State of the Science FACT SHEET

Atlantic Meridional Overturning Circulation (AMOC)

Scientists and communication experts from the National Oceanic and Atmospheric Administration (NOAA) developed this assessment of the Atlantic Meridional Overturning Circulation (AMOC).

The AMOC is the Atlantic Ocean component of the global Meridional Overturning Circulation, which is sometimes also referred to as the global ocean conveyor belt (Fig. 1). The AMOC carries relatively warm and salty upper ocean waters to the high-latitude North Atlantic and then to the Arctic, releasing heat into the atmosphere over the high-latitudes. As such, the warm and salty water cools along its path northward becoming denser, and sinking to form cooler deep water in the high-latitude North Atlantic. The newly formed deep water then moves southward and is slowly (over hundreds to thousands of years) transformed into upper ocean waters through mixing and upwelling in the Indo-Pacific and Southern Ocean. The AMOC transports heat, salt, carbon, nutrients, and other properties across the basin, meaning that variations in the AMOC's strength (commonly measured by the volume of upper ocean water transported northward in unit time) impacts sea level, marine ecosystems, shift temperature and precipitation patterns, and extreme weather. Thus, changes in the AMOC can significantly impact society.

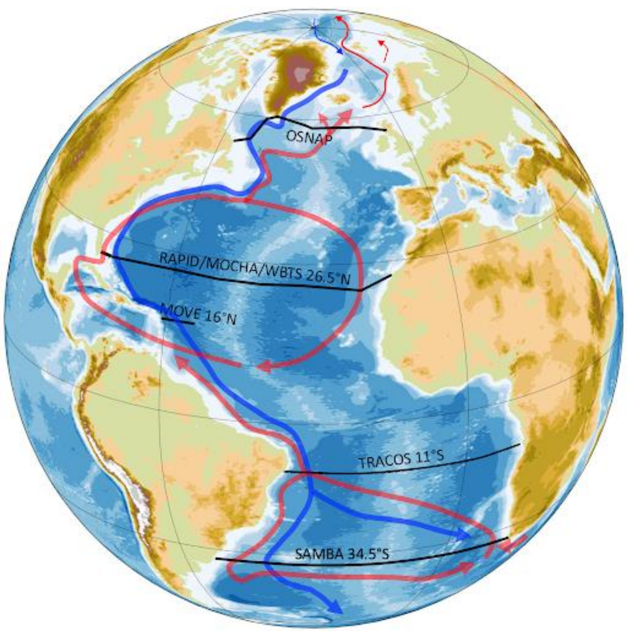

Fig. 1. The idealized schematic of the Atlantic Meridional Overturning Circulation (AMOC) represents the pathways of the upper (red) and lower (blue) limbs of the overturning circulation over the bottom topography (blue shading). Continuous AMOC observing arrays for transport estimates (black lines) are also listed. Modified from Figure 3.20 in Volkov et al. (2020a).

How does NOAA observe the AMOC and what do those observations show?

To monitor the AMOC, NOAA and many national and international partners observe ocean properties such as temperature, salt content, and dissolved oxygen concentration, from the ocean surface to sea floor, and measure ocean currents, surface winds, sea level, and ocean pressure variations. Most of these measurements are collected by using free-floating devices dispersed from ships, repeated hydrographic cruises, arrays of buoys at fixed locations, and other observing platforms including satellites. Along with its partners, NOAA uses trans-basin moored arrays in the South Atlantic (34.5S) and North Atlantic (26.5N) to directly measure AMOC changes in both hemispheres. NOAA also conducts sustained monitoring of key AMOC components in the subtropical North Atlantic, such as the Florida Current (i.e., the Gulf Stream across the Florida Channel), Antilles Current, and Deep Western Boundary Current at various latitudes. AMOC studies rely upon these direct measurements for ocean and climate model validation. There are several other trans-basin mooring systems operated by national and international oceanographic institutions (Fig. 1).

Most observational records agree on the average strength of the AMOC, which is roughly 16-18 million tons of water per second flowing northward in the upper ocean and southward in the deep ocean across both 26.5N and 34.5S. AMOC observations to date are beginning to show decadal-scale variations. However, observational evidence for a long-term trend across the entire Atlantic is yet to be established as most direct observations of the AMOC have not been collected for a long enough period to detect a statistically significant trend. The longer-term observations of the Florida Current at 26.5N, which carries the bulk of the northward transport in the upper limb of the AMOC in the subtropical North Atlantic, suggest that the current has remained remarkably steady over the last four decades.

How will the AMOC respond to increasing greenhouse gases?

The AMOC's response to changing radiative forcing has been simulated in climate models. As the Earth warms, sea- and land-based ice melts, adding buoyant freshwater to the surface of the North Atlantic and thus decreasing salinity. Rainfall may also increase, further decreasing salinity. Along with warming in the upper ocean, the decreasing salinity reduces the density of the upper ocean in the North Atlantic. The lighter water in the upper ocean reduces sinking, and in turn the amount of deep water that is produced is reduced, thus slowing down the AMOC. Sustained freshening to the decrease in salinity and warming of the North Atlantic is projected to lead to significant weakening of the AMOC. Evidence from the paleoclimatic record suggests that the AMOC may have been shut down during the last deglaciation around 17,500 years ago when portions of a massive ice sheet that covered Canada and the northern United States rapidly melted, thereby flooding the North Atlantic with massive amounts of fresh water.

The climate models assessed by the Intergovernmental Panel on Climate Change (IPCC) project a weakening AMOC in the future, but none showed a collapse before 2100. The IPCC concludes, with "medium confidence", that an abrupt collapse of the AMOC before 2100 is "very unlikely". However, the models do project a gradual weakening in the AMOC throughout the 21st century (34-45% reduction in strength by 2100) as stated by Weijer et al., 2020 and supported by the IPCC report (2021).

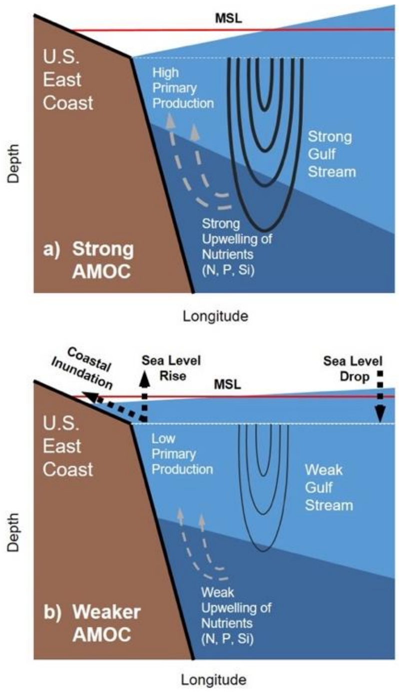

Fig 2. Idealized schematic of the AMOC's impacts on the Gulf Stream and associated sea level, nutrient upwelling, and primary production along the U.S. East Coast. The Gulf Stream strength is proportional to the cross-shore slope of sea level, with sea level off Florida being (on average) ~70 cm lower than off the Bahamas (Volkov et al. 2020b). A weakening of the AMOC, and an associated slow-down of the Gulf Stream, is accompanied by a decrease in the cross-shore sea level gradient leading to additional rise in sea level and potential increased coastal inundation along the U.S. East Coast. This coastal sea level rise is in addition to the larger scale projected mean sea level (MSL) rise due to thermal expansion and polar ice melt. Note that even if the AMOC collapses, the Gulf Stream would weaken - but would not cease to flow - as it is also driven by basin-scale wind fields. Changes in the AMOC would also contribute to a reduction in upwelling nutrients, such as Nitrate (N), Phosphate (P), and Silicate (Si) from deeper water (dark blue), leading to a reduction in coastal primary production.

What impacts will changes in the AMOC have on air temperature, sea level, marine ecosystems, and extreme weather?

As ocean water sinks in the high-latitude North Atlantic, it sequesters CO_2 (carbon dioxide) that it has absorbed at the surface and transitions it to the deep ocean. Through mixing and upwelling processes, the deep carbon-rich water is then returned to the surface. If the AMOC were to weaken, the rate at which CO_2 is absorbed into the deep ocean would decrease, leaving more CO2 to be emitted in the atmosphere and available to accelerate global warming.

A slowdown in the AMOC would be accompanied by a weakening and northward shift of the Gulf Stream and a weakening of the Northern Recirculation Gyre north of the Gulf Stream, which in turn leads to both an increase in sea level and a suppression of ocean upwelling of key nutrients along the North American east coast, negatively affecting the functions and services from regional marine ecosystems (e.g., fisheries) and the coastal communities and economies that depend on them (Fig. 2). Year-to-year variations in sea level along the US Southeast and Gulf coasts can also be forced by basin-scale ocean heat content changes associated with the wind-driven AMOC variations (Volkov et al., 2019).

A significant change in AMOC strength would also influence regional weather patterns, potentially leading to altered precipitation, more frequent droughts, or changes in storm intensity and tracks. These changes could impact agriculture and water resources, posing challenges for communities and economies.

How should research be directed to improve understanding and predictive capabilities of the AMOC?

To better monitor and prepare for the future change in the AMOC, it is important to maintain the existing observational systems (Fig. 1.) and develop a cost-effective and enhanced observing network across the Atlantic Ocean that can detect where AMOC changes originate and can be used to study the processes by which those changes will spread throughout the Atlantic, and potentially globally. These observations will continue to be used to validate and improve models, and will serve as indicators of AMOC weakening or signs of potential collapse. It is also crucial to focus on improving the models that are used to simulate the current state and future evolution of the AMOC and its impacts. Improvements will come from enhancements in ocean physics, biogeochemistry, representation of land-ice and ocean coupling, and the number of simulations that characterize potential future conditions. Increased model resolution improves the simulation of small-scale ocean eddies and other features, such as dense water formation and the interactions with ocean topography, that impact ocean circulation and the AMOC.

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