Cool Britannia: from Milankovich wobbles to Ice Ages

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Abstract: A lecture to the Society outlined recent research that has revealed a long history of multiple glaciations affecting Britain prior to the well-known Anglian event.

The snow and intense cold of December 2010 gave us the coldest month since meteorological records began. It is a timely reminder that despite living in a warm (interglacial) period, the Holocene, climate within recent Earth history has been markedly colder for periods lasting many thousands of years. These cold stages form part of the Quaternary, which spans the past 2.6 million years (Ma). It marks the transition from the sometimes greenhouse climates of the Cretaceous and earlier Cenozoic, through to Ice Age Earth. It is often said that the Quaternary is synonymous with the Ice Age, but this is somewhat misleading. While there were numerous extended cold periods or 'glacials' that did result in Ice Ages during the Quaternary, there were also many warm periods or 'interglacials' where the climate in Britain was at least as warm, if not warmer, than that of today.

Quaternary climate change has had a profound and lasting impact on our landscape. In particular, the form of much of the landscape is a legacy of our Ice Age history. Understanding this history is important in interpreting not just our landscape heritage and its conservation and sustainable use, but also in appreciating just how sensitive our land-mass is to the long-term forces of climate change. This paper explores the long-term history of Ice Ages in Britain and Ireland, focussing on why they occurred, and when and how big they were.

Cenozoic Ice Ages – a global perspective

Global climate has deteriorated progressively throughout the later part of the Cenozoic, with the first Ice Age, or glaciation, of Antarctica occurring as long ago as 34 Ma. In the Northern Hemisphere, such large-scale glaciation first occurred much later. Evidence from core samples collected from beneath the sea bed in the Nordic seas indicate the first presence of glaciers on Greenland during the Miocene about 12.7 Ma ago. The key evidence was thin layers of marine sediment known as ice-rafted detritus. These record the deposition of debris dropped from melting icebergs that have broken off or calved from floating, often marine-based, ice margins (Fig. 1). In simple terms, the detritus provides clues as to the extent of glaciers where land-based evidence such as moraines and till (boulder clay), may have been long-since removed. Geologists can also use a range of geochemical techniques to examine the composition of the ice-rafted detritus to determine which rocks have been eroded and incorporated into the glacier, and indeed, where the iceberg and its host glacier came from – a form of glacier forensic fingerprinting.

Despite evidence for glaciation in Greenland dating back into the Miocene, it wasn't until the Late Pliocene and Early Pleistocene, some 9 million years later, that widespread glaciation occurred within North America, Britain, Scandinavia and the Barents Sea region. Rather than being abrupt, the onset of glaciation was actually a gradual long-term transition that accompanied an increase in global ice volume that spanned a period of about 1.2 million years between 3.6 and 2.4 Ma. Records of ice-rafted detritus from the North Atlantic demonstrate the established presence of large ice sheets on Greenland and around the Barents Sea from about 3.3 Ma. Closer to home, ice sheets in Britain, Ireland and Scandinavia first became active at around 2.7-2.6 Ma. However, between their initial formation and the present day, their extent and the overall scale of glaciation has waxed and waned depending on the prevailing climate and the ability of the ice sheets to grow and maintain their size. Generally though, it has been recognised within the Northern Hemisphere that the scale and frequency of glaciation during the Quaternary cold stages has increased progressively over time.

Now we live in an interglacial – a period where the amount of water locked into the world's ice sheets and glaciers naturally declines, and water previously locked-up as ice within ice sheets returns to the oceans so that sea-levels rise. Since the peak of the

Figure 1. *Icebergs such as these at Jökulsárlón, in Southern Iceland, are common where a glacier terminates in water. They can leave plough-marks in the geological record, where they are dragged over sediment. When the icebergs melt, its rock debris falls to the sea or lake bed. It may include large erratic blocks, or be finer sediment in discrete layers, and known as ice-rafted detritus.*

last glaciation some 24,000 years ago, the progressive melting of glacier ice in high and mid-latitude areas has resulted in a global sea-level rise of about 130 m. This has drowned large parts of the European continental shelf and brought marine conditions into the North Sea and Irish Sea; both these basins were largely devoid of sea-water during the Ice Ages, when sea-levels were much lower because more water was locked-up within the world's ice sheets. The vast majority of the great Pleistocene ice sheets of the Northern Hemisphere have now melted and disappeared. This includes the Laurentide Ice Sheet, which once covered over a half of North America, and the British-Irish Ice Sheet which has been absent from our landscape for about the past 11,500 years. The majestic fjords of western Norway ,that were once cut by immense rivers of that formed part of the Scandinavian Ice Sheet, are now devoid of glaciers. Ice still clings to some of the high plateaus of western and northern Norway, with Jostedalsbreen the largest, although many of the small alpine glaciers are now in rapid retreat. The largest remaining body of ice in the Northern Hemisphere is the Greenland Ice Sheet. This has a surface area of about 1.7 million km^2, though its margins are rapidly constricting amid concerns of the impact of human-induced global warming. Should the entire mass of the Greenland Ice Sheet melt, it would result in a global sea-level rise of about 7.2 m.

What causes Ice Ages?

One of the most obvious questions is why glaciers and ice sheets have been able to grow so extensively during the Quaternary, and less frequently throughout other parts of the geological record. The precise answer to this question has baffled climate scientists for several decades. The consensus view is that the Quaternary and other geological episodes where Ice Ages have been commonplace are distinctive in combining a specific set of geological and geographic circumstances that accentuates a longer-term pacemaker that regulates global and regional climate.

This climatic pacemaker relates to long-term changes in the shape and nature of the Earth's orbit around the sun. Such astronomical phenomena have forced Earth climate throughout geological time, and have operated over a range of temporal time scales. Critical to our Ice Age story are millennial-scale changes in the Earth's orbit that follow regular and predictable cycles. These cycles are often referred to as Milankovitch Cycles, named after the Serbian astrophysicist who identified them. They correspond to subtle changes in the elliptical shape of the Earth's orbit around the sun (eccentricity) that occur over 100,000 year cycles, and slight tilts (obliquity) and wobbles (precession) of the Earth's axis that occur over 41,000 and 21,000 year time-scales respectively. These cycles impact upon both the amount of radiation that the Earth receives, and the seasonality of its spatial and temporal distribution over the Earth's surface through the seasons.

While this astronomical forcing exerts a dominant control on the background global climate, a range of regional to local geographical and geological controls are also required to enable ice sheets to develop and grow. One of the most important factors is the global configuration of the continents, due to the way it controls oceanic and atmospheric circulation, and in turn the distribution of heat and moisture around the planet. Land is also required in high and mid-latitude areas to enable ice to develop into ice sheets and glaciers.

By way of an example, ice sheets developed on Antarctica far earlier than in the Northern Hemisphere. This occurred when the continent of Antarctica detached from South America about 34 Ma ago and drifted southwards into the Southern Ocean by processes of continental drift. This led to the opening of the Drake Passage so that cold ocean currents then surrounded the Antarctic continent; Antarctica literally froze, and the Antarctic Ice Sheet soon developed.

The story from the northern hemisphere appears to have been more complex. Many scientists believe that the critical factor was the closing of the Central American Seaway that linked the tropical waters of the Pacific and Atlantic, by the formation of the Panama isthmus at about 5 Ma. This was critical because oceanic circulation – a global-scale conveyor belt that circulates water around the world's oceans – is principally driven by salinity differences between these two oceans. With the Central American Seaway open, the transfer and mixing of warm tropical surface-waters between the Pacific and Atlantic Oceans largely balanced the salinity differences between their waters. By contrast, closure of the seaway created a greater salinity imbalance between the two oceans, leading to enhanced global oceanic circulation and the more effective transfer of heat and moisture around the planet.

For northwest Europe and the British Isles, the Gulf Stream plays a key role in keeping our climate more temperate than places such as Labrador and Newfoundland that lie at similar latitudes. Closure of the Central American Seaway led to the Gulf of Mexico becoming more saline driving greater rates of heat and moisture circulation into higher northern latitudes via the Gulf Stream. When these warm saline surface waters are transferred northwards, they cool, increase in density and sink. From the Greenland Sea, these bottom-waters then flow back southwards via the Labrador Sea, drawing even more warm water into the conveyor. Moisture is not only essential in nourishing ice sheets, but it also contributes large amounts of cold freshwater into the Arctic Ocean either directly as snowfall or by rivers from northern Eurasia. Introduction of this cold freshwater into the Arctic Ocean made its surface waters much colder and less salty, making it possible for the regular development of seasonal and continuous sea ice. Extending like a blanket across the oceans in high latitudes and polar areas, this sea ice also played an important role in reflecting incoming solar radiation

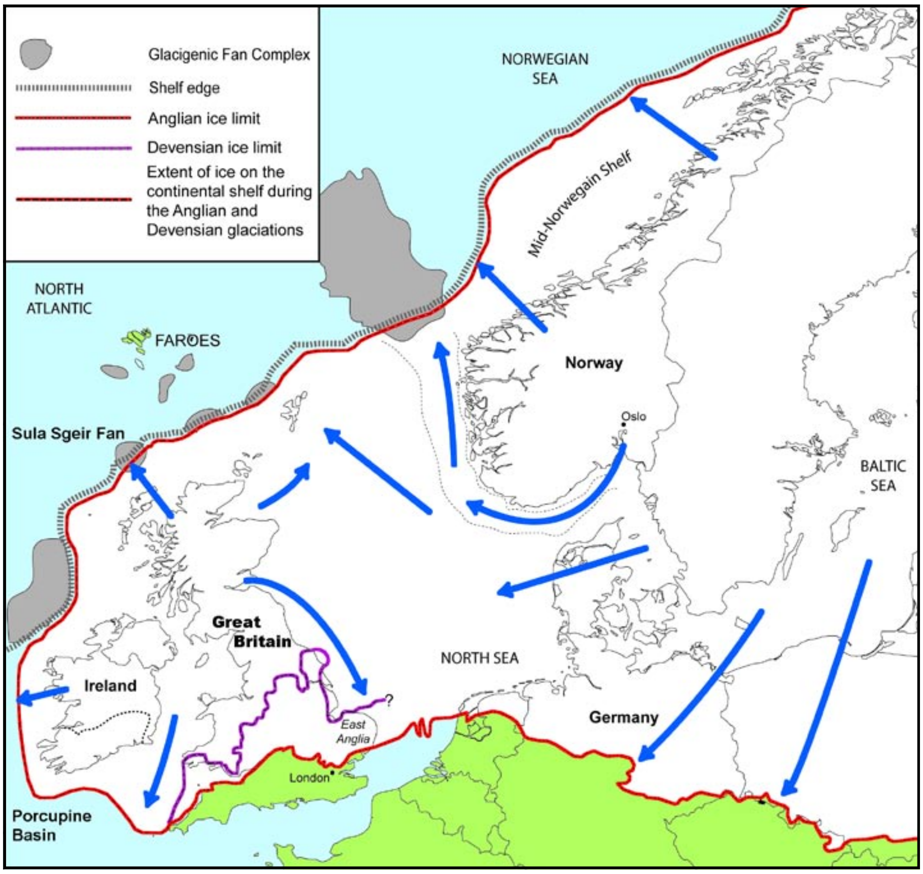

Figure 2. *The main Quaternary ice limits in Britain and Ireland and their extension into Europe, with blue arrows marking the main flow paths of elements of the British-Irish and Scandinavian ice sheets. The coastlines are as they are today, not as they were during the Ice Ages.*

back into space. This process is the albedo effect and is self-perpetuating – the more sea-ice, the greater reflection of solar radiation, the colder it gets, which encourages greater formation of sea-ice…and so on.

Together the astronomical and regional-scale mechanisms regulate climate; they then interact with local geographic factors such as elevation and latitude to control temperature, and so determine whether precipitation falls as rain or snow. These factors in turn drive the mass balance of an ice sheet or glacier – namely, the relative balance between accumulation (the snow fall and conversion to ice that make glaciers grow) and ablation (the loss of ice volume to melting and iceberg calving that makes glaciers shrink). Thus, for an ice sheet to form and grow rapidly, the rate of accumulation has to far exceed the ablation rate. By contrast, if the rate of ablation is far higher than that of accumulation, then either an ice sheet won't form or an existing ice sheet will shrink.

Cool Britannia

Until recently, geologists believed that Britain and Ireland remained ice-free for much of the Quaternary, with only two extensive glaciations during the time (Fig. 2). The first of these was the Anglian Glaciation, which occurred between 0.48 and 0.43 Ma. This was the largest glaciation to affect us during the Quaternary with ice extending across two-thirds of Britain and Ireland, as far south as Oxfordshire and north London, and laterally to the edge of the continental margin from western Ireland round to Norway. Both the North Sea and Irish Sea were land and were occupied by glacier ice. In the Midlands, Pennine Ice deposited the Thrussington Till as it moved west to east across the region. Later, British North Sea ice extended westwards across the Lincolnshire Wolds into the Midlands, depositing the chalky Oadby Till. The second glaciation was that of the Late Devensian, with a maximum ice sheet extent, referred to as the Last Glacial Maximum, achieved at around 27 ka. Again, glacier ice occupied much of the North and Irish Sea basins with ice extending southwards from Scotland into northern England. British North Sea ice reached the Wash but there is no direct evidence for ice ever reaching into the East Midlands. The area that lay beyond the Last Glacial Maximum ice limit, as with other glacial limits, was subjected to intense cold with large areas of frozen ground – permafrost (Fig. 3).

Together, this land-based evidence suggested that Britain and Ireland had a limited glacial history during the Quaternary. It implied that ice sheets and glaciers were only sporadically active within our landscape. This is somewhat puzzling, especially when the position of Britain and Ireland, relative to an abundant moisture source (the North Atlantic) and the Polar Front, is considered. Indeed, new data and re-examined information previuosly published, suggests that Britain and Ireland may have been glaciated on many separate occasions. The evidence for these extra glaciations is often very discrete, and is even open to different scientific interpretations. Equally, determining their precise ages has proved very problematic. A review all of the evidence paints a picture of numerous Ice

Ages (Fig. 4). In broad terms, our Ice Age history can be divided into three separate phases, each relating to different scales and frequencies of glaciation.

2.6 – 1.2 million years ago

The climate in Britain and northwest Europe during this time interval was driven by the short-term precession and obliquity orbital cycles that produced numerous episodes of climate change, albeit of small magnitude and duration. Several scientists have speculated that this global climatic backdrop was probably insufficient to generate permanent ice caps over highland areas of Britain such as Wales, the Lake District and Scottish Highlands, so that when glaciations did occur, they were of limited spatial and temporal extent.

Several lines of evidence have been discovered to support this assertion. On the Hebrides Margin, located to the northwest of the Hebrides, a large submarine fan called the Sula Sgeir Fan extends outwards from the edge of the continental shelf. Sediment cores obtained from the fan reveal that the earliest Quaternary deposits contain fragments of rock derived from northwest Scotland. It is believed that they were transported to the shelf edge by icebergs that then melted and dropped the rock fragments. The source for these icebergs is likely to be glaciers that extended from highland parts of western Scotland into coastal areas, where they eroded and entrained the rock material, before calving and releasing the icebergs. Further south, a number of far-travelled erratics from North Wales, some of which possess glacial striations, have been found within ancient deposits of the River Thames. These deposits date from the early part of the Quaternary when the upper reaches of the River Thames lay within Wales, far beyond their current margins in the Cotswolds. The erratics are considered to have been transported within blocks of ice by melt-water streams that eventually flowed into the Thames. Further downstream, the blocks of ice grounded, whereupon they melted and deposited the erratics. A minimum of ten separate restricted glaciations in North Wales have been speculated.

Figure 3. *Periods of intense cold during the Quaternary resulted in the growth of ice sheets. In areas not glaciated, cold arctic tundra could have looked like this, 24,000 years ago, in what became the southern part of the North Sea.*

Recently, new evidence from the Porcupine Basin, on the continental margin southwest of Ireland, has led scientists to radically reconsider the notion that ice sheets were limited in temporal and spatial extent during this time interval. Sediment cores reveal no less than 16 major pulses of ice-rafted detritus derived from western Britain and Ireland between 2.6 and 1.7 million years ago. Each of these pulses records separate occasions when glacier ice extended into coastal waters, depositing from the melting icebergs thin layers of ice-rafted sediment across the continental shelf and margin. It suggests that in parts of western Britain and Ireland, ice caps were likely to have existed for prolonged phases during this period.

1.2 - 0.48 million years ago

This second period of time extends up to our biggest glaciation – the Anglian. It spans a period where global climate was in state of transition from climate change driven by the smaller, more frequent, precession and obliquity orbital cycles, to the higher magnitude 100-ka eccentricity cycles. The effect of this Mid-Pleistocene Transition (as it has become known), was to make Britain, Ireland and other parts of northwest Europe far colder during cold stages and to reduce seasonality. It pushed the Polar Front further south, and for much longer periods of time led to parts of Britain becoming arctic tundra with the ground frequently frozen into either permanent or seasonal permafrost.

River systems, including the Thames and others that flowed through central and southern Britain, became much more active and dynamic. Not only did they possess a stronger seasonal flow due to melting permafrost and snow, but periglacial slope processes acted to supply them with much greater volumes of sediment. Rivers became more efficient at recycling larger volumes of material along the length of their catchments and over shorter periods of time.

There is also good evidence for an increase in the size and frequency of glaciation. Rather than simply being restricted to highland parts of Britain and adjacent coastal areas, ice also extended into more lowland parts of central England and the Thames Basin, and further eastwards into the North Sea Basin. Evidence from the North Sea and adjacent parts of East Anglia includes several generations of tills and meltwater-incised valleys, iceberg plough surfaces and ice-rafted erratics.

0.48 million – 11 thousand years ago

This time period spans the two big glaciations to have affected Britain and Ireland – the Anglian and Late Devensian glaciations – and the final decay of our last great ice sheet. Globally, the 100-ka eccentricity orbital cycle dominates and drives big oscillations in climate between warm temperate interglacial stages and cold glacial stages; in total, six major cold glacial stages and five major interglacial stages have been recognised.

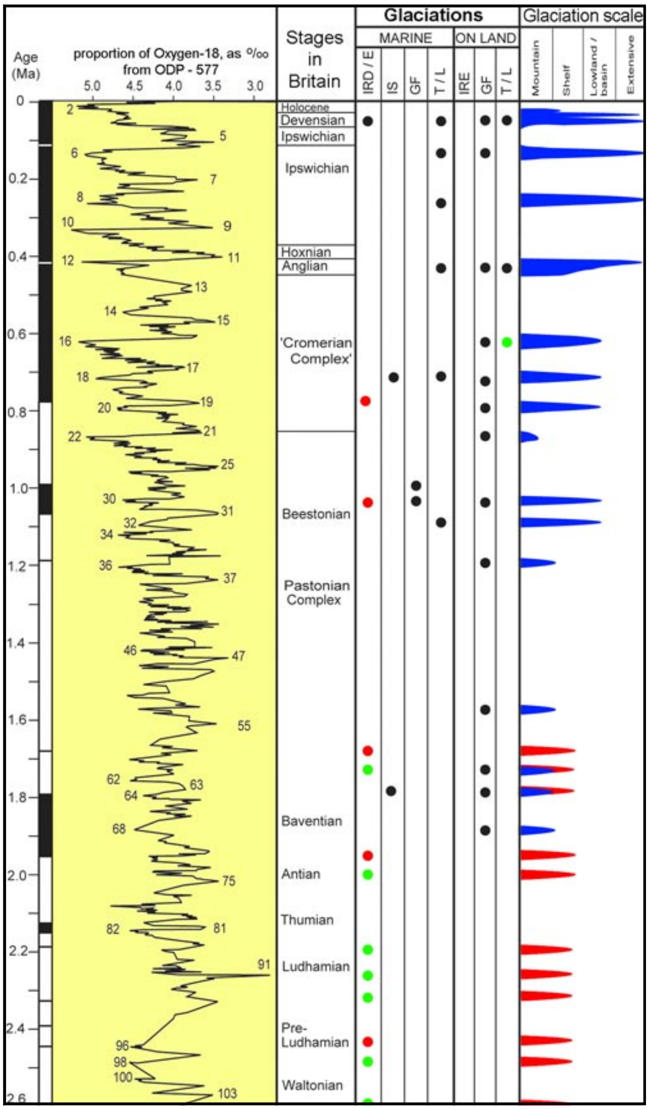

Figure 4. Summary of the evidence for glaciations within Britain, Ireland and adjacent marine areas. The line on the left shows an oxygen isotope curve that provides a crude global yard-stick for the volume of glaciation relative to sea-level; peaks to the left show 'glacials' with high global ice volume and low global sea-levels; peaks to the right show 'interglacials' with low global ice volume and high sea-levels. IRD = Ice Rafted Detritus; E = erratics; IS = iceberg scours and plough marks; GF = glacifluvial deposits; T = till; L= landforms. Red spots indicate multiple ice rafting events. Green spots are tentative. On the right, blue bars show the interpreted scale of glaciation, red bars are inferred from the ice rafted deposits.

During cold stages, the effect of this climate forcing is to promote the rapid build-up of ice volume within high and mid latitudes. Offshore cores and seismic data from around our continental margin demonstrate the presence of glacier ice on the continental shelf during each of the major cold stages. On land, evidence for glaciation is largely confined to the Anglian and Late Devensian glaciations. During the Anglian Glaciation (480-430 ka) the Midlands was extensively glaciated, with the region located some 175 km up-ice (northwards) of the maximum ice sheet extent.

The effect of the glaciation on the landscape of our region has been marked. Many of the old pre-glacial river systems were overridden and destroyed, though their host valleys can still be identified buried beneath the modern landscape. Widespread bedrock erosion occurred with vast quantities of sediment removed and deposited either by ice as till or by meltwaters issuing from the ice margin.

Late Devensian ice, although extensive in northern and western Britain and Ireland, the North Sea and Irish Sea, lay just to the west, north and east of the Midlands and did not directly affect the region. Within the Trent Valley, river terrace deposits that relate to this glacial episode contain ice wedge casts; these show that, while glaciers didn't reach the Midlands, the climate within the region was extremely cold and arid, enabling the development of permafrost ground. The maximum extent of the British-Irish ice sheet was reached about 27,000 years ago, with ice extending to the continental margin offshore from northwest Scotland, and southwards to the Isles of Scilly within the Irish Sea. Progressive wasting and collapse of the ice sheet followed, until ice was all but absent from marine areas by 17,000 years ago. The final glaciation to affect Britain and Ireland was a short-lived glacial event called the Younger Dryas, about 12,900-11,500 years ago, during the slow emergence of northwest Europe from the prolonged cold arid climates of the Late Devensian. This caused the growth of the Loch Lomond Stadial Ice Cap in Scotland and the re-appearance of small glaciers in highland areas of Britain. The cause of this short, sharp glacial event is believed to relate to the sudden influx of freshwater into the North Atlantic from Lake Agassiz (which had covered much of the Canadian Prairies) and the collapse of the North American Laurentide Ice Sheet. It is believed that this influx of freshwater disrupted oceanic circulation in the North Atlantic causing the Gulf Stream to shut down and plunging Britain into the deep freeze.

Whether additional glaciations occurred between those of the Anglian and Devensian is unclear. Part of the problem surrounds the interpretation of deposits traditionally assigned to the Anglian and Late Devensian glaciations that may in reality equate to glaciations that took place between the two. Resolving this issue has proved challenging, due both to different interpretations of the same geological information using different techniques, and the general paucity of materials for which absolute dates can be determined.

The wider context

Rather than possessing a limited record for glaciation during the Quaternary, as many scientists had previously considered, the geology of Britain and Ireland reveals a complex history of ice sheets and Ice Ages (Fig. 4). While the precise timing of many of these glaciations cannot reliably be constrained by absolute dating techniques, their broad relative timing and chronology can be determined thorough biostratigraphy and by their relationship to other geological sequences that possess a crude chronology. The long-term evolution of these events provides a basis with which we can understand the sensitivity of the British and Irish land-masses to climate change throughout the Quaternary.

Recommended Reading

Alley, R.B., 2000. *The Two-Mile Time Machine: ice cores, abrupt climate change, and our future*. Princeton University Press. [A highly recommended popular science book about ice core records and climate change; easy to read and to follow.]

Candy, I., Silva, B.N. & Lee, J.R., 2011. Climates of the early Middle Pleistocene in Britain: environments of the earliest humans in Northern Europe. 23-28 in Ashton, N.M., Lewis, S.G. & Stringer, C.B. (eds.), *Ancient Human Occupation of Britain*, Developments in Quaternary Science 14, Elsevier. [Short paper with an insight into the warm and cold climates experienced in Britain in the Quaternary and their relevance to ancient humans.]

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C. & Sejrup, H.P., 2011. Pattern and timing of retreat of the last British-Irish ice sheet. *Quaternary Science Reviews*, in press. [New paper that provides a lengthy summary of the Devensian British-Irish ice sheet.]

Lee, J.R., Busschers, F.S. & Sejrup, H.P., 2011. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews*, in press. [Paper that provides a regional overview of glaciations in Britain, the Netherlands and Norway based upon terrestrial and marine evidence.]

Lowe, J.J. & Walker, M.J.C., 1997. *Reconstructing Quaternary Environments*. Longman. [Background book on techniques used by Quaternary Scientists, plus some ideas on the causes of Quaternary glaciations.]

Thierens, M., Pirlet., Lee, J.R., *et al*., 2011. Ice-rafting from the British-Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. *Quaternary Science Reviews*, in press. [New paper that revolutionises the way we look at glaciations in Britain – many of them and some very old!]

Prior to 1.2 Ma, there is abundant evidence for the development of ice caps and localised glaciation in highland parts of western Britain and Ireland, and at times these extended onto the continental shelf. In many respects this is unsurprising, considering the abundant supply of moisture from the North Atlantic which in theory would enable ice volume to build up relatively quickly. However, these small orbitally-forced climate changes did not generally promote the development of permanent to semi-permanent ice caps in mid-latitude areas. Nor did they promote the maintenance of a moderate seasonality. In this respect, the inference that ice caps were either permanent or semi-permanent over parts of western Britain and Ireland is unique, and is not replicated in areas such as mid-latitude western Norway. It suggests that the Polar Front lay further to the south than it does today, and/or the moisture input into western Britain and Ireland was sufficient for the glaciers to maintain a largely positive mass-balance despite more moderate seasonality.

From 1.2 Ma onwards, the progressive switch to the longer-term, high-magnitude, orbital-eccentricity cycles pushed Britain and Ireland into the deep freeze during cold stages. The spatial scale of glaciation increased with ice extending occasionally into more lowland and mid-basin areas. Ice masses in Britain and Ireland were able to build-up larger ice volumes more quickly, which was not surprising given the reduced seasonality. A similar picture emerges from ice sheets in Scandinavia, the Barents Sea region and in Greenland and North America, which all experienced more widespread and frequent glaciation. For example, the first shelf-edge expansion of the Scandinavian Ice Sheet and the first known existence of a major ice stream off western Norway occurred at around 1.2 Ma.

By the time of the Anglian Glaciation, at 0.48-0.43 Ma, global climate was driven by the high magnitude eccentricity cycles. This glaciation generally equates to the maximum extent of global ice coverage during the Quaternary. Putting this into a context, the ground where Nottingham now stands lay beneath ice that was more than a kilometre thick. Furthermore, this glacier ice extended unbroken as far as eastern Siberia. From the time of this glaciation onwards, ice sheets possessed an even greater ability to rapidly build ice volume due to low seasonality. In Britain and Ireland, the precise number of glaciations we have had since the Anglian remains contentious.

Together, all the evidence presented demonstrates that Britain and Ireland possesses a long history of Ice Ages and glaciations spanning much of the Quaternary. The scales of these glaciations appear to increase towards the present day, with a series of marked steps in a manner similar to that of other ice sheets that bordered the North Atlantic. It shows that our land-mass was highly sensitive to climate change, and that glaciers quickly became established in highland areas when climate deteriorated.

Acknowledgements

This article has been written as a follow-up to the lecture given by the author to the East Midlands Geological Society in January 2011. It is aimed at a non-expert, general-science audience, and as such omits references to the numerous scientific papers that have been used. However, the author places on record a formal acknowledgement of their contributions to what is a fascinating aspect of the recent history of the British Isles and Ireland. In particular the author acknowledges many individuals who have directly influenced his thoughts and views on this matter, especially Freek Busschers, Ian Candy, Chris Clark, Richard Hamblin, Brian Moorlock, Jim Rose, Hans Petter Sejrup and Mieke Thierens. Steve Booth and Andrew Finlayson are thanked for their constructive and thought-provoking reviews.

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