

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

**Lecture 27**  
**Simulation of AMOC**

In the previous lecture, the focus was on understanding the major climate events that have occurred since the Last Glacial Maximum, approximately 20,000 years ago. These events included abrupt transitions between warm and cold periods, which highlight the instability and complexity of Earth's climate system. The primary motivation behind studying these past changes is the concern that future abrupt climate shifts could be triggered by ongoing anthropogenic influences.

However, uncovering the causes of these past changes is challenging, especially since our knowledge relies heavily on proxy data rather than direct observations. Proxies such as tree rings, ice cores, and marine sediments offer valuable insights but come with limitations, especially regarding the precise timing of events. Due to uncertainties in dating techniques, the timing errors in proxy records can span hundreds of years, making it difficult to pinpoint exactly when particular climate changes occurred.

To address these limitations, climate scientists combine proxy data with climate models. Today's sophisticated climate models simulate interactions among the atmosphere, oceans, land surface, and biosphere, providing a comprehensive framework to study past and future climates. Yet, even these models have limitations: their spatial resolution is typically around 50 km by 50 km, which means that smaller-scale processes are not explicitly resolved and must be parameterized or approximated. This can lead to uncertainties in the model outputs.

Given the complexity of these models, it is often difficult to interpret why certain changes occur in the simulations. Therefore, researchers also employ simple conceptual models, such as Energy Balance Models (EBMs), which help isolate key mechanisms and enhance understanding of the broader system. Thus, a multi-pronged approach involving proxy data, complex climate models, and simplified theoretical models is essential for reconstructing and interpreting past climate changes accurately.

A notable example illustrating the role of coupled climate models is the pioneering work of Syukuro Manabe, who was awarded the Nobel Prize in Physics in 2021. Manabe and his team developed one of the first comprehensive coupled atmosphere-ocean models to investigate the response of the Earth's climate system to perturbations. The atmospheric component of this model includes equations governing water vapor conservation,

radiative transfer, and atmospheric motions in the zonal, meridional, and vertical directions. This atmospheric model is dynamically linked with the ocean component, which plays a vital role by supplying moisture to the atmosphere through evaporation and transferring sensible heat via turbulent heat fluxes.

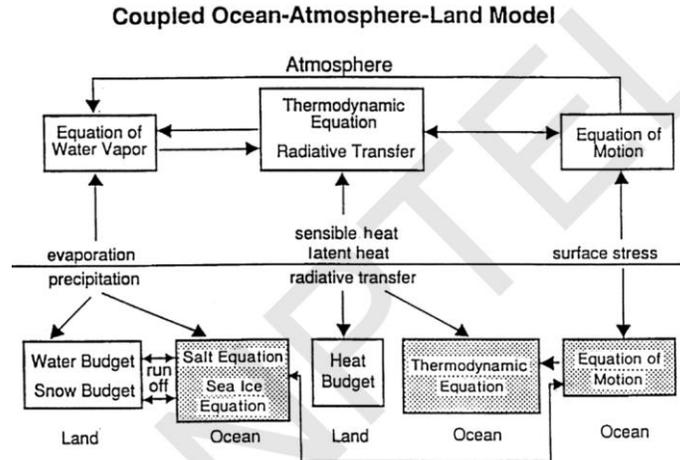


Fig. 1. The structure of the coupled ocean-atmosphere model.

Conversely, the atmosphere influences the ocean by exerting surface stress - the winds generate momentum that drives oceanic currents. Ocean circulation in this model is represented through two primary mechanisms: one driven by atmospheric winds and another driven by density differences resulting from temperature and salinity gradients - collectively known as thermohaline circulation.

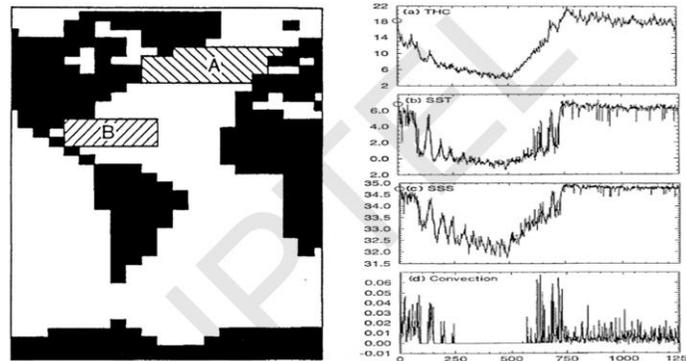


Fig. 2. Regions A and B indicate the areas where freshwater is discharged in the first freshwater integration (FWN) and the second freshwater integration (FWS), respectively (from MS97).

Fig. 10. Time series of annual mean values of (a) intensity of the THC (in units of  $Sv$ ,  $10^6 m^3 s^{-1}$ ), defined as the maximum value of the streamfunction in the North Atlantic Ocean, (b) SST ( $^{\circ}C$ ), (c) SSS (psu), (d) rate of NSF change ( $C \cdot d^{-1}$ ) due to convective adjustment, at a location in the Eemian Stage (30.0W, 45.3N) over the 1250 year period of the FWN. The initial values of THC, SST, and SSS are enclosed by circles (from MS97).

Manabe's group at Princeton was the first to simulate scenarios where freshwater is added to the North Atlantic, either due to melting of the Greenland Ice Sheet (region A in the figure) or from large river discharges into the Gulf of Mexico (region B in the figure). Both scenarios impact the salinity of the ocean, which in turn affects the density-driven circulation. One of their model experiments shows that when freshwater discharge is introduced at time  $t = 0$ , it leads to a weakening of the thermohaline circulation for approximately 500 years, after which the system gradually recovers.

Additional model outputs illustrate the associated changes in sea surface temperature and sea surface salinity, demonstrating how the addition of freshwater can disrupt the vertical motion in the ocean. These changes are critical because they reveal the sensitivity of global ocean circulation and thereby global climate to freshwater perturbations, such as those expected from melting ice sheets under global warming.

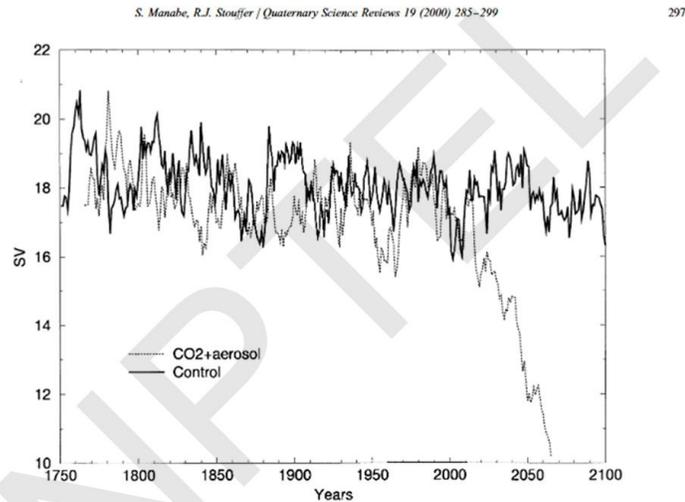


Fig. 13. Temporal variation of the intensity of the thermohaline circulation from the control (solid line) and the thermally forced experiments (dotted line) which were conducted by Haywood *et al.* (1997) using the coupled model. Here the intensity is defined as the maximum value of the stream function representing the meridional overturning circulation in the North Atlantic Ocean (from Manabe (1998)). Units are in Sverdrups ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ).

A time series analysis of the thermohaline circulation which encompasses both meridional (north-south) and vertical (up-down) oceanic motion is depicted in the above figure to illustrate the influence of anthropogenic factors. The model output includes two key simulations. The control simulation, represented by a black line, maintains pre-industrial levels of carbon dioxide, showing the natural variability of the circulation, with fluctuations typically ranging between 19 and 16 sverdrups (1 sverdrup = 1 million cubic meters per second). These fluctuations are attributed to natural climate variability.

In contrast, another simulation incorporated the observed changes in carbon dioxide and aerosol concentrations over the past 150 years (dotted line). This simulation revealed that around the year 2000, the thermohaline circulation began to weaken, which was directly linked to the anthropogenic changes. This weakening is a cause for concern, as it highlights the potential for human activity to disrupt large-scale oceanic circulation systems.

Notably, this model prediction was published in the year 2000, at which point the observational evidence for a weakening thermohaline circulation was still uncertain. However, in the present day, observations confirm that a weakening trend has indeed occurred. It is important to distinguish between natural year-to-year fluctuations and forced trends. Only when the circulation drops consistently below 16 sverdrups should anthropogenic influence be seriously considered. This early work laid the foundation for

numerous studies over the past two decades, which have since provided deeper insights into how rising greenhouse gas levels affect global ocean circulation.

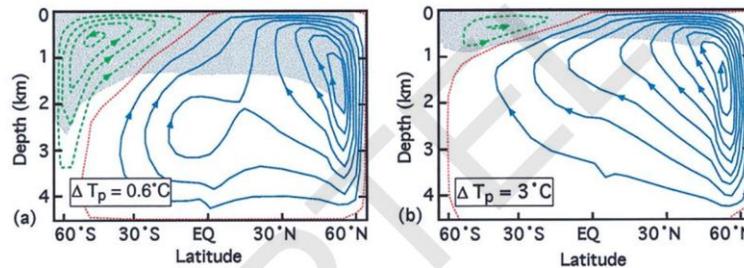


Fig. 1. THC streamlines (each contour denoting 2 Sverdrups) from an idealized three-dimensional model spanning both hemispheres of a single ocean basin. The blue solid lines mark the "northern" THC cell (sinking in NH) while the green, dashed lines mark the "southern" THC cell (sinking in SH). The red dotted lines demarcate the boundary between the cells. Shading represents temperatures higher than the minimum in the SH. The pole-to-pole imposed surface temperature difference is denoted by  $\Delta T_p$ . (a) Small asymmetries in surface forcing cause strongly asymmetric flows. (b) As the northern cell increases, the southern cell weakens by almost the same amount, leaving their sum nearly constant (adapted from ref. 9).

**Abrupt climate change and thermohaline circulation: Mechanisms and predictability**  
by Jochem Marotzke, PNAS, 15 Feb 2000

Another important study conducted around the same time was by Jochem Marotzke, who explored the sensitivity of thermohaline circulation to temperature differences between the North Pole and the South Pole using a simplified ocean-only model with no land. In this model, two simulations were compared: one with a small temperature gradient of  $0.6^\circ\text{C}$  and another with a larger gradient of  $3^\circ\text{C}$  between the poles. The results showed that the strength and structure of the thermohaline circulation changed significantly depending on this temperature difference. Specifically, when the temperature gradient was small, the circulation weakened considerably compared to when the gradient was large. The shading in the figures from the study represent the temperature above the southern hemisphere's minimum, which was more widespread under the smaller gradient condition.

This experiment demonstrated that the thermohaline circulation is highly sensitive to inter-hemispheric temperature contrasts. Given that global warming is altering this temperature gradient, particularly due to polar amplification, the study provided critical insight into how future changes in hemispheric temperatures could influence large-scale ocean circulation. This result remains relevant for understanding potential future disruptions in AMOC under climate change scenarios and will be revisited in more detail later.

Following the pioneering work by Manabe and others around the year 2000, several more simulations have been conducted to understand the behaviour of the Atlantic Meridional Overturning Circulation (AMOC). Among these efforts, collaborative projects like the Community Model Intercomparison Project (CMIP) have become important. In these projects, multiple climate modeling groups run standardized climate scenarios using their own coupled models, enabling comparisons across models. This approach helps

researchers assess how sensitive AMOC is to model-specific factors, such as differences in spatial resolution or cloud parameterization.

A significant simulation discussed in this context is the TraCE-21K project (Transient Climate Evolution over the last 21,000 years), conducted by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. This simulation employed a fully coupled ocean-atmosphere model known as CCSM-3. Due to the long time period covered (from 21,000 years ago to 1990) the model was run at a relatively coarse horizontal resolution of approximately 375 km x 370 km, which was a necessary trade-off to keep the computational cost manageable over such a long integration. However, the ocean model used higher resolution, especially in the equatorial region, to better resolve ocean circulation.

The simulation incorporated multiple external forcings, including changes in Earth's orbital parameters (eccentricity, obliquity, and precession), greenhouse gas concentrations derived from ice core records, ice sheet reconstructions from proxy data, and meltwater fluxes inferred from sea-level records along coastlines. Although these forcings were prescribed rather than internally generated by the model, they were based on reliable paleoclimate reconstructions.

A key advantage of using climate models like CCSM-3 is the ability to isolate the effect of individual forcings. In TraCE-21K, NCAR researchers performed a set of experiments where each forcing (orbital changes, greenhouse gases, ice sheets, and meltwater fluxes) was altered separately, while the others were held constant. This decomposition of forcings helped identify the specific contributions of each factor to changes in AMOC and broader climate dynamics. In contrast, such isolation is not possible in the real world, where all forcings change simultaneously. Thus, these model experiments provided valuable insights into the relative roles of different drivers of climate change during the deglacial period.

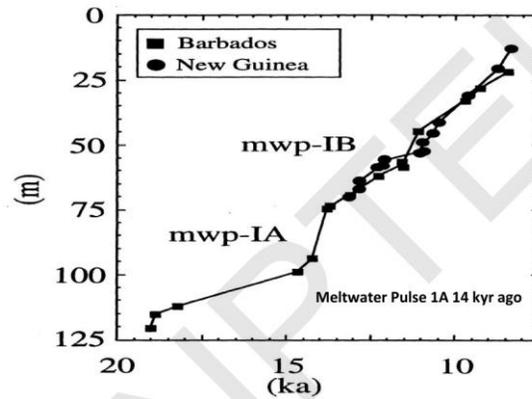
To begin any climate model simulation, it is essential to specify an appropriate initial condition. In the TraCE-21K project, researchers initiated their simulation from a prior model run that had already simulated the Last Glacial Maximum (LGM), approximately 20,000 years ago. By prescribing LGM boundary conditions and running the model for several hundred years, the system attained a quasi-steady state, representing a reasonable approximation of the climate and ocean circulation at that time. From this state, the model was then forced with time-varying inputs, including changes in solar radiation, greenhouse gas concentrations, ice sheet distributions, coastline positions, and meltwater fluxes.

Two key events in the simulation involved reductions in meltwater flux around 14,200 years and 14,670 years ago, aimed at evaluating how freshwater inputs influenced the

Atlantic Meridional Overturning Circulation (AMOC). To further investigate the causes of the Bølling-Allerød warming, a significant and abrupt warming event, additional experiments were performed. These included cases with and without AMOC changes, isolating the respective contributions of carbon dioxide increases and orbital forcing to this warming episode.

The model used in TraCE-21K was a global coupled ocean-atmosphere-sea ice-land surface model with interactive vegetation dynamics. Notably, it did not employ flux adjustment which is a method previously used in older climate models (20–30 years ago) to artificially balance the energy exchange at the ocean-atmosphere interface and prevent long-term model drift. Earlier models required this because they failed to reach a stable equilibrium state, often showing unrealistic trends in ocean temperature. By 2007, model physics had advanced sufficiently to eliminate the need for flux corrections, enhancing the realism and credibility of the simulations.

The atmospheric component of the model operated on a spectral resolution of T31, which corresponds to a horizontal grid of about  $3.75^\circ$  in both latitude and longitude. The land surface component included vegetation types, soil columns, glaciers, lakes, wetlands, and urban areas, all specified in detail. The ocean component, known as the Parallel Ocean Program (POP), had a horizontal resolution of  $3.6^\circ$  globally, but employed increased resolution of  $0.9^\circ$  near the equator to better resolve equatorial ocean dynamics. Additionally, the model included a sea ice thickness component, which is particularly relevant to studies of AMOC and high-latitude climate processes.



**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.

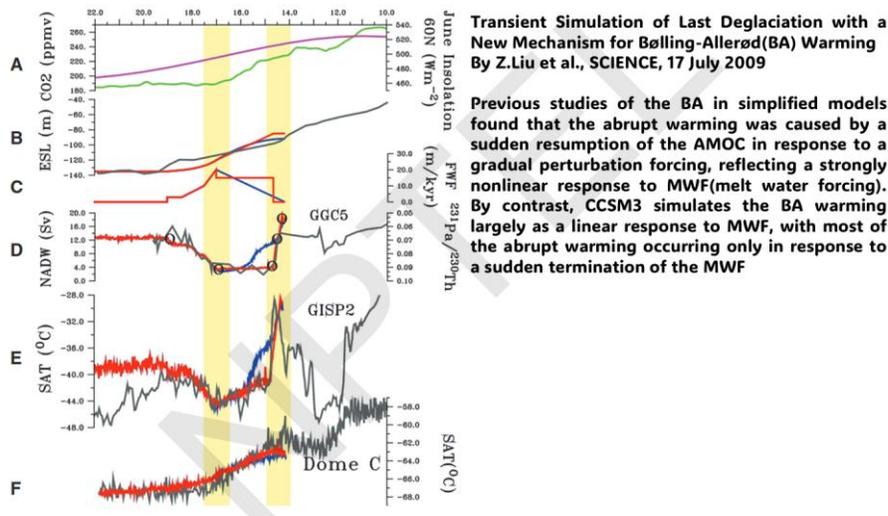
In the above illustration, sea level rise over the past 20,000 years shows that during the Last Glacial Maximum, sea level was approximately 125 meters below present-day levels. This was due to the large volumes of water locked in continental ice sheets. As global temperatures began to rise, the sea level responded with a gradual increase until about 15,000 years ago, after which it experienced two phases of rapid rise, interspersed

with slower periods of increase. These two major episodes of rapid sea level rise are termed Meltwater Pulse 1A and Meltwater Pulse 1B. These pulses are of particular interest because they represent abrupt injections of freshwater into the oceans, significantly affecting ocean circulation and climate, and will be discussed in detail later.

The data underlying these reconstructions come from two independent proxy datasets, derived primarily from geological evidence along former seashores. Although there are small differences between the datasets—an expected outcome given the nature of proxy records—they both clearly show the overall structure of sea level evolution.

In the TraCE-21K simulation, several external forcings were prescribed rather than dynamically calculated. These include the history of greenhouse gas concentrations, which was derived from ice core records, and changes in insolation due to variations in the Earth's orbital configuration, obtained from astronomical calculations. Similarly, ice sheet extents and meltwater discharge histories were specified using paleo-geological and proxy data, particularly from reconstructed sea level records.

The governing equations for the conservation of mass, momentum, and energy were solved using numerical methods on the Jaguar supercomputer at the Oak Ridge National Laboratory, enabling simulation of these complex climate dynamics over millennia. The current focus is on the 22,000 to 14,000 years ago period, with later lectures covering the full 21,000-year span.



The above figure shows few key results from the TraCE-21K simulation, focusing on the causes and responses of the climate system from 22,000 to 10,000 years ago. The topmost graph in the figure presented shows the changes in incoming solar radiation at 60°N, a critical latitude influencing Greenland's climate. Unlike global mean insolation (~1360 W/m<sup>2</sup>), polar climate is driven by regional insolation, which increased

significantly by about  $50 \text{ W/m}^2$  (from  $\sim 470$  to  $\sim 520 \text{ W/m}^2$ ) during this period due to orbital variations of the Earth.

This rise in insolation was accompanied by a significant increase in atmospheric  $\text{CO}_2$ , from about 200 ppm to 260 ppm. The primary mechanism behind this rise was the outgassing of  $\text{CO}_2$  from the warming oceans, as oceanic solubility for carbon dioxide decreases with temperature. This enhanced greenhouse forcing contributed further to global and regional warming.

The sea level curve is also shown, comparing observational proxy data with the model simulation. The model reasonably captures the rise in sea level from about 130 meters below present to 100 meters below by 14,000 years ago. While not perfectly aligned with observations, the simulation captures the main trend and timing of the rise reasonably well.

The third figure presents the evolution of the Atlantic Meridional Overturning Circulation (AMOC), specifically the North Atlantic Deep Water (NADW) formation. The simulation indicates a slight weakening of AMOC followed by a sharp recovery around 14,000 years ago, corresponding to a Heinrich event, which was characterized by massive iceberg discharges disrupting ocean circulation.

The simulation also presents surface air temperature trends in both Greenland and Antarctica. In Greenland, a sharp warming of about  $12^\circ\text{C}$  occurred during the Bølling–Allerød period ( $\sim 14,000$  years ago). This warming is reproduced by the simulation and is consistent with paleoclimate reconstructions. In contrast, Antarctica did not experience this abrupt warming, indicating that this was a regional, not global, climate event.

Furthermore, the simulation reveals asynchronous climate behaviour between the hemispheres. For instance, during the Heinrich event (18,000–16,000 years ago), Greenland cooled due to iceberg-induced freshwater forcing, while Antarctica warmed, suggesting a climate see-saw effect between the hemispheres. This phenomenon occurs because climate processes, including ocean circulation and radiative forcing, operate differently in the north and south.

The hemispheric asymmetry arises from both orbital forcing differences and geographical configuration: the Arctic is an ocean surrounded by land, while the Antarctic is a continent surrounded by ocean, leading to differing responses. The Antarctic is more isolated due to the Antarctic Circumpolar Current, which limits atmospheric and oceanic exchange with other regions. This isolation played a role in phenomena like the ozone hole, where limited mixing prevented dilution of ozone-depleted air. By contrast, the Arctic is more connected, allowing faster atmospheric exchange.

These results highlight the regional complexity of past climate change and the importance of ocean-atmosphere interactions, especially the asymmetric response of the poles, which will be discussed further in upcoming lectures.

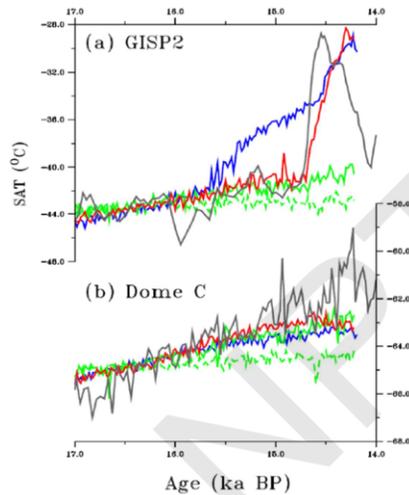


Fig.S4: Temperature (20-year running mean) evolution at (a) Greenland and (b) Dome C from H1 to BA for two sensitivity experiments that are forced the same as in Exp. DGL-A except that the transient  $\text{CO}_2$  ( $\text{CO}_2$  experiment, solid green) and insolation (orbital experiment, dash green) forcing is imposed separately starting at 17 ka. For comparison, the corresponding temperature evolution in the observation (black), Exp. DGL-A (red), DGL-B (blue) are also plotted the same as in Fig.1. It is clear that the warming in DGL-A is caused predominantly by the increase of  $\text{CO}_2$ .

A detailed examination of the simulation results was carried out to understand the role of meltwater fluxes and other forcings in driving the abrupt warming in Greenland during the Bølling–Allerød period. The comparison was made using 20-year average surface temperature data from Greenland ice cores (top panel) and Antarctic ice cores (bottom panel). Two key model simulations were compared: one with a meltwater pulse introduced earlier (blue line) and another with the same pulse introduced later (red line).

The results clearly show that the timing and location of meltwater input significantly affect the temperature evolution in Greenland. In the simulation with early meltwater introduction, Greenland experienced an earlier and more intense warming. In contrast, in the red case with later meltwater input, the warming occurred correspondingly later. This sensitivity emphasizes the importance of freshwater forcing in modulating the Atlantic Meridional Overturning Circulation (AMOC), which in turn controls the heat transport to the North Atlantic and influences the climate over Greenland.

However, the Antarctic region (Dome C) showed minimal response to these freshwater forcings. The red and blue curves for Antarctica differ only slightly, indicating that southern hemisphere climate was largely unaffected by the freshwater events in the North Atlantic. This reinforces the idea that Greenland’s abrupt warming was a hemispherically asymmetric event.

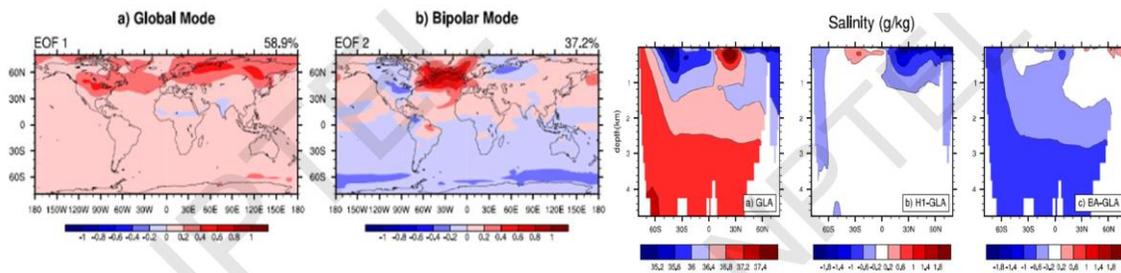
To isolate the roles of different forcings, additional simulations were performed with only carbon dioxide ( $\text{CO}_2$ ) changes, only orbital changes, and only meltwater forcing. The dotted line represents the orbital forcing and the green line corresponds to the  $\text{CO}_2$ -only simulation. Neither orbital variations nor  $\text{CO}_2$  changes alone were able to reproduce the

sharp warming observed in Greenland (shown in black). Only the simulation including meltwater forcing (red) successfully matched the observed temperature rise.

This analysis provides compelling evidence that freshwater input into the North Atlantic and its consequent weakening or disruption of AMOC was the primary driver of the Bølling–Allerød warming in Greenland. The lack of response in Antarctica further supports the concept of hemispheric climate see-saw behaviour, which will be examined in more depth in subsequent discussions.

A research study by Liu et al. provided further insight into the mechanisms behind the transition from the Heinrich event to the Bølling–Allerød warming phase. Their model successfully simulated the abrupt recovery of the Atlantic Meridional Overturning Circulation (AMOC) following its collapse during the Heinrich event, which was triggered by the breakup of large ice sheets. By introducing meltwater fluxes into the North Atlantic, the model reproduced the sharp warming observed over Greenland, similar to the patterns seen in paleoclimate records. However, the simulation also showed an overshoot in warming, particularly in the northern hemisphere, consistent with the modeled feedbacks.

In addition to freshwater forcing, the model highlighted the role of an increase in atmospheric carbon dioxide by about 40 ppm, which also significantly contributed to the Bølling–Allerød warming. From this, the study concluded that the abrupt and brief warming period observed within the broader 20,000-year deglacial period resulted from a combination of localized freshwater discharge and global radiative forcing from increased CO<sub>2</sub>.



The model simulations showed two distinct modes of climate response:

1. A global mode, characterized by warming across much of the globe, particularly in the northern hemisphere. This mode was primarily driven by the increase in CO<sub>2</sub>, which, being well-mixed in the atmosphere, exerts a global radiative effect by trapping outgoing longwave radiation.
2. A bipolar or "see-saw" mode, where Greenland warmed while Antarctica cooled. This pattern arose from freshwater-induced disruption of the AMOC, a regional

phenomenon centered around Greenland. The influx of freshwater from melting North American and Greenlandic ice reduced surface salinity and inhibited deepwater formation, altering ocean circulation patterns and shifting heat distribution between hemispheres.

Furthermore, vertical cross-sections of Atlantic Ocean salinity revealed detailed changes through different climatic phases. During the glacial phase, surface salinity near Greenland was already lower than deep ocean salinity. This contrast intensified during the Heinrich phase due to massive freshwater input, which further freshened the surface and disrupted stratification. In the Bølling–Allerød phase, warming near Greenland reversed this trend, restoring vertical mixing and AMOC strength. Such detailed subsurface oceanographic information, crucial to understanding these transitions, cannot be obtained from proxy data alone, highlighting the importance of climate modeling.