Climate Change Science
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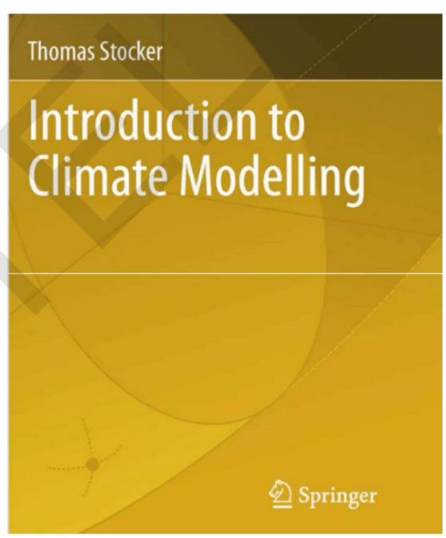
Lecture – 25
Last ice age

In the last lecture, we talked about how Earth's climate was in a glacial mode 20,000 years ago. And from this last glacial maximum, we moved to the present climate over a period of more than 20,000 years. Now, it is very important to understand how climate changed from the last glacial maximum to today because there were several abrupt changes in Earth's climate during that period. We need to understand what caused these changes in Earth's climate in this period. All the changes in this period were natural climate changes—nothing to do with human-induced impact. So, it is very important to understand that in order to predict how climate will change in the future on account of human impact.

Now, to study the climate of the Earth over the past 20,000 years, you need data. And the data that we have is primarily what is called proxy data. We did not have thermometers, and so we have to infer what the Earth's climate was in the past through indirect methods. Tree rings, ice cores, and looking at the core at the bottom of the ocean—all these things are examined to find out how the climate was in the past.

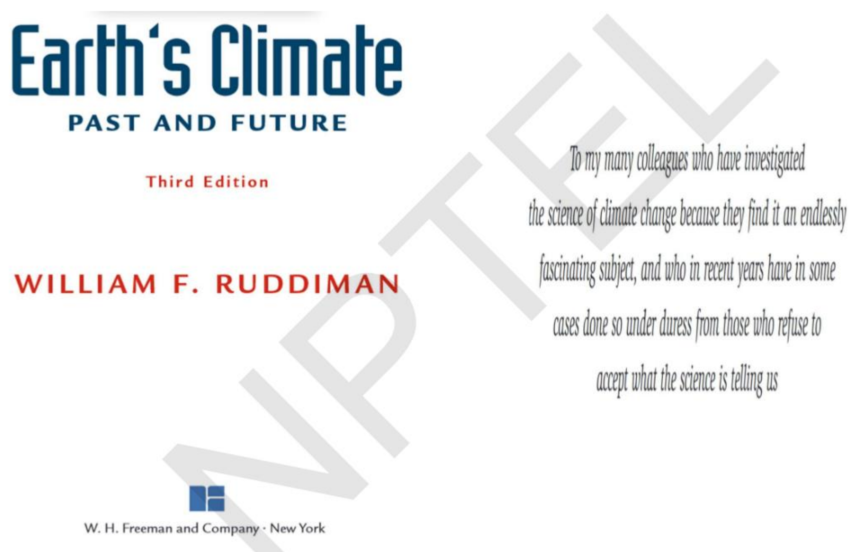
This method is fairly complex and, of course, there are some errors. So, in order to check how good these changes are, you need to complement the proxy data with climate models. We need to see whether climate models are able to reproduce the changes from the last ice age to today, during which time there was hardly any human impact on climate. So, to cover this topic, I will be depending on many books. One of them is a recently published book called *Global Warming Science* by Eli Tziperman from Harvard.



It is a very good book. It is the first good quantitative introduction to climate change and global warming. There are many books you can see which have been published on climate change. Most of them are qualitative. They are meant for popular exposition and not meant for serious scientific discussion.

So, this book was used for teaching students at Harvard. I think this is the ideal book for anybody who has a serious interest in climate change issues. The other book which is very good is by Thomas Stocker from Switzerland. This is *Introduction to Climate Modelling*. Climate modeling is a very important part of understanding the past and the future climate.

Climate models have become very important now because of the availability of high-speed computers. This is a good introduction to climate modeling with a lot of examples about numerical techniques and approximations. So, both these books I will be using extensively in my lectures. In addition, I will also be using a very important introductory book called *Earth's Climate: Past and Future* by William Ruddiman. This book is somewhat more qualitative but covers the entire spectrum of past climate and future climate and has excellent graphics.


Earth's Climate
PAST AND FUTURE
Third Edition
WILLIAM F. RUDDIMAN
W. H. Freeman and Company · New York

To my many colleagues who have investigated the science of climate change because they find it an endlessly fascinating subject, and who in recent years have in some cases done so under duress from those who refuse to accept what the science is telling us

I would strongly recommend that you have a look at the book. In the dedication of this book, there is a very interesting comment which is relevant to our discussion. He says, “This book is dedicated to my many colleagues who have investigated the science of climate change because they find it an endlessly fascinating subject and who in recent years have in some cases done so under duress from those who refuse to accept what science is telling us.” This is a problem that is occurring mainly in the United States, where there is a large group of climate change deniers who do not believe all the important discoveries that have been made in the last 60 years. Some of the scientists who were involved in the discoveries were actually attacked and were put under a lot of pressure by these deniers.

It took a lot of courage for many of them to continue their work. This is an issue I will come to near the end of the course. There are still many people who cannot believe that human beings can alter Earth's climate. They think we are too small and we cannot do much to Earth's climate. But some of them may have changed their minds when the COVID epidemic hit the Earth four years ago—a small virus, not even 400 nanometers wide, which we could not even see, had a huge impact on our lives. It completely stopped economic activity in most parts of the world. That made many people realize that even small things can have a profound impact on our lives. So, after this COVID epidemic, many people realized that carbon dioxide, whose concentration in the Earth's atmosphere is just 400 parts per million—a very small amount—can have an impact on the Earth's climate. Before that, people thought that all minor gases on Earth do not affect us. But today, there are still many people who do not believe that human beings are changing Earth's climate.

Some of the books I mentioned here were the first to explain the observations and show how models can reproduce these changes. These three books are essential reading for this course.

Table 1-1 Response Times of Various Climate System Components

Component	Response Time (range)	Example
	FAST RESPONSES	
Atmosphere	Hours to weeks	Daily heating and cooling Gradual buildup of heat wave
Land surface	Hours to months	Daily heating of upper ground surface Midwinter freezing and thawing
Ocean surface	Days to months	Afternoon heating of upper few feet Warmest beach temperatures late in summer
Vegetation	Hours to decades/centuries	Sudden leaf kill by frost Slow growth of trees to maturity
Sea ice	Weeks to years	Late-winter maximum extent Historical changes near Iceland
	SLOW RESPONSES	
Mountain glaciers	10–100 years	Widespread glacier retreat in 20th century
Deep ocean	100–1,500 years	Time to replace ocean deep water
Ice sheets	100–10,000 years	Advances/ retreats of ice sheet margins Growth/decay of entire ice sheet

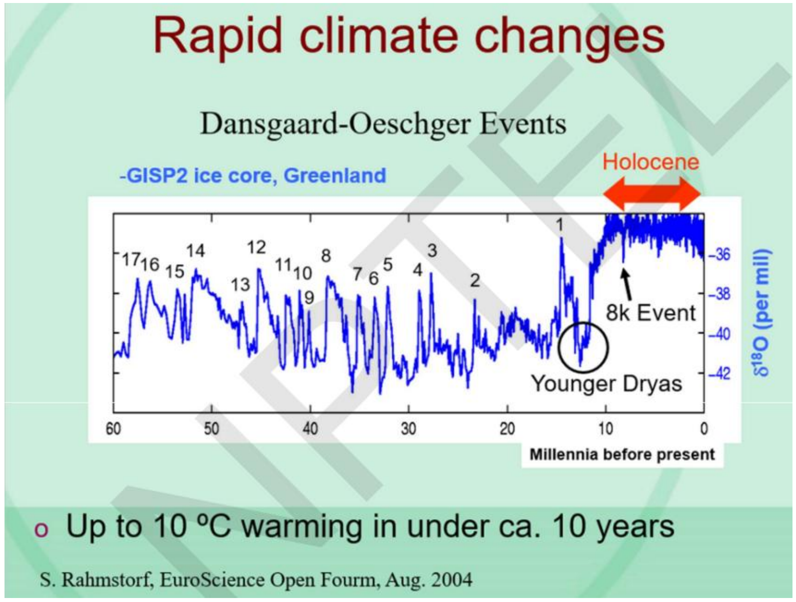
Now, you must understand that when you look at Earth's climate from 20,000 years ago to today, there are lots of timescales. They are not timescales confined to a human lifetime, which is approximately 80 or 90 years. The climate scales we are talking about include weather, which mostly spans hours to weeks.

Land surface response ranges from hours to months. Ocean surface changes occur over days to months or even years because it has a deep layer of water. Vegetation can respond from hours to decades to centuries as the vegetation changes—such as forests dying or regrowing. Sea ice can alter climate from weeks to years. These are called fast responses.

There are also slow responses from mountain glaciers, which respond over a period of 100 years. Then you have the deep ocean, where a lot of heat is stored. That heat can come out after 100 to 1,000 years. And ice sheets, which are large sheets of ice 1 to 2 kilometers thick, can respond over a scale of 100 to 10,000 years. When we study Earth's climate over the last 20,000 years, it is important to note that all these timescales play a role.

It is not always easy to understand because the timescales are much larger than what human beings are used to.

Now, here is a picture of how Earth's climate changed over the last 60,000 years based on ice core data.



This is the Greenland ice core, and it is based on the oxygen-18 isotope abundance in the ice as well as in the air. When this $\delta^{18}O$, which we discussed a few lectures ago, is low—minus 36—that is considered high actually, because it is less negative. This indicates a warm period called the Holocene, the last 10,000–12,000 years.

But as you go further into the past, you can see that $\delta^{18}O$ has gone down to as low as minus 42, which means a much colder climate. So, what this picture shows is that Earth's climate has fluctuated many, many times. Each of these events is numbered for convenience. You can see that there are many events of warming and cooling over the last 60,000 years. The most recent one, which we will discuss a lot in this lecture, occurred around 12,000 years ago when the Earth rapidly warmed.

After that, there was a period of fairly constant temperature except for a brief dip around 8,000 years ago. This period is well documented by proxy data, and it is the period we want to understand. We want to understand this period because if we can explain all the ups and downs of the climate of Greenland using observation as well as models, then we have some confidence that our predictions of how climate will change in the future will be more reliable. Unless our climate models correctly predict these events, we cannot be confident in using them for future forecasting. That is the purpose of looking at this period.

The best evidence for Dansgaard–Oeschger events is in the Greenland ice cores

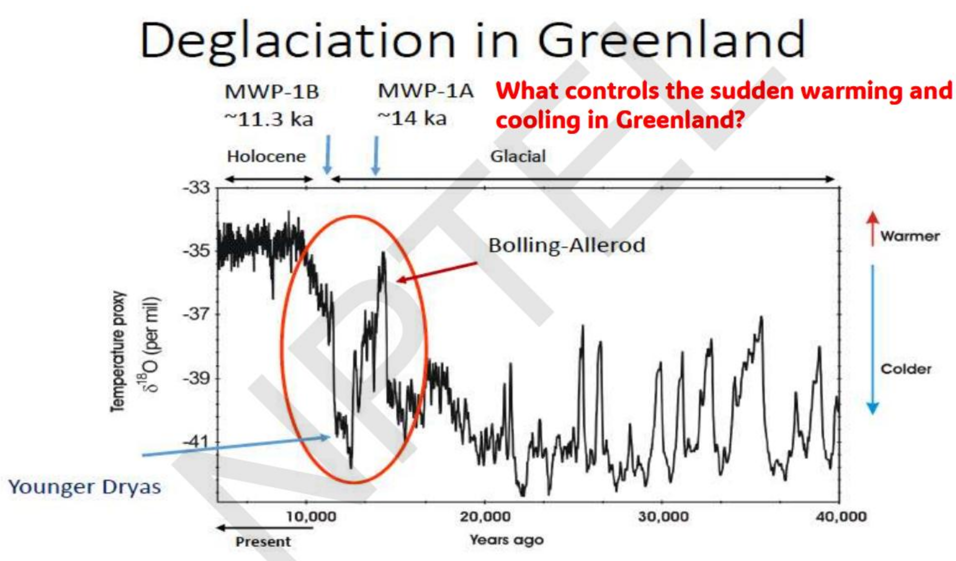
They are rapid climate fluctuations that occurred 25 times during the last glacial period. During the Last Glacial Period, a series of dramatic climatic fluctuations occurred in the North Atlantic. These are known as D–O events, during which atmospheric and oceanic conditions alternated between relatively mild (inter-stadial) and full glacial (stadial) conditions. Their amplitudes vary from 5 to 16 ◦C The duration of interstadials varies from approximately a century to many millennia

from
Dansgaard–Oeschger events in climate models : review and baseline Marine Isotope Stage 3 (MIS3) protocol
By Malmierca-Vallet et al., Climate of the past, 19,2023

The oscillations that occurred are called Dansgaard–Oeschger events, and there are about 25 of them in this period. Some of the bigger ones are numbered. During this time, Earth's climate changed globally and dramatically, with many changes in atmospheric and oceanic conditions—circulation, temperature, and so on. The amplitude of global temperature changes varied in the range of 5 to 16 degrees.

There were brief warm periods during the glacial time called interstadials—short warm periods during a long cold period. They lasted from a century to 1,000 years. These are the periods we want to understand because these oscillations occurred frequently. Finally, Earth reached a stable climate around 10,000 years ago and remained very stable. So, we need to understand why Earth's climate changed so many times between 60,000 and 20,000 years ago.

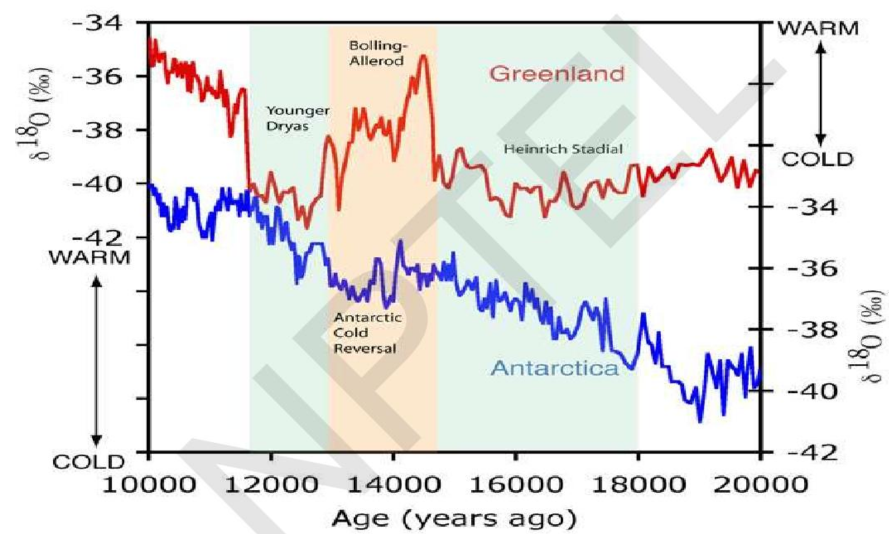
After that, there was a warming trend, and around 10,000 years before present, the climate stabilized. But in the last 150 years, it has risen again—that is due to human-induced change. We must understand all these changes and assess whether our ability to predict them is accurate. If it is, then we can trust our climate models for future forecasts.



(Please refer to the figure shown above) A close-up of the last 20,000 years shows the present warm period, the last cold period called the Younger Dryas (which we will study in detail), and various other climate fluctuations. There are two events we will study closely. Coming out of the last ice age, there was a sudden warming around 14,000–15,000 years ago called the Bølling–Allerød event. Then the Earth plunged back into a cold period for about 1,000 years before warming again. Each time the Earth warmed suddenly, a lot of polar ice melted.

These ice melts led to what are called meltwater pulses—sudden rises in sea level. Sea level can be measured using proxy data very accurately. If you go to the beach and have good geological knowledge, you can identify times when the sea level was higher than the present. Researchers have done this carefully all over the world and identified two key periods: one around 14,000 years ago, and one around 11,300 years ago.

In both cases, due to sudden warming, the sea level rose rapidly. This must be understood because climate models predict that due to human-induced climate change, sea level will again rise rapidly—possibly up to 1 meter above present levels by the end of this century. That is a large rise and would flood most coastal cities worldwide. So, we must know under what conditions that will happen. These two events—meltwater pulses 1A and 1B—will be looked at closely.



Here is a comparison of proxy data from Greenland and Antarctica ice cores. You'll notice a large difference between the red (Greenland) and blue (Antarctica) lines. The red shows drastic changes during Bølling–Allerød and Younger Dryas, while the blue does not show such sharp shifts.

This means that Antarctica's climate changes were somewhat different from the Arctic or the Northern Hemisphere. Antarctica is a major continent at a high altitude in the Southern Hemisphere, whereas the Arctic Ocean is surrounded by land. These two polar regions are very different. For example, Arctic sea ice is melting rapidly today due to global warming, but Antarctic sea ice is not melting as quickly because it is much colder. Ice melts only when the temperature rises above zero, which hasn't yet occurred significantly in Antarctica—while in the Arctic, summer melting is extensive.

So, the changes in climate in the Arctic and Antarctic are not the same. However, they are linked. They are linked because the ocean transports heat from the Southern Hemisphere to the Northern Hemisphere. The atmosphere over Antarctica and the Arctic is also linked, because global winds circulate air across the planet. That's why carbon dioxide levels are nearly the same everywhere—in Antarctica, the Arctic, India, and America.

Currently, most carbon dioxide emissions come from major urban areas between 50°S and 50°N, but that CO_2 eventually reaches both poles. Earth's atmosphere is one continuous system that mixes gases globally. So, while the Arctic and Antarctic behave differently, they are still connected through atmospheric and oceanic circulation.

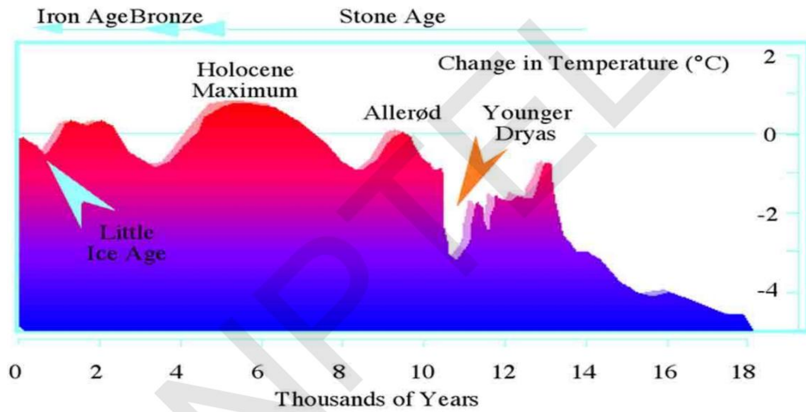
Now we'll study in detail the Younger Dryas event, when Earth suddenly cooled.

This near-glacial period is called the Younger Dryas, named after a flower (*Dryas octopetala*) that grows in cold conditions and that became common in Europe during this time.

Events similar to the Younger Dryas have occurred during the transition from cold glacial conditions to warm interglacials.
The Younger Dryas was preceded by a sudden warming interval beginning approximately 14,700 years ago. This interval, the Bølling-Allerød, saw the rapid retreat of the large ice sheets in the northern hemisphere
In the Bølling–Allerød period, rapid warming in the Northern Hemisphere offset by the equivalent cooling in the Southern Hemisphere The Southern Hemisphere cools and the Northern Hemisphere warms when the AMOC is strong, and the opposite happens when it is weak

The name "Younger Dryas" comes from a flower—Dryas—that thrives in cold climates and emerged during this period. It is called the "Younger" Dryas to distinguish it from an earlier "Older" Dryas. The Younger Dryas is important because it caused a glacial event in Europe. It was preceded by the warm Bølling–Allerød period, during which large ice sheets in the Northern Hemisphere rapidly retreated. These warm–cold swings provide valuable data on how Earth's climate can change quickly. We study this because the modern climate is also changing rapidly.

From about 10,000 years ago to 1850, climate hardly changed. That period is less interesting for modeling. But the Younger Dryas and Bølling–Allerød are very interesting due to the large shifts in the Arctic and Antarctic. These events are good tests for our models—if they can simulate them well, we can trust them more for predicting the future.



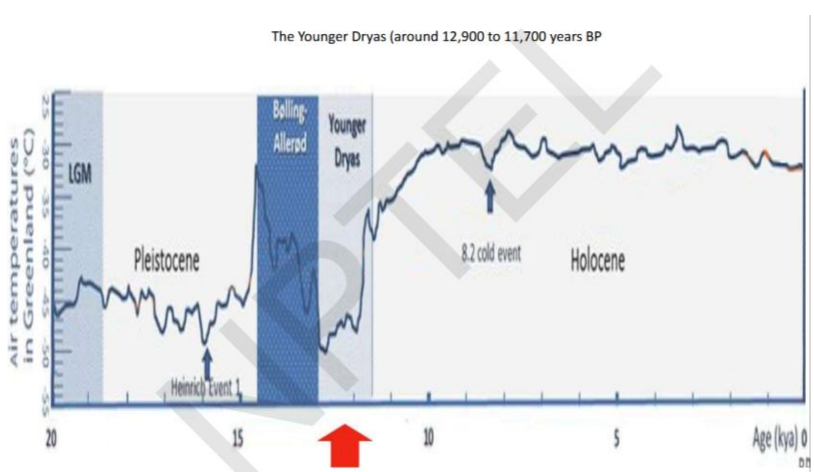
Robbie Mitchell https://www.historicmysteries.com/science/younger-dryas/39327/

A typical diagram shows that after the last ice age (~18,000 years ago), Earth gradually warmed. Then came a sudden warming (Bølling–Allerød), followed by rapid cooling (Younger Dryas), and then rapid warming again, stabilizing into the Holocene.

The Younger Dryas (YD) event occurred between 12,900 and 11,600 years Before Present (BP). The onset of the Younger Dryas took less than 100 years, and the period persisted for roughly 1,300 years. The Younger Dryas was named after Dryas octopetala, a wild flower that occurs in Arctic environments.

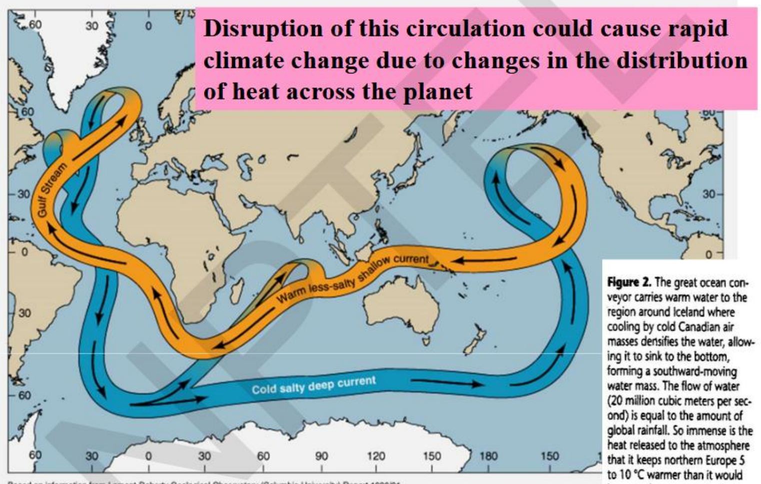
There was a sudden cooling in the Northern Hemisphere and annual air temperatures decreased by around 3 °C in North America, around 4°C in Europe and up to 10 °C in Greenland in a few decades. At the same time, the Southern Hemisphere experienced warming This period ended as rapidly as it began, with rapid warming in 50 years which brought earth into the Holocene era. The sea ice area increased because of ice-albedo feedback. This episode is characterized by abrupt changes in the AMOC on timescales of decades to centuries.

The onset of the Younger Dryas cold period took just 100 years. It lasted for 1,300 years. North America cooled by ~3°C, Greenland by ~10°C, and Europe by ~4°C. Surprisingly, at the same time, the Southern Hemisphere experienced warming.



The Bølling–Allerød Interstadial was an interstadial period which occurred from 14,690 to c. 12,890 years Before Present, during the final stages of the Last Glacial Period. There was a abrupt warming in the Northern Hemisphere, and a corresponding cooling in the Southern Hemisphere. There was major ice sheet collapse and corresponding sea level rise known as Meltwater pulse 1A.

Present Global Ocean Circulation Pattern



Based on information from Lamont-Doherty Geological Observatory (Columbia University) Report 1990/91, Fig. 4, p. 50; J. Imbrie et al. (1992). On the structure and origin of major glaciation cycles, 1: Linear responses to Milankovitch forcing *Paleoceanography* 7, Fig. 1b, p. 704, published by the American Geophysical Union.

Figure 2. The great ocean conveyor carries warm water to the region around Iceland where cooling by cold Canadian air masses densifies the water, allowing it to sink to the bottom, forming a southward-moving water mass. The flow of water (20 million cubic meters per second) is equal to the amount of global rainfall. So immense is the heat released to the atmosphere that it keeps northern Europe 5 to 10 °C warmer than it would be were the conveyor to shut down.

This puzzled scientists. It was due to an abrupt shift in ocean circulation. The Atlantic Meridional Overturning Circulation (AMOC)—which brings deep water to the surface and carries warm water north—was disrupted. This circulation has a volume flow of about 20 million cubic meters per second. For context, all rivers on Earth combined discharge ~1 million cubic meters per second. So, this ocean system moves 20 times more water than all rivers. It affects global climate strongly.

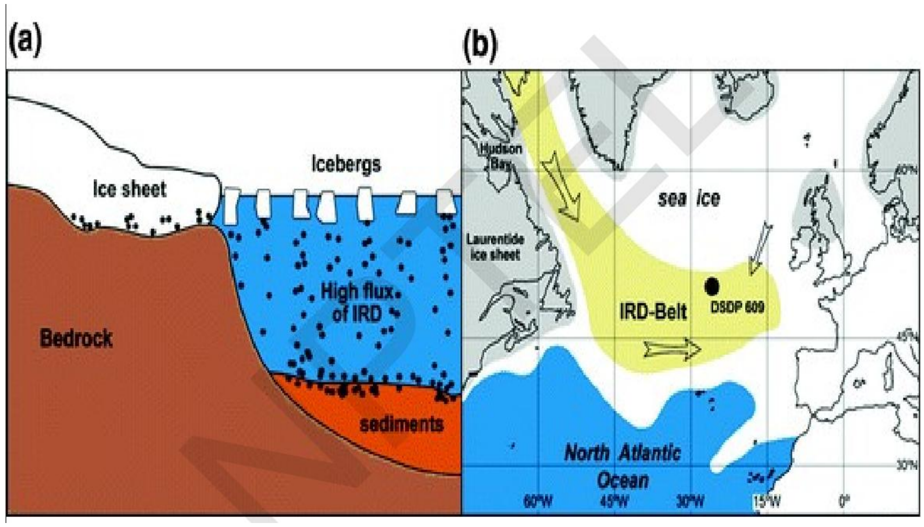
The surface current is warm and less salty (due to rain), but when it cools and becomes saltier, it becomes denser and sinks. This dense current flows deep in the ocean and reemerges in the Pacific, warming again before returning north as a surface current. This circulation is driven by temperature and salinity gradients and has helped maintain Earth's mean temperature of 15°C over the last 10,000 years.

A Heinrich event is a natural phenomenon in which large groups of icebergs break off from the Laurentide ice sheet and traverse the Hudson Strait into the North Atlantic. They occurred during five of the last seven glacial periods over the past 640,000 years. Heinrich events are particularly well documented for the last glacial period but notably absent from the penultimate glaciation. The icebergs contained rock mass that had been eroded by the glaciers, and as they melted, this material was dropped to the sea floor as ice rafted debris (abbreviated to "IRD") forming deposits called Heinrich layers.

Heinrich events are natural periods when icebergs break off from the Laurentide Ice Sheet in Canada and float into the North Atlantic. These have occurred frequently over the last 640,000 years, though not much in the past 10,000 years. Icebergs carry rocks and sediment from land into the ocean—called ice-rafted debris. When the ice melts, debris falls to the seafloor. Drilling ocean sediment cores reveals these deposits and helps date past iceberg collapses.

A Heinrich event is a natural phenomenon in which large groups of icebergs break off from the Laurentide ice sheet and traverse the Hudson Strait into the North Atlantic Heinrich identified six layers of abnormally coarse mineral deposits on the floor of the Atlantic Ocean in 1988. Each deposit contained high proportions of stony grains that clearly originated on a continent and could have been transported into the Atlantic only by ice-rafting. Such ice-rafted debris (IRD) is dominated by material that apparently originated in North America. The coarse material is concentrated into several distinct rock layers that are interbedded with fine-grained sediments typically found in the deep ocean between 40° and 55° N in a region of the North Atlantic known as the IRD

The Laurentide Ice Sheet was massive—covering most of eastern Canada and parts of the U.S. Another smaller one, the Cordilleran Ice Sheet, was located to the west. When these sheets collapsed, they dropped huge ice masses and debris into the Atlantic.



A diagram shows how ice carries debris and deposits it on the ocean floor. The right side shows where these deposits are found. Some drilling sites show clear evidence of ice-rafted debris, helping us trace ancient climate shifts.

We will continue this discussion in the next lecture. Thank you.