

The Potential Collapse of the Atlantic Meridional Overturning Circulation (AMOC): Chances, Timeframe, and Consequences

The Atlantic Meridional Overturning Circulation (AMOC) is a critical component of the Earth's climate system, acting as a vast conveyor belt that transports warm water from the tropics to the North Atlantic, where it cools, sinks, and flows back towards the equator. This circulation plays a pivotal role in regulating global weather patterns and maintaining the climate balance. However, recent studies have raised alarming concerns about the stability of the AMOC, suggesting that it may be on the brink of a significant slowdown or even a complete collapse.

The AMOC's stability is highly dependent on the delicate balance of temperature and salinity in the ocean. Climate change, driven by increasing greenhouse gas emissions, is disrupting this balance by warming surface waters and adding fresh water from melting ice sheets and increased rainfall. According to a [study by Boers](#), the AMOC is currently at its weakest point in over a millennium, and the "restoring forces" that keep it functioning have become more erratic.

The timeframe for a potential AMOC collapse is a subject of intense research and debate. Some scientists predict that the AMOC could shut down as early as 2025, while others suggest a more likely collapse window between 2039 and 2070 ([CNN](#)). The [Intergovernmental Panel on Climate Change \(IPCC\)](#) has stated that a total shutdown within the next 300 years is only likely under a worst-case emissions scenario. However, recent findings indicate that the critical threshold for collapse may be much closer than previously expected.

The consequences of an AMOC collapse would be profound and far-reaching. It could lead to drastic changes in weather patterns, including much more extreme winters in Europe and North America, significant sea level rises, and disruptions to tropical monsoon systems ([Nature](#)). The collapse could also trigger a rapid cooling event similar to the Younger Dryas period, which occurred around 12,000 years ago.

and caused significant climatic shifts in the Northern Hemisphere ([Inside Climate News](#)).

Given the potential for such catastrophic impacts, it is crucial to closely monitor the AMOC and take immediate action to reduce greenhouse gas emissions. The likelihood of an AMOC collapse increases with every gram of CO₂ added to the atmosphere, making it imperative to mitigate climate change to preserve this vital component of the Earth's climate system ([The Guardian](#)).

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Current State and Predictions of AMOC Collapse

Observational Data and Trends

The Atlantic Meridional Overturning Circulation (AMOC) has been continuously monitored since 2004 through a combination of moored instruments, induced electrical currents in submarine cables, and satellite surface measurements ([Nature](#)). Over the period from 2004 to 2012, a decline in the AMOC has been observed, but longer records are necessary to establish robust trends. To analyze changes over longer timescales, researchers have turned to surface temperature readings of the subpolar gyre between 1870 and 2020, which provide a 'fingerprint' for the strength of AMOC's circulation ([Live Science](#)).

Model Predictions and Uncertainties

Numerous climate model studies show a hysteresis behavior, where changing a control parameter, typically the freshwater input into the Northern Atlantic, makes the AMOC bifurcate through a set of co-dimension one saddle-node bifurcations ([Nature](#)). State-of-the-art Earth-system models can reproduce such a scenario, but the inter-model spread is large, and the critical threshold is poorly constrained. Based on the CMIP5 generation of models, the AR6 IPCC report quotes a collapse in the 21st century to be very unlikely. However, recent studies suggest that the AMOC is becoming increasingly unstable and could collapse as soon as 2025, with a more likely timeframe between 2050 and 2080 ([New Scientist](#)).

Early Warning Signals (EWS)

Early warning signals (EWSs) such as increased variance and autocorrelation have been identified as indicators of a forthcoming AMOC collapse. These signals are statistical equilibrium concepts and rely on the assumption of quasi-stationary dynamics ([Nature](#)). The AMOC fingerprint for the period 1870–2020 shows significant trends in the mean, variance, and autocorrelation, indicating early warning of a shutdown. However, a trend in the EWSs within a limited period of observation could be a random fluctuation within steady-state statistics. Thus, for a robust assessment of the shutdown, it is necessary to establish a statistical confidence level for the change above the natural fluctuations.

Societal Implications

The collapse of the AMOC would have profound societal implications, including rapid sea level rise in North America, a sudden and severe drop in temperatures across northern Europe, and serious disruption to monsoons across Asia ([New Scientist](#)). The AMOC plays a crucial role in regulating global weather patterns, and its collapse would lead to much more extreme winters and sea level rises affecting parts of Europe and the US, and a shifting of the monsoon in the tropics ([CNN](#)).

Probabilistic Estimates

Recent studies have provided observationally based estimates of the probability of an AMOC collapse. For instance, one study estimates the collapse time between 2037-2064 (10-90% CI) with a mean of 2050, and the probability of an AMOC collapse before the year 2050 is estimated to be $59 \pm 17\%$ ([arXiv](#)). This research suggests it's more likely than not to collapse by 2050, which is a significant shift from earlier predictions that considered such an event unlikely within this century ([CNN](#)).

Mechanisms and Driving Forces

The AMOC is driven by the transport of warm water from the tropics toward the North Atlantic, where the water cools, becomes saltier, and sinks deep into the ocean before spreading southwards ([CNN](#)). This process is influenced by factors such as river runoff, Greenland ice melt, and export from the Arctic Ocean, which are not well constrained ([Nature](#)). The mechanism keeps parts of the Southern Hemisphere from overheating and parts of the Northern Hemisphere from getting

unbearably cold, while distributing nutrients that sustain life in marine ecosystems ([CNN](#)).

Historical Context

The last time the AMOC slowed to a near stop was about 14,500 years ago, toward the end of the last ice age, as the planet began to warm. When that happened, the Northern Hemisphere was catapulted back into cold conditions for another 3,000 years ([Gizmodo](#)). Past research has shown that the critical current has slowed by about 15% since the 1950s, at least in part because of oceanic and atmospheric shifts wrought by human-caused climate change. Since the flow is so crucial for our climate's stability, the possible collapse of the current is considered a major "tipping point," or an irreversible and worrying threshold, among climate scientists ([Gizmodo](#)).

Future Research and Monitoring

To have better AMOC predictions for societal benefit, robust climate science and a sufficient understanding of the dynamics of the climate system are necessary. Even if we don't yet have the observational data sufficient to prove whether this is a shutdown or not, we should not wait for another 50 years to collect the data—because that might be already too late ([WHOI](#)). Scientists emphasize the need for continuous monitoring and advanced modeling to predict the timing and consequences of an AMOC collapse accurately.

Conclusion

While the exact timing and probability of an AMOC collapse remain uncertain, the potential consequences are severe enough to warrant immediate attention and action. The scientific community continues to refine models and gather data to better understand this critical component of Earth's climate system.

Contributing Factors to AMOC Instability

Freshwater Input and Salinity Changes

One of the primary factors contributing to the instability of the Atlantic Meridional Overturning Circulation (AMOC) is the increased input of freshwater into the North

Atlantic. This freshwater influx primarily comes from melting ice sheets in Greenland and increased river runoff due to climate change. The addition of freshwater reduces the salinity and density of the surface waters, which in turn weakens the sinking process that drives the AMOC. According to a study, the salinity data near the southern boundary of the Atlantic is optimal for estimating the time of the AMOC collapse ([arXiv](#)).

Temperature Variability

Temperature changes in the North Atlantic also play a crucial role in AMOC stability. The AMOC relies on the cooling of warm, salty water in the North Atlantic, which then sinks and drives the circulation. However, global warming is causing surface waters to warm, reducing the temperature gradient necessary for this process. This warming effect is exacerbated by the influx of freshwater, which further destabilizes the AMOC. Recent studies have shown that the AMOC is at its weakest point in over a millennium, indicating a significant loss of stability ([PBS](#)).

Atmospheric Circulation Patterns

Changes in atmospheric circulation patterns, such as the North Atlantic Oscillation (NAO), also impact the AMOC. The NAO influences the strength and direction of westerly winds in the North Atlantic, which in turn affects ocean currents and the distribution of heat and salinity. A positive phase of the NAO typically strengthens the AMOC by enhancing the cooling and sinking of water in the North Atlantic. Conversely, a negative phase weakens the AMOC by reducing these processes. The variability in the NAO adds another layer of complexity to predicting the future stability of the AMOC ([Nature](#)).

Ocean-Atmosphere Interactions

The interactions between the ocean and atmosphere are critical in maintaining the AMOC. For instance, tropical air-sea interactions can accelerate the recovery of the AMOC after a major shutdown. However, these interactions are also subject to variability and can be influenced by other climate phenomena such as the El Niño-Southern Oscillation (ENSO). Studies have shown that a weakening AMOC can influence global teleconnections, affecting weather patterns far beyond the North Atlantic region ([Nature](#)).

Anthropogenic Factors

Human activities, particularly the emission of greenhouse gases, are a significant driver of AMOC instability. The increase in atmospheric CO₂ levels leads to global warming, which in turn affects ocean temperatures and salinity. The Intergovernmental Panel on Climate Change (IPCC) has noted that climate models may underestimate the risk of an AMOC collapse due to the complexities involved in accurately modeling freshwater input and other factors. The likelihood of an AMOC collapse increases with every gram of CO₂ added to the atmosphere, making it imperative to reduce emissions to mitigate this risk ([PBS](#)).

Model Limitations and Uncertainties

While climate models are essential tools for predicting the future of the AMOC, they come with limitations and uncertainties. Many models struggle to accurately simulate the complex interactions between various factors that influence the AMOC. For example, the IPCC's most recent assessment estimated the chances of an AMOC breakdown this century at less than 10%, but newer studies suggest a much higher probability. This discrepancy highlights the need for continuous improvement in climate modeling to better understand and predict AMOC behavior ([Inside Climate News](#)).

Feedback Mechanisms

Feedback mechanisms within the climate system can either stabilize or destabilize the AMOC. Positive feedback loops, such as the melting of Arctic ice leading to more freshwater input and further weakening of the AMOC, can accelerate the process towards a tipping point. Conversely, negative feedback mechanisms, such as increased evaporation leading to higher salinity, can help stabilize the AMOC. Understanding these feedbacks is crucial for predicting the future of the AMOC and its potential collapse ([Nature](#)).

Paleoclimate Evidence

Paleoclimate evidence provides valuable insights into the behavior of the AMOC under different climate conditions. For instance, during the last ice age, the AMOC experienced significant slowdowns and even shutdowns, leading to abrupt climate changes. These historical events serve as analogs for understanding the potential future behavior of the AMOC under current and projected climate conditions.

Studies have shown that the AMOC has changed abruptly in the past, but the drivers of these changes were different from those we face today ([Phys.org](#)).

Socioeconomic Impacts

The potential collapse of the AMOC would have far-reaching socioeconomic impacts. A shutdown could lead to severe cooling in Europe, disrupting agriculture, energy supply, and infrastructure. It could also cause rapid sea level rise along the eastern coast of North America, leading to significant economic and social challenges. The disruption of global weather patterns would affect food security, water resources, and human health, making it a critical issue for policymakers and society at large ([New Scientist](#)).

Future Research Directions

To better understand and predict the future of the AMOC, ongoing research and monitoring are essential. This includes improving climate models, increasing the resolution of observational data, and studying the interactions between different components of the climate system. Collaborative efforts between scientists, policymakers, and stakeholders are necessary to develop strategies for mitigating the risks associated with an AMOC collapse. Continuous monitoring and advanced modeling will be crucial in providing early warning signals and informing adaptive measures ([WHOI](#)).

By focusing on these contributing factors, we can gain a more comprehensive understanding of the instability of the AMOC and the potential consequences of its collapse. This knowledge is vital for developing effective strategies to mitigate the risks and adapt to the changes that may arise.

Potential Consequences of AMOC Collapse

Global Climate Disruptions

The collapse of the Atlantic Meridional Overturning Circulation (AMOC) would have profound impacts on global climate systems. The AMOC plays a crucial role in regulating the climate by transporting warm water from the tropics to the North Atlantic. If this circulation were to collapse, it would lead to significant changes in temperature and precipitation patterns worldwide. For instance, the tropical Pacific

Ocean could cool, intensifying and shifting trade winds southward, resulting in a permanent La Niña-like state. This could trigger catastrophic monsoons and flooding in the South Pacific, along with increased drought and heat in parts of North America ([Gizmodo](#)).

Regional Climate Impacts

Europe

A collapse of the AMOC would likely lead to severe cooling in Europe. The AMOC is responsible for the relatively mild climate in Europe, particularly in regions like the United Kingdom and Scandinavia. Without the warm water transported by the AMOC, these areas could experience significantly colder winters, similar to the conditions during the last ice age when the AMOC slowed to a near stop ([Gizmodo](#)). This cooling could disrupt agriculture, energy supply, and infrastructure, leading to substantial economic and social challenges.

North America

In North America, the collapse of the AMOC could lead to rapid sea level rise along the eastern coast. The AMOC helps to balance sea levels by redistributing water masses. Without this circulation, the eastern coast of North America could see a significant increase in sea levels, exacerbating the risks of coastal flooding and erosion ([Inside Climate News](#)). This would have severe implications for coastal communities, infrastructure, and ecosystems.

Disruption of Ocean Currents

The AMOC is interconnected with other major ocean currents, such as the Gulf Stream. A collapse of the AMOC could lead to the partial or complete vanishing of these currents, further disrupting global climate systems. The Gulf Stream, for example, plays a critical role in regulating the climate of the eastern United States and Western Europe. Its weakening or disappearance would have far-reaching consequences for weather patterns, marine ecosystems, and human activities dependent on these currents ([Inside Climate News](#)).

Ecological Impacts

Marine Ecosystems

The AMOC is vital for the distribution of nutrients and heat in the ocean, which supports marine life. A collapse would disrupt these nutrient cycles, potentially leading to the decline of important fisheries and marine biodiversity. The redistribution of heat and changes in salinity could also affect the habitats of various marine species, leading to shifts in species distributions and the potential collapse of certain marine populations ([Gizmodo](#)).

Terrestrial Ecosystems

On land, the changes in temperature and precipitation patterns caused by an AMOC collapse would have significant impacts on terrestrial ecosystems. For example, the shift in rainfall patterns could lead to the failure of the Amazon Rainforest, which is already under threat from deforestation and climate change. The disruption of the AMOC could exacerbate these threats, leading to the loss of biodiversity and the release of large amounts of carbon stored in the forest, further accelerating global warming ([Inside Climate News](#)).

Socioeconomic Consequences

Agriculture

The changes in climate patterns resulting from an AMOC collapse would have profound impacts on agriculture. Regions that rely on stable weather patterns for crop production could face increased variability, leading to crop failures and food shortages. For instance, the cooling of Europe and changes in monsoon patterns in Asia could disrupt agricultural cycles, affecting food security and leading to higher food prices globally ([Gizmodo](#)).

Water Resources

Water resources would also be affected by the changes in precipitation patterns. Regions that depend on predictable rainfall for drinking water, irrigation, and hydropower could face increased droughts or flooding. The shift in monsoon patterns could lead to water scarcity in some regions and excessive rainfall in

others, complicating water management and increasing the risk of water-related conflicts ([Inside Climate News](#)).

Human Health

The disruption of climate patterns would have direct and indirect impacts on human health. Increased heatwaves, changes in disease vectors, and food and water shortages could lead to higher mortality rates and increased pressure on healthcare systems. The cooling of Europe, for example, could lead to higher incidences of cold-related illnesses, while changes in rainfall patterns could affect the spread of waterborne diseases ([Gizmodo](#)).

Mitigation and Adaptation Strategies

Given the potential severity of an AMOC collapse, it is crucial to develop mitigation and adaptation strategies. Reducing greenhouse gas emissions is essential to slow down global warming and reduce the risk of an AMOC collapse. Additionally, improving climate models and monitoring systems can help predict and prepare for potential changes in the AMOC. Adaptation strategies, such as building resilient infrastructure, developing sustainable water management practices, and enhancing food security, are also necessary to cope with the potential impacts ([NPR](#)).

Policy Implications

The potential collapse of the AMOC underscores the need for urgent and coordinated global action on climate change. Policymakers must prioritize reducing emissions, investing in climate research, and developing comprehensive adaptation plans. International cooperation is essential to address the global nature of the impacts and to support vulnerable regions that may be disproportionately affected by the changes in climate patterns ([Inside Climate News](#)).

In summary, the potential collapse of the AMOC would have far-reaching and severe consequences for global and regional climates, marine and terrestrial ecosystems, and human societies. Understanding these impacts and developing effective mitigation and adaptation strategies is crucial to minimize the risks and ensure a sustainable future.

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