Chapter 21
Pleistocene Glaciations

Abstract The Pleistocene glaciations are unique in geologic history as far as is known at present. The periodicity appears to be the result of the interaction of Milankovitch cycles and carbon dioxide. The 100,000 year cycles appear to have initiated the major glacial advances and carbon dioxide releases, perhaps as methane, appear to have resulted in interglacial episodes. As glaciers advanced, ocean and atmospheric currents were affected and carbon dioxide levels were lowered. As glaciers retreated, ocean and atmospheric currents returned to their previous paths and carbon dioxide levels increased. In order to place the periodicity of the Pleistocene in the proper time perspective, climate conditions leading up to the Pleistocene are outlined in this chapter.

Keywords Pleistocene • Glaciers • Milankovitch • Carbon-13 • PETM • Obliquity • Oscillation • Eccentricity • Yarmouth • Sangamonian • Laurentide • Cordilleran • IETM • Wisconsin • Clathrate • Würm • Kansan • Illinoian • Riss • Weichselian • Eemian • MI5

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

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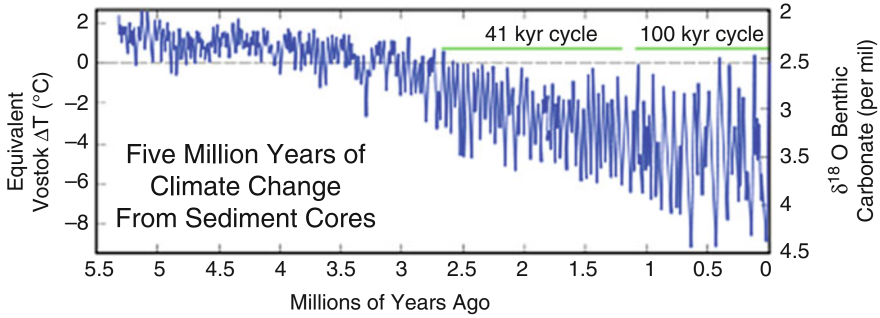

Fig. 21.1 Temperatures based on $\delta^{18}O$ during the last 5.5 million years (From Wikipedia, GNU Free Documentation License)

Things to Know	
Pleistocene	Yarmouth Interglacial
Obliquity	IETM
Paleocene-Eocene Thermal Maximum	Günz Glaciation
41,000-Year Cycle	Weichselian
Laurentide	PETM
Start of Antarctic Glaciation	30% of Earth's Surface
Carbon-13	Würm Glaciation
Clathrate Gun Hypothesis	Isthmus of Panama
Ocean's Biological Pump	Shelf-Nutrient Hypothesis
Eemian	$BaSO_4$
Cordilleran	Possible Cause of Arctic Freezing
Riss	Iron Fertilization Hypothesis
Wisconsin Glaciation	3,900 m
MIS1	2.5 million years
Mid-Miocene Climatic Optimum	ACEX

The Pleistocene geological record provides evidence of at least 20 cycles of advancing and retreating continental glaciers (see Fig. 21.1). Much of this glaciation occurred at high latitudes and high altitudes, especially in the Northern Hemisphere.

Glaciers covered up to 30% of the Earth's surface which was glaciated periodically during the Pleistocene. Large portions of Europe, North America (including Greenland), South America, all of Antarctica, and small sections of Asia were entirely covered by ice. In North America during the peak of the Wisconsin Glaciation approximately 20,000–18,000 years ago, there were two massive yet independent ice sheets. Both the eastern Laurentide and the western Cordilleran ice sheets were over 3,900 m (2.4 miles) thick. In Europe, ice covered Scandinavia, extended south and east across Germany and western Russia, and southwest to the British Isles. Another ice sheet covered most of Siberia. In South America, Patagonia and the southern Andes mountains were beneath part of the Antarctic ice sheet.

Because so much water was taken up as ice, global sea level dropped approximately 140 m (448 ft), exposing a great deal of the present-day continental shelf.

The causes of the Pleistocene cycle of glacial and interglacial episodes are still being debated. It appears that continental positions, oceanic circulation, solar-energy fluctuations, and Earth's orbital cycles combined to generate these glacial conditions, so perhaps it is inappropriate to pinpoint any single cause. However, a trigger for the first glacial episode was probably an orbital one and the apparent 100,000-year periodicity of the major advances strongly suggests an astronomical cause. However, the 100,000 year cycle, as we've seen, is the weakest of the astronomical cycles and many scientists think that it must have been a combination of factors that initiated the glaciation (Nebraskan in North America) about 680,000 years ago.

There are other periodicities found in the ice core records from both Antarctica and Greenland.

Some climate change scientists have calculated that changes in the concentration of greenhouse gases were a partial reason for large (5–7°C) global temperature swings between glacial advances and interglacial periods. This is the reason given for the rather abrupt changes between glacial and interglacial episodes. In all cases during the glacial-interglacial episodes, there was rapid warming and relatively slow cooling.

21.1 Glacials and Interglacials

Continental ice sheets expanded southward from Canada into the Eastern and Central United States ten or more (possibly as many as 50) times during the past 680,000 years (the latter part of the Pleistocene that began 2.588 million years ago). The area covered by ice varied from one glaciation to another. The glaciations were geologic events, and the events were recorded by deposits left behind by the glaciers. However, the subsequent glacial advance obliterated most evidence from the previous glacial advance and retreat. So the best evidence left is from the last glacial advance and retreat (the Wisconsin in North America, the Würm glaciation in the Alps, Devensian and Midlandian glaciation in Britain and Ireland, and the Weichselian glaciation in Scandinavia and the continent of Europe).

Table 21.1 gives the names of glacial events, the glacial index (from youngest at the top to oldest at the bottom), whether the event is a glacial or an interglacial, the period in thousands of years ago, the Marine Isotope Stage (MIS), and the Epoch.

The time interval between 35,000 and 11,150 calendar years ago is referred to informally as "late Wisconsin time" in North America. Late Wisconsin glaciation occurred during late Wisconsin time. During late Wisconsin glaciation, the ice sheet margin reached its maximum southern extent in many parts of the United States between 24,700 and 18,000 years ago, and it had retreated into Canada by about 11,400 years ago. The ice sheet margin fluctuated (retreated and re-advanced) during southward advances and northward retreats, and the extents of re-advances and retreats varied in different regions.

Table 21.1 Glacial events during the Pleistocene and Holocene Epochs

	Interglacial						
Glacial Index	Alps	N. American	N. European	Great Britain		MIS	Epoch
				Flandrian	Interglacial	1	Holocene
1st	Würm	Wisconsin	Weichselian or Vistulian	Devensian	Glacial period	2–4 & 5a–d	Pleistocene
	Riss-Würm	Sangamonian	Eemian	Ipswichian	Interglacial	5e (7, 9?)	
2nd	Riss	Illinoian	Saalian	Wolstonianor Gipping	Glacial period	6	
	Mindel-Riss	Yarmouth	Holstein	Hoxnian		200–300/380	
3rd–5th	Mindel	Kansan	Elsterian	Anglian	Glacial period	12	
	Günz-Mindel	Aftonian		Cromerian	Interglacial	13–15	
7th	Günz	Nebraskan	Menapian	Beestonian	Glacial period	16	

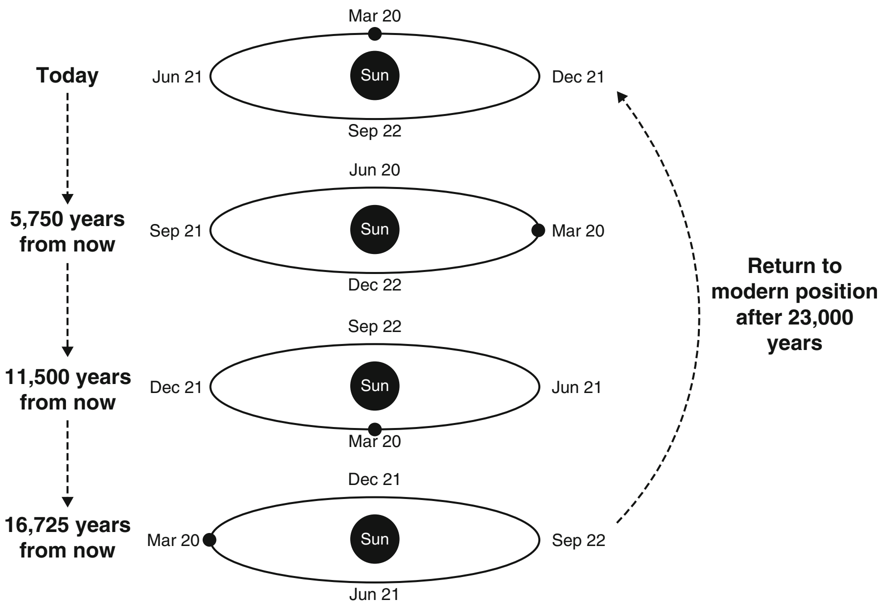

Fig. 21.2 Precession of the equinoxes caused by the slow turning of Earth's elliptical orbit and its wobble on its axis. Both the solstices and equinoxes move slowly around the orbital plane in cycles of 23,000 years (Credit: John Cook, based on Imbrie and Imbrie, Ice Ages: Solving the Mystery, 1979)

21.2 Causes of Glacial Advances and Retreats

The Pleistocene glaciations had their beginning in geologic events much earlier. The cooling that led to this glaciation was accompanied by an almost continuous loss of atmospheric CO_2, which dropped from a concentration of around 2,000 ppm at the beginning of the epoch to just under 300 ppm during the last million years. Figure 21.1 shows the temperature decline into the Pleistocene beginning at the end of the Mid-Miocene Climatic Optimum and this was accompanied by a similar drop in CO_2.

21.3 Paleocene-Eocene Thermal Maximum

The Paleocene-Eocene Thermal Maximum was a global warming event which lasted around 12 million years and had an enormous influence on the evolution of animal and plant life. The episode coincided with a major wave of extinctions among the existing fauna, both on the continents and in the oceans, and is coincident with the emergence of many new mammalian orders which have dominated the animal kingdom ever since. Flora adapted by changing the structure of their leaves and by migrating to higher latitudes, as is happening today.

Land temperatures, already high, rose again by between 5 and 7°C. In the ocean, the temperature of coastal surface waters in the Antarctic rose from 13 to 20°C, and in the Arctic, they reached as high as 24°C. Although the waters of subtropical regions also became warmer, the effect was much more noticeable in the higher latitudes. Today, the higher latitudes in the Northern Hemisphere are warming more rapidly than other parts of the planet.

Deep water temperatures also rose to around 12°C higher than the current-day mean. This was probably due to a change in the principal location at which deep waters were formed, which moved from the cold seas of the southern hemisphere to the warmer ones of the northern hemisphere. Carbon-13 analyses of sediments provide evidence pointing to this abrupt circulatory change.

It is believed that the Paleocene-Eocene Thermal Maximum (PETM) peak may have been caused by a sudden increase in methane or carbon dioxide release. The most reliable evidence of this sudden increase in methane seems to lie in an abrupt high-low oscillation of sedimentary carbon-13, since methane, due to its biological origin, is very poor in this isotope.

The sudden release of methane into the atmosphere would have come from the methane enclosed in ice crystals located in the sediments of the ocean floor (the Clathrate Gun Hypothesis). The eruption of the gas may have occurred after the temperature of ocean's deep waters passed a specific heat threshold, thus enabling the release of methane clathrates. It is possible that a change in ocean circulation triggered this process.

Nevertheless, the abundance of methane may also have been the result of intense bacterial production in either the wetlands that covered vast areas of tropical and mid-level regions during that period or the peat bogs which formed in higher latitudes. However, the suddenness of the episode seems to support the theory of the release of clathrates frozen in the marine substrate.

21.4 Initial Eocene Thermal Maximum (IETM)

Following the temperature peak at the end of the Paleocene, the temperature dropped, although it remained high throughout the whole first part of the Eocene, until around 48 million years ago. Particularly striking is the situation of the Arctic, which remained free of ice and enjoyed much milder winters than today. Recent studies carried out by the ACEX (Arctic Coring Expedition) project indicate the existence of sedimentary microfossils near the North Pole which are typical of waters with a temperature of 20°C.

21.5 The Cooling Begins

About 50 million years ago, following the initial Paleocene-Eocene Thermal Maximum, the climatic trend took a downturn and temperatures began to drop. Throughout the rest of the Eocene, in almost all of Europe and Asia, the climate became considerably colder and drier. This was the beginning of what was to be (on a long geological time scale and from the beginning of the Oligocene onwards) an ice-house period; namely a period in which abundant ice sheets and mountain glaciers can be found any season of the year. We are still in an ice-house period today, although ice is melting throughout the world.

One of the most significant characteristics of this downwards cooling trend is the evolution of the temperature of deep ocean waters, which dropped from around 12°C 48 million years ago to just 6°C at the end of the Eocene, 35 million years ago. Today, deep ocean waters have a temperature of just over 2°C.

There is evidence that the initial cause of this cooling trend was the reduction of CO_2 concentrations in the atmosphere during the warm climate of the Paleocene and early Eocene. A recent study (2005) of alkenones present in marine sediments registered a constant drop (with the occasional ups and downs) in CO_2 concentrations, which decreased from 1,500 ppm at the beginning of the Eocene to just 500 ppm by the middle of the Oligocene.

Research into the crystallization of different varieties of sodium carbonates has also come to the same conclusion. The precipitation of trona, instead of nacolite (another variant of carbonate) indicates a decrease in atmospheric CO_2 concentrations throughout the course of the Eocene.

According to this theory, the preceding warm Epoch came to an end because a major increase in oceanic plankton caused absorption of a large percentage of atmospheric CO_2. The existence of a vast accumulation of barite (barium sulphate, $BaSO_4$), a mineral of biological origin, in numerous marine sediments, seems to indicate a high level of oceanic productivity during the initial stages of the Cenozoic Era.

Other cooling factors also accompanied this drop in CO_2 levels, such as a decrease in water vapor and a rise in the albedo, triggered mainly by the formation of sea ice.

It is also possible that the warm climate itself, which would have been accompanied by higher humidity levels, accelerated the loss of atmospheric CO_2 through the weathering of silicate rocks.

Nevertheless, some oceanographers believe that more important than the drop in CO_2 levels were the changes in ocean circulation caused by large-scale geological movements, which in turn triggered changes in atmospheric circulation. One of these major modifications to ocean circulation contributed to the formation of the Antarctic ice sheet, which increased the planet's albedo and played an important part in global cooling.

21.6 Formation of the Isthmus of Panama and the Freezing of the Arctic

The flow of ocean currents was drastically modified at the end of the Pliocene when all communication between the Atlantic and the Pacific through Central America was closed off. The geological closure of the channel was a gradual process which began 13 million years ago and probably ended around 4 million years ago, when the gap between the two Americas, North and South, finally closed, allowing land mammals to emigrate in both directions.

The closure had an immediate effect on the world's oceans and probably changed the climate of the North Atlantic, sending the whole equatorial current flow northward and reinforcing the Gulf Stream.

According to a paradoxical theory, the warm water transported by the Gulf Stream actually helped to begin the glaciations which occurred in the higher latitudes of the Northern Hemisphere. Although one might logically assume that the redirection of tropical water to the North Atlantic should have provoked just the opposite effect, it seems that what it in fact triggered was the formation of the large North American and Northern European ice sheets.

According to this theory, the temperature increase in the North Atlantic increased evaporation. This in turn rendered the Atlantic air masses more humid which the westerly winds from mid-level latitudes transported towards the inland areas of the Eurasian continent and the rivers flowing into the Arctic Ocean added fresh water. The fresh water freezes, increases Earth's albedo and eventually forms an ice cap over the Northern Hemisphere.

At the beginning of the Pleistocene glacial advances and retreats, climatic oscillations followed cycles of around 40,000 years, which appear to coincide with the cycle of variation in the Earth's axial tilt. The ice masses which formed on the continents were not, at that time, particularly large.

Between 1.5 million and 680,000 years ago, the length of the cycles started to increase, and from 680,000 years ago onwards, glacial cycles have occurred at intervals of between 80,000 and 120,000 years, averaging around 100,000 years. The length of recent cycles is similar to that of the cycle of variation in the Earth's orbital eccentricity (Milankovitch cycle), which is around 100,000 years.

The periodicities reflected in Pleistocene glacial deposits, ice cores, and sediments are compared to Milankovitch cycles that were discussed earlier. Eccentricity has a periodicity of roughly 100,000 years but its effects on the climate system are the weakest of the cycles. However, the 100,000 year cycle stands out at the beginning of the major continental advances and may have been due to a combination of factors which coincided at 100,000-year intervals.

As Earth travels around the Sun in an elliptical orbit, the orbital plane changes and it moves about the plane on a cycle of 23,000 years.

Precession has the following components:

- An axial precession, in which the torque of the other planets exerted on the Earth's equatorial bulge causes the rotational axis to gyrate like a spinning top.
- An elliptical precession, in which the elliptical orbit of the Earth itself rotates about one focus.
- The net effect describes the precession of the equinoxes with a period of 22,000 years. This term is modulated by eccentricity which splits the precession into periods 19,000 and 23,000 years.

Like obliquity, precession does not affect the total amount of solar energy received by the Earth, but only its hemispheric distribution over time. If the perihelion

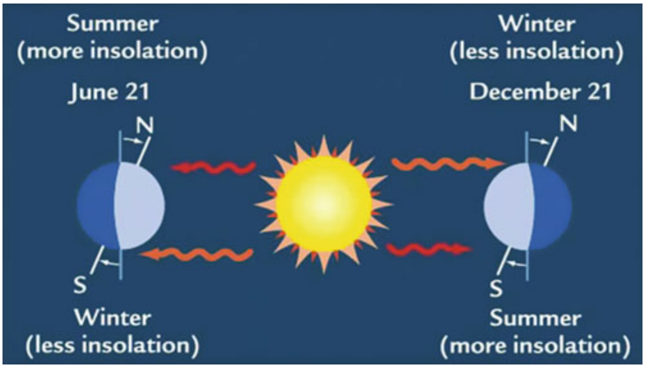

Fig. 21.3 The effect of Earth's obliquity on insolation, the amount of energy received by the Earth at different seasons of the year (summer and winter (Source: John Cook)

occurs in mid-June i.e., when the Northern Hemisphere is tilted toward the Sun, then the receipt of summer solar radiation in the Northern Hemisphere will increase. Conversely, if the perihelion occurs in December, the Northern Hemisphere will receive more solar radiation in winter. It should be clear that the direction of changes in solar radiation receipt at the Earth's surface is opposite in each hemisphere.

The illustration (Fig. 21.2) shows the precession of the equinoxes (so called because twice a year, the length of day and night is equal).

Precession has a periodicity of between 19,000 and 23,000 years and obliquity has a periodicity of 41,000 years. Do any of these periodicities show up in the geologic record?

From the present day to 700,000 years ago, the dominant periodicity is 100,000 years. From 700,000 years ago to 2.8 million years ago, the dominant periodicity was 40,000 years. This suggests a major change at 700,000 years.

The effect of obliquity on Earth's seasons is shown in the illustration above (Fig. 21.3). The obliquity of Earth's axis of rotation causes the seasons of the year and it regulates the amount of the Sun's energy hitting various parts of the Earth.

21.7 Other Influences and Possible Causes of Ice Ages

There are other natural cycles which may strengthen the 100,000-year Milankovitch cycle:

- Ice-sheet growth and retreat appears to have a 100,000 cycle and provides a positive feedback loop, i.e., as glaciers advance, they reflect sunlight and further cause cooling. As glaciers retreat, less sunlight is reflected reducing albedo and exposed ground absorbs more sunlight and causes further warming.
- Residence time of carbon in the ocean appears to be about 100,000 years. The atmospheric CO_2 concentration is in equilibrium with the surface CO_2 concentration. Scientists have conceived of a biological pump in the ocean that cycles CO_2

from the ocean surface to the deeper ocean waters where upwelling brings carbon back to the surface as nutrients.

- Shelf-nutrient Hypothesis: nutrient balance in the ocean reflects rates of supply and sediment burial; as glaciers grow, sea level is lowered exposing continental shelves rich in organic matter and nutrients like PO_4 to weathering and river transport to the ocean. This results in a feedback loop that enhances reduction of atmospheric CO_2 during glaciation. Nutrient supply to the surface ocean increases productivity which removes atmospheric CO_2 and causes cooling. Residence time of phosphate in the ocean is 40,000–100,000 years.
- Iron Fertilization Hypothesis: in cold upwelling of the oceans, iron limits primary productivity. Nitrogen fixation by cyanobacteria requires large amounts of Fe to build the enzyme that catalyzes N-fixation. In an oxygen-rich ocean Fe is brought to the sea by wind-derived particulates. When glaciers advance there is less moisture in the atmosphere, winds are stronger and carry more dust to the ocean and increasing primary productivity.

The illustration below (Fig. 21.4) summarizes information about major events that took place since the extinction of the dinosaurs and during the Cenozoic Era. The temperature-dependent isotopes of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$), and the climatic, tectonic, biotic events, and temperature variations are summarized in the illustration below.

21.8 Maximum Extent and Characteristics of Continental Glaciers

Continental glaciation is happening now in Greenland and Antarctica, although Greenland is not considered a continent and much of the glacial ice occupies valleys. By studying these glaciers it is possible to better understand the continental glaciers that covered up to 30% of the land area of Earth during the maximum glacial extent about 18,000 years ago during the Pleistocene "ice age." There were two major continental glaciers covering the northern part of North America during the Pleistocene, the Laurentide and Cordilleran ice sheets, and they coalesced and formed the North American Ice Line at their southernmost terminus.

The ice reached a maximum thickness of about 2 miles at its center and thinned toward its edges. It affected the global climate and disrupted the Jet Stream, increasing rainfall in areas that are now dry such as the southwestern United States. The ice sheets over Europe and Siberia also acted to increase rainfall in dry areas such as present day Iran and Afghanistan.

The increased rainfall periods in dry areas are referred to as pluvial periods and remnants today are Salt Lake, Utah, which is a remnant of the Pleistocene glacial Lake Bonneville. Lake Bonneville is estimated to have been 1,000 ft deep when it was at its maximum extent. The shoreline is seen in the photograph below (Fig. 21.5) identified by the wave-cut terraces on the hillside.

Pluvial lakes occurred throughout the southwestern United States and those in the Mojave Desert Region are shown in the reconstruction below in Fig. 21.7.

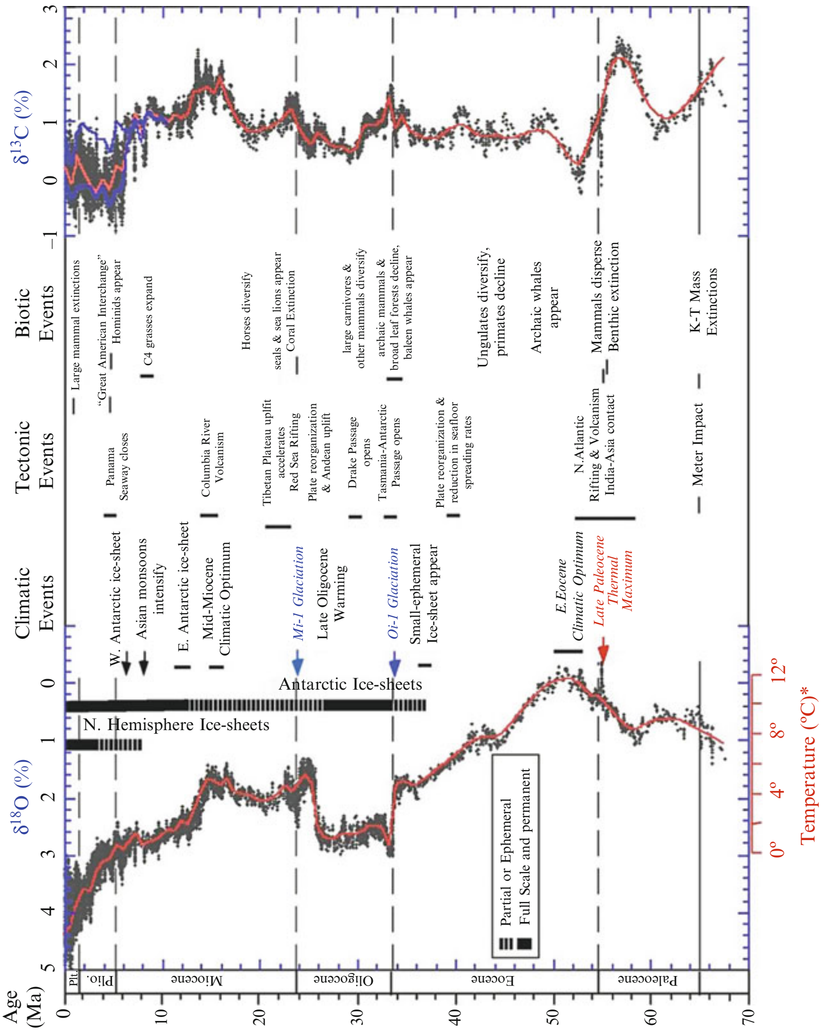

Fig. 21.4 Summary or composite timeline and events for the Cenozoic Era showing ages in millions of years, Epochs, carbon and oxygen isotopes, tectonic and biotic events. (used with permission)

Fig. 21.5 Wave-cut terraces of former Lake Bonneville above the bank of Great Salt Lake, Utah (Public Domain)

About 8,200 years before present, glacial lake Agassiz was the largest lake in the world. It covered over 840,000 km^2 in Canada (Manitoba, Saskatchewan, and Ontario) and the U. S. (North and South Dakota and Minnesota).

There were some very large glacial lakes throughout the Northern Hemisphere during the Pleistocene that formed from the meltwater as the ice receded. One of these was Lake Agassiz (Fig. 21.6), an immense glacial lake located in the geographical center of the continent of North America. It covered an area larger than the present Great Lakes and was equivalent to about 15 Lake Superiors in the amount of fresh water it held. This water was released rather suddenly into the Arctic Ocean and northern Atlantic through the Mackinzie River basin about 8,700 years ago and was probably witnessed by early North American settlers.

The draining of Lake Agassiz raised sea level world-wide almost 2 m (6 ft) and some scientists think that this caused a migration inland across Europe which greatly expanded agriculture in post-glacial Europe by Neolithic people (Fig. 21.7).

Another large glacial lake was Lake Bonneville as seen below (Fig. 21.8) with other glacial lakes in the northwestern U.S. The Great Salt Lake in Utah is a remnant of glacial Lake Bonneville.

Remnants of the Laurentide ice sheet are still found in northern Canada, such as the ice on Baffin Island as shown in the picture below (Fig. 21.9).

The extent of the ice during the Pleistocene is shown in the illustration below (Fig. 21.10) as well as the extent of the sea ice in the Northern Hemisphere as compared to their presence today.

21.8.1 The North American Ice Line

The southernmost extent of the Laurentide glacier in North America is marked by the terminus of the last glaciation (Wisconsin) as evidenced by the glacial deposits that it left behind as it receded. This lobate line is called the North American Ice Line and runs from Long Island in the east, westward to the Ohio River, irregularly through Pennsylvania, along the Ohio River to the Mississippi River, then to the

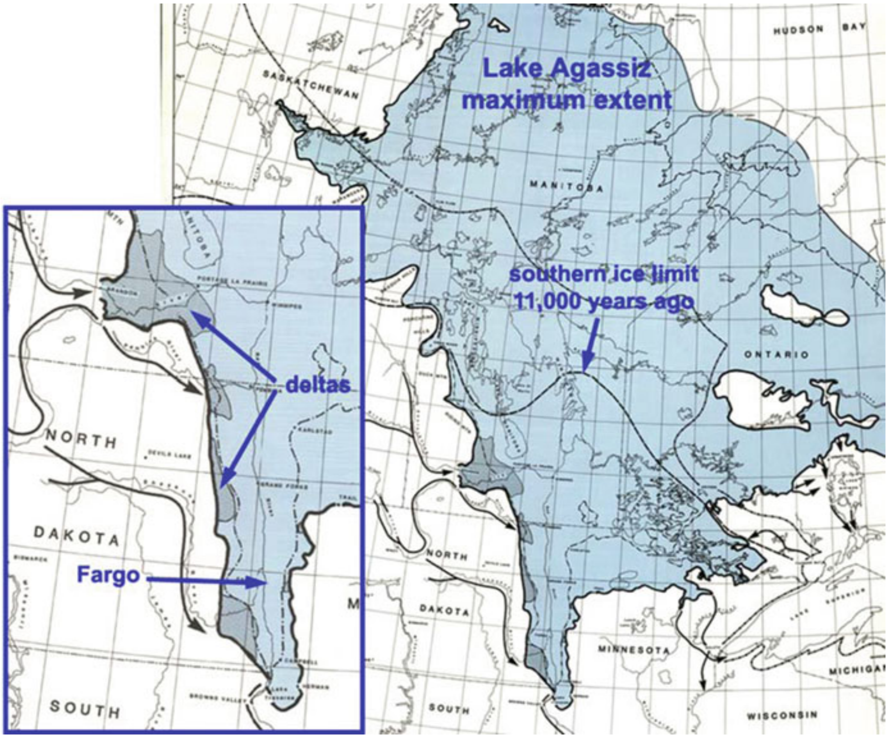

Fig. 21.6 The outbreak from Lake Agassiz about 8,700 years ago caused a world-wide rise in sea level (From the Geological Association of Canada)

Missouri River, along the Missouri River until it joins with the Cordilleran Ice Sheet (Fig. 21.11).

21.8.2 Europe and Asia's Continental Glaciation

Continental glaciation affected Europe and Asia during the Pleistocene as shown in the illustration below (Fig. 21.12).

The Great Lakes of North America were also formed during the Pleistocene (Figs. 21.13 and 21.14). The Laurentide Great Lakes were formed nearly 20,000 years ago when the Earth's climate warmed and the last glacial continental ice sheet retreated. But this was not a continuous retreat, as we've seen with the Interstadials and the rapid warming of the Greenland area.

During its retreat, the ice moved from time to time as the temperature went below freezing and the glacier, up to 2 miles thick, was so powerful that it gouged out the Earth's surface to create the lake basins. Meltwater from the retreating glacier filled the newly created basins. Approximately 3,500–4,000 years ago, the Great Lakes attained their modern levels and areal extent. The Finger Lakes of New York State were also formed at this time

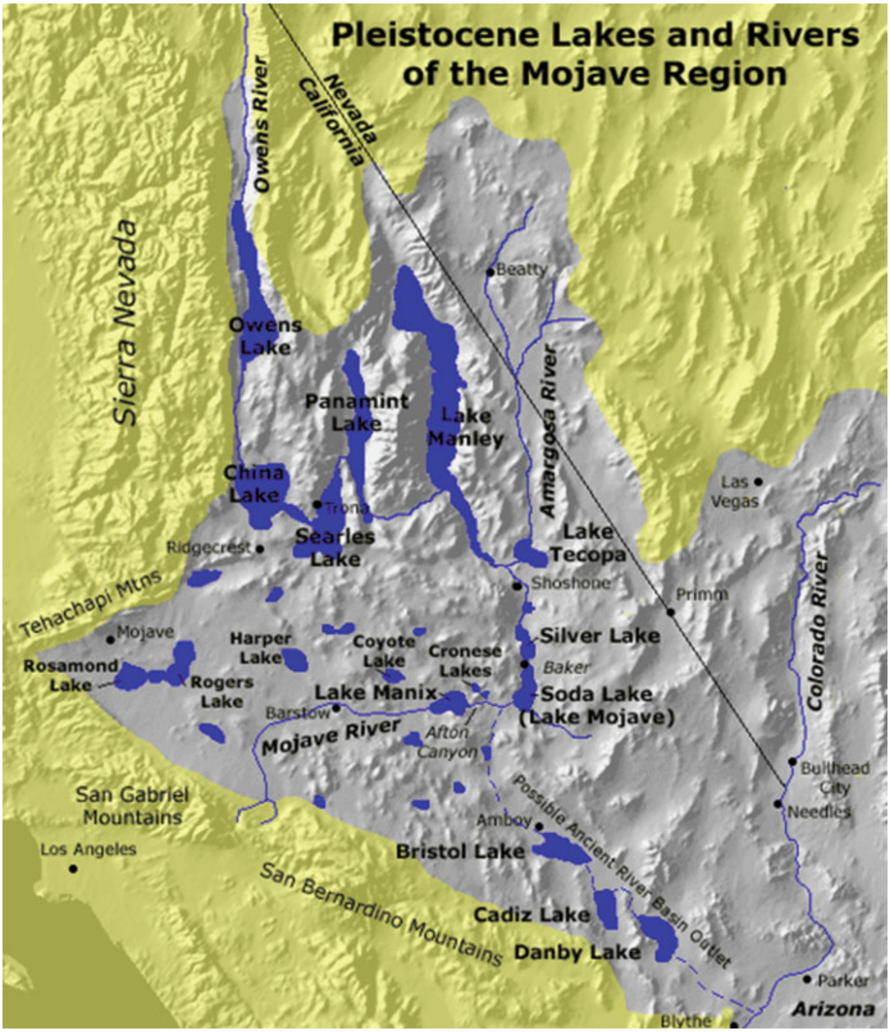

Fig. 21.7 Pluvial lakes and rivers of the Mojave region (National Park Service and USGS, Public Domain)

21.8.3 Southern Hemisphere Glaciation

One of the greatest unanswered paleoclimatic questions is why both the northern and southern hemispheres entered the last (Wisconsin) glaciation almost simultaneously, since the Earth's orbital geometry 115,000 years ago, which gave rise to cool northern summers, did not have the same effect in the southern latitudes, where solar radiation levels tended to fall in spring, rather than in summer.

According to the classic Milankovitch theory, the glaciation should have begun in the northern hemisphere. However, paleoclimatic sites in the southern hemisphere

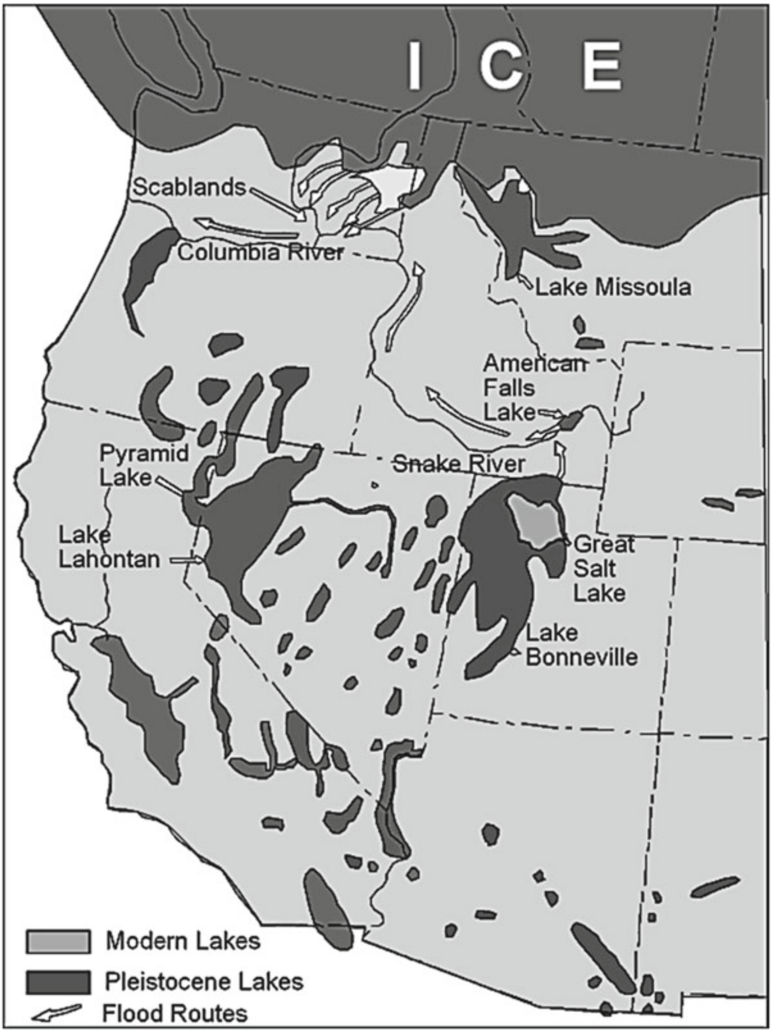

Fig. 21.8 Glacial and modern lakes in the northwestern U.S (From http://geology.isu.edu/Digital_Geology_Idaho/Module14/mod14.htm)

indicate that in this region also temperatures plummeted around 115,000 years ago, almost precisely at the same time as in the northern hemisphere, with the advance of glaciers from the southern Andes and Patagonia and the growth of sea ice that surrounded Antarctica.

The mechanism by which glaciation spread from one hemisphere to the other is still largely unknown. There are even indications that, in the southern seas, the cooling which marked the end of the Eemian (Sangamonian) began several thousand years earlier than 115,000 years ago; or in other words, before the conditions conducive to the start of the glaciation arose in the northern hemisphere. Similarly,

Fig. 21.9 A remnant of the Laurentide ice sheet on Baffin Island, Canada (NASA, Public Domain)

a comparison of ice measurements from Greenland and Antarctica offers no firm evidence that the northern glaciation predates the southern one. Only when we achieve time resolutions of less than 500 years for the interval in which the last glaciation began will we be able to determine the exact nature of the connection between the two hemispheres.

If the glaciation did begin in the high latitudes of the northern hemisphere, then it is possible that a drop in the thermohaline ocean circulation triggered the cooling of the Antarctic land mass. During warm interglacial eras, such as the one in which

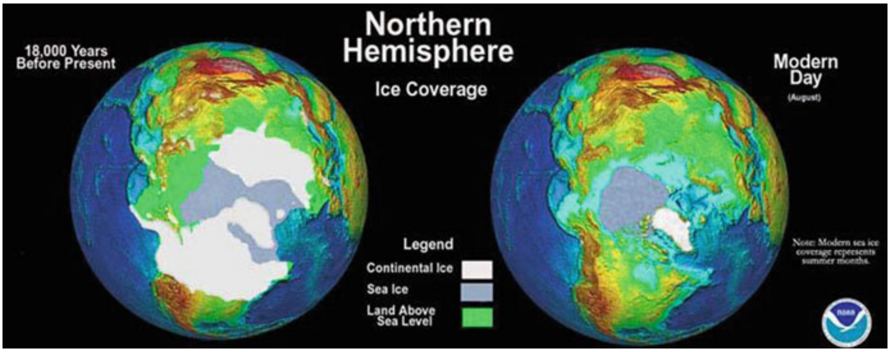

Fig. 21.10 Northern hemisphere ice coverage 18,000 years ago and today (August) (NOAA, Public Domain)

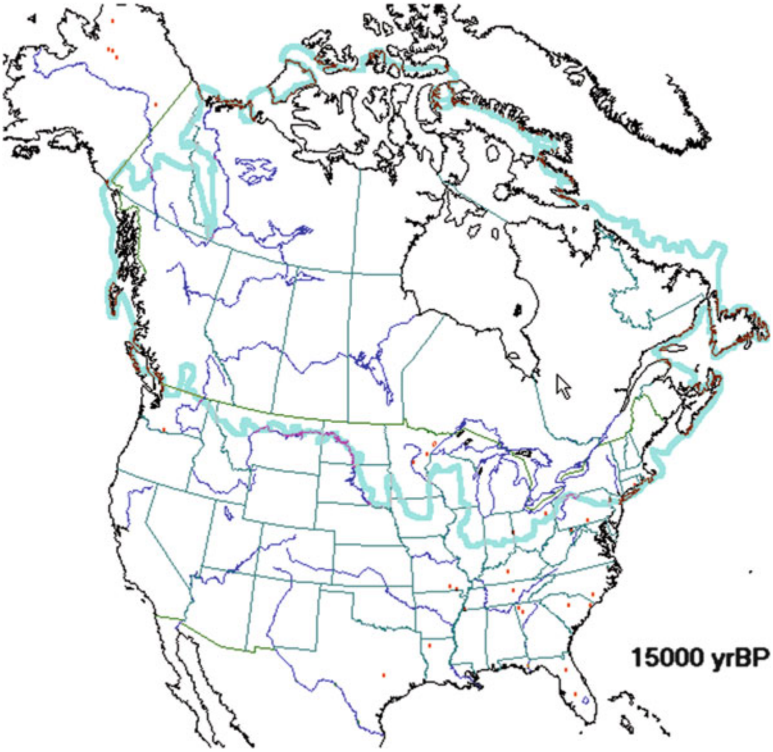

Fig. 21.11 The extent of the Laurentide and Cordilleran glaciers outline by the aqua line. The land north of this line was covered by continental glaciers (From NOAA, Public Domain)

we are living now, part of the NADW (North Atlantic Deep Water) upwelling in the Southern Ocean after crossing the whole Atlantic Ocean at both deep and intermediate levels. This mass of upwelling water, although cold, is not as cold as that formed

Fig. 21.12 A North Polar view showing the major Pleistocene ice sheets, the Laurentide, Inuitian, and Cordilleran in North America, the Greenland and Iceland ice sheets, and the Scandinavian and Kara ice sheets in Europe and Asia. Directions of ice movement are shown by the *arrows*

along the Antarctic Coast (known as AABW, Antarctic Bottom Water; Fig. 21.15), and as a result moderates the intense cold of the air which surrounds the coastline of the southern continent. However, once glaciation begins in the northern hemisphere, the Atlantic thermohaline circulation is weakened and this upwelling decreases, rendering the water layers of the Southern Ocean more stratified and colder. As a consequence, Antarctica also becomes colder.

Another hypothesis, which places the emphasis more on the southern hemisphere, is that an increase in the winter sea ice surrounding Antarctica (which is highly sensitive to air temperature changes), coupled with an increase in water salinity, may have triggered a greater production of AABW. This mass of very cold

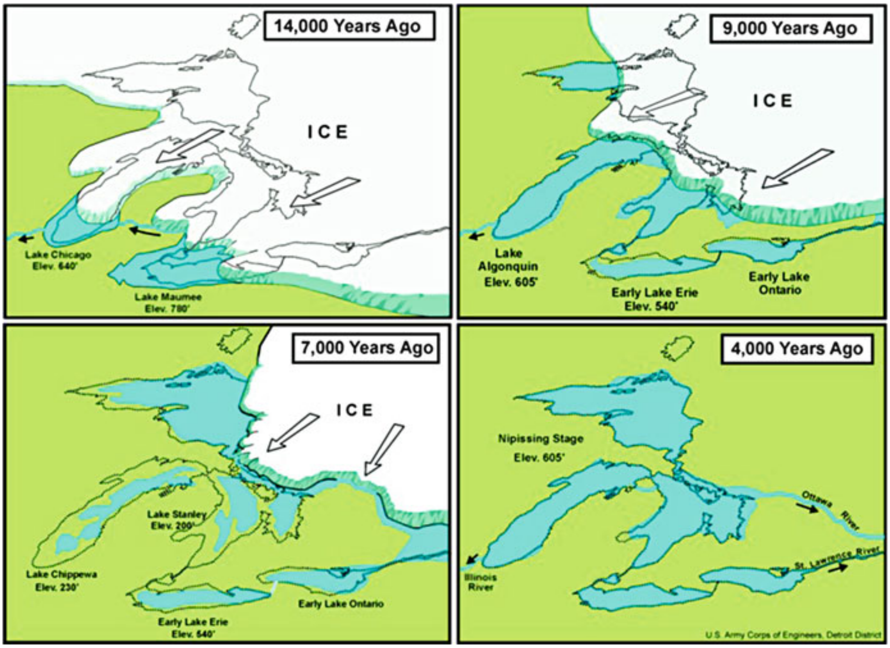

Fig. 21.13 Stages in the formation of the Great Lakes (NOAA, Public Domain)

Fig. 21.14 The glacial Great Lakes of Canada and the United States as they are today (SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. Image taken 24 April 2000, Public Domain)

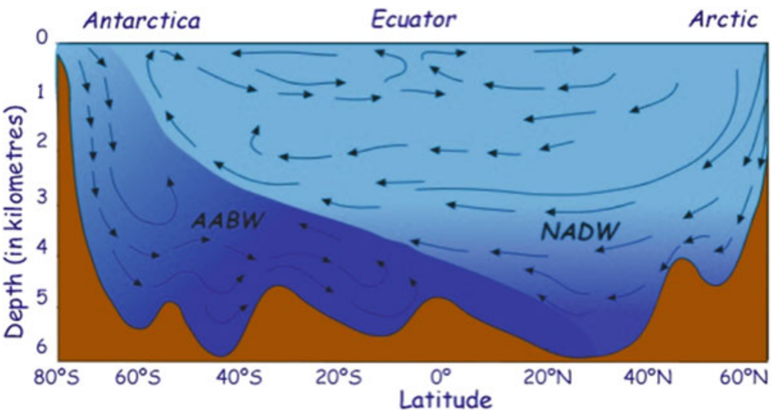

Fig. 21.15 Vertical, schematic cross-section of the deep waters and currents in the modern-day Atlantic. In the thermohaline circuit, surface water sinks in high latitudes. In the vicinity of the Arctic, the mass of water known as NADW (North Atlantic Deep Water) is formed, and in the vicinity of Antarctica, the even denser water mass known as AABW (Antarctic Bottom Water) is formed

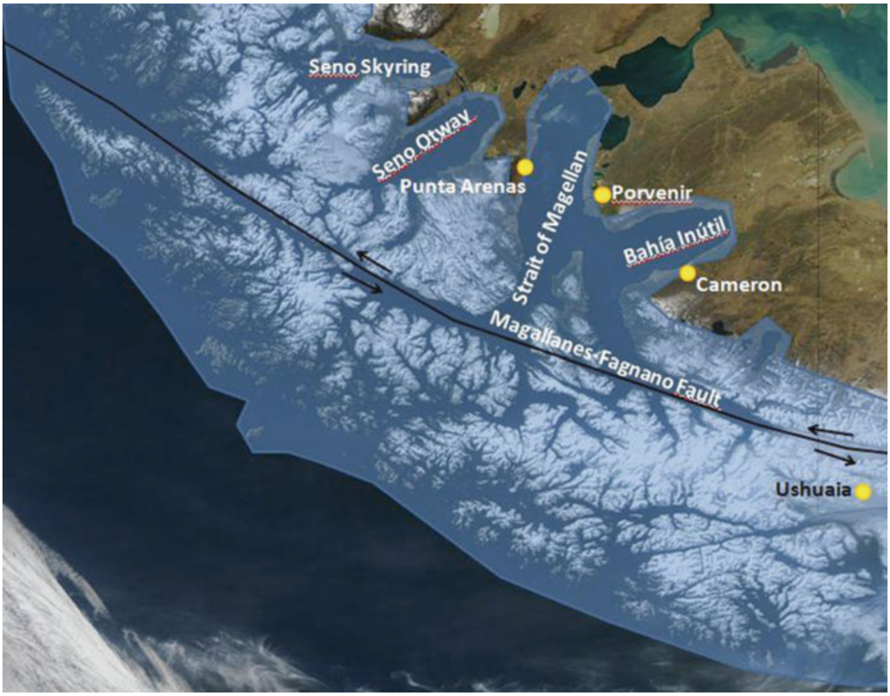

Fig. 21.16 Patagonian ice sheet (NASA, Public Domain)

water, which would have moved through the deep ocean layers towards the North Atlantic, may have increased the vertical stability of the water upon arriving in the north, thus reducing the production of NADW and slowing up the thermohaline circulation. This in turn would have accentuated the global drop in temperature.

In the Southern Hemisphere the Patagonian ice sheet (see Fig. 21.16) covered the southern one-third of Chile and adjacent areas of Argentina. On the western side of the continent the ice reached sea level as far north as 41° North latitude. The Straights of Magellan were iced over. Small glaciers formed in the Middle East and Africa and the Sahara, Gobi, and other smaller deserts were greatly expanded.

During the Last Glacial Maximum (LGM), around 18,000 years ago, the world was cold, dry, and inhospitable, with frequent storms and a dust-laden atmosphere. The massive sheets of ice locked away water, lowering sea level, exposing continental shelves, joining land masses together with land bridges, and creating extensive coastal plains. It has been estimated that sea level was lowered about 180 ft during the LGM exposing vast areas of what is today submerged continental shelf areas.

Additional Readings

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