Climate Change Science

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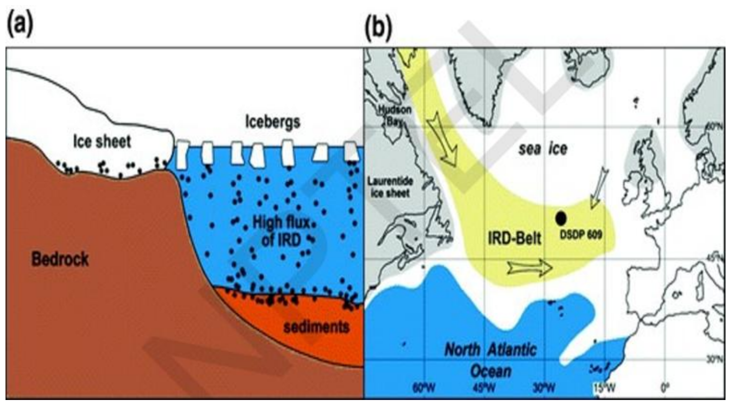
Lecture 26
Atlantic Meridional Ocean Circulation

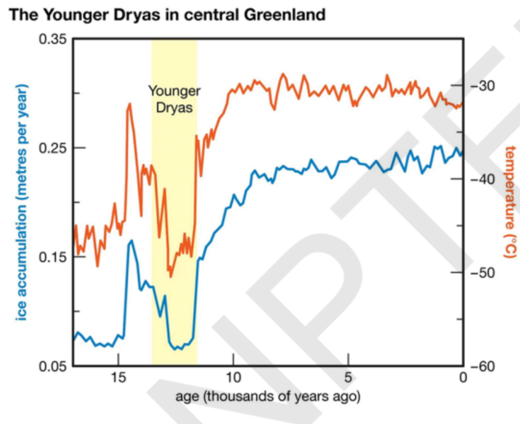
In the previous lecture, the role of ice-rafted debris in reconstructing past climate was discussed. This debris was transported by the Laurentide Ice Sheet, a massive glacial formation over Canada. As this ice sheet advanced toward the ocean's edge, large chunks of ice broke off and floated into the ocean, carrying with them rocks and sediments from the land. When these icebergs melted, the debris sank and accumulated on the ocean floor, forming layers of marine sediments.

By extracting and analyzing these marine sediment cores, scientists can infer changes in Earth's past climate. These marine cores complement the information obtained from ice cores, particularly those collected from the polar regions. Together, ice cores and marine sediment cores are two of the most critical sources of paleoclimate data, enabling researchers to understand the evolution of Earth's climate system over geological timescales. Without these natural records, our knowledge of long-term climate variability would be extremely limited.



An important component of the Earth's climate system is the Atlantic Meridional Overturning Circulation (AMOC), a critical element of the global ocean circulation. This circulation transfers heat from the tropics to the polar regions, helping to balance the uneven distribution of solar energy - since the tropics absorb more solar radiation, while the polar regions lose more heat to space. The AMOC plays a key role in maintaining a relatively stable and livable climate across much of the Earth.

This process is driven by density differences in ocean water, influenced by temperature and salinity. However, there is growing concern that increasing greenhouse gas concentrations, particularly carbon dioxide and methane, could weaken or disrupt this circulation. If the AMOC were to slow significantly or collapse altogether, it could trigger major and abrupt changes in the Earth's climate. Such a disruption could lead to a breakdown of current weather and agricultural patterns, rendering parts of the tropics and mid-latitudes less habitable. Due to its far-reaching implications, the potential collapse of AMOC remains an active area of scientific research and debate, and will be examined further in discussions on future climate scenarios.



The AMOC transports water northward in the top one kilometer of the north Atlantic ocean This water cools when it reaches near Greenland and becomes denser and sinks, and returns south between 2 and 3 km depth as the North Atlantic Deep Water

All the rivers in the world transport about 1 million m³ of water per second(called 1 Sverdrup)

AMOC transports about 20 Sverdrup while the Gulf stream transports about 100 Sverdrup.

A slow increase in CO_2 concentration past a certain threshold may lead to an abrupt AMOC collapse

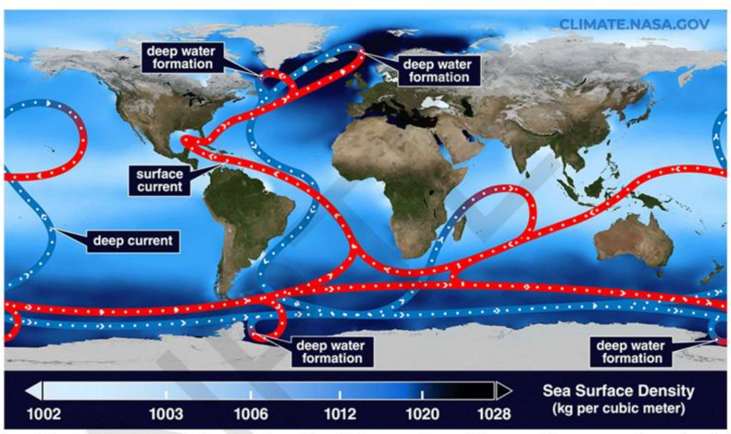
Sources: Lamont-Doherty Earth Observatory at the Earth Institute of Columbia University; and National Research Council, Abrupt Climate Change: Inevitable Surprises (2002).

One of the most significant abrupt climate events in recent Earth history is the Younger Dryas Cold Event, which occurred approximately 13,000 years ago, following the warmer Bølling-Allerød interstadial. Data from ice cores reveal an intriguing relationship between temperature and ice accumulation. Contrary to the common assumption that warmer temperatures always lead to less ice, the evidence shows that ice accumulation actually increases with rising temperature up to a point. This is because snow and ice formation require atmospheric moisture, and warmer air can hold more moisture.

In extremely cold regions like Greenland, where winter temperatures can drop to –60°C, the air contains very little moisture, resulting in minimal snowfall despite sub-zero temperatures. Only when temperatures rise moderately, still below freezing but not extremely cold, does snowfall increase substantially. For instance, a 20°C temperature increase from –50°C to –30°C in Greenland corresponds to a tripling of annual ice accumulation, from approximately 0.05 to 0.15 meters per year. This demonstrates a strong amplification of the hydrological cycle in cold regions as temperatures increase within the sub-zero range. A similar phenomenon occurs in parts of Antarctica, where some areas are so cold and dry that no snowfall has occurred for over two million years. Thus, the accumulation of ice is most efficient under conditions that are cold enough for snow to persist but not too cold for moisture to be present in the atmosphere.

Ocean circulation involves both horizontal and vertical movements of water masses, playing a crucial role in global climate regulation. While the vertical circulation, especially near the poles, is driven by density gradients and results in the sinking of cold, salty water, the ocean also exhibits significant horizontal motion. Water parcels in the ocean often circulate horizontally within gyres for several decades before eventually moving poleward and sinking near regions like Greenland, where they enter the deep ocean circulation. After sinking, these waters take hundreds of years to return to the surface, completing a vast global circulation loop.

The upper 25 to 100 meters of the ocean, known as the mixed layer, is vigorously stirred by winds and surface waves, leading to uniform temperature and salinity in this layer. Below the mixed layer lies the main thermocline, a region where temperature decreases sharply with depth, marking the transition from the well-mixed surface to the deeper ocean layers. Beneath the thermocline, the ocean enters a deep, nearly isothermal layer with relatively constant and cold temperatures. Understanding these vertical and horizontal circulation patterns is critical for grasping how heat, carbon, and nutrients are transported throughout the ocean.



The Atlantic Meridional Overturning Circulation carries cold water from near Greenland (blue line) southward along the seafloor toward Antarctica, while currents nearer the surface transport warmer water northward. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

The above figure is a detailed visualization of AMOC and global ocean circulation produced by NASA, illustrating the intricate pathways through which water moves across the planet. In this depiction, warm, less salty water originating near the tip of Africa travels northward, passing by South America and the east coast of North America, ultimately heading toward Greenland. Notably, although this circulation comes near the U.S. coast, it does not follow the shoreline directly. This distinction is important because another current, the Gulf Stream, operates in this region but is wind-driven, unlike the deep ocean circulation.

The Atlantic Meridional Overturning Circulation (AMOC), unlike the Gulf Stream, is primarily driven by density differences where warm, less saline water cools as it moves north, becomes colder and denser, and then sinks near Greenland into the deep ocean, depicted as a blue stream in the animation. This cold deep water flows southward toward South America, and then moves horizontally along the edge of the Southern Ocean, near Antarctica. From there, one branch moves toward Africa, warms up, and resurfaces, joining circulation in the Indian Ocean and eventually interacting with flows coming over from the Pacific Ocean.

This global circulation involves both horizontal gyres and vertical overturning, but it is the horizontal component that is particularly important for transporting heat from the tropics to the mid-latitudes, thereby helping to regulate Earth's climate. Understanding this complex system is crucial for comprehending how the oceans influence global heat distribution and long-term climate patterns.

It is important to distinguish the Gulf Stream from the Atlantic Meridional Overturning Circulation (AMOC), as they are driven by different mechanisms and follow distinct paths. The Gulf Stream is a wind-driven current that originates near the coast of Florida and flows closely along the eastern seaboard of North America. It then veers eastward into the Atlantic Ocean, where it forms vortices that aid in transporting heat across the ocean to Europe. The Gulf Stream plays a critical role in moderating the climate of both the eastern United States and Europe, making these regions more habitable.

In contrast, the AMOC operates further east in the Atlantic Ocean and is primarily driven by thermohaline circulation - variations in water density due to temperature and salinity differences. Despite their proximity and shared role in transporting heat, Gulf Stream and AMOC are distinct systems. This distinction is often misunderstood or misrepresented in the media, with some reports incorrectly discussing the AMOC as though it were part of the Pacific Ocean, which is inaccurate. Understanding the unique characteristics of both the Gulf Stream and the AMOC is crucial for correctly interpreting their roles in climate regulation and their potential responses to climate change.

The Atlantic Meridional Overturning Circulation (AMOC) is a complex ocean circulation system that involves both horizontal and vertical motion of water masses. It plays a critical role in Earth's climate because it is responsible for transporting large amounts of heat from the tropics to the higher latitudes. Due to its significant influence on global temperature distribution and climate stability, any sudden slowing down or collapse of the AMOC would lead to abrupt and potentially severe changes in Earth's climate. For this reason, the AMOC is a subject of intense scientific study, especially in the context of ongoing climate change and increasing greenhouse gas concentrations.

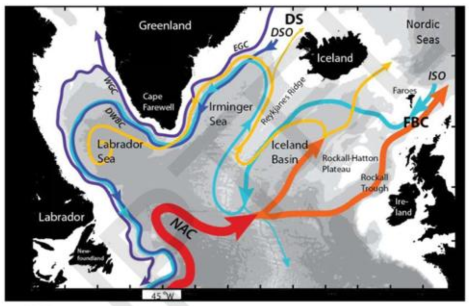
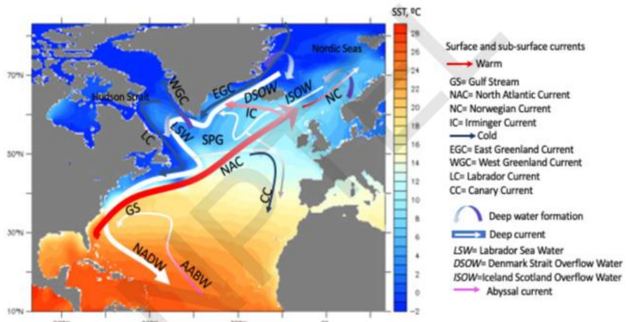
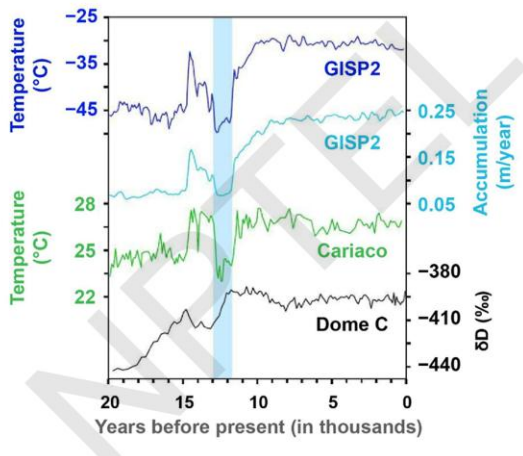


FIGURE 2.1 Schematic of the major warm (red to yellow) and cold (blue to purple) water pathways in the North Atlantic subpolar gyre. Acronyms not in the text: Denmark Strait (DS); Faroe Bank Channel (FBC); East and West Greenland Currents (EGC, WGC); North Atlantic Current (NAC); DSO (Denmark Straits Overflow); ISO (Iceland-Scotland Overflow). Figure courtesy of H. Furey (WHOI).



A closer look at the ocean currents near Greenland reveals a highly complex circulation system involving multiple localized currents. While a simplified explanation of the Atlantic Meridional Overturning Circulation (AMOC) is often used to highlight its role in climate regulation, the reality is far more intricate. Near Greenland, there exist several distinct currents such as the East Greenland Current, West Greenland Current, Labrador Current, and Canary Current, which all interact and influence the behavior of oceanic flow and heat distribution in the region. These currents, though not always emphasized, significantly affect regional climate dynamics and the overall functioning of the AMOC. Accurately simulating these oceanic flows requires high-resolution ocean-atmosphere models, as simple models are insufficient to capture the full complexity. Differences among model predictions often arise because not all models fully incorporate the fine-scale variations in these regional currents, particularly around Greenland, Iceland, and the North Atlantic.

Returning to the ice core data, the Greenland ice core reveals a sharp drop in temperature and ice accumulation during the Younger Dryas event. This cooling was not limited to the high latitudes of the Northern Hemisphere. Proxy records from the Cariaco Basin, located near Venezuela and close to the equator, also show a temperature drop of around 3°C. However, the surprising aspect of this period is that, while the Northern Hemisphere experienced significant cooling, Antarctica and the Southern Hemisphere warmed. This hemispheric asymmetry in temperature change is referred to as the "thermal bipolar see-saw." It indicates an inverse temperature response between the hemispheres during disruptions of the Atlantic Meridional Overturning Circulation (AMOC).



The mechanism behind this phenomenon involves the reduction or shutdown of the AMOC, which usually transports heat from the Southern Hemisphere to the Northern Hemisphere. When this circulation weakens, heat is retained in the Southern Hemisphere, leading to warming, while the Northern Hemisphere cools due to the lack of incoming heat. This pattern was reversed during the Bølling-Allerød warming, when a strong AMOC transported heat northward, cooling the Antarctic region. The Younger Dryas and Bølling-Allerød events clearly illustrate how changes in AMOC strength can drive opposite climate responses in the two hemispheres, underscoring the AMOC's central role in global climate dynamics.

Past changes in the Atlantic Meridional Overturning Circulation (AMOC) reveal that it is not a stable system; rather, it undergoes periods of both high and low heat transport. This instability is of major concern today because anthropogenic emissions of carbon dioxide are causing the Greenland ice sheet to melt, which may further weaken the AMOC, leading to significant impacts on global climate. As a result, climate scientists are deeply focused on understanding the drivers of AMOC variability and its broader influence on Earth's climate system.

To study these complex interactions, researchers rely on climate models of varying complexity. At the most basic level are Energy Balance Models (EBMs), which are useful for estimating global mean temperature but do not capture regional or circulation-specific dynamics. To improve on this, scientists use Earth System Models of Intermediate Complexity (EMICs), which incorporate some aspects of oceanic and atmospheric circulation, allowing for better representation of temperature and heat transport in both the Northern and Southern Hemispheres. These models are more detailed than EBMs, but faster to run than fully coupled models, making them suitable for long-term simulations over centuries.

For the most accurate simulations, especially for complex phenomena like the multiple interacting currents near Greenland, researchers turn to General Circulation Models

(GCMs). These fully coupled ocean-atmosphere models are capable of resolving fine-scale features and capturing the intricate behaviour of currents such as the AMOC. Although they require significant computational resources, GCMs are essential for realistic simulation of regional and global climate dynamics.

All three types of models, EBMs, EMICs, and GCMs, are necessary for a comprehensive understanding of Earth's climate. Each provides unique insights at different levels of complexity and resolution. Therefore, a combination of these models is employed to study key events like the Younger Dryas and Bølling-Allerød transitions in Earth's climate history.

It is important to emphasize that predictions from complex climate models should not be accepted blindly. Despite their sophistication, these models are often so intricate that users may fail to fully grasp their output. This concern is best captured by Nobel Laureate Syukuro Manabe, who famously stated that *"prediction of climate change without understanding is no better than prediction of a fortune teller."* This quote underscores the necessity of interpretability and physical understanding behind model predictions. In an era where machine learning and artificial intelligence are increasingly used which often function as black boxes, it becomes even more critical to ensure that predictions are rooted in fundamental physical principles. While these models may provide accurate outputs due to training on large datasets, their lack of transparency makes them unreliable if not well understood.

Complex climate models contain numerous approximations and cannot resolve all relevant scales, especially small-scale phenomena such as those occurring over kilometer scales. As such, even the best models can sometimes produce physically unrealistic results. This is why scientists advocate a balanced approach, combining observations, complex models, and simple models to obtain a more reliable understanding of Earth's climate.

Observational data, particularly proxy data, plays a crucial role in reconstructing past climates. However, proxy data also comes with limitations. To derive variables like temperature, rainfall, or ocean circulation from proxies such as tree rings or sediment cores, scientists must make assumptions often based on present-day analogues, which may not hold true in past climate conditions. Additionally, dating proxy records is challenging. Errors in estimating the timing of past events, sometimes as large as 100,000 years, can arise due to uncertainties in sediment deposition rates or the radioactive dating techniques used.

One way to increase confidence in proxy reconstructions is to use multiple independent proxies, known as multiproxy data. When different proxies converge on the same conclusion, it lends greater credibility to the reconstruction. Even so, to overcome the inherent uncertainties, climate scientists supplement proxy data with model simulations. This combined approach of using simple models, complex models, and proxy observations provides a more robust framework for understanding past and future climate changes.

In the next lecture, the focus will shift to examining climate changes over the past 20,000 years, analyzing how these changes have been inferred from proxy data and how well both simple and complex models reproduce them. This integrated understanding will strengthen our ability to interpret and predict Earth's climate behaviour.