Chapter 2  
Reading the Landscape

‘[A glacier] is an endless scroll, a stream of time, upon whose stainless ground is engraven the succession of events, whose dates far transcend the living memory of man.’ (Forbes 1843, p. 22).

Abstract  In this chapter the history of European knowledge of glaciers and their influence on landscape and climate is traced, from Ignatz Venetz-Sitten and Jean de Charpentier’s glacial hypothesis, to Louis Agassiz’s and Karl Schimper’s theory of the Ice Age, and the gradual acceptance of the latter by the end of the 19th century. Further details of climate history were later revealed through fossilised flora and fauna in sediment layers (strata) and various dating methods. By the late 20th century, temperature records of several glacial and interstadial periods had been derived from oxygen isotopes in fossilised shells in deep-sea sediment strata and glacial ice cores from Greenland and Antarctica. Theories on the astronomical causes of climate fluctuations are outlined, e.g. those of James Croll and Milutin Milankovitch on the influence of Earth’s orbital pattern and axial precession and tilt on solar radiation penetrating the Earth’s atmosphere. A summary of glacial epochs from 130,000 years ago until the present time is then related, with reference to specific periods, e.g. late glacial, the Holocene and the Little Ice Age. The role of the North Atlantic and the transportation of tropical oceanic heat in climate fluctuations is also discussed. A brief history of glaciers in Iceland follows, from the settlement of the country until the present day. Finally, there is a discussion on the current climate of Earth and possible future changes.

2.1  The Long, Winding Road to Understanding Ice Ages

For thousands of years, the peoples of the northern reaches of Europe and America inhabited an environment shaped by ice-age glaciers, living among glacially polished rock formations and erratic boulders on ancient outwash plains and in glacially-gouged valleys between jagged crests of mountains (Figs. 2.1, 2.2, 2.3 and 2.4). But even though these traces of ancient glaciers were there for all to see, it
Fig. 2.1 ‘Grettir’s lift’ or erratic boulder. Metcalfe (1861). NULI

Fig. 2.2 Ground moraine and an erratic boulder in the central interior of Iceland on the Sprengisandur highland route to the north of Lake Þórisvatn. HB, 2004
was not until the 19th century that it finally dawned on scholars that a glacier had previously covered their territories (see Imbrie and Imbrie 1979, for a fundamental source of this chapter). Up until then, they had been convinced that lands and oceans had been virtually unchanged for as far back as their ancestors’ memories and recorded sources reached. Accordingly, they believed fertile fields, forests, marshes, and steppes had always existed and that mountains and valleys were a permanent part of the landscape. No narratives or experiences had been preserved of their predecessors who, 12,000–14,000 years ago, had to fight for their very survival at the edges of ice-age glaciers in Europe and North America. Nordic mythology, however, did at least preserve some legends of an Earth and sky originating from a frozen giant, who had originally been created from the mists of thawing ice that had previously enveloped the universe. And in the end, the world would not be destroyed by fire, but by the freezing of lands and oceans at Ragnarök (Sturluson 1987, pp. 52–53).

In countries with glaciers, such as Iceland, Norway and Switzerland, farmers and travellers had long noticed that large boulders and stony screes in otherwise green and vegetated valley basins, and even on flat outwash plains, were similar to those they were familiar with far away up by the glaciers (Fig. 2.5). In Iceland these boulders were called ‘Grettir’s lifts’ and in other countries ‘erratics’ because the rocks were unlike anything in their nearest environments and it was if they had somehow strayed there. Those who had often visited glaciers knew that their snouts

Fig. 2.3  Glacial terrain. The jagged peaks of Þverártindur (1554 m) with glacially eroded corries and steep outlet glaciers to the west of Kálfafellsdalur, inland from the Suðursveit district of Austur-Skaftafell County (Chap. 8). The pinnacles Karl (‘man’) and Kerling (‘woman’) are on the far right.
could advance with tremendous power, shaping the land they traversed, and they thought it only natural to conclude that glaciers had previously borne onto their home fields and meadows the gigantic boulders that no human power could ever possibly remove. Such reflections had been preserved in oral traditions, but the first written observation that erratic boulders could reveal the size of ancient glaciers came in 1787 from the Swiss lawyer Bernard Kuhn (1762–1825). Eight years later, in 1795, a Scottish geologist, James Hutton (1726–1797), the founder of modern geology, stated that he believed a great glacier had covered the Alps in former times and had deposited granite rocks all over the Jura Mountains, which are themselves made of limestone. Hutton’s (1795, 1959) observations were given scant attention, however, as his writings were stilted, a chore to read, and often obscure. Early in the 19th century, a German geologist, Leopold van Buch (1774–1853), put forward the theory that erratic boulders had come from Mont Blanc, the highest mountain of the Alps, which had suddenly surged upwards and scattered these rocks far and wide; erratic boulders in northern Europe had similarly arrived from Scandinavia. Neither craters from such a shower of rocks, nor scattered debris from such boulders shattering on impact, were anywhere to be seen, however. Most natural scientists thought it more likely that an enormous flood had transported these rocks, while at the same time creating kettle holes on mountain summits. It was well known how

Fig. 2.4 Single-standing mountains are sometimes all that remain of high promontories between deep valleys carved out by ice-age glaciers. Kirkjufell (463 m a.s.l.) in Grundarfjörður on the Snæfellsnes peninsula. HB, August 1998
rivers left behind large rocks, gravel and sand in their beds, and so until the second
decade of the 19th century, it was generally considered that all the debris dispersed
over the land, containing a mixture of large rocks, gravel and sand, had been
deposited there by one or more catastrophic floods similar to those described in the
tales of ancient peoples, such as the Egyptians. Moreover, as such a flood had been
recorded in the Bible, it was thus an irrefutable fact. On the other hand, however,
there were no comparable examples of more recent catastrophic floods, though
there was evidence to the fact that in 1755 a huge flood wave (what today would be
called a tsunami) had catapulted large boulders ashore at Lisbon during the great
earthquake which took place just off the shores of Portugal.

Did icebergs transport erratic boulders? It was obvious that large boulders
could not float and that, no matter how powerful, no current of water would be
capable of moving granite rocks 1500 m high up onto the valley sides of the Jura
mountains, on the border between France and Switzerland, or the hundreds of
kilometres from Norway over the North Sea to the northern parts of England and
Germany. The English geologist Charles Lyell (1797–1875) put forward the
hypothesis in 1833 (Principles of Geology) that the boulders had been transported
by floating icebergs, which had drifted from the polar regions when the sea level
was higher than it was now (Lyell 1830–1833, 1865, 1990–1991). Originally frozen
to the icebergs, the boulders finally broke off and sank when the icebergs melted.
Such icebergs were familiar to seafarers in the northern seas and fossilized fish and

![Fig. 2.5 View from Steinasandur up to Brókarjökull, just visible at the head of Kálfafellsdalur (Chap. 8). It is hard to believe this apparently small outlet glacier had once extended right out onto the outwash gravel plain. HB, July 1999](image-url)
Fig. 2.6 Early thinkers of glacial landscaping. (From left to right, top to bottom) James Hutton (1726–1797), Scottish geologist. Jens Esmark (1763–1839), Norwegian geologist. Ignatz Venetz-Sitten (1788–1859), Swiss civil engineer. Jean de Charpentier (1786–1855), German-Swiss geologist. Louis Agassiz (1807–1873), Swiss scholar of natural sciences. Karl Friedrich Schimper (1803–1867), German natural scientist. William Buckland (1784–1856), English geologist. Georges Cuvier (1769–1832), French palaeontologist. Otto Andreas Lowson Mørch (1828–1878), Danish conchologist.
shells in sediment strata in Europe revealed that the ocean had once covered land. It thus seemed more logical to assume that ice had travelled from northern regions by floating across the ocean rather than by crawling over land. Icebergs could also have been borne south in gigantic floods. The icebergs highest in the Jura Mountains, however, must presumably have originated from ice in lakes. Drifting ice not only carried large boulders, but also dispersed a haphazard mixture of clay, sand, stones and gravel, which was why this kind of debris was given the name ‘drift’ in English.

**Did glaciers disperse erratics?** This is how things stood until early in the 19th century (1815), when Jean-Pierre Perraudin, a guide in the southern part of the Swiss Alps, opined that one might conclude from the striation in the bedrock, which all slanted downwards, that glaciers had previously descended slowly along these valleys and bore with them rocks. He failed to arouse the interest of the German-Swiss geologist Jean de Charpentier (1786–1855) in his ‘glacier hypothesis,’ but he did succeed in gaining the attention of the civil engineer Ignatz Venetz-Sitten (1788–1859), who in 1821 published the conclusions to his own observations on landscape formation far from glaciers supporting the idea that glaciers in the Alps had previously extended far down into the valleys and moulded the topography there (Venetz-Sitten 1861). In 1824, the Danish-Norwegian geologist Esmark (1763–1839, 1824) came to the conclusion, completely independently from the Swiss scientists, that glaciers had formerly covered a large part of Norway and its offshore seabed and had transported erratic boulders and pushed up moraines (Fig. 2.6).

### 2.2 Venetz-Sitten, de Charpentier and the Glacial Hypothesis

In 1829, Venetz-Sitten (1861), in an instructive lecture for the Swiss Society of Natural Sciences, maintained that the lowlands to the north of the Alps, and indeed the whole of northern Europe, had previously been covered by a glacier. He described erratic boulders in the valleys, often high up on mountainsides, which were both striated and with sharp edges similar to rocks in the vicinity of active glaciers; he also gave an account of the curved ridges of gravel and rock that stretched right across vegetated valleys, similar to those in pastures high up near the Alpine glaciers. This now aroused the curiosity of Jean de Charpentier, the overseer of Swiss salt mines, who had become interested in glaciers in 1818 after a large number of people perished in a flood caused by a proglacial lake bursting its ice-dam. De Charpentier himself began examining erratic boulders and glacial moraines, and at a meeting of the Swiss Society of Natural Sciences in 1834, he systematically presented a variety of evidence supporting the idea of landscapes being formed by glaciers that had long-since disappeared. De Charpentier was a meticulous and highly-regarded scientist, and he presented facts that are now
considered indisputable evidence of ancient glaciers, but his lecture was nonetheless greeted rather indifferently by his colleagues. He later mentioned that on his way to the meeting a woodcutter had told him how he believed ancient glaciers had formed the landscape, exactly as de Charpentier himself had been similarly convinced. Opponents of the glacier hypothesis, on the other hand, inclined to agree with Lyell’s idea that icebergs had previously floated on the sea above Switzerland and, when they melted, erratic rocks had broken free from them and been deposited on the land. In the Alps, mountains are indeed more noticeable than glaciers, so that hypotheses about giant glaciers seemed unlikely, especially since the huge glaciers that actually did exist on Earth at that time still remained unknown to man.

Proclaiming the theory of a large glacier, which had long-since vanished. Jean de Charpentier was not particularly interested in making his views widely known or accepted, but he did want his colleagues to appreciate them. One of these colleagues was a former grammar school student of his, Louis Agassiz (1807–1873), an ambitious biologist who had become chairman of the Swiss Society of Natural Sciences. Agassiz had researched fish fossils in sediment strata and his work had attracted a great deal of attention from geologists because he could differentiate between freshwater and oceanic fish and thus decide whether sedimentary deposits had been formed in lakes or the open sea. In 1836 de Charpentier invited Agassiz to spend some time with him during the summer at his mountain retreat, where he showed him the traces of what he considered evidence that great Alpine glaciers had once covered the land there. Agassiz had listened to de Charpentier’s lecture in 1834, but had been sceptical about his glacial hypothesis. Seeing with his own eyes, however, how the landscape had been formed by glaciers pushing ahead of them rubble and striating and smoothing the bedrock, it then became clear to him that the erratic boulders lay in demarcated areas at the mouths of valleys, which glaciers had previously traversed, and were thus not dispersed as haphazardly as might be supposed if they had been transported there by floating icebergs at sea. Moreover, the erratics’ sharp edges seemed to indicate they had not been eroded in the tumbling waters of a massive flood. The fact that rocks were found over a much wider area than oceanic fossils also countered the idea that erratics had sunk from icebergs to the ocean bed. Agassiz not only concurred with the ideas of Venetz-Sitten and de Charpentier, but he also became captivated by a new vision (see Carozzi’s translation of Agassiz 1967).

2.3 Agassiz, Schimper, and the Birth of the Theory of the Ice Age

Agassiz was a fervent man, imaginative, energetic and indefatigable. His task would not give him any peace, neither by day nor sleepless nights. He now turned all his energy towards glacial research and investigated in detail the movements of the Aar glacier in Switzerland, becoming convinced that glaciers could transport
huge boulders. He sent for his old friend and schoolfellow, the botanist Karl Friedrich Schimper (1803–1867), who was also a passionate observer of nature. Schimper encouraged Agassiz, when others tried to dissuade him, and thus began a collaboration which led to Venetz-Sitten and de Charpentier’s glacial hypothesis becoming transformed into the theory of the Ice Age. At first the two collaborators pointed out to their colleagues that glaciers had covered the Alps from the Jura Mountains to Bavaria. The glacier then grew so rapidly in their minds, however, that in the end they considered that at an even earlier point in Earth’s history a thick glacier had enveloped the northern hemisphere from the North Pole area to as far south as much of the continental mainland of Europe, Asia and North America. This hypothesis of a continental glacier was very daring. No human being lived near the remains of an ice-age glacier in Antarctica and it was still not clear then that one complete ice-shield covered the whole of Greenland. The idea that there had been a period in Earth’s history when a glacier had covered land from the North Pole to Germany, had actually been promulgated earlier, in 1832, by the German professor and forester Reinhard Bernhardi (1797–1849), who was familiar with the work of Jens Esmark in Norway, but Bernhardi’s publication (1839) had attracted little attention.

Agassiz and Schimper pointed out that the existence of an ancient, enormous continental glacier could only ultimately be explained by the Earth cooling so extensively that an Ice Age had suddenly been unleashed. Since then, the Earth had gradually become warmer once more, but never reaching the temperature prior to the Ice Age, thus in the long term the Earth had cooled overall. This was a revolutionary idea that had not occurred to anyone previously, for it had always been assumed that Earth had been in a continuous cooling state ever since it had come into existence. Lyell had always maintained that, despite a few local and minor fluctuations, Earth’s climate had been stable. De Charpentier stated that the large Alpine glaciers had been formed because the mountains had then been higher than in modern times and thus much colder. Agassiz and Schimper put forward yet another more radical idea: that the Ice Age had been a catastrophe for the natural environment and had exterminated all forms of life wherever ice had covered the Earth. Agassiz presented this theory to the Swiss Society of Natural Sciences in 1837, going a step further than Esmark, Venetz-Sitten and de Charpentier, who had proposed that only glaciers in the Swiss Alps and Norway had thickened and extended over nearby areas of land. De Charpentier now considered the young enthusiast to be making reckless assertions about ice-age glaciers covering whole continents, and felt that Agassiz had gone well beyond what his evidence could prove, especially since he had never even been to North America or Asia.

Agassiz became an energetic bearer of these new tidings and published his theory of the Ice Age three years later in 1840 in his book *Études sur les glaciers*, which he dedicated to Venetz-Sitten and de Charpentier. Both they and Schimper, however, felt that their contributions were given scant acknowledgement in Agassiz’s book (1840, 1867), and they never forgave him for this. De Charpentier had himself been working for a long time on a book and considered he had the right to publish his own findings first, and thus Agassiz’s dedication of his book to him
which had been published a few months ahead of de Charpentier’s work) did not make up for this. Furthermore, Agassiz had included Schimper’s diagram in his publication, showing how fluctuating temperatures on Earth could have brought about ice ages, without even citing his original source (Fig. 2.7).

Schimper had become the first to put forward the concept of the Ice Age, *Eiszeit*, in 1837, and he was a much more likely scholar than Agassiz to leap, without evidence, from the glacial hypothesis to the Ice Age theory. Schimper was a romantic scientist who was searching for a comprehensive, universal and perfect coherence in the natural world. He was looking for a complete picture, without closely examining its individual pieces, as he created the whole by fitting them together, as in a jigsaw puzzle; the theory of the Ice Age was a vision similar to a model he was looking for to illustrate the pattern of plant life. Agassiz, on the other hand, was more down-to-earth, and his conclusions always strictly adhered to factual evidence; he did not regard his results as a theory, but as established facts. Later in his life, and using a similar tone to that of his mentor, the French pioneer in palaeontology Georges Cuvier (1769–1832), who had always scoffed at romantic scientists, Agassiz wrote scornfully of Schimper’s contribution, claiming that Schimper had merely put forward some speculations. It is now an impossible task to distinguish exactly between Agassiz’s original contribution to the theory of the Ice Age, on the one hand, and Schimper’s on the other, but it is clear that both of them made such vital contributions that neither of them could have put forward the theory without the work of the other. Indeed, it is a needless simplification to attribute the theory of the Ice Age to a single man, as is so often done. Nonetheless, it should be pointed out that if the pioneers of the Ice Age theory had restricted themselves to only the obvious facts, they would not have advanced knowledge beyond the stage it had reached in 1830. Neither Agassiz nor Schimper attempted to explain the cause of the Ice Age, and indeed they did not completely understand all the implications of the Ice Age hypothesis, as will be noted later.

**Difficulties of promulgating the theory of the Ice Age.** Agassiz preached the Ice Age theory with religious conviction and eloquence. Sheets of ice had destroyed all life forms, buried mammoths, covered inland lakes, oceans, and large tracts of land, so that the silence of death reigned there: rivers ceased to flow, the Sun rose over a frozen Earth, the northern winds howled, and deathly-deep crevasses in the ocean of ice groaned and rumbled. Agassiz considered the frozen remains of whole mammoths, which had been discovered in Siberia, as illustrating two points: how rapidly the Ice Age had descended and what kind of catastrophe had caused the mammoths’ extinction. There had been previous hypotheses that a gigantic flood...
had swept the mammoths along great rivers from their southern climes all the way north to Siberia, where they froze to death, for indeed the land there was uninhabitable because of the cold and there was nowhere near enough forage for such a large land animal (Fig. 2.8).

Georges Cuvier had in 1796 previously come to the conclusion from his study of the mammoths’ skeletons that they were an extinct species unrelated to African elephants. Agassiz had now presented the hypothesis that they had become extinct because of an ice age and not due to a catastrophic flood. The son of a pastor, Agassiz felt that this could well accord with his belief in God and even be cited as God’s direct intervention in history and His creation of a new world following catastrophes. Ice instead of water could hardly be seen as seriously contradicting the words of the Bible. The Ice Age completely destroyed all life, and when it came to an end new species of life forms immediately arose without being connected to any predecessors on Earth, and they would remain unchanged until they too became extinct. Agassiz thus supported the stance of his mentor Cuvier, as opposed to the theory of evolution of Jean-Baptiste Lamarck (1744–1829) that species developed into other species. Agassiz considered his and Cuvier’s stance not as a theory but a fact! The existence of fossils in sediment strata was explained in the 18th and 19th centuries by natural catastrophes that had swept over the Earth and destroyed life.
again and again, making species extinct, and that life had then been revived once more by an intelligent instigator who had a continuing interest in maintaining his creation. This was how life developed through natural catastrophes. Agassiz believed that all connections between life forms before and after the Ice Age had been severed and he never accepted the theory of the origins of species by Charles Darwin (1809–1882).

The response to Agassiz’s message was a mixture of apathy and denial. More was clearly needed to overturn the ideas then current and to introduce new ones. Agassiz was a tireless herald of the theory of the Ice Age and gained a tremendous victory when he managed to persuade an important adversary to support his views: William Buckland (1784–1856), Professor of Geology at the University of Oxford in England. Buckland (1836) had been a convinced spokesman for the theory of the catastrophic flood, which had once inundated the entire world, and believed it explained the irregular distribution of rocky debris in the British Isles. Being a geologist, his contribution to supporting the text of the Bible had increased respect for geology within the conservative British society; one of his publications, for instance, was titled: Geology and Mineralogy, Considered with Reference to Natural Theology. It was evident to the geologist, nonetheless, that the supposed dispersal of rocks from a catastrophic flood could not be specifically attached to one area, or be an indication of one forty-day Biblical flood.

Daring scientific theories often greeted with scepticism. In 1838 Buckland travelled around Switzerland with Agassiz and saw the polished and striated rocks and moraines that Agassiz considered traces of ancient glaciers. Buckland was not convinced, however, until in 1840, when he travelled with Agassiz in Britain and saw for himself similar landscapes in Scotland, Wales and northern England. From then on, Buckland became a sincere spokesman for the theory of the Ice Age, as this explained the existence of sediment layers in large areas of Britain far better than the Great Flood. Buckland then showed these landscapes to Lyell which resulted in the latter also agreeing with the Ice Age theory, though he did not become its spokesman. Indeed, Lyell never believed that ice ages had destroyed all life on Earth and, like his predecessor James Hutton, always criticised theories founded on the Biblical version of the creation of the world, which presented catastrophes as an explanation for the existence of fossils of extinct life forms. Both Lyell and Hutton maintained that fossils had been buried in sediment strata which would have been layered at exactly the same pace as in contemporary time. Thus the present would be the key to the past. Past events in geological history could be explained through processes which were still ongoing and which always obeyed and revealed the same laws of nature; processes and natural laws remaining constant are the core principles of uniformitarianism. Hutton’s theories, however, had been more or less dismissed because they implied that Earth was much more than 6000 years old, contradicting a belief the ruling social powers strictly adhered to in the 18th century.

British geologists still maintained the old opinions, therefore, and could not envisage large glaciers in Wales or anywhere else in the British Isles. The mountains were simply not high enough in order to help create considerably large
glaciers, and inland lakes were too big to have been buried under the ice of small glaciers. British scientists could agree to earlier glaciers in the Alps once being larger than they were currently, for indeed it was clearly visible towards the end of the Little Ice Age that the Alpine glaciers were variable and had recently advanced significantly. On the other hand, it was extremely difficult for people to imagine gigantic continental glaciers many kilometres thick and thousands of kilometres in length. Moreover, physicists were unfamiliar with glaciers and could not understand how they could move, let alone creep up mountainsides. Scientists did not then know that a glacier came into existence through the accumulation of snow, which then travelled downwards from its accumulation zone towards its snout. Agassiz was more than convinced, however, that glaciers had pushed up moraines, transported large boulders, and polished and grooved the bedrock over which they traversed; uncertainty as to how exactly this was done did not alter the fact! Pioneers of the glacier hypothesis thought it enough to know this, they did not need to understand it. Indeed, none of the original spokesmen of the Ice Age theory then understood the connection between glaciers and climate. Schimper and Agassiz believed that colder temperatures had caused an ice age, and that was sufficient. Coldness on its own is not enough for the formation of glaciers, it also needs snow: i.e. it is a combination of cold temperatures plus precipitation. Nor was it enough to suggest that mountains had been higher when glaciers were formed, as de Charpentier had maintained, because if the climate had remained unchanged the ice would have melted as it reached the lowlands. What was still needed was an understanding that glaciers had been formed by cooling weather conditions and an increasing accumulation of snow.

A sceptical reception of radically new scientific ideas is nothing new, for naturally such ideas had to be tested and proved. But the reluctance to accept them was also connected to the fact that many highly-respected scientists in the 19th century had gained their rank and reputation in a conservative society because their explanations of nature had strengthened the theories on how God had created the world and all its living creatures. Opposition to the Ice Age theory, however, was not primarily because it was not in accord with the Bible’s narrative and the academic works of scholars on the creation of the world, for there was already in existence an opposition to the policy of religiously explaining nature exclusively from the Holy Scriptures. All Agassiz and Schimper had done was to suggest an Ice Age had been unleashed instead of a Great Flood, but scholars were so fixed in their opinion that only flowing water could transport rocks and debris that it took the foremost natural scientists of that time three decades to bring others round to accepting the indications of ice ages as indisputable facts, even though no explanation had been found as to their cause.

In the middle of the 19th century it became clear that a huge glacier covered all of Greenland, and only then did many scholars finally come to agree that continental Europe might also have been buried under glaciers. Convincing indications came to light decades later that erratic boulders and bedrock striation in Scotland (Geikie 1874) had been caused by glaciers that had extended all the way from Scandinavia. The Swede Otto Torell (1828–1900) later traced the expansion of
glaciers from Scandinavia to northern Germany. He had previously travelled around Iceland and been convinced that the island had been covered by an ice-age glacier. Moreover, awareness of the enormous expanse of the ice sheet on Antarctica only finally became common knowledge later in the 19th century.

As for Agassiz, he immigrated to the United States in 1846, became a professor of zoology at Harvard University in New England in 1848, and made a tremendous impact on the development of teaching and research in the natural sciences in America. He returned to researching fish fossils, but he also investigated the expansion of an ice-age glacier in the New World, eventually even going so far as to claim that glaciers had covered all the continents of the Earth and had decimated all forms of life. God had then created the world once again.

2.4 Locating and Dating the Ice-Age Glacier

Research was now concentrated on investigating the extent of the ice-age glacier by marking the limits of the furthest glacial moraines. This was done by trying to trace where the ice had been originally transported from and by examining the directions of glacial striations and the location and origins of erratic boulders. This was mostly completed around 1875 when it seemed clear that one continuous glacier had covered all of Scandinavia and expanded towards more central latitudes, even reaching as far south as southern England (London) and the English Channel, northern Germany and Poland, the western parts of Siberia, and to Canada and far south on the North American continent. In the northern part of Alaska, the snowfall had not been sufficient to form a glacier even though its mean temperature was low. One continuous glacier had not reached all the way from the North Pole, as the pioneers of the Ice Age theory had believed. In the tropics, glaciers were larger and more numerous than they are today. At least a half of Earth’s dry land was covered by ice and snow in one way or another: ice caps carpeted about 30% (40,000,000 km²), permafrost about 20% (27,000,000 km²), and sea ice was present on half of the Earth’s oceans (Fig. 2.9; Flint 1971; Denton and Hughes 1981; CLIMAP 1981; Clark et al 1996; Bradley 1998). Ice sheets were 3 km thick over a wide area and at their centres there was so much water stored in glacial ice that, at the high point of the last glacial period, sea levels were 120 m lower than they are now. The average thickness of the ice can be calculated from the extent of the glaciers and the level of the sea. There are still remnants of this ice-age ice in Greenland and Antarctica.

Land masses during the last glacial period were different to what they are today. There were terrestrial bridges between England and continental Europe, and settlers crossed to North America over another land bridge between eastern Siberia and Alaska. Land animals inhabited wetlands where the North Sea and English Channel are now situated. The ice-age glacier advanced over land that had previously been under the sea, scraping up and bulldozing onto land shells from shallow waters, just like erratics, a long way inland in Germany, Scotland, England, and even New
England in North America. The Scot James Croll (1821–1890) drew attention to this in 1865, for it had previously been thought that the presence of shell and fish fossils in sediment layers on dry land proved that these areas had previously been suboceanic. Croll’s contribution (1864, 1875, 2012) to theories on climate change will be referred to again later.

So gigantic was the overburden of ice-age glaciers that they compressed the Earth’s crust, pushing it even further below the already lowered sea level. Eroding seas thus scoured far inland from the coast, and relics of oceanic life can be found in the hinterland at a great distance from the shoreline. When the ice age ended, the water that had been frozen in glaciers was once more discharged into the oceans and
seas, which immediately flooded over dry land. The habitat of mammoths between
England and the Netherlands became the North Sea. Coral that had been formed on
shorelines in southerly climes are now 120 m deep underwater. Sea also swept over
land that had been previously compressed by glaciers, but the Earth’s crust quickly
began to uplift again, once the weight of the ice had been removed, and coastal
regions began to arise slowly out of the ocean. Where there had once been a thick
glacier, ancient tidelines are now visible far inland and high above the ocean,
indicating an elevation of land far greater than the rise of the sea level due to glacial
melting. Fossils of oceanic organisms can thus be found in sediment layers at the
same height on dry land in many countries.

Palaeontological research also made it clear that even though organisms disap-
ppeared wherever a glacier covered land, ice ages had not totally decimated life, for
plants and animals had retreated before the ice, moving to more viable habitats and
adjusting to climate changes. Glacial periods became a catalyst for changes in flora
and fauna, and indeed modern man developed considerably during the last ice age.
Organisms were under pressure from the various effects of climatic changes, but
such a slow development was completely unlike the theory of natural catastrophes
held by Agassiz. It is now believed that the mammoths he believed had been frozen
to death, when an intense and mortal cold had been unleashed, had actually fallen
through the thin ice of the tundra that had begun to thaw during the end of the last
glacial period. They had drowned in cold water and then floated downriver. Climate
warming had tolled their death knell, not the ice age. The extinction of mammoths

Fig. 2.10  Gerard Jakob de Geer (1858–1943), Swedish
geologist who discovered the
chronology of varves
and other large mammals that had multiplied very slowly during the ice age is still an unsolved riddle, nonetheless. Many causes for this extinction have been considered, including climate change, transformed ecosystems, epidemics, and the excessive hunting of tribes that had crossed over the land bridge of the mountainous Aleutian Isles from Asia to the new world, America, when the sea level was lower during the last glacial period.

Once the enormous effects of the ice age had become evident, geologists then tried to evaluate how long ago it had come to an end. The American Grove Karl Gilbert (1843–1918), using the same hypothesis as Hutton, that geological processes of the present were the key to the past, investigated how long it would take the Niagara Falls to erode its edges and then, by applying the same erosion speeds since the ice-age glacier had disappeared from the area, he calculated that the gorge beneath the falls had been gouged out during a period of about 7000 years (Gilbert 1890). The Swede Gerard de Geer (1858–1943; Fig. 2.10) then discovered a more exact way to determine the age of deposits when he found regular annual layers of sediment (varves, Fig. 2.11) that glacial rivers had dispersed around the ancient Baltic Sea, which had previously covered a large part of Sweden (de Geer 1912). In summer a thicker, rougher sediment was deposited and in winter this was super-

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**Fig. 2.11** Holocene sediment strata in the banks of the Jökulsá á Dal preserve a history of climate change. This is now all submerged under the Háslón reservoir (Chap. 8.8.5). HB, August, 2002
imposed with a thinner more refined deposit, so that distinct varves were created. It has proved possible to count these layers 12,000–13,000 years back in time and so it became clear how long ago the meltwaters had been discharged from the glaciers. The oldest part of the ice-age glacier in Scandinavia had retreated rapidly 12,000 years ago, although all the ice had not disappeared completely until 6000 years ago.

2.5 Traces of Many Glacial and Interglacial Periods in Sediment Layers

In the 1850s and 1860s, sediment strata visibly revealed how ice-age glaciers had advanced and retreated many times. Beneath lifeless remnants of an ice age, sediment layers could be found with fossilised plants and animals that had lived in a warmer climate and then been buried under ground moraine. This indicated that there had not been one continuous ice age, but rather a series of cold periods during which glaciers had lain over the land. These cold periods were interrupted by short warmer interludes during which the glaciers melted enough to enable flora and fauna to inhabit land previously covered by ice.

By the beginning of the 20th century, geologists had already distinguished four separate advances of a glacier far south on the continents. In Europe these periods of glacial advances were named after rivers in which traces of their progress were visible: Günz (the oldest), Mindel, Riss and Würm (Penck and Brückner 1909); in North America they were named after states: Nebraska, Kansas, Illinois and Wisconsin (in order of age). Geologists traced their deposit layers far back in time according to such characteristics as chemical composition and size of grains. Fossils of flora and fauna bore witness to the climate when the layers of sediment came into existence, and microscopic windborne pollen grains revealed the composition of the contemporary vegetation. All discussion on this topic was marked by uncertainties because geologists found it difficult to date sediment deposits and remnants of glaciers, for varves and annual rings in tree trunks were only of use after the last glacial period ended. Glaciers had destroyed older deposits in previous expansions. At the end of the 1930s, however, there was a watershed in the study of ice-age remnants when Willard Libby (1908–1980) at the University of Chicago discovered that the age of seashells and remains of vegetation in deposit layers could be determined by measuring their levels of radioactive carbon ($^{14}$C; Libby 1952); at first it was only possible to date them back to 40,000 years ago, but later, due to improved measuring techniques, these objects could be dated back to 75,000 years ago. This resulted in a huge increase in knowledge, not only of the last cold period of the ice age, which reached its peak about 18,000 years ago, but also of the late glacial period that succeeded it, and finally of the present contemporary time period,
the Holocene. This history will be dealt with in more detail later, but first let us return to the Ice Age theories.

A Radiocarbon Clock Measures the Age of Terrestrial Layers

Dating sediment layers through the measuring of radioactive materials opened up new methods for researching ancient climates. When organisms die, a radioactive clock begins to tick that measures the time from their decease. The radioactive isotope carbon-14 ($^{14}$C) has a half-life of 5730 years and it decays exponentially, thus by measuring its current levels in animal and plant remains, their age can be deduced if the original level of the organisms’ carbon content at death is known. The radioactive isotope carbon-14 spreads evenly throughout the upper atmosphere because of the constant impact of cosmic rays on nitrogen, and it binds with oxygen to form radioactive carbon dioxide ($^{14}$CO$_2$), which then mixes with ordinary carbon dioxide in the atmosphere (CO$_2$ with the isotopes $^{12}$C and $^{13}$C). Plants then absorb this carbon dioxide (CO$_2$), combined with hydrogen (H), through photosynthesis to form sugar, which is then ingested by animals feeding on the vegetation, and this is how carbon-14 enters the food chain of all living organisms. When they die, this photosynthesis ceases and the radioactive clock begins to tick.

The proportions of $^{14}$C/$^{12}$C are measured in the remains of once living organisms. After 40,000 years, 7 half-life periods of radioactive carbon, there is only 0.8 % of its former level left, 0.006 % after 75,000 years (13 half-life periods); it has not proved possible to measure lesser amounts. Many things can impair the clock’s accuracy once it has been activated, however. Material containing new or old radioactive carbon has perhaps been added to the remains of the organism in question, e.g. by entering its plant roots or by its being soaked in carbon-rich waters. The levels of carbon-14 have also varied in the Earth’s atmosphere over thousands of years. When compared to its current level, if the carbon-14 had been higher at the time of the organism’s death, its carbon dating will now be too low. A comparison of the ages of tree rings reveals the necessity of adding 700 years to an age calculated to be about 6000–9000 years old, because the carbon-14 level was greater then, than now. In a 200-year period about 12,000 years ago, and shortly after 10,000 years ago, it is impossible to date things accurately. Willard Libby received the Nobel Prize for chemistry in 1960 for his research into carbon dating (Fig. 2.12).

It later became possible to calculate the age of much older objects in the geological history of the Earth, inorganic volcanic rocks, for example, through radioactive materials that have longer half-lives than radioactive carbon. Radioactive kali ($^{40}$K) has a half-life between $1.25 \times 10^{9}$ years and then becomes argon ($^{40}$Ar); it is assumed that during a volcanic eruption minerals are without argon ($^{40}$Ar); it is assumed that during a volcanic eruption minerals are without argon. Using the uranium series (Th$^{230}$, U$^{234}$ and U$^{235}$) of radiometric dating, ages between thousands and hundreds of millions of years can be calculated.
Once the dating of objects through radioactive material had been established, it was possible to correlate such data with the results of other methods involving the analysis of tephra layers, pollen dispersal, and amino-acids (decay of protein after death of an organism, which is actually related to temperature). Furthermore, geologists learned to utilise magnetic directions when analysing layers of rock (Fig. 2.13). The Earth’s magnetic field has constantly been changing because the location of the magnetic poles has slowly oscillated, though considerably more during Earth’s geological history. During lava flows, minerals adjust themselves to the direction of the magnetic field; so too do iron-rich particles in deposits such as drifting soil and volcanic ash. Magnetic directions are thus one of the features of Earth’s strata, and by calculating the magnetic direction of rocks and dating them with the K-Ar method, changes in the directions of the Earth’s magnetic fields through the ages have been recorded. Furthermore, the specific turning points of Earth’s sudden geomagnetic reversals (the last being the Brunhes/Matuyama reversal about 780,000 years ago) can be utilised as a clear reference point in determining the historical layers of geological strata.

Fig. 2.12 Willard Frank Libby (1908–1980), the American physicist who discovered how to date objects by measuring their levels of radioactive carbon, a method since used in archaeological and geological sciences
In 1842, just two years after Agassiz published his book on the Ice Age theory, the French mathematician, Joseph-Alphonse Adhémar (1797–1862), put forward the idea that it was periodical oscillations in solar radiation, in correlation with Earth’s orbit in space, which caused ice ages (Fig. 2.14). Adhémar reiterated that the Earth had seasons because its axis of rotation was at an angle of 23.4° in its elliptical orbit around the Sun (Adhémar 1842). Winter was thus a week shorter than summer in the northern hemisphere because the Earth was nearest to the Sun during the winter and moved faster in its orbit due to gravitational forces; daylight in spring and summer was 168 h longer than from autumn until the end of winter. This, he
believed, explained why there was currently no ice age in the northern hemisphere. It was the direct reverse in the southern hemisphere, where there was a week longer of darkness than daylight and thus a huge sheet of ice—though no one then had actually seen Antarctica.

Adhémar then pointed out that because of long-term changes in the direction of Earth’s axial tilt in space, the seasons changed according to its orbit around the Sun. He put forward the hypothesis that due to Earth’s precessional cycles its polar regions had large ice sheets in turn. About 13,000 years ago, Earth had been nearest to the Sun in summer in the northern hemisphere, interglacial periods had been short, and ice sheets had covered the northern hemisphere all winter long, while the southern hemisphere had been free of ice. There was little support for Adhémar’s hypothesis. The great natural scientist Alexander von Humboldt (1769–1859) did not believe that the differing distribution of solar radiation during the seasons could explain ice ages. He pointed out that Earth’s hemispheres received the same sum total of solar radiation over the year as a whole; what was lacking in solar radiation
in one half-year was compensated for in the other. Nor does Adhémar’s hypothesis actually explain the existence of an ice sheet at Antarctica, either. It came into being 30–35 million years ago with the cooling of the early Oligocene period, reaching its full extent 10 million years ago, and has remained little changed ever since. Isolated from warm oceanic currents, it rises high above the sea and reflects almost all the solar radiation it receives and so maintains an intense coldness.

Indications appearing in the 1850s, that there had been glacial and interglacial periods in turn, helped maintain a continuing search for the causes of fluctuations in climate. Approximately two decades after the publication of Adhémar’s work, James Croll pointed out that in addition to axial precession, eccentricities in Earth’s orbit could also cause regular oscillations in the levels of solar radiation that reached Earth. Croll believed that the combined effect of Earth’s orbital eccentricities and precession could explain the appearance of ice ages. The level of solar radiation is fairly equal all year when Earth’s orbit around the Sun is almost circular, but varies according to seasons when it is mostly elliptical. When the inclination of Earth’s axis is tilted away from the Sun and its orbit is at its furthest distance from it, the period of darkness increases by five weeks (36 days) from when it is in a circular orbit. Croll believed that, in such circumstances, cold winters over thousands of years could produce ice ages. Even though the hemispheres received the same amount of solar radiation over the whole year, small irregularities in Earth’s orbit could still affect the seasons just enough to produce glacial periods. When the orbit is mostly elliptical, Earth’s hemispheres take it in turn to bear ice-age glaciers for a period of around 11,000 years, and regular interglacial periods would exist when the orbit was almost circular.

Scientists generally felt that fluctuations in solar radiation caused by these influences would be too small to have an impact on climate. Croll’s main idea, however, was that the influence of small variations in solar radiation could be amplified by their multifarious effects on air flow patterns and ocean currents influencing changes in the transportation of humidity in the air and sea from the equatorial to the polar regions. An increased difference in temperature between the equatorial and polar regions would strengthen moisture-laden winds and snowfalls that reached northern areas. Once a glacial period has begun, it starts to grow in magnitude, because as glaciers expand there is a greater reflection of solar radiation from Earth, reducing its energy gain, and thus temperatures continue to fall. Croll was thus the originator of the idea that scientists are now concentrating on, i.e. that astronomical causes could instigate, rather than fully explain, the fluctuations between glacial and interglacial periods.

Croll did not know how long the cycles between axis inclinations could be, and nor could he evaluate their effects on solar radiation; other things being equal, however, glacial periods usually begin when Earth’s axial obliquity is small, the polar regions receive the least solar radiation, and the difference in temperature is at its greatest between the polar and equatorial regions. We now know that this cycle lasts for 41,000 years (Fig. 2.15).
(a) Period ~ 100,000 years

Elliptical

Period ~ 100,000 years

Almost circular

(b) Period ~ 41,000 years

Axial tilt

21.4°

24.4°

(c) Period ~ 22,000 years

Axial precession

23.5°

Now

Winter

Summer

After about 11,000 years

Increased heat in summer in northern hemisphere

Reduced heat in summer in northern hemisphere

Fig. 2.15 Astronomical causes of climate change
Hypotheses on Astronomical Causes of Climate Change Clarified

From the mid-19th century onwards, hypotheses emerged about how the regular changes in Earth’s orbit around the sun and the direction of its axial rotation could affect the levels of solar radiation that reached Earth’s atmosphere and could even cause ice ages. The Serb Milutin Milankovitch (1879–1958) is best known for his theories concerning this matter (Fig. 2.16). About 175 years after Johannes Kepler (1571–1630) had explained how Earth’s orbit around the Sun is elliptical, the mathematician and astronomer Joseph-Louis Lagrange (1736–1813), who was born in Italy, but spent most of his career in France and Germany, discovered that its orbit oscillates between being elliptical and almost circular. This was caused by the varying and accumulative effects of other planets’ gravity in our solar system; they all lie in the same orbital plane and circle the Sun at varying lengths of time, so that the gravitational effects between them change accordingly. When Earth’s orbit round the Sun is almost circular, the levels of solar radiation on the planet’s surface are even all year round, but when its orbit is mostly elliptical, the seasons vary in length. The limiting effect on solar radiation that reaches Earth is minimal (less than 0.7 % over the year), but there are great fluctuations, nonetheless, because this radiation energy is unevenly dispersed over the seasons and longitudes due to the direction and tilt of Earth’s axis changing in the course of time.

During its orbit around the Sun, Earth’s axis tilts at an angle of 23.4° from an imaginary vertical line through the centre of the ellipsis. In winter, Earth’s northern part tilts away from the sun, but in summer it tilts towards it, so that the midnight sun reaches the Arctic Circle at 66.6°N. The tilt of Earth’s axis oscillates, on the other hand, over a period of 41,000 years between 22.0° and 24.5°. The Arctic circle crossed Hrísey island in Eyjafjörður 5000 years ago, but it now crosses Grimsey, off the northern shore of Iceland, and is still moving northward at about 14 m a year, though its movements fluctuate. With an increased axial tilt, the Sun reaches higher in the sky and summers are warmer, but conversely winters are darker and colder; the lengths of seasons increasingly vary.

The direction of Earth’s axis in space also changes and this also affects the lengths of seasons; the solstices (when the Earth is nearest to and furthest from the sun) and the equinoxes are moved on the orbital ring. Earth thus rotates like a spinning top so that the axis completes a whole circle in 26,000 years, and its spinning pattern can be visualised as outlining the shape of a cone. Due to changes in the Earth’s orbit, mentioned above, the axial tilt is reckoned from the Earth’s perihelion point (nearest Sun) every 22,000 years. Thus the seasons have moved during the Earth’s orbit round the Sun by almost three months since the time of the Ancient Egyptians about 5000 years ago. About 11,500 years ago, the perihelion was in June, when the southern hemisphere faced the Sun, and the aphelion in January, and winters were longer in the northern hemisphere than in the southern. About
4000 years ago, Thuban in the Draco constellation was the Pole Star, and in 12,000 years’ time it will be Vega in the Lyra constellation.

Astronomers in ancient times discovered Earth’s precession (changes in axial direction). They had studied the fixed stars of the night skies and their relative positions to the Sun during various seasons for centuries. In the 2nd century before the birth of Christ, the Ancient Greek astronomer Hipparchus (ca. 190–125 BC) realised that Earth’s axis no longer pointed in the same direction into space as it had done during the time of Timocharis’s observations 150 years previously. Though the Earth’s axis is fairly stable and points almost directly towards the star we call the Pole Star, its direction changes in space over a long period of time (the axial tilt itself still remains the same during the orbit round the Sun, 22.0°–24.5°). It was not until Isaac Newton (1642–1727) put forward his laws of gravity that this precession was explained. The Earth rotates on its axis like a spinning top as it orbits the Sun. Its mass is irregularly dispersed around the globe, which is not a regular circle. The gravitational pull of both the Sun and Moon is around its bulging equatorial centre as they attempt to correct its axis. Because Earth is continuously revolving around itself, the centrifugal force causes it to sway from side to side and create a cone-shaped spin. We have all seen how a spinning top lies flat on the floor once it has ceased to spin. We know the effects of centrifugal force from observing gyrocompasses, bicycles, and aeroplane propellers. If Earth’s axis was at right angles in its orbit around the sun, then every day of the year would have twelve hours and there would be no seasons and an everlasting, freezing cold in the polar regions. It is believed that early in the globe’s history a planet the size of Mars might have collided with Earth and nudged its axis from its vertical position. Let’s be thankful for that chance encounter.

Milankovitch’s numerical models of solar radiation reaching Earth. Croll’s calculations indicated that 250,000–80,000 years ago Earth’s orbital pattern and axial precession had coincided to have a maximum effect on the levels of solar radiation, and he believed that this was the time span when warm and cold periods alternated regularly between the northern and southern hemispheres, each period lasting about 10,000 years. There would not have been a glacial period since then. But although geologists believed that they saw signs of a glacial period about 10,000 years ago, they could find no evidence that cold and warm periods had alternated between the southern and northern hemispheres, and thus support for Croll’s ideas had dwindled by the end of the 19th century. Two decades after his death, however, the Serb Milutin Milankovitch (1879–1958) took up the thread and wove it into the detailed calculations that the German Ludwig Pilgrim made (1904) concerning the collective effect of orbital eccentricities and axial obliquity on the movement of equinoxes. With extensive calculations, Milankovitch illustrated the influence of all three factors (axial precession, orbital variation, and axial tilt) on the
levels of solar radiation over the last million years. He calculated the temperature on specific places on Earth for the entire year for the last 130,000 years; he evaluated the levels of radiation at the furthest reaches of the atmosphere and then how it wanes on its way to Earth’s surface. Previously, only the overall influence of this radiation had been calculated for the southern and northern hemispheres. A convincing correlation emerged between the temperatures in many parts of the world, although heat levels calculated near the equator were a little too high, and those in northern latitudes a little too low. This was to be expected as the calculations did not take into account heat fluxes in the oceans and winds (Milankovitch 1930). The greatest collective influence of all three factors would be the equivalent of summer solar radiation being reduced at 65°N to what it is now at 77°N; i.e. solar radiation in the middle of Iceland would be equal to that on the southern part of

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Fig. 2.16 (From left to right, top to bottom) James Croll (1821–1890), Scottish geologist. Joseph-Louis Lagrange (1736–1813), Italian-French mathematician and astronomer. Milutin Milankovitch (1879–1958), Serbian engineer. Wladimir Köppen (1846–1940), Russian-German meteorologist. Alfred L. Wegener (1880–1930), German geophysicist. Oswald Heer (1809–1883), Swiss palaeontologist
Milankovitch believed that although axial tilt oscillated only about one degree within a 41,000-year cycle, it would nonetheless have a tremendous impact on the differing temperatures between winter and summer. With an increase in axial tilt, solar radiation in the northern hemisphere would increase in the summers, but conversely decrease in the southern hemisphere; there would then be the greatest difference in temperature between summer and winter. The effect of the cycle on Earth’s axial tilt would be greatest in the northern hemisphere, because that is where the largest land areas of the world are upon which snow could accumulate.

**Supportive meteorologists, doubting geologists.** Just like Croll, Milankovitch believed that cold winters were the cause of glaciation, but the Russo-German meteorologist Wladimir Köppen (1846–1940) and his son-in-law Alfred L. Wegener (1880–1930) pointed out that it was summer temperatures rather than winter ones that mostly dictated the accumulation of snow and formation of glaciers. With reduced solar radiation during the summer and colder weather, melting would be less, so that a surplus of the winter snowfall would survive the summer. Solar radiation would then be reflected into space at an increasing rate, temperatures would continue to fall, glaciers would expand, and then a glacial period would begin. Milankovitch (1920, 1930, 1941) presented a model of how a growing reduction of the levels of solar radiation reaching the Earth’s surface would lower the snowline and cause perennial snow to be more widely dispersed. At Köppen’s request, Milankovitch calculated the temperature over the last 600,000 years and they believed that their model predicted four glacial periods when solar radiation was at its minimum in the northern hemisphere: 400,000, 300,000, 250,000 and 125,000 years ago. Köppen and Wegener published these predictions in *Die Klima der geologischen Vorzeit* (1924), and believed they correlated well with the conclusions of Austrian geologists on four glacial periods in the Quaternary period in the Alps and in North America. But it was then discovered that the geologists’ dating methods proved to be unreliable. Milankovitch’s calculations had also predicted many more cold periods than traces of which could be found in sediment layers, and the date that had been attained with radiocarbon (14C) and U-Th measurements did not match his predictions on cold periods. Geologists also found remains of interglacial vegetation in 25,000-year-old peat in Europe and North America, whereas Milankovitch’s model predicted that solar radiation in the summer had then been at a low level and the summers thus supposedly cold. About 7000 years later, the ice sheets of the last glacial period had actually been at their largest extent ever. Milankovitch then put forward the hypothesis that the reaction time of glaciers could be 5000 years and that a 2000-year margin of error could also be assumed. Fewer and fewer scientists supported Milankovitch’s theories, though he himself believed in them until the day he died in 1958. Within two decades of his death, however, data emerged concerning global climate variations that was deemed to confirm the main gist of his theories.
2.7 Reading Climate History in Suboceanic Strata and Glacial Ice

Until beyond the mid-20th century, climate history was deducted from glacial remains from many countries and the evidence assembled to create one intermittent narrative thread. With each new advance, ice-age glaciers and glacial rivers had wiped out traces of earlier glaciers both on land and on shallow sea beds. There were some regions, however, beyond the furthest extents of glaciers that revealed a long, continuous history of climate. The glacial deposits in the Rhine delta in the Netherlands and the loess in central China, for example, showed that cold, ice-age winds had blown from the high-pressure area of the Tibetan plateau. It had become evident that climate changes had been simultaneous over the whole globe.

In the 1960s, however, a radical new knowledge of ancient climates, far distant from glaciers, emerged from deep-sea sediments where glaciers had never disturbed the ocean floor. Physicists had by then discovered methods to calculate temperatures of oxygen isotopes in tiny fossilised calcareous foraminifera shells, which had sunk to the ocean floor for thousands of years and been buried there in mud. The

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**Fig. 2.17** Harold C. Urey (1893–1981), American physicist

Photographed by Fritz Eschen, ca 1962
shells covered fauna and flora that had once floated on the ocean surface or above the seabed. Besides being preserved in seashells, temperatures are also recorded in the oxygen and hydrogen isotopes in ice cores retrieved from the glaciers of Greenland and Antarctica.

**Oxygen and Hydrogen Isotopes in Water Reveal Air Temperature**

Urey (1947; winner of the Nobel Prize for chemistry in 1934; Fig. 2.17) discovered in 1946 how oxygen isotopes ($^{16}$O and $^{18}$O) could be utilised as thermometers because the ratio of these two isotopes in seashells and glacial ice is related to their temperature when they are formed and begin to absorb oxygen. Isotopes with a low atomic mass ($^{16}$O) evaporate more easily from oceans than those with a high mass, so that a higher percentage of heavy $^{18}$O.

![Diagram](https://example.com/diagram.png)

**Fig. 2.18** Oxygen isotopes in glacial ice record atmospheric temperatures. In water ($H_2O$) there are both heavy ($^{18}$O) and light ($^{16}$O) molecules of oxygen, and the ratio between their numbers in a sample of water depends on the temperature when the vapour condenses and produces liquid water. Precipitation thus bears a temperature marker; the ratio of the number of heavy to light oxygen isotopes records annual fluctuations in atmospheric temperature as well as long-term climate changes. The explanation lies in the fact that when water vapour condenses there will be an enrichment of heavier isotopes ($^{18}$O) to lighter ones in condensed water and the precipitation that falls to Earth. Comparatively more lighter isotopes ($^{16}$O) will be remaining in the air masses and with continuing cooling of the air and condensation the precipitation will gradually contain still relatively more lighter isotopes; an increase in coldness and a higher percentage of lighter isotopes go together. Changes in the ratio of isotopes ($R = \frac{^{18}O}{^{16}O}$) are described as a deviation from the mean value in the sea (a standard value $R_0$), so that $\delta = 10^3 \left( \frac{R - R_0}{R_0} \right)$. The number of heavy isotopes decreases during evaporation from the sea (are depleted) and thus $\delta$ is always a negative size. In winter, more light oxygen falls in precipitation than in summer, and this applies also to both cold and warm climate periods. When glaciers expand on land, the water accumulated has a relatively large amount of light oxygen ($^{16}$O), while in the sea there is an increasing amount of heavy oxygen isotopes ($^{18}$O). With evaporation from the sea, proportionately more water with light oxygen isotopes ($H_2^{16}O$) than with heavy ones ($H_2^{18}O$) enters the atmosphere and is borne onto the glaciers when precipitation accumulates there as snow. In cold periods, glaciers preserve even larger amounts of light oxygen isotopes ($^{16}$O), and there is thus proportionately more numerous lighter isotopes ($^{16}$O) remaining in the atmospheric water vapour sum of heavy oxygen isotopes in the ocean ($^{18}$O).
isotopes ($^{18}$O) remains in the sea. Vapour with light oxygen isotopes is borne through the atmosphere and falls as precipitation on ice sheets (Fig. 2.18). Thus, during glacial periods, a large amount of light oxygen isotopes accumulates as snow on land, while conversely the sea has a relatively higher number of heavy isotopes. The ratio of the heavy and light oxygen isotopes in ice cores thus reveals the temperature of the atmosphere, whereas seashells reveal how much of the Earth’s water is stored in ice sheets on land.

The ratio of heavy and light isotopes (called $\delta^{18}$O) in ocean sediment cores is a much clearer measure of atmospheric temperatures than one might suppose, because in deep oceans temperatures change very little and very slowly. When glaciers melt, the lighter isotopes return to the sea where its ratio will increase while the ratio of heavier ones will decrease. Similarly, hydrogen isotopes in water (protium $^1$H and deuterium $^2$H) also provide a means of measuring temperature.

### 2.8 The Emergence of a Complete Picture of Past Global Climate Variations

Within two decades of Milankovitch’s death in 1958, as mentioned above, climate records emerged from deep oceanic deposits, and later from glaciers, that once again made his theories increasingly credible. It was immediately apparent that the four glacial periods previously described, and that were known about at the beginning of the 20th century, are the last in a series of many glacial periods which reach back millions of years in time. In 1971 a continuous core of deposits from the Pacific Ocean illustrated 19 oscillations from glacial to interglacial periods over the last 700,000 years, and this indeed seemed to support Croll’s main hypothesis that the main causes of regular climate changes were 100,000-year fluctuations in the Earth’s orbit around the Sun. Two year later, in 1973, three of these fluctuations (100,000, 41,000, and 22,000 years ago) were visible in a core from the Indian Ocean that reached back as far as 450,000 years ago, and in 1976, a complete picture of the series of glacial periods appeared in a deep core from the Pacific that spanned the entire 2.5 million years of the ice age (Hays et al. 1976; Imbrie and Imbrie 1979). The oxygen isotopes in this core revealed about 50 cold periods and between them short interglacial periods that lasted for 10–20,000 years each. In the first part of the ice age, the cold periods lasted for 40–50,000 years, but for the last million years they have been maintained for about 90,000 years, have been much colder than previously, and their glaciers larger than in earlier cold periods (Figs. 2.19 and 2.20). An ice core from Antarctica (Vostok, 3623 m long) goes back 420,000 years in time and shows the last four glacial periods that reached their high points 335,000, 245,000, 135,000 and 18,000 years ago. Ice cores from the Greenland ice cap (GISP2, 3053 m long, and GRIP, 3029 m long; Figs. 2.21 and
clearly reveal an interglacial period that ended about 125,000 years ago as well as all of the last glacial period. There was, in fact, no continuous cold period, for 23 interglacial periods interrupted it, though none of them have been as stable as over the last 10,000 years, during which average temperatures have only fluctuated about 2–4 °C.

The frequency analysis of the climate records from the deep-sea sediment and glacial ice cores reveal that climate fluctuations are in accordance with the predictions of Milankovitch’s model of the collective influence of Earth’s orbit, axial precession and tilt on solar radiation at various points of latitude and in different seasons. The analyses indicate that fluctuations in levels of solar radiation instigate long-term climate changes. Radiation dictates whether snow survives the summer and continues to accumulate in order for the glacial period to set in, and the latter ends when radiation consistently increases once more in northern regions. Milankovitch’s theory does not explain, however, why there is a glacial period simultaneously in both hemispheres, or why they come to an end so abruptly, or why the atmospheric temperature can increase without warning about 5–10 °C within a single decade. There must be other factors beyond those in his theory to explain how the amplifying effects of solar radiation can influence and maintain climate changes. Ocean currents, ice caps on land, sea ice, and the atmosphere’s circulation patterns, all play a part in distributing heat around the globe, from the equator to the polar regions. The complex effects of ice are important and include glacial surges and the discharging of glacial meltwater into the oceans, which lower the salinity of seawater, and the expansion of sea ice and snow cover that increases

Fig. 2.19  Ice-age climate oscillations. Oxygen isotopes in fossil shells of foraminifera in ocean sediment cores reveal great and frequent changes in climate over the last 1.3 million years. They expose fluctuations in ocean isotopes during the ice age. The climate has nonetheless grown colder over a long period during this time (see direct line) and it has been at its coldest over the last 750,000 years. More than 2.75 million years ago there were few glaciers on Earth, but they then began to form and disappear in a regular ca. 41,000-year cycle. This changed about 900,000 years ago, however, and glaciers have since appeared and departed in 100,000-year intervals, while at the same time becoming much larger than ever before. ("Ice Age" website; Emiliani 1955, 1966; Shackleton 1967, 1984; Raymo 1994; Marchant and Denton 1996; Maslin et al. 1998; Shackleton et al. 1990; Berger 1977a, b, 1978; Berger and Loutre 1991; Geirsdóttir 1990; Geirsdóttir and Eiríksson 1996; Geirsdóttir et al. 2007; Hafldason et al. 2000)
Fig. 2.20  Connection between solar radiation, carbon dioxide and atmospheric temperature. Oxygen isotopes in 3-km-long ice cores from Antarctica (from Dome-Concordia in 2004) have recorded climate changes over the last 740,000 years, from a total of eight glacial periods (top graph). It became increasingly colder during each cold period, though temperatures fluctuated somewhat. It then grew warmer very rapidly for a few thousand years, but this warm period did not last long. The graph shows deviations from the mean value (shown as 0 °C) at the end of the last glacial period. Temperatures fluctuated in accordance with carbon dioxide levels in glacial air bubbles (middle graph). The level of carbon dioxide was about 180–190 units (ppmv, parts per million by volume) during glacial periods, and 280–300 units during interglacial periods. At the beginning of the Industrial Revolution at the end of the 18th century, the level was 280, but it is now (2015) around 400 and has never been as high as this over the last 750,000 years. It is thus predicted that, by the end of the 21st century, the level of carbon dioxide could be between 530 and 980 units, depending on how much pollution mankind generates. Long-term climate changes are believed to be connected to fluctuations in levels of solar radiation caused by changes in the Earth’s orbit around the Sun, and the tilt and direction of the Earth’s axis, see e.g. the increased levels of solar radiation at the beginning of the interglacial periods 12,000, 130,000, 220,000, 285,000 and 350,000 years ago (bottom graph). (EPICA 2004; Petit et al. 1999; Berger 1977a b, 1978; Hays et al. 1976; Raynaud et al. 1993; Barnola et al. 1987; Heinrich 1988)
the reflection of solar radiation. It is believed that climate changes begin in the northern hemisphere and, if they endure long enough, the cycle of oceanic currents begins to have an effect in the southern hemisphere. Fluctuations longer than 2000 years can be seen in both hemispheres. One of the features of long-term fluctuations is that cooling is a slow process while warming is sudden and rapid (a theory associated with the Dane Willi Dansgaard [1922–2011, Fig. 2.23] and the Swiss Hans Oeschger [1927–1998]). This serrated pattern of climate fluctuation is believed to be caused by the interaction of ocean currents and glacial ice caps, which form much more slowly than they disintegrate. Some sudden changes take place simultaneously over the whole globe, while other fluctuations, especially the smaller and more frequent ones, are not always synchronous everywhere on Earth. These sudden variations are believed to be connected to rapid changes in ocean
currents, changes in the North Atlantic being especially important for the climate all over the world. The boundaries between cold polar and warm southern ocean currents can move and may be likened to a door that opens during interglacial periods to allow warm seawater and air to flow far into the northern oceans. This door is closed during cold periods, but in-between times it is half ajar. Thus sudden climate changes are believed to have been a result of changes in the currents of the North Atlantic. Each event began with an increasing coldness, but finally ended with a sudden warming, until it cooled again and the same pattern was repeated. Each group of Dansgaard-Oeschger events is called a Bond-event and it ends with glaciers surging into the sea, dispersing icebergs and sediment layers. The sediment settles in layers named after the German paleo-oceanographer Hartmut Heinrich. The glacial period finally ended around 14,700 years ago, when the warm Bølling period began. Around 14,000 years ago there came a short 300-year cold period (Older Dryas), but at the end of this the climate became rapidly warmer during the Allerød period, until a cold period returned about 12,900–11,500 years ago (Younger Dryas). Finally, the present, stable climate of modern times emerged, with a temperature 9 °C warmer than during the coldest point of the glacial period. (Dansgaard et al. 1984; Dansgaard et al. 1985; Bond et al. 1993; Grootes et al. 1993; NorthGRIP members 2004; Johnsen et al. 1998; Andrews et al. 2000; Eiriksson 1980, 2008; Ingólfsson et al. 1997; Larsen and Eiriksson 2008; Simonarson 1979; Simonarson and Leifsdóttir 2007; Maclennan et al. 2002; Ingólfsson 1984, 1985, 1987a, b, 1988, 1991; Pétursson 1986; Hubbard et al. 2006)

The Emergence of a Complete Picture…

Fig. 2.22 Temperature fluctuations from the last glacial period until the present. Oxygen isotopes in 3-km-long ice cores from the Greenland ice sheet have recorded climate changes over the last 125,000 years. The last glacial period began about 120,000 years ago, but it did not, indeed, become really cold until about 40,000 years later, and it was coldest during the period’s final 20–30,000 years. Twenty-three sudden fluctuations of climate have been distinguished during the period and are named after two glaciologists as Dansgaard-Oeschger events. The events are believed to have been a result of changes in the currents of the North Atlantic. Each event began with an increasing coldness, but finally ended with a sudden warming, until it cooled again and the same pattern was repeated. Each group of Dansgaard-Oeschger events is called a Bond-event and it ends with glaciers surging into the sea, dispersing icebergs and sediment layers. The sediment settles in layers named after the German paleo-oceanographer Hartmut Heinrich. The glacial period finally ended around 14,700 years ago, when the warm Bølling period began. Around 14,000 years ago there came a short 300-year cold period (Older Dryas), but at the end of this the climate became rapidly warmer during the Allerød period, until a cold period returned about 12,900–11,500 years ago (Younger Dryas). Finally, the present, stable climate of modern times emerged, with a temperature 9 °C warmer than during the coldest point of the glacial period. (Dansgaard et al. 1984; Dansgaard et al. 1985; Bond et al. 1993; Grootes et al. 1993; NorthGRIP members 2004; Johnsen et al. 1998; Andrews et al. 2000; Eiriksson 1980, 2008; Ingólfsson et al. 1997; Larsen and Eiriksson 2008; Simonarson 1979; Simonarson and Leifsdóttir 2007; Maclennan et al. 2002; Ingólfsson 1984, 1985, 1987a, b, 1988, 1991; Pétursson 1986; Hubbard et al. 2006)
changes in the levels of so-called greenhouse gases and air pollution. Results indicate that changes in solar radiation first instigate warming, and this is then later amplified by increasing levels of greenhouse gases. A change from a glacial to an interglacial period has always been followed by an increase in carbon dioxide. This link between changes in temperature and the level of greenhouse gases is believed to be connected to the temperature of the oceans and the exchange of gases between sea and air.

**Surges of Ice-Age Glaciers Dispersed Sediment Layers on the Seabed**
The German paleo-oceanographer Hartmut Heinrich (1988) found six thin, white stone deposits in sediment strata from the North Atlantic. The layers were thickest nearest the Hudson Bay in northern Canada (0.5 m) and they contained grains of limestone originating from the eastern part of Canada. They had sunk to the seabed from the enormous amount of ice-rafted detritus during surges of the Laurentide ice sheet at intervals of 7–10,000 years about 10,500–70,000 years ago; the layers are called H1 (16,500 years old, shortly before the ice-age glacier began to recede), H2 (23,000 years old, at the high point of the glacial period), H3 (29,000 years old, when it was quite warm) and then H4 (37,000 years old), H5 (51,000 years old) and H6 (~70,000 years old). It then emerged that sediment deposits from Iceland and northwest Europe had also been deposited there, which indicated that ice sheets on the other side of the Atlantic had surged at the same time. The causes of these surges are believed to be connected to either climate change
(Denton’s model, which is believed to explain why ice sheets in different parts of the world surged simultaneously), or irregularities in the flows of the ice sheets (MacAyeal’s model, whereby a glacier becomes so thick that its base had warmed to freezing point and it surged forward, thinning out, freezing again at the base and thickening once more before surging again).

2.9 Climate Fluctuations During the Last Glacial Period

There was an ice-cold glacial period about 130,000 years ago, which was then followed by an interglacial period that reached its warmest climax about 125,000–120,000 years ago. Remains of vegetation and oxygen isotopes indicate that it had been 2 °C warmer on Earth than it is today; glaciers had correspondingly been smaller and the sea level 5–8 m higher, probably because the western part of Antarctica had been free of ice. There is a layer of oceanic sediment from this interglacial period at the bottom of strata in Ellíðavogur Bay near Reykjavík (Einarsson 1968). Then, 118,000 years ago, there was a sudden cooling and 3000 years later the Würm/Wisconsin glacial period began. Mankind’s predecessors then lived far from glaciers in the warm regions of Africa and in caves in Asia. The climate history of this glacial period is well known. The last remnants of ice caps, which had begun to be formed at the beginning of this period, disappeared from Europe and North America about 8000–8500 years ago, and traces of this glacial period are still visible on Earth. Most of the traces of older glacial periods, however, have been destroyed by these later glaciers.

The cold period that began about 118,000 years ago was not continuous but interrupted six times, so that there was some temporary warming and glaciers retreated for a while, but at the end it grew increasingly colder until its lowest temperature was reached about 18,000 years ago. The cold period was rather mild at first, but it suddenly cooled about 75,000 years ago and then the real glacial period first began. Conglomerate rock and then lignite were deposited over the sediment strata in Ellíðavogur Bay. Finally, Reykjavik dolerite lava flowed over these layers, and this prevented glacial erosion from reaching and destroying the strata. There was extreme cold for 15,000 years. Ice covered northern Europe and the sea dropped to 100 m below its current level. But then a rather warm 45,000-year period followed and vegetation grew, and animals and mankind proliferated over a wide area. Glaciers still maintained themselves, though, and the sea level may have been about 50 m lower than it is today.

Neanderthal man had disappeared about 30,000 years ago and Cro-Magnons were ascendant all over Europe. In small groups, and continually on the move, they adjusted to their environment and developed technical skills and artistic creativity, as can be seen in the cave drawings in southern France and Spain (Figs. 2.24 and 2.25). But then, around 25,000 years ago, the temperature cooled significantly and
Fig. 2.24 An ice-age man 15,000 years ago, clad in animal skins, bringing some wood to his home, a shelter made from mammoth bones. American Museum of Natural History

Fig. 2.25 An approximately 14,000-year-old chalk drawing of a bison in a cave in Lascaux in southern France
glaciers began to expand rapidly in continental Europe and North America, and there are many indications that they reached their greatest size in the regions further north, on Svalbard, and in Canada and Greenland. A glacier up to 3 km thick covered all mainland Europe and the sea level was 120 m lower than it is currently. A third of the world’s land mass was then covered in ice, and from the ice sheets blew constant, dry, cold katabatic winds across the frozen tundra to as far south as the Mediterranean Sea. The earth in the forefields of ice sheets was then bound in permafrost, just as it is now in Siberia and the highlands in northernmost Scandinavia.

Homo sapiens was now the only humanoid species on Earth. Bones of large mammals have been found in caves from this time along with artistic petroglyphs. Mean winter temperatures were about 20–25 °C lower than they are today, especially in the northern parts of the globe, and the weather was drier. At the equator, the average temperature may have been 3 °C colder, but by then the high point of the glacial period had been attained and ahead lay 8000 years of a late glacial period.

Earth began to be warmer around 17,000 years ago (when solar radiation increased according to Milankovitch’s calculations), and glaciers on land shrank and seasons of vegetation lengthened, though vegetation on the steppes and tundra were slow to recover. A land bridge over the Bering Strait to North America became ice-free and peoples from Asia crossed over it, settling and moving south along the western side of the continent, west of the Laurentide ice sheet. Temperatures then rose sharply around 15–14,000 years ago. In the British Isles the summer heat rose by an average of 8–10 °C. It is believed that half of the warming from the complete glacial period of about 14,600 years ago had occurred in one decade. During this blooming Bølling interstadial period forests spread rapidly over northern regions, and pollen grains, insect and marine fossils, and glacial ice cores all bear witness to this warming. Glaciers shrunk at a much faster rate than they had previously formed and expanded, and the sea level rose rapidly, 5 m in a century.

The glacial period did not surrender without a fight. There was then a sudden end to the retreat of ice-age glaciers about 14,000 years ago, and a five-century cooling episode succeeded. Glaciers began to advance once more, pushing up moraines. This glacial period is called the Older Dryas after the alpine and tundra plant, the fossilised traces of which can be found in sediment strata from this time (Fig. 2.26).

This cold period ended suddenly when, within a few decades, temperatures rose by about 10 °C on the shores of the North Atlantic, and there are even examples of 16 °C warming and a doubling of precipitation. The warm Allerød interstadial period succeeded. Forests spread out over a great part of Europe, reindeer, musk-oxen and mammoths moved northward, where there were still tundra, and the hunters followed them. There was still dry land between England and France and large parts of the North Sea were not as yet underwater. Meltwater first flowed from the Laurentide ice sheet south to Mississippi and the Bay of Mexico, also down the Hudson River, and finally eastward through the Gulf of St. Lawrence into the North Atlantic Ocean. Huge, ice-dammed lakes were formed at the margin of the
retreating glacier in North America, the largest being Lake Agassiz, which, at its
greatest extent around 13,000 years ago, had covered much of Manitoba, western
Ontario, northern Minnesota, eastern North Dakota, and Saskatchewan, or as much
as 440,000 km², larger than any currently existing lake in the world (including the
Caspian Sea). Finally, about 11,000 years ago, the lake burst out from beneath the
glacier’s margin and for a few months freshwater flowed through the Gulf of St.
Lawrence into the Labrador Sea, where it floated on the surface of the more saline
Gulf Stream.

But suddenly, 11,500 years ago, this warm period ended. An ice-age cold
descended and within a hundred years a 1200-year-long cold episode had begun
called the Younger Dryas period. The temperature in northwestern Europe dropped
by about 8–10 °C, and long winters maintained at 20 °C frost. There were snow-
falls from September until May. Cold, arctic airstreams swept over the country,
glaciers advanced about 30–40 km in western Norway and Iceland, and formed
once more in the highlands of Scotland. Treelines descended and retreated south-
ward. The boundary between cold and warm ocean currents moved as far south as it
had been 18,000 years ago, and sea ice encroached over a large area of the North
Atlantic.

Did glacial meltwater turn off the heating system of northern regions? It has
long been a puzzle as to what caused the reversal into an ice-age cold during the

Fig. 2.26 Two sudden cold episodes at the end of the last glacial period are named after the white
dryas plant (Dryas octopetala) because its fossilised leaves are found in sediment layers from this
time. The first cold episode (the 500-year long Older Dryas) began about 12,000 years ago and the
later episode about 11,000 years ago (the ca. 1200-year-long Younger Dryas). Þóra Ellen
Bórhallsdóttir
Younger Dryas period; the answer was not to be found in Milankovitch’s theory, for solar radiation levels were high at this point in time. It is now believed that the huge flow of freshwater from melting ice sheets had so diluted the saline content of the sea that ocean currents changed course, thereby disrupting the oceanic heat flux into the northern regions (Fig. 2.27). Previously, warm and salt-laden surface seas flowed from the south into the northern oceans and, once this heat had been absorbed into the atmosphere, the cold, saline and denser seawater sank and became deep ocean currents that flowed to the South Atlantic and Antarctica and then into the Pacific and Indian Oceans. The seawater in the northern oceans around Iceland and in the Labrador and Greenland Seas had now mixed with freshwater, so that it no longer sank to form a deep oceanic current, while the freshwater floated above the saline sea and then froze, covering the ocean area with ice. Sea ice confronted

![Diagram of the heating system of the world's oceans](image-url)
the Gulf Stream, which then veered off course and stopped bearing heat to the
northern regions. The conveyor belt of heat that had nurtured the warming of
northern regions for 3000 years came to a halt, heat no longer reaching the North
Atlantic or warming polar air masses. With new courses for ocean currents, the
tracks of low-pressure weather systems also moved in the North Atlantic. The
sudden warming of the Allerød period had in this manner turned off the conveyor
belt of heat into northern regions. It is this kind of sequence of events that modern
scientists are now bearing in mind when considering global warming due to the
increased greenhouse effect and the rapid melting of glaciers. Glaciers are much
smaller now than they were at the end of the last glacial period 11,000 years ago, so
scientists are not afraid the conveyor belt of oceanic currents will cease, though it
could slow down, causing the sea to cool around the shores of Iceland.

2.10 Late Quaternary Glaciation of Iceland

At the climax of the last glacial period, around 20,000 years ago, the temperature
was lowered by 5–6 °C in Iceland and the snowline reached right down to sea level.
Iceland was covered by one complete ice sheet that extended in all directions from
the central highlands right down into the sea and over the offshore continental shelf.
Judging by the tuyas that rose through and above the ice, it can be estimated that it
had been all of 1000–1500 m thick in the centre of the country and had compressed
the land by about 300–500 m. The highest mountains on the shores of western,
northern and eastern Iceland might also have risen above the ice as nunataks. The
ice sheet was thinnest along the shorelines, and land compression correspondingly
less there too. Both on land and on Iceland’s offshore oceanic bed, there is visible
evidence of this ice sheet’s erosive powers and the sediments which were borne
with it: striation in rocks, troughs gouged into malleable deposits, channels through
which water had flowed beneath the ice, sediment strata, erratic boulders and
moraines. The furthest moraines can be found between 50 and 120 km from
Iceland’s current shoreline. In all, the land-based ice covered an area twice the size
of what Iceland is today. It is still not totally clear, however, where the exact
boundaries of this ice mass was at the climax of the last glacial period. The sub-
oceanic troughs end at the edge of the continental shelf (see Chap. 3, Fig. 3.3).
Beneath the ice shelves, sediments accumulated on the ocean floor at the mouth of
rivers gradually forming deltas. Repeated glacial surges had increased sediment
loads and jökulhlaups had also borne sediment from subglacial volcanic eruptions.

It is estimated that the ice sheet had been divided into 30–40 ice streams, each
some 2 km wide, and they had borne most of the ice into the sea, the ice being
transported much more rapidly than surrounding matter. Water had lubricated the
soft sediments beneath the ice streams and basal movement had been much more
rapid beneath the ice than at its margins. Meltwater resulting from geothermal
heating at the glacial bed could also have facilitated sliding at certain places. These
major ice flows of the central mass gouged out the main valleys, fjords and bays of
Iceland and harrowed out and dissected the continental shelf with deep troughs, right to its very edge.

Ice continuously crept forwards from land out into the ocean, where flat ice shelves began to float on the surface of the sea. At the furthest edges of the continental shelf, however, ice bergs broke off from the ice mass and floated away until they melted. Further away they would also meet very thin sea ice. For a long time there was a balance between the snow accumulation on the main ice sheet, its high plateaus, and the ice streams down to the floating shelves, where the ice calved into the sea. In some places the ice shelves would collide with islands, which would then form a buttress against further advancement out to sea.

The shrinking of Iceland’s ice sheet. When it began to grow warmer in the northern hemisphere, around 17–15,000 years ago, the mass balance of the ice sheet on land was gradually reduced and the ice streams into the ocean abated. The ice shelves became thinner and ice resting on the sea bed gradually uplifted and the grounding line of ice finally moved inland. This resulted in a reduction in offshore buttressing against advancing ice streams, so that ice could flow more rapidly to the coast, where it calved into the sea. The climate then suddenly grew even warmer 15–14,000 years ago at the beginning of the Bölling Period. This mild interlude is named after Kópasker in northeastern Iceland, as oceanic sediments with fossilised shells from this time can be found there beneath ground moraine.

Meltwater flowed in increasing volume along glacial beds and this increased the basal sliding of land-based ice into the sea. Warm, southern oceanic currents also flowed into the deep offshore troughs and melted the ice from below. The sea levels also rose about 20 m in 500 years (4 cm per annum) because of the rapid melting of ice sheets in North America (Laurentide), Scandinavia and the Barents Sea. This began a chain of events which would not end until all the ice shelves had collapsed. It appears that all the ice mass had disappeared from Iceland’s continental shelf just over 13,000 years ago and had withdrawn up onto land by about 12,500 years ago. In spite of a short cold period (the Older Dryas, about 14–13,000 years ago) the collapse of the ice shelves continued because the ice streams supplying them had become unstable. In Iceland the Older Dryas period is named after the Álftanes peninsula, where glacial moraines from that time are to be found, as well as in the Melasveit district. During the warm Allerød period, called the Saursbræ period, after a farm in Dalir County, where shells can be found in oceanic sediment strata, the glaciers retreated far inland, the seas following them, and so came into existence the well-known Fossvogur sediment layers on top of the glacially striated Reykjavík dolerite. Finally the glaciers advanced during the Younger Dryas period, called the Búði stage in Iceland, after a waterfall in the river Þjórsá. The glacial moraines on Rangárvegur plain, which stretch southeastward to Keldur, are from this time.

When the ice melted at the end of the last glacial period, the sea levels of the world’s oceans rose rapidly and followed the shrinking glacial margins inland, inundating the continental shelves and flowing over lowlands previously covered by glaciers. The waves of the Atlantic penetrated shorelines below coastal cliffs. When the large ice masses of the northern hemisphere had completely melted, there was no further rise in sea levels, but the Earth’s crust began to uplift after the
overburden of the ice had been removed, and land was thus uplifted from the sea along the coasts of Iceland. It is believed it could have risen as fast as 10 cm a year, and it is estimated that it had reached its maximum height around 9000 years ago. Glaciers only then existed in the central highlands and in southeastern Iceland. For further details see Kjartansson (1939), Einarsson (1968), Hjartarson and Ingólfsson (1988), Hjartarson (1989), Sveinbjörnsdóttir and Johnsen (1990), Ingólfsson (1991), Ingólfsson and Norðdahl (1994), Ingólfsson et al. (1997), Eiríksson et al. (2000), Harðardóttir et al. (2001), Geirsdóttir et al. (2007).

2.11 Holocene Climate and Glaciers

Around 11,500 years ago, the extreme cold of the last glacial period finally gave way and the so-called Holocene period began and is still continuing (Fig. 2.28). In around 50 years, the climate was sharply transformed from the Younger Dryas period into a warm and humid Pre-Boreal age. Earth has remained relatively warm ever since, although climate and vegetation have fluctuated, so that the period might be divided into a few vegetation periods correlating with air temperatures and moisture (Table 2.1; Hallsdóttir 1990; Hallsdóttir and Caseldine 2005). The floating surface layer of freshwater on the sea had gradually become thinner, summer

Fig. 2.28 Temperature levels from the end of the last glacial period. Earth’s average temperature at the end of the last glacial period 11,000 years ago, calculated as a deviation from the average of the 20th century; data compiled from suboceanic sediment layers along with ice core readings from the Greenland and Antarctica ice sheets. The climate rapidly grew warmer 11,000 years ago and then maintained a stable average for the next 6000 years, during which most of the glaciers disappeared from Iceland. It then cooled for the next 3000 years, and glaciers expanded once again. (“Holocene Temperature Variations 2008; Website; Dansgaard et al. 1969, 1984; Denton and Karlen 1973; Oeschger and Langway 1989; Masson-Delmotte et al. 2005; Vinther et al. 2006; Bond et al. 1997, 2001; CAPE Project Members 2001; COHMAP Members 1998; Chapman and Shackleton 2000; Andrews et al. 2001; Eiríksson et al. 2000; Kaufman et al. 2004; Zielinski et al. 1994; Guðmundsson 1997; Ingólfsson and Norðdahl 1994; Ingólfsson et al. 1995)
warmth had melted sea ice, and saline seawater began to sink at the margins of ice and form deep ocean currents thus reviving the heat flux from the equator to the polar regions. The heating pump of the North Atlantic, which had been turned off for over 1000 years, had once again been reactivated. The cold episode of the Younger Dryas period ceased as suddenly as it began, and now permanently. The expansion of ice sheets in North America during this millennium-long cold episode could have directed meltwater southward to the Mexico Bay once more instead of letting it flood into the North Atlantic.

Tremendous changes occurred in climate, vegetation and animal life. Pollen grain analyses of sediment deposits reveal that tundra disappeared and birch trees took root in land vacated by retreating glaciers. The glacial shield over Iceland mostly disappeared within 1000 years. It retreated rapidly from the lowlands and around 9500 years ago there was only an ice cap over the central highlands and the southeastern part of the country; 1000 years later even that had gone. Continuous sea ice no longer encroached on its shorelines. About 8000 years ago, Iceland was free of glaciers on the Tungnaáðörfi wilderness, from where the Þjórsárhraun lava field emanated and flowed south to the sea. The glacial shield over northern Europe and North America disappeared within 3000 years. Great pine and deciduous forests spread out over the northern parts of continental Europe and America and large mammals such as mammoths roamed the land, although they were soon wiped out by hunters. Until this moment, mammals had survived many fluctuations from one cold to warm period after another. About 8–10,000 years ago, mankind learned how to grow and utilise wheat and corn, and a static agricultural mode of life

### Table 2.1 Post-glacial time divided into climate periods according to vegetation patterns in Iceland (Hallsdóttir and Caseldine 2005; Hallsdóttir 1990, 2008, personal communication 2009)

<table>
<thead>
<tr>
<th>Period</th>
<th>Age in carbon-dated years</th>
<th>Climate and vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Boreal</td>
<td>10,000–9000</td>
<td>Cool and dry. Plants began to grow, first resilient grasses and herbs and later bushes, heather and species of wood. Moors began to bear vegetation</td>
</tr>
<tr>
<td>Borea birch</td>
<td>9000–8500</td>
<td>Juniper spread out, then dwarf-birch, and finally trees took root</td>
</tr>
<tr>
<td>Atlantic</td>
<td>8500–5000</td>
<td>Warm and moist. Birch trees proliferated and reached their greatest extent in modern times, about 6000 years ago</td>
</tr>
<tr>
<td>Sub-Boreal</td>
<td>5000–2500</td>
<td>Cooling. Birch and brushwood receded in the lowlands and on moors while marshlands increased. Birch trees receded and advanced in turn, their last expansion probably being about 6000 carbon-dated years ago</td>
</tr>
<tr>
<td>Sub-Atlantic</td>
<td>2500–present</td>
<td>Increasingly cooler and damper, increase in marshland areas</td>
</tr>
<tr>
<td></td>
<td>1500–present</td>
<td>After the settlement of Iceland there were major changes in the island’s vegetation. Forests and brushwood disappeared, grasslands spread out along with arable grass and weeds. Soil erosion soon began</td>
</tr>
</tbody>
</table>
replaced that of the peripatetic hunter-gatherers. Birch woods spread out over Iceland 8–9000 years ago, and this time span is thus called the Birch period in Iceland and the previous millennium was called the Birch-free period. Glaciers retreated rapidly, although the most active still managed to push forward some marginal moraines during this time.

**Vegetation Tells the Story of Climate History**

It is possible both to calculate the age of trees and to analyse the climate changes during their growth by counting the annual rings and measuring their width (Fig. 2.29). Annual rings are formed in tree trunks while they are

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**Fig. 2.29** Cross section of the trunk of a coast redwood tree (Sequoia sempervirens) from California which the United States of America presented to Iceland in 1974 to mark the 1100th anniversary of the island’s settlement. Marked on the tree rings are the years of important events in Iceland’s history: the settlement (874), the establishment of the Althing (930), the acceptance of Christianity (1000), the end of the Commonwealth (1262), the Reformation (1550), the Skaftá fires volcanic eruption (1783), the resurrection of the Althing (1843), and the establishment of the Republic of Iceland (1944). The cross section is about 2 m in diameter.
growing in the warm and damp times of the year. Trees are in hibernation during cold and dry periods. Each year adds another ring, and its width depends on the warmth and precipitation of that year. The paler part of the ring is made from larger cells that form at the beginning of each growing season, and the darker parts of the ring are from smaller cells from the late summer. A tree does not have to be cut down in order to count its rings, for a 0.5-cm-thick core sample from a borehole is sufficient for this purpose, and its extraction does not harm the tree. The climate history of Europe and North America has been traced back thousands of years over a wide area by examining tree rings and treelines; in some places this history has been traced as far back as Roman times, and in a few special locations, even up to 6000 years ago.

The history of vegetation has been determined in historical times by analysing the species of pollen grains dispersed by plants that have been preserved in marshes and lakes. Each annual pollen rain records the history of vegetation, from which may be drawn conclusions about climate history. The age of vegetation can be determined through radiocarbon dating and tephra layers. Thus it can be seen when birch trees grew on land and when they were subsequently driven into marshes, when moss began to proliferate, and when treelines moved higher or lower and different species of grass multiplied. Vegetation can also be affected by volcanic activity, the encroachment of humans and animals, and wind erosion. Pollen analysis can thus be utilised in many ways in studying and researching natural history.

With the rapid shrinking of glaciers, huge amounts of meltwater were discharged into the sea. Powerful rivers bore jökulhlaups that gouged out great canyons. Around 8800 years ago, a large inland lake covering the centre of Jamtland in Sweden emptied and deposited a thick layer of sediment that the Swede de Geer used as a reference point in his dating of varves. All over the globe the sea level rose and seawater flooded over lowlands, hewing new shorelines along the coast and submerging land bridges. An ocean swept through the English Channel 8500 years ago, finally dividing Britain from continental Europe, and the southern part of Scandinavia also disappeared under water. About 8200 years ago, two large lakes emptied at the margins of the ice sheet in North America on the Hudson Bay causing the sea level to rise considerably. As a result, the North Atlantic cycle slowed down and a short-lived cold episode was unleashed, temperatures falling by as much as 6 °C. Around 7800 years ago, the atmospheric circulation began once more with low air pressure over Iceland and high pressure over the Azores. Strong westerly winds bore heat and moisture over the Atlantic to Europe. This period, from 8000 to 5000 years ago, has thus since been called the Atlantic period, though it is also named the Alder-elm-lime period in Scandinavia, while in Iceland birch trees proliferated. About 5600 years ago, the Mediterranean (Marmara Sea) rose to fill up the Bosphorus and within a few years it had torn a pass through the earthen
dam and rushed through along a 30-km-broad channel into the Black Sea, raising its water level by 150 m; until then the Black Sea had been a freshwater ocean, but it has been a saltwater one ever since. Its water levels rose 15 cm per day. These catastrophic events could have been the origins of the story of Noah’s Flood.

**Features of post-glacial times: taking the rough with the smooth.** Land that glaciers had compressed rose slowly out of the sea once the overburden of ice was reduced, and tidelines can now be seen dozens of metres above the current sea surface. They rise toward areas which the central ice sheet covered and are highest where the ice-age glacier was thickest, in the basin of the Baltic Sea and by Hudson Bay on the northern coast of Canada, 300 m above today’s sea level. The Earth’s crust rose so quickly in Iceland, once the weight of the glaciers had been reduced, that 2000 years after the ice-age glacier had dissolved, 9000 years ago, the land had risen to its fullest extent. There was still a huge amount of ice bound up in glaciers all over the world and so the sea level was then 20 m lower than it is today.

Research in Europe indicates that the warmest period had been about 6000 years ago, the average temperature being around 2–3 °C higher in the northern hemisphere than it is today. Although there had been ample moisture in the air, there were probably no glaciers in Iceland except on its highest peaks; the snowline is believed to have been at a height of about 1400 m in southern Iceland. The ice sheet in North America finally disappeared, the ocean was about 3 m higher than it is now, and there was little sea ice in northern oceans. Highly civilised cultures were then developing along the banks of the great Indus, Nile and Hwang Ho rivers. A cultured society was flourishing 5000 years ago in Sumer in Mesopotamia, between the Euphrates and Tigris rivers. The Pyramid of Cheops was constructed around 4600 years ago and a bit younger is the 4500-year old bristlecone pine (*Pinus aristata*) in California, the oldest organism still with us today, and which shared its childhood on Earth with the last of the mammoths (although a few of the latter are believed to have survived on the arctic islands north of Siberia until about 2000 years ago).

Around 5500 years ago it gradually began to cool, as changes in vegetation bear witness. The Sub-Boreal period began in Scandinavia, although in Iceland birch trees were giving way to increasingly encroaching marshlands. The frozen Copper-Age man, widely known as Ötzi the iceman, who was found in 1991 at an altitude of 3200 m in the Tyrol on the borders of Austria and Italy, died of exposure there 5300 years ago and was preserved in ice until our times (Fig. 2.30). High, mountain glaciers that had survived the warm and humid period from 8000 to 5000 years ago, then began to expand 4500 years ago. There are ancient Egyptian sources on the distress and hardship, caused by the climate fluctuation of 4000 years ago, especially drought. There was tremendous air pollution from the eruptions of Hekla 4200 and 3100 years ago, possibly followed by a few years of hunger in many parts of the world. Mycenaean civilisation flourished just over 1000 B.C. on the Peloponnesian peninsula, to be followed by the Hellenic civilisation for the next nine centuries. The climate then began to cool even more, however, 3000–2500 years ago, and precipitation increased. A cool and damp time began in Europe at the beginning of the Iron Age in Scandinavia, where oak receded and spruce
proliferated, while in Iceland wetlands became even more widespread. The climate then entered the phase that it has for the most part followed ever since, although there have been some fluctuations. It may well have been from this time that the eldest narratives could have emerged of freezing cold winters, when a wolf swallowed the Sun, Moon and stars. Glaciers, which had not been particularly large at the time, began to expand and have remained in existence ever since. In Iceland it is believed that the glaciers on the highest mountains converged to form the great ice caps of Vatnajökull, Langjökull and Hofsjökull. Glacial ice covered vegetated moorlands and wooded mountainsides and finally hid from sight the large marshes in the valley basins. Birchwood branches and slabs of peat from this era are still emerging on outwash plains from beneath Vatnajökull’s outlet glaciers, especially Skeiðarárjökull and Breiðamerkurjökull.

There was a warm climate for centuries during the age of Hellenic civilisation in Greece, the Celts in the British Isles, the Gauls in central Europe, and then later the Romans and their empire, right up to the end of the Middle Ages. In the rain forest belt, the civilisation of the Mayan Indians was at its peak from 300 to 900 A.D. The Middle Ages were warmest from 800 to 1200 A.D. with an average temperature 0.5–2.5 °C above that of the beginning of the 20th century. Human life and activity flourished around the North Atlantic. Monks sailed to Iceland in search of a sanctuary, longships appeared, and a Nordic people claimed and settled Iceland and

Fig. 2.30 The body of a Copper-Age man was found in the autumn of 1991 at a height of 3200 m near Ötztal on the border of Austria and Italy. His mumified corpse had been frozen there for 5300 years, or from the end of the Atlantic period. Ötzi the iceman, as he has been called, is now preserved in the Tyrol Museum in Bolzano, Italy. Photo Austrian police
Greenland and reached as far as Vinland, or North America. Glaciers were lean and sailing routes were much less disrupted by sea ice. Crusades and Gothic cathedrals bear witness to a time of prosperity and expansion in medieval Europe. From tree rings, the position of treelines in the Alps, and written sources, it can be deduced that forests, cornfields, and vineyards reached further north and up to 200 m higher on mountainsides than they do today.

2.12 Climate and the Glaciers of Iceland Over the Last Millennium

During the first centuries of the settlement of Iceland and the Icelandic Commonwealth (ca. 870–1262 A.D.), the climate was mild, though there had been occasional severe winters. Sea ice seldom appeared and glaciers were smaller than they are now. Natural scientists believe that, during the first centuries when Icelanders were settling the island, three quarters of the land had vegetation and just under half of the land was covered by trees. In those days, Kjölur, at an elevation of almost 700 m between the Langjökull and Hofsjökull ice caps, and the Móðrudalsöraefi wilderness had both been covered with vegetation, but there has been little work done on trying to evaluate how widespread vegetation was in the central highlands between these two glaciers. There is much to indicate that, during the first centuries of the settlement, the highland routes of Iceland were frequently travelled and the interior utilised, e.g. the Pjórsárver wetlands. Today the land is drastically changed; just less than a fourth of Iceland has vegetation, only 1 % is covered by trees, and the highest continuous vegetation limit in the central highlands is now 100–200 m lower than at the time of settlement. Only in a very few places is there any significant continuous vegetation above a height of 630 m, but there is a considerable amount in the central highlands at around 500–600 m.

At the end of the 12th century, the warm period of the North Atlantic during the Middle Ages drew to a close as winters often became cold and damp, westerly winds piled up snow, and summers were cool. Glaciers grew and extended further than had previously been known. There was not one continuous cold period, however, but rather unpredictable weather conditions with irregular fluctuations in temperature and precipitation. These periods repeatedly oscillated, few lasting longer than for twenty-five years, with very cold winters being followed by a few years of frequent currents of mild air crossing the North Atlantic. Climate fluctuations did not come in slow stages but rather suddenly, and differently, from year to year and from one area of the country to another. Tree rings and ice cores reveal that cooling began in Greenland and other northern regions around 1200. It is possible the Gulf Stream had changed direction, as had first been visible in agriculture and in the sea journeys of Greenlanders and Icelanders. Harbours froze and contact between the Nordic peoples in Greenland and the rest of Scandinavia and Europe ceased, the settlers starving, dying out, or blending with the Inuit natives.
Pope Alexander stated in a letter dated 1492 that very few ships sailed to Greenland because of the ice. The appearance of sea ice off the coasts of Iceland became frequent and with them came cold summers. Sea ice drifted southward along the eastern fjords and surrounded Iceland annually, months on end, for many years. Iceland became isolated from the rest of the world. Worsening weather conditions had already played a large part in the cessation of grain farming (barley) in Iceland, first in the north and then the south, though wheat was grown in southern Iceland until well into the 16th century. At the end of the 13th and beginning of the 14th century, there were many years of crop failure and starvation in Europe. Around 1400 the weather became stormier than previously and remained rather cool, but then grew even colder as the 16th century progressed. In the latter part of the 16th century, drought harried the inhabitants of North America from Mexico to Canada. We do not know if this coldness was only in the North Atlantic, but late in the 17th century it is known for certain that glaciers began to advance over the entire world, in the Alps, in the Andes, and in China and in New Zealand. It was coldest in Asia during the 17th century, and in North America in the 19th century.

In Iceland it is believed the 17th, 18th, and 19th centuries were the coldest since the settlement (Fig. 2.31). A lowering of the average temperature during the growing seasons influenced both the speed and magnitude of production. The livestock of farms was reduced, because in times of starvation there was a gradual long-term shortage of winter fodder. The cold period from 1550 to 1900 was a

Fig. 2.31  Iceland had a warm climate during its Settlement and Commonwealth periods (870–1262). Oxygen isotopes in ice cores from the Greenland ice sheet indicate that temperatures there (black line) had fluctuated in a similar way as they are believed to have done in Iceland (white line, graph without numerical value; Póraríssinsson 1974). It was coldest during the 14th century and from the end of the 17th until the beginning of the 20th century. Not only Iceland’s environment was shaped by climatic fluctuations during these cold centuries, but also the history and societies of Europe, from the medieval Renaissance to the Enlightenment, from the French and Industrial revolutions to modern times. (Dansgaard 2000, 2005; Johnsen et al. 1995; Mann et al. 1999; Póraríssinsson 1974; Sveinbjörnsdóttir and Johnsen 1990; Sveinbjörnsdóttir 1993; Geirsdóttir et al. 2009; Harbardóttir et al. 2001; Crowley 2000; Masse et al. 2008; Shindell et al. 2001; Sicre et al. 2008; Thompson et al. 1993; Ogilvie 1986, 1992; Ogilvie and Jónsson 2001; Finnsson 1970; Thoroddsen 1916–1917; Bergþórsson 1969; Guðmundsson 1912–22, 1948; Storm 1888; “1000 Year Temperature Comparison” 2005)
difficult time for vegetation and it was very susceptible to the effects of volcanic activity and human habitation. The destruction of soil and vegetation increased in the central highlands and caused additional livestock grazing in the lowlands, which, together with erosion, brought about the abandonment of farms. Avalanches became more common and they also destroyed vegetation and transported mud and debris over cultivated land. The migrations of fish were also diverted due to changes in the biological environment of the ocean and this also increased Icelanders’ difficulties. A cold sea drove fish away from the shore, thus catching them meant going further out to sea for longer periods. Cod often disappeared from Icelandic fishing grounds altogether as it thrives badly in very cold waters.

**The expansion of glaciers in Iceland.** The climate changes from the 13th to the end of the 19th centuries had the most effect on countries with a maritime climate, because when temperatures drop in areas with wet weather systems, an increasing part of precipitation falls as snow. Snow-free areas also grew fewer because of cold summers. From the middle of the 16th until the end of the 19th centuries, it is believed the snowline fell to a height of 700–800 m to the south of Vatnajökull, 300 m below what it usually was during the 20th century. On peninsulas and promontories in northern Iceland, the snowline could have been as low as 800 m, and in the western fjords even below 600 m above sea level. Further inland, however, the snowline in northern Iceland has often been above 900 m and in the central highlands at about 1100 m while to the north of Vatnajökull it had been even higher because there was little precipitation there during all of this period. In depressions and hollows all over the country, snow has lain for years below the snowlines described above. Vegetation often appeared late from under snow cover and, during most years, snow settled high up on mountain tracks between glaciers before winter returned, although vegetation in the highlands could survive up to an elevation of 600 m. This has been proved by sources from the 18th century, such as the ruins of the outlaw Fjalla-Eyvindur’s hut in Eyvindaver and bridle paths at a height of 600 m in Arnarfellsmúlar and Púfuver (south of Hofsjökull). Permafrost had increased in the highlands, on the other hand, and is even believed to have reached as low as 400 m above sea level.

Glaciers probably began to advance just before the end of the 12th century, but with increasing power in the 16th century, and the progress of the largest glaciers was unimpeded until the end of the 19th century. While creeping forwards, these glaciers destroyed moraines from the Sub-Atlantic period. In Norway and the Alps, glaciers expanded from 1200 to 1550, but the first sources relating to advancing glaciers in Iceland are to be found in Íslandslýsing (‘Account of Iceland’) by Oddur Einarsson (1559–1630) from about 1590 (Einarsson 1971). Glaciers then progressed considerably from 1600–1620 and 1640–1650. Glacial lakes grew larger too, encroaching on, flooding and destroying farmland. Glaciers advanced the most in the dampest and coldest areas of the country, along the south coast and in the western fjords. In the first part of the 18th century, the outlet glaciers from Drangajökull on the western-fjords peninsula had spread out extensively, forcing five farms to be abandoned. Around 1700 the settlement farms of Breiðá and Fjall disappeared under Breiðamerkurjökull in the south, which had by then advanced
15 km over Breiðamerkurjökull plain. The Breiðá farm was abandoned in 1698 and the farmstead buildings were in ruins and virtually covered by the glacier by 1712. The Fjall farm was probably abandoned before 1694 and had disappeared under the glacier (Fjallsjökull) by early in the 18th century. Árni Magnússon reported changes in Sólheimajökull glacier in the years 1702–1712 and described the advance of outlet glaciers from Drangajökull (Magnússon 1955). In Eggert Ólafsson and Bjarni Pálsson’s (1981) Ferðabók (‘Travelogue’) there is mention of glaciers becoming larger, and around the middle of the 18th century they gave an account of how a glacier expanded on Skarðsheiði and how a new glacier had come into existence. This glacier was a quarter of a square mile when Sveinn Pálsson (1945, 2004) saw it on 27 August 1791. Due to the cold, glaciers began expanding again in Iceland in the years 1810–1860, as did glaciers in the Alps and elsewhere in the world, e.g. in Alaska and Karakoram in the Himalayas. Steep, fast-moving valley glaciers in Óræfi attained their greatest expansion from 1750 to 1850. The country’s largest glaciers, on the other hand, continued to advance until the end of the 19th century, the glaciers in Iceland then being larger than they had ever been since the last glacial period had ended; indeed Vatnajökull had become larger than it had been for 8–9000 years. It is believed that the main outlet glaciers from Vatnajökull had extended 10–15 km further than they had been during the time of the settlement and that by 1900 glaciers had covered, in all, about 15 % of the country. Breiðamerkurjökull was just under 300 m short of reaching the sea. The land was compressed by the tremendous overburden of ice and tidelines rose higher due to this subsidence. Evidence of this can be seen in Hornafjörður in southeastern Iceland and will be discussed in more detail in the chapter on Vatnajökull.

Was the Little Ice Age a Result of a Minimum Number of Sunspots or Increased Volcanic Activity?

The cooling of the Little Ice Age has been connected to the fact that there were hardly any sunspots over a 70-year period from 1645 until 1715 (a theory named after the Englishman Walter Maunder [1851–1928]), and prior to that there had been a minimum amount of sunspots for a period twice as long (1420–1570; associated with the German astronomer Gustav Spörrer [1822–1895]). No convincing physics-based explanation has been advanced to explain the link between sunspots and weather, however. Normally, there are 11-year oscillations in the Sun’s activity, visible on Earth as sunspots. A higher number of high-speed particles then reach the outer layer of the Earth’s atmosphere, or stratosphere, and northern lights are seen more frequently. The total solar energy varies about 0.1 % but the ultraviolet part of the sun’s light about 20 %. The stratosphere completely absorbs this ultraviolet part of solar radiation and this is where any effect on the inner layer of Earth’s atmosphere, the troposphere, would have to come from, although no one has yet worked out how this could cause fluctuations in climate. There are those who believe there are statistical calculations, however, which do
indicate that the number of sunspots can indeed be correlated with changes in precipitation and temperatures on Earth.

As well as the low number of sunspots, the Little Ice Age has also been linked to high levels of volcanic activity in the period from the 14th to the 19th centuries. In major volcanic eruptions, hundreds of cubic kilometres of ash and volatile materials, such as sulphur dioxide, have been borne through the troposphere and up into the stratosphere where they have mixed with water vapour, so that microscopic drops float for years on the outer edges of the troposphere, reflecting solar radiation and thus reducing the amount of solar energy reaching the Earth. This haze, when cooling, descends into the troposphere and changes the atmospheric circulation around the globe. This cooling of the Earth is rather short-lived, however, because the winds high in the atmosphere blow rapidly around the world and engulf the floating drops so that they eventually fall to Earth as precipitation. The best-known volcanic eruptions that are believed to have influenced weather conditions all over the world were Vesuvius in Italy (79 A.D.), the Laki fires in Iceland (1783), Tambora (1815) and Krakatoa (1883) in Indonesia, El Chichón in Mexico (1982), and Pinatubo in the Philippines (1991).

2.13 Climate in the 20th Century and the Future of Iceland’s Glaciers

There was a worldwide increase in warming after the middle of the 19th century, and at the beginning of the 20th century the cold period that had lasted from about 1300 in northern Europe had finally ended (Fig. 2.32). A period succeeded with a temperature on average 1–2 °C warmer than it had been for seven centuries.

![Fig. 2.32 Outline of average temperatures in Iceland since 1820. Data from Stykkishólmur indicates a running 11-year average (with triangular weight). (IMO data 2009; Eybórssón 1950; Eybórssón and Sigtryggsson 1971; Sigtryggsson 1972; Sigfúsdóttir 1969; Einarsson 1984, 1991, 1993; Jónsson 1991; Hanna et al. 2004)]
Vegetation expanded and new species of birds began to settle and breed in Iceland. The greatest warming in the North Atlantic was in the 1920s and was connected to low-depression systems reaching further north than previously. The warmest period in Icelandic history was from 1930 until 1960 and almost all glaciers retreated except for a few surging ones. From around 1940 the temperature started to drop once again, and during the 1950s and 1960s it was on average 1 °C colder over the summer months than in the previous years of the Second World War. With this cooling, there was a reduction in summer meltwater from the glaciers and a greater percentage of precipitation fell as snow. The retreat of glaciers in Iceland gradually slowed down and over the next thirty years or so (1970–1995) most glaciers either remained stationary or advanced little because of the increasingly colder weather. It has been suggested that the causes of this cooling after 1940 may have been air pollution, especially due to smog from coal-burning, which had reduced the levels of solar radiation reaching Earth. By the end of the 20th century, Earth began to get warmer very quickly, especially after 1995, and glaciers have retreated all over the world; the effect of air pollution on atmospheric radiation now weighs more in importance than the dispersal of solar radiation on its way to Earth. It is also believed, however, that some oscillations might be caused by irregular fluctuations in the transporting of heat by air and ocean currents over the last decades.

Although changes in temperature levels over the last 1000 years may be connected to fluctuations in solar radiation and volcanic activity, the influence of mankind after 1850 is still considered the main cause of global warming: i.e. an enlarged absorption of terrestrial radiation in the atmosphere due to an increased concentration of greenhouse gases (IPCC 1995, 2007, 1990). The Earth is now warmer than it has been for 90 % of its 4600-million-year history due to two centuries of atmospheric pollution. Further warming is rated likely to continue for several hundred years, even if there were to be a reduction of so-called greenhouse gas emissions. Glaciers here in Iceland are now smaller than they have been since the 17th century, and if the climate change forecasts prove correct (i.e. +2 °C warmer per century), most of the country’s main glaciers will disappear within the next 100–200 years (Jóhannesson 1997; Jóhannesson et al. 2004, 2006b, 2007; Jóhannesson et al. 2006a; Bergström et al. 2007; Björnsson and Pálsson 2008). Runoff waters from areas now covered by glaciers will increase around 25–50 % over the next 30–100 years before being reduced, and once glacial water reserves have drained away the only source of water will be from precipitation. Increasing meltwater flows and changes in waterways will have a great impact on the design and construction of bridges and roads and the operating of hydro-electric power stations that utilise water from the central highlands of Iceland.

Fluctuating ice ages in the future. We are living in a warm period of an ice age with exceptional circumstances in the history of the Earth because warm periods have only taken place during 10% of the last 2,000,000 years. The last time the Earth was as warm as it is today was 120,000 years ago. The ice age continues, nonetheless, and cannot be considered to have ended until ice has mostly disappeared from the world’s mountain ranges and polar regions. Glaciers currently cover almost 11 % of the Earth’s land surface (15,000,000 km²) and in addition
there is an equally large area of frozen tundra on Earth in North America and Eurasia (14,000,000 km²). During winter, sea ice covers around 12 million km² of ocean in the northern hemisphere, and 20,000,000 km² around Antarctica during the summer (when it is, of course, winter in the southern hemisphere). In comparison, the whole of the Greenland ice cap is 1.7 million km². About 90% of all the freshwater of this Earth, the blue planet, is now frozen in glaciers, most of it in Antarctica and Greenland.

According to Milankovitch’s theories, there lies ahead of us a series of 50 glacial periods that will endure for about 100,000 years before there is any let-up. The Earth will gradual cool due to its orbit and axial tilt, even though precession would still promote warming. A combination of these factors will cause a gradual cooling and a move towards a cold period after 10–15,000 years, and after 20–25,000 years a glacial period will begin which will reach its peak after 60,000 years (Berger 1977b, 1978). Mankind cannot avoid having to deal with a glacial period. Cities in the northern hemisphere will then be covered in ice, crushed, pulverised and bulldozed by glaciers. A massive flow of refugees southward will follow with the consequent fight for survival and danger of wars. Human life will only be a shadow of what it is today in a modern, technological civilization. The question can thus be raised as to whether polluting the atmosphere could in fact delay this cooling of Earth and that global warming from the greenhouse effect might therefore be welcomed? Experience of how a sudden warming during the Younger Dryas period led to the shutting down of the conveyor belt of heat to northern regions, however, raises fears that an increasing greenhouse effect could actually speed up the coming of a cold period. A tremendous melting of glaciers would change the saline content of seas and the routes of ocean currents in the North Atlantic and bring about a cooling of the whole northern hemisphere; there would be severe weather around the North Atlantic, in Greenland, the British Isles and Scandinavia. We can no longer rely on an increase in solar radiation, as in the beginning of this post-glacial, or Holocene period. But all of this is difficult to predict, for scientists still do not fully understand the causes of sudden climate changes (Alley 2000, 2004; Masse et al. 2008). On the other hand, we do know from the climate history of the Earth, that climate has often suddenly been jolted out of an equilibrium when a slow-working change has pushed Earth’s climate system over a certain threshold. Effects are then amplified and continue for centuries; and it appears that ocean currents in the North Atlantic have the final say in this. It is thus ominous news that ocean currents southward between Scotland and the Faroe Isles have slowed by about 20% since the middle of the 20th century (Häkkinen and Rhines 2004; Hátún et al. 2005). Being at the centre of North Atlantic oceanic currents, Iceland is very sensitive to climate change and it has occurred there in the past more rapidly than in most other countries.

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