Chapter 9
Ice cores, abrupt climate shifts, and ecosystem change

> ...ice contains no future, just the past, sealed away...clear and distinct.
>
> Haruki Murakami (1995)

In 1958, at the height of the Cold War, the USA developed a secret plan for a network of mobile nuclear missile launch sites beneath the Greenland ice sheet. It was codenamed Project Iceworm. Feasibility studies, involving experimental ice drilling and tunnelling, took place at Camp Century (77°N) in the northwest corner of Greenland. Sub-glacial living quarters were constructed for 250 personnel. It soon became apparent, however, that the motion of the ice was crushing the tunnels. The project was abandoned in 1966: but not before drilling trials retrieved the first long ice cores from a polar ice sheet. By drilling ice cores and melting the layers of ice for analysis, it is possible to obtain remarkably detailed records of the ice age past.

Willi Dansgaard (1922–2011) (Figure 28) was the first scientist to demonstrate that the ice sheets themselves provided an extended record of Earth's climate history. In the early 1960s, when Nick Shackleton was perfecting the measurement of oxygen isotopes on benthic foram shells in Cambridge, Dansgaard was setting up his own isotope laboratory in Copenhagen, but with very different kinds of samples. Dansgaard was interested in oxygen isotope

28. **(a) Willi Dansgaard in Greenland in 1979 (b) Annual banding in a 1m section of ice core from Greenland from a depth of 1837 to 1838 metres**

ratios in rainfall, snow, and ice. He made the landmark discovery that the oxygen isotope profile in ice cores provided a long-term record of changing air temperature in the Polar regions. He was able to show that as air temperature falls, more molecules of H_2O containing the heavy (oxygen-18) isotope condense and are lost from clouds as rain and snowfall. Thus atmospheric water vapour becomes more and more depleted of ^{18}O in a poleward direction. Dansgaard analysed rainfall samples and temperature data from around the world to test this idea—he even collected samples in beer bottles in his back garden in Copenhagen.

Rapid climate change

In 1966, the Americans obtained a 1,390 m ice core from Camp Century—the first ice core to penetrate the Greenland ice sheet down to bedrock. Greenland ice cores typically have very clear banding (Figure 28b) that corresponds to individual years of snow accumulation. This is because the snow that falls in summer under the permanent Arctic sun differs in texture to the snow that falls in winter. The distinctive paired layers can be counted like tree rings to produce a finely resolved chronology with annual and even seasonal resolution. The section of ice core shown in Figure 28b was produced by snow that fell around 16,250 years ago. Recent work on Greenland ice cores has allowed the end of the Pleistocene epoch and the onset of the Holocene interglacial to be dated very precisely to 11,700 years before AD 2000.

By sampling each layer of ice and measuring its oxygen isotope composition, Dansgaard produced an annual record of air temperature for the last 100,000 years. He had produced the first annual weather report for the last glacial stage. Perhaps the most startling outcome of this work was the demonstration that global climate could change extremely rapidly. Dansgaard showed that dramatic shifts in mean air temperature (>10°C) had taken place in less than a decade. These findings were greeted with scepticism and there was much debate about the integrity of the Greenland record, but subsequent work from other drilling sites vindicated all of Dansgaard's findings.

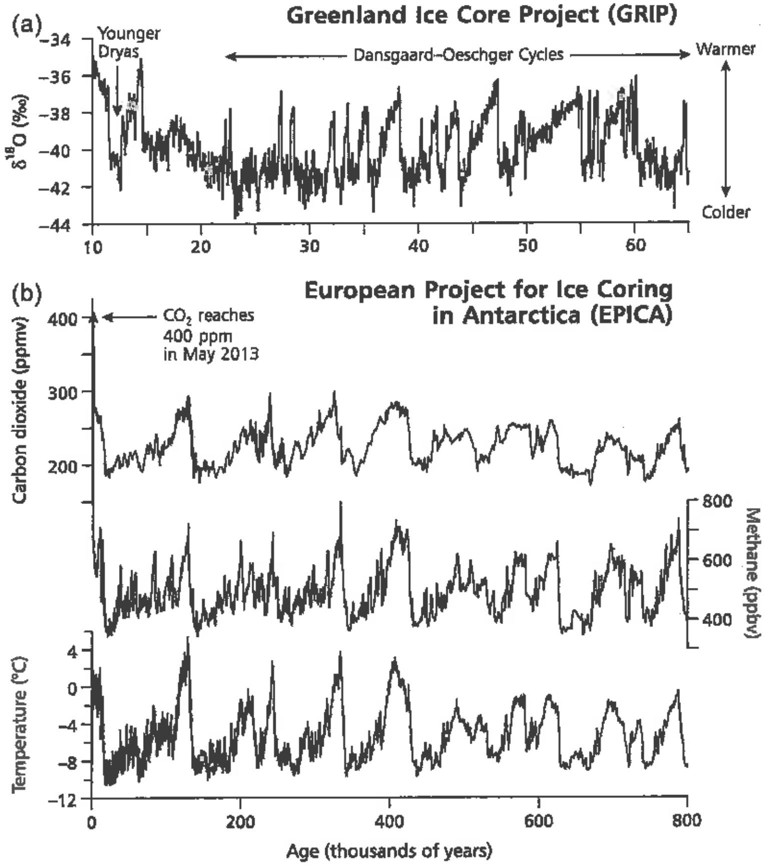
Dansgaard was to ice core research what Shackleton was to the study of marine sediments. It was therefore fitting when, in 1995, the Royal Swedish Academy of Sciences awarded its prestigious Crafoord Prize (widely regarded as the equivalent of a Nobel Prize) jointly to Shackleton and Dansgaard for their work on isotopes in geoscience.

The ice age atmosphere

As layers of snow become compacted into ice, air bubbles recording the composition of the atmosphere are sealed in discrete layers. This fossil air can be recovered to establish the changing concentration of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). The ice core record therefore allows climate scientists to explore the processes involved in climate variability over very long timescales.

A Swiss physicist, Hans Oeschger (1927–98), made fundamental contributions to our understanding of ice age climate change. He pioneered the measurement of greenhouse gases in the bubbles trapped in ancient ice. In his laboratory at the University of Bern, Oeschger analysed many thousands of samples from Greenland and Antarctica. In 1979 his team was the first to show that CO_2 concentrations during glacial stages were almost half those of the present. Oeschger showed that atmospheric CO_2 concentrations were about 180 ppm (parts per million) during glacials, but around 280 ppm during interglacials.

Ice accumulation is generally much slower in Antarctica, so the ice core record takes us much further back in time. The lower part of Figure 29 shows an 800,000-year Antarctic ice core record that spans eight glacial–interglacial cycles. This was produced by the European Project for Ice Coring in Antarctica (EPICA). Note how the changes in temperature closely track the changes in methane and CO_2. Methane is a potent greenhouse gas—it is stored in large volumes in the frozen biomass of the permafrost and as methane hydrate within sediments beneath the ocean floor. Ice core data have been fundamental in demonstrating that changes in the composition of the atmosphere played a key role in the shifting climates of the Quaternary, but there is still much debate about the processes involved and the leads and lags. CO_2 exchange between the oceans and atmosphere is the key link between the Milankovitch Cycles and the glacial and interglacial shifts of the



29. (a) Temperature fluctuations in the Greenland ice core record between 65,000 and 10,000 years ago (b) An 800,000-year record of CO_2, methane, and air temperature from Antarctica. Note the different timescales for the Greenland and Antarctic records

Quaternary. A key challenge, however, is to develop a better understanding of the processes that lead to marked shifts in atmospheric greenhouse gases during the course of glacial and interglacial cycles.

The ice age does not give up its secrets easily. Ice coring involves huge logistical challenges—pushing equipment and people to the limit. The Icelandic geophysicist Sigfús Johnsen (1940–2013) designed the specialist ice drilling equipment for the later Greenland projects. Bone chilling temperatures and powerful winds make the elevated interiors (where the ice is thickest) of the polar ice sheets some of the most inhospitable places on Earth. The lowest temperature ever measured at the Earth's surface (−89.2°C) was recorded at the Vostok Station in the middle of the East Antarctic Ice Sheet on 21st July 1983. Vostok also holds the record for the longest ice core. In late 2012, a Russian team drilled 3,768 m to reach Lake Vostok: the largest of the sub-glacial lakes in Antarctica and the third largest lake by volume in the world.

Dansgaard-Oeschger Events

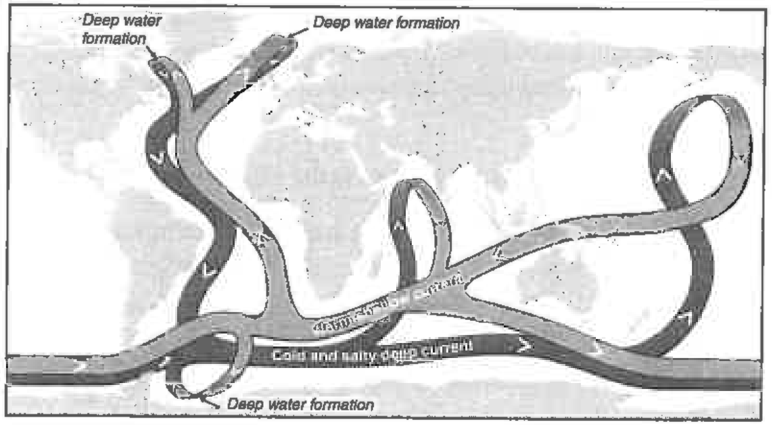
The ice core records from Greenland reveal a remarkable sequence of abrupt warming and cooling cycles *within* the last glacial stage. These are known as Dansgaard-Oeschger (D–O) cycles. The upper part of Figure 29 shows a series of D–O cycles between 65,000 and 10,000 years ago when mean annual air temperatures on the Greenland ice sheet shifted by as much as 10°C. Twenty-five of these rapid warming events have been identified during the last glacial period. This discovery dispelled the long held notion that glacials were lengthy periods of stable and unremitting cold climate. The ice core record shows very clearly that even the glacial climate flipped back and forth.

There has been much discussion about the cause of these D–O cycles and their relationship to the Heinrich Events. Changes in ocean circulation triggered by influxes of freshwater from the continents have been implicated. D–O cycles commence with a very rapid warming (between 5 and 10°C) over Greenland followed by a steady cooling (Figure 29). The most pronounced coolings are associated with Heinrich Events when severe glacial climates with extreme cold and aridity characterized many parts of the northern hemisphere.

The great ocean conveyor

Figure 30 shows the circulation system linking the world's oceans that moves vast quantities of heat around the globe. This circulation includes warm, shallow currents and deeper flows of denser, colder water. It is known as the thermohaline circulation because it is driven by contrasts in water temperature (thermo) and salinity (haline). These properties control the density of seawater. It takes about 1,000 years for a body of water to complete a full cycle. This circulation has been called the great ocean conveyor—it plays a fundamental role regulating global climate.

There are strong thermal gradients in both hemispheres because the low latitudes receive the most solar energy and the poles the least. To redress these imbalances the atmosphere and oceans move heat polewards—this is the basis of the climate system. In the North Atlantic a powerful surface current takes warmth from the tropics to higher latitudes: this is the famous Gulf Stream and its northeastern extension the North Atlantic Drift. Two main forces drive this current: the strong southwesterly winds and the return flow of colder, saltier water known as North Atlantic Deep



30. Ocean currents: the thermohaline circulation