Climate change and ice cores

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Abstract

Predicting how climate will change in the future requires a sound understanding of physical processes. This is underpinned by observation of how and why climate has changed in the past. Ice cores are a rich source of such information, and a topic that combines exciting fieldwork with a highly relevant academic discipline. In this article I will describe what ice cores are, and how we collect them, and describe some of the important results obtained from them.

Introduction

For climate, as in other spheres of life, knowing about the past is important if it gives us confidence that our understanding is adequate for informing us about the future. However, instruments that have directly recorded climate (temperature, pressure, etc.) have been common only for about the last century. Before that we are forced to infer the climate from a range of environmental archives. In most of them, something is laid down in a chronological sequence: for instance the concentric rings of cellulose that make tree rings, or the layers of fine mud in a marine sediment. We can then measure some property of that layer which responds to the climate variable (such as temperature) that we are interested in.

This article is concerned with one such archive, the layers of ice that make an ice sheet, and that can be accessed by drilling an ice core. Good ice core records can be obtained anywhere where it snows, and there is no significant melting. The layers of snow build up year by year, eventually squashed into solid ice by the weight of layers on top of them. This is generally true on the large ice sheets of Antarctica and Greenland. The layers of ice may be more than 3000 metres thick in places. The rate of snowfall can be anything from a few centimetres per year in the interior of Antarctica, up to several metres near the coast. However, ice sheets flow, with the result that the deeper layers are thinned. By choosing the right location we can find places where we can distinguish each year for the last few centuries at high resolution, or alternatively where we can reach back hundreds of thousands of years at low resolution.

What is an ice core and how does it work?

An ice core is a cylinder of ice extracted vertically from the ice sheet. Typically, an ice core is 10 cm in diameter. Although the longest cores have extended through 3500 metres of ice sheet to the rock below, they were brought to the surface in lengths of perhaps 3 metres at a time using a drill on a long cable. As a scientist, I have spent weeks at a time waiting at the surface as the drilling engineers lower the drill, collect the core and bring another length to the surface every couple of hours (Figure 1). We then section the ice in the field – ice is a surprisingly strong substance that can be cut with bandsaws – and make some physical

Figure 1 Drilling an ice core in Antarctica. Copyright and reproduced with permission of EPICA.

Figure 2 An ice core showing the air bubbles from which gas measurements are made. Copyright and reproduced with permission of British Antarctic Survey

and chemical measurements in makeshift laboratories in the field. The rest of the ice is returned in insulated boxes inside mobile frozen shipping containers at -20°C to our home laboratories.

The information in ice cores is held in three different ways. The first is in the water molecules themselves. Although most water consists of the isotopic combination $H_2{}^{16}O$, a small proportion has hydrogen with an atomic mass of 2 or oxygen with an atomic mass of 18. That proportion changes every time water is evaporated or condenses. It turns out that the proportion of these other isotopic combinations that survives to fall in snow in Antarctica or Greenland is determined mainly by the temperature at the time the snow falls – a vital source of climatic information.

A host of other material falls with the snow – for example after a large volcanic eruption, sulphur dioxide is injected into the upper atmosphere, oxidised to sulphate and falls out to the Earth's surface. We can measure the concentration of sulphate by melting and analysing successive layers of ice from our core – in the 2-3 years immediately after a large volcanic eruption (such as Krakatoa in 1883) we see a clearly identifiable spike of increased sulphate concentration. This is just one example – other analyses tell us about many other aspects of the environment, from the amount of sea ice in the ocean around Antarctica to the way that the concentration of lead in the atmosphere over Greenland increased and then decreased as leaded petrol was introduced to Europe and North America in the mid-20th century and then phased out in the 1980s.

The third way ice cores record information relies on the fact that, as the snow is compressed, it sinters together to form solid ice with air bubbles trapped inside (Figure 2). These bubbles can each be thought of as individual containers of ancient air. We can open them (several at a time) and measure how the proportions of different gases, including of course carbon dioxide, have changed with time.

The recent past – carbon dioxide

Although there are many arguments about how much climate may change in the future, the basic ideas that lead us to expect climate to warm are very simple. Firstly there is some very well-known physics that tells us that CO_2 absorbs and re-emits infrared radiation, and that adding more of it to the atmosphere causes warming. Secondly, we know that the concentration of CO_2, as well as of a second greenhouse gas, methane, has increased substantially and continuously over the last 200 years. Direct and reliable measurements in the atmosphere go back only about 50 years, but ice cores show clearly that CO_2 rose by about 40% between 1830 and 2010, from a background of 280 parts per million by volume (ppmv) to today's value of about 390 ppmv (Figure 3) (MacFarling Meure *et al.*, 2006). This concentration is 30% higher than at any time probably for the last 800,000 years. The increase is certainly due mainly to the burning of fossil fuels, supplemented by contributions from cement production and the loss of forests. The rate of increase is also stunning: as we will see CO_2 concentrations have risen naturally in the past, but

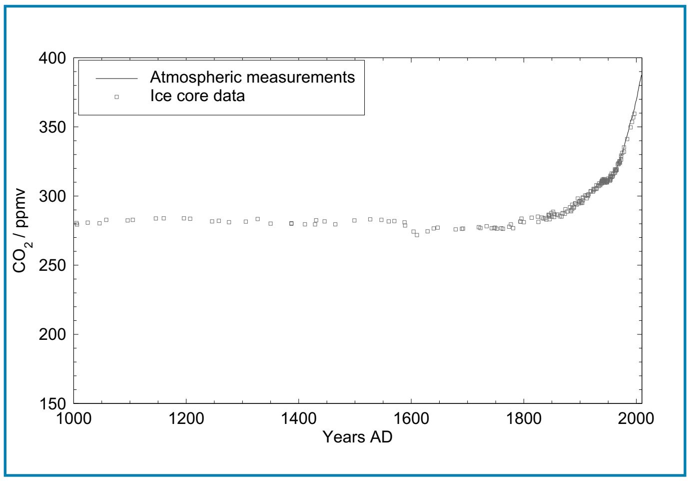

Figure 3 Atmospheric CO_2 concentration over the last 1000 years. The line at the far right is from measurements made in the atmosphere over the last 50 years. The squares are all from the Law Dome (Antarctica) ice core (MacFarling Meure *et al.*, 2006).

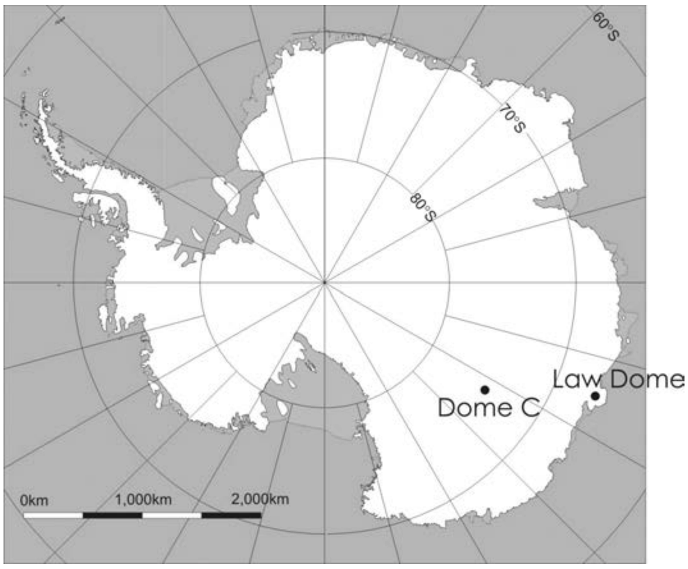

Figure 4 Map of Antarctica

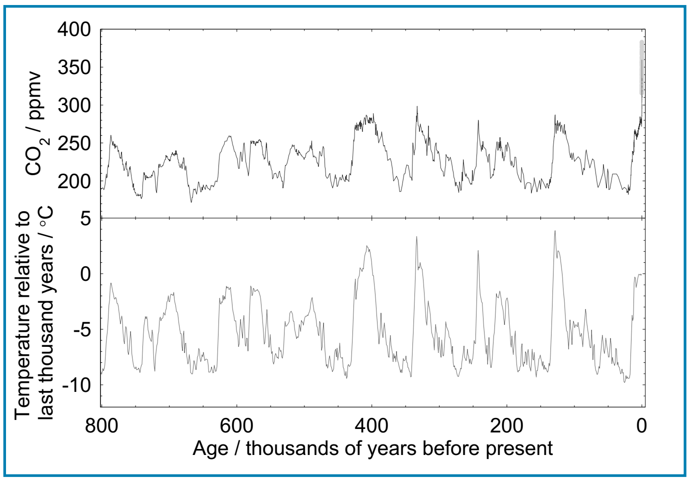

Figure 5 Antarctic temperature and CO_2 over the last 800,000 years. Temperature (relative to the last 1000 years as zero) from the EPICA Dome C ice core (Jouzel *et al.*, 2007) based on measurements of changes in the ratio of isotopes of water. CO_2 from the Dome C and Vostok sites (Lüthi *et al.*, 2008), along with recent data from Law Dome and atmospheric measurements (thick line at right side of figure).

the fastest sustained rate we can see before the last two centuries is about 20 ppmv in 1000 years. In contrast, the concentration has risen by 20 ppmv in the last 11 years!

The EPICA project: 800,000 years of climate change

The oldest ice core record we have came from a project called the European Project for Ice Coring in Antarctica (EPICA). Involving dozens of scientists and engineers from 10 different European nations, this project drilled two ice cores, one of them to 3270 metres depth at Dome C, a high point on the ice sheet 1000 km from the coast of Antarctica (Figure 4).

The climate record from this core, based on the concentrations of the different isotopes of water, shows successive cycles of warming and cooling (*Jouzel et al.*, 2007) over the 800,000 years the core records (Figure 5). Although the mean annual temperature at Dome C today is -54°C, we see that the last 10000 years have been relatively warm in the context of the whole record. The temperature in Antarctica was about 9°C colder still in the period we call the last glacial maximum (LGM), 20000 years ago. This was actually the time when large ice sheets extended over much of North America and northern Europe, but it was cold all around the Earth, including Antarctica. This alternation of cold and warm was just the last of a series of alternations, returning roughly every 100,000 years. We know that these changes were paced by periodic variations in the Earth's orbit around the Sun, which altered the amount of sunlight received at particular latitudes and seasons. However, for this to cause massive changes in Earth's climate, the small orbital changes had to be amplified.

It turns out that one of the most important amplifiers was CO_2. The ice core data shows that CO_2 varied in a very similar pattern to Antarctic climate (Figure 5) (Lüthi *et al.*, 2008). Although never reaching the values of the 20th and 21st centuries, these natural changes added significantly to the climate shifts, in turn inducing the waxing and waning of the northern hemisphere ice sheets. We don't yet fully understand the causes of the CO_2 changes, although they are certainly largely related to processes that partition CO_2 between the atmosphere and surface ocean on the one hand, and the deep ocean and sediments on the other. Understanding this feedback process is important if we want to constrain how strongly human emissions of CO_2 will affect the concentration in the atmosphere over the next decades to millennia.

Rapid climate change and ocean circulation

One other phenomenon that ice cores have revealed is that of rapid climate change. During the last glacial period (especially between 80000 and 20000 years ago), ice cores from Greenland reveal a sequence of extremely fast regional climate shifts. Over Greenland, the temperature jumped, often by more than 10°C, in just 40 years. It then stayed warm for some centuries, before relaxing back to its cold state for several more centuries, until another abrupt warming event. While seen most strongly in Greenland, the warmings certainly extended through the whole North Atlantic, with an amplitude of several degrees over Europe. These events (known as Dansgaard-Oeschger events after two leading ice core scientists) were almost certainly caused by changes in the amount of heat transported northwards in the surface ocean. Today, we in the UK benefit greatly from this heat transport, which is seen here as the Gulf Stream, but is part of the overall pattern of circulation and overturning of ocean water around the globe. It seems as if freshwater from icebergs and meltwater draining from the great ice sheets altered the density structure of the ocean, and this disrupted the whole circulation pattern.

This explanation is consistent with the more subdued and somewhat out of phase climate signal seen in Antarctica at the same time.

It is important to emphasise that this particular mechanism was possible only when there were large ice sheets surrounding the North Atlantic Ocean. Nonetheless they show that even something as apparently fixed as the circulation of the ocean can suddenly alter, and we should be sure that we do not approach thresholds where similar events could occur.

Conclusion and future studies

Ice cores have been a rich source of information about the past, particularly valuable because some of the causes of climate change are seen in the same record as the polar climate response. They have given us certainty about the changes to the atmosphere that human activities have already induced. They have also given us valuable clues about how aspects of the Earth work – here I have highlighted the feedbacks between climate and CO_2, and the possibility of changes in the way the oceans circulate.

There is much more that ice cores can still reveal, including the regional patterns of change around the huge continent of Antarctica. It is hoped that a new core will eventually be drilled that will go back even further into the past, beyond a million years.

Further information

The British Antarctic Survey has produced a briefing about ice cores, which can be downloaded from **http://www.antarctica.ac.uk/press/journalists/resources/science/icecorebriefing.php**

References

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Lüthi, D., *et al*. (2008), High-resolution carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, **453**, pp.379-382.

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Comment from the Editor
The Geological Society of London has prepared a statement about Climate Change (focused on geological evidence) which was published in November 2010. **http://www.geolsoc.org.uk/gsl/policy/policy_statements/climatechange**

My mother didn't do any recycling until she got a grey bin and then she turned green