INTERNATIONAL ACADEMY OF VINE AND WINE

Le changement climatique change…
The climate change changes…

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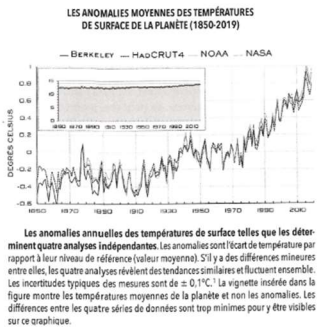
Dans ma présentation 'Les engagements de l'association G*i*ESCO' lors du 23ème G*i*ESCO de Geisenheim le 31 juillet 2025, j'avais alerté notre communauté sur la part d'incertitude dans notre connaissance du changement climatique, reprenant en cela les analyses du climatologue américain et conseiller scientifique du président Barack Obama, Steven E. Koonin (Climat, la part d'incertitude. Éditions l'Artilleur) :

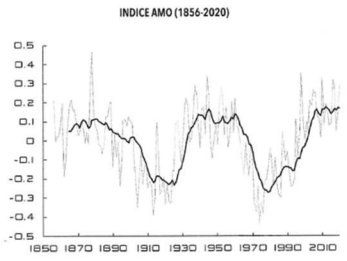
In my presentation, "The Commitments of the GiESCO Association," at the 23rd GiESCO meeting in Geisenheim on July 31, 2025, I alerted our community to the degree of uncertainty in our understanding of climate change, drawing on the analyses of American climatologist and scientific advisor to President Barack Obama, Steven E. Koonin (Climate: The Uncertainty of Climate Change, L'Artilleur Publishing) :

MONITORING CLIMATE CHANGE BY REGION:

Climate change has been documented since the 1980s, and the work of the IPCC (Intergovernmental Panel on Climate Change) forms the basis of our knowledge of thermal and water effects. However, there are still many uncertainties that must be considered. For example, Steven Koonin is not a climate skeptic! Regional disparities: How will the Gulf Stream AMOC (Atlantic Meridional Overturning Circulation) evolve? What effect will the AMO (Atlantic Multidecenal Oscillation) have? Will Atlantic Europe eventually cool down? Mediterranean summers will certainly be drier!



Les anomalies annuelles des températures de surface telles que les déterminent quatre analyses indépendantes. Les anomalies sont l'écart de température par rapport à leur niveau de référence (valeur moyenne). S'il y a des différences mineures entre elles, les quatre analyses révèlent des tendances similaires et fluctuent ensemble. Les incertitudes typiques des mesures sont de ± 0,1°C.[1] La vignette insérée dans la figure montre les températures moyennes de la planète et non les anomalies. Les différences entre les quatre séries de données sont trop minimes pour y être visibles sur ce graphique.



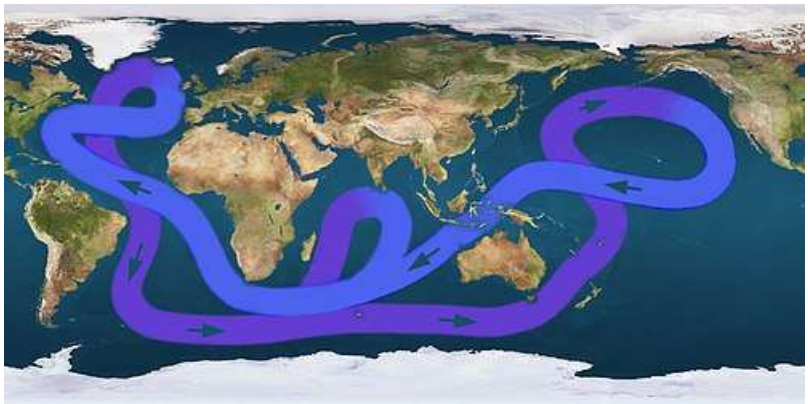
Indice de l'oscillation multidécennale atlantique (AMO), construit à partir des températures de la mer en surface dans l'Atlantique nord. La ligne noire est la moyenne glissante des dix dernières années.[1]

L’incertitude majeure qui plane sur les prévisions des effets du changement climatique est liée à l’évolution du flux de l’immense courant marin planétaire qui brasse en particulier les eaux de l’océan atlantique, nommé ‘circulation méridionale de retournement de l'Atlantique’ internationalement connu sous l’acronyme AMOC (Atlantic Meridional Overturning Circulation). C’est le principal système de courants océaniques de l'océan Atlantique, le Gulf Stream engendré par des vents s’y rajoutant. L’AMOC est partie intégrante du système de circulation océanique terrestre et joue un rôle important dans le système climatique. En ce début de 2026 nombreux sont les médias qui communiquent sur l’AMOC, probablement en raison des évènements climatiques pluvieux-neigeux assez inhabituels de cet hiver. Certains grands organismes comme le Ministère des Armées de la France l’ont même déjà intégré dans leurs projections vers l’avenir. Il est donc grand temps de résumer nos connaissances sur le sujet.
Laissons s’exprimer sur internet des spécialistes des courants marins et du climat:

The major uncertainty surrounding predictions of the effects of climate change is linked to the evolution of the flow of the immense global ocean current that circulates, in particular, the waters of the Atlantic Ocean, known internationally as the Atlantic Meridional Overturning Circulation (AMOC). This is the main system of ocean currents in the Atlantic Ocean, with the Gulf Stream, generated by winds, also contributing to its influence. The AMOC is an integral part of the Earth's ocean circulation system and plays a significant role in the climate system. At the start of 2026, many media outlets are reporting on the AMOC, likely due to the rather unusual rain and snow events of this past winter. Some major organizations, such as the French Ministry of the Armed Forces, have even already incorporated it into their future projections. It is therefore high time to summarize our current understanding of the subject. Let's hear from specialists in ocean currents and climate who have been sharing their insights online:

A/ https://fr.wikipedia.org/wiki/Circulation_thermohaline).
« La **circulation thermohaline**, appelée aussi **circulation océanique profonde**, est la circulation océanique engendrée par les différences de densité (masse volumique) de l'eau de mer, à l'origine de courants marins de profondeur. Ces différences de densité proviennent des écarts de température et de salinité des masses d'eau, d'où le terme de thermo — pour température — et halin — pour salinité.

À l'échelle de la planète, la circulation océanique de surface et la circulation océanique profonde forment une immense boucle de circulation que l’on nomme **boucle thermohaline** à l'origine d'un grand cycle qui brasse les eaux et convoie la chaleur à l'échelle du globe.



Caractéristiques

Température, salinité et densité sont reliées par la fonction d'état de l'eau de mer. Les eaux refroidies et salées plongent au niveau des hautes latitudes dans l'Atlantique-Nord (Norvège, Groenland, et mer du Labrador) et descendent vers le sud, à des profondeurs comprises entre 1 et 3 km, formant l'eau profonde Nord-Atlantique. La remontée de ces eaux se fait principalement par mélange vertical dans tout l'océan. Les scientifiques estiment qu'une molécule d'eau fait ce circuit entier en environ 1 000 à 1 500 ans. Il existe également des zones de formation d'eau dense dans l'océan Austral, au niveau des mers de Ross et de Weddell. Dans la réalité, il est difficile de séparer la circulation engendrée par les gradients de densité seuls des autres sources de mouvement des masses d'eau, telles que le vent ou les marées. Pour étudier cette circulation à grande échelle, les scientifiques préfèrent donc utiliser une notion mieux définie : la **circulation méridienne de retournement** (CMR ou MOC pour *Meridional Overturning Circulation*). Elle a des conséquences encore mal estimées aujourd'hui sur le climat.

La notion de circulation thermohaline ou circulation méridienne de retournement est imprécise et il en existe plusieurs définitions. Si elle est majoritairement vue comme la circulation liée aux forçages thermique et halin qui lui donnent son nom, il est maintenant établi que ces seuls forçages ne sont pas suffisants pour maintenir cette circulation et que le mélange turbulent lié au vent et aux marées joue un rôle primordial, notamment dans la remontée des eaux profondes. Progressivement, la notion de circulation méridienne de retournement, ou MOC, s'est substituée à celle de circulation thermohaline.

…

Circulation méridienne de retournement Atlantique (AMOC)

Lorsque l'intégration zonale de la vitesse se limite au bassin atlantique, on parle d'AMOC pour 'Atlantic MOC'.

C'est dans l'océan Atlantique que la circulation méridienne de retournement est la plus intense et la plus étudiée. Elle est constituée de deux cellules convectives. Dans la cellule supérieure, les eaux chaudes et salées de surface sont transportées vers le nord, où elles se densifient sous l'effet de leur refroidissement. La perte de flottabilité de ce flux d'eau l'amène alors à plonger pour devenir l'eau profonde nord-atlantique. Cette eau profonde est transportée vers le sud à une profondeur comprise entre 1 et 4 km. Une partie finit par remonter en surface dans l'océan Austral, fermant ainsi la cellule. Le transport vers le sud de l'eau profonde nord-atlantique et sa remontée au niveau de la divergence antarctique forment également la branche supérieure de la seconde cellule convective. Cette cellule est alors fermée par la formation d'eau profonde et d'eau de fond au niveau de la mer de Weddell, qui tapissent le fond de l'océan Atlantique.

À 26,5° N, les débits moyens des cellules supérieure et inférieure sont estimés à 18,7 ± 2,1 Sv et 2 ± 0,5 Sv respectivement. [NB : Sv ou Sverdrup est une unité de débit volumique, et 1 Sv vaut 106 m^3/s .]

Observations

La très grande échelle de l'AMOC rend son observation difficile.

Les premières estimations étaient basées sur des sections hydrographiques zonales, c'est-à-dire suivant un parallèle, à quelques latitudes choisies, majoritairement 24,5° N, 38° N et 48° N dans l'Atlantique Nord et 24° S et 34° S dans l'Atlantique Sud. Ces mesures ont fourni une première estimation de la valeur de l'AMOC à un instant donné, mais doivent être longuement répétées pour estimer sa variabilité. En 2010, l'échantillonnage temporel reste faible, ce qui peut engendrer des erreurs liées au phénomène de repliement de spectre. Ainsi, la diminution d'AMOC identifiée à

partir de sections hydrographiques répétées en 1957, 1981, 1992, 1998 et 2004 à 26,5° N était en 2010 suspectée d'être dominée par la variabilité intra-annuelle.

Depuis mars 2004, dans le cadre du projet international Rapid Climate Change Program (RAPID), on mesure en continu (deux mesures par jour) l'AMOC à 26,5° N, ce qui a amélioré l'évaluation de sa variabilité pour les échelles mensuelles à interannuelles. La série temporelle est cependant encore trop courte pour évaluer une variabilité décennale.

En 2009 un dispositif similaire à RAPID a été déployé dans l'Atlantique Sud à 34,5° S : SAMBA pour 'South-Atlantic MOC bassin-wide Array'.

Début 2021, *Nature Geoscience* publie une étude concluant au début de ralentissement (plus important que ceux qui se sont produits au moins dans les 1 000 ans précédents) et en août 2021, le sixième rapport d'évaluation du GIEC, en se basant sur les données et modélisations disponibles, estime que l'AMOC ralentira 'très probablement' au XXIe siècle, asséchant ainsi l'Europe.

Variabilité

En 2008, un cycle saisonnier de 6,7 Sv d'amplitude est décrit à 26,5° N sur 4 ans (2004-2008), avec un maximum de transport en automne et un minimum au printemps. Mais ce cycle saisonnier n'est plus clairement identifiable sur les observations faites les huit années suivantes (2008-2016). À cette même latitude, la variabilité journalière est élevée, atteignant 30 Sv.

Il n'existe pas encore de série temporelle d'observation assez longue de l'AMOC pour décrire de manière fiable sa variabilité décennale à multidécennale, mais en 2005, des études montrent que l'oscillation atlantique multidécennale (**AMO ou Atlantic Multidecenal Oscillation**) de la température de surface est liée à l'AMOC. Ceci suggère des cycles à ces échelles de temps. Cette variabilité multidécennale était observée dans de nombreux modèles, mais au début des années 2000 il n'y a pas d'accord entre scientifiques sur les processus qui la contrôlent.

De 2010 à 2021, un consensus se précise sur le fait qu'un ralentissement de l'AMOC est en cours, qu'il n'a jamais été aussi marqué depuis au moins 1 000 ans, et que sa continuation aurait des conséquences météorologiques néfastes à l'échelle de la planète. Les chercheurs ont contourné le manque de séries longues de mesure en utilisant des données indirectes, résumées par une étude publiée début 2021 dans *Nature Geoscience*. Les auteurs s'y appuient d'une part sur les données de plus en plus précises acquises entre 1960 et 2015, et d'autre part sur l'observation de plusieurs facteurs indirects maintenant solidement documentés montrant que 'la circulation thermohaline atlantique [Amoc] a été très stable depuis environ un millénaire mais qu'au cours du dernier siècle, il s'est produit une réduction marquée de ces courants atlantiques'. Ce consensus est repris par le sixième rapport du GIEC qui estime que l'AMOC ralentira 'très probablement' encore au XXIe siècle, en asséchant l'Europe (*Nature Geoscience* a publié début 2021 une étude montrant un début de ralentissement, plus important que ceux qui se sont produits au moins dans les 1 000 ans précédents).

En 2024, 44 scientifiques alertent sur un risque d'effondrement de l'AMOC, aux conséquences climatiques très lourdes. Selon une étude publiée le 11 juin 2025 dans la revue *Geophysical Research Letter*, le nord-ouest du territoire européen serait affecté par un froid caractérisé par des températures hivernales chutant par endroits de 15 degrés, et par l'avancement de la banquise arctique à proximité des côtes écossaises.

Conséquences du ralentissement

Selon Didier Swingedouw (CNRS, université de Bordeaux) interrogé en février 2021 : 'dans la région du Sahel, une diminution de l'Amoc entraînerait une baisse importante des précipitations, avec des

répercussions humaines importantes dans cette région très peuplée'. Selon Jean-Baptiste Sallée (chercheur, laboratoire LOCEAN ; université Paris-Sorbonne) 'en Europe du Nord, une diminution de l'Amoc a comme conséquence une augmentation de la fréquence des tempêtes et une augmentation du niveau des mers en Amérique du Nord et en Europe. Elle produira aussi une baisse importante de la production biologique marine'. Pour Didier Swingedouw (CNRS, université de Bordeaux) 'il est aussi possible qu'en Europe, le contraste entre les saisons soit plus marqué, avec des hivers plus rigoureux et des étés très chauds'. Pour Didier Swingedouw, la question n'est plus de savoir si le ralentissement est certain, il est 'très probable. La question est plutôt de quantifier l'amplitude de cette baisse et son horizon temporel.'.

Le ralentissement de l'AMOC pourrait entraîner la libération d'hydrates de méthane dans certaines eaux peu profondes de l'Atlantique. Les eaux profondes ne seraient plus refroidies par les eaux arctiques, et en se réchauffant libéreraient le méthane.

Moteurs de la circulation thermohaline et convection profonde

L'eau de mer est d'autant plus dense que sa température est basse et sa salinité élevée. La colonne d'eau océanique est généralement stratifiée de manière stable, avec les eaux les plus denses (c.-à-d. plus lourdes) au fond, et les eaux moins denses (c.-à-d. plus légères) en surface. À la surface, les échanges de chaleur et d'eau douce avec l'atmosphère modifient la densité de l'eau. Dans certains cas, ces modifications peuvent créer une instabilité avec des eaux en surface plus denses que les eaux sous-jacentes. Il se créé alors une cellule de convection locale, générant un mélange vertical des eaux. Ce mélange homogénéise les propriétés de l'eau sur la colonne (c.-à-d. température, salinité, etc.), et engendre un flux de masse vers le fond.

Ce processus, responsable de la formation d'eau dense dans l'Atlantique Nord, a longtemps été considéré comme le moteur principal de la circulation thermohaline ou de l'AMOC. Une production importante d'eau dense augmenterait l'intensité du transport de ces eaux vers le sud en profondeur. Cette anomalie de transport de masse vers le sud est compensée par une augmentation du transport vers le nord en surface, ce qui revient à une augmentation de l'intensité de l'AMOC. C'est ce paradigme qui a valu à l'AMOC le nom de circulation thermohaline. Cependant, l'amélioration des observations et de l'échantillonnage, ainsi que l'amélioration des modèles, ont progressivement mis en évidence que la variabilité de la formation d'eau dense n'est pas directement reliée à la variabilité de l'AMOC. Le vent et les tourbillons jouent également un rôle important.

Rôle

La circulation océanique contribue de manière substantielle à la redistribution de chaleur sur le globe terrestre.

La MOC est responsable d'une large part du transport méridien de chaleur. Ce transport méridien diffère d'un bassin à l'autre. Dans l'océan Atlantique, l'AMOC transporte de la chaleur vers le nord à toutes les latitudes, y compris au sud de l'équateur, engendrant un transport net de chaleur de l'hémisphère Sud vers hémisphère Nord. Ce transport de chaleur vers le nord dans l'océan Atlantique est de 0.5PW au niveau de l'équateur, et atteint son maximum à 24-26°N avec un transport de 1.3PW (1PW = 1015 watts), ce qui représente 25 % du transport total (transport océanique et atmosphérique) de chaleur vers le nord à ces latitudes. Cette particularité de l'océan Atlantique est attribuée à la cellule supérieure de l'AMOC incluant la formation d'eau dense au nord. Dans l'océan Pacifique, la MOC est principalement liée à la circulation des gyres subtropicaux, sans formation d'eau dense au Nord. Le transport de chaleur y est dirigé vers les pôles de part et d'autre de l'équateur, ce qui revient à un transfert de chaleur de l'équateur vers les pôles.

Ce rôle important de la MOC dans le transport méridien de chaleur suggère que des variations d'intensité de la MOC peuvent engendrer des variations du contenu de chaleur océanique et en particulier de la température de surface. Dans l'Atlantique Nord, la variabilité décennale à multi-décennale de la température de surface, appelée oscillation atlantique multidécennale (AMO) pourrait être reliée à la variabilité de l'AMOC selon les modèles. Ce lien ne peut pas encore être observé, faute d'observation de l'AMOC suffisamment longue dans le temps. L'oscillation atlantique multidécennale exerce une forte influence sur le climat des régions environnantes, notamment sur les pluies au Sahel, les sécheresses sur l'Amérique du Nord et l'activité des cyclones tropicaux. L'hypothèse selon laquelle elle serait en partie contrôlée par la circulation à grande échelle est une des raisons pour lesquelles l'AMOC est considérée comme une possible source de prévisibilité pour le climat à l'échelle interannuelle à décennale dans la région Nord-Atlantique.

La convection océanique joue aussi un rôle important dans le cycle du carbone. En effet, en plongeant, les eaux marines entraînent une grande quantité de dioxyde de carbone (CO_2) qui a été capturé de l'atmosphère et qui y est dissous. Ce dioxyde de carbone est restitué en partie à l'atmosphère lorsque les eaux profondes refont surface. »

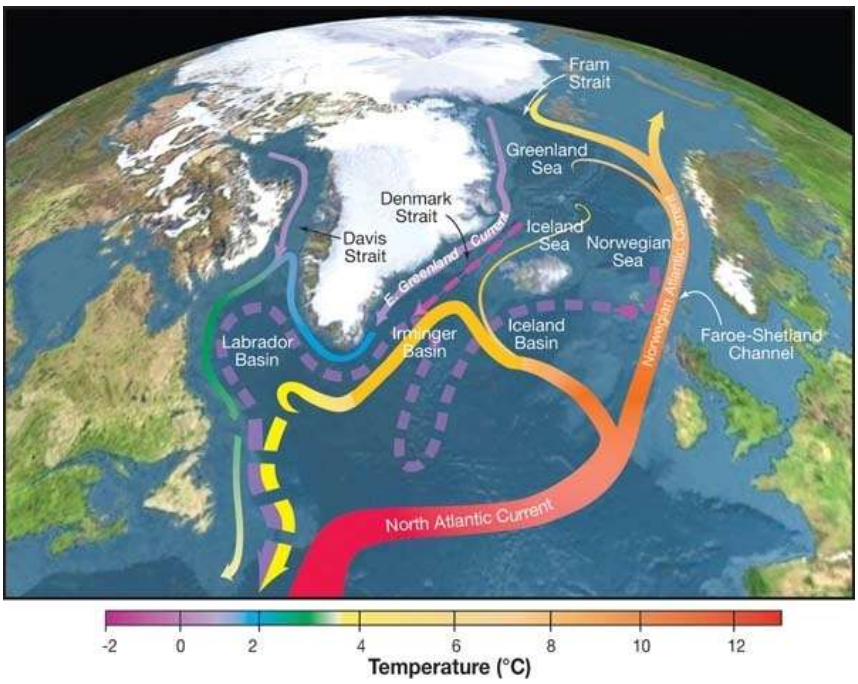
B/ https://en.wikipedia.org/wiki/Atlantic_meridional_overturning_circulation

[NB : les informations suivantes sont à la fois une traduction en anglais de celles du point A et une illustration cartographique de l'ensemble des phénomènes marins et climatique.

Note: The following information is both an English translation of that in point A and a cartographic illustration of all marine and climatic phenomena.]

«The **Atlantic meridional overturning circulation** (**AMOC**) is the main ocean current system in the Atlantic Ocean. It is a component of Earth's ocean circulation system and plays an important role in the climate system. The AMOC includes Atlantic currents at the surface and at great depths that are driven by changes in weather, temperature and salinity. Those currents comprise half of the global thermohaline circulation that includes the flow of major ocean currents, the other half being the Southern Ocean overturning circulation.

The AMOC is composed of a northward flow of warm, more saline water in the Atlantic's upper layers and a southward, return flow of cold, less salty, deep water. Warm water from the south is more saline ('halocline') because of the higher evaporation rate in the tropical zone. The warm saline water forms the upper layer of the ocean ('thermocline'), but when this layer cools down, the density of the salty water increases, making it sink into the deep. This is an important part of the motor of the AMOC system. The *limbs* are linked by regions of overturning in the Nordic Seas and the Southern Ocean. Overturning sites are associated with intense exchanges of heat, dissolved oxygen, carbon and other nutrients, and very important for the ocean's ecosystems and its function as a carbon sink. Changes in the strength of the AMOC can affect multiple elements of the climate system.

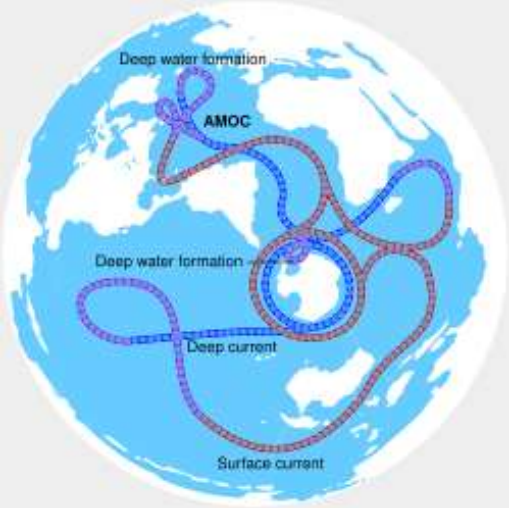


Topographic map of the Nordic Seas and subpolar basins with surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic meridional overturning circulation. Colors of curves indicate approximate temperatures.

Climate change may weaken the AMOC through increases in ocean heat content and elevated flows of freshwater from melting ice sheets. Studies using oceanographic reconstructions suggest that as of 2015, the AMOC was weaker than before the Industrial Revolution. There is debate over the relative contributions of different factors and it is unclear how much of this weakening is due to climate change or the circulation's natural variability over millennia. Climate models predict the AMOC will further weaken during the 21st century. This weakening would reduce average air temperatures over Scandinavia, Great Britain, and Ireland, because these regions are warmed by the North Atlantic Current. Weakening of the AMOC would also accelerate sea level rise around North America and reduce primary production in the North Atlantic.

Severe weakening of the AMOC may lead to a collapse of the circulation, which would not be easily reversible and thus constitutes one of the tipping points in the climate system. A collapse would substantially lower the average temperature and amount of rain and snowfall in Europe. It may also raise the frequency of extreme weather events and have other severe effects.

Overall structure

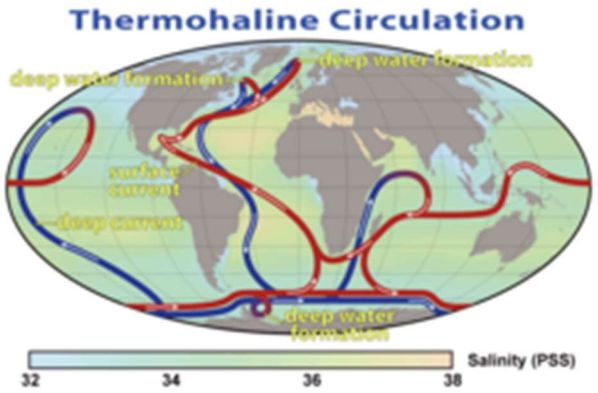


AMOC in relation to the global thermohaline circulation

The Atlantic meridional overturning circulation (AMOC) is the main current system in the Atlantic Ocean and is also part of the global thermohaline circulation, which connects the world's oceans with a single "conveyor belt" of continuous water exchange. Normally, relatively warm, less-saline water stays on the ocean's surface while deep layers are colder, denser and more-saline, in what is known as ocean stratification. Deep water eventually gains heat and/or loses salinity in an exchange with the mixed ocean layer, and becomes less dense and rises towards the surface. Differences in temperature and salinity exist between ocean layers and between parts of the World Ocean, and together they drive the thermohaline circulation. The Pacific Ocean is less saline than the other oceans because it receives large quantities of fresh rainfall. Its surface water is insufficiently saline to sink lower than several hundred meters, meaning deep ocean water must come from elsewhere.

Ocean water in the North Atlantic is more saline than that in the Pacific, partly because extensive evaporation on the surface concentrates salt within the remaining water and partly because sea ice near the Arctic Circle expels salt as it freezes during winter. Even more importantly, evaporated moisture in the Atlantic is swiftly carried away by atmospheric circulation before it can fall back as rain. Trade winds move this moisture across Central America and to the eastern North Pacific, where it falls as rain. Major mountain ranges such as the Tibetan Plateau, the Rocky Mountains and the Andes prevent any equivalent moisture transport back to the Atlantic.

Due to this process, Atlantic surface water becomes salty and therefore dense, eventually downwelling to form the North Atlantic Deep Water (NADW). NADW formation primarily occurs in the Nordic Seas and involves a complex interplay of regional water masses such as the Denmark Strait Overflow Water (DSOW), Iceland-Scotland Overflow Water (ISOW) and Nordic Seas Overflow Water. Labrador Sea Water may play an important role as well but increasing evidence suggests water in Labrador and Irminger Seas primarily recirculates through the North Atlantic Gyre and has little connection with the rest of the AMOC.

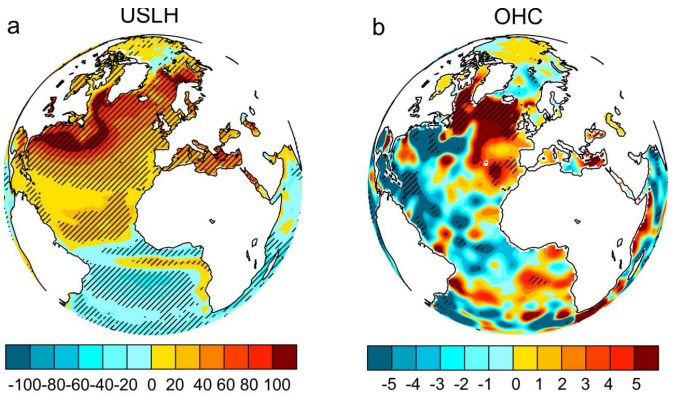


A summary of the path of the thermohaline circulation. Blue paths represent deep-water currents, while red paths represent surface currents

The NADW is not the deepest water layer in the Atlantic Ocean; the Antarctic bottom water (AABW) is always the densest, deepest ocean layer in any basin deeper than 4,000 metres (2.5 mi). As the upper reaches of the AABW flow upwells, it melds into and reinforces the NADW. The formation of the NADW is also the beginning of the *lower cell* of the circulation. The downwelling that forms the NADW is balanced by an equal amount of upwelling. In the western Atlantic, Ekman transport, the increase in ocean-layer mixing caused by wind activity, results in strong upwelling in the Canary Current and the Benguela Current, which are located on the northwest and southwest coasts of Africa. As of 2014, upwelling is substantially stronger around the Canary Current than the Benguela Current, though an opposite pattern existed until the closure of the Central American Seaway during the late Pliocene. In the Eastern Atlantic, significant upwelling occurs only during certain months of the year because this region's deep thermocline means it is more dependent on the state of sea surface temperature than on wind activity. There is also a multi-year upwelling cycle that occurs in synchronization with the El Niño/La Niña cycle.

At the same time, the NADW moves southward and at the southern end of the Atlantic transect, around 80% of it upwells in the Southern Ocean, connecting it with the Southern Ocean overturning circulation (SOOC). After upwelling, the water is understood to take one of two pathways. Watersurfacing close to Antarctica will likely be cooled by Antarctic sea ice and sink back into the lower cell of the circulation. Some of this water will rejoin the AABW but the rest of the lower-cell flow will eventually reach the depths of the Pacific and Indian oceans. Water that upwells at lower, ice-free latitudes moves further northward due to Ekman transport and is committed to the *upper cell*. The warm water in the upper cell is responsible for the return flow to the North Atlantic, which occurs mainly around the coast of Africa and through the Indonesian archipelago. Once this water returns to the North Atlantic, it becomes cooler and denser, and sinks, feeding back into the NADW.

Role in the climate system



Heat transfer from the ocean to atmosphere (left) and an increase in Atlantic Ocean heat content (right) observed when the AMOC is strong

Equatorial areas are the hottest part of the globe; due to thermodynamics, this heat moves towards the poles. Most of this heat is transported by atmospheric circulation but warm, surface ocean currents play an important role. Heat from the equator moves either northward or southward; the Atlantic Ocean is the only ocean in which the heat flow is northward. Much of the heat transfer in the Atlantic occurs due to the Gulf Stream, a surface current that carries warm water northward from the Caribbean. While the Gulf Stream as a whole is driven by winds alone, its northern-most segment, the North Atlantic Current, obtains much of its heat from thermohaline exchange in the AMOC. Thus, the AMOC carries up to 25% of the total heat toward the northern hemisphere, and plays an important role in the climate around northwest Europe.

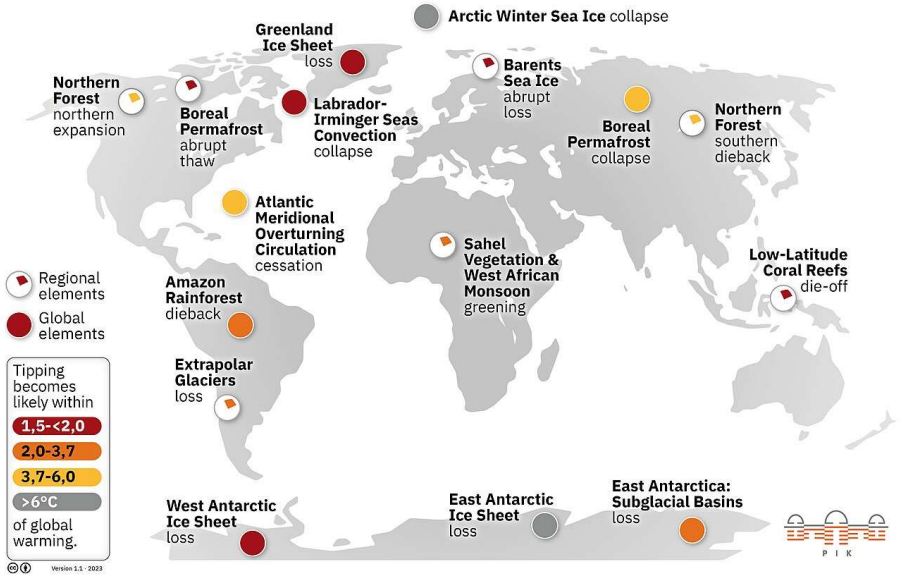
Because atmospheric patterns also play a large role in heat transfer, the idea the climate in northern Europe would be as cold as that in northern North America without heat transport via ocean currents (i.e. up to 15–20 °C (27–36 °F) colder) is generally considered incorrect. While one modeling study suggested collapse of the AMOC could result in Ice Age-like cooling, including sea-ice expansion and mass glacier formation, within a century, the accuracy of those results is questionable. There is a consensus the AMOC keeps northern and western Europe warmer than it would be otherwise, with the difference of 4 °C (7.2 °F) and 10 °C (18 °F) depending on the area. For instance, studies of the Florida Current suggest the Gulf Stream was around 10% weaker from around 1200 to 1850 due to increased surface salinity, and this likely contributed to the conditions known as Little Ice Age.

The AMOC makes the Atlantic Ocean into a more-effective carbon sink in two major ways. Firstly, the upwelling that takes place supplies large quantities of nutrients to the surface waters, supporting the growth of phytoplankton and therefore increasing marine primary production and the overall amount of photosynthesis in the surface waters. Secondly, upwelled water has low concentrations of dissolved carbon because the water is typically 1,000 years old and has not been exposed to anthropogenic CO2 increases in the atmosphere. This water absorbs larger quantities of carbon than the more-saturated surface waters and is prevented from releasing carbon back into the atmosphere when it is downwelled. While Southern Ocean is by far the strongest ocean carbon sink, The North Atlantic is the largest single carbon sink in the northern hemisphere.

… **Trends**

Until 2024 there was a disagreement between observations showing a slowdown of the circulation and climate models showing a stable circulation. In November 2024, *Nature Geoscience* published a study which tried to solve the problem. The scientists used "Earth system and eddy-permitting coupled ocean–sea-ice models". Then observations and models corresponded to each other much better. The study found a slowdown of 0.46 sverdrups per decade since 1950. …

Major review studies (state of the art)



AMOC is considered to be one of the several major parts of the climate system which could pass tipping point around a certain level of warming and eventually transition to a different state as a result. The graphic shows the levels of warming where this tipping is most likely to occur for a given element

Large review papers and reports are capable of evaluating model output, direct observations and historical reconstructions to make expert judgements beyond what models alone can show. Around 2001, the IPCC Third Assessment Report projected high confidence the AMOC thermohaline circulation would weaken rather than stop and that warming effects would outweigh cooling, even over Europe. When the IPCC Fifth Assessment Report was published in 2014, a rapid transition of the AMOC was considered 'very unlikely' and this assessment was offered at a high level of confidence.

In 2021, the IPCC Sixth Assessment Report again said the AMOC is 'very likely' to decline within the 21st century and that there was a "high confidence" changes to it would be reversible within centuries if warming was reversed. Unlike the Fifth Assessment Report, it had only 'medium confidence' rather than 'high confidence' in the AMOC avoiding a collapse before the end of the 21st century. This reduction in confidence was likely influenced by several review studies that draw attention to the circulation stability bias within general circulation models, and simplified ocean-modelling studies suggesting the AMOC may be more vulnerable to abrupt change than larger-scale models suggest.

The synthesis report of the IPCC Sixth Assessment Report summarized the scientific consensus as follows: 'The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (high confidence), however an abrupt collapse is not expected before 2100 (medium confidence). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities.'

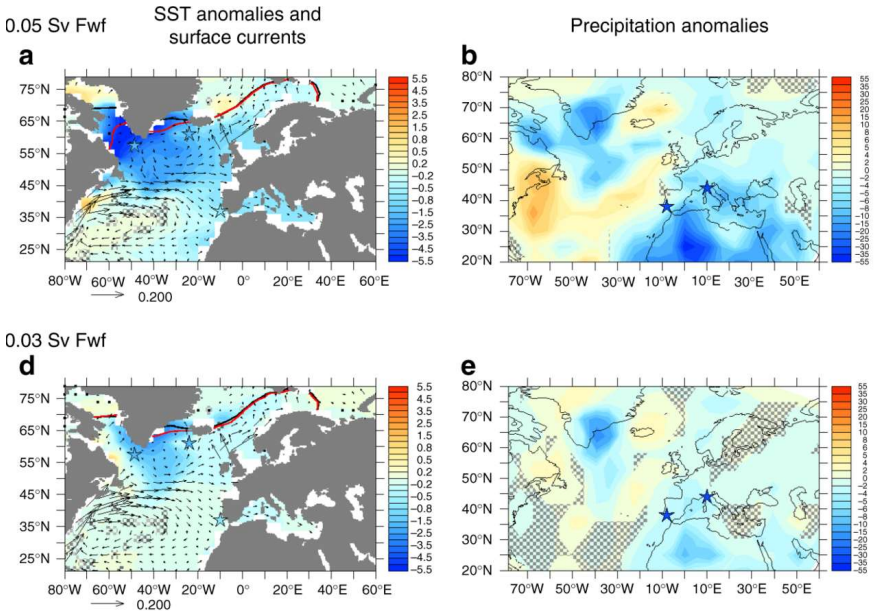
In 2022, an extensive assessment of all potential climate tipping points identified 16 plausible climate tipping points, including a collapse of the AMOC. It said a collapse would most likely be triggered by 4 °C (7.2 °F) of global warming but that there is enough uncertainty to suggest it could

be triggered at warming levels of between 1.4 °C (2.5 °F) and 8 °C (14 °F). The assessment estimates once AMOC collapse is triggered, it would occur between 15 and 300 years, and most likely at around 50 years. The assessment also treated the collapse of the Northern Subpolar Gyre as a separate tipping point that could tip at between 1.1 °C (2.0 °F) degrees and 3.8 °C (6.8 °F), although this is only simulated by a fraction of climate models. The most likely tipping point for the collapse of Northern Subpolar Gyre is 1.8 °C (3.2 °F) and once triggered, the collapse of the gyre would occur between 5 and 50 years, and most likely at 10 years. The loss of this convection is estimated to lower the global temperature by 0.5 °C (0.90 °F) while the average temperature in Europe would decrease by around 3 °C (5.4 °F). There would also be substantial effects on regional precipitation levels.

The 'State of the cryosphere' report dedicates significant space to AMOC, saying it may be enroute to collapse because of ice melt and water warming. Impacts will include cooling of Northern Europe faster than 3 °C per decade, 'with no realistic means of adaptation'. At the same time, the Antarctic Circumpolar Current (ACC) is also slowing down and the Weddell Sea Bottom Water is losing volume, what can impact global ocean circulation and climate. UNESCO mentions that the report in the first time 'notes a growing scientific consensus that melting Greenland and Antarctic ice sheets, among other factors, may be slowing important ocean currents at both poles, with potentially dire consequences for a much colder northern Europe and greater sea-level rise along the U.S. East Coast.'

In February 2025, a study published in *Nature* concluded that the AMOC is resilient to extreme greenhouse gas and North Atlantic freshwater forcings across 34 climate models, suggesting that an AMOC collapse is unlikely in the 21st century.

Effects of an AMOC slowdown

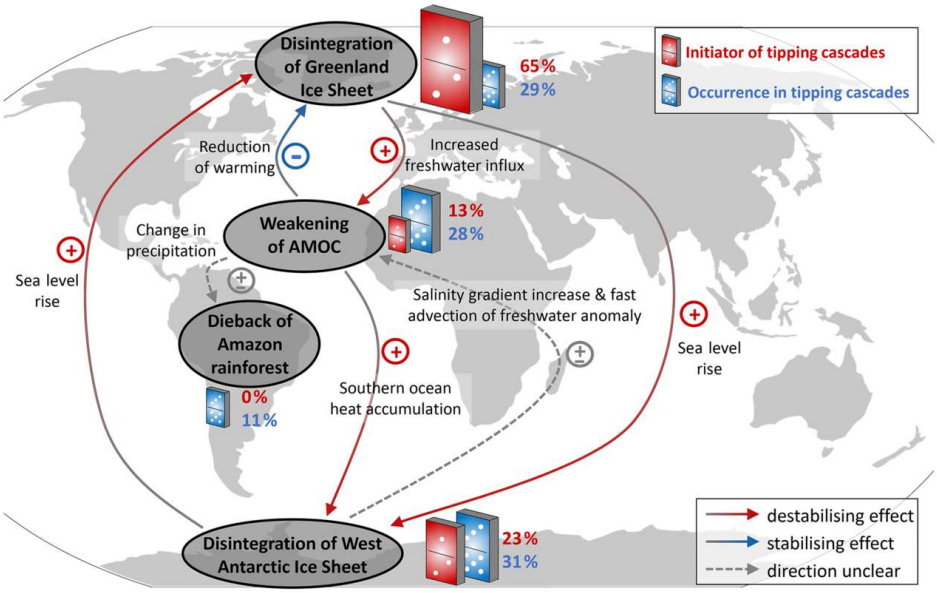


AMOC was weaker than now during the last interglacial period, and this had been connected to the cooling of North Atlantic Ocean temperatures and the reduction in precipitation over Europe and Africa (blue)

As of 2024, there is no consensus on whether a consistent slowing of the AMOC circulation has occurred but there is little doubt it will occur in the event of continued climate change. According to the IPCC, the most-likely effects of future AMOC decline are reduced precipitation in mid-latitudes, changing patterns of strong precipitation in the tropics and Europe, and strengthening storms that follow the North Atlantic track. In 2020, research found a weakened AMOC would slow the decline

in Arctic sea ice and result in atmospheric trends similar to those that likely occurred during the Younger Dryas, such as a southward displacement of Intertropical Convergence Zone. Changes in precipitation under high-emissions scenarios would be far larger.

A decline in the AMOC would be accompanied by an acceleration of sea level rise along the U.S. East Coast; at least one such event has been connected to a temporary slowing of the AMOC. This effect would be caused by increased warming and thermal expansion of coastal waters, which would transfer less of their heat toward Europe; it is one of the reasons sea level rise along the U.S. East Coast is estimated to be three-to-four times higher than the global average.



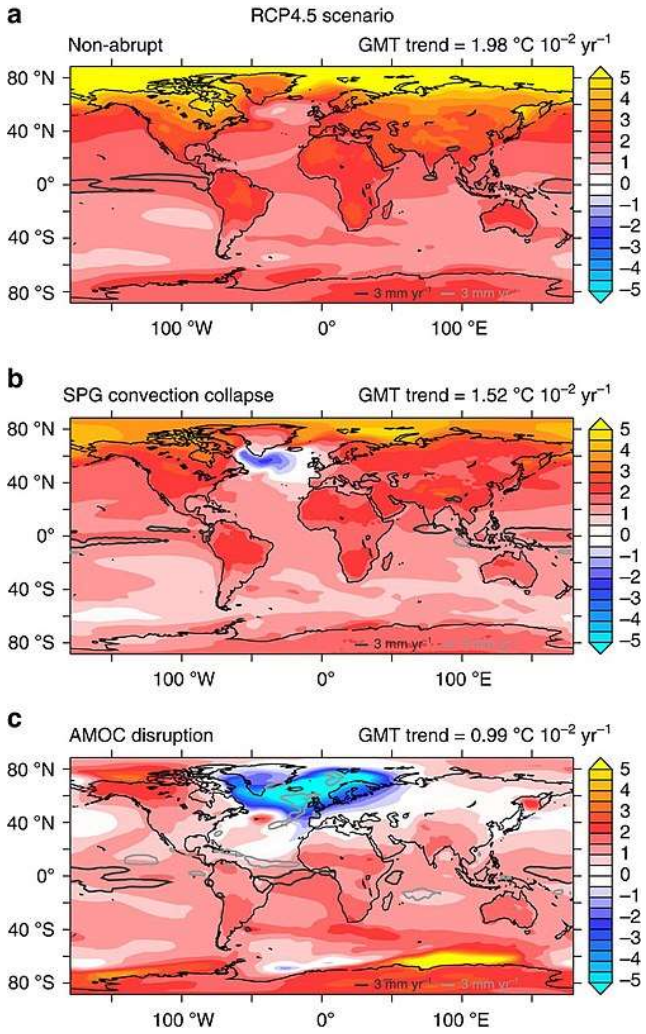
A proposed tipping cascade where the AMOC would mediate a connection between the other tipping elements.

Some scientists believe a partial slowing of the AMOC would result in limited cooling of around 1 °C (1.8 °F) in Europe. Other regions would be differently affected; according to 2022 research, 20th-century winter-weather extremes in Siberia were milder when the AMOC was weakened. According to one assessment, a slowing of the AMOC is one of the few climate tipping points that are likely to reduce the social cost of carbon, a common measure of economic impacts of climate change, by −1.4% rather than increasing it, because Europe represents a larger fraction of global GDP than the regions that will be negatively affected by the slowing. This study's methods have been said to have underestimating climate impacts in general. According to some research, the dominant effect on an AMOC slowdown would be a reduction in oceanic heat uptake, leading to increased global warming, but this is a minority opinion.

A 2021 study said other well-known tipping points, such as the Greenland ice sheet, the West Antarctic Ice Sheet and the Amazon rainforest would all be connected to the AMOC. According to this study, changes to the AMOC alone are unlikely to trigger tipping elsewhere but an AMOC slowdown would provide a connection between these elements and reduce the global-warming threshold beyond which any of those four elements – including the AMOC itself – could be expected to tip, rather than the thresholds that have been established from studying those elements in isolation. This connection could cause a cascade of tipping over several centuries.

Effects of an AMOC shutdown

Cooling



Modelled 21st century warming under the "intermediate" global warming scenario (top). The potential collapse of the subpolar gyre in this scenario (middle). The collapse of the entire Atlantic Meriditional Overturning Circulation (bottom).

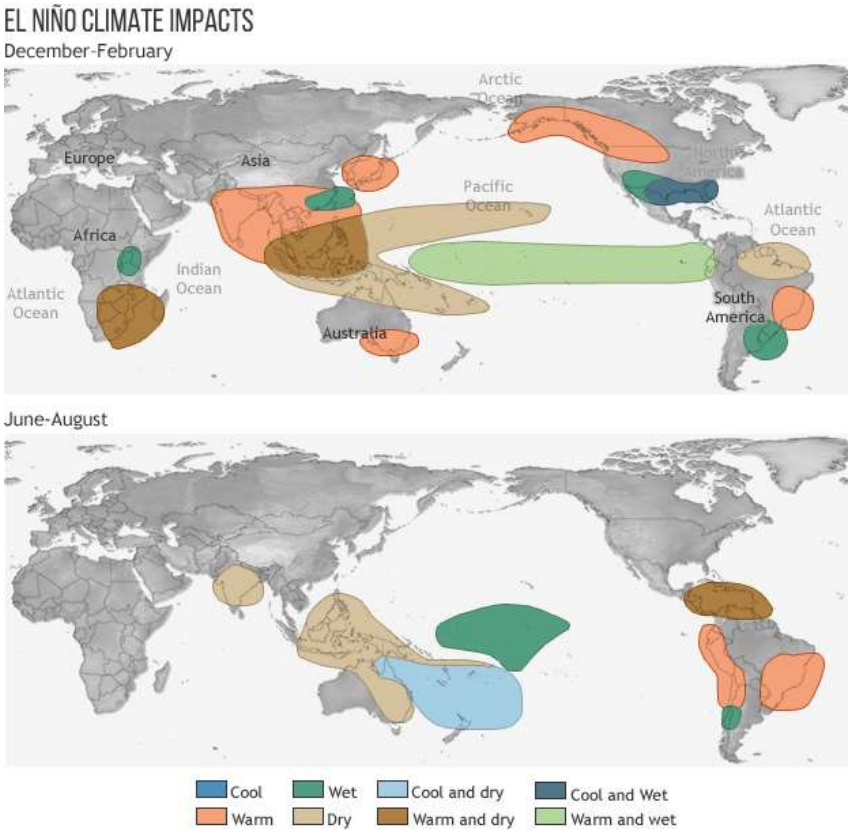
A complete collapse of the AMOC will be largely irreversible and recovery would likely take thousands of years. A shutting down of the AMOC is expected to trigger substantial cooling in Europe, particularly in Britain and Ireland, France and the Nordic countries. In 2002, research compared AMOC shutdown to Dansgaard–Oeschger events – abrupt temperature shifts that occurred during the Last Glacial Period. According to that paper, local cooling of up to 8 °C (14 °F) would occur in Europe. In 2022, a major review of tipping points concluded an AMOC collapse would lower global temperatures by around 0.5 °C (0.90 °F) while regional temperatures in Europe would fall by between 4 °C (7.2 °F) and 10 °C (18 °F).

A 2020 study assessed the effects of an AMOC collapse on farming and food production in Great Britain. It found within Great Britain an average temperature drop of 3.4 °C (6.1 °F) after the effect of warming was subtracted from collapse-induced cooling. A collapse of the AMOC would also lower rainfall during the growing season by around 123 mm (4.8 in), which would in turn reduce the area of land suitable for arable farming from 32% to 7%. The net value of British farming would decline by around £346 million per year – over 10% of its value in 2020.

In 2024, one study that modeled the effect of an AMOC collapse on a pre-industrial world, predicted a more severe cooling in Europe. It predicted the average sea surface temperatures in northwest Europe falling 10 °C (18 °F) and the average February temperatures on land falling between 10 °C (18 °F) and 30 °C (54 °F) within a century in northern and western Europe. This change would result in sea ice reaching into the territorial waters of the British Isles and Denmark during winter while Antarctic sea ice would diminish. These findings do not include the counteracting warming from climate change, and the modeling approach used by the paper is controversial.

A 2015 study led by James Hansen found a shutdown or substantial slowing of the AMOC will intensify severe weather because it increases baroclinicity and accelerates northeasterly winds up to 10–20% throughout the mid-latitude troposphere. This could boost winter and near-winter cyclonic "superstorms" that are associated with near-hurricane-force winds and intense snowfall. This paper has also been controversial.

Other



Changes to temperature and precipitation during El Niño (left) and La Niña (right). The top two maps are for Northern hemisphere winter, the bottom two for summer. While the El Niño–Southern Oscillation occurs due to the processes in the Pacific Ocean, a connection between the Pacific and the Atlantic means that changes in AMOC can conceivably affect it

Several studies have investigated the effect of a collapse of the AMOC on the El Niño–Southern Oscillation (ENSO); results have ranged from no overall impact to an increase in ENSO strength, and a shift to a dominant La Niña conditions with an about 95% reduction in El Niño extremes but more-frequent extreme rainfall in eastern Australia, and intensified droughts and wildfire seasons in the southwestern U.S.

A 2021 study used a simplified modeling approach to evaluate the effects of an AMOC collapse on the Amazon rainforest, and its hypothesized dieback and transition to a savanna state in some climate-change scenarios. This study found an AMOC collapse would increase rainfall in the southern Amazon due to the shift of an Intertropical Convergence Zone, and this would help to counter the dieback and potentially stabilize the southern part of the rainforest. A 2024 study found the seasonal cycle of the Amazon could reverse with dry seasons becoming wet and *vice versa*.

A 2005 paper said severe disruption of the AMOC would collapse North Atlantic plankton counts to less than half of their normal biomass due to increased stratification and the large decline in nutrient exchange among ocean layers. A 2015 study simulated global ocean changes under AMOC slowing and collapse scenarios, and found these events would greatly decrease dissolved oxygen content in the North Atlantic, although dissolved oxygen would slightly increase globally due to greater increases across other oceans. ».

Conclusion

La densité des informations précédentes est de nature à noyer notre jugement. Mais elle traduit deux faits certains : l'importance des conséquences du changement climatique d'une part, et le contraste régional qui peut amener des changements de tendance en matière de réchauffement et de régime hydrique d'autre part. La part de l'incertitude de nos connaissances reste grande, comme en témoignent les controverses, mais tend à se réduire. Une seule attitude pour gérer l'avenir de nos viticultures : ménager un **éventail de scénarios afin de guider nos choix d'adaptation**. Pour ce faire et en avant-première, prévoir de lire **'Les vignobles du futur'** aux éditions GFA d'Alain Carbonneau et Giovanni Cargnello.

The sheer volume of information presented here can overwhelm our judgment. However, it reflects two undeniable facts: the significant consequences of climate change, and the regional contrasts that can lead to shifts in warming trends and water regimes. While a considerable amount of uncertainty remains in our knowledge, as evidenced by the controversies, it is gradually diminishing. There is only one approach to managing the future of our vineyards: consider a ***range of scenarios to guide our adaptation choices****. To this end, and as a preview, consider reading* ***'The Vineyards of the Future'*** *by Alain Carbonneau and Giovanni Cargnello, published by GFA.*