Climate Change Science
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Lecture – 28
Simulation of AMOC (continued)

In the last lecture, we were discussing the mechanisms that cause a change in the Atlantic Meridional Overturning Circulation. We looked at the results from a coupled model. Now, coupled models are fairly complicated. They are very rigorous models. So, normally, people compare the coupled model with what is called the box model. In a box model, you have just three boxes.

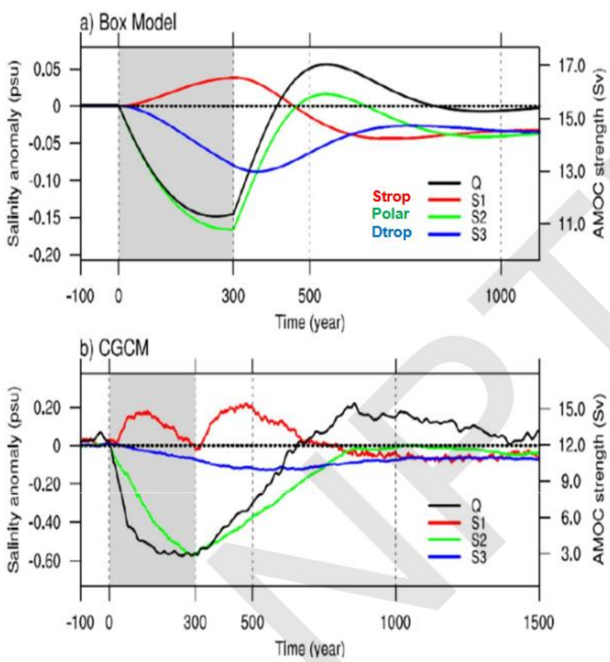


Fig.S7: Time series for AMOC transport (black) and box salinities, for an idealized hosing experiment in (a) a 3-box model and (b) the CCSM3 (salinity in ppt and transport in Sv.), illustrating a mechanism of AMOC overshoot associated with salinity adjustment. (see SOM, text 4 for more details). The box model is a hemispheric 3-box model, with a surface tropical box (box 1, red), a pola box from the surface to the bottom (box 2, green) and a deep tropical box (box 3, blue) (S9). The boxes are of equal latitudinal width for the tropical and polar boxes, and equal thickness for the surface and deep tropical boxes. A perturbation freshwater pulse is added into the polar box at a constant rate from t=1 to 300 years. The AMOC transport anomaly (black) decreases during hosing, and recovers subsequently, with an overshoot peak at t=520 years. In the recovery stage, the negativ salinity anomaly recovers faster in the polar box (green) than in the deep tropical box (blue), generating an anomalous southward deep pressure gradient and therefore an overshoot of the AMOC. (b) Similar to the box model, but for an idealized hosing experiment in CCSM3 with the meltwater flux imposed over the North Atlantic at the constant rate of 33-mslv/1000-yr for 300 years on the glacial state (from 19 -18.7ka), The Atlantic basin is partitioned into box 1 (45°S – 20°S, 0-500-m), box 2 (35°N – 80°N, 0 – 2000-m) and box 3 (45°S – 20°S, 500 – 2000-m). Qualitatively, the evolution in CCSM3 seems to resemble that of the box model.

The three boxes are: the polar region as one box, and then the tropical surface and the deep tropical. So, this is the deep tropical box that is close to the equator, and this is the surface, because the difference between surface and deep is important. Then, you have a polar box where all the action takes place. Now, this simulation should be compared with another simulation that is more complicated.

This involves many, many layers in the atmosphere and ocean. Now, the reason I am showing the box model is to point out that the box model more or less reproduces the changes simulated by the coupled GCM. In the coupled GCM, we have many more layers and many more regions, but we average for the same region as the box model. We find that the box model does quite well—not perfectly, but quite well—compared to the coupled GCM. This is to illustrate that once we have got a coupled model which correctly simulates the observed changes in the circulation, it still needs even a simpler model to understand how these changes occurred. So, we have the observation, we have a complex coupled model, and a simple model which go together.

Now, subsequent to this work going on with a coupled model, Stephen Rahmstorf did a lot of work to understand the Atlantic Meridional Overturning Circulation. For that, a group of scientists ran about 12 to 13 models of various complexities.

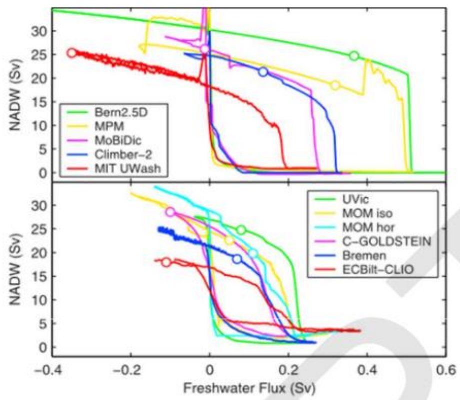


Figure 2. Hysteresis curves found in the model intercomparison. The bottom panel shows coupled models with 3-D global ocean models, the top panel those with simplified ocean models (zonally averaged or, in case of the MIT_UWash model, rectangular basins). Curves were slightly smoothed to remove the effect of short-term variability. Circles show the present-day climate state of each model.

Stefan Rahmstorf, Geophysical Research Letters, 32,2005

We present results from an intercomparison of 11 different climate models of intermediate complexity, in which the North Atlantic Ocean was subjected to slowly varying changes in freshwater input. All models show a characteristic hysteresis response of the thermohaline circulation to the freshwater forcing; which can be explained by Stommel's salt advection feedback.

Table 1. Models Participating in This Study[a]

Model Name	Ocean Component	Atmosphere Component	Reference for Model Details
Bern 2.5D	zonally averaged, 3 basins	zonally averaged energy moisture	[*Stocker et al.*, 1992]
Bremen	large-scale geostrophic	energy balance	[*Prange et al.*, 2003]
Climber-2	zonally averaged, 3 basins	statistical-dynamical	[*Petoukhov et al.*, 2000]
ECBilt-CLIO	3D primitive equations	quasi-geostrophic	[*Goosse et al.*, 2001]
C-GOLDSTEIN	3D simplified	energy-moisture balance	[*Edwards and Marsh*, 2005]
MIT_UWash	3D prim. equations, square basins	zonally averaged	[*Kamenkovich et al.*, 2002]
MoBiDic	zonally averaged, 3 basins	zonally averaged	[*Crucifix et al.*, 2002]
MOM-hor	3D primitive equations (MOM)	simple energy balance	[*Rahmstorf and Willebrand*, 1995]
MOM-iso	as above, with isopycnal mixing	simple energy balance	
MPM	zonally averaged, 3 basins	energy-moisture balance	[*Wang and Mysak*, 2000]
UVic	3D primitive equations (MOM)	energy-moisture balance	[*Weaver et al.*, 2001]

[a]All of the ocean models use z-coordinates.

Somewhere at the bottom here are full three-dimensional models. There is a model which has just three basins, and then there is a zonally averaged model. You do not worry about zonal variation. So, the idea is to run many models with various levels of complexity and find out how the North Atlantic Deep Water, which is created by this Atlantic Meridional Ocean Circulation, when it goes down near Greenland, causes the formation of deep water. So, it is a measure of the AMOC.

You can see the different models produce—as you introduce a freshwater flux near Greenland in millions of cubic meters per second—the deep-water formation starts slowing down. So, the whole purpose of this exercise is to see how the introduction of fresh water slows down the circulation. You can see that there are five models here and about six models here—11 models total. All the models show a slowing down of the circulation, but they slow at different rates. Some models like the ECBilt show a rapid decline, while the University of Victoria model shows a slow decline.

This is a big challenge for us now. Because we know that as the Greenland ice melts, more and more fresh water is being deposited in the North Atlantic. It is going to slow down, but the models do not agree on when it will slow down as the fresh water goes on increasing. When it will slow down—that is one part. The second part is very important.

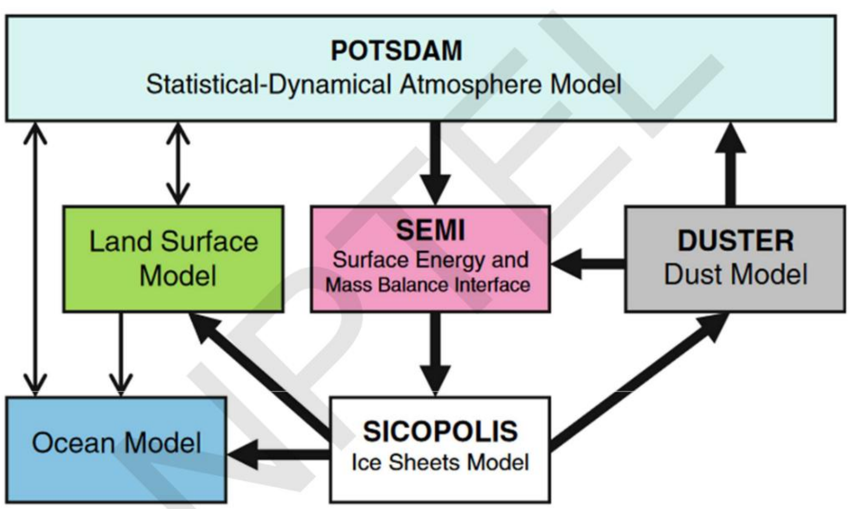
We will discuss that in detail. When does it shut down? Shut down means no flow. Starting with around 20–25 cubic meters per second, all the models show that at some point, they will completely shut down. If that shutdown occurs, it will have serious consequences for the Earth's climate. This is one of the concerns which was discussed at great depth before the Paris Agreement among nations.

These model simulations showed that due to the increase in carbon dioxide, if the global mean temperature went above 2ºC, then there is a chance that this Atlantic Meridional Overturning Circulation will come to a stop. If that happens, there will be very serious consequences for the global climate. So, these simulations tell you that yes, it is slowing down, but they show that the shutdown occurs at different times. For example, one model says shutdown occurs when you add a freshwater equivalent to 0.2 sverdrups, while the model in blue says it occurs around 0.35, and the green one says it will occur around 0.45. Now, this is a very big difference, because these changes occurring at different freshwater inputs imply a difference in time. So, between here and here, there may be a difference of 100 years. So, this is an issue.

There are some people now saying that due to global warming, the Atlantic Meridional Overturning Circulation will stop in another 20 years. Others are saying it will stop in 50 years, and other simulations show 100 years. Now, this is of course a cause of worry. Twenty years is a very short time. If AMOC is going to shut down in 20 years, we will have serious consequences for the global climate.

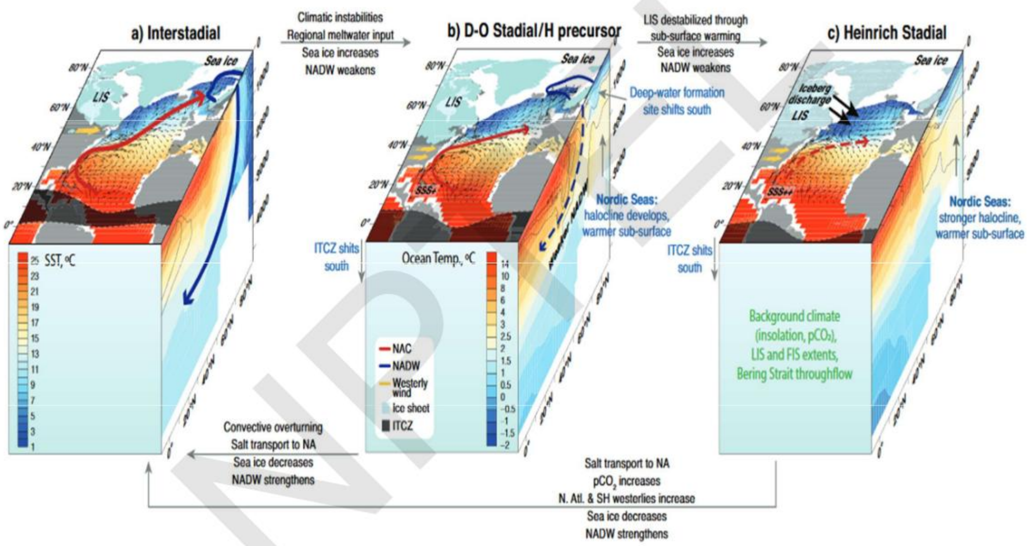
But if it is going to occur after 100 years, we still have time. We can do some quick changes to our emission of fossil fuels and slow down the time it takes for the AMOC to shut down. So, these models show there is a lot of variation. Of course, these models were done about 20 years ago, but more recent models show better agreement—though still, there are differences.

Now, one of the models that was discussed by Stefan Rahmstorf was known as the POTSDAM model, and it has a statistical-dynamical atmospheric model—not the full atmospheric model, but a statistical-dynamical model.



It has a land surface model, an energy balance model, and a dust model. The dust model is important because during the last ice age, when the Earth's temperature was about 5 to 6 degrees lower, there was a lot less rainfall over the globe and hence a lot more dust in the atmosphere. There were many more deserts, and so the dust storms increased. Dust, of course, reduces the solar radiation entering the Earth's surface and also absorbs solar radiation and warms the atmosphere. So, dust plays an important role in Earth's climate, and it has been included. They also had an ice sheet model and an ocean model. So, the only simplicity that POTSDAM introduced is regarding the atmospheric model, because their main focus was on the ocean model.

Now, some of these models show details about both the variation with latitude as well as the vertical structure. Here, the longitude is shown around Greenland and, of course, the latitude and also the height. So, this is a three-dimensional picture you are getting, and it is showing that when the Heinrich event occurred—that is, a lot of icebergs fell from North America and Greenland (iceberg discharge)—it caused a lot of cooling in the North Atlantic.



On the other hand, around the equator, the temperature increased because the Atlantic Meridional Overturning Circulation had slowed down. So, the three-dimensional picture gives an idea as to what happened during the event when icebergs fell into the ocean.

Now, this is a simpler thing—to look at the vertical structure only—and you see that you only compare these two.

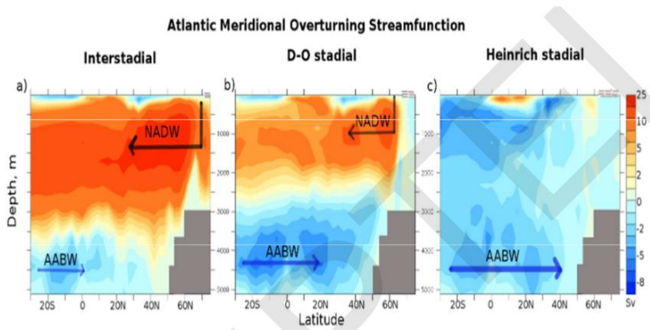


Figure 4. Possible AMOC states for stadials and interstadials. Possible states of the Atlantic Meridional Overturning Current (AMOC) for interstadials (panel **a**), Dansgaard–Oeschger (D–O) stadials (panel **b**) and Heinrich stadials (panel **c**). Positive values indicate a clockwise ocean circulation associated with North Atlantic Deep Water (NADW), whereas negativ values indicate an anticlockwise circulation associated with Antarctic Bottom Water (AABW). The grey areas at the surface represent possible winter sea-ice extension in the Nordic Seas.

When the icebergs fell into the ocean, you can see that the circulation pattern—they are showing here in Sverdrups (that is, in millions of cubic meters per second), weakened.

On the other hand, when the warm event occurred, the circulation started increasing. Finally, during the Bølling–Allerød phase, called the interstadial (that is, a warm phase during the glacial phase), the circulation went up further. So, what it shows is that when icebergs fell in the Greenland region, the circulation became weak. Then it slowly recovered and it became stronger. So, the AMOC strengthened here and was weak here.

Another thing which happened and is also well known is that when the water came out of the melting of the ice—both over land in North America as well as in Greenland—it also brought a lot of debris.

> **Marine sediment cores from the North Atlantic have revealed that some of the D–O events identified in Greenland ice are associated with thick layers of ice-rafted debris (IRD), inferred to be sourced from fast-flowing terrestrial ice from Hudson Strait. These high-IRD episodes are known as Heinrich events and occur within longer cold phases referred to as Heinrich stadials. D–O cycles and Heinrich events are not restricted to the last glacial period: ice-core and speleothem records suggest they are prevalent over at least the past 800,000 years. Although strict background thresholds for the occurrence of D–O variability are difficult to define precisely, it is clear that D–O variability has generally been suppressed during peak interglacial and peak glacial states.**
> **Palaeoproxy records and numerical simulations provide strong evidence that D–O variability (including Heinrich stadials) was associated with changes in the strength of the AMOC. So far, no climate model has fully replicated all observed climatic and biogeochemical characteristics associated with D–O variability**

This is called the ice-rafted debris, or IRD. And this debris falls into the deep ocean, and once you go and drill into the deep ocean, you will see layers of this debris at certain times, showing when the Heinrich event occurred. So, the Heinrich event is very well documented in the marine core taken from the bottom of the ocean. So, what it shows is that during the last 800,000 years, the Atlantic Meridional Ocean Circulation fluctuated a lot. These are called the DO variability. Let me just mention clearly here: these are the Dansgaard–Oeschger oscillations. These oscillations occurred every few thousand years during the last 800,000 years. You keep seeing these oscillations in the marine core data, in the ice core data, in the Northern Hemisphere.

You see these oscillations which are well documented and studied in great detail because we want to understand what causes oscillations and how such oscillations may occur in the future. So, both the paleoproxy records and numerical simulation provide strong evidence that the Dansgaard–Oeschger variability was associated with changes in the strength of the AMOC. So, that was a major discovery which was very important: that the oscillations we saw in the ice core data and the marine core data are linked to the changes in the ocean circulation—that is, the Atlantic Meridional Overturning Circulation.

Of course, no climate model has fully replicated all observed climatic and biogeochemical changes, but they are pretty good at demonstrating the occurrence of this oscillation. But the details—we still do not get all the details correct.

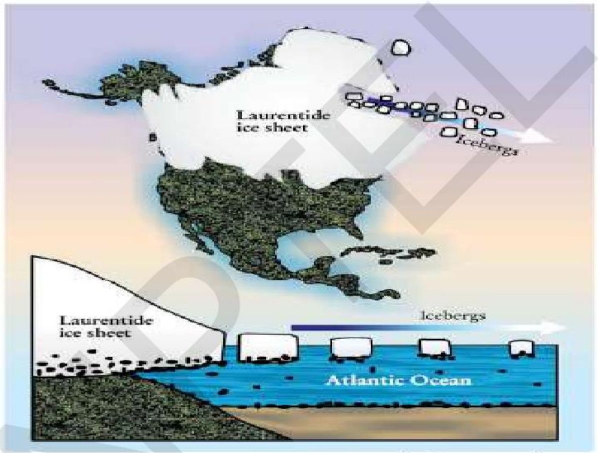


FIGURE 3. DURING A HEINRICH EVENT, icebergs surge into the North Atlantic Ocean. The lower panel illustrates the entrainment of debris (black) by icebergs and the subsequent sedimentation of the debris in the deep North Atlantic.

Let me again show you through this cartoon how this ice-rafted debris came. They came because of the huge Laurentide Ice Sheet, which occupied most of Canada and North America. When it started melting and water came out from these melts, they brought along with them—because glaciers carry rocks and stones along with them—those stones and rocks fell into the ocean and ultimately dropped into the bottom of the ocean. Today, we can recover it by drilling ocean cores. So, ocean cores are a very important proxy indicator for the occurrence of ice-rafted debris. So, whenever ice-rafted debris is seen, you know that during that period the Laurentide Ice Sheet was melting and depositing icebergs which contained these rocks and debris. So, this is very important data which was obtained from the Atlantic Ocean deep ocean cores.

Now, for you to appreciate how the ocean circulation is sensitive to what is happening at the surface, here is a counter example from the tropics, where they show that during weak monsoon years, the Nile River does not provide much water to the Mediterranean Ocean.

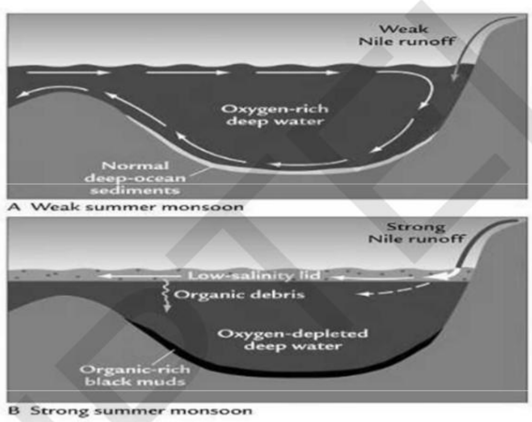
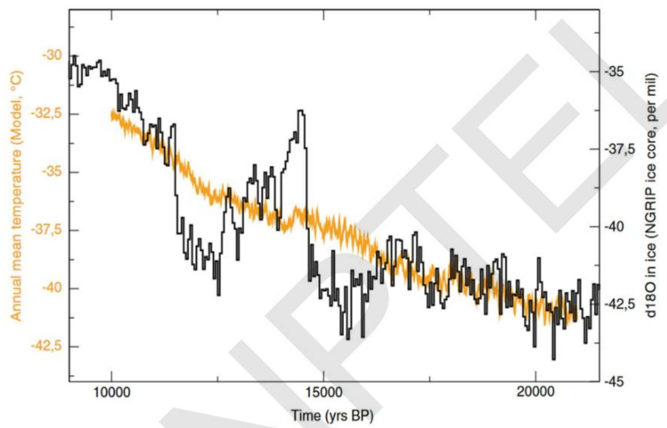


Figure 1.8: *Simplified Mediterranean circulation. A) Present day situation: Salty surface water chilled by cold air in winter sinks and carries dissolved oxygen to deeper layers. B) During minimum precession increased discharge from the river Nile could create a low-density surface-water lid that inhibited sinking of surface water and caused the deep ocean to lose its oxygen and deposit organic-rich black muds. From Ruddiman (2001).*

At that time, there is a normal deep ocean circulation, because when ocean water evaporates at the top, it becomes denser and it sinks. But during strong monsoon years, when a lot of Nile River water flows on top of the ocean, it provides a lid which prevents the ocean from losing water by evaporation. So, the salinity does not change, and there is no circulation.

And the deep ocean does not get oxygen. The oxygen comes to the ocean only from circulation of oxygen-containing water at the surface to the deep ocean—that is completely gone. So, we can, by looking at the ocean cores, see when the circulation was active and when it was not active. So, you must remember that the surface of the ocean—whether it is getting river discharge or ice discharge—controls the deep ocean circulation.

I want to show another simulation here and data.



Meltwater forcing not included

Modeling the Interglacials of the Last 1 Million Years
Andre´ Berger and Qiuzhen Yin

The data is in black, based on oxygen isotope-18 data in ice in Greenland. The orange line is a simulation for the last million years in a model which did not include meltwater forcing. You see the meltwater forcing is not there. It correctly reproduces the gradual decline in the annual mean temperature of the Earth over 1 million years, but does not reproduce these oscillations. So, what it shows clearly is that these oscillations—whose time scale is 1,000 to 5,000 years—are not caused if you do not introduce the meltwater forcing. So, this shows beyond reasonable doubt that the Heinrich event and the Bølling–Allerød phase were a response to meltwater fluxes.

This is the advantage of using models. You can shut off the meltwater forcing, add the meltwater forcing, and see what changes occur to the global mean temperature.

Now comes the important understanding of why the Atlantic Meridional Ocean Circulation shut down. It shut down because AMOC is sensitive to freshwater forcing, which also depends on CO_2. If the freshwater forcing is very large, the circulation suddenly stops. This is the stable phase of the circulation, which is slowly declining in response to either CO_2 increase or freshwater forcing.

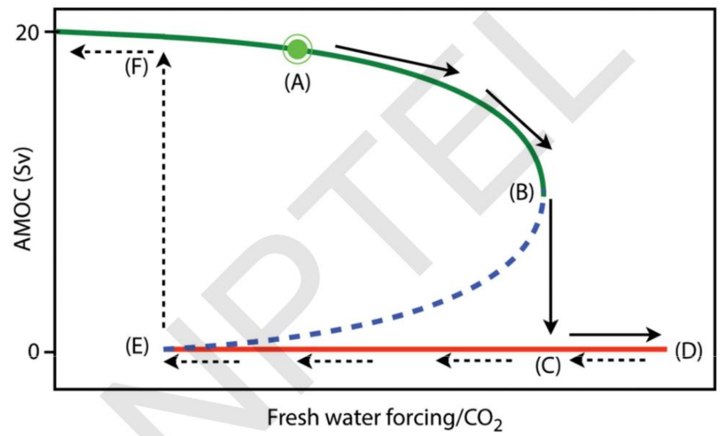
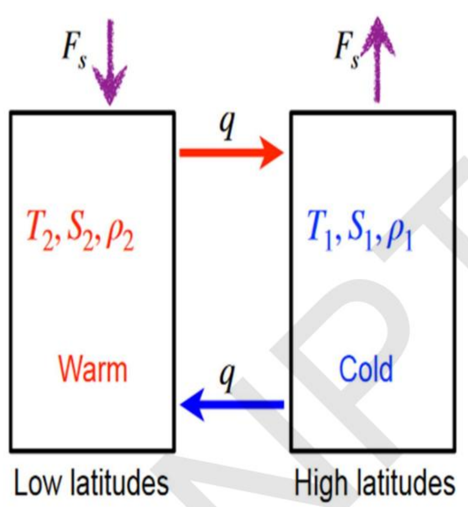


Figure 6.6: A schematic of the hysteresis and tipping point behavior in the two-box Stommel model

At some point, it suddenly stops, because this part of the curve is not stable. So, this is the stable part of the AMOC circulation; this is the unstable part. So, as soon as it goes to the point B, it just shuts down suddenly. So, our interest is knowing when point B will occur, because right now the Atlantic Meridional Overturning Circulation is slowly declining. But we do not know whether it is due to the melting of Greenland and—for example—sea ice in the Arctic, or is it due to natural variability?

We saw that the Atlantic Meridional Overturning Circulation has a natural variability in sverdrups due to year-to-year variation in ocean temperature and circulation. But we are concerned about the long term, because we know that sometimes this circulation stops. So, this is the thing which we want to understand and which we will now discuss in some detail.

To understand this, the famous oceanographer Henry Stommel proposed a model which is very simple.



In Box 1,

$$V\, dS_1/dt = q(S_2 - S_1) - F_s$$

In Box 2,

$$V\, dS_2/dt = q(S_1 - S_2) + F_s$$

Define $\Delta T = T_1 - T_2$ and $\Delta S = S_1 - S_2$, we obtain the transport between the two boxes as (assuming the volume of the two boxes to be the same) Where α and β represent the variation of density with T and S

$$q = K(\rho_1 - \rho_2) = K(-\alpha \Delta T + \beta \Delta S)$$

Courtesy: Chapter 6 Global warming science E.Tziperman

So, I am going to discuss the model because for me it is very important that you do not just believe the simulation of a climate model. You must understand why that circulation stopped through a simple model which you can run on your own computer or even a calculator.

So, for that, Henry Stommel proposed a simple model, and I have taken the next couple of slides from the book *Global Warming Science* by Eli Tziperman, which I mentioned earlier. And this model consists of just two boxes: a warm box and a cold box. The cold box represents the polar regions, and the warm box represents the low latitudes. The idea is that, due to the Atlantic Meridional Overturning Circulation, some flow comes in here. So, flow with a different temperature, salinity, and density comes into this box and alters the temperature, salinity, and density of this box. Due to mass conservation, a similar amount of mass has to go back to the tropics. In addition, there is, of course, freshwater addition at the top—either at a low latitude or high latitude.

In the two-box model, we look at the change in salinity of box 1 here, due to Atlantic Meridional Overturning Circulation coming in here. And this shows the difference in salinity between the two boxes, which drives the flow into the box. If you are getting flow from this box and S2 is not equal to S1, then this difference will cause a change in S1—plus, of course, the role of the freshwater flux, which can reduce salinity. Now, in box 2, we have the reverse. Whatever happens here happens in reverse there. This changes, and the freshwater flux also has to change.

Now, what controls q, the flow rate between the warm box and the cold box? Henry Stommel assumes a simple model: the flow must be proportional to the difference in density between the two boxes. The density difference multiplied by some empirical constant controls the flow rate. And the density difference is due to either a change in temperature or salinity. Both play a role. So, α is the rate of change of density with temperature. β is the rate of change of density with salinity. So, the density of water can change both due to temperature and salinity. So, we accounted for both these factors.

Now, this is a repetition of that fact.

The meridional flow (q in m 3 / s) is proportional to density difference between the boxes.

The density is approximated to be a linear function of temperature and salinity

$$q = K(\rho_1 - \rho_2) = K(-\alpha\Delta T + \beta\Delta S)$$

The change in the volume of the ocean is related to evaporation of water from the surface

dV/dt = - EA where E is the evaporation and A is the surface area

The salt budget equation is d/dt (SV) =0

Hence V dS/dt = - S dV/dt = SEA

The salinity of the ocean varies between 34 and 36 parts per thousand.

We assume that circulation changes occur only due to salinity changes

And we also calculate the salinity change in the box due to evaporation of the surface of the ocean to the atmosphere. A is the area of the ocean. One point is that the salinity in the ocean varies between around 34 to 36 parts per thousand. And we are going to assume that all the change in the circulation occurs only due to salinity. This is a simplification. In reality, both the temperature and salinity change contribute to the change in density and the flow rate, but we will only focus on the change due to salinity.

$$-V\, d\Delta S/dt = 2q\,\Delta S + 2F_s$$

$$-V\, d\Delta S/dt = 2K(\beta\,\Delta S - \alpha\,\Delta T)\Delta S + 2F_s$$

Define X= α ΔT and Y= β ΔS

The solution to the quadratic equation(in steady state) for ΔS gives

For Y < X

$$Y = \frac{X}{2} - \frac{1}{2}\left(X^2 + 4\frac{\beta F_s}{K}\right)^{1/2}$$

For Y > X we get

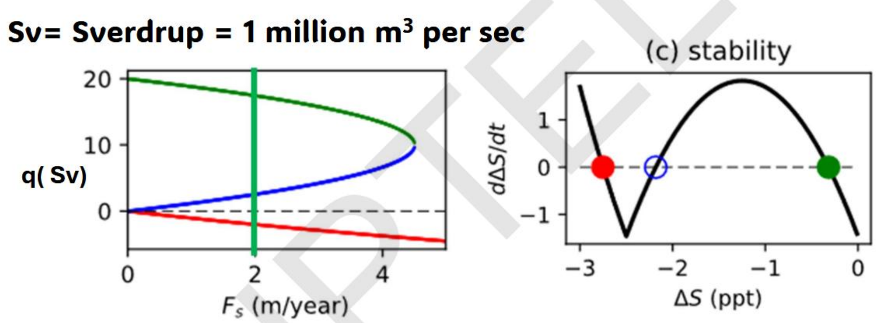
$$Y = \frac{X}{2} \pm \frac{1}{2}\left(X^2 - 4\frac{\beta F_s}{K}\right)^{1/2}$$

Courtesy: Chapter 6 Global warming science E.Tziperman

If you take those two equations and write down (T_1 - T_2) as ΔT and (S_1 - S_2) as ΔS, then you get the two equations simplified for the two boxes—and this is the freshwater forcing.

For convenience, we define **x = αΔT**, and **y = βΔS**, and you can write those equations for **y < x** and **y > x**. You get one solution for y < x and two solutions for y > x. So, there are three solutions which we have to be concerned about, because this problem has multiple solutions. Just to remind you: this is an attempt to understand this problem.

It has multiple states, and we are trying to understand those two states. Now, in the steady state, when the change in salinity difference with time is zero—that is what we are looking for as a solution—and you see that there are three solutions here where d(ΔS)/dt = 0, i.e., steady state. Two are shown in solid, and one shown in open.



Filled circles are stable solution while the unfilled circle in the middle is an unstable solution

Courtesy: Chapter 6 Global warming science E.Tziperman

Two are stable, and one is unstable state. So, why do I say that? This is similar to what we discussed when we discussed the stability of the global mean temperature. There they showed three solutions as well—two of them stable, one unstable. The same argument applies here: because we are at this red point (which is stable), and you slightly change the salinity, you will find a reaction that forces the salinity to return to this spot. Same thing with the green point—if you slightly perturb it, the salinity will slightly change, which will change the temperature and bring the system back. So, one can show that there are two stable and one unstable state.

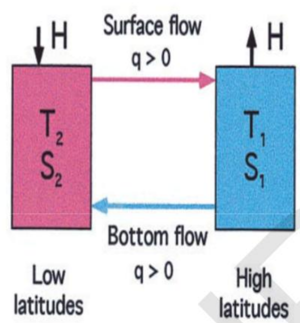


Fig. 3. Stommel's conceptual model of the THC.

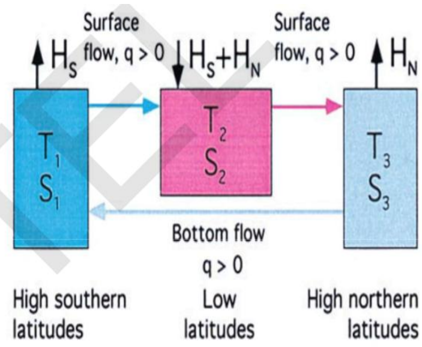
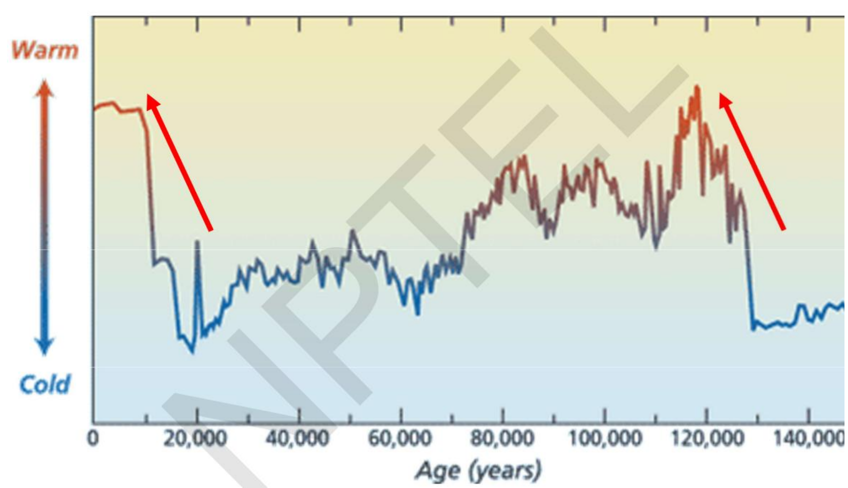


Fig. 4. Rooth's interhemispheric conceptual model of the THC.

Marotzke PNAS | February 15, 2000 | vol. 97 |

This is a model that Stommel proposed more than 63 years ago, but there are some people not happy with the model. They like to introduce a tropical box. Here we have only two boxes—low latitude and high latitude. Now, some people have introduced a slightly more complex picture with high-resolution southern latitude, high-resolution northern latitude, and a tropical region. So, this is a slight extension of this model, but the spirit is still the same. You will still get similar solutions, but it is a little more complicated.

Now, we just explained how the circulation changes occurred in the period from 20,000 years ago to 40,000 years ago due to changes in the Atlantic Meridional Overturning Circulation. To test this model, we will also look at the last interglacial. Remember, we are in an interglacial right now.



We came out of the Ice Age, and we are in an interglacial. But we should also look at the last interglacial, which occurred around 120,000 years ago. And then also the Earth's system came out of a cold climate to a warm climate, but there are differences between those two. So, people are trying to simulate these two periods to get an idea of what controls the changes here and here.

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

So, this I will discuss in the next class, where I will look at a paper where they have compared the AMOC changes in two different periods. One is the present simulation between 20,000 to 40,000 years ago, and the other one is 100,000 years ago. By comparing those two, we will be better able to understand how these changes occurred—because we have one more data set going back to 120,000 years ago. We will continue the discussion in the next class.