

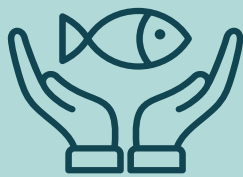


ACEAS

Australian Centre for Excellence
in Antarctic Science



What is the
Meridional Overturning Circulation
and why is it important?



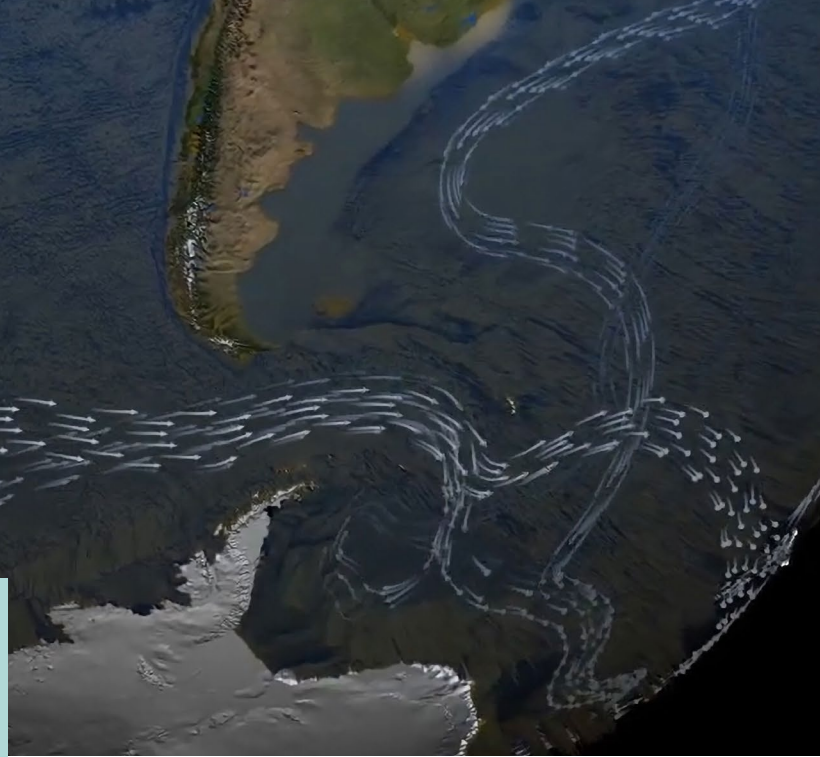
The Meridional Overturning Circulation transports heat, salt, nutrients and carbon throughout the oceans, regulating our climate and supporting marine ecosystems and fisheries.



The Meridional Overturning Circulation depends on changes in seawater density, with the sinking of dense water in the North Atlantic and the Southern Ocean contributing to powering the circulation.



The circulation is weakening in response to climate change, and it will continue slowing down in the future, with significant consequences for our climate.



Introduction

The Meridional Overturning Circulation (MOC) is a system of ocean currents that circulate water across the globe. Just as blood circulation transports oxygen, nutrients and heat throughout our bodies, the MOC moves oxygen, nutrients, heat and carbon throughout the oceans, regulating our climate and sustaining ocean life.

The strength of the MOC depends on changes in seawater density, which is controlled by temperature and salinity – cold or salty water is denser and sinks, while fresh or warm water is less dense and tends to stay at the surface. The North Atlantic and the Southern Ocean are two key regions of the MOC where dense, cold, salty water sinks.

However, with climate change and melting ice sheets in Antarctica and Greenland, significant amounts of freshwater are added to these regions, disrupting the formation of dense water and weakening the MOC. Climate and ocean model simulations alongside observations suggest that the MOC has weakened in both the North Atlantic and the Southern Ocean over the past several decades.

The MOC is expected to keep slowing in the future and could weaken by nearly 50% within the coming century, with significant consequences for our climate. If the circulation were to shut down – which is unlikely to happen this century, but is projected to occur for unmitigated climate change beyond 2100 – these impacts could become even more severe.

Here, we explore the importance of the MOC and discuss the implications of its weakening or potential shutdown under future climate change.

An overview of the MOC

In the Atlantic Ocean, surface currents such as the Gulf Stream transport warm, salty water from the tropics towards the North Pole (Figure 1). As this salty water travels polewards, it cools and becomes denser. When it reaches the high latitudes in the North Atlantic, particularly the Norwegian and Labrador Seas, it becomes very cold and sinks to depth, forming a deep water mass known as North Atlantic Deep Water (NADW). This cold, dense water flows southward through the Atlantic Ocean towards the Southern Ocean.

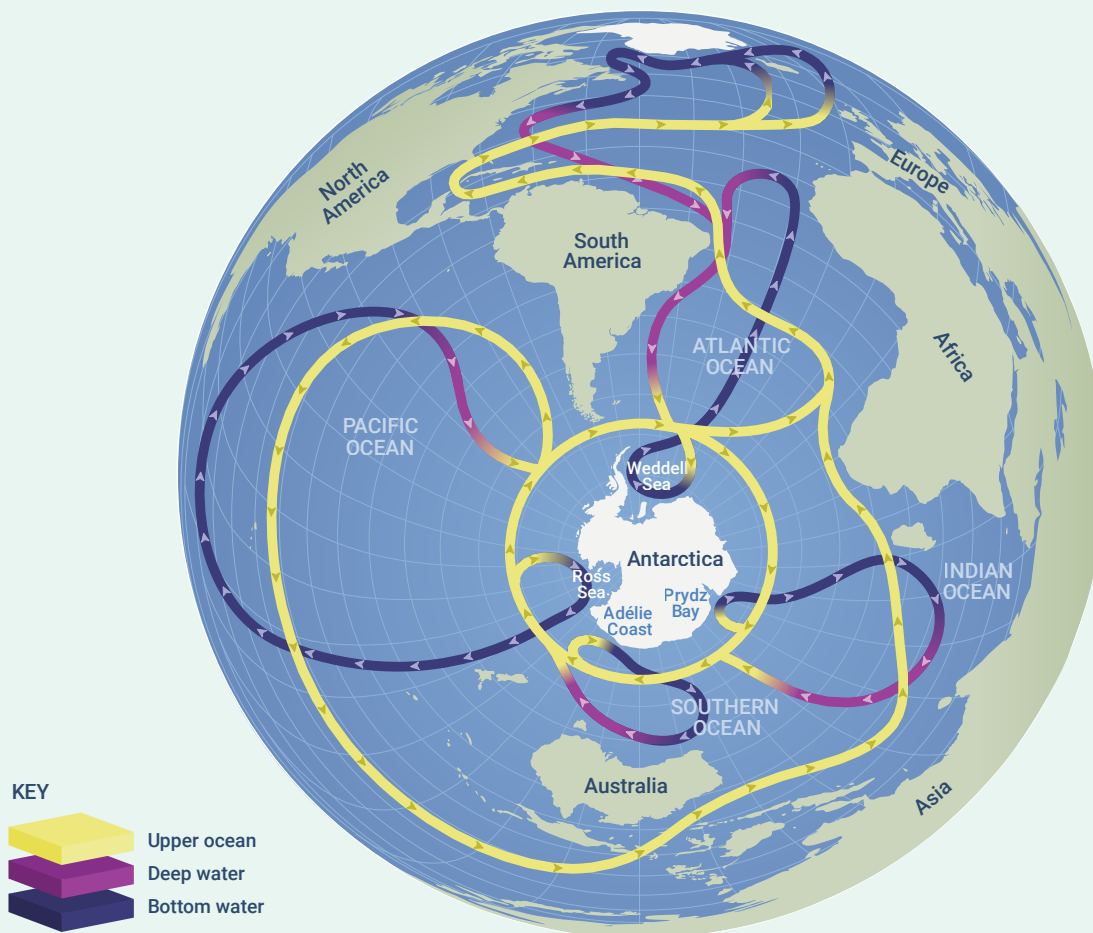


Figure 1. Overview of the circulation. This simplified schematic shows the main flow pathways across the world's oceans at different depths: surface waters are shown in yellow, while deep and bottom waters are highlighted in purple and dark purple, respectively. Credit: ARC Australian Centre for Excellence in Antarctic Science

In the Southern Ocean, the NADW mixes with other water masses and rises towards the surface. This mixture of water masses, known as Circumpolar Deep Water (CDW), circles around Antarctica. Some of the CDW also makes its way towards the very cold regions of the Antarctic coast. At specific coastal regions, including the Weddell and Ross Seas, the Adélie coast and Prydz Bay, the combination of intense winds and sea ice formation produces an extremely dense, cold, and salty water mass known as Antarctic Bottom Water (AABW). The AABW sinks to the ocean abyss and then spreads northwards along the seafloor into all the ocean basins, filling approximately 40% of the global ocean's volume. As it travels northwards, AABW mixes with other water masses, and most of this mixture eventually resurfaces in the Southern Ocean, where it either flows north to eventually return to the North Atlantic, or south to contribute to new AABW production.

The Atlantic part of the MOC is known as the Atlantic Meridional Overturning Circulation (AMOC), and the part occurring in the Southern Ocean is often referred to as the Antarctic Meridional Overturning Circulation, or also as the Abyssal Overturning Circulation. While the AMOC is better known than its Antarctic counterpart, both circulations form key branches of the global MOC, with the sinking of water masses in the North Atlantic and the Southern Ocean playing an important role in global circulation, biogeochemistry and climate. It is important to note that the MOC is a large and slow global circulation with water often taking about a thousand years to complete a full circuit.

Why is the MOC important?

Climate regulation

The MOC helps to maintain the balance of heat and energy between different regions of the planet. The MOC transports warm tropical surface waters polewards and cold water from the high latitudes equatorward. The poleward transport of warm water in the Atlantic Ocean via the Gulf Stream helps maintain Western Europe's mild climate. Without this transport, Europe would experience significantly lower temperatures. By balancing heat between the Northern and Southern Hemispheres, the MOC also influences weather patterns, storm tracks and the location of the Intertropical Convergence Zone (ITCZ) – an intense rainfall belt in the tropics.

Oxygen, nutrient and carbon cycling

Oceans contain oxygen, nutrients and carbon, supporting diverse ecosystems. The MOC plays a vital role in redistributing these elements across the globe, maintaining healthy marine ecosystems and supporting fisheries. Regions where water rises (also known as upwelling zones) bring deep, nutrient-rich water to the surface, fueling the growth of tiny plants called phytoplankton, which form the base of marine food webs. These zones are typically rich in biodiversity.

How did the MOC change in the past?

The Atlantic part of the MOC varied significantly in strength over the past 100,000 years. Particularly, the AMOC weakened during Heinrich events. These abrupt climate change events were marked by large iceberg discharges, which added significant amounts of freshwater into the North Atlantic, reducing the sinking of water in this region and weakening the AMOC. As the AMOC weakened, the poleward transport of warm tropical water decreased, leading to significant cooling in the North Atlantic region and causing the ITCZ to shift southward. Southern Europe received less rainfall and became drier, while the southern tropics experienced increased rainfall.

There is also evidence that the Antarctic Overturning Circulation weakened in the past. In particular, AABW formation may have decreased during the fastest sea-level rise event around 14,600 years ago, known as Meltwater Pulse 1A¹.

The cold blob: a sign of recent slowdown

There are indications that the AMOC has slowed down by around 15% since the middle of the twentieth century due to global warming and the melting of the Greenland Ice Sheet². The most evident sign of this slowdown is the so-called 'cold blob'—a region of unusually cold temperatures in the North Atlantic observed on maps of recent global surface air temperature changes³ (Figure 2). While the entire globe has warmed over the past decades, the 'cold blob' indicates that the North Atlantic has cooled. Because this is the region where the AMOC usually delivers much of its heat, this suggests a weakening of the AMOC.

Additionally, increased salinity and sea surface temperatures in the South Atlantic have provided further evidence of the 20th century AMOC slowdown⁴.

There is also some evidence that the Antarctic Overturning Circulation has weakened, with observations showing a freshening, warming, and a decline in oxygen of the ocean abyss over the past five decades. Some studies have shown a ~30% decrease in AABW formation and export occurring in the Australian Antarctic basin and the Weddell Sea since the 1990s^{5,6}. These changes have been linked to increased glacial melt and freshening of shelf waters as well as changes in winds flowing off the continent.

What does the future of the MOC look like?

Climate model simulations suggest that the AMOC will continue to slow down in response to global warming. The sixth IPCC report found that, in a low emission scenario, the AMOC could weaken by up to 46% by 2100⁷. Some authors are now suggesting that there is a non-negligible chance of a shutdown of AMOC this century⁸.

In contrast to our understanding of the AMOC, future changes in the Antarctic Overturning Circulation are less certain due to known limitations in the representation of deep water formation and increased meltwater in climate models. However, specifically designed model experiments aiming to bridge some of these limitations suggest that we are heading toward a decline and possible shutdown of the circulation. In particular, one study has shown that increased Antarctic ice melt will cause the circulation to slow down by around 40% by 2050⁹. The rapidity of this decline might even be underestimated, according to recent observations⁵. The proximity of Antarctic ice sheet melt to some of the main regions of AABW formation is a particular concern.

Warming Between 1850–1900 and 2011–2021

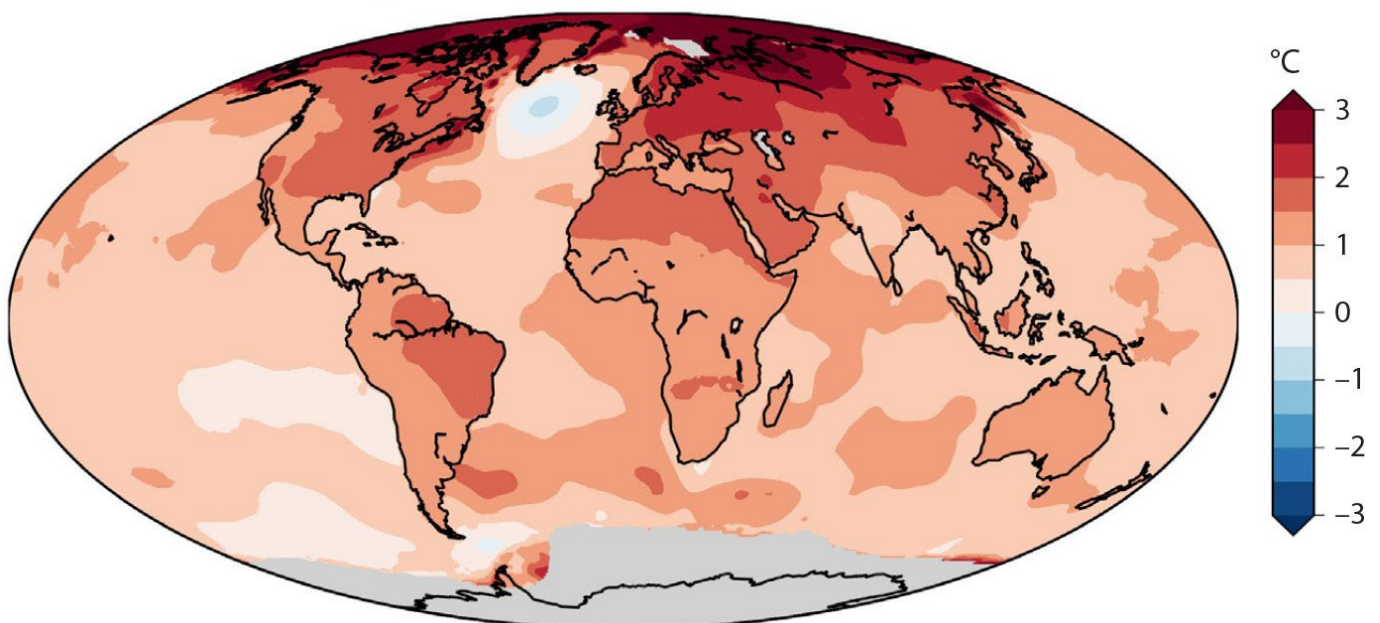


Figure 2. Map of observed near-surface air temperature changes since the late nineteenth century. Note the cold region southeast of Greenland known as the 'cold blob'. Credit: Zeke Hausfather, Berkeley Earth. Source: Rahmstorf, 2024.





What would happen if the MOC shut down?

If the AMOC were to shut down, western Europe would experience significant cooling and other disruptions to the climate. The temperature contrast between northern and southern Europe would change weather dynamics, potentially leading to major weather events, such as unprecedented storms. The ITCZ would shift southward. Northeastern Brazil could experience increased rainfall, while Central America, Southeast Asia and Europe could become drier¹⁰ (Figure 3). A shutdown of this part of the circulation could also shift Earth's climate to a more La Niña-like state, with more flooding rains over eastern Australia and worse droughts and bushfire seasons over the southwest United States¹¹.

On the other hand, a shutdown of the Antarctic Overturning Circulation could shift tropical rainfall bands northward and significantly impact marine life, with depleted oxygen levels in the deep ocean (at depth > 4km) and a decrease in nutrient upwelling back to the upper ocean.

Future implications

Although uncertainties remain regarding how much the MOC will weaken in the future, its recent slowdown alongside projections of further change are cause for concern. The MOC is a slow process, meaning that the changes to the circulation we are witnessing now will set the stage for future climate and oceanic conditions. A further weakening or shutdown of the circulation would have significant and lasting consequences for the global climate, ecosystems, fisheries, and biodiversity, with possible downstream impacts on human migration and regional security.

Further research will need to focus on better understanding and evaluating the risk of a shutdown of the circulation. In the meantime, drastically reducing greenhouse gas emissions will help limit the weakening of the MOC and preserve the delicate balance of our planet's climate system and the ecosystems it supports.

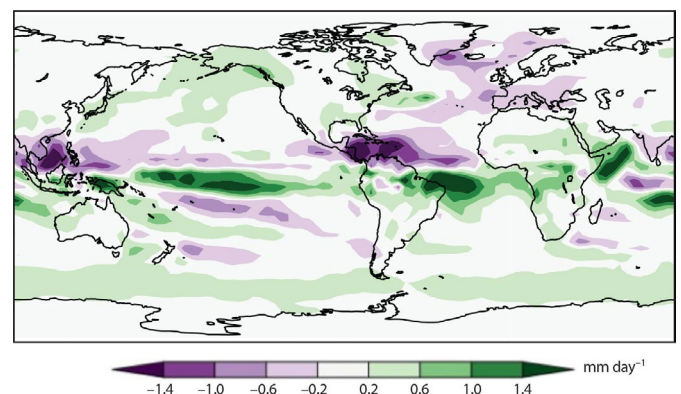


Figure 3. Annual mean precipitation changes resulting from an AMOC shutdown. Source: Liu et al. (2017)

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