Climate Change Science
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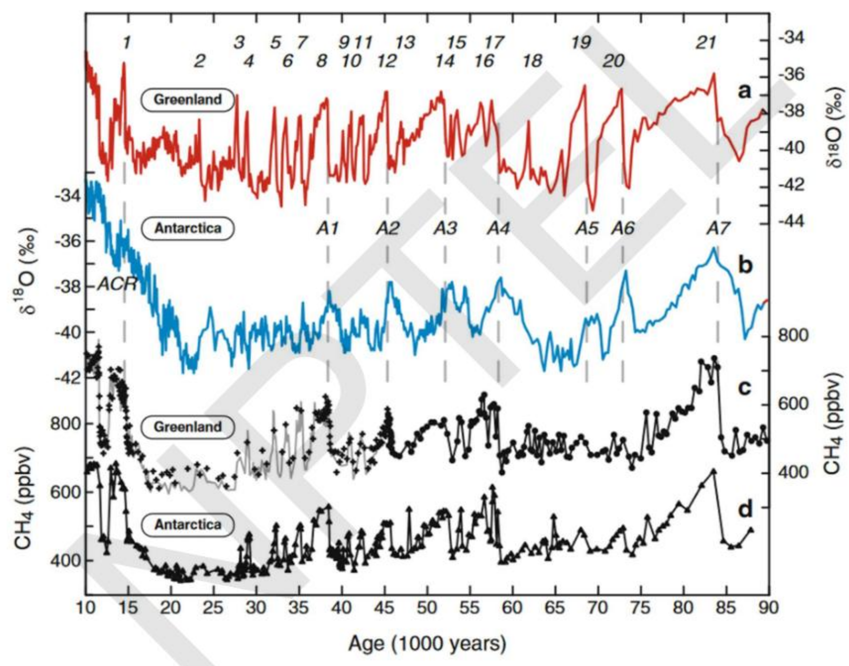
Lecture – 30
Dansgaard-Oeschger events



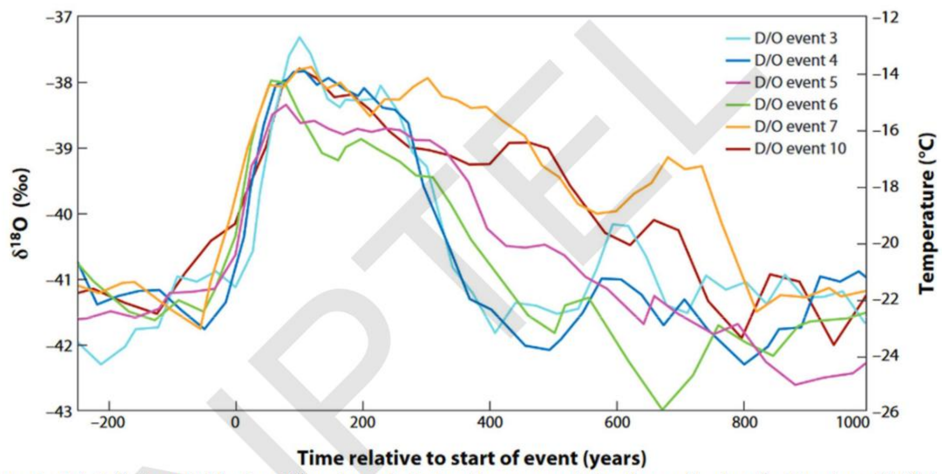
In the last lecture, we looked at this figure, where we compared the changes in Antarctica and Greenland, which is in the Arctic. We noticed that the temperature changes, which are deduced from the changes in the oxygen-18 isotope, are much greater in Greenland than in Antarctica. And the question is, of course, that because the Northern Hemisphere is land, and the Southern Hemisphere is mostly ocean, the changes in the Northern and Southern Hemispheres will not be identical. But still, you notice that certain warming events are coincidental, while in many other cases, they go in the opposite direction. For example, here it is the same—the cooling here is the same as the cooling here—but look here, it is warming, while it is cooling here.

So, there are two kinds of phenomena here. For certain climate events, Greenland and Antarctica go together; in others, they go in the opposite direction. To understand that, we also have to look at methane. Methane is a greenhouse gas, which is also measured in the ice core.

For example, in this event here, when there was a cooling coming from 85,000 years ago, there was cooling in Antarctica, there was cooling in Greenland, and the methane declined. So, the decline of methane triggered a cooling in both hemispheres. That is because methane is a gas—it is uniformly mixed in the atmosphere.

Hence, the concentration of methane both in Greenland (in this graph) and in Antarctica is similar. The changes in methane over Antarctica and over Greenland are very similar because methane is uniformly mixed. But surface temperature need not follow in the two hemispheres, because Antarctica responds to temperature in a different way than the Arctic. Antarctica is a landmass surrounded by ocean, while the Arctic is an ocean surrounded by land. So, they respond differently to temperature changes. But in certain events, they are similar. In some of the events, this change is similar, but for others it is different. Where methane did not change much, they are different. So, we have to understand a little bit further.

So, what people have done is they took the simulation of all the abrupt changes that occurred, and they put them together by looking at the sudden warming event. That is, the zero time is the warming event in all six events they have looked at. These are six Dansgaard-Oeschger oscillation events that they studied.



D/O events 3, 4, 5, 6, 7, and 10 (colored lines) are plotted on the same relative time axis, showing the abrupt initial warming from stadial to interstadial conditions and staying in an interstadial state for several hundred years (varies in duration) before dropping back down to stadial conditions. A slow cooling is evident during the interstadial period. Reproduced from Ganopolski & Rahmstorf (2001)

To show how similar they are, they rearranged them with the same timeline, starting 200 years before the sudden warming—that is, the Bølling-Allerød kind of event—and the subsequent 1000 years. So, they are looking at how the warming event started and then how it cooled slowly. The key message here is that the warming event, temperature change—from around -22ºC in Greenland to -14ºC, so 8ºC change in temperature—occurred in 100 years, which is very rapid.

Remember, right now the global mean temperature change over the last 100 years is about 1ºC. So here in Greenland (not global mean), a change of around 8ºC occurred in a matter of 100 years. So, this is a very rapid event that occurred in the past. One cannot rule that out in the future. This point will come up when we talk about the impact of climate change.

Although it has warmed only 1.5 degrees in the past 150 years, one cannot rule out much faster change in temperature in the future as CO_2 keeps increasing—because it has happened in the past. But what is interesting is that, although the warming was very similar in all these six events, the cooling was not. The cooling shows a lot of difference. So, that is the message: the warming events are very similar, probably triggered by increasing greenhouse gases, but the cooling events—the next 1000 years—occur at different rates.

So, cooling depends on many more factors other than greenhouse gases, and they do not show the same trend. Some of them cool slowly; some of them cool rapidly. So, there are many more factors that come into play when you look at the cooling events. Now, in order to understand some of these features, you have to understand what happened in North America. In North America during the last Ice Age, there was a huge ice sheet called the Laurentide Ice Sheet, which covered almost all of Canada.

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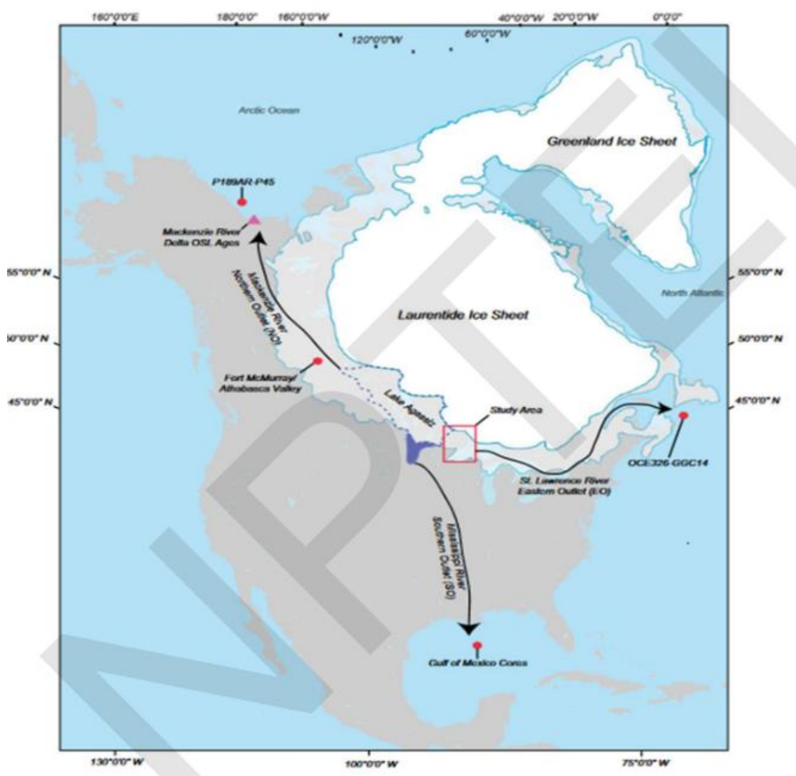


That ice sheet was very big, and then it started melting rapidly around 20,000 years ago. When this figure was drawn, the ice had retreated from here to here. When the ice retreats, water is left behind the ice sheet. So, a lake forms—even now it is happening in the Himalayas—as the ice melts, a lake forms behind the ice. Here is that lake, and one of those lakes is very famous, called Lake Agassiz, named after a famous geologist who was one of the first to propose the idea of multiple ice ages. So, this Lake Agassiz was a huge lake containing a lot of ice-melted water

The retreat of the Laurentide Ice Sheet allowed Lake Agassiz to drain eastward into the Atlantic Ocean. Wallace Broecker postulated that large amounts of fresh water were discharged into the North Atlantic about 12,900 years ago. Broecker and George Denton proposed that this large influx of fresh water may have stopped higher-density seawater in the North Atlantic from descending to lower depths, thereby interrupting thermohaline circulation and initiating a short-term return to glacial conditions. The temperatures were relatively low prior to the Younger Dryas in the Antarctic and rose during the Younger Dryas. This warming in trh Antarctic was on account of the deceleration of the AMOC.

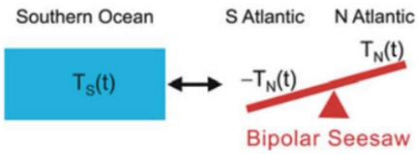
If the thermohaline circulation were to slow, less heat would be transported from the South Atlantic to the North Atlantic. This would cause the South Atlantic to warm and the North Atlantic to cool. This pattern, called the "bipolar see-saw,"

Now, when Lake Agassiz grew and broke through all the ice sheets, it discharged into the Atlantic Ocean. This was a major event that occurred in the Atlantic—when Lake Agassiz could break through the ice sheets and start discharging into the Atlantic Ocean. This was one of the meltwater pulses. When this huge amount of water, trapped behind the Laurentide Ice Sheet, came out, it caused a very large rise in sea level in a very short time—and that is what we will be looking at. So, the retreat of the Laurentide Ice Sheet allowed Lake Agassiz to drain eastward into the Atlantic Ocean.

The famous oceanographer Wallace Broecker postulated almost 60 years ago that a large amount of freshwater was discharged into the North Atlantic about 12,900 years ago. Broecker and George Denton proposed that this large influx of freshwater may have stopped the higher-density seawater in the North Atlantic from descending into lower depths. Their argument is that a large amount of freshwater coming in would have reduced the salinity of the top layer. So, the density goes down. If the density is lower, it cannot sink, thereby interrupting the thermohaline circulation. The thermohaline circulation demands that the water near Greenland should lose heat, become cold, and start descending. But if a lot of freshwater is added from Lake Agassiz, this water will not be dense enough to sink—because freshwater reduces both salinity and density.

So, the temperatures were relatively low prior to the Younger Dryas in Antarctica and rose during the Younger Dryas. This warming of Antarctica was on account of the deceleration of the AMOC. They argue that when AMOC decelerated, Antarctica warmed. Why did Antarctica warm? Because normally, when AMOC is strong, it is transferring heat from Antarctica to the Arctic. The Arctic remains at constant temperature, but when this movement of water from Antarctic to Arctic stops—because AMOC stops—then heat is not transported from Antarctica. So, Antarctica starts warming up because it is no longer losing heat to the Arctic.

If thermohaline circulation slows down, less heat would be transported from the South Atlantic to the North Atlantic. This would cause the South Atlantic to warm and the North Atlantic to cool. This pattern is called the *bipolar seesaw*. That is, the changes in the Northern and Southern Hemisphere Atlantic are different. As the circulation weakens, less heat is transported to the Northern Hemisphere, so the Southern Hemisphere warms while the Northern Hemisphere cools.



$$\frac{dT_S(t)}{dt} = \frac{1}{\tau}\left(-T_N(t) - T_S(t)\right)$$

$$T_S(t) = -\frac{1}{\tau}\int_0^t T_N(t-t')\, e^{-t'/\tau}\, dt' + T_S(0)\, e^{-t/\tau}$$

Bipolar seesaw coupled with a southern heat reservoir to form the thermal bipolar seesaw.

Figure from Stocker and Johnsen (2003)

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Now, this bipolar seesaw was simulated by Stocker and Johnsen in 2003. So, this bipolar seesaw involves the Southern Atlantic to cool while the Northern Atlantic is warming. You can write down the rate of change of temperature as the change in temperature between North and South, and the rate of change is given here. Now, this is a simple equation, a linear equation. You integrate that using the Laplace transform, and you see that the present temperature of the Atlantic is dependent upon the North Atlantic temperature before.

So, this T_N(t minus t prime) tells you what the temperature was in the period before time t, and that affects the integral. So, the integral is a contribution of temperature of the North Atlantic—not in the present, but in the past. This is, of course, the Southern reservoir temperature decay. So, there is a decay of Southern temperature and also a decay of the past temperature. Now, this term is an integral term—it is complicated to understand. It is a direct term which shows how temperature will decay in response to certain warming of the Antarctic.

Now, the bipolar seesaw, with a certain heat reservoir, causes this bipolar seesaw. So, you have a lot of heat stored in the Northern Hemisphere, and the North Atlantic Oscillation builds up—it shifts the heat from South to the North. So, that is the point.

Here is again a long time series of data from Greenland and Antarctica. Antarctica is shown in green; Greenland is shown in blue.

For this simulation, Stocker and Johnsen assumed that the time scale is around 1100 years—the time constant they have used in their model. Now, what they are showing is that the abrupt Dansgaard–Oeschger oscillation in the North is clearly seen in the simulation, and is similar to what is there in Antarctica. So, what they are saying is that their model, for an assumed time constant of around 1100 years, is able to reproduce the major warm events which occur in the Northern Hemisphere. Of course, they also occur in the Southern Hemisphere, and they are able to simulate it.

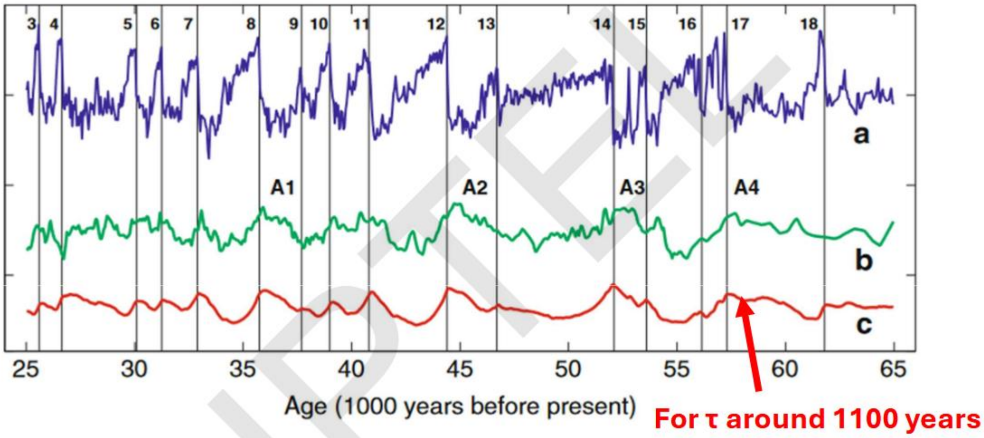


Fig. 9.3 High-pass filtered time series of the temperatures in Greenland (**a**) and Antarctica (**b**) derived from ice cores. (**c**) is the simulated temperature according to (9.2) with input (**a**). The abrupt Dansgaard–Oeschger events of the north hence become manifest in the local isotope maxima in Antarctica (A1, A2, ...). Figure from Stocker and Johnsen (2003).

So, this gives us some confidence that although the models are fairly approximate, they still carry enough information about how the Atlantic Ocean will respond to increases in CO_2.

Now, another interesting result they got from this simulation: they show that the rate of change of surface temperature decays rapidly.

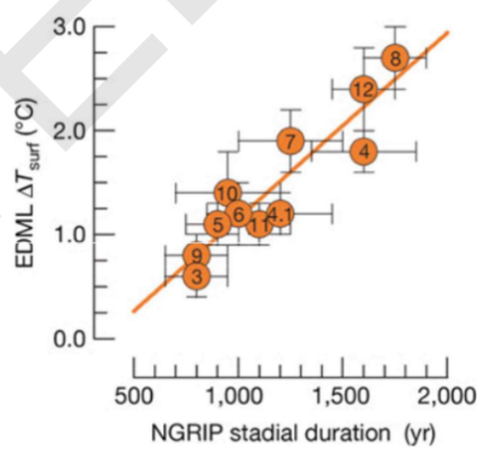
Linear correlation between the duration of the cold stadial preceding the Dansgaard–Oeschger events in Greenland and the temperature amplitudes of the warmings in Antarctica

$$T_S(t) = \frac{1}{2}\,\Delta T\left(1 - e^{-t/\tau}\right)$$

If the northern polar region has a sudden cooling by ΔT/2 then the temperature in the southern ocean becomes (see above) and for small times can be approximated as

$$T_S(t) \approx T_S(0) + \left.\frac{dT_S}{dt}\right|_{t=0} t \approx \frac{\Delta T}{2\tau}\,t\,,$$

Hence the temperature increase in the southern hemisphere is linear function of duration of the Greenland stadial
EDML is EPICA ice core from Dronning Maud Land



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They expand this in a Taylor series and get the leading term. It goes as $\frac{\Delta T}{2\tau}t$, where τ is the time constant. And when they plot the duration of the event with the actual ΔT, it goes along a linear line. This is remarkable. So, this approximation they are making is—they are taking the first term and the second term in the Taylor expansion for small time. So, dTs/dt at time t equals t. And if you assume that, then the change in temperature in the Antarctic should be linearly proportional to the duration of the warming of the Greenland stadial—that is, the cool period.

To me, this is a very nice proof of the simple model because it shows that how much temperature rise will occur is related to the duration of the Greenland stadial—that is, a short glacial period. So, to me, this is a good show that the simple model they developed—of the bipolar seesaw between Southern and Northern Hemisphere—is quite good, because it shows a very good correlation with about 10 DO events. So, the total warming in the DO events is related to the duration of the Greenland stadial, as found in the EPICA ice core from Antarctica.

To me, this shows the value of simple models. Although simple models make many approximations, so you must be somewhat suspicious, they are useful to make such predictions, which can be verified against observations, and if they agree, our confidence in these models increases.

Now, here is another simulation done by Stocker and Schmittner, using a somewhat simpler model—not the full coupled model—called the Bern 2.5-dimensional model. So, to predict the evolution of the meridional overturning circulation (MOC) during a warming scenario.

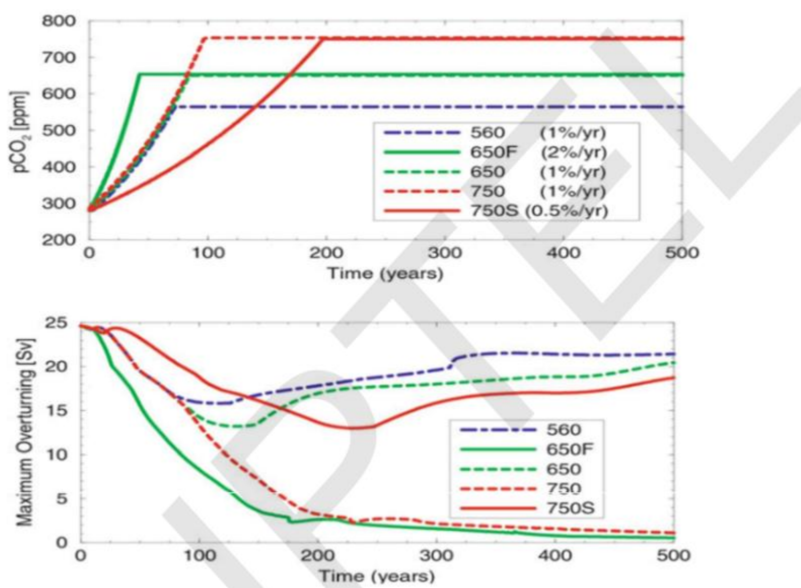


Fig. 9.10 Simulations with the Bern 2.5d model for the evolution of the meridional overturning circulation (MOC) in the Atlantic considering a warming scenario. The different simplified CO_2-scenarios (**upper panel**) consist of an exponential increase at different rates, leveling off at a given maximum value. The MOC reveals a bifurcation in its behaviour (**lower panel**): for small maximum values or slow rates of CO_2 increase, the threshold for a complete shut-down may be avoided. Figure from Stocker and Schmittner (1997).

In this scenario, they show an increase in carbon dioxide; they have various increases. They have artificially put in various kinds of warming: fast warming, slow warming, and fast warming followed by constant values, slow warming. In this case, warming occurred in 50 years—the increase in CO_2 occurred in 50 years. Here, the increase in CO_2 occurred in 200 years and then remained constant. The rate of increase in CO_2 was not the same in all these. And then you look at the maximum overturning circulation—because of this warming, because of this increase in CO_2—the circulation weakens.

Remember that we are all worried about the fact that CO_2 is increasing now from 280 to 420 already, and will continue to increase over the next 80 years. How fast will AMOC decline? Because the decline has serious consequences, which we will talk about later in this course. So, this shows that because of this warming introduced in this simulation, AMOC (Atlantic Meridional Overturning Circulation) declines over a 158-year period gradually, but there are cases where it totally shuts down. This green line, which corresponds to this green (the fast change)—that is, an increase in CO_2 by around 450 ppm in about 50 years, which is a very fast change—it almost goes to zero.

So, what this simulation shows you—it warns you that any rapid increase in CO_2 in 100 years will have a serious consequence. So, this is an important message for policymakers. Because if we continue to burn fossil fuels the way we are doing now, we may get a couple of hundred ppm change in 100 years. It is quite possible. So, at the rate of 2 to 3 ppm per year, over 100 years, we will get a change of 200 to 300 ppm, which is comparable to what they have done here. The AMOC will decline rapidly and may come to a stop in about 20 years. So, this simulation is a clear warning that a rapid increase in CO_2 can lead to a shutdown of the AMOC. So, this has again created a lot of discussion and warning among scientists and policymakers that a rapid increase in CO_2 is not safe.

Abrupt climate change may not have been merely a feature of the past but may be induced by the buildup of CO_2 in the atmosphere. Coupled model studies have shown that global warming can lead to a collapse of the North Atlantic thermohaline circulation. Higher atmospheric temperatures lead to a generally wetter atmosphere and hence increased moisture transport from low to high latitudes. The increased precipitation in the North Atlantic leads to reduced surface salinity and density, interrupting deep convection and bringing the Atlantic thermohaline to a halt. As a consequence, northern Europe might cool even under global warming and, more alarming, this cooling might occur much more rapidly than the gradual global warming, thus making

So, abrupt climate change may not have been merely a feature of the past, but may be induced by the buildup of CO_2 in the atmosphere. Coupled model studies have shown that global warming can lead to a collapse of the North Atlantic thermohaline circulation. So, this is a question that is of great concern for everybody. Because the North Atlantic Meridional Overturning Circulation is beginning to decline, higher atmospheric temperatures and generally wetter atmosphere and increased moisture transport from low to high latitudes will lead to increased precipitation in the North Atlantic and reduced surface salinity and density, interrupting the deep convection and bringing the Atlantic thermohaline to a halt. So, that is the concern now—that the world is warming rapidly and moisture is increasing, and that may trigger a collapse of the Atlantic Meridional Ocean Circulation. As a consequence of this collapse of the Atlantic Meridional Ocean Circulation, Northern Europe might cool even under global warming. This is a very interesting result. Right now, Europe is warming rapidly, but if the AMOC stops, it will start cooling rapidly, thus leading to an abrupt change in the climate of the European continent.

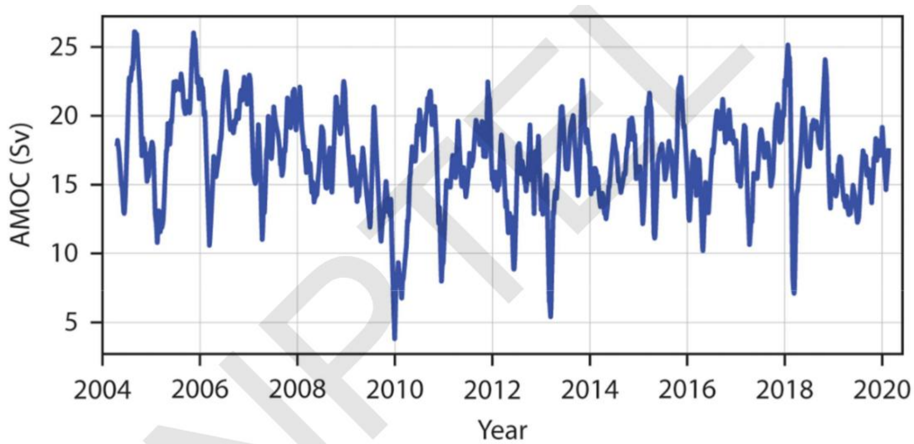
The risk of the AMOC tipping as global warming continues should be taken very seriously, considering the devastating consequences of such an event

On the basis of a whole series of new studies in recent years, the risk already appears to be significantly greater in this century than scientists had long assumed

Stefan Rahmstorf, Potsdam Institute for Climate Impact Research

Stefan Rahmstorf, a well-known expert on this AMOC, has said: the risk of AMOC tipping as global warming continues should be taken very seriously, considering the devastating consequences of such an event. On the basis of a whole series of new studies in the last 10 years, the risk already appears to be significantly greater in this century than what we had assumed in the past. So, Stefan Rahmstorf has said recently that the last report of the IPCC may have been too conservative. They thought that the chances of AMOC halting, collapsing, were very low—maybe 10 percent. But today, based on more recent simulations and more data, it looks like it may not be 10 percent—it may be much higher. If that is the case, it calls for a major change in the way we plan to decarbonize the world. So, this calls for a rapid decarbonization, which was agreed upon during the last Paris Agreement in 2015. But nothing much has happened so far. After 2015, many countries made promises to rapidly reduce their CO_2 emission, but nothing much has happened because the Paris Agreement is not a binding agreement. It is a voluntary agreement of all the countries. Those countries have not kept their word, and they have been distracted by other events occurring in the world. So, action has to be taken, and Stefan Rahmstorf has been warning that this may have serious consequences. Now, let us look at the actual data.

This is from the book *Global Warming Science* by Eli Tziperman, and it shows that between 2004 and 2020, there has been a decline in the AMOC—a substantial decline—but it recovered.



Courtesy: Chapter 6 figure 6.1 Global warming science E.Tziperman

So, based on these sixteen years of data, one may be complacent and assume that this variation between 25 sverdrups and 5 sverdrups is a part of the natural oscillation of the AMOC. So, for the long term, people say it's alright—it goes up and down; this is to be expected for natural climate variation. But the recent work that I have shown you warns that this may not be the right conclusion to make. Based on just 16 years of data, you cannot make any categorical statement about what could happen in the next 100 years. So, this is the warning.

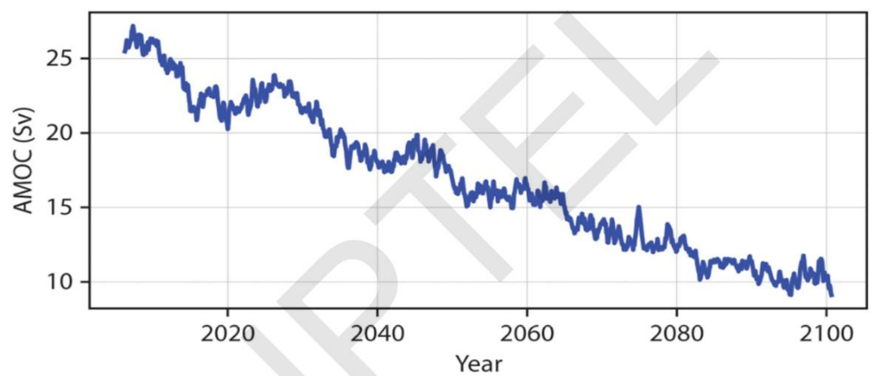


Figure 6.2: An AMOC future projection.
A projected AMOC transport time series in a climate model run under the RCP8.5 scenario.

Courtesy: Global warming science by E.Tziperman, Chapter 6 figure 6.2

Now, if you look at model simulation, they are showing a decline from around 25 Sverdrups now, all the way to 10 Sverdrups—it is almost collapsing by 2100, if we follow what is known as RCP 8.5. This is the business-as-usual scenario—that is, you continue to burn fossil fuels at the same rate we are doing now. So, the CO_2 will increase by 2 to 4 ppm per year, and if we do that, this model clearly shows that there will be a decline of the AMOC, and by 2100, it will almost collapse.

So, to me, this is a clear warning coming out from model simulations that we cannot afford to go at the present rate at which we are burning fossil fuels. We have to make very, very drastic changes to our economic system to cut down on fossil fuel emissions and move to solar, wind, and other renewable energy sources, so that this drastic decline in the AMOC does not occur. So, that was the part of this lecture to warn you that AMOC decline is a real possibility.

Now, in the next lecture, I will talk about how the Earth came out of the last interglacial 20,000 years ago to the present. And there, one of the mysteries was—we saw changes in carbon dioxide and changes in temperature going almost together, because some of the data we had got about 30–40 years ago were not of a high resolution.

So, we could not show whether the temperature increase occurred first or the CO_2 increase occurred first. Which came first is very important, because in the last 50–60 years, both the CO_2 increase and temperature increase occurred together. And most scientists believe that the temperature increase which occurred in the last 60 years is triggered by the CO_2 increase. But many climate change deniers and skeptics say, no—it may be possible that because temperature went up, the CO_2 came out of the ocean and CO_2 increased.

So, they are not convinced. So, in the last few years, more accurate data has been obtained, and they show that the increase in CO_2 occurred first, and this was followed by an increase in temperature. This is very important work done about 10 years ago by Shakun, which I will discuss in great depth in the next lecture, because this completely removes any doubt about which came first—the CO_2 increase or the temperature increase. Till recently, people kept arguing that we do not have to worry because this CO_2 increase is caused by an increase in temperature, and CO_2 is coming out of the ocean and land, and whatever caused the temperature increase, if it stops, it will stop. But now, the recent data shows that it is not true.

So, that will be the focus of my next lecture, which is very important—to show that the increase in CO_2 is a trigger for global warming. Thank you.