14

The Holocene Interglacial

14.1 Holocene Climate Change

We live in the Holocene. If we want to get some idea of how its (and our) climate may evolve into the future, we need to see how it developed over the past 11 700 years, since the end of the Younger Dryas cold event. A recent review by John Birks of the Bjerknes Centre for Climate Research of the University of Bergen explores the early stirrings of inquisitiveness about Holocene climate change[1]. Natural historians noted back in the late 18th century '*the impressive occurrence of large fossil trunks and stumps (megafossils) of pine trees buried in peat bogs in northwest Europe*'[1]. A Mr H. Maxwell observed in 1815 that '*one of the greatest enigmas of natural science is presented in the remains of pine forest buried under a dismal treeless expanse on the Moor of Rannoch, and on the Highland hills up to and beyond 2000 feet altitude*'[1]. Similar changes in Denmark were attributed in the late 19th century to changes in moisture and to cooling in the postglacial period. The Norwegian botanist Axel Blytt (1843–1898) interpreted tree layers in peat bogs and changes from dark, humified peat to pale, fresh peat as evidence for alternations between dry and wet periods. The Swedish botanist Rutger Sernander (1866–1944) added ideas about summer temperature changes to propose the famous four Blytt-Sernander periods of postglacial time: Boreal (warm, dry), from 10 000 to 8000 years ago; Atlantic (warmest, wet), from 8000 to 5000 years ago; Sub-Boreal (warm, dry), from 5000 to 2500 years ago; and Sub-Atlantic (cool, wet), from 2500 years ago to the present. These were preceded by a Pre-Boreal period (cool, sub-Arctic) prior to 10 000 years ago. This Eurocentric scheme '*became the dominant paradigm for Holocene climate history*' during the early part of the 20th century[1].

Birks also reminded us that another late-19th-century scientist, the Swedish botanist Gunnar Andersson (1865–1928), while searching peat bogs, had discovered plant fossils, including hazel nuts, well north of their current range, suggesting that the climate had once been warmer than today. This led Anderson to present the idea of a gradually rising temperature curve reaching a long early to mid Holocene period of temperature warmer than today (a thermal maximum), followed by a subsequent decline. The notion of a Holocene thermal maximum seems to have arisen independently in the minds of other natural historians, including the Scottish palaeontologist Thomas F. Jamieson (1829–1913), based on his study of the molluscan fauna of mid Holocene estuarine clays in Scotland[1].

Early in the 20th century, a Swedish geologist, Lennart Von Post (1884–1951) proposed that '*pollen analysis … [be used] as a technique for relative dating and for reconstructing past vegetation and past climate*'[1]. In contrast to megafossils and macrofossils, it could provide a continuous record of changing vegetation and climate. Von Post integrated the Blytt and Salander phases of climate with Andersson's notion of gradual climate change and the findings of his own pollen analyses. This led to pollen analysis being used as a key means of determining Holocene geological time and climate change prior to about 1960. Quoting Ed Deevey, Birks told us that '*Von Post's simple idea that a series of changes in pollen proportions in accumulating peat was a four-dimensional*

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look at vegetation, must rank with the double-helix as one of the most productive suggestions of modern times'[1]. So it should be no surprise that, for his contributions, Von Post was awarded the Vega Medal of the Swedish Anthropological and Geographical Society in 1944.

Holocene climate change was the stuff of particular fascination for H.H. Lamb, whom we met in Chapter 8. In his 1966 book *The Changing Climate* (written in 1964), Lamb produced a chronicle of climate change for the Holocene[2]. The first version of this chronicle, dated 1959, began with the disappearance of the last major ice sheet from Scandinavia between 10 and 9 Ka ago, followed by warming to a postglacial 'climatic optimum' of 6–4 Ka ago, when he thought that world temperatures were 2–3 °C warmer than now. Later, we will see just how 'global' that so-called 'optimum' was. The warming roughly coincided with a 'subpluvial' period in North Africa between 7.0 and 4.4 Ka ago, when there were settlements in the Sahara. As well as archaeological evidence for the presence of humans, the development of major river systems draining from the interior down to the Atlantic coast of the Sahara, now almost completely dry, attests to a formerly much more humid climate. These rivers include the Oued Souss (reaching the coast at about 30° 30′ N) and the Oued Dra (reaching the coast at about 28° 30′ N), which are largely dry, and the Seguia del Hamra (reaching the coast at 27° 30′ N), which is almost always dry[3]. The 'climatic optimum' was well known to students of the Holocene, and was recognised in deep-sea cores by Emiliani in 1955, for instance[4].

Lamb found that subsequent cooling and increased rainfall in Europe was followed by a drier and warmer climate during the Roman Era, and by a second climatic optimum between 400 and 1200 AD, with a peak around 800–1000 AD. During this medieval peak, the Vikings colonised the southern coast of Greenland and reached the shores of North America, and wine was produced in England as far north as York (almost 54° N). Summer temperatures in England were about 1–2 °C higher than today. Cooling then set in towards the period 1550–1850 AD, which Lamb referred to as the Little Ice Age (a term first introduced by Matthes in 1939, used to describe an '*epoch of renewed but moderate glaciation which followed the warmest part of the Holocene*'[5,6]) – a period whose cold winters were immortalised by Pieter Brueghel the Elder in his February 1565 painting 'Hunters in the Snow'. Lamb's research suggested that the decline from the 1300s onwards was not uniform and that there was a partial recovery in the period 1440–1500 AD. A warming at this time seems slightly odd in retrospect, because it coincides with the Spörer sunspot minimum (1450–1550 AD). We will look at the effects of sunspots in more detail later. Although Lamb was attempting to build a global picture, his focus at the time was Eurocentric, not least because that's where he got most of his data.

By 1961, in a paper delivered in Rome to the WMO/UNESCO Symposium on Changes of Climate, Lamb expanded on his chronicle by incorporating climatic data from other parts of the world[2]. By this time, he had concluded that – compared with present values (meaning 1960) – temperatures were raised 2–3 °C in the warm epochs of the Holocene and lowered 1–2 °C in the Little Ice Age. According to Lamb, the Little Ice Age ranged from 1430 to 1850 AD and was coldest from 1550 to 1700 AD. He associated the cooling with weakening of both atmospheric circulation and incident radiation, and thought that the latter might have been caused by a veil of dust from volcanic activity.

Following the Holocene Climatic Optimum, glaciers began to readvance. George Denton of the University of Maine referred to this new period of glacial advance (the Little Ice Age of Matthes) as the 'Neoglaciation'[7,8]. It incorporates the narrower range of Lamb's Little Ice Age.

Lamb referred to his secondary Holocene climatic optimum (1000–1200 AD) as the 'Early Middle Ages Warm Epoch'. Elsewhere in *The Changing Climate*, he called it the 'Little Optimum'. Later, in 1965, he referred to it as '*The early medieval warm epoch*'[9]. It is now commonly termed the Medieval Warm Period, Medieval Climatic Optimum or Medieval Climate Anomaly. We will look at the Little Ice Age and Medieval Warm Period in more detail in Chapter 15. In passing, we should note that, aside from suffering from a paucity of records compared with what was available later, Lamb also had a lower-resolution chronology and fewer climate proxies to work with.

Moving forward in time, the success of CLIMAP in mapping the climate of the Last Glacial Maximum (see Chapter 12) stimulated the formation of a successor project, COHMAP, to look at the climate of the Holocene. Starting out as 'Climates of the Holocene – Mapping Based on Pollen Data', COHMAP quickly became global both in its scope and in the climate proxies it considered. Renamed the 'Cooperative Holocene Mapping Project', it ran from 1977 to 1995. COHMAP was a turning point for the palaeoclimate community studying the Holocene. It tied Holocene models and proxy data together for the first time, and stimulated international collaboration in Holocene research[1]. Key organisers were John Kutzbach, whom we met in Chapter 6, and his colleagues Tom Webb and Herb Wright. They aimed to use the Community Climate Model, an atmospheric general circulation model (GCM) of the US National Center for Atmospheric Research (NCAR), to simulate past climates in 3000-year-long time slices centred on 18, 15, 12, 9, 6, 3 and 0 Ka ago and to compare the outputs with palaeoclimate maps based on data from pollen, lake levels, pack-rat middens and marine plankton[10, 11]. These simulations ignored events of short duration, like Bond cycles.

André Berger's astronomical calculations showed that at the start of the Holocene around 10 Ka ago, Northern Hemisphere summers (in June at 65° N) were warm, while Southern Hemisphere summers (in December at 65° S) were cool[12]. Over time, summer insolation in the Northern Hemisphere fell gradually by 45 W/m^2 to present levels, while that in the Southern Hemisphere rose by 30 W/m^2. Winters in both hemispheres were cool at the start of the Holocene (December at 65° N and June at 65° S), then gradually warmed very slightly, by 5 W/m^2 in the Northern Hemisphere and by 3 W/m^2 in the Southern (Figure 14.1)[13].

The Northern Hemisphere now has cooler summers and warmer winters than the Southern Hemisphere. Matters are a little more complicated than these data might suggest, however. We can draw on the work of Huybers and Denton[14] (see Chapter 13) to infer that, although insolation increased during the Holocene in the Southern Hemisphere summer, it decreased during the Southern Hemisphere spring. Also, when summer insolation was high in the Southern Hemisphere, the length of summer was shorter and the length of winter was longer than average, because the Earth was then at perihelion (close to the sun). These factors conspired to cool the Earth throughout the Holocene. If insolation was cooling the Earth, how do we explain the mid Holocene Climatic Optimum? As we shall see in more detail further on, it was a Northern Hemisphere phenomenon that arose because the melting of the great ice sheets at the beginning of the Holocene used up all the available solar energy, keeping the region cool until the ice sheets had gone.

Berger and Loutre's astronomical calculations of the influence of the other planets on the Earth's orbit and axial tilt enable us to determine insolation well into the future[15]. Their calculations show that the Earth should have cooled from 10 000 years ago to the present, and will remain cool for the next 5000 years. We can confidently predict that the present low level of summer insolation at 65° N, which has persisted for the past 2000 years, will remain more or less unchanged for at least another 1000 years.

Berger and Loutre's solar radiation parameters were entered into the COHMAP model as an external forcing variable. Other boundary conditions within the model provided internal climate forcing through changes in aerosol loading (dust), ice volume, sea surface temperature and atmospheric CO_2. These were not allowed to change between 18 and 15 Ka ago. After 15 Ka ago, dust was decreased to around present levels by about 12 Ka ago, and ice volume to around present levels by 9 Ka ago (there was still some ice on North America and Scandinavia at that time). Sea surface temperature increased to present levels and CO_2 to preindustrial levels between 15 and 9 Ka ago, with CO_2 increasing again in modern times[10].

COHMAP's results, which started appearing in 1988, were stunning[10]. The combination of climate data and models enabled palaeoclimatologists to understand for the first time what caused global climate changes to occur at different times between the last glacial and the present, and how these changes were distributed across different regions. Previously, the role of the Earth's orbital variations had been discounted, the full impact of changes in ice sheets had not been understood and climate models had not been well enough developed to test the influence of these and other factors.

Changes in the precession and tilt cycles made seasonality increase in the Northern Hemisphere and decrease in the Southern Hemisphere between the 15 and 9 Ka-ago time slices. By 9 Ka ago, the Northern Hemisphere received 8% more solar radiation in July and 8% less in January than today. After this, these extremes diminished towards modern values. These changes increased the thermal contrast between land and ocean, causing strong monsoons between 12 and 6 Ka ago in the northern tropics and subtropics, particularly in Africa and Asia, and raising lake levels in regions that are arid today, such as the Sahara. Crocodiles and hippos expanded into the Saharan region, and people settled on the lake shores. At the same time, summers became warm and dry in the northern interiors.

After 6 Ka ago, as July insolation continued to decrease, temperatures fell over the land, monsoon rains weakened, deserts expanded and the present climate regime developed. In the southern tropics, the changed insolation (more in July, less in January) had the opposite effect, producing decreased seasonality and less intense rains in tropical South America, southern Africa and Australia.

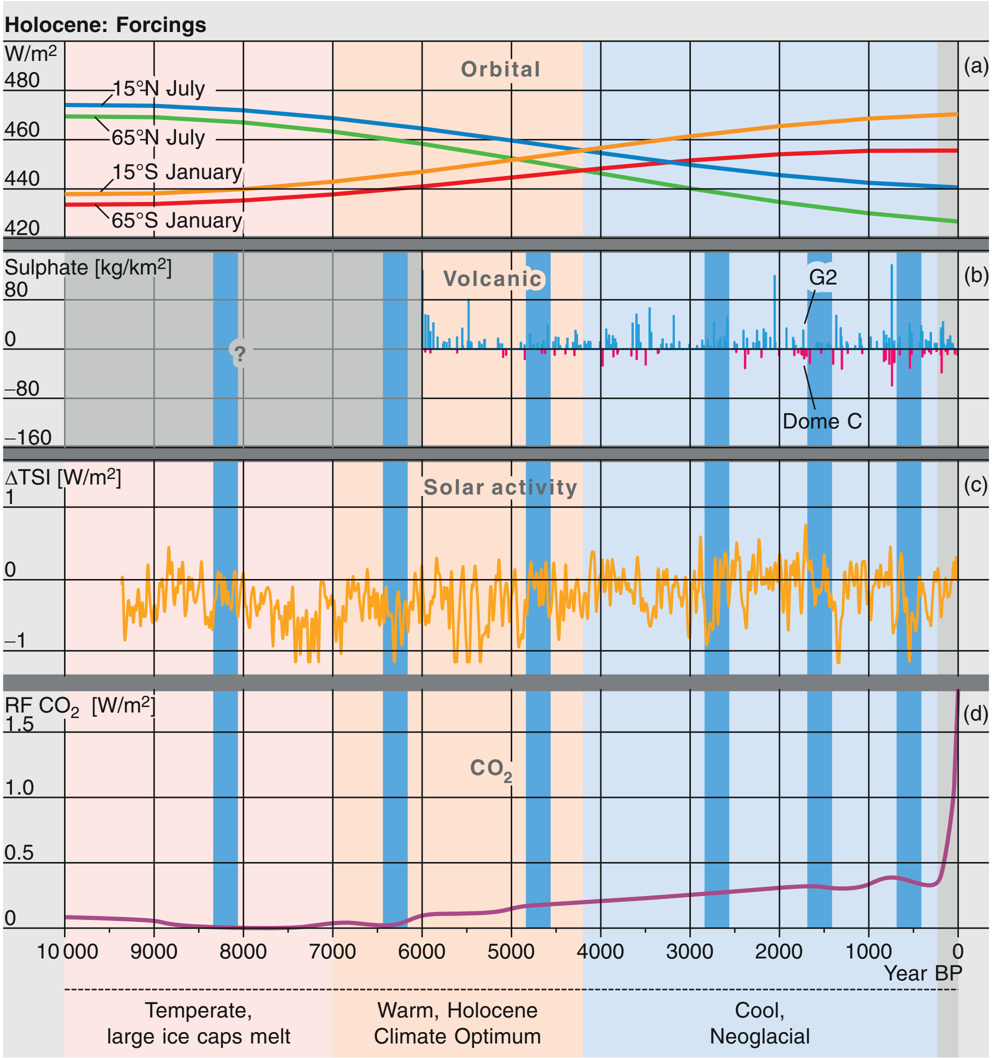

Figure 14.1 *Main forcings during the Holocene. (a) Solar insolation due to orbital changes from two specific sites in the Northern and Southern Hemispheres during the corresponding summer. (b) Volcanic forcing during the past 6 Ka, depicted by the sulphate concentration of two ice cores form Greenland (above the line) and Antarctica (below the line). (c) Solar activity fluctuations based on ^{10}Be measurements in polar ice. (d) Forcing due to rising CO_2 concentrations. The six vertical bars show the timing but not the duration of six cold periods.*

The initial COHMAP model suggested that, during the glacial period (the 18 and 15 Ka-ago time slices), the large North American ice sheet split the westerly winter jet stream over North America into a northerly branch, running along the Arctic shore then down the Labrador Sea between Canada and Greenland, and a southerly branch, running over the American southwest and joining the northerly branch over the mid Atlantic, before heading for Europe. A later, more advanced version of the model, along with a mixed-layer ocean model and an ice sheet reconstruction that gave a lower height to the Laurentide Ice Sheet, found that the ice sheet did not split the jet stream at 18 Ka ago[16]. Apart from that, the results seemed robust, with good coherence between the outputs from the earlier and later versions of the model and between both models and the palaeoclimate data.

The COHMAP data and models showed that there is no simple description of Holocene climate. Orbital change forced climate changes that varied across the globe, not only in magnitude, but also in space and time. Patterns of variation in both precipitation and seasonality changed along with temperature. Lamb's Europe was not globally representative.

As a result of the increase in Northern Hemisphere insolation, which peaked around 10 Ka ago (Figure 14.1), and the subsequent absorption of heat to melt the Northern Hemisphere ice sheets, temperatures remained cool in Europe until about 9 Ka ago, when the combination of moderately high insolation and much reduced ice sheets created the Holocene Climatic Optimum between 9 and 5 Ka ago; this is also known as the 'Holocene Thermal Maximum' and the 'hypsithermal'. In the Arctic, at 70° N, June insolation 11 Ka ago was about 45 W/m^2 greater than today. By 4 Ka ago, it had dropped to about 15 W/m^2 greater than today[17]. During the optimum, temperatures were up to 4 °C above later Holocene levels there, but while northwest Europe warmed, southern Europe cooled, and there was little or no change in the tropics. This so-called 'event' was not globally uniform in either magnitude or timing.

Overall, the decrease in insolation from 10 Ka ago to the present cooled the Northern Hemisphere significantly. For example, sea surface temperatures off Cap Blanc, Mauretania, declined by between 4 and 6 °C. There, the input of dust rose abruptly at around 5.5 Ka ago, when the African Humid Period came to an abrupt end[18, 19]. This is an example of a 'tipping point': an abrupt response emerging from a gradual change. The former existence around 6 Ka ago of a wide belt of enlarged lakes occupying the tropics between 32° N and 18° S implied a northward shift of the equatorial rain belt, as well as greatly enhanced monsoonal transport of moisture into the tropical continents at that time[20].

As more data poured in from tree rings, corals, ice cores, stalactites and sediment cores from lakes and oceans, the Holocene climate record was further refined. Richard Alley was among the first to assess Holocene climate change from Greenland ice cores[21]. His calculations of past temperature change there were based on '*site-specific calibrations using ice-isotopic ratios, borehole temperatures, and gas-isotopic ratios*' and were modified from earlier data provided by other researchers[22]. They show some warm periods alternating with cold periods at the start of the Holocene between 10 and 7 Ka ago, rather lower values between 7 and 5 Ka ago, moderately high values between 3.5 and 2.0 Ka ago, a steep decline to around 1850 AD and then a gradual increase leading into the modern warm period. It was not obvious from Alley's data[21, 22] that Greenland had experienced the gradual decline in temperature throughout the Holocene expected from the decline in Northern Hemisphere insolation[15].

This begs the question, just how valid was Alley's Greenland temperature record? The question was addressed by Bo Vinther of the Centre for Ice and Climate at the Niels Bohr Institute of the University of Copenhagen[23]. Examining ice cores from Greenland and Arctic Canada in 2009, Vinther's team saw that both altitude and past thinning caused by warming shaped the $\partial^{18}O$ record that Alley had used for his temperature reconstruction. '*Contrary to the earlier interpretation of $\partial^{18}O$ evidence from ice cores*', Vinther said, '*our new temperature history reveals a pronounced Holocene climatic optimum in Greenland coinciding with maximum thinning near the GIS [Greenland Ice Sheet] margins*'[23]. His new record of Greenland's temperature history (Figure 14.2) shows a steep warming of around 6 °C between 12 and 10 Ka ago, a slight rise of a further 0.5 °C to a peak around 8 Ka ago, then a steady fall of around 2.5 °C to between 1600 and 1850 AD, followed by the rise into the modern era that Alley had also seen. Evidently, the broad pattern of rise and fall in temperature that Vinther found in Greenland ice[23], which Alley had missed in examining a more limited Greenland data set[21], did broadly follow the pattern of Northern Hemisphere summer insolation.

Incidentally, Vinther's data show that the Greenland Ice Sheet responds much more rapidly to warming than had formerly been supposed, making it '*entirely possible that a future temperature increase of a few degrees Celsius in Greenland will result in GIS mass loss and contribution to sea level change larger than previously projected*'[23].

The existence of an early to mid Holocene thermal maximum is well documented in proxy records of sea surface temperature from the high-latitude North Atlantic and the Nordic Seas, where polar amplification is clear[24]. The sea surface temperature maximum there was forced by the summer insolation maximum, and is not simply a result of advection of sea surface temperature anomalies from further south. Superimposed on the sea surface

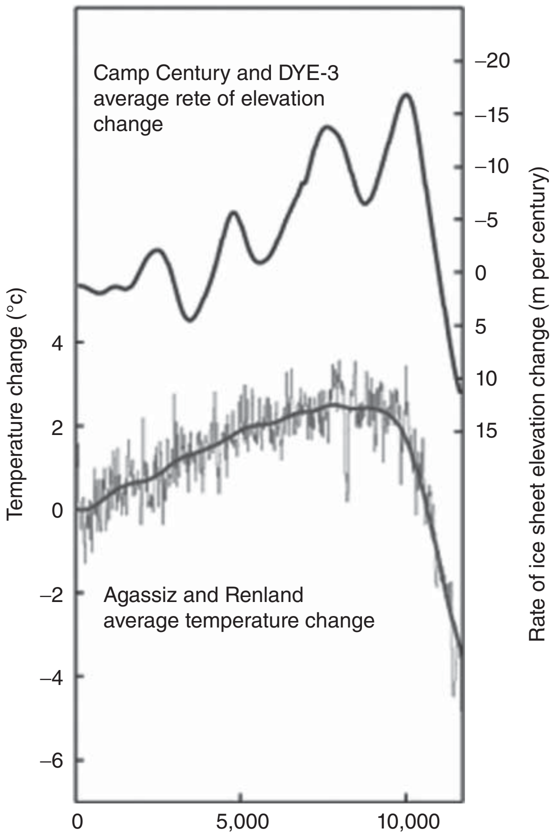

Figure 14.2 *Greenland temperatures adjusted for changing elevation. Temperature change in Greenland derived from Agassiz and Renland ^{18}O records and average rate of elevation change of ice sheets at the DYE-3 and Camp Century drill sites. Elevation changes distort the temperature records for these drill sites.*

temperature trends is variability at the century or millennial scale, the amplitude of which increased after the mid Holocene. There is very little persistence in the main frequencies of variability through the Holocene. The increased climatic variability affected primarily wintertime conditions, such as sea ice, and was consistent with the onset of Neoglacial conditions in Europe. According to Eystein Jansen and his team, '*Increased sea ice cover following the reduced summer insolation may have put in place amplification mechanisms leading to stronger ocean temperature variability … In the absence of a clear attribution of this variability to external forcings (e.g. solar, volcanic …), it appears most likely that the century to millennial scale variability is primarily caused by the long time-scale internal dynamics of the climate system*'[24].

Polar amplification can come about for a variety of reasons, not least of which is reduction in sea ice, land ice and snow cover, which reduces albedo and allows the exposed ocean to absorb heat, which is then given up to the atmosphere, causing more sea ice to be lost and so on, through positive feedback. Gifford Miller of the Institute of Arctic and Alpine Research of the University of Colorado, Boulder explored this phenomenon in some detail in the Arctic in 2010[25]. Miller and his team found that Arctic temperature change exceeded the Northern Hemisphere average by a factor of 3 to 4. For example, warming compared to today during the Holocene Thermal Maximum was $+1.7 \pm 0.8$ °C (Arctic), $+0.5 \pm 0.3$ °C (Northern Hemisphere) and 0 ± 0.5 °C (global). During the last interglacial, it was $+5 \pm 1$ °C (Arctic) and $+1 \pm 1$ °C (global and Northern Hemisphere). And during the mid Pliocene it was $+12 \pm 3$ °C (Arctic) and $+4 \pm 2$ °C (global and Northern Hemisphere)[25].

A comprehensive survey of Holocene climate variability, based on some 50 globally distributed palaeoclimate records from a wide range of environments extending from Greenland to Antarctica, was carried out in 2004 by a team led by Paul Mayewski of the Climate Change Institute of the University of Maine at Orono[26]. In recognition of his extensive research on climate change in Greenland and Antarctica, Mayewski was awarded the Seligman Crystal of the International Glaciological Society in 2009 and the science medal of the Scientific Committee on Antarctic Research in 2006. He has an Antarctic peak named after him.

Mayewski's team found clear signs of cooling in line with the decline in summer insolation in the Northern Hemisphere from about 7400 years ago to the present[26]. Norwegian glaciers advanced, the Swedish tree line moved downwards and temperatures (from $\partial^{18}O$) fell in Soreq Cave, Israel. Africa's Lake Victoria and Ethiopia's Lake Ahhe began shrinking, and the Trade Winds began to weaken over Venezuela's Cariaco Basin. Peru's Huascaran ice cap and Antarctica's Taylor Dome began cooling, as did sea surface temperatures in Namibia's Benguela Current.

In 2006, Stephan Lorenz, then at the Max-Planck-Institut für Meteorologie, Hamburg, used alkenone data and a coupled ocean–atmosphere circulation model forced by orbital changes to examine, with colleagues, global patterns of sea surface temperature for the past 7000 years[27]. As in COHMAP, the patterns proved to be heterogeneous. While the higher latitudes cooled over time, the tropics warmed slightly. In the North Atlantic region, many aspects of the regional climate are dictated by the behaviour of the North Atlantic Oscillation, measured from the difference in air pressure between the high-latitude Iceland low-pressure centre and the low-latitude Azores high-pressure centre. When the pressure difference is high, the North Atlantic Oscillation is positive, westerly winds are strong, Europe has cool summers and mild, wet winters and the Mediterranean area is dry and cool. This difference has decreased towards the present, making the North Atlantic Oscillation more negative, which has weakened the westerlies, making European winters colder and dryer and the Mediterranean warmer and wetter. This trend is consistent with the observation that the Little Ice Age late in the Holocene was characterised in Europe by very cold winters (more on this in Chapter 15). The trend in the North Atlantic Oscillation operated *against* the trend in orbital insolation, which *increased* in winter in the Northern Hemisphere – a good example of how local effects can override Milankovitch variations. Overall, summer insolation in the Northern Hemisphere over the past 7000 years decreased by more than 30 W/m^2 at middle and northern latitudes, while winter insolation increased by about 25 W/m^2 at low latitudes. Lorenz's study noted that '***Northern Hemisphere summer cooling during the Holocene*** *[meaning the last 7000 years]* ***is of the same order of magnitude as the warming trend over the last 100 years***'[27] (my emphasis).

Several more extensive studies of Holocene climate change were later carried out by Heinz Wanner (1945–), the former director of the Oeschger Centre for Climate Change Research at the University of Bern in Switzerland, which was named after the ice core expert Hans Oeschger. Among other things, in 2011 Wanner and his colleagues used high-resolution records of Holocene climate change to produce a Holocene Climate Atlas containing 100 anomaly maps representing 100-year averages of climatic conditions for the last 10 Ka[28]. In recognition of his contributions to climate change research, he was awarded the Vautrin Lud Prize – regarded unofficially as the Nobel Prize in Geography – in 2006.

In 2008, Wanner and his colleagues published a comprehensive review of mid to late Holocene climate change, spanning the last 6000 years[29]. They chose this period because '*the boundary conditions of the climate system did not change dramatically*' during it[29]. The large continental Northern Hemisphere ice sheets had melted, and there were no large outflows of freshwater from melting ice sheets, nor any major rises in sea level. Plus, there were abundant, detailed regional palaeoclimatic proxy records. The team mapped the distribution of temperature and precipitation through time, supplementing the data with results from GCMs and Earth system models of intermediate complexity (EMICs) fed with data on the agents forcing climate change: orbital variations, solar variations, large volcanic eruptions and changes in land cover and greenhouse gases. The goal was '*to establish a comprehensive explanatory framework for climate changes from the Mid-Holocene (MH) to pre-industrial time*'[29]. One of their sources of information was the international Paleoclimate Modeling Intercomparison Project (PMIP), which started in the early 1990s in an effort to improve palaeoclimate models. Another source was the IGBP's Paleovegetation Mapping Project (BIOME 6000), which provides a global data set derived from pollen and plant fossils for use as a benchmark against which to test the outputs from palaeoclimate models.

In 2013, Wanner was part of another team, which produced a detailed analysis of the global climate of the past 2000 years[30] as a contribution to the IGBP's Past Global Changes (PAGES) programme, a successor to COHMAP. One of the PAGES subgroups, the '2k Network', aims to produce a global array of regional climate reconstructions for the past 2000 years. It coordinates with the NOAA World Data Center for Paleoclimatology to maintain a benchmark database of proxy climate records for that period[30]. By 2013, the PAGES 2k data set included 511 time series of tree rings, pollen, corals, lake and marine sediments, glacier ice, speleothems and historical documents recording changes in processes sensitive to variations in temperature. Resolution is annual, enabling the team to examine multidecadal variability by focusing on 30-year mean temperatures.

Wanner's various studies, made at much higher resolution than the COHMAP ones, confirmed that decreasing solar insolation in the Northern Hemisphere summer led not only to Northern Hemisphere cooling but also to a southward shift of the summer position of the Inter-Tropical Convergence Zone (ITCZ) and a weakening of the Northern Hemisphere summer monsoon systems in Africa and Asia, associated with increasing dryness and desertification[13,29]. The southward shift in the ITCZ and the weakening of the monsoons came about as a result of the interplay between decreasing insolation in the

Northern Hemisphere summer and increasing insolation in the Southern Hemisphere summer. Insolation in the Northern Hemisphere declined by more than insolation in the Southern Hemisphere increased (Figure 14.1), so the cooling associated with the former had a wider effect on tropical systems than did the warming associated with the latter.

The cooling of the Northern Hemisphere summer with time increased the activity of the El Niño–La Niña system in the Pacific up to around 1300 AD, since when that activity has fluctuated significantly. The cooling also led to development of an increasingly negative North Atlantic Oscillation between 6 and 2 Ka ago, followed by a weak reversal[29]. As mentioned earlier, the negative phase of the North Atlantic Oscillation is associated with colder winters over Europe and a warmer, drier climate over the Mediterranean. Sea surface temperatures declined in the North Atlantic and the Norwegian Sea, along with southward retreat of the Arctic tree line, implying declining summer temperatures[29]. Glaciers advanced across the Arctic, in the Alps and in the Western Cordillera of North America, and decreased in the Western Cordillera of South America. In the Southern Hemisphere, lake levels were low from 6.0 to 4.5 Ka ago, but increased towards the present – the opposite of the trend in the Northern Hemisphere subtropics. This seems to reflect an intensification of northward-migrating westerlies, consistent with an increase in upwelling along the Pacific coast of South America[29].

The spectacular decrease of vegetation in the Sahara between 6 and 4 Ka ago was '*related to a positive atmosphere-vegetation feedback, triggered by comparatively slow changes in orbital forcing*'[29]. As Wanner explained, '*Due to a decrease in the intensity of the African monsoon, related to the decrease in summer insolation, precipitation decreases in the Sahara during the Holocene. This induces a decrease in the vegetation cover, and thus an additional cooling [caused by an increase in albedo, or reflectivity] and reduction of precipitation that amplifies the initial decrease in vegetation cover. The amplification is particularly strong when a threshold is crossed, leading to a rapid desertification and … fast changes*'[29].

In marine records, the coherent long-term cooling of between 1 and 2 °C over the past 9–10 Ka was not confined to the North Atlantic Ocean. It also extended to the Mediterranean[31–33], which is consistent with glacial readvance in Iceland, with Greenland ice cores and with pollen data in Europe and North America that indicate southward migration of cool spruce forest[34]. Tim Herbert pointed out[34] that this appeared to be a regional rather than global pattern, because alkenone data from the Indian Ocean, South China Sea and western tropical Atlantic showed very slight warming from the early Holocene to the present[35], while data from the western margin of North America showed no trend at all during last 9 Ka, apart from minor millennial oscillations of about 1 °C.

The PAGES 2k team showed that the long-term continental cooling driven by the fall in insolation continued right through the past 2000 years, during which '*all regions experienced a long-term cooling trend followed by recent warming during the 20th century*'[30]. I noticed one important caveat: while Antarctica showed the same cooling as the other continents, it did not – in the data available to the PAGES group – show the recent warming of the 20th century[30]. This perception is clearly wrong, as subsequent data show, because some parts of Antarctica – in particular, the Antarctic Peninsula, but also, to a lesser extent, West Antarctica – do show this recent warming[36]. It is evident in an ice core from the ice cap of James Ross Island in the western Weddell Sea, for example (Figure 14.3)[37,38], and at an Ocean Drilling Programme site (1089) in the Palmer Deep just south of Anvers Island[39,40]. More on that in Chapter 15.

Studying the Antarctic changes, Amelia Shevenell and her team found that the insolation in the southern *spring* at 65° S (September–November) *decreased* in parallel with the decrease in temperature seen in cores from the Ross Sea and the Palmer Deep[39]. This suggests local orbital control. As we saw in Chapter 13, there are ample reasons for invoking local orbital control on Antarctic climate rather than forcing by the orbital patterns of the Northern Hemisphere, where summer insolation at 65° N followed that same decrease[41]. This local insolation influenced the westerlies near the Antarctic Peninsula, which play a key role in warming and cooling locally, as well as in regulating the emission of CO_2 from the Southern Ocean and its subduction in Antarctic Bottom Water or Intermediate Water[39].

Based on the declining insolation in the north and its effects, Wanner subdivided the Holocene into three periods[13]. First was an early deglaciation phase, between 11.7 and 7.0 Ka ago, characterised by high summer insolation in the Northern Hemisphere, a cool, temperate climate near the melting ice sheets in North America and Eurasia and strong monsoonal activity in Africa and Asia. Second came the Holocene Thermal Optimum, between 7.0 and 4.2 Ka ago, which had high summer temperatures in

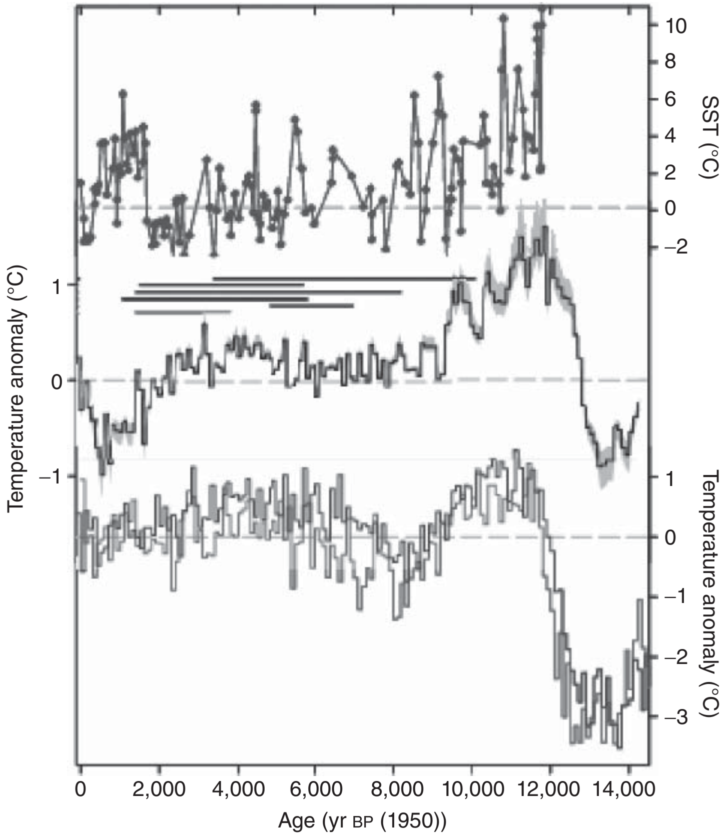

Figure 14.3 *Holocene temperature history of the Antarctic Peninsula. Top panel: Sea surface temperature (SST) reconstruction from off the shore of the western Antarctic Peninsula. Middle panel: James Ross Island ice-core temperature reconstruction relative to the 1961–1990 mean, in 100-year averages, with grey shading indicating the standard error of the calibration. Lower panel: Temperature reconstructions from the Dome C (uppermost) and Dronning Maud Land (lowermost) ice cores from East Antarctica. Horizontal bars show intervals when open water was present in the area of the Prince Gustav Channel.*

mid- and high-latitude parts of the Northern Hemisphere and active but weakening monsoonal systems at low latitudes. Third, there was a neoglacial period, with falling summer temperatures in the Northern Hemisphere, terminating with the sharp rise in global temperature as we entered the modern era.

In 2013, Shaun Marcott of Oregon State University and colleagues presented a slightly different reconstruction of global temperature change for the Holocene[42]. Most of their data came from marine cores, but they tell basically the same story as that of Wanner and his colleagues. Combining their data into a single global temperature stack, Marcott and colleagues found a rise in temperature of around 0.6 °C between 11.3 and 10.0 Ka, with Early Holocene warmth remaining more or less stable between 10 and 7 Ka ago. This stable period was followed by 0.7 °C of cooling, largely biased by a 2 °C cooling of the North Atlantic, which culminated in the coldest temperatures of the Holocene in the Little Ice Age about 200 years ago. After that there was a sudden rise of 1 °C to the warm temperatures of the modern era. The global stack was most similar to the data from the Northern Hemisphere between 30 and 90° N, suggesting a primary control by Northern Hemisphere summer insolation. The tropics (30° N to 30° S) warmed by 0.3 °C from 11.3 to 5.0 Ka ago, then cooled by a similar amount up to around 250 years ago, before warming sharply to modern values. Southern Hemisphere temperatures varied more. The narrowly defined mid Holocene thermal optimum between 6 to 7 and 4 Ka ago in the Northern Hemisphere identified by Lamb and Wanner was not readily evident in Marcott's global data.

Marcott's data show that the Northern Hemisphere signal of climate change tends to dominate the Holocene global signal, as it does today[49]. In part, the predominance of this signal is due to the greater area of land in the Northern Hemisphere. Land tends to heat and cool much faster than water, and water dominates the Southern Hemisphere. The global cooling had an impact on the North Atlantic Current, which takes heat to western Europe. Less heat was transported northwards, helping Europe to cool[43].

In the Arctic, Gifford Miller's team found that sea ice first decreased during the early Holocene as insolation increased, then increased in the late Holocene as insolation declined[17]. Likewise, the tree line expanded northwards to as much as 200 km beyond its current position, before beginning to retreat southward starting 3–4 Ka ago. Permafrost followed much the same pattern, melting south of the Arctic Circle, then refreezing after 3 Ka ago. Summer temperature anomalies along the northern margins of Eurasia in the thermal optimum ranged from 1 to 3 °C above today's, and sea surface temperatures were up to 5 °C warmer than today's. As elsewhere, cooling began between 6 and 3 Ka ago. Most Arctic mountain glaciers and ice caps expanded during the 'neoglaciation' of the late Holocene, as did the Greenland Ice Sheet. This cooling trend ended in most places in the mid 19th century[17,44,45].

Much the same broad-brush picture of sea ice was true of the Antarctic (Figure 14.4). There, Xavier Crosta found evidence for minimal distribution of sea ice as Holocene temperatures rose in the summer months between 9 and 4 Ka ago, followed by a substantial expansion as temperatures fell over the next 3000 years[46].

The results of Mayweski[26], Wanner[13] and Marcott[42] confirm that the continued existence of ice sheets in the Northern Hemisphere until around 7 Ka ago prevented temperatures from rising far despite high insolation between 10 and 7 Ka ago. The disappearance of the great ice sheets, combined with moderately high insolation, created the Holocene Thermal Optimum between 7.0 and 4.2 Ka ago. Then neoglacial conditions set in, with glacier advances across the Northern Hemisphere and the reformation of ice shelves along the northern coast of Ellesmere Island in northern Canada[47]. The most recent advance of glaciers, in the Little Ice Age, was the most extensive in all areas, making it the coldest episode of the Holocene[47]. The cooling of the North Atlantic after the thermal optimum may represent weakening of the Thermohaline Conveyor system, associated with the increase in Northern Hemisphere winter insolation[43]. Volcanic activity continued at variable levels throughout the Holocene, with no significant trend, making forcing from this source an unlikely driver of the overall cooling in the climate system (Figure 14.1)[13,26,42].

The pattern of climate change leading into the Late Holocene neoglacial and the Little Ice Age reflects the pattern of insolation calculated by André Berger and Marie-France Loutre[15,48]. Insolation peaked in the Northern Hemisphere 11 Ka ago, then declined to the present, with a substantial flattening of the rate of decline over the past 1000 years or so. Insolation is calculated to stay just as low for at least another 1000 years[15,48]. Taken together, the astronomical and the palaeoclimate data suggest that the world should have continued to cool, so it is more than a little surprising that '*in the brief interval of less than two centuries, the Northern Hemisphere (at least) has experienced the warmest and the coldest extremes of the late Holocene*'[47]. Recent warming bucks the trend imposed by orbital forcing, which should have kept our climate in a cool neoglacial state. We will explore this issue further in Chapter 15.

14.2 The Role of Greenhouse Gases: Carbon Dioxide and Methane

Did changes in CO_2 have a significant role to play in driving the cooling seen in the Holocene? Eric Sundquist of the US Geological Survey at Woods Hole reminded us that measurements of fossil atmospheric CO_2 from the Taylor Dome ice core, from near McMurdo Sound in the Ross Sea, showed that CO_2 declined from around 270 ppm at 10.5 Ka ago to 260 ppm at 8 Ka ago, and then increased to values near 285 ppm by 1000 AD (see Figure 14.1)[49]. Much the same picture emerged from ice cores at Law Dome in the Australian sector of Antarctica and at the Russian Vostok station on the Polar Plateau[50]. Andreas Indermühle of the University of Bern and colleagues explained the initial decrease in CO_2 as being due to the expansion of vegetation into formerly glaciated areas in the Northern Hemisphere, and the subsequent increase as due to a gradual release of carbon caused by global cooling and drying, the cooling being a response to the

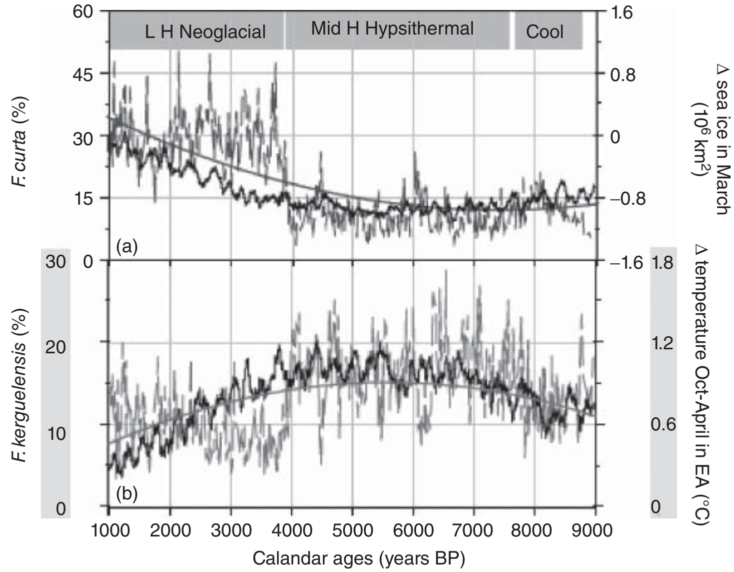

Figure 14.4 *Sea ice area around Antarctica. Relative abundances of (a) the* Fragilariopsis curta *group (ragged grey line) and (b) the* Fragilariopsis kerguelensis *group (ragged grey line) versus calendar ages in core MD03-2601 close to the coast of Adelie Land, Antarctica.* F. curta *is a sea ice diatom, whose abundance represents denser and longer-lasting coverage of the ocean by sea ice.* F. kerguelensis*, in contrast, is most abundant along the polar front, where there is less sea ice and temperatures are warmer. Polynomial regressions indicate the first-order evolution for the* F. curta *group (solid smooth line in (a)) and the* F. kerguelensis *group (solid smooth line in (b)), compared to simulated time series of the March sea ice area (black zigzag line in (a)) and the October–April temperature for East Antarctica over the last 9000 years (black zigzag line in (b)), plotted as deviation from the preindustrial mean. The data show warming from a cool early Holocene into a warm mid Holocene hypsithermal with low sea ice, then into a cool late Holocene neoglacial with abundant sea ice.*

orbitally controlled decline in insolation[50]. Glen Macdonald of the University of California at Los Angeles and colleagues found in 2006 that circum-Arctic peatlands began to develop rapidly as ice and snow began to disappear 16.6 Ka ago and expanded between 12 and 8 Ka ago, when insolation was at its highest, drawing down CO_2 during the early Holocene[51]. In a moment we'll see what Bill Ruddiman thought of this CO_2 picture.

Methane in ice cores from Taylor Dome and from Dome C changed over the same period, but in a different way, as shown by Jérôme Chappelaz of the Laboratoire de Glaciologie et Géophysique de l'Environnement of the University of Grenoble and colleagues in 1997. CH_4 declined from values near 700 ppb at 10.5 Ka ago to values between 550 and 600 ppb at 5 Ka ago, before increasing to near 700 ppb again by 1000 AD[52]. Many scientists attributed the late Holocene increase in CH_4 values to an expansion of boreal wetlands. Not surprisingly, as most wetlands are found in the Northern Hemisphere, the Holocene data showed a gradient in CH_4 from north to south, with between 30 and 50 ppb more in air from the north. The addition of recent anthropogenic sources of CH_4 in the north increased this gradient by a factor of three[49]. The CH_4 data showed a sudden short-term drop at 8 Ka ago, which corresponded to the widespread climatic event linked to a major flood of freshwater into the North Atlantic from a melting event in the Laurentide Ice Sheet.

The rise in atmospheric CO_2 values from 260 ppm around 8 Ka ago to 285 ppm 200–400 years ago (Figure 14.1) might be expected to have led to a small warming. Instead, cooling continued, showing that the forcing by declining Northern Hemisphere insolation had a much greater effect on climate than did forcing by the 25 ppm addition of CO_2. Much the same argument applies to the rise in methane, which increased by about 160 ppb towards the preindustrial era[26] – mostly over the past 3 Ka, despite continued cooling[29]. It is worth recalling at this point the divergence of temperature and CO_2 typical of the re-entry into glacial conditions from the peaks of past interglacials that we saw in Chapter 13, with temperature falling faster than CO_2. As in those cases, the lack of correlation between CO_2 or CH_4 and temperature between the early and late Holocene is likely to have much to do not only with the decrease in insolation *per se*, which drives temperature, but also with its effect on albedo, through the growth in sea ice, land ice and snow cover into the neoglacial. This temporary lack of correlation changed as we moved into the modern era, when massive increases in the two gases caused a sharp increase in temperatures unprecedented in the previous millennium[47], as we see in more detail in Chapter 15.

This seems like a good point to review the ideas of Bill Ruddiman concerning the effect humans may have had on climate since the beginning of the Holocene[53]. But we should first recall Berger's calculations suggesting that the Holocene interglacial may last 30 Ka or more – like marine isotope stage (MIS) 11, which occurred some 400 Ka ago (see Chapter 12)[54, 55]. Furthermore, Michael Crucifix reminds us that EMICs[a] show that when the CO_2 was maintained above 240 ppm in the Holocene, the system remained in an interglacial state[56]. This, he says, '*further shows that even if CO_2 concentration decreased in the future down to glacial levels, glaciation will not occur before 50,000 years*'[56], because insolation does not get low enough. In contrast, Bill Ruddiman argued that the fall in insolation during the Holocene should have led to the formation of new ice sheets by now[57]. He suggested that '*CO_2 and CH_4 concentrations should [also] have fallen steadily from 11,000 years ago until now*'[57] Indeed, they did start to fall from the beginning of the Holocene, but then '*CO_2 and CH_4 began anomalous increases at 8000 and 5000 years ago, respectively*'[57]. He thought that these rises were most probably due to human activities, and, further, that those increases had prevented the occurrence of a new glaciation. He attributed the slow, small rise of CO_2 over the past 8 Ka or so to forest clearance and the development of agriculture[57, 58].

Birks reminded us that there is some independent support for this idea, in that the distribution of charcoal, an index of the existence of fires, parallels the increase in CO_2 concentrations, suggesting that biomass burning may have been a cause for the rise in CO_2[1]. Nevertheless, 'mainstream' thinking suggests that the rise most probably had several causes, including changes in calcite compensation in the ocean, changes in sea surface temperature and the postglacial build-up of coral reefs, and was not caused by major changes in the storage of carbon on land. More data are needed before we have a definitive solution[29]. For example, Broecker argued in 2006 that the latest measurements of $\partial^{13}C$ in CO_2 from Antarctic ice suggest that the main changes in atmospheric CO_2 over this period were the result of changes in the world's oceans[59].

Reviewing the various arguments for and against Ruddiman's hypothesis in 2009, Michael Crucifix concluded, '*the early anthropogenic theory implies – if it is correct – that there was a bifurcation point during the past 6000 years during which the climate system hesitated before opting for a glacial inception or staying interglacial. The anthropogenic perturbation gave it the necessary kick to opt for a long interglacial*'[56]. While that may sound satisfying, he went on to remind us that '*This hypothesis cannot be easily proved or disproved*'[56].

This did not stop people from trying. As we saw in Chapter 13, the discovery in 2007 that the ratio of boron to calcium (B/Ca) in species of benthic foraminifera is directly related to the concentration of carbonate ions (CO_3^{2-}) in bottom water has greatly improved our understanding of the behaviour of the carbonate system in the ocean[60, 61]. Jimin Yu and colleagues used the B/Ca ratios in deep-sea cores to show that the concentration of CO_3^{2-} in the deep waters of the Pacific and Indian Oceans declined during the Holocene[61]. They thought it likely that the build-up of coral reefs during the Holocene caused the whole ocean concentration of CO_3^{2-} to decline. This decline reduced the ocean's alkalinity, causing the solubility of CO_2 in the ocean to decline, so contributing to the 20 ppm rise in atmospheric CO_2 over the past 8 Ka. Much the same conclusion is reached by numerical modelling[62]. Ruddiman may thus be wrong about early humans having increased CO_2 in the air.

Having carefully examined Ruddiman's hypothesis, Wally Broecker and Thomas Stocker reasoned that, as the amount of CO_2 in the air had increased, so too must the amount of CO_2 in the ocean. In other words, much more CO_2 had been emitted than could be accounted for by deforestation alone[63]. Instead, they proposed that the CO_2 rise was triggered by the ocean's response to the extraction of CO_2 from the ocean to create the early Holocene increase in forest cover. Removing that CO_2 from the ocean lowered early Holocene CO_2 in the air

[a] EMICs = Earth Models of Intermediate Complexity

and increased the carbonate ion concentration of ocean water, hence deepening the carbonate compensation depth (CCD) and causing calcium carbonate to accumulate. That drew down the carbonate ion concentration, making the CCD rise and increasing the CO_2 content of ocean water, which fed back to increase the CO_2 in the air. This is a story of natural ocean chemistry, not anthropogenic deforestation.

Ruddiman attributed the small rise in CH_4 that began about 5 Ka ago to the increasing culture of rice in Asian wetlands[57, 58]. Although Wanner thought in 2008 that the cause still '*eludes a simple explanation*'[29], a numerical simulation of the climate system by Joy Singarayer, Paul Valdes and colleagues in 2011 found that the rise in methane was most likely the result of a natural expansion in wetlands[64]. That, in turn, was related to changes in orbital precession and its control over insolation, especially at low latitudes. As Eric Wolff explained, '*Insolation reaches its maximum during the part of the precession cycle when the elliptical orbit of the Earth takes the planet closest to the Sun during northern summer. The result is a stronger monsoon in Asia and other regions, with more summer precipitation, and consequently greater wetland areas and methane production by soil-dwelling microorganisms*'[65]. The methane increase of the past 5 Ka departed from that pattern, increasing when northern summer insolation was on the wane. The reason seemed to be that during the late Holocene there was an increase in wetland sources in South America that outweighed the expected decreases in Eurasia and East Asia. The South American source was reacting to Southern Hemisphere insolation with a different phase from that in the Northern Hemisphere. Hence, there was no need to call upon human intervention as Ruddiman had.

More recent data provide Ruddiman with some support. Celia Sapart of Utrecht University and colleagues recently reviewed variations in the abundance of atmospheric methane and its carbon isotopic composition for the past 2000 years[66]. Their new high-resolution data came from the recent North Greenland Eemian Ice Drilling programme (NEEM) and EUROCORE ice cores from the Summit site in central Greenland. These data confirmed that methane had increased by about 70 ppb from 100 BC to 1800 AD, and that there was an accompanying fall in its $\partial^{13}C$ composition. These trends appeared mainly to be driven by biogenic emissions related to a growing increase in agriculture. After 1800 AD, CH_4 rose abruptly, with an accompanying rapid rise in its $\partial^{13}C$ composition, consistent with increased emissions from fossil fuel burning associated with the onset of industrialisation. The measurements also revealed three centennial-scale falls in $\partial^{13}C$ concentration between 100 BC and 1600 AD that were not previously recognised, and which were superimposed on the declining long-term trend in $\partial^{13}C$. These were attributed to biomass burning associated with the clearance or maintenance of cropland. Clearly, human activities must have played an important role in governing the long-term increase in CH_4 over this period[66].

Nevertheless, the analysts of the Vostok core, led by Jean Jouzel, were keen to point out that in MIS 11 – the 420 Ka interglacial sampled in the ice cores from Vostok and EPICA Dome C, – '*the highest levels [of methane] were observed at the very beginning of the interglacial period, then, rather similarly for the Holocene, decreased for 5,000 years, and then began to increase. This increase could obviously not be attributed to human activity … and it weakened Ruddiman's argument, which was also not obviously supported by the records of concentrations of carbon dioxide recorded at Vostok and at Dome C throughout that interglacial period*'[67]. They regarded this as crucially important information, because the long interglacial of MIS 11 is likely to be the best analogue for the Holocene.

Much has been made in the popular press of the possibility that continued warming may melt the Arctic permafrost, releasing large amounts of methane trapped within or beneath it. Eric Wolff[65] pointed out that the modelling by Singarayer and others[64] showed that, during the last interglacial, atmospheric methane decreased slightly at a time when temperatures globally and in the Arctic were a few degrees warmer than at present. This suggests that a large influx of additional emissions from methane hydrates currently trapped in permafrost may be unlikely with continued warming in the immediate future[65]. The existence of a natural envelope for methane, like that for CO_2, over the past 800 Ka of the Dome C core (Figure 13.5) suggests that continued warming to the levels typical of past interglacials will not release large extra amounts of CH_4.

Before we leave this topic, we should return to the subject of volcanoes and their emission of CO_2. As we saw in Chapter 13, volcanism increased two to six times above background levels during the last deglaciation between 12 and 7 Ka ago, probably due to decompression of the Earth's mantle in deglaciating regions[68]. The increase in CO_2 from these increased volcanic emissions provided a positive feedback, helping to warm the deglaciating world, and may have accounted for the addition of 40 ppm

CO_2 to the atmosphere. Huybers and Langmuir pointed out that, '*Conversely, waning volcanic activity during the Holocene would contribute to cooling and reglaciation, thus tending to suppress [further] volcanic activity and promote the onset of an ice age*'[68]. However, there is no evidence to suggest that volcanic activity contributed to the cooling of the late Holocene (Figure 14.1).

Having a strong interest in predicting what the effect on our climate and sea level of further emissions of CO_2 might be, Jim Hansen of NASA was keen to see how much warmer than the Holocene were some recent interglacial periods[69]. He found that the temperatures of the major interglacials of the past 450 Ka tended to be close to or above those of the Holocene, while the smaller interglacials of the preceding 400 Ka tended to be cooler than the Holocene. The large warm interglacials, he thought, had '*moved into a regime in which there was less summer ice around the Antarctic and Greenland land masses, there was summer melting on the lowest elevation of the ice sheets, and there was summer melting on the ice shelves, which thus largely disappeared. In this regime, we expect warming on the top of the ice sheet to be more than twice global mean warming*'[69]. Why? Because melting of the sea ice and ice shelves created large areas of warm open ocean that reduced albedo and thus affected temperature year round, something unlikely to have happened in the smaller interglacials prior to 450 Ka ago.

Hansen went on to suggest that the relative stability of Holocene climate came about because orbital controls kept global temperature just below the level required to melt enough ice to decrease albedo in the same way. His calculations suggested that during the peak warm interglacials at 420 and 120 Ka ago, the global climate was only about 1 °C warmer than the Holocene Climatic Optimum, or about 2 °C warmer than the preindustrial Holocene. For that reason, Hansen and his colleague Sato considered that, with the modern temperature rise having returned Earth's mean temperature close to the Holocene maximum, the planet was poised to experience the strong amplifying polar feedbacks that likely led to the warmest interglacials of the past 450 Ka. The continued decline in extent of September sea ice in the Arctic is one sign that Earth's climate is already on that path. Melting of all or parts of the Greenland and West Antarctic Ice Sheets would be expected to follow, albeit much more slowly.

Undoubtedly, there have been human influences on climate through the Holocene, not least via fire, forest clearance, agriculture, the killing of large mammals and changes to the hydrological cycle through the damming of rivers. Even so, the vast majority of the Holocene changes we examine in this chapter came about naturally, rather than being affected by human activities.

Sceptics of the influence of CO_2 on climate point to the fact that the decline in temperature over the latter part of the Holocene accompanied a 25 ppm rise in CO_2, taking this as evidence against CO_2 as a driver of modern climate change. Looking at just temperature and CO_2 is not the most appropriate way to check the influence of CO_2 on climate, however, since global temperature is driven by other factors, too, such as change in albedo, which may be caused by both changes in vegetation and changes in ice cover, along with changes in insolation, and the balance between them all. All forcings have to be considered simultaneously. Climate change is not a single-issue game.

14.3 Climate Variability

As we saw in Chapter 12, Gerard Bond discovered that the deposition of ice-rafted debris during the last glacial period seemed to follow a climate cycle of roughly 1500 years, which continued into the Holocene[70]. Although Bond's cycles were very much more prominent during the last glacial period, dating back to 80 Ka ago, than during the Holocene, the amount of variability in any one grain type (Icelandic glass or red-stained grains) was about the same in both periods; only the absolute abundance decreased[70]. That suggested that the cycles were independent of orbital forcing and carried on regardless of glacial state. Some periodic or quasi-periodic forcing agent must cause ice streams to grow, thereby increasing the rates of discharge of icebergs and thus freshening surface waters in the North Atlantic. During the glacial periods of the Ice Age, some threshold (or tipping point) was eventually passed, beyond which there was a major iceberg discharge and cooling event, from which the system eventually recovered, passing back across the threshold as it warmed up. Such tipping points were not exceeded during the Holocene interglacial, because, with the melting of the major ice sheets on North America and Scandinavia, there was no longer a sufficient mass of cold ice to respond in such a way in the Northern Hemisphere. Consequently, the cycles in the Holocene had a very much lower amplitude than those in the last glacial period.

Looked at more closely, the length of Bond's cycles varied from a low of 1328 ± 539 years between 43 and 31 Ka ago to a high of 1795 ± 425 years between 79 and 64 Ka ago, with the Holocene cycle being 1374 ± 502 years[71].

Although there is a difference of 400 years between the extremes of these averages, the standard deviations about the means all overlap to some degree, making it difficult to differentiate between them statistically. Spectral analysis of the record of red (hematite)-stained grains revealed a slightly different picture, with peaks at around 4.7 and 1.8 Ka ago[70, 71]. Ignoring the apparent cycle at 4.7 Ka ago, Bond felt confident that his team had identified a natural millennial-scale cycle of 1–2 Ka, and he thought that the Little Ice Age, which we'll come to later, was the most recent cold phase of that cycle[71].

Bond was not alone. In 1999, Giancarlo Bianchi and Nick McCave of Cambridge University confirmed that sediments from a Holocene core taken south of Iceland also followed a quasi-periodic 1500-year cycle[72]. Peter De Menocal found much the same signal in marine sediments off west Africa[18]. The supposed 1500-year climate signal was also identified in 2011 in Holocene cave formations known as speleothems in Israel[73]. These are precipitates of calcium carbonate, which most people know as stalactites (growing down from the cave ceiling, like icicles) and stalagmites (growing up from the cave floor). Their internal layering is a reflection of the history of local rainfall, and the individual layers may be analysed for their $\partial^{18}O$ characteristics, which provide climate signals through time.

More recently, a team led by Philippe Sorrel found similar variability in its examination of Holocene records of high-energy estuarine and coastal sediments from the south coast of the English Channel[74]. '*High storm activity occurred periodically with a frequency of about 1,500 years, closely related to cold and windy periods diagnosed earlier*', Sorrel's team concluded[74]. These oscillations, linked to Bond cycles, appeared within an array of different spectral signatures, ranging from a 2500-year cycle to a 1000-year one. There was no consistent correlation between spectral maxima in records of storminess and solar irradiation, making solar activity seem an unlikely cause of millennial-scale variability. Rather, to Sorrel, the storminess reflected a natural periodic cooling of the North Atlantic.

Also in 2012, Dennis Darby of Old Dominion University, Virginia, found Bond's 1500-year cycle in an 8000-year record of ice-rafted iron-rich grains in sediments from the Arctic[75]. These grains were rafted to the Alaskan coast from Russia's Kara Sea during strongly positive phases of the Arctic Oscillation. Darby and colleagues used the sediment record to document an 8000-year history of the Arctic Oscillation. Recognising that there was no 1500-year solar cycle (see Chapter 15 for a detailed discussion of solar cycles), they attributed the forcing to internal variability within the climate system, or to an indirect response to solar forcing at low latitudes[75]. Low-latitude palaeoclimate records do show significant linear solar forcing, suggesting that the El Niño–Southern Oscillation system in the Pacific acts as a mediator of the solar influence on the climate system's low-latitude heat engine, rather than on the high-latitude one[76]. That may explain why Bond's ice-rafting events correlate well with sea surface temperatures from the low-latitude Atlantic[74]. Solar heating of the tropics would create a stronger Equator-to-pole thermal gradient, strengthening winds and storms, and in due course leading to southwardly-directed outbreaks of ice-rafting[75]. The link would be indirect. As yet, the precise mechanism for propagating low-latitude forcing through the climate system to high latitudes is unknown[76].

Other researchers also realised that, superimposed on the significant changes of temperature that were driven by orbital changes in insolation through the Holocene, there were slight variations on the millennial scale of the kind – although not the magnitude – identified by Dansgaard and Oeschger in ice records and by Bond in marine sediment records from the last glacial period. For instance, Vinther's data showed that temperatures on the Greenland Ice Sheet varied on the millennial time scale by up to 1 °C both above and below the background Holocene temperature trend[23]. Among these variations was a warm period centred near 1000 AD that might represent Lamb's Medieval Warm Epoch, followed by a subsequent cold period more or less coinciding with Lamb's Little Ice Age. Alley, too, identified in Greenland ice a warm period centred on about 1030 AD, followed by a cold one reaching maximum lows between around 1650 and 1850 AD[21].

Working with Mayewski and others, Alley also identified a significant short-lived cooling event at 8.2 Ka ago[77], most likely caused by a North American glacial lake draining into the adjacent North Atlantic, as mentioned earlier. Vinther calculated the amount of cooling in that event to be around 2 °C[23]. Careful scrutiny of palaeoclimate records from the early Holocene by Eelco Rohling and Heiko Pälike of the UK's National Oceanography Centre in Southampton showed that the 8.2 Ka event was the peak of a cooling event that started at 8.6 Ka ago and lasted 400–600 years[78]. Rohling and Pälike concluded that, while the peak event may well have been caused by outflow from glacial Lake Ojibway-Agassiz, its regional and even global extent was difficult to estimate because of its occurrence within a longish cool period of the Holocene. Nevertheless there was good evidence to suggest that the freshwater lid formed over the North Atlantic by discharge from the lake did cause the Meridional Overturning Circulation to slow at about 8.2 Ka ago, with global effects[79].

Mayewski's team's analysis of a global data set provided an opportunity to obtain a global picture of millennial events in the Holocene[26]. They identified six globally distributed events they called 'rapid climate change events' at 9–8 Ka, 6–5 Ka, 4.2–3.8 Ka, 3.5–2.5 Ka, 1.2–1.0 Ka and 600–150 years ago. Polar cooling, tropical aridity and major changes in atmospheric circulation characterised most of these events, while the 6–5 Ka-ago event marked the end of the Holocene humid period in tropical Africa, beginning a trend towards tropical aridity. Several of these events coincided with major disruptions of civilisation, suggesting the impact of climatic variability on past civilisations.

Like Alley and Vinther, Mayewski documented the brief cooling event at 8.2 Ka ago, which lay within his 9–8 Ka-ago period. At that time, there were still remnants of the ice sheets on North America and Scandinavia. Conditions were cool over much of the Northern Hemisphere. There were major episodes of ice-rafting, stronger winds over the North Atlantic and Siberia, outbreaks of polar air over the Aegean Sea and glacier advances in Scandinavia and North America. In contrast, glaciers retreated in the Alps, as the air became drier there. In the tropics, the monsoon weakened and there were widespread droughts. In the Southern Hemisphere, sea surface temperatures warmed around southern Africa, and grounded ice retreated in the Ross Sea.

Most of the other global events reviewed by Mayewski shared the twinning of cool poles with dry topics that also characterised cool periods during the Ice Age. Evidence for the events at 4.2–3.8 and 1.2–1.0 Ka ago (the latter equivalent to 800–1000 AD) appeared in fewer of the records, but their widespread distribution and synchrony suggested the operation of global connections. At these latter times, winds weakened over the North Atlantic and Siberia, and temperatures fell in North America and Eurasia.

The most recent of these events covered the end of the Holocene, from around 600 years ago (or 1400 AD) to the beginning of the modern era[26]. It differed from previous events in being characterised by cool poles and wet tropics. There were rather fewer records to draw upon than one might expect for this relatively recent period, leading Mayewski to complain: '*Unfortunately, determining the nature and duration of later stages of this interval is difficult because high-resolution records for this time are relatively scarce and because several records are missing recent sections as an artifact of sampling. Moreover, interpretation is complicated by potential anthropogenic influences*'[26]. As a consequence, his team investigated this event only from 600 to 150 years ago (1400–1850 AD). In the Northern Hemisphere, this cool event had the fastest and strongest onset of any of the Holocene events, with glaciers advancing and westerlies strengthening. While Venezuela, Haiti and Florida became more arid, tropical Africa became more humid and monsoon rains increased in India. While parts of the Antarctic Peninsula warmed, East Antarctic cooled. Glaciers advanced in New Zealand, rainfall increased in Chile and southern Africa became cool and dry. This event corresponds to the Little Ice Age.

Heinz Wanner and his group also identified six 'cold relapses' in their collection of global samples from the Holocene, with peaks at 8.2 Ka, 6.3 Ka, 4.7 Ka, 2.7 Ka, 1.55 Ka and 550 years ago[13]. Each of these peaks lay amid a period spanning about 500 years. One might expect these cool peaks to correlate reasonably well with the cool events identified by Mayewski and his team and with the cold peaks of Bond cycles. Table 14.1 compares the ranges of Wanner's and Bond's cold peaks and Mayewski's cold events.

The comparison looks close for all three for Bond cycles 5a and 5b, 2 and 0. It is less good for Bond cycle 4, where Wanner's cool period does not closely match the other two. Moreover, Mayewski's 6–5 Ka-ago event is not, strictly speaking, a cold event, but rather the end of the Saharan pluvial period. The comparison is also less good for Bond cycle 3, which does not fit Wanner's cool period, although it does match Wanner's glacial advance. Bond cycle 1 fits with Wanner's glacial advance, but only overlaps slightly with Mayewski's and Wanner's cool periods, which themselves fail to overlap. Neither Wanner nor Mayewski identified Bond cycle 6 as a cool period.

Discrepancies like these may arise because of inadequacies in the chronology of the core samples used. Can we rely on Mayewski and Wanner's data? They all come from published sources, but one of these was later found to be suspect: Alley's 2000 AD Greenland data profile[21], which Vinther showed to be misleading as a guide to Greenland temperature[23]. Nevertheless, the discrepancies are likely to be real and to reflect the geographical and temporal heterogeneity of the climate signal globally. For instance, Mayewski observed advances in glaciers over North America and Scandinavia during his 9–8 Ka-ago event, at the same time that glaciers were retreating in the

Table 14.1 Comparison of the ranges of Heinz Wanner's and Gerard Bond's cold peaks (both measured from Figure 3 in Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P. and Jetel, M. (2011) Structure and origin of Holocene cold events. *Quaternary Science Reviews* **30**, 3109–3123) and Paul Mayewski's cold events, in 1000 years (Ka) before present.

Bond cycles (Ka)	Mayewski events (Ka)	Wanner peaks (Ka)	Wanner glacial advances (Ka)
6. 9.6–9.2			
5a. 8.6–8.25	9–8	8.55–8.0	8.6–8.1
5b. 7.8–7.2			7.8–7.5
4. 5.95–5.1	6–5	6.45–5.9	
3. 4.6–3.8	4.2–3.8	4.8–4.6	4.5–4.0
2. 3.4–2.65	3.5–2.5	3.35–2.45	3.6–3.1
1. 1.6–1.0	1.2–1.0	1.8–1.5	1.8–1.0
0. 700–100 years	600–150 years	850–150 years	600–150 years

Alps, and each of Wanner's events showed a high degree of spatial and temporal variability. Selecting the boundaries of a global cool period is likely to be a more subjective process than identifying a Bond cycle or a glacial advance. Discrepancies between the North American and European climate are not unexpected, because the North American ice sheet took much longer to melt away than did the Scandinavian and British ice sheets.

What about the rapidity of change? Contrary to Mayewski's conclusions, with regard to the past 6 Ka, Wanner's PAGES team did not '*find any time period for which a rapid or dramatic climate transition appears even in a majority of … time series*', although rapid shifts were recognised at certain times and in particular regions[30]. However, Wanner did agree that there had been a rapid and short-term climate change event at 8.2 Ka ago[13].

What are we to make of the various warm and cool periods that are superimposed on the gradual cooling driven by the orbital decline in insolation throughout the Holocene? If we are to extrapolate into the future what we know of the past, we need to be sure the cycles are real and to understand what caused them. The MIT oceanographer Carl Wunsch (1941–) called Bond's 1500-year cycle into question on the grounds that it might be a simple alias of inadequately sampled seasonal cycles[80]. When Wunsch removed this signal from ice-core and marine-core data, climate variability appeared as a continuous process, suggesting that the finding of a narrowly defined 1500-year cyclicity in the data set might not represent actual millennial events. His analysis supported the idea that Heinrich events and Dansgaard-Oeschger events might be quasi-periodic and driven by several different influences.

Richard Alley disagreed. Since the periodicity was evident in a wide variety of analyses, regardless of sampling interval and other details, Alley thought it could not be an alias of any shorter periodicity, such as the annual cycle, as Wunsch had suggested[81]. Wanner, on the other hand, was inclined to agree with Wunsch, noting, '*There is thus scant evidence for consistent periodicities and it seems likely that much of the higher frequency variability observed is due to internal variability or complex feedback processes that would not be expected to show strict spectral coherence*'[29]. Wanner's view of Bond cycles was that '*the origin of these cycles remains unknown*'[29], and he went on to question the relevance of Bond cycles for the Southern Hemisphere.

Bianchi and McCave agreed with Bond that the 1500-year cycles probably represented some manifestation of the internal circulation of the ocean of unknown cause, but they did not rule out the possibility of some modulation of climate behaviour by Earth's orbital properties[72]. Bond and his team dismissed that possibility. Millennial-scale climate change could arise from harmonics and combinations of the three main orbital periodicities, but cycles originating in those ways were mostly longer than the observed 1500-year cycle[70].

How might the internal circulation of the ocean have changed? The most likely culprit was the Atlantic Meridional Overturning Circulation, which transports warm salty water to high latitudes, where they cool, sink and return southwards at depth. David Thornally, Harry Elderfield and Nick McCave investigated this possibility by using Mg/Ca and $\partial^{18}O$ ratios measured in foraminifera from a sediment core taken in 1938 m of water close to Iceland[82]. The temperatures of near-surface waters oscillated between about 10 and 11 °C over the past 10 Ka, while their salinity slowly increased. Subsurface waters from below the thermocline showed much greater variability in both salinity and temperature, depending on whether they were drawn from the cold, fresh subpolar gyre or the warm, saline subtropical gyre. From

12.0 to 8.4 Ka ago, the North Atlantic was well stratified, with fresh surface water – probably from melting ice – overlying warm, saline tropical gyre water. Then there was a switch to well-mixed waters, followed by an oscillation between stratified and well-mixed waters roughly every 1500 years, attributable to changes in ocean dynamics, much as suggested by Debret and colleagues in 2007[83]. This appeared to be very much a North Atlantic phenomenon. A strong link is likely between the behaviour of the Atlantic Meridional Overturning Circulation and the North Atlantic Oscillation, which is in turn linked to the behaviour of the Arctic Oscillation. And as we saw earlier, the 1500-year cycle also shows up in the Arctic, where ice-rafting occurred during positive phases of the Arctic Oscillation[75]. These linkages help to explain why Bond cycles tend to be focussed around the North Atlantic, rather than elsewhere.

Greenhouse gases were an equally unlikely cause of millennial change. Neither CO_2 nor CH_4 showed sufficient variability at the millennial scale during the Holocene to have caused the observed millennial cooling events, nor did volcanic eruptions[13,26].

Can we blame multicentennial internal oscillations in the ocean for these millennial events? There is ample evidence for their operation on the decadal scale, for instance in the shape of the Pacific Decadal Oscillation or the Atlantic Multi-Decadal Oscillation[29]. When the Pacific Decadal Oscillation is positive, we get warm conditions in the central tropical Pacific and up the American west coast to Alaska, along with cold conditions in the northwest Pacific. The opposite occurs during the negative phase. Analyses of tree-ring data from the region show that the Pacific Decadal Oscillation signal is recognisable at least back to 1470 AD, but is not a persistently dominant feature. The Atlantic Multi-Decadal Oscillation is recognised from sea surface temperature patterns in the North Atlantic, which warm by around 0.2 °C in the positive phase, and decline by the same amount in the negative phase, at intervals of around 20 years – much like the time scale of the Pacific Decadal Oscillation. Part of the global warming in the 1930s is likely to have been caused by the positive mode of the Atlantic Multi-Decadal Oscillation, as is the American dustbowl of the same era[56]. These quasi-periodic oscillations supply much of the background high-frequency 'noise' in the climate spectrum. Similar variability, on time scales of between 35 and 120 years, has been detected in the Atlantic Meridional Overturning Circulation – the Atlantic branch of the global ocean conveyor belt. Shorter-term variations attributable to El Niño are superimposed on these larger-scale cycles.

Long-period oscillations may arise within the ocean system through nonlinear processes affecting either **advection** – the transport of heat and salt – or **convection** – the vigorous vertical mixing of water that occurs when denser water lies atop lighter water[56]. Much of what we know about advection started with Henry (Hank) Stommel (1920–1992), who was appointed to the US National Academy of Science in 1962 and awarded the US National Medal of Science in 1989. His 1961 box model of the thermohaline circulation of the oceans showed that it could feature a sharp decrease in advective transport, which we might think of as a shutdown of the Thermohaline Conveyor[84]. While such shutdowns did occur in glacial times, they have not taken place during the Holocene, unless temporarily during the 8.2 Ka-ago cool event. According to Crucifix, '*A refined version of Stommel's model incorporating realistic propagation times suggests that advective processes may also cause sustained oscillations … associated with the propagation of temperature and salinity anomalies through the conveyor belt, and their periods range between two and four millennia*'[84]. Such advective oscillations may explain Bond's millennial cycles[56].

The role of oceanic convection is to restore gravitational stability. As Crucifix explained, it is a self-maintained process – the exchange of heat between the ocean and the atmosphere can make surface waters denser, promoting further convection. Deep convection occurs today in the Norwegian-Greenland Sea, the Labrador Sea and the Weddell and Ross Seas. Modelling shows that convective instability may induce repeated stops and starts of convection, which may explain the abrupt warming and cooling observed by Bond in the Norwegian-Greenland Sea during the Holocene. During a convective shutdown, sea ice may advance southwards, maintaining the shutdown and pushing the system into a cold state. Such a state may become persistent in the presence of external forcing, for example in the form of a decrease in solar radiation, or cooling caused by a volcanic eruption. The probability of such events occurring will tend to increase through the Holocene, with the long-term cooling brought about by the persistent decrease in orbital insolation during summer in the Northern Hemisphere. Convective instability and the inception of a temporary cold state may have prolonged the cooling 8.2 Ka ago caused by the discharge of freshwater from Lake Agassiz. That discharge would have taken place within a few years at most, while the cooling event lasted at least 100 years[56].

Pulling these various bits of information together, the basic theme of Holocene climate is one of initially high insolation leading to the demise of the Northern Hemisphere ice sheets, apart from Greenland, followed by a mid Holocene Climatic Optimum in the Northern Hemisphere as the influence of ice diminished, followed by declining insolation leading to the development of a neoglacial period culminating in the Little Ice Age. Most of these changes were typical of the Northern Hemisphere. The tropics tended to warm slightly.

Superimposed on this overall decline were climate variations on the millennial or centennial scale[19]. Some distinct oscillations or climate steps appear to be widespread, for example across the North Atlantic region, notably at 8.2, 5.5–5.3 and 2.5 Ka ago, where they punctuated the gradual Holocene decline in temperature. In that region, the coldest points of each of these millennial steps in sea surface temperature were 2–4 °C colder than the warmest part[19]. The event at 8.2 Ka ago was the most sudden and striking of the Holocene, bringing cool, dry conditions to the North Atlantic region. It is picked up in ice cores from as far away as Greenland and Antarctica. That particular event represents a massive flood of glacial lakewater into the Arctic and North Atlantic. There was a broader and less intense shift to colder and drier conditions at 5.5 Ka ago, and a similar shift at 4 Ka ago that coincided with the collapse of a number of early civilisations[19]. While it is possible that solar forcing played a role in causing these cycles, it may have merely exacerbated the effects of oscillations caused by natural variability in oceanic advection and convection. That being said, it is more likely that the effects of advection and convection will be focused in specific regions, like the North Atlantic and Arctic provinces, rather than globally.

Now we turn to Chapter 15, to see what role the Sun may have played in driving millennial or centennial climate change, and to explore in some detail climate change over the last 2000 years.

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