Climate Change Science
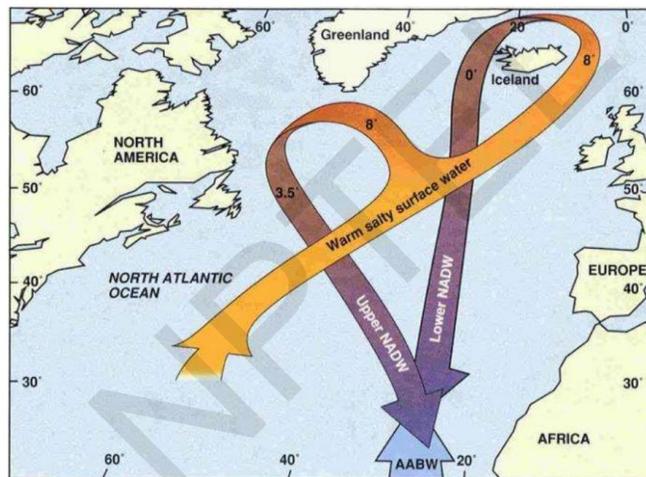**Prof. J. Srinivasan**
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Lecture – 29
AMOC during deglaciation

In the last lecture, we were looking at the abrupt changes in climate in the North Atlantic as we came out of the last Ice Age. The key factor there was the warm, salty water coming from the tropics.


This water is warm because it is on the surface, coming from the tropics, which are at high temperature. It is salty because it is losing water by evaporation, but not salt. This warm, salty water is heavier than the layers below it, which are cold and less salty. So, this water starts sinking around Greenland in many ways.

When it goes down, it forms what is called the North Atlantic Deep Water. So, this water, which is warm and salty, cools as it approaches Greenland. Because it cools, it becomes even heavier, and it drops down—at two different layers, one called upper and one called lower, depending on its density. Then it flows southward toward the Southern Hemisphere. This pattern of change in circulation between Greenland and Antarctica is what is called the Atlantic Meridional Ocean Circulation, or AMOC. So, these changes in AMOC had a big impact on the climate of Greenland and, ultimately, on the global climate.

This is what we talked about in the last lecture, and we will continue in this lecture. I mostly talked about AMOC, but note that AMOC and NADW are connected. They are part of the same system. So, in some of the graphs I showed you, instead of AMOC, they would have shown NADW— North Atlantic Deep Water. If AMOC accelerates, you have more formation of NADW and vice versa.

So, remember that the two terms are used somewhat interchangeably, although AMOC refers to the large-scale meridional ocean circulation between the Southern and Northern Hemispheres. NADW—the North Atlantic Deep Water—refers to the formation of this water around Greenland, because this warm, salty water, after cooling, goes down and settles at a lower level.
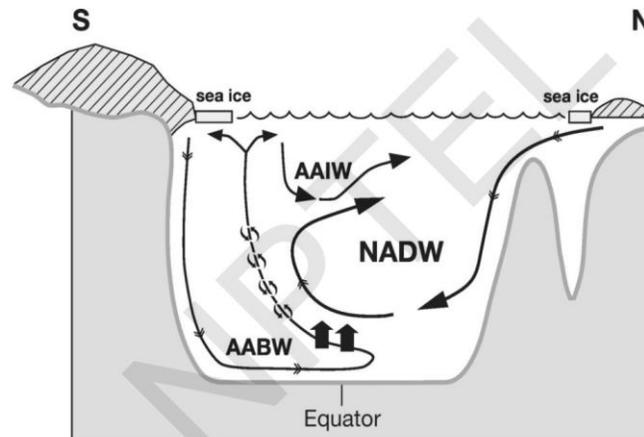
Now, to give you a clear picture, I am showing a vertical cross-section where you see the warm, salty water near Greenland cools both by exposure to the atmosphere and by melting ice. That water, after becoming cooler and heavier, settles down in the interior of the Atlantic Ocean. Now, at what level this settles down depends on the density of this water.

Some water may settle down here, another may settle further down. So, the precise layer where this water—coming down due to higher density—settles depends on its density. In the meantime, in the Antarctic, the water is much colder and it comes all the way down and settles at the bottom. It is called the Atlantic Bottom Water. These names are given by oceanographers because once you are below the top layer, where there is mixing due to winds, below that, there is hardly any mixing. Once you get below the upper mixed layer of the ocean, the water maintains its identity. The identity of water is defined by its temperature and salinity. These are the only two parameters. Temperature and salinity tell you what the characteristics of that water are.

As that water goes down into the deep ocean, you can clearly identify where it came from, because its temperature and salinity remain unchanged. It changes when you are on the surface—because of evaporation, ice melting, and other factors. But once it goes below the mixed layer, the blobs of water maintain their identity. So, they are defined by their temperature and salinity. If it is a certain temperature and salinity, it is called NADW. If there is a different salinity and temperature, we know it came from elsewhere. We call it Antarctic Bottom Water or Antarctic Intermediate Water. This water has slightly lower density, so when it comes down, it settles somewhere in the mid-depths. Remember that the density depends on salinity and temperature. If the temperature is low, it will settle deeper. If the temperature is high, it will settle at a shallower depth. If the salinity is low, it will be higher up. If the salinity is high, it will sink lower.

Note that salinity changes are not that easy unless freshwater comes in—like ice melting. So, the main change that occurs is due to temperature—if the water loses or gains heat.

These terms are used because they help identify water masses that persist for long periods—sometimes centuries.

Now, we are going to talk about something we mentioned before: one event in the period between 20,000 years ago and today. But now, to fully understand how this phenomenon occurs, I am discussing a paper that compared two of these events.
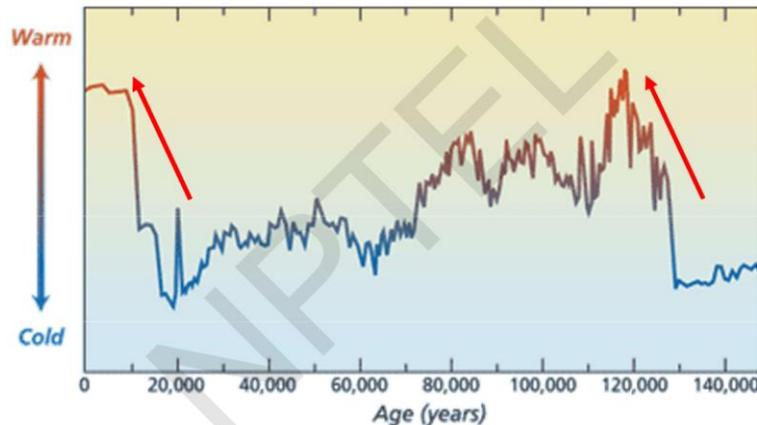
One is the one we already studied, in which the North Atlantic region near Greenland went through a cold period called the Younger Dryas and then immediately became warm. The same thing happened 100,000 years earlier. This data is from ice cores. Ice core data is very well documented, and we have data going back to 600,000 years. In every one of those datasets, we see these kinds of events. That is why they are called DO events—oscillations of the ocean system. Since there are many of them, it is good to compare them and see whether your models are actually able to simulate these changes. We saw one such event that happened in the last 20,000 years. Now, we will compare it with something that happened 100,000 years earlier.

There were significant differences between the last two deglaciations, particularly in Atlantic Meridional Overturning Circulation (AMOC). Here, we present transient simulations of deglaciation using a coupled atmosphere–ocean general circulation model for the last two deglaciations focusing on the impact of ice sheet discharge on climate changes associated with the AMOC.

We show that a set of abrupt climate changes of the last deglaciation, including Bolling–Allerod warming, the Younger Dryas, and onset of the Holocene were simulated with gradual changes of both ice sheet discharge and radiative forcing.

On the other hand, penultimate deglaciation, with the abrupt climate change only at the beginning of the last interglacial was simulated when the ice sheet discharge was greater than in the last deglaciation by a factor of 1.5. The results, together with Northern Hemisphere ice sheet model experiments suggest the importance of the transient climate and AMOC responses to the different orbital forcing conditions of the last two deglaciations, through the mechanisms of mass loss of the Northern Hemisphere ice sheet and meltwater influx to the ocean.

We used the MIROC4m AOGCM, the same model used in the simulation of the last deglaciation. The atmospheric component wasT42 (about 2.8° × 2.8°) with 20 vertical levels, and that of the ocean component was about 1.4° × 1° with 43 vertical levels

Obase et al., Scientific Reports, 25 November 2011

The paper, published in *Scientific Reports* in November 2011, says there were significant differences between these last two deglaciations in the Atlantic. They present transient simulations from a coupled ocean–atmosphere general circulation model. They are focusing on the changes in

the last two deglaciations and the impact of ice sheet melting and discharge on climate changes associated with AMOC. They show that these events occurred due to gradual changes in the ice sheet melting, discharge, and also changes in carbon dioxide and methane—i.e., radiative forcing.
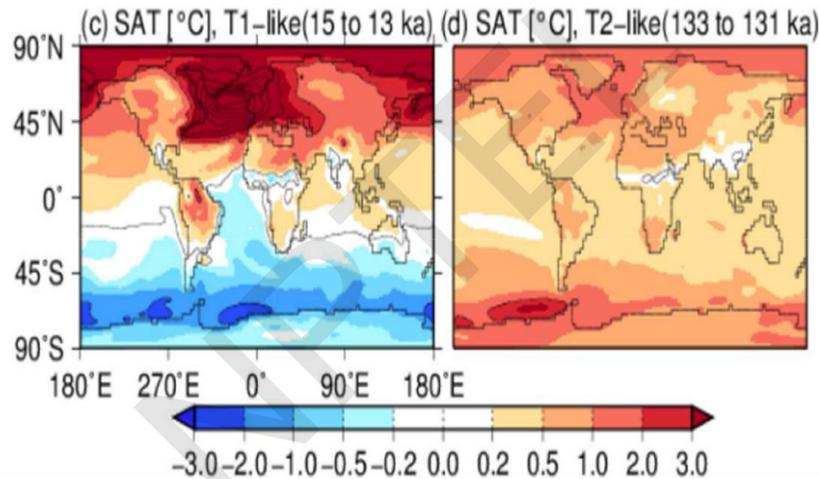
They say that the previous deglaciation—not the one in the last 20,000 years—was simulated when the ice sheet discharge was greater than in the last deglaciation by a factor of 1.5. So, what they say is that the orbital conditions—that is, the Earth's orbit around the Sun—were not the same 20,000 years ago compared to 120,000 years ago. Over these 100,000 years, there was a big change in Earth's orbit, which we will talk about more in the next lecture. Because of that, these two deglaciations occurred differently. The simulation they used was similar to what we discussed with the TRACE model—around 280 km resolution in latitude and longitude, with the ocean having somewhat finer resolution.
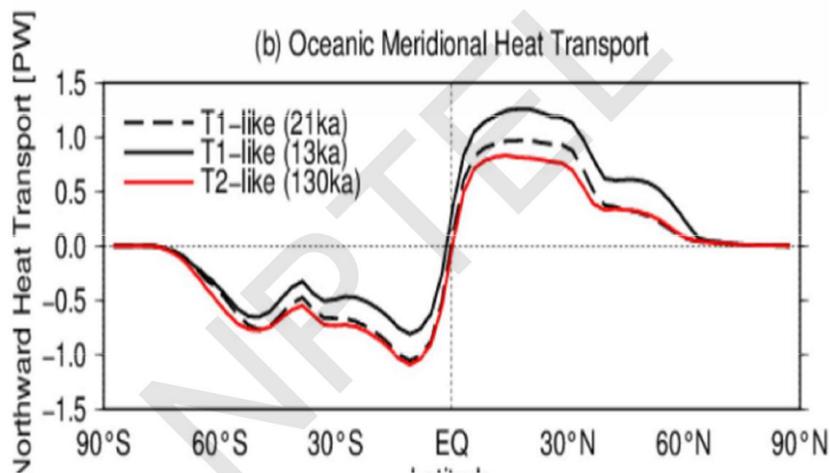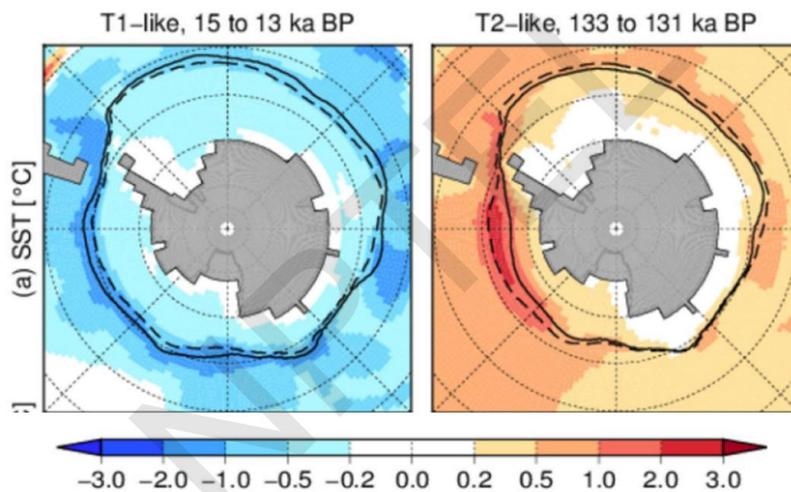

Now, here is a comparison: you see three curves here, all showing the latitudinal variation of heat transport in petawatts (that is, 10^{15} watts). The red line is the simulation for the deglaciation that occurred 130,000 years ago. We see that the heat transport was somewhat less than the black line, which represents what happened around 13,000 years ago, which we discussed in the last lecture. So, the amount of heat transported is a factor of almost three higher here.

They attribute this to the fact that the Earth's orbit around the Sun 13,000 years ago was quite different from that 130,000 years ago. That changed the amount of radiation falling in the Northern Hemisphere during summer. That is what controls this change.

Now, here is the comparison for the temperature change in the atmosphere between the periods 15,000–13,000 years ago and 133,000–131,000 years ago. The temperature scale is given, and you see clearly that the warming was much more during this event—a warming event we call the Bølling–Allerød.

(c) SAT [°C], T1–like(15 to 13 ka) (d) SAT [°C], T2–like(133 to 131 ka)

−3.0 −2.0 −1.0 −0.5 −0.2 0.0 0.2 0.5 1.0 2.0 3.0

The warming was around 2 to 3°C in Greenland, while 133,000 years ago, the warming was around 1.5°C. So, there's a big difference between the two. The second big difference is in the Southern Hemisphere. In the Southern Hemisphere, the temperature was colder than normal—around 2 to 3°C—while here it was warmer. So, you see a big difference in the north–south temperature variation in the most recent deglaciation compared to what happened 100,000 years ago. They attribute this to changes in the Earth's orbit around the Sun.

T1–like, 15 to 13 ka BP   T2–like, 133 to 131 ka BP

(a) SST [°C]

−3.0 −2.0 −1.0 −0.5 −0.2 0.0 0.2 0.5 1.0 2.0 3.0

Here's a picture of what is happening in the Southern Hemisphere. This is Antarctica in a model, and these lines show the melting of the sea ice. What you see is that 15,000 to 13,000 years before present, the ocean around Antarctica was around 1–2 degrees colder than the present.

While in the period 133,000 to 131,000 years ago, Antarctica was about 0.5 to 1 degree warmer. So, there was a different climate. This is the present interglacial, and this was the last interglacial. Actually, the last interglacial was warmer than the present day.

It is very important to study this because if we want to know what will happen to Earth's climate in the next couple of hundred years, then it's useful to study this past period—it was as warm as or warmer than the present. That is why this period is of great interest.
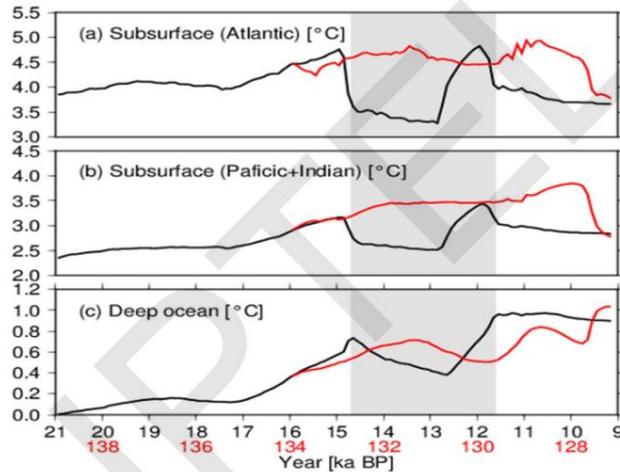
Fig. S4 Time series of mean ocean temperature in the subsurface and the deep ocean from the T1-like (black) and T2-like (red) experiments. The subsurface ocean is defined as 60°S–60°N and 500–2500 metres depth, and the deep ocean is defined as global and deeper than 2500 metres.

Now, look at the time axis here. There are two: one from 21,000 to 9,000 years ago, and the other from 138,000 to 128,000 years ago. So, a ~10,000-year span in one case and a ~12,000-year span in the other. The red line corresponds to the last interglacial 130,000 years ago, and the black line to the most recent deglaciation about 15,000 years ago. You see that the deep ocean was actually colder in the last interglacial than in the more recent one. The average is taken between 60°S and 60°N and depths from 500 to 2,500 meters. That's the subsurface ocean. The deep ocean is defined as deeper than 2,500 meters.

Let's first look at the deep ocean: it was colder during the last interglacial than during the warming event 15,000 years ago. As the warming occurred during the Bølling–Allerød, the deep ocean was 0.5 degrees warmer than it was in the interglacial 130,000 years ago. But if you look at the subsurface—between 500 and 2,500 meters—you see the last interglacial was warmer than the recent one.

This includes the Pacific and Indian Oceans. If you look at the Atlantic only—which is of particular interest—you also see that the last interglacial 130,000 years ago was warmer than the present interglacial. And you see that the abrupt warming—the Bølling–Allerød—was not seen in the last interglacial. This temperature difference had an impact on the Heinrich, Younger Dryas, and Bølling–Allerød events and how they behaved in the Atlantic subsurface.

So, by studying two deglaciations separated by 100,000 years, we better understand the role of subsurface and deep ocean temperature. These events are sensitive to the temperature of the ocean below the surface.

Now, here's a comparison of AMOC, which is of great interest to us. Again, note the two timescales.
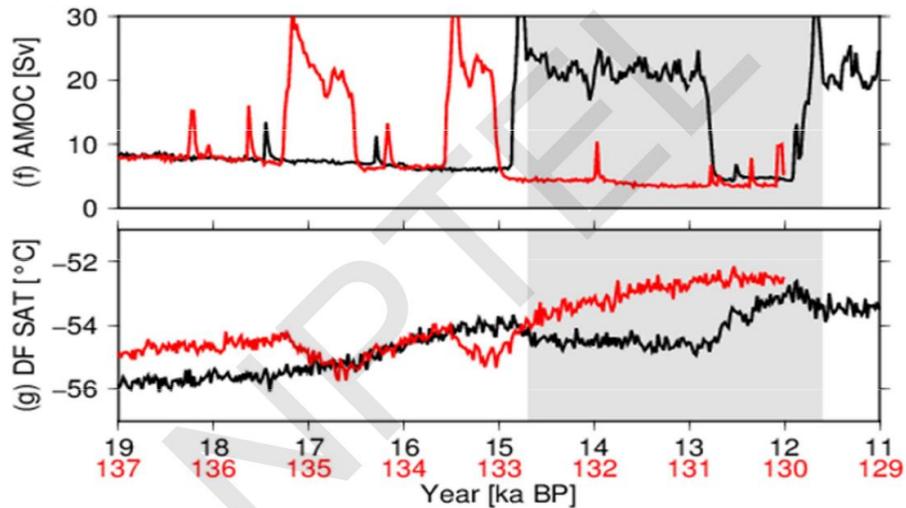
Red is 130,000 years ago. Black is the present interglacial starting ~19,000 years ago. You'll notice large changes in AMOC early in the last interglacial and then stabilization. In contrast, during the present interglacial, we saw warming ~15,000 years ago, then the Younger Dryas, and then the Bølling–Allerød. That sequence didn't occur in the earlier interglacial.

So, these warming events occurred a few thousand years earlier in the last interglacial than in the present one. December–February surface air temperature is different between the two periods. By comparing two warming events 100,000 years apart, they show how sensitive AMOC is to ocean–atmosphere conditions.

The North Atlantic Ocean Is in a State of Reduced Overturning
by Smeed et al., Geophysical research Letters,2008

The Atlantic Meridional Overturning Circulation (AMOC) is responsible for a variable and climatically important northward transport of heat. Using data from an array of instruments that span the Atlantic at 26°N, we show that the AMOC has been in a state of reduced overturning since 2008 as compared to 2004–2008. This change of AMOC state is concurrent with other changes in the North Atlantic such as a northward shift and broadening of the Gulf Stream and altered patterns of heat content and sea surface temperature. These changes resemble the response to a declining AMOC predicted by coupled climate models.

Recently, a paper by Smeed et al. (2008) used actual data from an array of instruments placed at 26°N in the Atlantic. They showed that AMOC has been in a state of reduced overturning since 2008, compared to 2004–2008. This raises concerns: is AMOC beginning to decline in response to CO_2 increases?

This AMOC weakening is concurrent with other changes in the North Atlantic, such as a northward shift and broadening of the Gulf Stream, and altered heat content and sea surface temperature.

These resemble model-predicted responses to AMOC decline. So, observations since 2008 hint at a decline in AMOC, which is consistent with model predictions under global warming. This caused both concern and excitement.

Changes in Greenhouse gases at the end of the last ice age
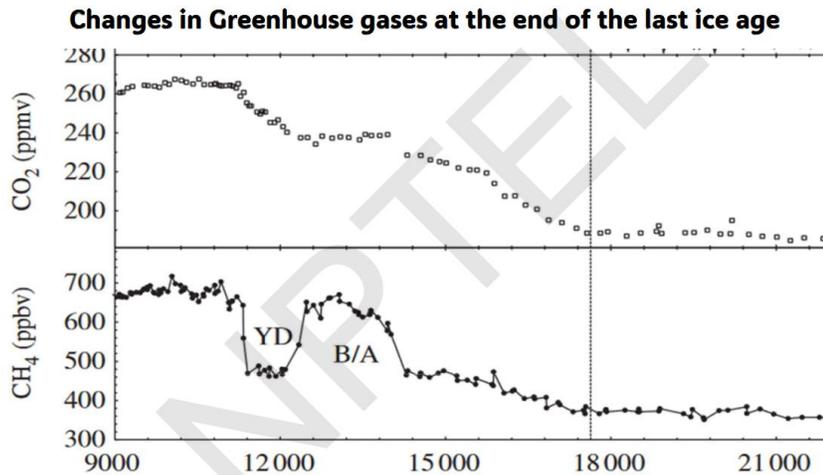
Now look at the graph of GHG changes at the end of the last Ice Age (~15,000 years ago). You see a big difference between CO_2 and methane. During the Younger Dryas (a cold event), methane dropped from ~600 ppb to ~450 ppb, and then recovered. During the Bølling–Allerød, it went up to ~650 ppb, but then declined again. This shows methane is sensitive to ocean temperature. In contrast, CO_2 didn't respond the same way. It kept increasing. This is interesting: CO_2 was increasing even though there were no human emissions—this was natural variation. Methane and CO_2 are driven by different processes. Methane comes from melting permafrost, methane hydrates, wetlands, and natural biomass burning. In the northern Eurasian permafrost zone—from Sweden to Siberia—as global warming occurs, the permafrost melts.

Global mean temperature has risen 1.5°C since pre-industrial times (1750). In the polar regions, it's more like 3–4°C. That's due to the ice–albedo feedback. As ice melts, more radiation is absorbed, warming accelerates. This doesn't happen in India (except the Himalayas). India shows less warming than the poles. Methane drops during cold periods because the permafrost refreezes and stops emitting methane.

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Why did CH_4 change but not CO_2?
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The natural concentration of CH_4 in the atmosphere is driven by changes in a range of sources (most notably wetlands, either boreal or tropical, biomass burning, and perhaps the release of methane hydrates from the seafloor) or by changing sinks (most notably the concentration of the OH radical in the atmosphere)

CO_2 doesn't respond as quickly to that. Its atmospheric residence time is much longer. So, methane responds quickly; CO_2 does not. Methane is oxidized by OH radicals in the atmosphere to CO_2 and

water vapor. So even if the source doesn't change, changes in OH can affect methane levels. Methane shows rapid fluctuations due to its short lifetime and variable sources.

We've observed rapid changes in methane over the past 40–50 years. These changes aren't fully understood because there are many natural sources: wetlands, permafrost, forest fires, etc. That's why methane shows variability that CO_2 does not.

D–O events are abrupt, large climate changes that punctuated the Last Glacial Period

There is uncertainty whether current IPCC-class models can effectively represent the processes that cause D–O events. We have shown that reduced ice sheets relative to LGM, low obliquity values, and low to medium CO_2 values are more likely to lead to unforced quasi-oscillatory D–O-type behavior. However, the simulations need to be run long enough to allow the strong positive AMOC feedbacks, along with negative feedbacks on long timescales, which can then lead to D–O-type oscillations. Around 40 % of the simulations set up with full LGM like conditions have a run length of less than 2000 model years, which makes it difficult to tell whether any of these simulations are capable of or likely to exhibit D–O-like behavior.
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

Now let's summarize a recent paper by Malmierca and Vallet in *Climate of the Past* (2023). They highlight uncertainty over whether current IPCC-class models can simulate DO oscillations effectively. They claim that reduced ice sheets (compared to the Last Glacial Maximum), low obliquity (Earth's axial tilt), and near-maximum CO_2 levels are more likely to lead to unforced, quasi-oscillatory DO behavior.

However, simulations must run long enough to allow both positive (e.g., AMOC feedbacks, GHG increase) and negative feedbacks on the right timescales. They say ~40% of simulations with full LGM conditions ran fewer than 2,000 model years, making it hard to assess whether they could show DO oscillations. So, the lack of DO-like behavior could be due to short run times. More simulations are expected over the next decade.

Now, what happens when you take a model and abruptly increase CO_2 by a factor of 4? This "shock test" shows how climate responds. You run a steady-state model with LGM conditions and then quadruple CO_2 in year 1. Why 4x? Because doubling often isn't enough to produce a clear signal. It's an artificial test, but it tells us a lot.

When CO_2 is quadrupled, AMOC declines rapidly. The model shows AMOC (black), sea ice (blue), and sea surface salinity (red). As CO_2 rises, sea ice melts, salinity drops quickly, and AMOC weakens. After several hundred years, recovery begins—but it's slow and damped. You get a fast reduction, a slow recovery, and a damped oscillation.
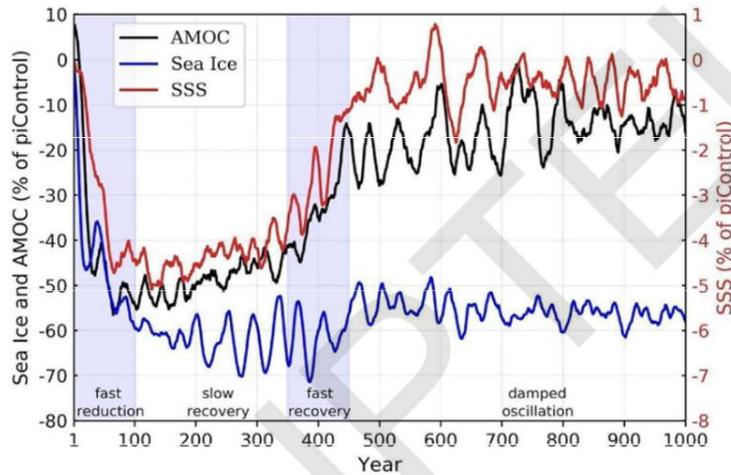
Figure 1. Abrupt4xCO₂ minus piControl percent change-time series relative to the piControl run of the Arctic sea-ice volume in March (blue), the AMOC strength (black), and the NATL (60° W–20° W, 40° N–60° N) SSS (red) lines are plotted. The named periods, i.e., fast reduction, slow recovery, fast recovery, and damped oscillation, are indicated at the base of the figure.

Though we're not quadrupling CO_2 in the real world, we are increasing it faster than at any point in the past 50 million years—150 ppm in just 170 years. Proxy data show no similar change in that entire span. This makes such simulations useful.
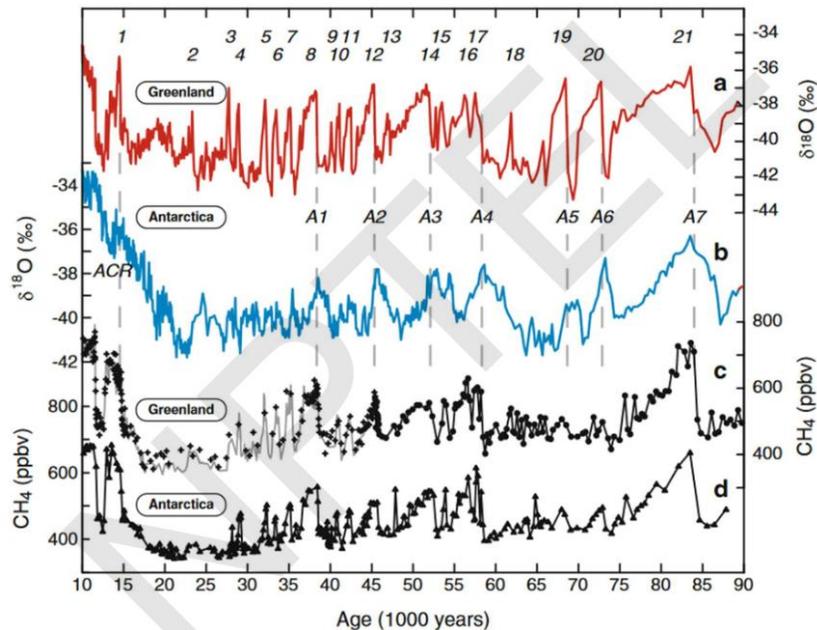
Finally, ice core data from the past 90,000 years (Greenland and Antarctica) show that Greenland records have more fluctuations than Antarctic ones. This is because the Northern Hemisphere is land-dominated, while the Southern Hemisphere is ocean-dominated. Land surfaces respond more abruptly to climate forcing.

We'll stop here and continue this in the next period.