Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bangalore

Lecture – 24
Last ice age

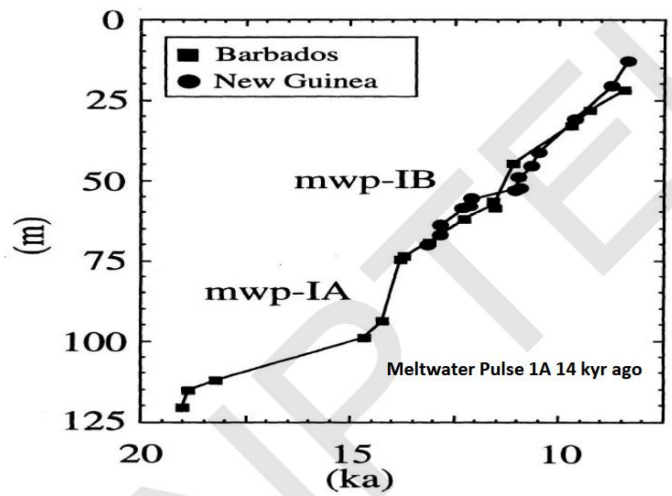


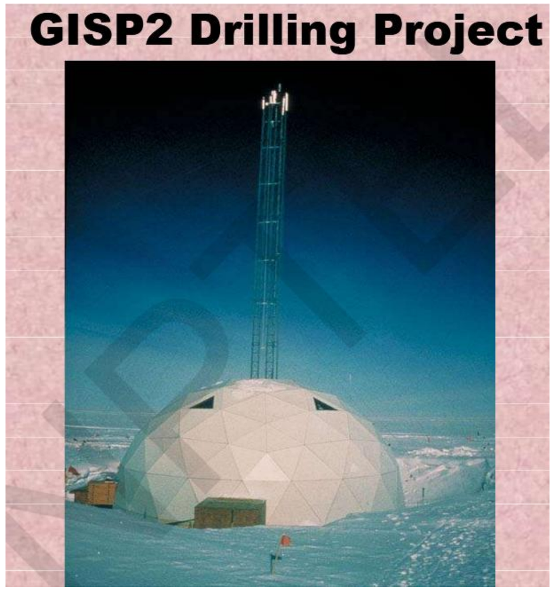
Figure 1. Coral records of sea level dated by U/Th from Barbados [*Bard et al.*, 1990a, 1993] and New Guinea [*Edwards et al.*, 1993]. Two periods of rapid rise of sea level are identified as mwp-IA and mwp-IB.

In the last lecture, we saw that the sea level rose by around 125 meters during the last 20,000 years. This is based on proxy data of sea level rise. This is the global mean. We also saw that the sea level rise was not uniform. It rose quite slowly in the beginning, then very rapidly, and then again slowly. So, this is very important information.

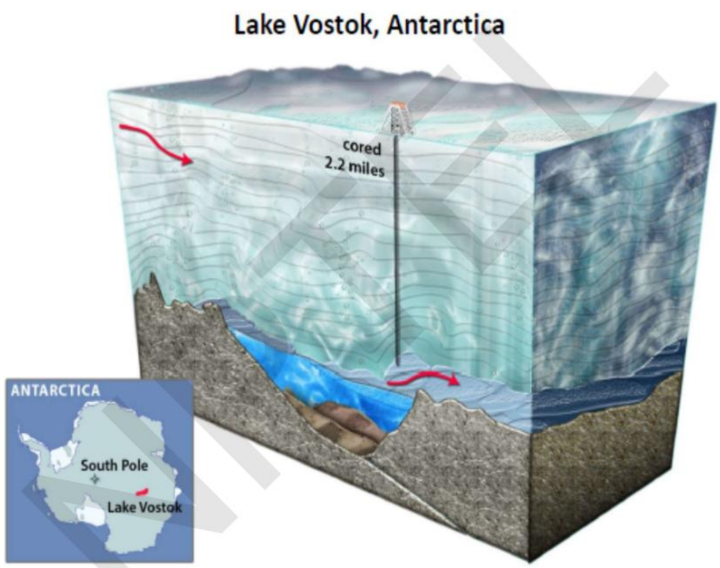
The question is: can we predict the sea level rise that occurred in the past 20,000 years using climate models? If the models can predict this sea level rise—both the rapid and gradual changes—then we can be confident that we are in a position to predict what will happen in the future on account of global warming.

Now, you must know something about how this proxy data was obtained. One of the ways to get proxy data is to go to polar regions with large ice sheets—one or two kilometers thick—and drill through them, like you drill for a borewell. Get a thick layer of ice, study it carefully, and see whether we can infer what changes were occurring in the past.

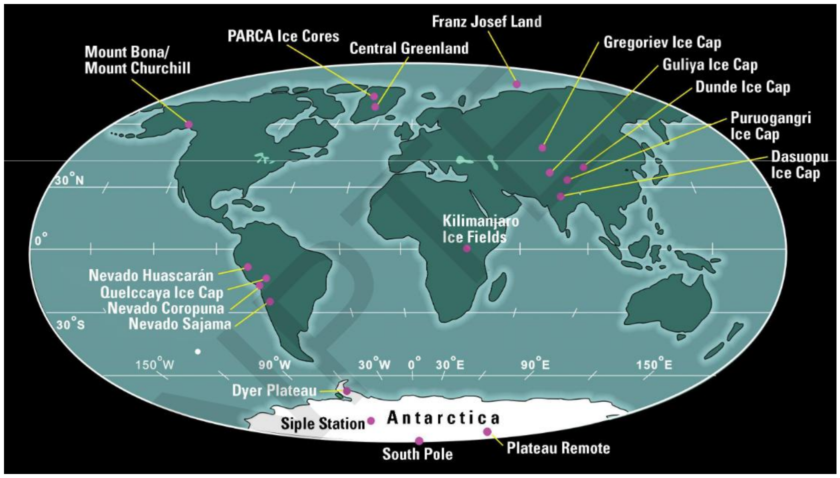
One of the most famous drilling projects is the Greenland Ice Core Drilling Project, where scientists went to Greenland and drilled for ice.



Another famous one is the drilling of an ice core in Lake Vostok in Antarctica. Lake Vostok has an ice layer almost 4 kilometers thick. This gave us the longest sequence of climate change in the past. This was an amazing contribution by an international team of scientists.

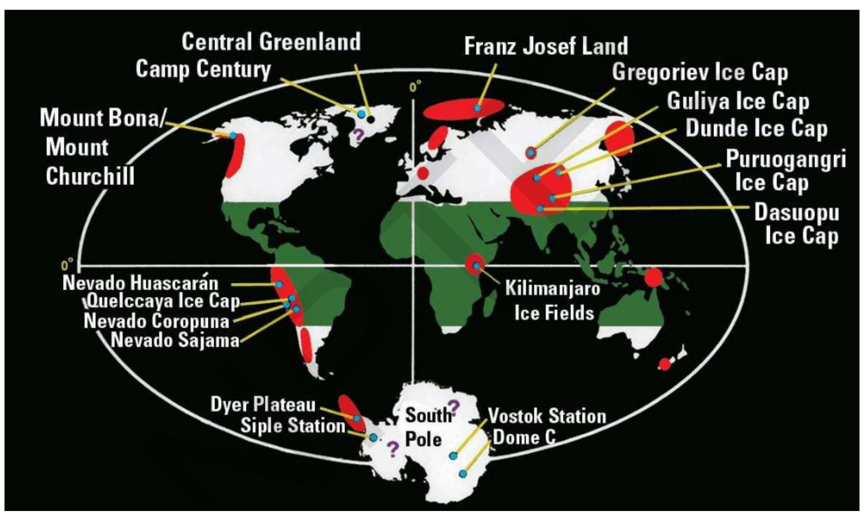


This is such a challenging task—to go to that remote place in Antarctica, drill all the way down to 4 kilometers, take the ice core out, and carefully bring it to the laboratory. There, they study how the ice deposition varied over time. The ice contains air trapped inside it, and from that, scientists understand how the composition of the atmosphere varied at that time, in terms of the amount of carbon dioxide and methane. So, this was one of the most important achievements in proxy data: being able to get a long ice core to infer the climate of the past.



Here is an example of various other ice cores. People have gone all over the world—they have gone to Kilimanjaro, to various parts of the Himalayas—and collected many ice cores. Of course, Antarctica has many ice cores. Greenland, Canada, and South America also have them. This has been a very adventurous effort by scientists from all over the world to get as much information as possible from ice cores. Remember that these ice sheets and glaciers are melting rapidly. So, people have to do this very quickly, because many of these ice cores may disappear in the next 100 to 200 years.

Here is another example—a map showing various ice cores, and the most important ones, of course, are Vostok in Antarctica and the Dome C site, which we will talk about, along with various other locations in the world.



So, data from all these ice cores, as well as ocean cores, were combined. One ice core gives data only over one location—that is, a local climate, not the global climate. If you want to get global climate change, you need to take data from all these locations and average over them. Ice cores give you data only over land; you also need data from the oceans. For that, you need ocean cores—ocean sediments. You have to go with ships, drill deep into ocean sediments, and bring out the core. This is a very challenging engineering and scientific task, but scientists all over the world have taken up this challenge. They have collected hundreds of ocean and ice cores and stored them in special laboratories kept very cold, where these cores are studied in great depth. The composition of those cores was studied very carefully. From there, we were able to infer the temperature and rainfall that occurred in the past in those regions.

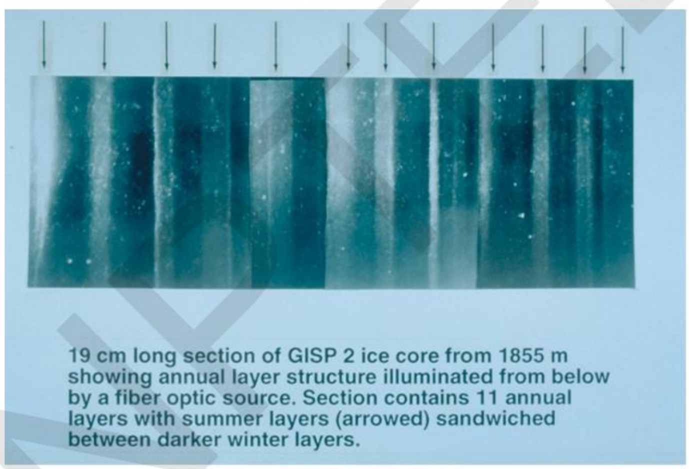
Here is a picture of an ice core that was taken out. That ice core is carefully wrapped in insulation. This is from the British Antarctic Survey.

Permission from the British Antartic Survey (BAS), Eric Wolff (BAS) and Keith Shine at the University of Reading.

The core is taken to the lab. In the lab, these ice cores are cut into small, thin layers. Each layer represents a couple of years of ice deposition. Based on the isotopic composition of the ice in that layer, one can infer the temperature at the time the ice was deposited. In the lab, scientists carefully examine the ice core.

Extracting An Ice Core

Annual Layers In Ice Core



Then they see various layers. If they are lucky, and if the rate of ice deposition was very rapid, they can see separate layers for each year. You can identify, for example, 11 annual layers. This makes it easy to date the layers and determine the year in which the ice was deposited. But suppose the deposition rate was not that high and there are no clear annual layers—then you have to depend on other techniques to determine the date of deposition.

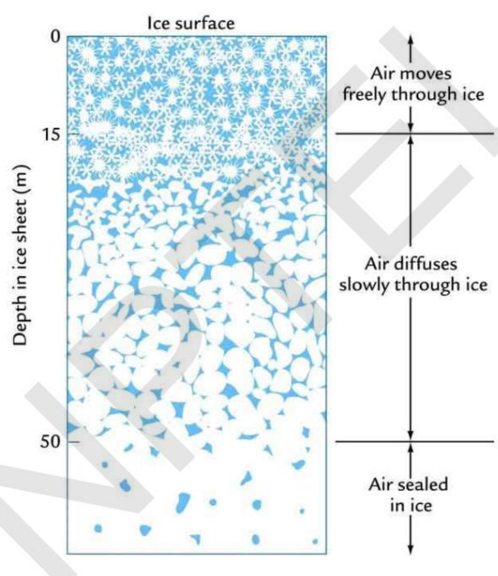
One of them is the well-known radioactive decay. All of you know that if a layer contains uranium or some other radioactive species, it will decay over time. So, based on the amount of uranium or other radioactive isotopes, and their abundance, we can infer how far back the ice was deposited. This technique, developed over the last 80 years, has been extremely useful for dating the deposition of ocean or ice layers by comparing how much of the radioactive species remains today relative to the time of deposition.

Here is a close-up of an ice core showing bubbles.

These bubbles are very useful because they contain air that was present at the time the ice was formed. The ice essentially sealed those bubbles completely. So, the composition of the air in the bubbles represents the composition of the atmosphere at the time the ice was deposited. This is a remarkable achievement, and all of you must appreciate the effort that went into getting accurate data on the atmosphere's composition 10,000–20,000 years ago—data like carbon dioxide and methane concentrations in parts per million and parts per billion. Appreciate the complexity of this: scientists take the ice core to the lab and use a hypodermic needle to extract that air sample without contaminating it with lab air.

It is not easy at all. It is a very tough technique, and it has been mastered. People have spent hours extracting the sample and measuring the composition of air at that time—mainly methane and carbon dioxide—very accurately.

Here is a picture showing how snow falling on polar regions slowly becomes ice and gets compressed from the top. At a depth of 50 meters, air bubbles become trapped



So, we infer the air bubble composition not near the surface—surface air is continuously in contact with the ambient atmosphere—but from air sealed in deep ice, below 50 meters. That is the air we want. Air is sealed naturally by ice and contains information about the past climate.

Oxygen Isotopes

- A small fraction of water molecules contain the heavy isotope ^{18}O instead of ^{16}O.
- $^{18}O/^{16}O \approx 1/500$
- This ratio is not constant, but varies over a range of several percent.
- Vapor pressure of $H_2{}^{18}O$ is lower than that of $H_2{}^{16}O$, thus the latter is more easily evaporated.

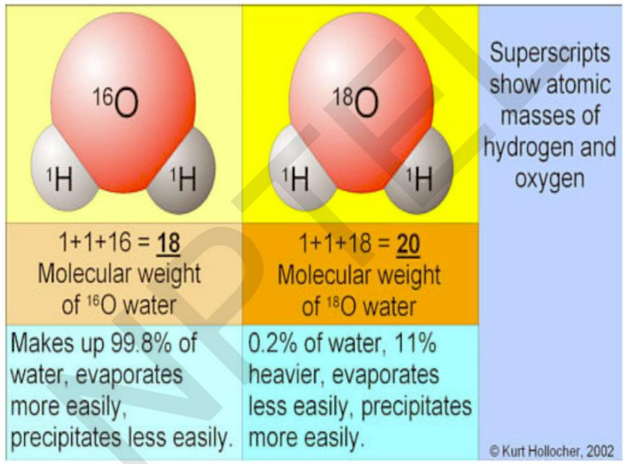
Now, one of the most important ways to infer temperature in the past is to look at the composition of two different isotopes of oxygen in the ice. Oxygen has many isotopes. The two we will focus on are O-16 and O-18. O-18 is a heavier isotope; O-16 is lighter. The abundance of O-18 is very small—about 0.2 percent, or 1 in 500 compared to O-16. So, this small amount of O-18 must be measured very accurately to determine Earth's temperature at that time.

Remember that water containing O-18 is heavier than water with O-16. So, when water evaporates from the ocean, $H_2{}^{16}O$ evaporates more easily than $H_2{}^{18}O$ because it is lighter.

As water evaporates from the ocean, the composition of water vapor in the atmosphere becomes different from that in the ocean. As this air moves through the atmosphere and water vapor condenses again, $H_2{}^{18}O$ condenses more readily than $H_2{}^{16}O$. So, as water vapor travels from the ocean to the polar regions, the ratio of O-16 to O-18 in polar water becomes very different from that in the ocean. There are two processes where change occurs: evaporation (differential evaporation) and condensation over polar regions (differential condensation).

The final point is that the amount of O-18 in polar region water is less than in ocean water. Why is this important? Because in the glacial age, a lot of ocean water appeared over the polar regions as ice. The relative amount of O-18 and O-16 in polar ice versus ocean water gives an idea of how much water vapor was transported from the ocean to the polar regions. So, the relative amount of O-18 and O-16 in an ice core is a direct measure of the water transported to polar regions.

The picture below is showing the difference between H_2O^{18} and H_2O^{16}.



We measure the small amount of O-18 using a value called $\delta^{18}O$, which is the ratio of O-18 to O-16 in the sample minus a standard value provided by a standards agency. This tells you the deviation of O-18 in your ice sample from the standard.

$\delta^{18}O$

- As water vapor is transported poleward in the hydrologic cycle, each cycle of evaporation and condensation lowers the ratio of $H_2{}^{18}O$ to $H_2{}^{16}O$, in a process called fractionation.
- This ratio is expressed as $\delta^{18}O$.

$$\delta^{18}O = \frac{{}^{18}O/{}^{16}O_{sample} - {}^{18}O/{}^{16}O_{std}}{{}^{18}O/{}^{16}O_{std}} \times 1000$$

Everyone uses the same standard, so we can compare results. This number is multiplied by 1000 because it's so small, and is expressed in “per mil” (per thousand, as opposed to percent, which is per hundred). So, you’ll see many graphs showing $\delta^{18}O$, indicating the amount of O-18 in the sample per thousand.

$\delta^{18}O$ and Global Ice Volume

- As ice sheets grow, the water removed from the ocean has lower $\delta^{18}O$ than the water that remains.
- Thus the $\delta^{18}O$ value of sea water in the global ocean is linearly correlated with ice volume (larger $\delta^{18}O \rightarrow$ larger ice sheets).
- A time series of global ocean $\delta^{18}O$ is equivalent to a time series of ice volume.

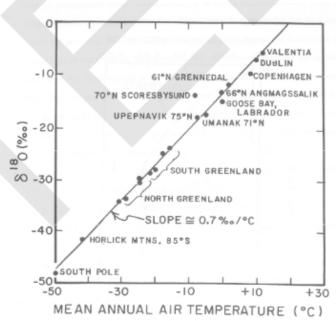
The key point is that as ice sheets grow, water removed from the ocean has lower O-18 than what remains. Thus, the $\delta^{18}O$ value of seawater is linearly correlated with the volume of ice present. So, there is a direct connection between delta-O-18 in the ice core and the amount of ice volume at that time. So, this is a very important result.

A time series of global ocean O-18 is equivalent to a time series of ice volume. As the amount of O-18 increases in ocean water, it indicates that more and more water vapor has been deposited in polar regions and turned into ice. Remember that there is not much water vapor stored over land, except in a few lakes. It is the polar regions that store water for long periods.

Also, you can correlate $\delta^{18}O$ with temperature.

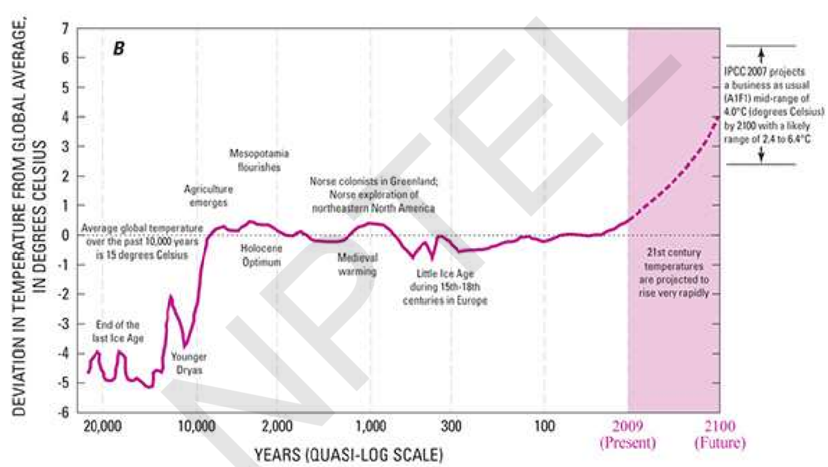
$\delta^{18}O$ vs. Temperature

- As a consequence of fractionation, $\delta^{18}O$ in precipitation decreases with decreasing temperature.
- Ice sheets have very low $\delta^{18}O$ values.



Observed $\delta^{18}O$ in average annual precipitation as a function of mean annual air temperature (Dansgaard 1964). Note that all the points in this graph are for high latitudes (>45°). (From Broecker 2002)

Here is a graph showing the mean annual temperature at various Earth latitudes and the $\delta^{18}O$ in rainfall from those regions. When rainfall occurs, samples are collected and $\delta^{18}O$ is measured. The y-axis shows $\delta^{18}O$, and the x-axis shows the mean annual temperature of that region. This graph shows a linear relationship. So, $\delta^{18}O$ is also a useful, though not as accurate, proxy for local temperature. Ice volume is more reliably inferred from delta-O-18, but temperature can also be estimated.



Now let us look at how global mean temperature changed from 20,000 years ago to today, based on samples from ice cores, ocean cores, sediments, and other proxies (Please refer to the figure shown above). Today is marked at 2009. (There is a projection beyond this, which we will not discuss now.)

We see that compared to the present climate, the global mean temperature 20,000 years ago was about 5°C lower. This is significant information. The last ice age was only about 5°C colder than today, yet it resulted in vast ice sheets over North America and Europe. So, while 5°C may not seem large—since seasonal differences are often greater—this change in global mean temperature is enormous. A 5°C shift globally is a huge change. It means even greater changes at specific latitudes.

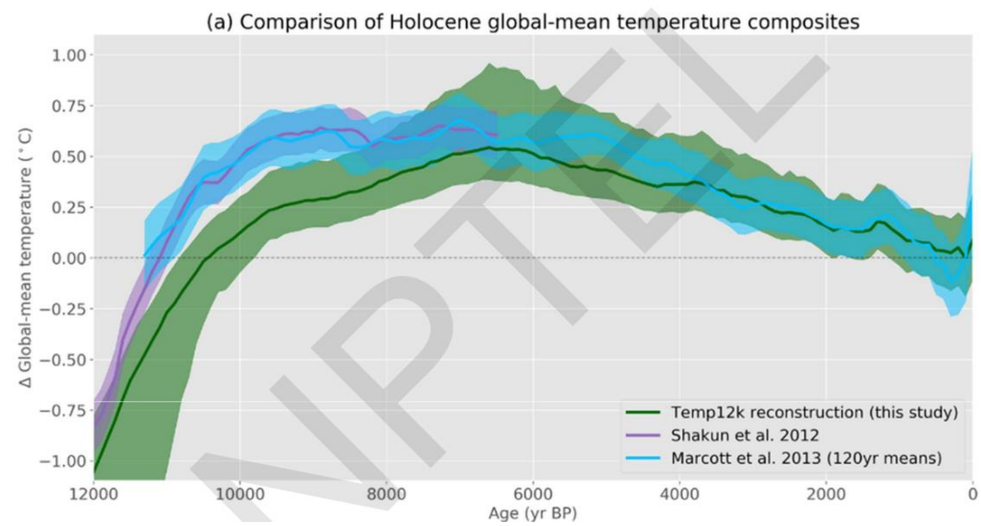
The Younger Dryas (around 12,900 to 11,700 years BP

Here is another example from Greenland, where many ice cores have been taken. This shows temperature in Greenland—not global temperature—over the last 20,000 years. It was around –45°C during the last ice age, with abrupt fluctuations—sudden warming by about 15°C locally (not globally), then cooling again to –50°C, and then rising once more.

These are abrupt changes. They are important because they show that Earth's climate is not always stable. Climate can change suddenly, at least locally—like in Greenland. Around 10,000 years ago, it warmed to about –30°C and remained fairly constant for the next 10,000 years. This is the period in which human beings thrived. Agriculture became possible because the temperature was stable.

With successful agriculture, humans were able to produce more food, and their population grew. Human population was less than a million 20,000 years ago. Today, it is 8,000 million. This illustrates how climate has played a key role in the growth of human civilization. Now, we humans are altering Earth's climate, which is warming rapidly, and this could cause a major crisis, even a sudden decline in human population.

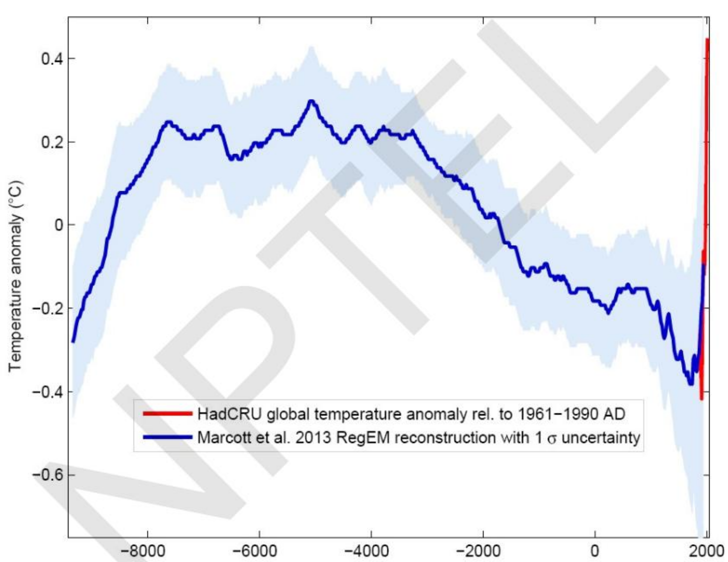
That is possible because we have been used to a very stable climate between 10,000 years ago and 1850. After 1850, Earth started warming rapidly, and we don't yet fully understand the consequences. That's why we need to examine this historical period closely. We can use this data to tune our climate models and try to predict how climate may vary over the next 100–200 years.



Here is a close-up of the last 10,000 years, reconstructed from various proxies. You should realize that different proxies do not give exactly the same answer.

There is a difference of about 0.25°C in global mean temperature. That's not surprising—every proxy has its own limitations and error margins. For example, one proxy suggests that 10,000 years ago, Earth was only 0.1°C warmer than in 1850, while another says it was 0.4°C warmer. That's a significant difference. We need more data to determine which proxy is more reliable.

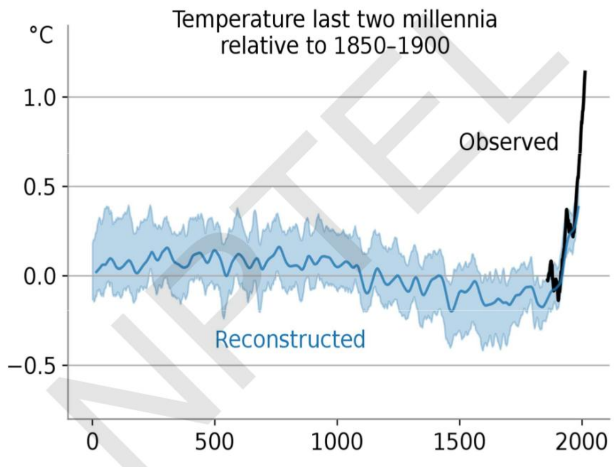
Even this proxy, reported in this study, has an error bar of about 0.1°C. So remember: global mean temperature cannot be measured with perfect precision. There's an error of about ±0.1°C, because proxies are not perfect. They involve converting indirect indicators—like tree rings or sediment layers—into temperature. Also, dating the proxy—determining when it was formed—has its own uncertainties. The dating error can be as much as 100 to 200 years.



Here is another example: data from Marcott et al. (2013). The red curve shows thermometer-based data for the last 150 years. Around 9,000 years ago, global mean temperature was 0.3°C below

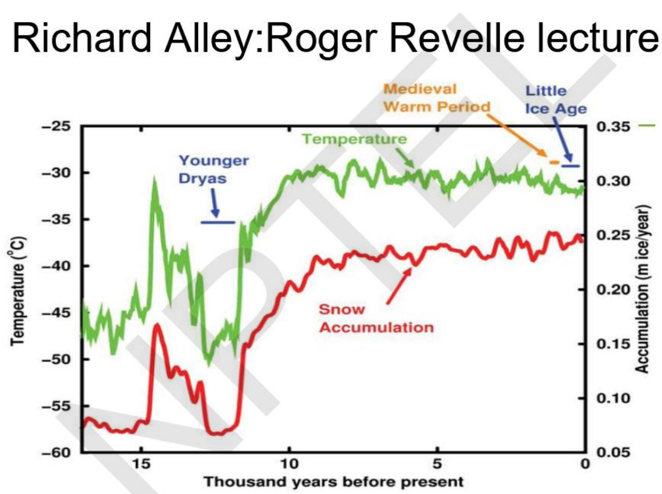
1850 levels. Then it rose by about 0.5°C, remained fairly constant for about 4,000 years, and then gradually cooled to reach 1850 values again.

After 1850, the temperature suddenly started rising. The rise seen in the proxy data agrees with thermometer data. This confirms the reliability of proxy data for global mean temperature. In the last couple of hundred years, both proxy and direct measurements show the same rapid rise. So we must appreciate the hard work of scientists worldwide who collected proxy data. Thanks to their effort, we now have global mean temperature estimates with ±0.1°C accuracy. We can improve further, but this is already quite good.



Here is one more example of proxy data from the last 2,000 years. Historical records also exist, based on what people in the past wrote about their climate. Again, this proxy data reproduces the sudden warming of the last 150 years. So, based on this, all of you must be convinced that proxy data is a good reference for tuning climate models. As you know, climate models include assumptions and approximations. When we run a model, some parameters are not known precisely. So, these parameters are adjusted so the model agrees with the proxy data. That's why proxy data is extremely useful.

Now let's look at a close-up of the last 15,000 years.

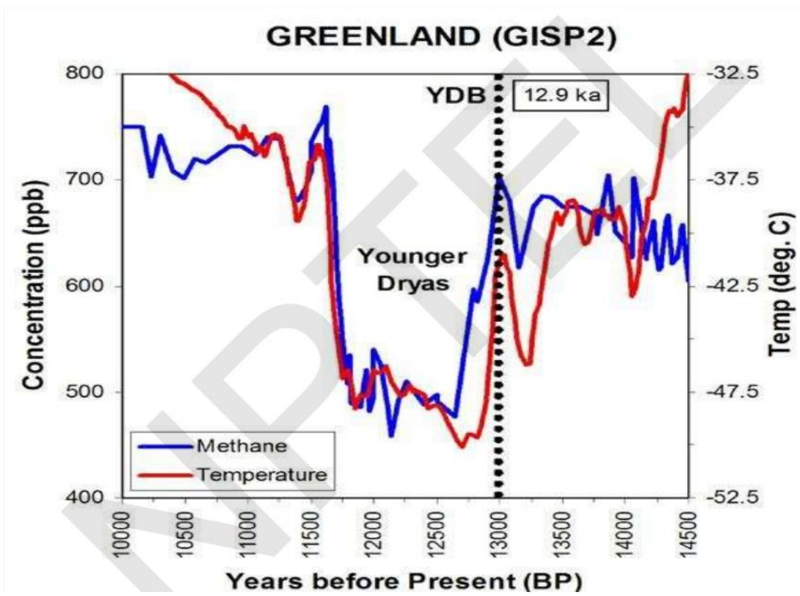


Here, we see temperature in Greenland on the right and snow accumulation in Greenland on the left. Red represents snow accumulation, green represents temperature. Greenland experienced many rapid changes—warm and cold periods.

We see that cold periods were followed by sudden warmings. This shows that rapid climate change is possible at specific locations. Places like Greenland—or possibly India, Africa, or America—can experience sudden local climate shifts. For example, a 10°C change in 1,000 years is possible.

So, this should not come as a surprise. These changes occurred in the past and may happen again in the future. Here, we see that snowfall increased as temperature rose. Remember: snowfall in high latitudes depends on temperature. If it's very cold, the atmosphere contains very little water vapor.

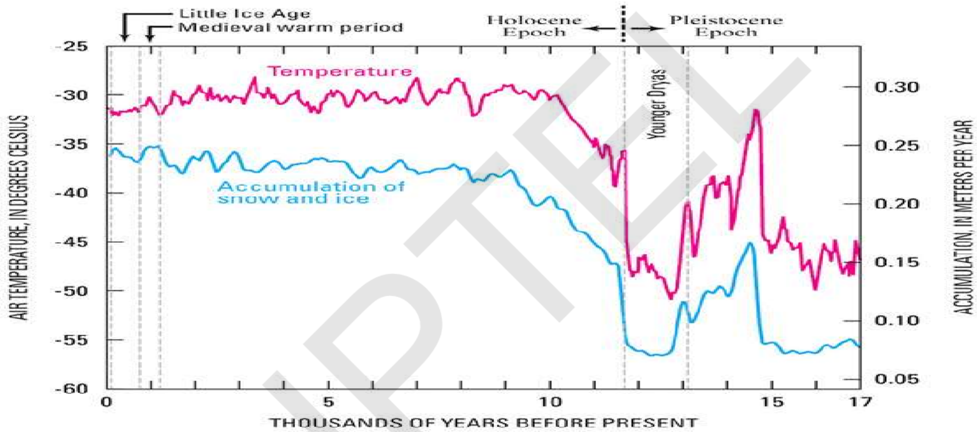
So, very low temperatures (e.g., –60°C) result in little snowfall—perhaps only 5 cm. At –40°C, however, snowfall may be 25 cm—five times more. This increase is due to higher temperatures and higher humidity. This is a very important point to remember.



Here is another close-up showing how changes in temperature in Greenland affected methane levels. Methane in the atmosphere is closely coupled with temperature. At higher temperatures, areas with vegetation in water (like rice paddies) emit more methane.

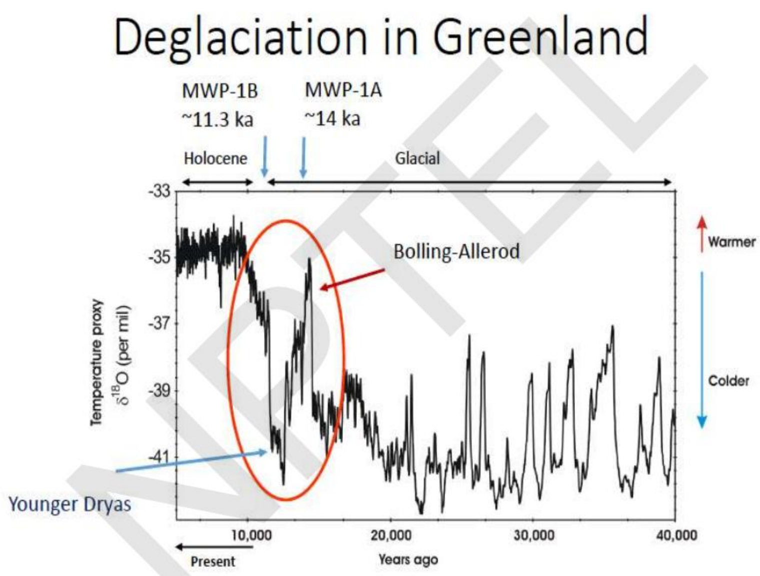
Also, permafrost (frozen soil) in mid-latitudes stores methane. As temperature rises, methane trapped in permafrost is released—this is already happening in Siberia. It happened in the past too. So, the fact that methane and temperature are correlated increases our confidence in past measurements.

These are all reasons to trust paleo data. Paleo measurements are difficult—they require extensive work in the field and lab, and many sources of error must be accounted for. So, we look for reassurance by comparing methane levels in trapped air bubbles with temperature data from the same ice layers. When they agree, it boosts confidence in the data. Here is another sample from Greenland showing the last 17,000 years.



Temperature variations during the late Pleistocene Epoch and near the beginning of the Holocene Epoch, determined as proxy temperatures from ice cores extracted from the central part of the Greenland ice sheet. Note the 1,000-year Younger Dryas cold interval (about 10 ka to 11 ka), the short Medieval Warm Interval (about 1100–1300 C.E.), and the Little Ice Age (about 1400–1880 C.E.). Modified from Alley (2000, p. 9, fig. 12).

Again, recent snow accumulation was higher than during the ice age. As before, we see a correlation between accumulation and temperature.



This again highlights the abrupt climate changes in Greenland. Some of these events are named—the Younger Dryas Cold Period, the Bølling-Allerød Warm Period. These were named after the scientists who discovered them. They are very important and are associated with meltwater pulses that affected sea level rise.

This data is crucial for understanding how Earth's climate changed in the past. This lecture will continue in the next session, where we will try to understand how temperature changed over the last 20,000 years based on this data. Thank you