The Eurasian Arctic During the Last Ice Age

A vast ice sheet once covered the Barents Sea. Its sudden disappearance 100 centuries ago provides a lesson about western Antarctica today

Martin J. Siegert, Julian A. Dowdeswell, John-Inge Svendsen and Anders Elverhøi

In the 1970s, long before global warming had become much of a public concern, an Ohio State University glaciologist named John Mercer made a disturbing observation. He pointed out that the geography of western Antarctica is strikingly similar to the Eurasian Arctic: Both of these polar regions contain a large continental shelf no more than a few hundred meters deep. The major difference is that western Antarctica has a 2.5-kilometer-thick ice sheet resting on it, whereas the Eurasian Arctic is now comparatively free of grounded ice. Mercer argued that if global warming continued, there was a real threat that the immense ice sheet covering western Antarctica could disintegrate, adding enough water to the ocean to raise sea level by six meters, which would inundate coastlines throughout the world.

Mercer understood the task his observation demanded: To gauge whether the west Antarctic ice sheet is truly in danger of breaking up, scientists must look for clues at the other side of the Earth, in the geological remnants of the former ice sheets that covered northern Eurasia. Many earth scientists took heed and applied their specialties to the investigation, and their work soon began to reveal the glacial history of the Eurasian Arctic. By the mid-1980s, however, the interpretation of the geological observations varied enormously. Whereas some saw evidence for a massive, 3.5-kilometer-thick ice sheet over the whole of northern Europe and Siberia at the height of the last ice age (known to geologists as the Last Glacial Maximum, or LGM), others disputed this appraisal, preferring to believe that there was virtually no ice at all on the seafloor to the north of the Norwegian and Russian mainlands. Contradictory views sparred in the literature. The problem was partly that the geological record in the Arctic can be difficult to read and thus open to misinterpretation. Another obstacle was the paucity of reliable observations from this remote and inhospitable region.

To resolve the issue, the European Science Foundation mounted back-to-back research programs to gather new geological evidence in the vicinity of the former ice sheets in the Eurasian Arctic. These efforts involved more than 50 scientists from seven European countries, including the four of us. The first, dubbed PONAM (for POlar North Atlantic Margins) concentrated on the western side of the Barents Sea. During the follow-up program, named QUEEN (QUaternary Environments of the Eurasian North), the focus shifted east to the Russian Arctic. These efforts provided a great deal of information about the status of northern Eurasia in the Ice-Age world. To grasp the full significance of the results, however, requires that one gain at least a broad understanding of glaciological processes. So here we take a moment to review the basics of how glaciers operate.

Glaciology 101

Ice is, of course, a solid, but it deforms very slowly when a large stress is applied—such as the stress induced in an ice sheet by its own great weight. This deformation causes a parcel of ice within a glacier to move slowly over time. Also, a piece of ice on the surface of an ice sheet is buried by subsequent snowfalls, which cause it to move downward into the ice sheet at a significant velocity with respect to the deformation. Overall the motion tends to be down in the middle and out to the sides.

More specifically, the flow at the center of an ice sheet radiates from the ice divide, the place where there is no lateral movement on the surface. As the ice moves away from the ice divide, its lateral velocity increases from an initial value of perhaps a few meters per year. Nearer their margins, ice sheets are effectively "drained" by fast-flowing rivers of ice, known as ice streams. The velocity of an ice stream is typically several hundred meters per year. These streams flow quickly because water at the base reduces friction, allowing the ice to slide across the underlying ground, with internal deformation making only a small contribution to the total velocity.

Broadly speaking, the ice continues to flow faster and faster until it reaches its demise in one of two ways. The ice sheet may terminate on land (stopping because the ice at the surface melts as fast as it is supplied) or it can terminate at sea. Where an ice sheet flows into the ocean intact and becomes afloat, it forms an ice shelf. Such an ice

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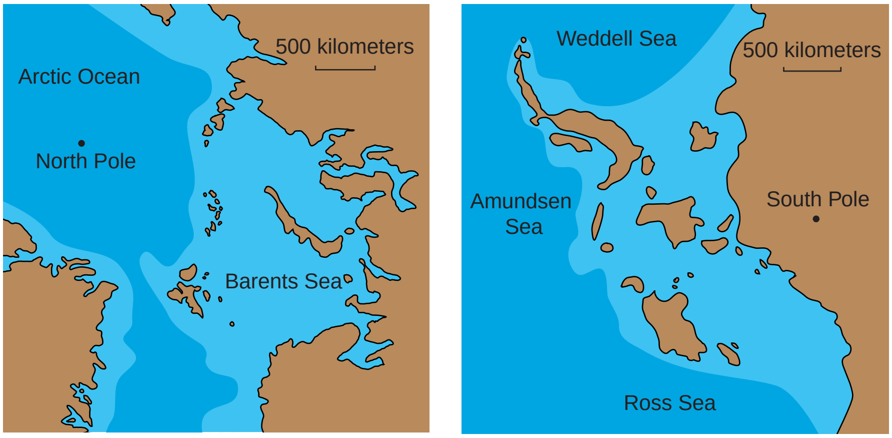
Figure 1. Floating shelf of ice (above) surrounds the frigid coast of Antarctica. Should global warming destroy such buffers, the massive marine ice sheet of western Antarctica would be exposed directly to the sea, speeding its melting and flooding the world's coastlines. The authors and their colleagues have examined a similar occurrence in the Northern Hemisphere some 15,000 years ago—the demise of a great ice sheet that once occupied the Barents Sea. The analogy is apt because the wide continental shelf of the Barents Sea (light blue, right) resembles the configuration western Antarctica would assume if the ice there melted (far right). (Reconstruction of ice-free Antarctic seas is from Mercer 1970.)



shelf loses mass by "calving" icebergs from its edge and by melting at the bottom.

As they flow over land, ice sheets erode and entrain sediments at their bases. They can transport this rocky material great distances before ultimately depositing it at their margins. This is why in front of any glacier you will see moraines, piles of sediment resembling building rubble. After glaciers and ice sheets melt away, moraines are left behind, providing a geological marker of the extent of the ice in the distant past. The problem of reconstructing the boundaries of an ancient ice sheet would thus appear to be simple—just map the location of the terminal moraines. In reality, the situation is more complicated because in some areas terminal moraines are either absent or are now hidden below sea level. Often several moraines from different glacial advances are jumbled together, making the relevant one difficult to distinguish.

Sorting Through the Rubble

After 10 years of concerted effort, investigators working on the PONAM and QUEEN programs have collected a great deal of geological information about the former ice sheets that from time to time blanketed vast areas of the Eurasian Arctic. In a nutshell, our work provided three important findings. First, it documented that a large, marine-based ice sheet formed on the continental shelf in the Barents Sea during the LGM, some 20,000 years ago. At

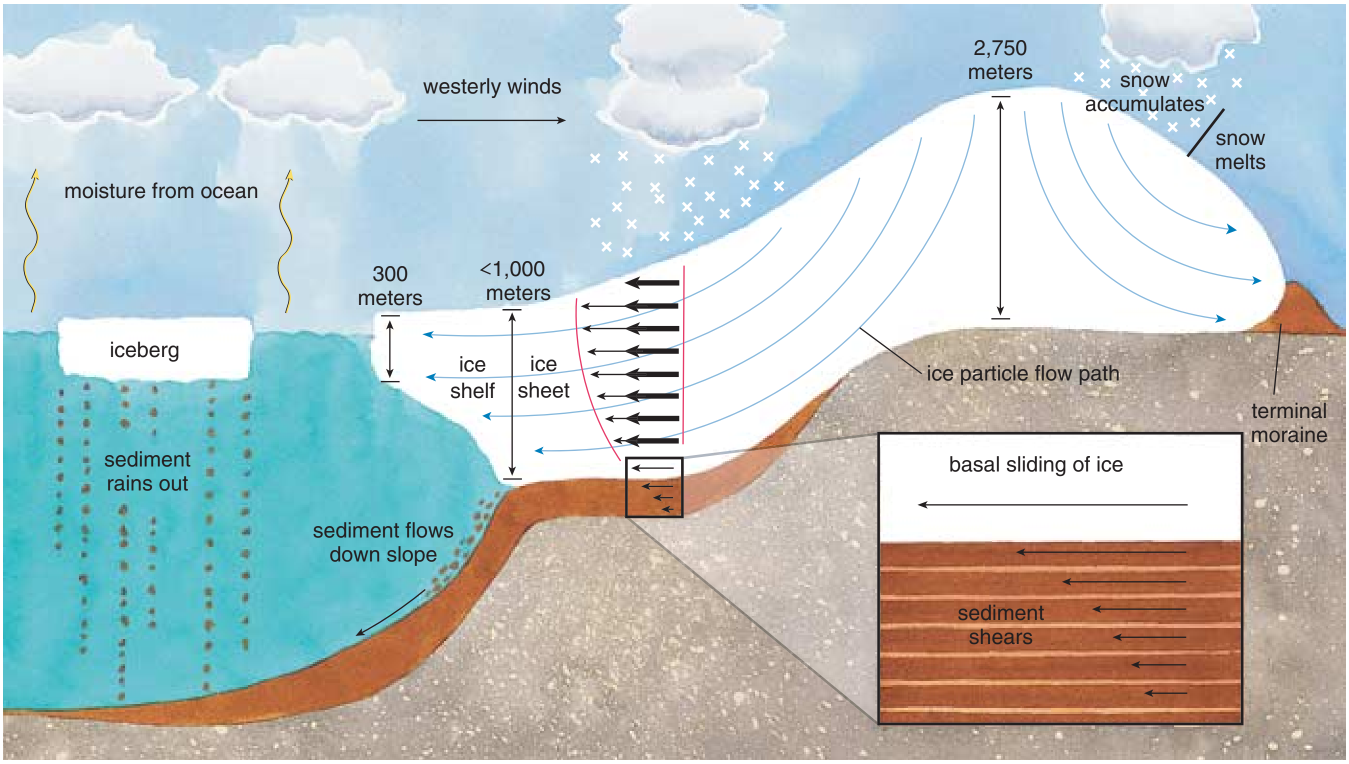


Figure 2. Schematic cross section of the Barents Sea region during the height of the last ice age shows the flow of ice (blue arrows). To the far right (representing the southern boundary of the ice sheet), melting takes place as rapidly as the ice is supplied. Here, deposition of rocky material caught up in the ice forms a terminal moraine. To the far left (representing the northern and western boundaries of the ice sheet), a floating ice shelf forms. Just inland is the marine portion of the ice sheet—the part that rests on rock below sea level. Here ice flows relatively quickly, because the horizontal motion has two components: internal deformation (thin black arrows) and sliding over the base (thick black arrows). Sliding can indeed be considerable, lubricated by the underlying sediments, which shear to accommodate the motion (inset).

that time, the Barents Ice Sheet coalesced with the Scandinavian Ice Sheet, forming a continuous ice cover that extended from Germany and the United Kingdom, across Scandinavia and the Barents Sea shelf, and east to the Kara Sea. Second, this work showed that fast-flowing ice streams transported large volumes of glacial sediment to the continental margin. Third, the research demonstrated that the ice sheet disintegrated quickly at the end of the Ice Age. How exactly did we come to these conclusions, and why are they significant?

We know that the Barents Sea was glaciated during the recent geologic past because, in general, the seafloor is underlain by only a few meters of soft mud: The sediment found underneath this thin layer of mud is full of glacially derived debris and has been heavily compacted by the enormous weight of the last ice sheet. This sediment layer, which is a till (a characteristic glacial deposit), is widely distributed on the continental shelf. In central parts of the Barents Sea, the ice sheet also left behind a series of long parallel furrows, which reflect former ice movements. To evaluate the dimensions and age of this ice sheet, we and our many colleagues undertook various geological investigations in the Barents Sea region and along the northern margin of the Eurasian continent.

The geological field studies started on Svalbard, a group of islands situated 600 kilometers north of the Scandinavian mainland. The pattern of raised shorelines on this archipelago and on Franz Josef Land farther east told us that the northern Barents Sea most likely had been weighed down by a major load of ice during the LGM. (Such raised shorelines form because breaking waves carve flat zones along the strand. Then after the ice sheet melts, the crust springs upward, transforming these beaches into raised terraces.) Along the western coast of Svalbard there are also several uplifted beaches with shells and whale bones, which were found to be more than 40,000 years old using radiocarbon dating. Most of the scientists involved believed that the presence of organic material this old proved that glaciers could not have reached the coast after these uplifted beaches were formed. Jan Mangerud, a Norwegian geologist from the University of Bergen, then made a ground-breaking discovery. He found that at least some of the old raised beaches had been overridden by ice, implying that during the LGM glaciers covered much more of Svalbard than anyone had imagined.

Subsequent work revealed that the main fjords were in fact filled by ice at this time and that the entire archipelago was covered by an ice sheet that was centered on the seafloor to the east of Svalbard. To determine the western boundary of the ice sheet, many investigators together made a major effort to map the sedimentary characteristics of the seafloor across the western Eurasian continental margin using various kinds of seismic and acoustic soundings as well as sediment coring. This work revealed large volumes of glacial sediments arrayed in huge fan complexes along the continental slope. The top layer of these sediments originates from the last extensive glaciation, so these fans clearly place the edge of the former ice sheet at the shelf margin. The vast amount of material transported to these fans demonstrates that fast-flowing ice streams must have been active along the western side of the ice sheet.

Establishing the southern and eastern margin of the former ice sheet has been a more difficult task. In the late 1970s, Mikhail Grosswald, a well-known geographer from the Russian Academy of Sciences in Moscow, hypothesized that a 3.5-kilometer thick, pan-Arctic ice sheet covered vast areas of the European Arctic and Siberia during the LGM. His hypothesis, questioned by many Russian scientists, was soon adopted by the majority of the scientific community in the west. Meanwhile, Valery Astakhov, a geologist from the National Institute of Remote Sensing Methods for Geology in St. Petersburg, was digging in the frozen earth of western Siberia searching for the hidden remnants of the last ice sheet. He found that a former ice sheet centered on the Kara Sea shelf did indeed advance south across the Yenissei river valley—but that this episode took place much earlier than the LGM. Thus, it was clear that something was wrong with Grosswald's hypothesis.

Research undertaken in the QUEEN program showed that a fresh-looking belt of moraines in the European part of the Russian Arctic (to the east of the White Sea) were, in fact, deposited as long as 60,000 years ago—some 40,000 years before the LGM. To locate the ice margin of the LGM, it was therefore once again necessary to turn our eyes towards the sea.

Examination of the seafloor sediments offshore of the Russian mainland has confirmed that the most recent ice sheet terminated on the continental shelf. Cores recovered from the Pechora Sea show that marine sedimentation in this area has gone on throughout the last 40,000 years, whereas inside the inferred margin of the ice sheet the oldest marine deposits above the upper surface of the till are less then 14,000 years old. Geological investigations on the Yamal Peninsula, which juts into the Kara Sea, have shown that the ice sheet did not reach that area either. Thus the southern limit of the ice sheet must have been somewhere to the north, within the shallows of the Kara Sea.

The position of the eastern margin of the ice sheet is similarly hard to pin down precisely. One avenue of investigation has been to study sedimentary deposits within the many lake basins of the Taymyr Peninsula, east of the Kara Sea. The sediments that accumulated at the base of these lakes comprise fine-grained muds. If an ice sheet had been located over this peninsula, these sediments would have been replaced or covered by coarse, glacially derived material, which is easily distinguishable. However, the sediment sequences in these lakes reflect a continuous accumulation of nonglacial sediments throughout the LGM, which means that the central parts of Taymyr Peninsula were free of ice when the ice sheet existed to the west across the Barents and Kara seas.

Interestingly, a team of geologists led by Christian Hjort at the Lund University, Sweden, concluded that the northwestern fringe of the Taymyr Peninsula was indeed touched by glacial ice after 20,000 years ago. However, this group of investigators believe that this ice was not an extension of the large marine ice sheet that covered the Kara Sea. More likely, it was part of a more restricted glacier located on the shallow sea floor just off the coast.

On Severnaya Zemlya, an island group to the north of the Taymyr Peninsula, Russian scientists have reported finding mammoth tusks dating from the period between 25,000 and 19,000 years ago, suggesting that the glaciers on this archipelago during the LGM were, surprisingly, even smaller than they are today. So the eastern boundary of the former ice sheet remains rather difficult to delineate.

Primary Causes

To understand fully the glacial history of the Eurasian Arctic during the last ice age, one needs to appreciate why ice ages arise in general and how they can cause a continental sea to fill with ice that is more than a kilometer thick. The geological record indicates that huge ice sheets repeatedly formed and decayed in the Eurasian Arctic as a response to pronounced climatic oscillations throughout the past 2.7 million years. The previous interglacial interval, when the climate on Earth was comparable with the present, lasted from 128,000 to 115,000 years ago. It was followed by an ice age that suddenly ended 11,700 years ago. During this ice age as many as three periods of glacial advance and decay took place. The most recent ice sheet that spread across the shelf areas started to form some 30,000 years ago and reached its maximum extent some 10,000 years or so later.

In an ice age, huge volumes of water shift from the oceans to the polar ice sheets, which lowers sea level, at times by as much as 120 meters. The clearest record of this vast redistribution of water comes from the examination of the three naturally occurring oxygen isotopes (^{16}O, ^{17}O and ^{18}O) in various geological materials. Why are these oxygen isotopes so telling? Water containing the lightest form of oxygen (^{16}O) evaporates more rapidly than water with the heavier isotopes (^{17}O and ^{18}O). So water comprising "light

Figure 3. Geological investigations in recent years have helped to pinpoint the margin of the ice sheet (solid line) during the Last Glacial Maximum, some 200 centuries ago. Dashed portion of the lines show where the location of the ancient boundary remains somewhat uncertain.

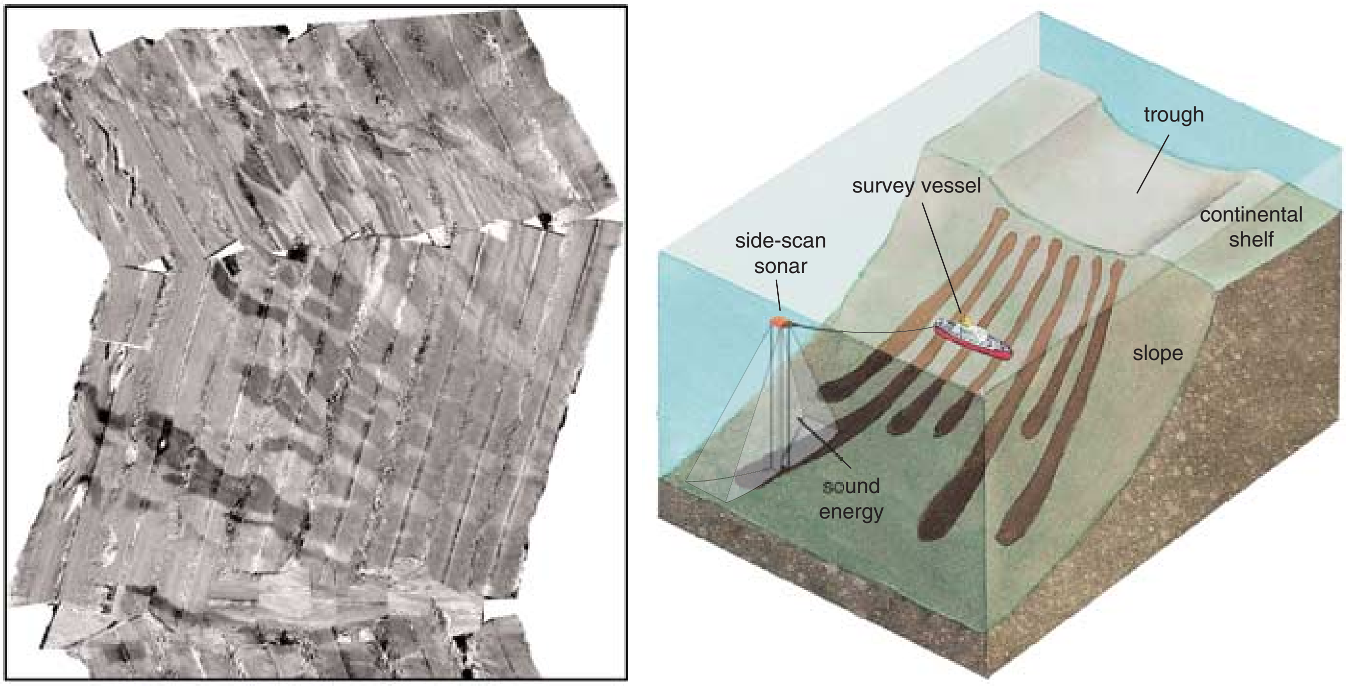


Figure 4. Surveys of the seabed using side-scan sonar reveal long tongues of glacial sediment (dark zones, left). These deposits extend from the edge of the continental shelf down the continental slope and toward the deep sea (right). The great quantity of sediment needed to form such characteristic deposits indicates that they must have been carried by a marine ice sheet that once reached all the way to the edge of the continental shelf. (Sonar image courtesy of the authors.)

oxygen" preferentially goes into the ice sheets, and during an ice age the water in the oceans becomes enriched in heavy oxygen. If, say, a marine organism forms a shell of calcium carbonate ($CaCO_3$) at this time, it will contain a larger than average dollop of heavy oxygen. When that organism dies, its shell drops to the sea floor leaving a convenient record of the isotopic state of the ocean in the past.

Geologists have collected many long records of the ocean's shifting oxygen isotopes from the analysis of sediments recovered from the floor of the deep sea. They have also measured the isotopic composition of the ice that has accumulated in Antarctica. The oxygen-isotope signals from the ice and ocean sediments tell a remarkably similar story: The climate changes associated with ice ages repeat at frequencies of about 100,000, 40,000 and 20,000 years. Why does the climate oscillate at these three frequencies? The answer lies in the orbit of the Earth around the Sun.

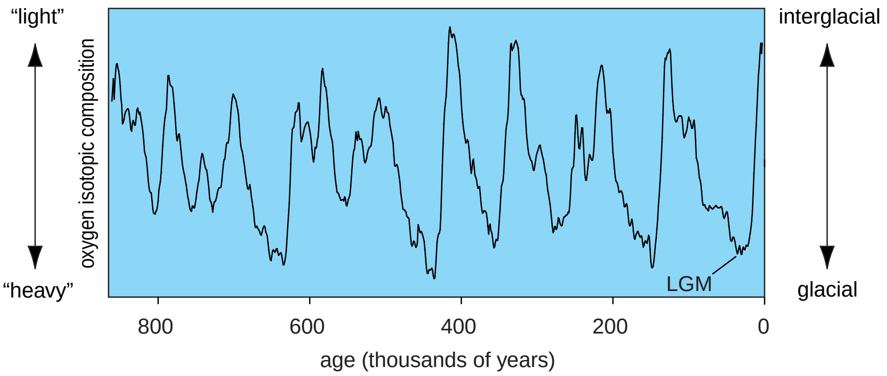


Figure 5. Variations in the oxygen-isotope composition of shells record many repeated swings between glacial and interglacial conditions. During glacial times, "light" oxygen-16 is preferentially sequestered in polar ice, making the ocean water (and shells that form from it) especially rich in "heavy" oxygen-18. The authors' geological investigations of ice-age Eurasia since the time of the Last Glacial Maximum (LGM) are complicated by the many equally severe glaciations that went on before.

The first orbital parameter to consider is eccentricity, the deviation from perfect circularity. The Earth's orbit changes from an elliptical to a circular path with a frequency of roughly 100,000 years. The second parameter of interest is the tilt of the Earth's axis, which oscillates between 22.2 and 24.5 degrees at a frequency of about 40,000 years. The third is the position of the Earth within its elliptical orbit during Northern Hemisphere summer, which changes at a frequency of approximately 20,000 years. These oscillations affect the amount of radiation received at the Earth's surface at various times of the year. If the three orbital parameters conspire to reduce the radiation to the Northern Hemisphere in the summer, glaciers and ice sheets expand, bringing on an ice age.

The relation between observed climate oscillations and the theoretical predictions about their periods is excellent. There is, however, a slight problem: The changes to the solar inputs associated with orbital variations are far too small to cause the climate changes required to grow an ice sheet. What is needed is a means by which subtle orbital effects can be amplified into drastic shifts in climate. Several such feedback mechanisms are possible; all probably contribute in some way to the waxing and waning of ice ages.

Perhaps the simplest mechanism to understand is ice-albedo feedback. The reflectivity of the Earth's surface (its albedo) controls the amount of solar radiation that bounces back from the Earth into space. If the albedo is high, more radiation reflects, and the Earth cools. If the albedo is low, the planet's surface absorbs more radiation, and the world warms. Snow and ice are, of course, very reflective. As snow fields and ice sheets expand in response to global cooling, the increase in surface albedo causes an increase in the reflection of solar radiation, resulting in a further reduction in air temperature.

Another feedback mechanism depends on atmospheric carbon dioxide (CO_2), which affects climate because it enhances the greenhouse effect. For reasons not yet fully understood, during glacial times the concentration of atmospheric CO_2 diminishes. Hence, a cooling that arises from other causes lowers CO_2, which lessens the greenhouse effect, yielding further cooling.

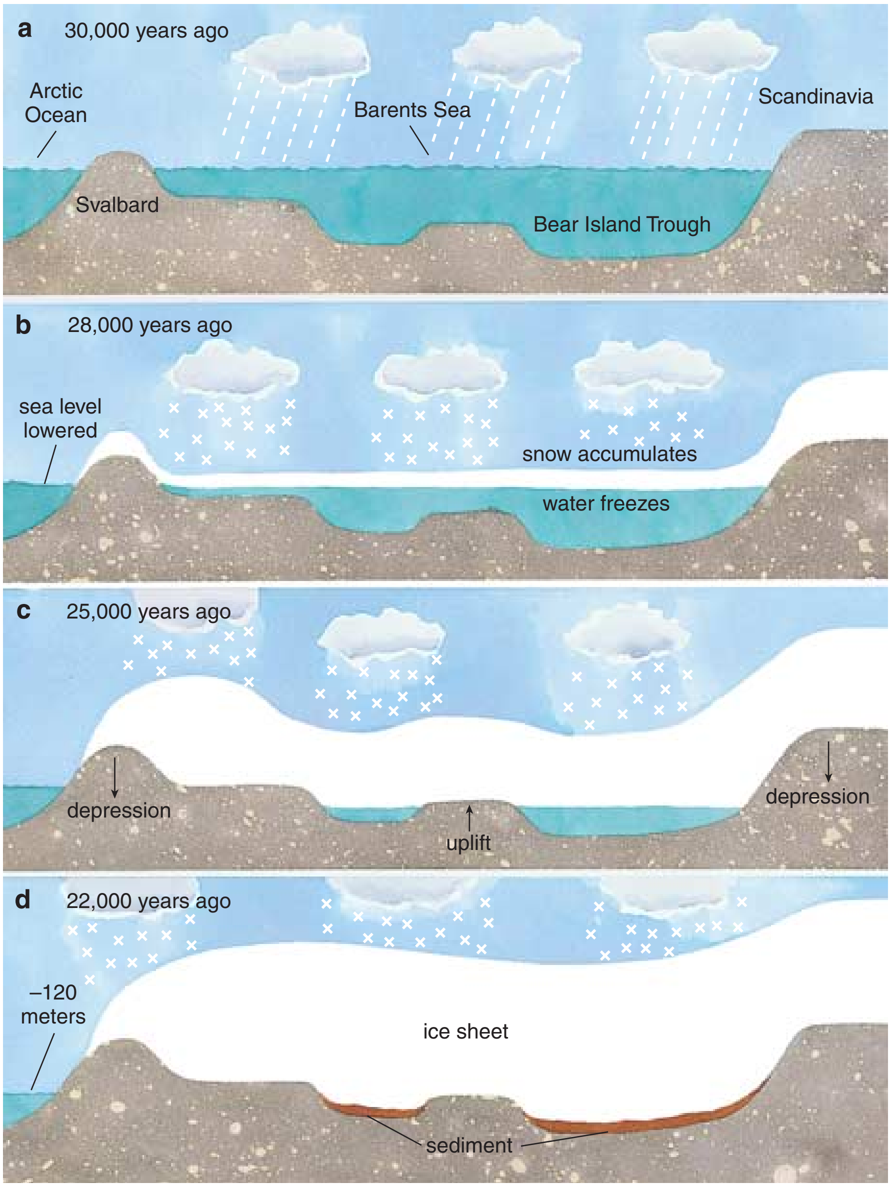


Figure 6. Conceptual model shows how a marine ice sheet began to form in the Barents Sea region after open-ocean conditions (a) gave way to a perennial cover of sea ice (b). The weighty accumulation of snow and ice on islands to the north (left) and on the mainland (right) forced the crust downward in these places, causing the seafloor between to move upward just as sea level was dropping (c). These processes continued until the thickening mass of ice rested directly on the seafloor, with deposits of wet sediment left in local topographic depressions (d).

The Ice Sheet Cometh

With a general knowledge of orbital variations and feedback mechanisms, it is quite easy to envision how the deterioration of climate results in the growth of ice on land. It is, however, not so easy to see how global cooling causes an ice sheet to form on the seafloor. The method by which a large continental shelf can become covered by an ice sheet has been debated for many years. The main problem is that the calving of icebergs at the grounded margin of an ice mass intensifies with increasing water depth. So as the margin of an ice sheet migrates into deeper water, the rate of calving will increase, and this process should act to curtail the further spread of ice.

Terence Hughes of the University of Maine proposed that an ice sheet within the Barents Sea basin could form from a pre-existing ice shelf—a solid mass of ice floating on the surface. He suggested that permanent sea ice (a few meters thick) would thicken into an ice shelf (a few hundred meters thick) if the surface accumulation of ice exceeded the basal melt rate for a few thousand years. An ice shelf within the Barents Sea would encourage the growth of an ice sheet in two ways. First, the calving of icebergs from an adjacent ice sheet would cease: Ice would simply flow into the ice shelf. Second, as the ice shelf thickened, it would eventually touch the sea floor and become part of the grounded ice sheet itself.

Another mechanism may also be at least partly responsible for the growth of an ice sheet within the Barents Sea. Several scientists have suggested that ice accumulated initially over the island archipelagos located across the northern edge of the Eurasian continental shelf. As it did so, its great weight pushed the crust downward under it, causing the crust in the shallow central regions of the Barents Sea to bulge upward—just as a downward force applied to the center of a steel beam causes it to flex upward at either side. This uplift, combined with the lowering of sea level (of up to 120 meters' worth), may have allowed ice to fill the shallows. This ice may have flowed in from adjacent ice sheets, or it may have formed in place from thickening sea ice.

Indeed, both these processes may have operated during the last ice age. In addition, evidence from the nearby Norwegian-Greenland Sea shows that open-ocean conditions reigned there during the last ice age. This relatively

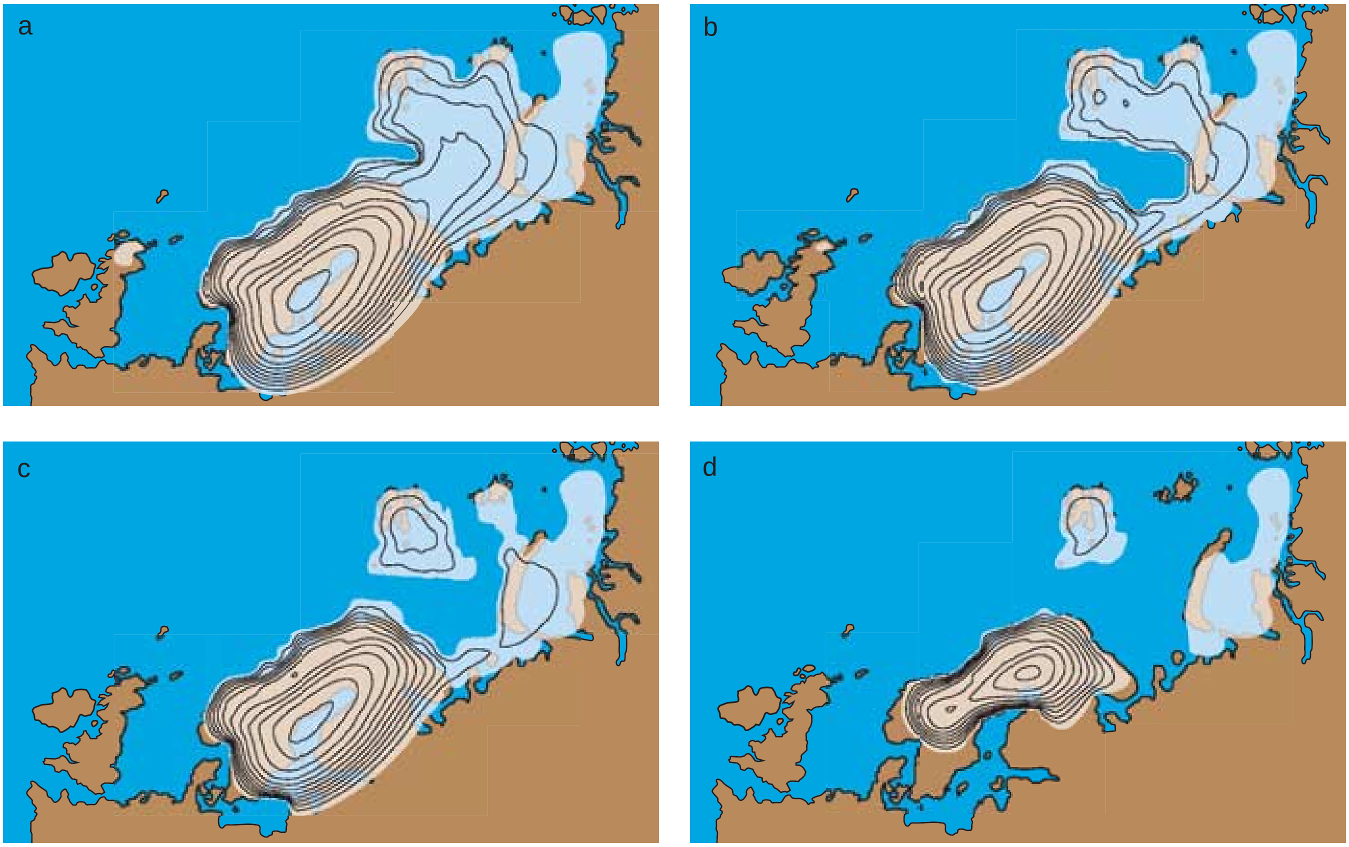


Figure 7. Numerical simulations show how the Barents Sea ice sheet probably decayed from a maximum thickness of about 2,750 meters, which persisted until some 14,000 years ago (a). By 13,000 years ago, much of the region between Scandinavia and Novaya Zemlya was free of grounded ice (b). By 12,000 years ago, the ice covering Svalbard separated from the sheet that still blanketed Scandinavia and the Russian Arctic (c). By 11,000 years ago, the ice in the region had further thinned and separated into three disjoint masses (d). (Light colors show where the ice sheet was at least 50 meters thick. Contour lines of ice thickness are given at 250-meter intervals.)

warm ocean water provided an ample source of moisture for snowfall over the Barents Sea. The combined influence of enhanced snowfall, uplift and thickening ice shelves probably led to rapid glaciation of the Barents Sea. So the real question for geologists is not how this ice came to be, but how it disappeared.

There are several clues to the nature of the breakup of the ice sheet that once covered this portion of the Eurasian Arctic. The oxygen-isotope content of tiny shells within sea-floor sediments across the nearby Fram Strait and continental slope records a substantial amount of "light" oxygen in the water 16,000 years ago. In this case, the oxygen isotopes do not reflect the general state of the global ocean. Rather, they indicate a massive influx of glacial meltwater in the region, which in turn reflects the disintegration of the ice mass over the Barents Sea quite early during the last deglaciation.

We and others have also charted moraines left by the retreating ice front across the floor of the Barents Sea using shipborne sonar and seismic imaging. These data indicate that the deeper-sea regions of the ice sheet broke up first. By 14,000 years ago the Bear Island Trough and several smaller local depressions were deglaciated, leaving a series of open ocean embayments surrounded by crumbling walls of ice. By 12,000 years ago, the ice sheets had decayed further such that they were limited to the northern archipelagos and the shallow seas that surround them.

The pattern of ice decay within the Barents Sea is also recorded by the uplift that has gone on around Svalbard and Franz Josef Land. Raised beaches on these islands have been dated by the radiocarbon technique on whale bones, mollusk shells and driftwood. The dates show that deglaciation of the archipelagos took place several thousand years after the decay of ice in the deeper regions of the Barents Sea.

Computing Collapse

In an effort to reconstruct more fully the history of this former ice sheet, we have conducted various numerical simulations. The principle behind such numerical modeling is that an ice sheet can be divided into a number of "ice columns." Each of these columns represents a "cell" within a two-dimensional grid. Ice-sheet models are usually arranged in a computational loop that begins by applying a series of algorithms that determine in each cell the flow of ice, mass balance and interaction with the Earth. The loop is completed by application of a final equation (the continuity equation) to the full grid to calculate the flow of ice between cells. To simulate the glacial history, one must specify sea level, air temperature and snowfall though time. By forcing the model to form an ice sheet compatible with the geological observations, we can assess the causes of ice-sheet growth and decay.

Both the PONAM and QUEEN programs employed ice-sheet modeling to provide quantitative details about the size and dynamics of the former ice sheet. We adjusted the model's environmental inputs until the size of the ice matched the ice margin determined from the geological data. The model was able to provide information on the size, thickness and flow velocity of the former ice sheet.

Having modeled the full-sized ice sheet, we next needed to make the simulated ice sheet decay in a manner consistent with the geological evidence for the real deglaciation. We found that this was actually quite difficult to achieve. To mimic the deglaciation on our computers, we had to enhance the rate of iceberg calving in the model rather strongly.

So why did the real ice sheet break up so quickly? The modeling work suggests that the answer lies with the mechanism responsible for iceberg production. As the world entered the first phase of deglaciation, the sea level rose, albeit gradually. Sea-level rise had two effects on the marine-based ice sheet covering the Barents Sea. First, the water depth increased, causing enhanced rates of calving, assuming the ice was grounded on the seafloor. Second, the effective weight of the ice sheet was reduced, leading to a reduction in basal drag, higher ice velocities and, thus, a more rapid transfer of mass from the interior of the ice sheet to the margin where calving takes place. These effects produced a positive feedback by which the decay of the ice sheet here and elsewhere led to an increase in sea level, which in turn led to further iceberg calving. Thus, a relatively small change in sea level at the onset of the last deglaciation was likely the trigger that caused the Eurasian ice sheet to break up.

Implications for Western Antarctica

During the last ice age, the west Antarctic ice sheet was considerably larger than it is today. Grounded ice was probably in place across the whole continental shelf, just as it was in the Barents Sea. Yet the decay of this enlarged west Antarctic ice sheet was different from the decay of ice in the Barents Sea in two ways. For one, deglaciation in Antarctica began much later than in the Barents Sea. Also, ice decay resulted in the formation of large floating ice shelves between the open ocean and the grounded ice sheet. The Filchner-Ronne and Ross ice shelves, for example, are each now about 500,000 square kilometers in area.

These differences suggest two important conclusions about the stability of the west Antarctic ice sheet. First, the ice shelves may be influential in maintaining the stability of the ice sheet because they act as buttresses to support the grounded margin of the ice sheet, whereas in the Barents Sea they were absent and the grounded margin was actively calving icebergs. Second, given the buttressing effect of the ice shelves on the ice sheet, the present changes in sea level are not large enough to encourage ice decay in western Antarctica to the extent witnessed in the Barents Sea. One reassuring note relating to the latter conclusion is that during the last interglacial, sea level was several meters higher than it is at present, yet the west Antarctic ice sheet did not decay. The majority of the water responsible for the higher sea level at that time probably came from Greenland.

The west Antarctic ice sheet is clearly capable of resisting substantial rises in sea level—but why? The answer could well be that the floating ice shelves in western Antarctica help maintain the grounded ice upstream. If that is true, one should therefore be concerned with the stability of the ice shelves in western Antarctica. Their decay will not in itself raise sea level (just as the melting of a floating ice cube does not raise the water level in a glass). But if they do melt, the west Antarctic ice sheet will look much more like the former Eurasian ice sheet just before it broke apart.

What might cause the ice shelves to decay? The answer lies in the ocean. Melting from the bottom causes much of the mass lost from ice shelves. So if the ocean around Antarctica warms, the rate of melting will increase. If this is not balanced by the increase in evaporation and snowfall that would accompany warming of the Southern Ocean, the ice shelves will thin, and ultimately they will disappear. The west Antarctic ice sheet would then be poised to collapse rapidly. People must not ignore this possibility—and the rise in global sea level that would ensue.

Mercer called the present situation a "threat of disaster." Understanding the glacial history of the Eurasian ice sheet suggests that the threat will not be acute unless the existing ice shelves disappear. Still, this research makes it abundantly clear that such a disaster has taken place in the opposite hemisphere in the not-so-distant past, and people must be on guard for it recurring in the future.

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"The Eurasian Arctic
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