3 Ice Ages Through Geological Time

a) The 'Ice Age' discovery

The 19th century discovery that the world has experienced an 'Ice Age' was of great importance for our understanding of the Earth and its history. It was the Swiss scientist Louis Agassiz in the late 1830s who introduced the concept of continental glaciation, in which ice sheets extended over large areas of the mid-latitudes. His theory of 'a great Ice Age' made it possible to explain for the first time many of the landforms of glaciation that are discussed later in this book. The first scientific observations of existing glaciers were made in the European Alps, paving the way for identifying signs of glaciation in places where glaciers no longer exist today, such as in the British Isles. Since the idea of an 'Ice Age' was proposed, evidence for past glaciation has been found over large areas of North America and Eurasia from high to mid-latitudes (southwards to approximately 40°N).

In addition to providing the key to explaining landscapes across much of the globe (particularly at high latitudes and altitudes), the discovery of an 'Ice Age' also revolutionised our understanding of the Earth's climate and how it changes over long periods of time. Research in the 20th century, especially since the 1970s, has shown that the planet has experienced not one 'Ice Age' as originally conceptualised in the 19th century, but several ice ages; and we currently occupy the most recent ice age – the **Quaternary** Ice Age. Ice ages themselves are subdivided into phases of extensive glaciation (**glacials**) separated by phases of warmer conditions with retreat of glaciers (**interglacials**). As explained later in this chapter, the large changes in climate that occurred between, and during, glacials are now known to have been remarkably rapid, rather than slow and gradual as once thought.

b) The Quaternary

We are currently living during the period of geological time known as the **Quaternary**. It began around 2 million years ago as the Tertiary Period ended, and it is distinguished from the preceding Tertiary by the onset of global cooling, which led to the expansion of ice sheets across large areas of the globe at high to mid-latitudes. For this reason the Quaternary Period is also known as the Quaternary Ice Age. The exact time when it became cold enough to mark the transition between the Tertiary and the Quaternary is a matter of interpretation still debated among geologists, and estimates range between 2.6 and 1.8 million years ago.

Although glacier ice is not as extensive today as it has been at other times during the Quaternary, the ice age continues. This is because the existence of the Antarctic and Greenland ice sheets (and smaller glaciers elsewhere) sets our time apart from most other periods of Earth's history when there was little or no permanent ice anywhere on the globe. For example, during the Cretaceous Period from 135 to 65 million years ago (dinosaurs became extinct at the end of the Cretaceous), average global temperatures were over 5°C warmer than today and the Earth was ice-free. Sea level was much higher than at present, and there were forests at high latitudes. Prior to the Quaternary Period, the last time the Earth experienced an ice age was around 280 million years ago during the Carboniferous and Permian periods. Throughout the whole of Earth's history, there is geological evidence for at least seven alternations between ice ages and warmer periods.

4 Multiple Glacials and Interglacials During the Pleistocene

a) Characteristics of the Pleistocene

The Quaternary Period is subdivided into two epochs of geological time – the **Pleistocene** and the **Holocene**. The Pleistocene Epoch covers the time span from the beginning of the Quaternary to about 11 500 years ago, when the most recent glacial ended and the present interglacial began. The Holocene interglacial in which we now live is similar to previous interglacials, and it can be argued that there is no reason to mark the present interglacial as the start of a new geological epoch. However, what distinguishes our interglacial from previous ones is that it has seen the development of agriculture and the growth of civilisation.

When viewed in relation to the very long timescale of Earth's geological history, the relatively cold Quaternary Period can be regarded as a single 'ice age', which continues to this day (as described in the previous section). However, during the Quaternary Ice Age itself, conditions have not been uniformly cold. Instead, there has been much variation in the Earth's climate over shorter timescales, and large ice sheets have advanced and retreated many times as the climate has repeatedly shifted between colder and warmer, causing the oscillation between glacials and interglacials. As the Holocene refers only to our present interglacial, the multiple phases of glaciation (and intervening interglacials) that characterise the Quaternary Ice Age are all contained within the time-span of the Pleistocene.

Glacial phases during the Pleistocene have left evidence on land in the form of erosional and depositional features created by glaciers (described in Chapters 3 and 4). However, the landforms produced by glaciers during earlier glaciations have usually been reshaped or destroyed by later glaciations, making reconstruction of the pattern of past glaciation difficult. Only the four most recent Pleistocene glacial phases are easily recognised from evidence on land. The names given to these four glacials are different in different parts of the world. Starting with the most recent and moving back in time, in the British Isles they are known as the **Devensian**, the **Wolstonian**, the **Anglian** and the **Beestonian** glaciations. In the European Alps the corresponding names are the Würm, Riss, Mindel and Günz glaciations, and in North America the Wisconsin, Illinoian, Kansan and Nebraskan glaciations.

In comparison with the evidence on land, evidence from the sea floor provides a much longer and more complete record of past glacial/interglacial cycles. This is because in oceans the shells and skeletons of marine organisms are continually deposited on the sea bed, building up undisturbed layers of sediment on the ocean floor over many thousands, and in some places even millions, of years. By sampling this ocean sediment and analysing the chemistry of shells dating from different time periods it is possible to infer what the ocean environment was like (for example, sea temperatures) at the times when the marine organisms were alive. Continuous samples taken down through ocean sediment (sediment cores) in many of the world's oceans have made it possible to produce detailed reconstructions of how the ocean environment has changed during the Pleistocene that have been important for understanding the pattern of glaciation on land.

This has been achieved mainly by analysing the oxygen isotope ratios (the ratio of $^{18}O/^{16}O$) found within the shells of marine organisms that have been deposited on the ocean floor.

- More of the heavier type of oxygen (^{18}O that has ten neutrons as opposed to the lighter ^{16}O that has just eight) within shells indicates times when more of the Earth's water was locked up in ice sheets and glaciers.
- Shells with less ^{18}O relative to ^{16}O were formed during times when ice sheets and glaciers were less extensive.
- This is because when water is evaporated from the oceans, H_2O containing ^{16}O is more easily evaporated than H_2O containing ^{18}O.
- In order to build up large ice sheets, a lot of water from the oceans must be evaporated and deposited as snow over landmasses. This process results in taking more $H_2{}^{16}O$ out of the oceans while leaving $H_2{}^{18}O$ behind, causing an enrichment in ^{18}O of sea water during glacials.
- As marine organisms build their shells with oxygen from surrounding sea water, the increased $^{18}O/^{16}O$ ratio of the sea water during glacials becomes preserved in the shells of the organisms that were living at the time. The $^{18}O/^{16}O$ ratios reach their maximum when global ice volume is at a maximum.

Depending on how the oxygen isotope ratios in ocean sediments are interpreted, there appears to have been between 30 and 50

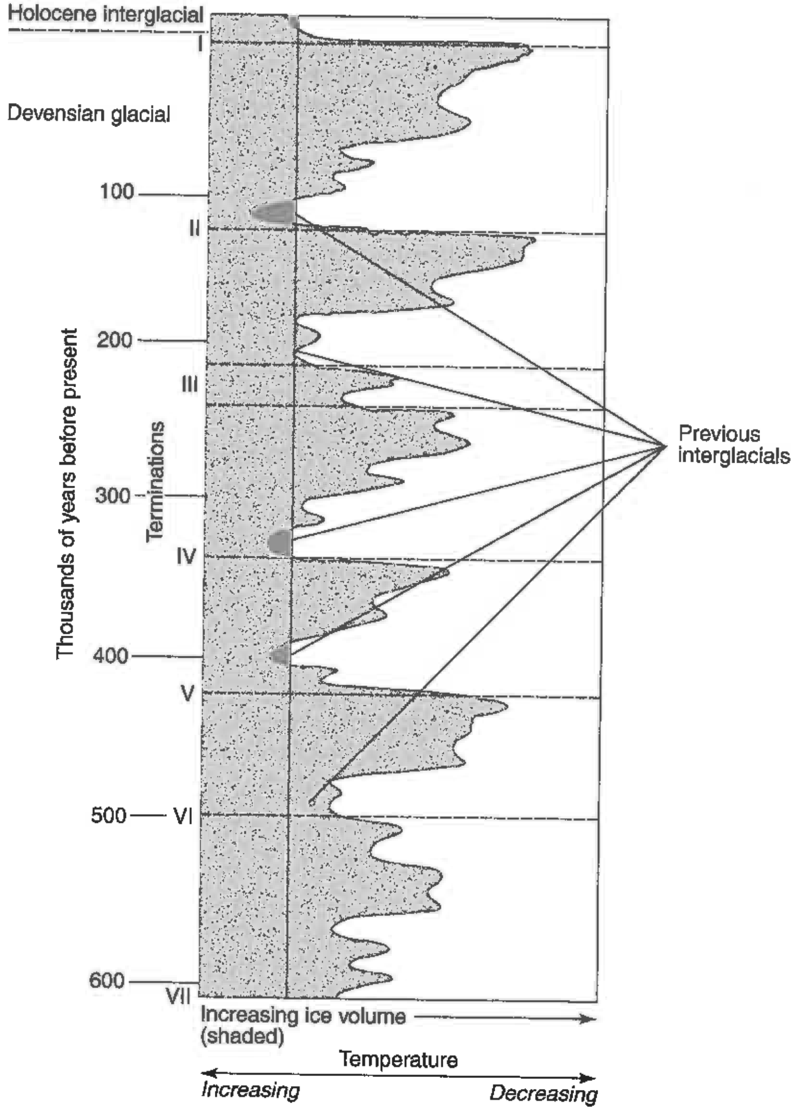

Figure 3 Global ice volume plotted against time as inferred from oxygen isotope data in ocean sediment cores (vertical line represents isotope ratio typical of late Holocene). *Source*: Lowe and Walker (1997).

cold/temperate cycles since the Pleistocene began. During the earlier part of the Pleistocene, shifts between glacial and interglacial phases occurred approximately every 41 000 years, but after about 900 000 years ago the oscillations became longer, showing a periodicity of around

100 000 years. For example, over the past 600 000 years there have been six pronounced phases of glaciation, each followed by an interglacial when the global ice volume decreased substantially (Figure 3). The pattern also shows that the global ice volume tends to build up relatively gradually during a glacial, but decreases rapidly at the beginning of an interglacial.

The majority of the Pleistocene has been characterised by colder conditions with a greater global ice volume than exists today, and times of interglacial warmth similar to the present Holocene are relatively short. Figure 3 shows that over the past 600 000 years there have been only three short periods of time when temperatures were as warm as they are today. Over the past 1 million years or so, today's type of climate has only occurred for around 10% of the time, whereas most of the time it has been colder, and ice sheets and glaciers have been much more extensive.

b) Cause of glacial/interglacial cycles during the Pleistocene

Long-term changes in the Earth's orbit around the sun are the main cause for the oscillations between glacial and interglacial conditions that have occurred during the Pleistocene. The idea that changes in the Earth's orbit could explain the expansion and retreat of continental ice sheets dates back to the 19th century when the Scottish scientist James Croll first speculated about how such changes might be linked to climate and to glaciation. However, it was the Serbian Milutin Milankovitch, in the early 20th century, who first calculated how the amount of solar energy received by the Northern and Southern Hemispheres in different seasons changes as the Earth's orbit changes.

The **Milankovitch astronomical theory** of glacial periods takes into account three characteristics of the Earth's orbit. First, the orbit changes from being more elliptical to more circular and back again over a period of about 96 000 years. This cycle is known as the **eccentricity** of the orbit. Second, the tilt of the Earth's axis varies from 21.8° to 24.4° relative to the plane of its orbit (the plane of the ecliptic) over a period of 42 000 years. This is known as the **obliquity of the ecliptic**, and today the Earth's axis is tilted at 23.5°. Third, the Earth wobbles on its axis like a top causing long-term changes in where different seasons occur along the Earth's orbital path. For instance, today the Northern Hemisphere summer occurs when the Earth is near its furthest point from the Sun on its orbit (aphelion), whereas around 10 000 years ago the Northern Hemisphere summer occurred when the Earth was nearest the Sun on its orbit (perihelion). This cycle, known as the **precession of the equinoxes**, averages out over a period of 21 000 years.

The Milankovitch theory combines all three of these cycles to determine when solar energy is minimised or maximised in the

Northern Hemisphere summer in explaining when glacials and interglacials occur. The input of solar energy into the Northern Hemisphere is more important than the Southern Hemisphere for controlling glaciation during the Quaternary Period because there is much more land at high latitudes in the Northern Hemisphere, allowing build up of continental ice sheets. Milankovitch recognised that glacials are most severe when the three orbital cycles come together to minimise the amount of solar energy reaching the Northern Hemisphere during summer (resulting in cooler summers). This is because lower temperatures in summer mean that less of the snow that fell during the winter will be melted, allowing snow and ice to build up over many years into large ice sheets.

On the other hand, interglacials occur when the three orbital factors combine to maximise solar energy in the Northern Hemisphere summer (warmer summers). Orbital factors cause increased solar energy input to the Northern Hemisphere during summer when the Earth has a greater tilt than average, and the Northern Hemisphere summer occurs when the planet is nearest the Sun on its orbit. This effect is further enhanced when the orbit is more elliptical than circular. With higher summer temperatures, less of the snow and ice that formed in winter survives through the summer, and over many years this stops the ice sheets from growing, eventually causing them to retreat. The evidence from ocean sediment cores shows that the 96 000-year cycle of eccentricity has been the dominant cycle governing oscillations between glacials and interglacials over the past 900 000 years or so.

c) Abrupt climatic changes during the Pleistocene

If the Milankovitch theory alone explained climatic changes during the Pleistocene, we would expect long and gradual shifts between glacial and interglacial conditions, just as the changes in solar energy input caused by orbital cycles are long and gradual. However, in the 1980s and 1990s it became clear from studies of past climate that the shifts between glacials and interglacials were remarkably rapid, and that glacials themselves were characterised by strongly fluctuating temperatures rather than being uniformly cold. Evidence contained in ancient layers of ice drilled from the Greenland ice sheet illustrates this best.

Two major ice-drilling projects in Greenland, the European Greenland Ice-core Project (GRIP) and the North American Greenland Ice Sheet Project 2 (GISP2), extracted long cores of ice from the summit of the Greenland ice sheet to depths of over 3000 m. The deepest layers of ice in the cores exceed 100 000 years in age, and annual layers of ice can be identified along the cores extending from the base all the way up to ice at the top that was laid down in recent years. This has made it possible to develop an incredibly detailed picture of how the climate has been changing at Greenland (and in the North Atlantic region generally) from the present to as far back as the beginning of the last glacial.

Information about past climate has been gained from ice cores in a number of ways.

- The thickness of an ice layer shows how much snow accumulated in a single year.
- Air bubbles trapped within the ice are used to infer the atmospheric concentrations of trace gases, like carbon dioxide and methane, when the ice was formed.
- The acidity of the ice is also measured to identify past volcanic eruptions that caused temporary increases in the amount of sulphuric acid in the atmosphere.
- Past air temperatures are reconstructed by studying the oxygen isotope composition of the ice itself.

As already described, $H_2{}^{16}O$ is more readily evaporated from the sea than $H_2{}^{18}O$. This means that snow falling on the Greenland ice sheet will always have a lower (more negative) $^{18}O/^{16}O$ ratio than sea water. Additionally, colder air is less effective at evaporating $H_2{}^{18}O$ from the sea than warmer air. As the air temperature in the North Atlantic region decreases, the $^{18}O/^{16}O$ ratio of snow falling on Greenland also decreases, becoming even lower (more negative) in relation to the ratio of sea water. Conversely, an increased $^{18}O/^{16}O$ ratio of snow (less negative in relation to sea water) relates to a time of increased temperature. The snow eventually forms a layer of ice that becomes part of the ice sheet, in this way preserving the $^{18}O/^{16}O$ ratio of the snow at the time that it fell.

Changes in the oxygen isotope ratio of layers of ice spanning the GRIP and GISP2 ice cores show that temperatures in the North Atlantic region have been highly variable over the past 110 000 years (Figure 4). Throughout the most recent glacial phase (the **Devensian** in the British Isles), which was well underway by about 73 000 years ago, there have been many large and abrupt climatic changes involving mean annual temperature swings of as much as 8°C occurring within just a few decades. The coldest phases of the Devensian, when $^{18}O/^{16}O$ ratios reach their most negative values on Figure 4, represent average air temperatures in the North Atlantic region that were about 12–13°C lower than the present day. These relatively short phases of intense cold that occurred during the last glacial, and during previous glacials, are known as **stadial** periods. Most of the peaks in $^{18}O/^{16}O$ ratios before the beginning of the Holocene Interglacial 11 500 years ago represent air temperatures that were 5–6°C lower than present, and these brief phases of relative warmth during glacials, lasting 500–2000 years, are known as **interstadial** periods. At about 11 500 years ago the ice core data show a rapid warming to maximum temperatures followed by sustained warmth, with less temperature variation during our current Holocene interglacial.

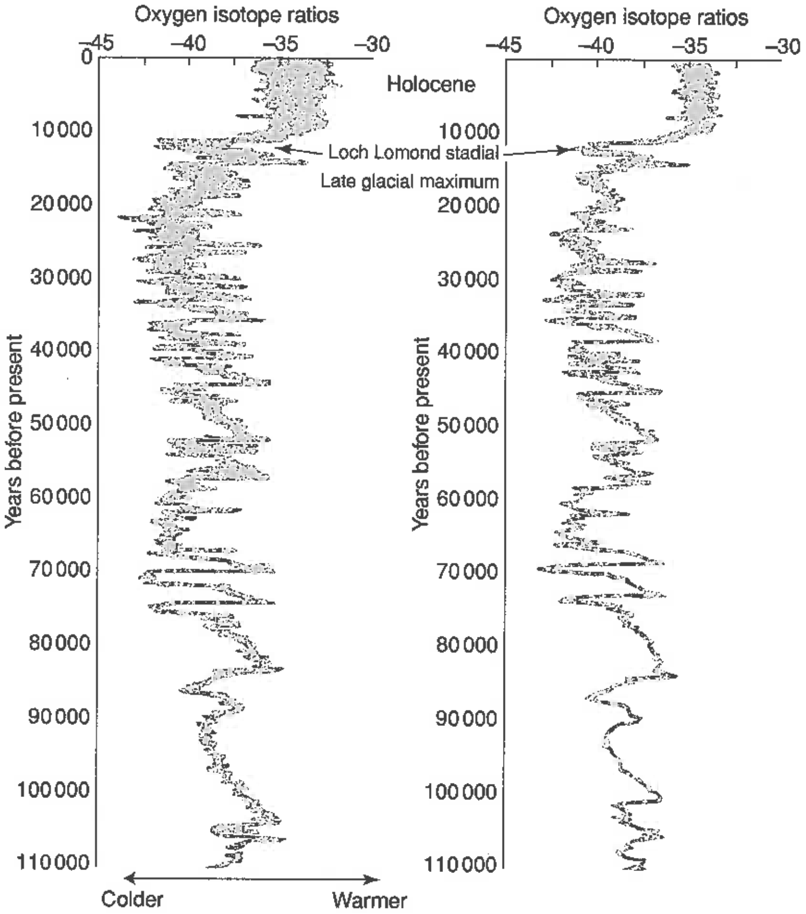

Figure 4 Oxygen isotope ratio data from the GRIP and GISP2 ice cores plotted against time (more negative values indicate lower temperatures). *Source*: Anderson (2000). Data from the National Snow and Ice Data Center.

During a glacial phase, the stadials represent times when ice sheets increase their size and tundra-type vegetation replaces woodland across mid-latitude land areas in the Northern Hemisphere, whereas the interstadials represent times of temporary ice sheet retreat and the northward spread of woodland. Although the interstadials are phases of relative warmth, they are not of long enough duration to be classed as interglacials. From the ice core data in Figure 4, it is seen that the shifts from cold stadials to warmer interstadials occur more rapidly than the shifts from interstadials to stadials. These abrupt and severe fluctuations in temperature during the last glacial are referred to as **Dansgaard–Oeschger events**, in honour of two ice core scientists who described them.

It is likely that all glacial phases during the Pleistocene have experienced similar climatic fluctuations to those identified from the ice core records for the most recent glacial. These rapid transitions between glacial/interglacial and stadial/interstadial affected the whole planet, although the magnitude of the temperature swings is greatest in the North Atlantic region, including north-west Europe and eastern North America. The cause of these Dansgaard–Oeschger events is thought to involve successive phases of build up and collapse of the large northern ice sheets, as discussed in Chapter 2.

5 Late Pleistocene Glaciation

a) Past glacier ice cover

The maximum extent of glaciers during the Late Pleistocene was reached during the last glaciation between 20 000 and 18 000 years ago when glacier ice covered over 30% of the Earth's land surface. The Antarctic and Greenland ice sheets only covered a slightly larger area than they do now, but there was far more ice across North America and Eurasia. Table 2 shows estimates of Late Pleistocene maximum ice cover and volume for different parts of the world.

Table 2 Estimates of the area and volume of regions of glacier ice during the Late Pleistocene maximum. *Source*: Smithson *et al.* (2002)

Region	Est. area (10^6 km^2)	Est. volume (10^6 km^3)
Antarctica	14.50	37.7
Greenland	2.35	8.4
Laurentide ice sheet	13.40	34.8
Cordilleran ice sheet	2.60	1.9
Andes	0.88	–
European Alps	0.04	–
Scandinavian ice sheet	6.60	14.2
Asia	3.90	–
Africa	0.0003	–
Australasia	0.07	–
British ice sheet	0.34	0.8
Total	**44.68**	**97.8**

The two major ice sheets of North America, as shown previously on Figure 2, were the **Laurentide ice sheet** to the east and the **Cordilleran ice sheet** to the west. The Laurentide ice sheet extended past the Great Lakes reaching as far south as latitude 39°N during the

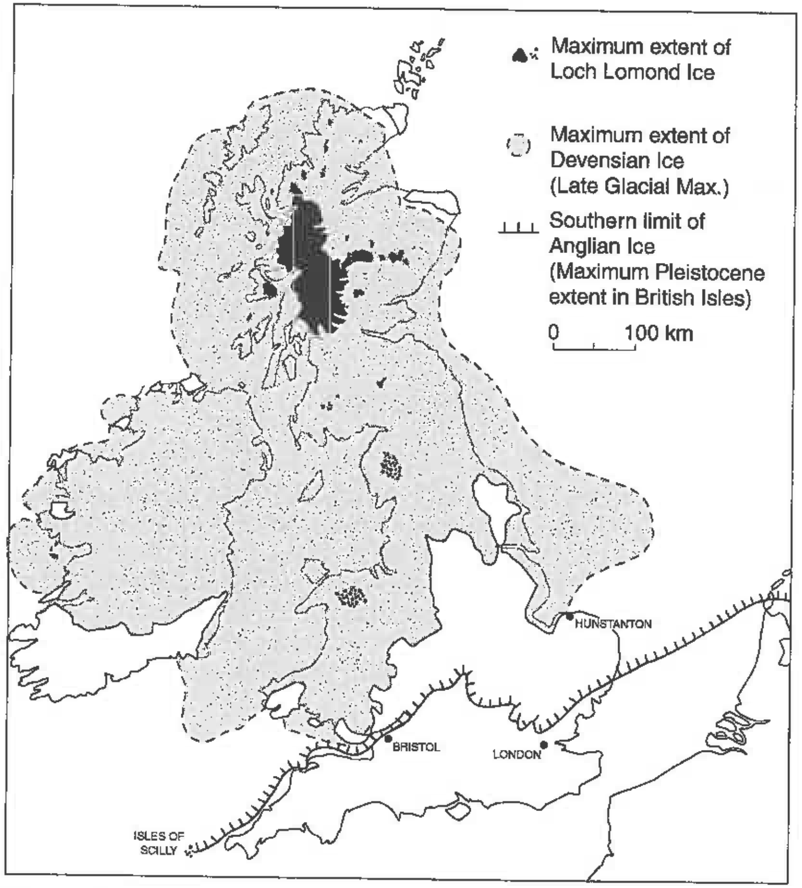

Figure 5 The extent of glaciation in the British Isles. *Source*: Goudie (1992).

last glaciation. At its centre around Hudson Bay the ice sheet grew to a thickness of nearly 4000 m. The **Scandinavian ice sheet** was thickest over Norway and Sweden, probably exceeding 3000 m in places. It extended eastwards across Russia, merging with glaciers from the Ural Mountains, and to the west it covered much of what is now the North Sea, at times coalescing with the British ice sheet. In the British Isles ice covered most of Ireland, Wales and Scotland and extended over much of northern England and the midlands as far south as East Anglia (Figure 5). There were also large accumulations of ice in Eastern Siberia, in Central Asia, the Andes, New Zealand and in the European Alps.

b) Effects of the ice cover

With so much water locked up in ice sheets during the last glaciation (over 5% of the world's water) sea level was more than 100 m lower than at present, and large areas of continental shelf that are currently submerged were dry land. For example, there was no English Channel; and Asia and Alaska were connected by the Bering land bridge, which is now the Bering Strait. As the ice sheets retreated, prehistoric people were able to migrate from Asia into North America by crossing this land bridge.

The great weight of ice sheets depressed underlying continental crust and, since glacial retreat, areas of crust have been rising in response to the removal of this overburden. This process of **isostatic uplift** is most pronounced where the ice was thickest. For example, in the eastern Hudson Bay region of Canada, where the Laurentide ice sheet was centred, land is still uplifting at a rate of about 1 cm per year.

The average global temperature was about 5°C lower than today during the height of the last glacial, and average temperatures were more than 10°C lower at high latitudes. Weather patterns across the globe were also very different. For instance, there was abundant rainfall in some regions that are now desert. The expansion of ice sheets in the Northern Hemisphere caused jet streams and mid-latitude depressions to track further south, for example increasing precipitation in the presently arid American South-west. Many other continental regions were drier than they are today.

The northernmost extent of woodland in the Northern Hemisphere was pushed far south during the last glacial maximum. In Europe woodland was restricted to Spain, Italy and the Balkans, and to the north the terrain was open, consisting of steppe and tundra-type vegetation. This landscape provided ideal habitat for large, cold-adapted grazing animals such as the mammoths that became extinct as the last glacial ended. Permafrost extended as far as southern France to the west and the Black Sea to the east, and periglacial processes affected much of Europe (as explained in Chapter 6). In the tropics the climate was cooler and drier, and tropical rainforest was less extensive.

c) The Lateglacial/Interglacial transition

The ice sheets began retreating about 18 000 years ago, with deglaciation proceeding rapidly by 15 000 years ago as the climate warmed. The period between 15 000 and 12 800 years ago is known as the **Lateglacial Interstadial**. At the beginning of this warm phase, average temperatures in north-west Europe were almost as high as they are today, and woodland began to spread northwards as the ice retreated. However, 12 800 years ago temperature plunged back to glacial conditions, remaining low until about 11 500 years ago when temperature again rose rapidly and the Holocene began. This cold phase at the end of the last glacial lasted approximately 1300 years and is known as the **Younger Dryas event**. During the Younger Dryas the retreat of ice was halted, and glaciers re-advanced in many parts of the world. Glacier ice had almost disappeared from the British Isles during the Lateglacial Interstadial, but during the Younger Dryas an ice field was re-established in the Scottish Highlands. In Britain this phase of glaciation is referred to as the **Loch Lomond Stadial**, and it saw the expansion of cirque and valley glaciers in upland regions of Scotland, England and Wales (Figure 5).

The transition from the Younger Dryas to the Holocene interglacial was characterised by rapid warming and glacier retreat. Data from the Greenland ice cores suggest a mean annual temperature rise of about 7°C in less than 50 years, with most of this warming occurring in as little as 3 years (Figure 4). The pollen from various plants preserved in lake and peat sediments shows that steppe-tundra vegetation was replaced by birch, pine and hazel woodlands across much of north-west Europe within 500 years, followed later by the arrival of temperate deciduous trees such as elm and oak. Sea level also rose as the ice sheets melted, finally stabilising around 7000 years ago once the Laurentide ice sheet had completely disappeared.