OCEAN COLLAPSE? HISTORICAL, CONTEMPORARY, AND PHYSICAL BASIS OF THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC)

SUMMARY: This paper examines how scientific understanding of the AMOC has evolved, key physical processes that sustain it, and what observations and models suggest about its future.





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The 2004 Science Fiction disaster film "The Day After Tomorrow" depicted the world instantly plunged into an Ice Age with the cessation of the "North Atlantic Current". While highly exaggerated, such narratives reflect a broader and persistent concern: the stability of the Atlantic Meridional Overturning Circulation (AMOC). In recent years this concern has been amplified by recurring coverage in the mainstream media suggesting the possibility of a rapid AMOC collapse, including coverage from The Guardian [1], the New York Times [2], the Globe and Mail [3], and the CBC [4]. While at times sensational, the coverage underscores the significant role that ocean circulation plays in the climate and the uncertainty surrounding its future behavior under anthropogenic forcing.

Ocean circulation is driven by a combination of boundary processes (wind stress, solar heating, evaporation, precipitation, and bottom friction) together with internal fluid dynamics (pressure gradients, viscosity, and convective instabilities). These motions are fundamentally shaped by fluid flow on a rotating sphere, where Earth's rotation and orbital geometry influence circulation across a wide range of spatial and temporal scales. Although the oceans are geographically distinct, they are connected through a global network of currents that redistributes heat, salt, nutrients, and carbon throughout the climate system.

The AMOC is a part of this network of currents and is a system of meridional (north–south) overturning circulation that links surface and deep ocean flows in seas adjacent to the North Atlantic (Labrador and Greenland-Irminger-Norwegian (GIN)) through the decadal variations of western boundary currents in the sub-polar North Atlantic [5] and interactions between currents and ocean bottom topography [6].

Surface circulation, primarily driven by wind, fluctuates at time scales of days to decades within an ocean basin. Deep ocean circulation, principally propelled by Southern Ocean winds and modulated by buoyancy changes in the sub-polar North Atlantic, spans the globe and has response timescales of decades to millennia. Thus, AMOC circulation strength is not solely controlled within the North Atlantic but derives much of its energy from the Southern Ocean, where wind-driven upwelling and abyssal-water formation regulate the return pathway of deep waters that ultimately feed the Atlantic overturning circulation. Figure 1 simplistically depicts the structure, pathways, and drivers of the global meridional overturning circulation.

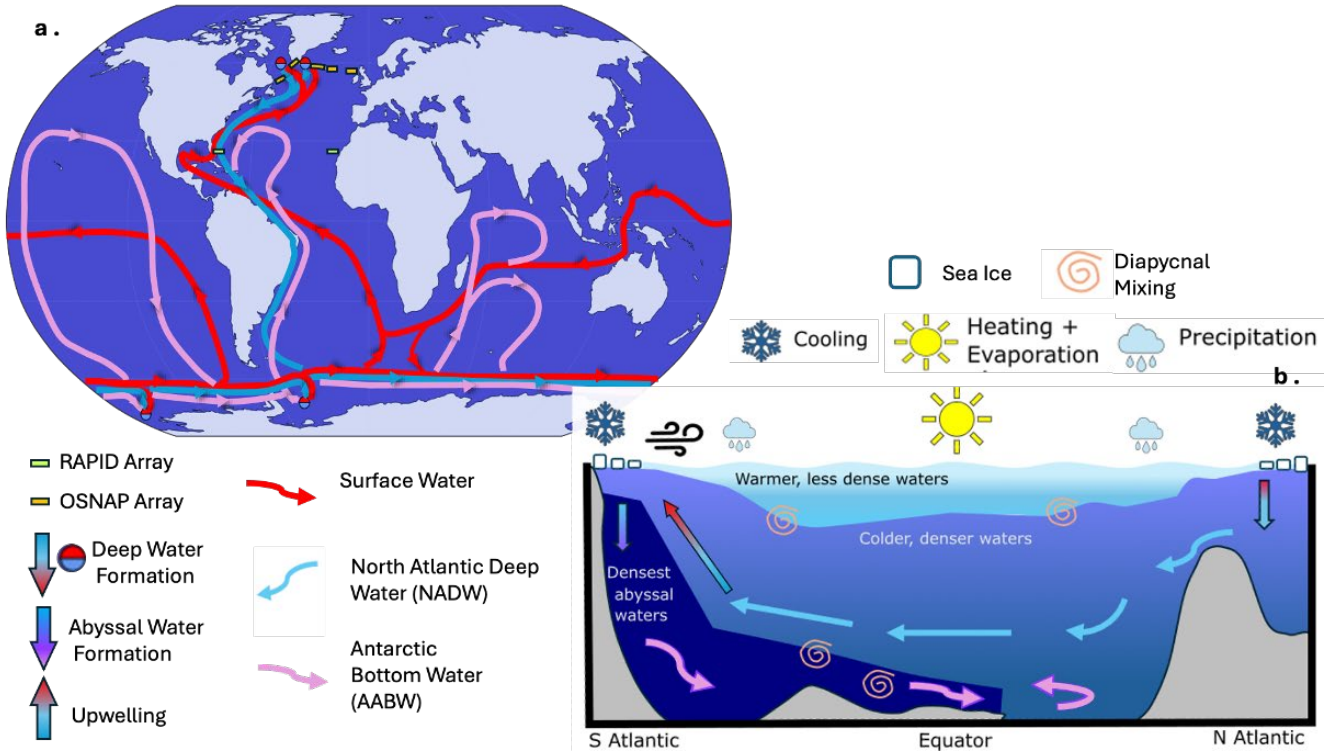


Figure 1. Conceptual diagrams of meridional overturning circulation. a. Global map, modified from [7], with warm/surface circulation (red), cold/deep circulation (blue), and abyssal circulation (pink). Circles indicate regions of deep-water formation. The locations of the RAPID (yellow) and OSNAP (gold) observational arrays are shown. b. Meridional depth section of the Atlantic Ocean, modified from [5], showing key physical processes controlling overturning circulation and their locations in the basin.

The strength and structure of the AMOC depend on the climate; warm climates generally support a stronger, deeper AMOC while glacial climates favor a weaker, shallower circulation. Yet, climate models show that the AMOC can behave in different ways under the same external conditions, including transitions between multiple stable states or natural oscillations between strong and weak

circulation. AMOC collapse, a state where the average current strength is reduced by 70-80%, has happened before during transitions from ice age climates to warm climates, through the stratification of the water column with the release of fresh water from retreating ice sheets.

Atlantic Canada's ecosystems, communities, and cultures, from the First Peoples of Turtle Island through to present inhabitants, are connected to the ocean. The meeting of warm Atlantic currents with the cool Labrador Sea supports a rich marine ecosystem. With AMOC shaping ocean conditions, weather patterns, and the global distribution of heat and nutrients, concerns about its changes are heightened by the risks of stronger hurricanes, increased storm surge, and impacts on coastal livelihoods. Here, we provide a brief introduction from the historical to present understanding of the AMOC, the underlying physics, and discuss what might happen in the future.

HISTORICAL TO PRESENT AMOC

Understanding of the AMOC has developed incrementally, beginning with observations of its surface expression. The Gulf Stream, the surface limb of the AMOC, was first noted in European records by Spaniard Juan Ponce de León in the 16th century and later charted by Americans Benjamin Franklin and Timothy Folger in 1768. Progress in understanding ocean circulation accelerated in the late 19th and early 20th centuries. Observations from high Arctic expeditions by Scandinavian explorers Nansen and Sverdrup informed the theoretical work of Vagn Walfrid Ekman, whose formulation of wind-driven surface transport laid the foundation for modern physical oceanography.

Despite these advances, the AMOC remained poorly characterized until the mid-20th century. The post–World War II period marked a turning point, driven by improved bathymetric mapping and expanded hydrographic observations. Pioneering theoretical work by Henry Stommel validated by observational data collected by Walter Munk integrated wind-driven and thermohaline processes, providing the first coherent framework for basin-scale and global ocean circulation.

Integrating decades of ocean chemistry observations and marine sediment core research, Wally Broecker introduced the term "The Great Ocean Conveyor" in the mid-1980s to describe the global ocean circulation that redistributes heat and proposed that it could switch on and off. Later work attempting to identify the energetic drivers that sustain this global circulation led to the identification of wind-driven Southern Ocean upwelling as fundamental to Atlantic overturning. This led to a change in terminology from thermohaline circulation to meridional overturning circulation [8-11].

Contemporary understanding of the AMOC comes from observational data obtained at different locations in the circulation. In the Florida Strait, at 26.5°N, there is the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID) which has been collecting hourly data on a series of vertical moorings since 2004, complemented by ocean glider data [12]. This location is where peak northward transport of the surface component of the circulation is observed due to the narrowing of the Gulf Stream current through the Florida Strait. Farther to the North is the Overturning in the Subpolar North Atlantic (OSNAP) arrays; deployed in 2014, they consist of two mooring arrays and a series of float and ocean glider data spanning 52-60°N [13]. The OSNAP arrays are located to

enable observations of both the surface transports as well as deep-water return flows, from which deep-water formation rates can be estimated. With the OSNAP arrays, there is the ability to compare between the two North Atlantic sites of deep-water formation, the Labrador Sea and the GIN Seas.

These two data sets have provided immense insight into the variability of the AMOC. The average AMOC strength is ~17 Sverdrups (Sv, with 1 Sv = 10^6 m^3 s^{-1}), and the data captures the seasonal and inter-annual high frequency fluctuations of the current (Fig. 2). However, observational records span at most two decades and may therefore fail to capture the original state of the circulation and instead may observe the circulation already in a state of decline. Ocean transport operates on long timescales; a parcel of water in the deep and abyssal circulation can take on the order of ~2000 years to complete a full circuit of the global ocean, further complicating our understanding of the state of the system.

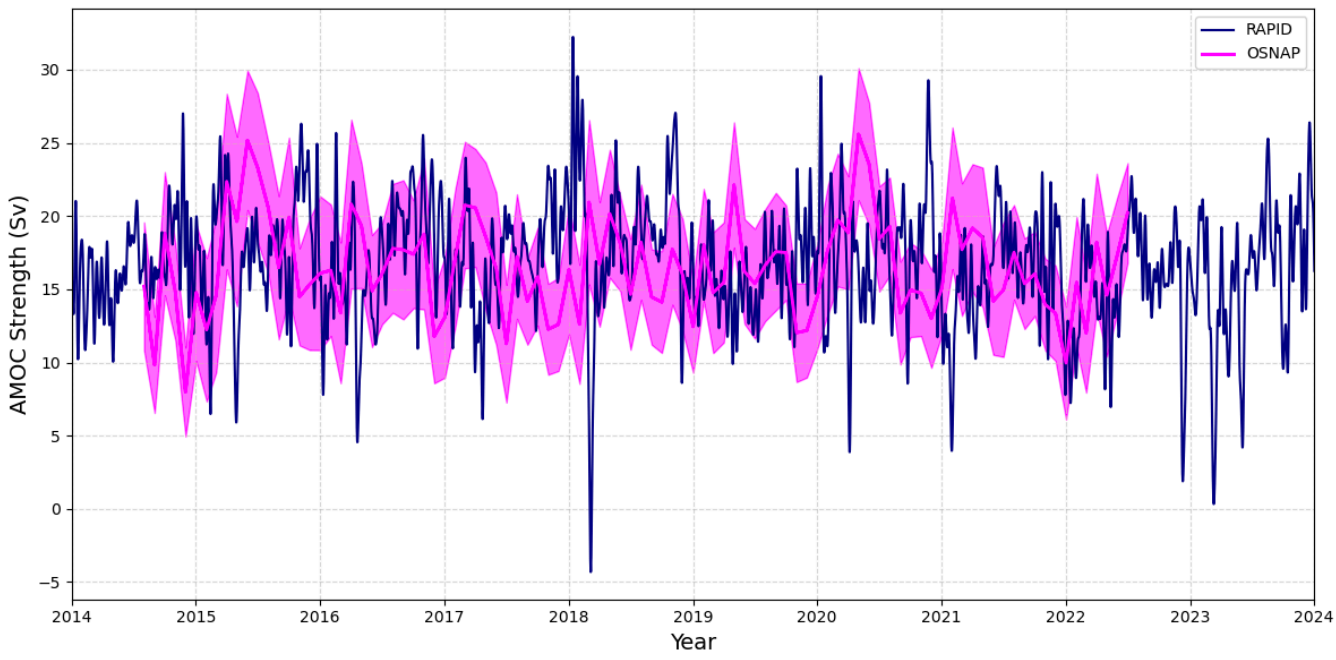


Figure 2. Meridional Overturning Circulation strength data from RAPID (navy) and OSNAP (magenta) from 2014 to 2024.

The emergence of geophysical fluid dynamics combined with increasing computational capacity enabled the transition from observations and simple theoretical models to robust quantitative modeling of the global overturning circulation through ocean General Circulation Models (GCMs). Modeling can bridge the gap between limited present and historical data and provides a physics-based understanding as to how changes in the current transpire. Ocean models provide our current understanding of the AMOC's sensitivity to climate change and the timescales over which it responds.

AMOC PHYSICS

The physics of the AMOC is complex. While these descriptions capture the large-scale circulation, they omit seasonal variability and smaller-scale processes such as eddies, tidal turbulence, and other energetically significant features found along boundary currents and in individual basins. Surface Western Boundary currents can be found in all ocean basins, including the Kuroshio in the Pacific and the Agulhas in the Indian Ocean. Likewise, there are multiple locations globally where deep-water forms, such as the Weddell and Ross Seas in Antarctica. What makes the AMOC unique is that it links wind-driven surface circulation in the Atlantic Ocean to deep-ocean circulation through high-latitude overturning convection. It is driven by a combination of wind forcing, buoyancy forcing (associated with temperature and salinity contrasts), and diapycnal mixing. These forcings interact nonlinearly.

Upwelling in the Southern Ocean supplies much of the water that feeds the upper branch of the AMOC. Strong westerly winds coupled with diapycnal mixing (interactions between stratified flow and rough topography) over the Southern Ocean drive Ekman transport, causing surface waters to diverge, and be replaced by deep water that upwells to the surface. Once at the surface, this water is transported northward through the Atlantic by the wind-driven subtropical gyre, where it is warmed and becomes increasingly saline through evaporation. As the flow approaches the western side of the basin, it is concentrated into a narrow, fast current by western boundary intensification, first described by Stommel [14]. This produces the Gulf Stream, which transports warm, saline water poleward along the eastern coast of North America before the water eventually reaches the high-latitude North Atlantic.

Thermohaline circulation is dependent on the nonlinearity of the equation of state for sea water. As water moves north in the Atlantic it cools and the density increases. Wintertime sea ice formation continues to increase the density of high latitude water through brine rejection, increasing sea water salinity and decreasing stratification of the water column. The resulting dense waters in the top 1000 m of the water column sink and form North Atlantic Deep Water (NADW) that moves towards the equator as the southward-flowing limb of the AMOC, connecting the Atlantic to the global circulation. This process occurs primarily in the Labrador Sea and in the GIN Seas. While flowing south, NADW can continue to increase in density as it interacts with Antarctic waters to further sink and form a component of Antarctic Bottom Water (AABW). Alternatively, NADW may upwell in the Southern Ocean, returning to the surface in processes described previously.

AMOC FUTURE

In a warming climate, the future response of the AMOC is complicated by competing mechanisms. Deep-water formation will be maintained or enhanced by increased evaporation, enhancing surface salinity and density of the surface water, supporting overturning. However, deep-water formation will decrease through increased stratification through ocean warming and increased freshwater input from melting Greenland and Antarctic ice sheets. Additionally, with increased water temperature less sea ice forms, reducing brine rejection and decreasing the production of dense waters that contribute to deep-water formation. Some factors can have opposite effects depending on the timescale analyzed. For example, a sustained positive phase of the North Atlantic Oscillation can have an immediate reducing effect on the AMOC followed by a strengthening effect approximately a decade later [15,16].

Modeling of past episodes of AMOC collapse (strength of ~5 Sv, 70% reduction of 17 Sv) were largely driven by the release of fresh water from the retreat of continental ice sheets in North America and Eurasia. The meltwater fluxes into the North Atlantic and Arctic Oceans were far greater than those expected from modern Greenland melt and strongly freshened and stratified the upper ocean. Importantly, these events occurred during deglaciations, when large ice sheets were retreating and the climate system was transitioning from glacial to interglacial conditions, rather than within our current warm state. This challenges the use of historical collapse for projections of the AMOC.

Although observational records remain relatively short, removing high frequency variability from the RAPID and OSNAP arrays suggests that the AMOC is declining by 0.6–1.4 Sv/decade [17]. Coordinated climate model experiments assessed by the IPCC project forecast continued AMOC weakening across all future socioeconomic pathways throughout the twenty-first century, with current strength declines ranging from approximately 10–50% by 2100 [18]. Baker *et al.* [19] analyzed 34 climate models and found that although the AMOC weakens substantially under extreme greenhouse gas and freshwater forcing, Southern Ocean wind-driven upwelling prevents a complete collapse by sustaining a reduced overturning circulation. In several models, prolonged AMOC weakening also promotes the development of a Pacific Meridional Overturning Circulation (PMOC), suggesting that deep-water formation can shift from the Atlantic to the Pacific under sufficiently altered climate conditions. However, model projections remain uncertain due to differences in how key oceanic and atmospheric processes are represented, particularly those governing deep-water formation, mixing, and freshwater forcing. In addition, the IPCC models likely underestimate or incompletely represent freshwater input from Greenland Ice Sheet melt, which may influence the magnitude of future AMOC weakening.

Not all modeling work suggests long term collapse. Nobre *et al.* [20] demonstrated that greenhouse warming can produce a pronounced but reversible AMOC weakening, highlighting the roles of Arctic sea-ice loss, freshwater input, and salt advection in controlling overturning circulation. Additionally, the grid resolution of the ocean model also impacts the resulting AMOC circulation. Modeling work by Pennelly and Myers [21] at an unusually high resolution of $1/60^{o}$ in the Labrador Sea indicated mesoscale and sub-mesoscale eddies control the mixing of coastal freshwater into the interior of the Labrador Sea. Coarser-resolution models do not explicitly resolve these eddies and instead tend to overestimate freshwater exchange across the shelf break, which could amplify the slowdown of the AMOC in their model results.

Predicting the future behavior of the AMOC, both near and long term, remains difficult; anthropogenic warming may be pushing the system beyond conditions previously experienced during the paleoclimate record. Past AMOC variability may not fully constrain the future response. Foundational, theoretical work done by Stommel [22] proposed that overturning circulation may possess multiple stable states, including the modern vigorous circulation and weaker salinity-driven mode. Once the transition between bistable states is made it could be very hard to reverse. While the magnitude and timing of future AMOC change remain uncertain, climate warming is expected to alter overturning dynamics. The AMOC strongly influences Canadian climate and ocean conditions, and continued research spanning paleoclimate reconstructions, modern observations, and future projections remains

essential to assess the range of possible outcomes. Unlike "The Day After Tomorrow", however, any AMOC weakening would unfold over decades to centuries and is expected to produce regional climate changes rather than an abrupt transition to an ice age.

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