenge. The fluid filled hole also provides access for measuring ice sheet temperature profiles, useful for paleothermometry (*see* Borehole Temperature Records). The deepest cores (>3,000 m) in Greenland and Antarctica are collected during multi-year campaigns from temporary or permanent scientific camps.

Perhaps the most unique aspect of ice cores is that they trap ancient atmosphere when surface snowfall compacts to ice. This happens at the base of the firn, or unconsolidated snow layer, typically 50–100 m below the surface in polar regions, and shallower at high accumulation sites with warmer temperatures (*see* CO_2 Studies, Methane Studies, Thermal Diffusion Paleotemperature Records, Correlations Between Greenland and Antarctica).

Ice-Core Chronology

Accurate chronology is obviously key to using ice core records to study past environmental changes, particularly to compare features of ice-core records with data from other locations (*see* Historical Climatology). Counting of annual layers is the most powerful and well-known technique, but a variety of other methods are employed.

The most accurate chronologies are established by annual layer counting (*see* Chronologies). Annual layering can be discerned visually due to seasonal

Figure 2 Annual layers in the GISP2 ice core. This section of ice core is approximately 30 cm long. The horizontal line is the edge of a plastic sample tray.

variations in snow properties (Fig. 2), but annual signals are also present in a variety of geochemical parameters, including stable isotopes, electrical conductivity, and a variety of soluble chemical species. Recent work uses several of these parameters at the same time to construct chronologies.

Annual layers are not discernable at all sites, and thinning makes them difficult to discern in older sections of deep ice cores. In many cases, other techniques are needed to establish ages of deep ice cores.

Radiometric dating of ice has so far not been very successful. A number of isotopic systems have been investigated for this purpose but low levels of the radioactive species in question have hampered progress. Improvements in analytical techniques may change this situation in the future and a robust radiometric dating technique for ice is highly desirable.

Another common strategy is to use the well-understood physics of ice flow and thinning to estimate the depth-age relationship for an ice core (*see* Chronologies). Such estimates can be checked or constrained by assuming the ages of key climate transitions (e.g., example glacial-interglacial transitions) recorded in ice-core isotope (or other) records can be correlated to chronologies of ocean sediment records. The deepest Antarctic records have been dated in this way (EPICA Community Members, 2004).

Gas records in ice cores also provide dating techniques. One approach is to use globally synchronous variations in trapped atmospheric gases as tools to create precise relative chronologies between ice-core records (*see* Correlations Between Greenland and Antarctica) (Bender *et al.*, 1994; Blunier and Brook, 2001). This allows two ice cores (e.g., one in Greenland, another in Antarctica) to be placed on common chronologies, allowing precise comparisons between them. The isotopic composition of atmospheric oxygen in the ice-core record can also be correlated with the marine isotope record and its established chronology (Sowers *et al.*, 1993). More recently, Bender (2002) showed that the O_2/N_2 ratio of trapped air in the Vostok ice core varies in a way that appears to be coherent with insolation variations on time scales associated with orbital precession, which may allow O_2/N_2 records to be tuned to the timing of precession (*see* Chronologies).

Correlation of various parameters in ice cores to a variety of other independently dated records can also assist in creating ice-core chronologies. Variations in cosmogenic isotopes (e.g., ^{10}Be) in ice cores can be correlated to well-dated oscillations in the tree-ring ^{14}C record (Taylor *et al.*, 2004). Stable isotope records from cave deposits (*see* Speleothems) are dated accurately using U-series dating (*see* U-Series Dating) and show variations that are apparently synchronous with fluctuations in Greenland ice-core records (Wang *et al.*, 2001). Peaks in volcanic sulfate in ice cores can be correlated to dates of historically known volcanic eruptions, providing an extremely important check on layer counting chronologies (Meese *et al.*, 1994).

Proxy and Other Measurements in Ice Cores

A variety of chemical and physical measurements are performed on ice-core samples, intended to infer various aspects of past environmental conditions. Some of the more notable environmental 'proxies' are reviewed briefly below. Space limitations prevent mention of all areas of study, and the reader is referred to other sections of the Encyclopedia for more detailed information.

Visual Stratigraphy and other Physical Measurements

The thickness of annual layers provides a first-order record of snowfall variations (**Fig. 2**), after corrections for thinning due to glacier flow, which can be made fairly accurately in many situations (Cuffey and Clow, 1997). Past precipitation rates are an extremely important paleoenvironmental parameter and often correlated with temperature in polar regions. Layer counting is laborious, but extremely informative. New techniques combine visual stratigraphy with seasonal variations in other parameters to provide multi-parameter dating and accumulation-rate estimates, and algorithms are being developed to automatically count annual layers in some of these variables (Taylor *et al.*, 2004).

The distribution of summer melt layers in ice cores is another visual measurement that provides climate information (more melt layers associated with warmer summer temperatures) (Alley and Anandakrishnan, 1995). Melt layers are formed when surface snow melts and the meltwater percolates into the snowpack. in a layer at shallow depth, probably along high-density snow surfaces. Melt layers are visible as bubble-free ice layers, and their distribution can be counted as a function of time.

Other physical properties of the ice accessible by visual observation or basic physical measurements include the orientation and size of ice crystals, size and distribution of bubbles, disappearance of bubbles as clathrate forms at depth, and ice density. Careful measurements of these properties provide a context for interpreting climate records and understanding stratigraphic discontinuities, anomalous ice flow, and ice-sheet dynamics in general (Gow *et al.*, 1997).

Stable Isotopes

The stable isotopic composition of ice ($\delta^{18}O$ and δD) have long been used as paleotemperature indicators (*see* Stable isotopes), with original work on this subject in the 1960s and 1970s (*see* Stable isotopes, Greenland Stable Isotopes, Antarctic Stable Isotopes). The temperature dependence of the isotope ratios arises due to fractionation during transport from moisture source to the ice-core site. In detail the processes involved are complex (*see* Stable isotopes) but the basic concept is that cooler temperatures allow a greater isotopic 'distillation' as moisture travels to the ice-core site. Measurements of isotope ratios in high latitude precipitation show the expected trend of lighter ratios with lower temperature. The modern relationship can be used to calculate past temperature change from ice-core isotope records, but numerous recent studies employing borehole temperatures and nitrogen and argon isotopes show that the modern 'spatial' slope is probably not always appropriate for past conditions (*see* Borehole Temperature Records). These studies suggest that in Greenland, past isotope variations have a greater sensitivity to temperature change than indicated by the spatial slope (Severinghaus and Brook, 1999), but in Antarctica the spatial and temporal sensitivities appear to be similar (*see* Antarctic Stable Isotopes).

The ratios $\delta^{18}O$ and δD have been measured somewhat interchangeably in the history of ice-core research (*see* Stable isotopes). There are small differences between them, though, expressed as a parameter called 'deuterium excess'. Deuterium excess is discussed more completely (*see* Stable isotopes). Its primary use is as a monitor of conditions (primarily temperature) at the moisture source.

This is important for understanding the impact of moisture source changes on the isotope-temperature calibration, as well as low latitude climate change.

In contrast to the polar regions, the systematics of isotope records in mid- and tropical latitudes is more complex, and inferences of temperature change are more difficult. These records are discussed in more detail (*see* South America, Chinese, Tibetan Mountains, Africa).

Greenhouse and Biogenic Gases

The most unique aspect of ice-core records is the archive of ancient atmosphere that they provide (*see* Chronologies, Thermal Diffusion Paleotemperature Records, CO_2 Studies, Methane Studies, Correlations Between Greenland and Antarctica). Air is trapped at the base of the firn layer where compacting snow finally turns to ice, and trapped air is present in small bubbles (**Fig. 3**).

The depth of this transition varies with temperature and accumulation rate but is ~50–100 m below the surface at polar sites. For this reason there is an offset between the age of the air and the age of the ice (*see* Chronologies, Thermal Diffusion Paleotemperature Records, CO_2 Studies, Methane Studies, Correlations Between Greenland and Antarctica), which is accounted for with glaciological models of firn densification and gas trapping. Air in bubbles is extracted by melting, crushing, or grating ice in a vacuum. Dry techniques of crushing or grating are required for some gases, such as carbon dioxide.

Detailed records of the three main biogenic greenhouse gases, carbon dioxide, methane, and nitrous oxide, are available from ice cores from Greenland and Antarctica. These records cover time periods as recent as the rise of the levels of these gases over the last few centuries to long term glacial–interglacial cycles going back over 650,000 years. The overall reliability of the gas records can be demonstrated by the overlap of ice-core records with instrumental measurements that started in the 1950s, and agreement between ice cores from different locations. Analytical or preservation artifacts affect these data in some cases, but are fairly well recognized. Early carbon dioxide records from Greenland are compromised by melt layers, which have elevated carbon dioxide levels because of the high solubility of carbon dioxide in water. As a result, only carbon dioxide records from colder locations in Antarctica are deemed reliable. Methane records do not suffer from this problem, but very occasionally high levels are found in basal ice from ice cores, possibly related to the presence of microbes (*see* Biological Material) associated with particle rich layers (Tung *et al.*, 2005). Nitrous oxide has proved somewhat more problematic. Elevated levels of nitrous oxide are associated with elevated dust levels in several ice cores (Sowers, 2001; Spahni *et al.*, 2005) and the controls on these elevated levels are not completely understood. Nonetheless, in some cases, reliable data can apparently be obtained by selecting samples with low particulate concentrations (Sphani *et al.*, 2005).

More recent work expands this field by using the stable isotopic composition of the three major biogenic gases to constrain sources and sinks (Sowers *et al.*, 2003; Ferretti *et al.*, 2005; Indermuhle *et al.*, 2000; Smith *et al.*, 1999) and by investigating the possibility of reconstructing levels of rarer gases that are important components of global biogeochemical cycles, for example carbonyl sulfide, methyl bromide, and methyl chloride (Aydin *et al.*, 2004; Montzka *et al.*, 2004; Saltzman *et al.*, 2004).

Finally, trace gas records from firn air deserve to be mentioned. The firn is the unconsolidated snow pack. Gas diffusion in the firn is sufficiently slow that firn contains air with a mixture of ages that increases in age with depth. The significance of this is that large volumes of air can be pumped from the firn for measurements that would otherwise be impossible with traditional ice samples (Montzka and Edkins, 2004).

N, O Ar, and other Noble Gases

Although greenhouse gas records from ice cores receive attention with respect to the modern global warming problem, equally interesting paleoenvironmental information is available from the major gases in air trapped in ice (O_2, N_2, and Ar), other noble gases, and the isotopes of these gases.

Figure 3 Air bubbles in a thin section of ice from ~140 m depth at the GISP2 ice coring site in Greenland.

Atmospheric O_2 is important in ice-core records because its stable isotopic composition ($\delta^{18}O$) is slaved to that of the ocean through global photosynthesis and respiration. Ocean $\delta^{18}O$ varies as the ice sheets grow and shrink through glacial–interglacial cycles (*see* Oxygen Isotopic Composition of Seawater). The turnover time of O_2 in the ocean-atmosphere system is long with respect to the atmospheric mixing time, so $\delta^{18}O$ of O_2 variations are synchronous everywhere on the Earth, providing stratigraphic markers for ice-core chronologies (Bender *et al.*, 1994).

The isotopic composition of nitrogen ($\delta^{15}N$ of N_2) is influenced by gravitational fractionation in the firn, and can be used to correct other isotopes for this fractionation (atmospheric $\delta^{15}N$ of N_2 is thought to be constant on million-year timescales). More importantly, nitrogen and argon isotope ratios have also been used together as paleothermometers, taking advantage of a phenomenon known as thermal diffusion, which causes fractionation in a temperature gradient (*see* Thermal Diffusion Paleotemperature Records). Together, nitrogen and argon data can be used to deconvolve gravitational and thermal signals, and calculate the magnitude of temperature change associated with fast changes in climate recorded in ice-core records (Severinghaus *et al.*, 1998; Severinghaus and Brook, 1999; Grachev *et al.*, 2003), providing an important independent paleothermometer.

These gases also have other uses. Ratios of O_2, N_2, Ar, Xe, and Kr provide important information about gas loss during bubble close-off or storage (Severinghaus and Battle, 2006) (because of size dependence of loss processes), and the possible influence of melting on the gas content of ice samples (because of differences in solubility). Studies of these gases in firn air provide an insight into processes that transport air in the firn and their significance to interpreting the ice-core record (Kawamura *et al.*, 2006).

Borehole Temperatures

The vertical temperature profile of an ice sheet can contain information about the past surface temperature history. Borehole temperature profiles are measured by suspending temperature sensors in fluid-filled boreholes and recording temperature as a function of depth using highly accurate and precise instrumentation. This is an important area of study because it can provide independent estimates of temperature change that complement the stable isotopes of oxygen and hydrogen in ice and the nitrogen and argon isotopic work described above. The basic idea is that the ice sheet 'remembers' past surface temperature changes because these propagate through the ice due to heat transport (*see* Borehole Temperature Records). If heat transport properties of the ice are known, and the geothermal heat flux is known, the temperature profile can be inverted to provide a record of surface temperature change that is independent of proxy calibration. Analogous work is done with continental boreholes to measure warming trends over the past few centuries. Such records are smoothed representations of more abrupt changes due to the nature of heat transport, but provide extremely important information, for example, the first estimate of very large glacial–interglacial temperature change in Greenland, revealing problems with the stable isotope thermometer (Cuffey *et al.*, 1995).

Glaciochemistry

The chemical composition of ice-core samples provides information about past changes in atmospheric circulation, dust loading, volcanic eruptions, biological activity, human impact on the environment, and a wealth of other information. In general, this area of research includes measurements of soluble species (those released to solution when ice samples are melted), as opposed to studies of insoluble particles (below). The distinction between soluble species and very small particles is operational but not significant for the purposes of this discussion.

Chemical measurements at a variety of sites reveal the human impact on the atmosphere. For example, records of lead concentration in Greenland ice (Fig. 4) reveal the large impact of industrial lead, and show how it has changed with regulation of leaded gasoline and other global political-environmental changes (McConnell *et al.*, 2002). Many other pollutant species are also present in the ice.

On longer timescales, soluble chemistry records the impacts of major volcanic eruptions through peaks in volcanic sulfate deposition. These data provide information about the frequency of eruptions, the climate impact of large volcanic eruptions, and when the age of the eruption event is known (Zielinski *et al.*, 1994) they provide independent tests of ice-core chronology.

The major ion chemistry of ice cores is useful in a more general way as a tracer of the input of chemical species from continental dust, sea salt, and biogenic processes. For example, calcium concentrations are believed to largely reflect the dustiness of the atmosphere, and sodium and chloride are largely derived from the ocean concentrations may reflect the proximity to open water (which may change as climate changes), other aspects of meteorology that influence the transport of marine air to ice-core sites, or more

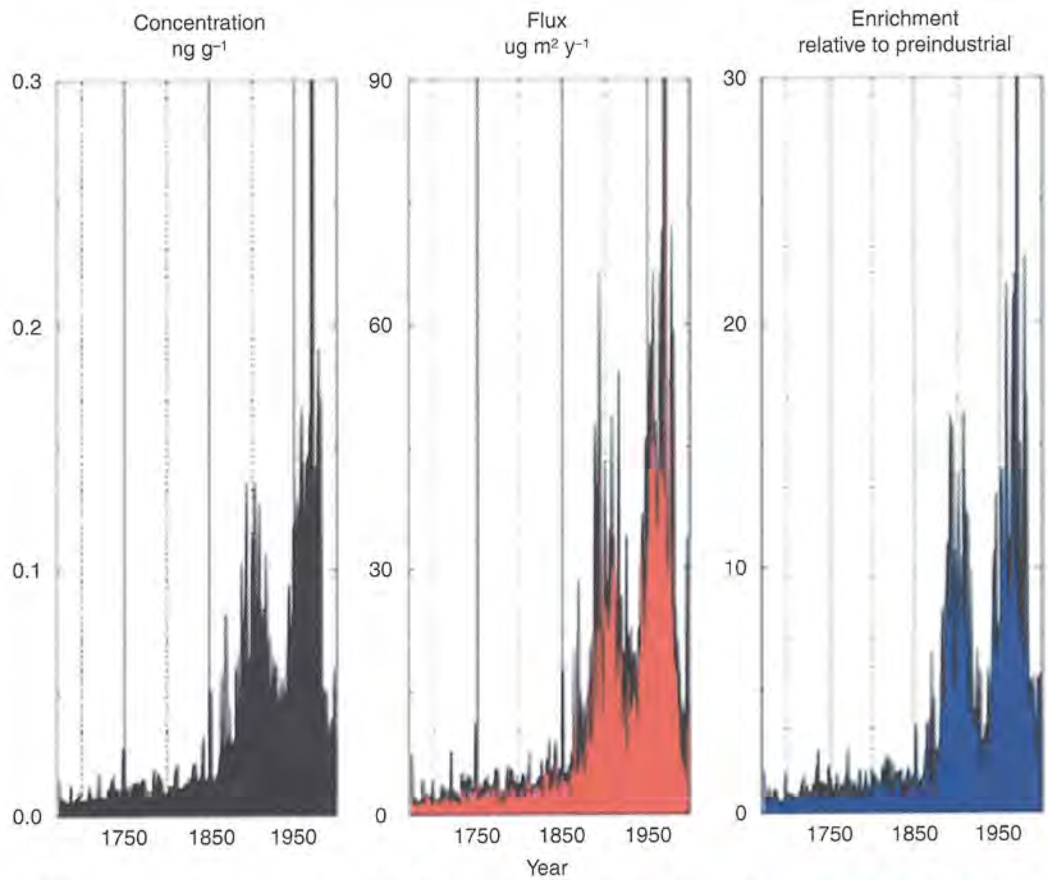

Figure 4 A 330-year continuous ice-core record of Pb concentration, flux, and relative enrichment at the D5 ice core site (68.5°N, 42.9°W) in west central Greenland. (*see* Microparticle and Trace Element Studies).

complex processes related to behavior of salts on sea ice surfaces (Rankine *et al.*, 2002). Major ions commonly measured in ice include Na^+, Mg^{2+}, Ca^{2+}, K^+, NH_4^+, Cl^-, NO_3^-, SO_4^{2-}, and organic acids like methylsulfonate, CH3SO$^-$. Multivariate statistical analysis has been used to attempt to describe the relationship between the deposition of these species and meteorological parameters (*see* Glaciochemistry). Many of these species are measured by ion chromatography using continuous melter systems that provide a continuous sample stream, creating very high-resolution data sets.

More recently, the advent of high sensitivity ICP Mass Spectrometers has opened a new window in glaciochemistry, allowing measurements of many trace species in ice at unprecedented resolution (McConnell *et al.*, 2002).

Insoluble Particles

The insoluble particulate content of ice cores includes mineral dust, volcanic ash, and extraterrestrial material (discussed below), and potentially contains important information about the dustiness of the atmosphere in past times, and through particle size distribution, possibly information about past wind speed (*see* Microparticle and Trace Element Studies). Particle abundances in most ice cores are very low and optical or electrical sensing methods on solid or liquid samples have been used to produce continuous or semi-continuous records of particle numbers and sizes. Bulk dust data generally reflect strong glacial–interglacial cycles, with higher levels of dust in cold glacial periods. For example, a recent long dust record from the East Antarctic EPICA Dome C core clearly shows glacial–interglacial dust cycles (**Fig. 5**). The amplitude of the cycles is too large to be explained by changes in ice accumulation rate alone, implicating a dustier, drier atmosphere, or changes in atmospheric circulation patterns that bring dust to this high latitude site.

The chemical and isotopic composition of insoluble dust can provide important information about the source of dust to remote ice-coring sites (*see* Microparticle and Trace Element Studies). This work is difficult because of the low levels of dust involved and the sample size requirements for some of the techniques. Isotopic fingerprinting using lead,

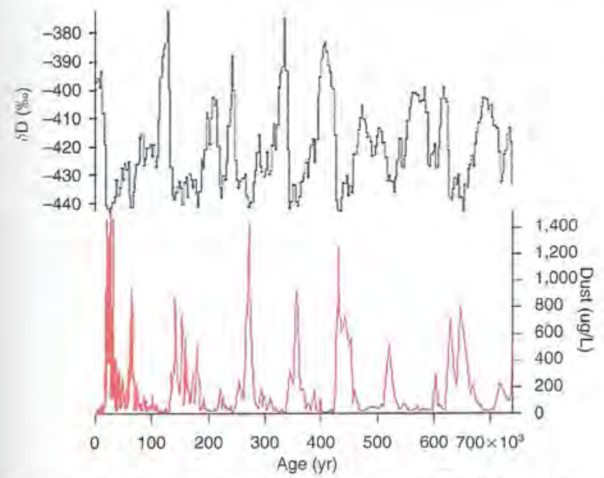

Figure 5 The dust and δD records from the EPICA Dome C ice core in Antarctica (EPICA Project Members (2004)).

strontium, and neodymium isotope ratios suggests, for example, that most dust at central Greenland sites is derived from low latitude regions of east Asia (Biscaye *et al.*, 1997) and that the dust in east Antarctica originates mainly from the Patagonian region of South America, with possible contributions from other areas. (Delmonte *et al.*, 2004).

Particles of volcanic origin (glass shards or tephra) can sometimes be specifically identified in ice-core samples, providing a history of volcanic activity, and in some cases datable time horizons useful for ice-core chronology.

Cosmogenic Isotopes and Extraterrestrial Material

Ice cores contain several kinds of information about extraterrestrial phenomena. Cosmogenic isotopes (produced by cosmic rays) produced in the atmosphere are deposited on the ice sheet, providing a record of the processes that produce and modulate the cosmic ray flux, and influence their deposition rates. ^{10}Be (half life 1.5×10^6 years) and ^{36}Cl (3.0×10^5 years) are the most commonly measured cosmogenic isotopes in ice. ^{10}Be data record the influence of a geomagnetic excursion (the Laschamp Excursion) around 41,000 years ago, and detailed records show variations related to the modulating effects of the solar wind on cosmic ray flux at high latitudes (Finkel and Nishiizumi, 1997). In addition to revealing modulating effects, these features provide chronological ties that can be used to correlate ice cores and constrain ice chronologies. These data have relevance beyond ice-core studies because of the significant influence of these modulation processes on the production of radiocarbon in the atmosphere and resulting implications for the radiocarbon time scale. ^{10}Be data have also been used as accumulation rate constraints, assuming a constant ^{10}Be flux (Steig *et al.*, 1998; Raisbeck *et al.*, 1987), although in detail this assumption may not be correct.

Ice cores also contain meteoritic material, albeit in small quantities given, the limited sample availability. Micrometeorites have been extracted from large surface samples of melted snow and ice for some time, but given the limited size of ice samples this type of work is not practical for deep ice cores. Isotopic and elemental measurements of species enriched in meteoritic material, including iridium (Gabrielli *et al.*, 2004, Karner *et al.*, 2003) and ^{3}He (Brook *et al.*, 2001), can be used as tracers to examine possible changes in the flux of extraterrestrial dust to the Earth, although this field is in its infancy.

Biological Material in Ice

Although the existence of life in harsh environments has been a topic of research for some time, studies of life in ice have flourished in the last decade or so and are described in more detail (*see* Biological Material). This work is difficult due to potential contamination issues and low levels of biological material preserved in ice. Current attention focuses on the possible viability of microorganisms in ice, characterization and preservation of ancient DNA and RNA, preservation of fungi, spores, and other organisms, and implications for life in subglacial lakes and in ice on other planets. A recent book on this topic (Castello and Rogers, 2005) provides a detailed picture of the status of this field.

Major Highlights of Ice-Core Research

This section is a brief review of some of the major patterns and findings of ice-core research. Space limits this review to a few key issues – the remainder of the ice-core section of the Encyclopedia provides much more relevant detail.

Glacial–Interglacial Cycles

Deep ice cores from Antarctica are the only ice-core records to penetrate beyond the end of the last interglacial period (*see* History of Research, Greenland and Antarctica, Antarctic Stable Isotopes). In Greenland there are tantalizing hints of this penultimate interglacial (*see* History of Research, Greenland and Antarctica, Greenland Stable Isotopes) near the base of the ice sheet but no complete sections have yet been obtained. Until recently, the oldest Antarctic record was that of the east Antarctic core from Vostok station, extending back through four glacial–interglacial cycles to ~440,000 years BP (Petit *et al.*, 1999).

A new ice core on Dome C drilled by the European Program for Ice Coring in Antarctica (EPICA) collaboration recovered a core with at least 720,000 years of interpretable record, and perhaps slightly more, almost doubling the Vostok achievement (EPICA Community Members, 2004). Records from EPICA Dome C (**Fig. 6**) clearly show the strong 100,000 year cyclicity in climate well-known from marine sediments (*see* Antarctic Stable Isotopes), and show that the oldest two cycles have lower amplitude than the younger ones. Some of the major achievements of this drilling program are the complementary carbon dioxide, methane, and nitrous oxide records (Spahni *et al.*, 2005; Siegenthaler *et al.*, 2005), which clearly show how closely the concentrations of these gases follow Antarctic climate patterns (*see* CO_2 Studies, Methane Studies) and how unusual the modern values of these gases are, viewed in the context of over 650,000 years of Earth history.

The relationship between the gas records, particularly carbon dioxide, and Antarctic and global temperatures is a subject of intense research, and has been so since the original publication of long Antarctic carbon dioxide records in the 1980s (*see* CO_2 Studies). One major question concerns the timing of carbon dioxide and temperature change on these timescales. Most studies of this issue have concluded that there is a lag of several hundred to several thousand years between temperature change and carbon dioxide change (temperature leads carbon dioxide), suggesting that warming, triggered by other factors, causes a

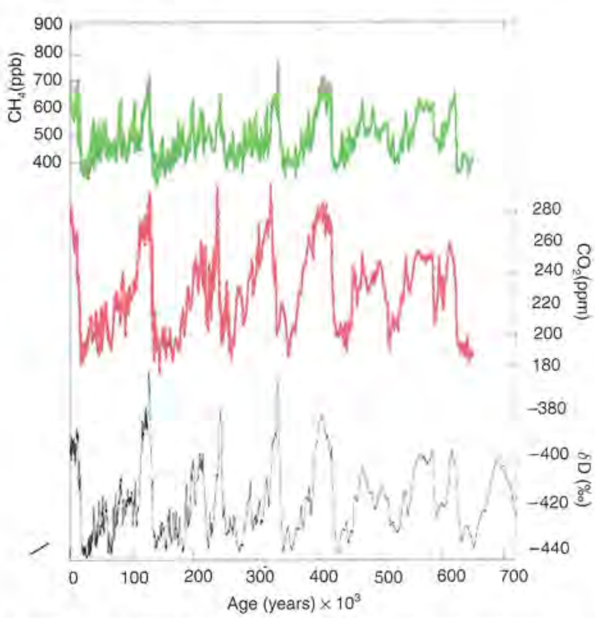

Figure 6 Composite records of atmospheric carbon dioxide and methane from the EPICA Dome C, Vostok, and Taylor Dome ice cores in Antarctica (Siegenthaler *et al.*, 2005; Spahni *et al.*, 2005) and the δD record from EPICA Project Members (2004).

change in the carbon cycle that increases carbon dioxide, which is then a positive feedback on warming (*see* CO_2 Studies). Another major question concerns the ultimate cause of the carbon dioxide variations. It is widely believed that they are caused by changes in the ocean carbon cycle, either due to changes in partitioning of carbon between the deep and surface ocean due to changes in ocean circulation, or changes in biological productivity that transfer carbon from the surface to the deep ocean (Sigman and Boyle, 2001). Despite several decades of work, the ultimate cause of the carbon dioxide cycles is still elusive.

Abrupt change, the last ice age, and the Holocene

In contrast to the march of long-term climate cycles seen in the longest Antarctic ice cores, cores from central Greenland have revealed a remarkable pattern of more rapid climate change during the last ice age (*see* Greenland Stable Isotopes, Correlations Between Greenland and Antarctica, Sub-Milankovitch (DO/Heinrich) Events) (**Fig. 7**). This more abrupt style of climate change is often referred to as millennial-scale climate change, although the abrupt warmings and coolings in the Greenland records are just specific examples of change on this timescale.

Although the first deep ice cores drilled in Greenland showed these abrupt climate shifts, it was not until the recovery of the parallel GRIP and GISP2 ice cores from central Greenland in the early 1990s (*see* History of Research, Greenland and Antarctica, Greenland Stable Isotopes) that the significance of these abrupt shifts was more widely recognized outside.

The stable isotope records from central Greenland deep cores (**Fig. 7**) show a sequence of more than 20 abrupt warming and cooling events during the last ice age (from ~120,000 to 10,000 years ago). These events, called Dansgaard–Oeschger events after their discoverers, Hans Oeschger and Willi Dansgaard, are remarkable for their frequency, size, and abruptness. Detailed study of the isotopic variations and associated changes in layer thickness indicate that the cold-warm transitions are very abrupt (changes in mean accumulation rate take place over decades or less; Alley *et al.*, 1993), and represent large temperature changes (~10–15 degrees). These observations have lead to a large amount of research dedicated to understanding the causes of abrupt climate change, their manifestation in other parts of the world, and the possibility of their recurrence in the future (*see* Sub-Milankovitch (DO/Heinrich) Events).

An intriguing aspect of millennial-scale climate change is that Antarctic ice cores do not record a

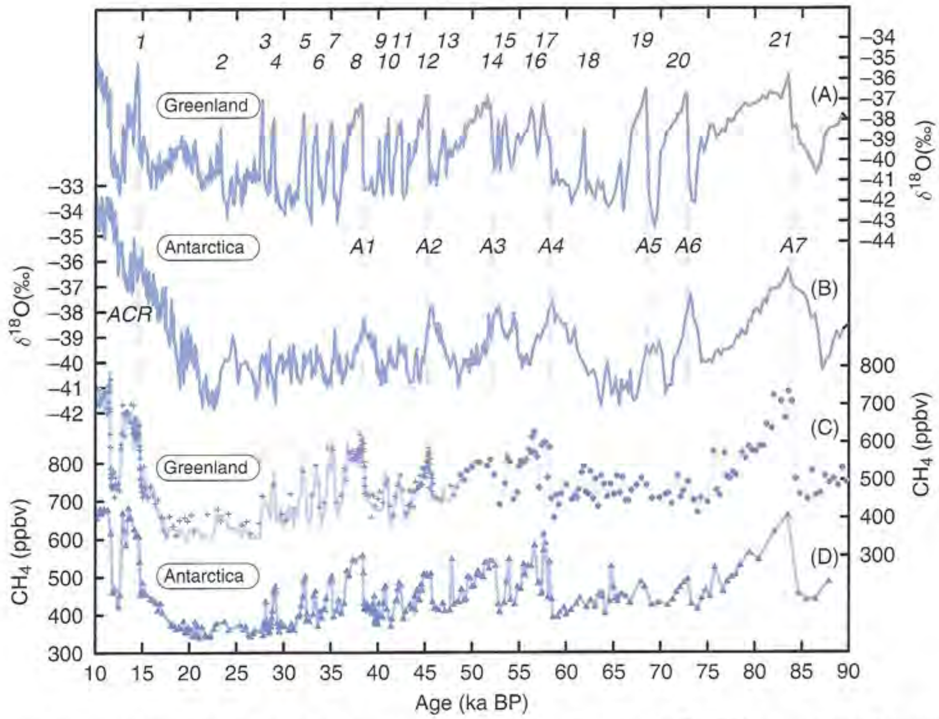

Figure 7 Records of millennial scale variations in stable isotope records from Greenland (GISP2 ice core) and Antarctica (Byrd ice core) from Blunier, T., and Brook, E. J. (2001). Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science* **291**, 109–112, EPICA community-members. 2004. Eight glacial cycles from an Antarctic ice core. *Nature* **429,** 623–628.

pattern similar to that of Greenland. Instead, Antarctic isotope records seem to show a 'see-saw' relationship, where large warming events in the Northern Hemisphere are preceded in the south by more gradual warming that terminates at the time of abrupt warming in the North. The pattern has been attributed to changes in ocean heat transport associated with the D–O events (Knutti *et al.*, 2004 and references therein), although other explanations have been suggested (Wunsch, 2003).

Following the last abrupt climate shift recorded in Greenland (the end of the Younger-Dryas period), climate variation was significantly muted compared to the last ice age, with one notable abrupt cool event at about 8.2 ka (Alley *et al.*, 1997). Other aspects of the Greenland records are not as uniform in the Holocene. For example, Mayewski *et al.* (2004) discuss oscillations in major ion concentrations that relate to polar cooling and tropical drying. Atmospheric methane levels drop dramatically during the early Holocene, then rise after ~5,000 years ago (*see* Methane Studies). Atmospheric CO_2 rises from an early Holocene low at ~8,000 years ago to late Holocene values of ~280 ppm by 1,000 years ago (*see* CO_2 Studies). Antarctic stable isotope records also do not contain large abrupt changes during the Holocene, but there are apparent temporal trends related to changes in ice-sheet elevation, an early Holocene climate optimum 11,500 to 9,000 years ago, and shorter-term millennial events (Masson *et al.*, 2000).

Recent and Anthropogenic Change

As mentioned above, ice cores record, in great detail, the anthropogenic impact on the remote atmosphere. Records of pollutants such as lead and sulfate are preserved at annual resolution, and the rise of greenhouse gases in the ice-core records provides fundamental information relevant to the modern global warming problem (Fig. 8).

New data on a variety of trace gas species and their isotopes in firn air and ice promises to improve our understanding of anthropogenic change, as do high-resolution studies of trace elements. Equally important are new networks of annually resolved records that will allow for greater understanding of the spatial distribution of climate change at high latitude and altitudes, through programs like International Trans Antarctic Scientific Expedition (ITASE) and Program for Arctic Regional Climate Assessment (PARCA). These regional assessments are critical for adequately assessing the influence of greenhouse warming at high latitudes.

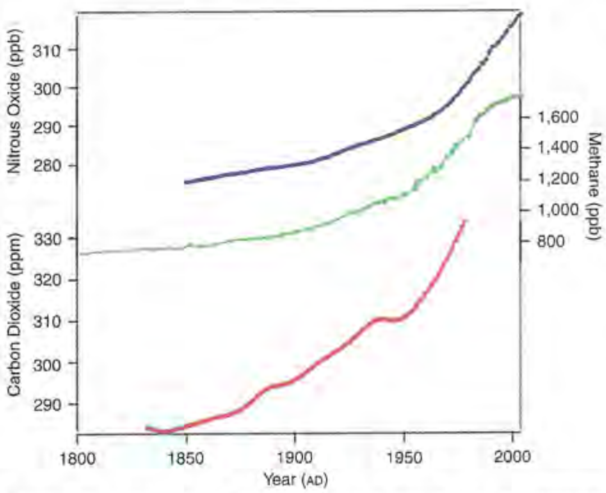

Figure 8 Records of the greenhouse gases carbon dioxide, methane, and nitrous oxide showing the anthropogenic increase over the last two centuries. Data from ice cores and direct atmospheric measurements, compiled by Brook (2005).

Future of Ice Coring

Data from ice cores underpins much of global change science, and in the last two decades has provided more detailed and longer views of atmospheric and environmental change in polar regions than perhaps originally envisioned. The oldest records are almost 800,000 years old, and records from areas of high snow accumulation provide annual data for tens of millennia. Cores from high elevation sites in the tropics and mid-latitudes, obtained by heroic measures, provide important information about climate change in these regions, unavailable from other means (*see* South America, Africa).

The future of ice coring involves both collecting more cores, to examine spatial variations in environmental change, and collecting deeper (older) cores, to extend the record as far back as possible. A broad-based international program called the International Partners in Ice Coring Sciences (IPICS) is involved in planning major new coring programs. For example, cores penetrating the last glacial transition in Greenland and Antarctica show significant interhemispheric differences, as well as differences in the character of deglacial climate change within Antarctica. Fully understanding the nature of this large change in the Earth system requires a detailed, well-dated spatial map of the progression of the deglaciation, and a network of deep ice cores in Greenland and Antarctica could accomplish this. On shorter timescales, a key global change question concerns separating anthropogenically forced climate change from natural variability. For this question it is desirable to develop a network of cores in both polar regions and other parts of the world covering the last 2,000 years. For older cores, a major goal in Antarctica is an ice-core record stretching back to 1.2 or even 1.5 million years. Such a core would extend through the mid-Pleistocene transition, a time period where Earth's climate shifted from 40,000-year to 100,000-year climate cycles. This core would allow investigation of the role of greenhouse gases in this transition, as well as provide a detailed land-based record of the evolution of temperature and other environmental variables over this time period. In Greenland, a core in a location that will allow recovery of the Eemian, or last interglacial period, is a major goal.

See also: **Ice Core Methods**: Biological Material; Borehole Temperature Records; Chronologies; CO_2 Studies; Conductivity Studies; Glaciochemistry; Methane Studies; Microparticle and Trace Element Studies; Stable isotopes. **Ice Core Records**: Africa; Chinese, Tibetan Mountains; South America; Antarctic Stable Isotopes; Greenland Stable Isotopes; Correlations Between Greenland and Antarctica; Ice Margin Sites; Thermal Diffusion Paleotemperature Records. **Ice Cores**: History of Research, Greenland and Antarctica; Dynamics of the Greenland Ice Sheet; Dynamics of the West Antarctic Ice Sheet; Dynamics of the East Antarctic Ice Sheet. **Paleoclimate Reconstruction**: Sub-Milankovitch (DO/ Heinrich) Events. **U-Series Dating**.

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Biological Material

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Introduction

Snow falling on polar and high-altitude regions has formed $\sim 1.6 \times 10^7\,km^2$ of glacial ice that provides an invaluable archive of past conditions on Earth. The expansive ice sheets of Greenland and Antarctica cover $\sim 10\%$ ($>1.5 \times 10^7\,km^2$) of the Earth's terrestrial surface with ice and contain $\sim 70\%$ of the freshwater on the planet (Paterson, 1994). Temperate glaciers cover more than $5 \times 10^5\,km^2$ and comprise $\sim 3.5\%$ of the glacial ice on our planet (**Table 1**). The present volume of the Earth's glacier ice, if totally melted, represents about 80 m in potential sea-level rise with 91%, 8%, and 1% represented by the East and West Antarctic Ice Sheets, the Greenland Ice Sheet, and mountain glaciers, respectively (Hambrey and Alean, 2004).

Table 1 Aerial coverage of selected glaciated areas on Earth

Region	Surface area (km^2)	Percent of world total
Polar		
Antarctica	13,593,310	87.5
Greenland	1,726,400	10.88
Polar total	15,319,710	96.58
Temperate		
Africa	10	<0.01
Asia and Eastern Europe	185,211	1.17
Australasia (i.e., New Zealand)	860	0.01
Europe (Western)	53,967	0.34
North America excluding Greenland	276,100	1.74
South America	25,908	0.16
Temperate total	542,056	3.42
World total	15,861,766	

Data from the World Glacier Monitoring Service, 1989.

Research on ice cores from polar and temperate glaciers has focused primarily on the reconstruction of the paleoclimate record to determine the mechanisms responsible for ice-sheet mass balance, associated sea-level change, and the processes leading to the transition between glacial and interglacial periods (e.g., Petit *et al.* (1999) and Alley (2002)). Ice cores collected from Greenland before the 1990s provided important evidence showing persistent climate instability over the last glacial cycle. Data from the Antarctic Vostok ice core have shown that over the past 400 kyr, there was a clear correlation between temperature and greenhouse gases, implying that greenhouse gases contributed to the temperature observations during this period. A recent ice core collected at Dome C as part of the European Project for Ice Coring in Antarctica (EPICA) has extended this record to 650 kyr and may ultimately produce a gas record 900 kyr old (EPICA, 2004; Brook, 2005; Siegenthaler *et al.*, 2005; Spahni *et al.*, 2005). Information derived from the ice-core record allows predictions of future changes in climate and provides important data to anticipate how these changes will impact future societal issues on our planet.

Atmospheric impurities deposited in glacial ice include aerosols emitted by the oceans and the continents, and anthropogenic activity. **Figure 1** shows the process of glacial deposition together with the global distribution of glaciers on our planet. The cold, dry conditions typical of glacial periods reduced the hydrological cycle and precipitation rate. The reduced precipitation increased the residence time of aerosols and dust allowing them to disperse to great distances. This paradigm is revealed in the dust record from the Vostok ice core, which shows that dust concentrations during glacial periods were ~ 50