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CLIMATE CHANGE OVER THE PAST 21,000 YEARS

The past 2.6 million years have been the epoch of the ice ages, known as the Quaternary period. They have seen the repeated growth and decay of continental-scale ice sheets, sea-level fluctuations of over 100 metres, and major changes in the global distribution of almost every species of plant and animal.

This **Geofile** gives an overview of climatic changes over the past 21,000 years – a timeframe which runs from the peak of the last ice age, through the last deglaciation, and into the current warm interglacial phase known as the Holocene. It also examines the different types of evidence used to reconstruct the past climates.

21,000 BP: Last glacial maximum

Global climates have oscillated between glacial and interglacial states during the Quaternary. The most recent ice age reached its maximum severity and extent 21,000 years before present (BP).

Much of the British Isles was covered with glaciers up to 300 m thick, and ice-free parts of England were tundra landscapes of periglaciation and frost-shattering. Icebergs were found as far south as the latitude of Spain. Plants and insects found in Britain at that time live only in the high Arctic today. Temperatures in the coldest winter months were probably between –20°C and –25°C.

15,000 BP: Lateglacial interstadial

About 15,000 years ago, a sudden and dramatic warming took place. In a few hundreds of years or less, temperatures rose rapidly to levels close to today's. This was the Lateglacial interstadial (*interstadial* referring to a milder period of climate within a glacial episode). Temperatures reached about 17°C in summer, and 0°C in winter. By about 13,000 BP, glaciers had melted and soils and temperate trees were growing in Britain.

Orbital variations in solar radiation inputs are the pacemaker of the ice ages. However, deglaciation occurred so rapidly that other processes must have amplified those subtle changes in day length and solar intensity. Ocean currents seem to have been particularly important. The warm Gulf Stream is largely responsible for Britain's mild climate today; it is linked to the circulation of North Atlantic deep-water, which in turn depends on the ocean water's temperature and salinity. The Gulf Stream had ceased to operate at the Last glacial maximum. Changes in ice cover and evaporation during deglaciation allowed it to restart during the Lateglacial interstadial warming.

Figure 1: A timeline of climate change over the past 21,000 years

Years before present (BP)	
21,000	Last glacial maximum
15,000	Rapid Lateglacial warming
12,900–11,500	Younger Dryas cold event
10,000	Average climate similar to today's
8200	8200 BP cooling event
7000–5000	Climatic optimum
1250–700	'Medieval warm period'
400–150	'Little Ice Age' cool period

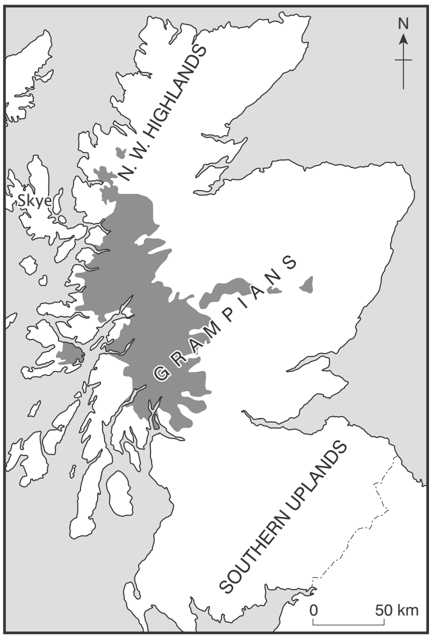
12,900–11,500 BP: The Younger Dryas cold period

There was one more dramatic cold episode before the final development of sustained temperate conditions. The warm Lateglacial interstadial lasted no more than 2000 years before temperatures plunged again, to almost full glacial conditions.

The cold episode began around 12,900 BP. It had a powerful impact on landscapes and ecosystems; the clearest glacial features and moraines in the British Isles date from this time. It is often referred to as the *Younger Dryas* stadial, named after the arctic flower species *Dryas octopetala*, whose pollen is found in abundance from this time. (It is sometimes known in Britain as the Loch Lomond stadial.)

The Younger Dryas episode is the most dramatic climatic event of the last 21,000 years. Over a 1400-year period, glaciers grew in the uplands – valley glaciers in the Lake District and North Wales, and an ice cap more than 50 km across and 400 m thick in the western highlands of Scotland (Figure 2). The analysis of insect species found from this time indicates that mean annual temperatures were about –8°C. Beyond glacial limits, spring snowmelt floods deposited coarse gravels in lowland areas, and permafrost and solifluction also occurred. Tundra vegetation returned, with tree pollen recorded only from hardy northern species such as the dwarf birch.

Figure 2: Glaciers and ice-caps (shaded) in Scotland during the Younger Dryas, around 12,000 BP



Source: J. B. Sissons (1979). *Nature* (278) 518-521.

The causes of the Younger Dryas episode have been the subject of much debate. Ocean currents again seem to hold the key. North Atlantic deep-water circulation suddenly ceased at the onset of the Younger Dryas, probably because huge meltwater inputs reduced the density of surface sea waters. The Gulf Stream ceased flowing northwards towards the British Isles, causing temperatures to fall.

The episode ended as suddenly as it had begun. At about 11,500 BP, the Gulf Stream restarted and temperatures rose again close to present-day levels. The change may have occurred in just a few tens of years. Many scientists consider that these Younger Dryas 'step-changes' give an unsettling insight into our climate system.

The Holocene climate: The past 10,000 years

By about 10,000 BP, climates close to today's were reached, and temperate species of trees and animals had spread north to Britain from southern Europe. By 8000 BP, sea levels had risen by over 100 m to around present-day levels, separating island Britain from the continent.

The past 10,000 years or so of the present interglacial, known as the Holocene, have been a period of relative climatic stability. However, recent work has highlighted the importance of environmental fluctuations during this time.

The 8200 BP event

The most significant climatic fluctuation is a sudden dip of up to 6°C in the Greenland ice core record at 8200 BP, lasting for 200 years. Evidence for the event is seen in pollen and insect evidence as well. This event is also thought to have been caused by disturbance of the Gulf Stream, perhaps due to a sudden overflow into the Atlantic of giant meltwater lakes in North America.

Climatic optimum

There have been other, more subtle trends. There is some evidence that temperatures may have been about 2°C warmer than today during a period 7000 to 5000 years ago known as the 'climatic optimum'. This is seen in ice cores, and in the distribution of plant and animal distributions across Europe. Tree species such as hazel were found at higher latitudes and altitudes than their current distribution. The European pond tortoise spread north into areas including Denmark, from which it is absent today.

Recent fluctuations

More recent fluctuations have also been intensively studied. In a medieval warm period from around AD 750 to 1300, vineyards were found as far north as York. In the 14th century, later frosts and wetter summers coincided with the Black Death and ended these prosperous conditions for British farmers.

Figure 3: The discovery of past ice ages in the 19th century

> We have evidence of almost every conceivable kind, organic and inorganic, that within a very recent geological period, central Europe and North America suffered under an Arctic climate. The ruins of a house burnt by fire do not tell their tale more plainly, than do the mountains of Scotland and Wales, with their scored flanks, polished surfaces, and perched boulders, of the icy streams with which their valleys were lately filled.

Source: Charles Darwin (1859) *On the Origin of Species* (http://darwin-online.org.uk/)

This was followed by the so-called 'Little Ice Age', dating from about 1600 to 1850 and marked most notably in a widespread glacial expansion in the Alps. Most Alpine glaciers today sit within the moraines deposited by much larger glaciers, dating from about 1850.

Bond cycles

The causes of these more recent fluctuations are not completely understood. However, one theory suggests that they may be linked parts of a long-term cycle of changes, rather than isolated events. 'Bond cycles' (named after the scientist who proposed them in 1997) were identified by comparing ice and sea cores across the North Atlantic. They appear to show abrupt climate shifts occurring on average every 1470 years, with cool ice-bearing ocean water from north of Iceland flowing south to the latitude of Britain. Both the 8200 BP event and the Little Ice Age may be cold episodes in a rhythmic climatic oscillation which has operated throughout the Holocene.

Evidence from landforms

It was landform evidence which persuaded 19th-century scientists that a major glaciation had occurred in geologically recent times (Figure 3). Features such as U-shaped valleys, roche moutonées, erratic boulders and moraines showed that glaciers had been present in areas of the UK which are now ice-free; and that Alpine glaciers had formerly extended many kilometres beyond their present limits. It is more difficult to use landforms to provide quantitative evidence for the magnitude of climate changes, however.

Some periglacial landforms can be used to give numerical estimates of climate changes. For example, deep ice wedges occurred widely in ice age Britain; they occur only where air temperatures are below –6°C. Pingo remains are visible in East Anglia – these large ice-filled mounds can have developed only when temperatures were below –3°C for long periods.

Valley glaciers have been used in the most detailed work to translate landform evidence into estimates of past temperatures. The most common method is the accumulation area ratio technique. In valley glaciers today, the accumulation area (the area above the summer snowline) is often found to occupy approximately the upper two-thirds of the glacier surface area. The height of the summer snowline has been shown to correlate with average temperature for present-day glaciers.

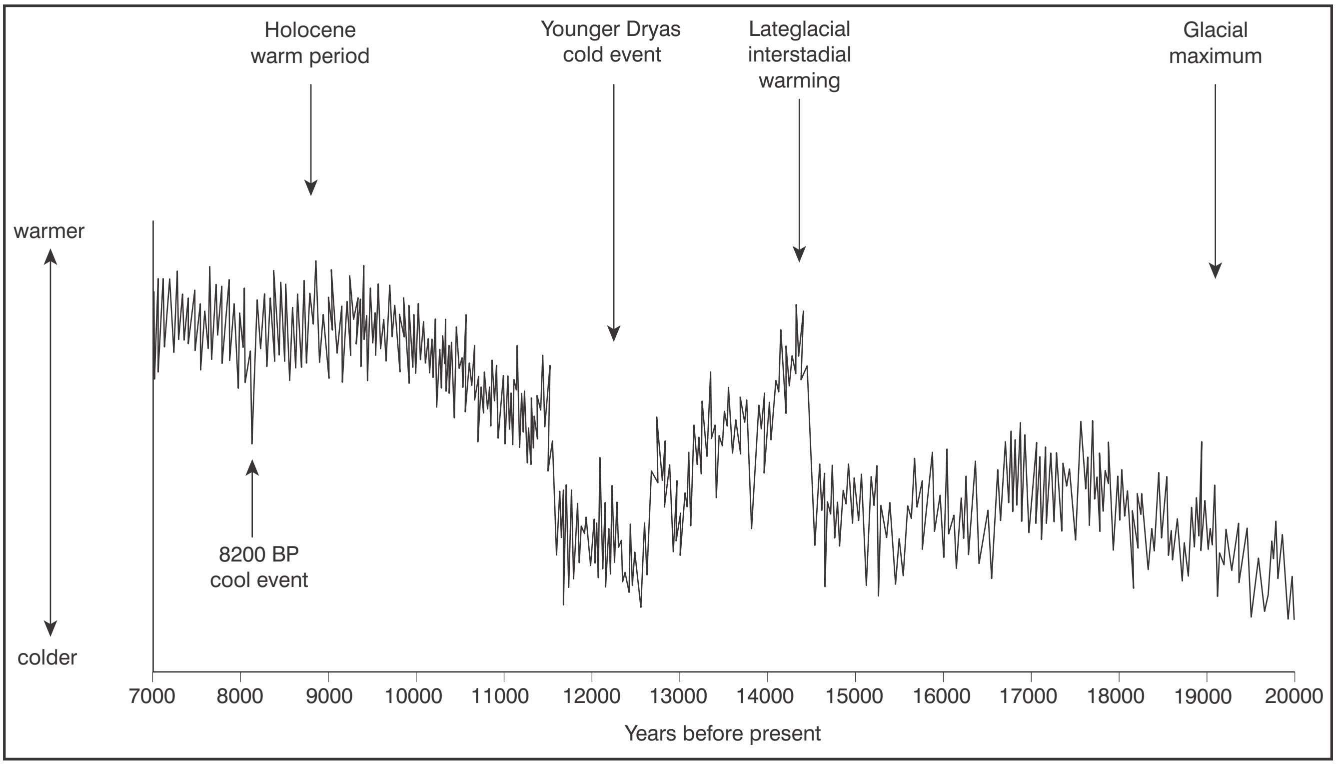
Mapping the surface area of a former glacier from the field evidence for moraines and glacial erosion means that the likely altitude of the glacier's summer snowline can be estimated. The accumulation area ratio technique therefore allows the size and shape of the former glacier to be used to estimate average temperature.

Ice cores: high resolution evidence for past climates

Ice cores have given us a very high resolution picture of climate changes over many thousands of years. Cores several kilometres in length have been extracted from the high dome of the Greenland ice sheet, dating back over 100,000 years (the GRIP and GISP cores); and the Antarctic EPICA and Vostok ice cores record even longer periods. Cores have been dated with a high degree of accuracy by annual layer counting.

Climatic information includes measures of snowfall totals, atmospheric gas in bubbles within the ice (a major source of information for changes in

Figure 4: Temperature trends reconstructed from oxygen isotope ratios in the GRIP ice core, Greenland, 20,000 to 7,000 years BP. One unit on the y axis is equivalent to approximately 1.5°C.



greenhouse gases such as CO_2), and dust concentration (information on windiness and aridity).

Temperatures at the time of snow accumulation can also be reconstructed from ice core data. This is done by analysing the chemistry of oxygen molecules within the snow. Oxygen naturally exists in two isotopic forms, known as ^{16}O and ^{18}O. These isotopes form water molecules which condense at slightly different temperatures (^{18}O water molecules condense preferentially when a moisture-bearing air mass is cooled). The ratio between the ^{16}O and ^{18}O forms of water in the ice core can therefore be used to reconstruct the temperature of the site at the time the snow fell.

Figure 4 shows an example of temperature trends reconstructed from the GRIP ice core in Greenland. One degree of temperature change translates into a variation of about 0.6 to 0.8 parts per thousand in this ratio (the y axis in Figure 4). The major events of the period 21,000 to 7000 BP are visible in the record from this high-arctic ice cap.

There are limits to the accuracy of temperatures estimated from these oxygen isotope records. As global ice sheets grew during the ice age, the huge volume of water stored as ice altered the oxygen isotope composition of sea water. Furthermore, the increasing elevation of surface of a growing ice cap would itself be expected to lead to a decrease in temperatures.

Evidence from plant and animal remains

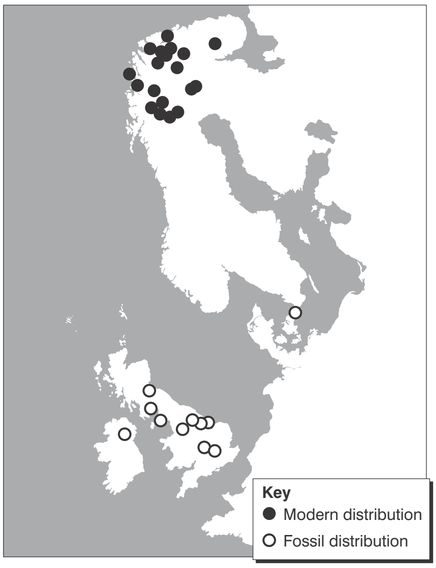
A third area of research is in the analysis of plant and animal remains to estimate past climates. This combines the spatial coverage of landforms with some of the precision of ice core data.

Temperature and precipitation are primary controls on the distribution of many plant and animal species. Comparison between species' fossil and present-day distributions can be used to estimate past environmental conditions.

Plant pollen is the best-known biological tool for studying Quaternary environments. Pollen is produced in great quantities by flowering plants, and its long-distance wind-dispersal means that a single site can give a broad picture of the surrounding vegetation diversity. The durable exine (outer wall) of the pollen grain can survive for thousands of years in suitable conditions such as bogs or lake-bed sediments. Other organic remains used in this way range from 'macro-fossils' such as seeds, bones and snail-shells, down to microscopic aquatic organisms such as diatoms.

One disadvantage of biological indicators is that there may be a time lag between climatic change and the organism's response – time for seed dispersal from existing sites to a newly suitable environmental site, for example.

Figure 5: Modern and last glacial maximum distribution of the ground beetle Diacheila arctica



Source: A.C. Ashworth (2001) *Geological Perspectives of Global Climate Change*, American Association of Petroleum Geologists

Beetles and the mutual climatic range

Many beetle species are highly mobile and sensitive indicators of environmental change, however. They are also abundant in the fossil record. Beetles have been used in some of the most detailed climatic reconstructions from organic remains.

Figure 5 shows the example of one species of ground beetle found in Britain during the last glacial maximum, together with its present distribution north of the Arctic Circle.

A single fossil beetle species today may be found living in a range of environments, however. More precise climatic information can be gathered if the remains of several different beetle species are found together in the fossil record. In that case, the climatic preferences of all of the beetle species can be compared to find the most probable environment at the time of deposition. This approach, identifying the climatic overlap between the different species, is known as the 'mutual climatic range' approach. It is shown in Figure 6.

Summary

A wide variety of indicators has been used to give evidence for past climates. The overall picture is one of a switch between two broad climatic modes – glacial and interglacial – interrupted by the extraordinary see-saw change of the Younger Dryas cold episode. Smaller temperature and precipitation changes since the last ice age may possibly be parts of an ongoing climatic cycle. The complexity of past environmental changes suggests that future climate change may be difficult to understand and control.

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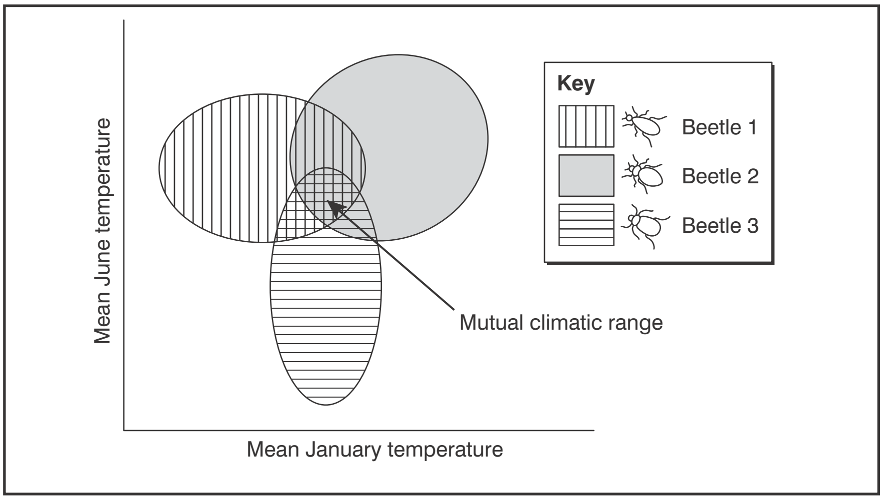
Figure 6: The mutual climatic range technique. Each species is found today across a range of environments - the shaded areas show each beetle's present-day distribution. The three beetle species could occur together only in the area of climatic overlap.



FOCUS QUESTIONS

1. How has the climate of the British Isles varied over the past 21,000 years?

2. Explain how landforms, ice cores and biological indicators can be used to reconstruct past environments.