Review

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Past, present and future of the Atlantic meridional overturning circulation

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Summary: The global climate has undergone substantial palaeoclimatic changes, such as the rhythmicity between glacial and interglacial periods, during the last three million years. These changes imply the existence of major variations in the latitudinal distribution of heat, with a changing Atlantic meridional overturning circulation (AMOC) likely playing a major role in the Earth's shift between different climatic states. The anthropogenic-driven warming and melting of the subpolar North Atlantic is now turning its surface waters more buoyant, opening the possibility of an AMOC breakdown that could drive the Earth towards a new state. The debate remains open: available instrumental data tell us that the AMOC has remained fairly stable during the last two decades, while global coupled climate models predict a moderate weakening during this century. Additionally, complex-theory statistics of some regional ocean indexes, assumed to be fingerprints of the AMOC's intensity, suggest that the AMOC may be approaching a tipping point leading to collapse in the coming decades. Furthermore, the Earth's growing radiative energy imbalance, caused primarily by the increase in atmospheric greenhouse gases, causes a huge amount of energy to be stored in the ocean, which will be distributed and released in yet unknown manners that will likely affect the AMOC. Though the available in situ data are robust, the diversity of analyses warns us that transitions may take place faster than projected by numerical models, emphasizing the urgent need to reduce pressures that risk undermining the climate system and the well-being of future generations.

Keywords: Atlantic meridional overturning circulation; global climate; palaeoclimatic changes; instrumental data; global climate models; complex systems; Earth system science; living Earth.

Pasado, presente y futuro de la Circulación Meridional Atlántica de Retorno

Resumen: El clima global ha experimentado cambios paleoclimáticos sustanciales, como la ritmicidad entre los períodos glaciales e interglaciales durante los últimos 3 millones de años. Estos cambios implican la existencia de grandes variaciones en la distribución latitudinal del calor, con una circulación meridional Atlántica de retorno (CMAR) cambiante que probablemente desempeñó un papel importante para la transición de la Tierra entre distintos estados climáticos. El calentamiento y deshielo por causa antropogénica del Atlántico Norte subpolar están causando ahora que sus aguas superficiales sean más boyantes, abriendo la posibilidad de una ruptura de la CMAR que podría llevar a la Tierra hacia un nuevo estado climático. El debate está abierto: los datos instrumentales disponibles nos indican que la CMAR se ha mantenido bastante estable durante las últimas dos décadas, mientras que los modelos climáticos globales acoplados predicen un debilitamiento moderado durante este siglo. Además, las estadísticas de teoría compleja para algunos índices oceánicos regionales, que supuestamente son indicadores de la intensidad de la CMAR, sugieren que la CMAR podría estar acercándose a un punto de inflexión hacia el colapso, que ocurriría en las próximas décadas. Más aun, el creciente desequilibrio energético radiativo de la Tierra, causado principalmente por el aumento de los gases atmosféricos de tipo invernadero, ocasiona que se estén almacenando enormes cantidades de energía en el océano, que se distribuirán y liberarán de maneras aún desconocidas, lo cual probablemente afectará la AMOC. Si bien los datos in situ disponibles son robustos, la diversidad de análisis nos advierte que las transiciones podrían ocurrir más rápido de lo previsto por los modelos numéricos, instándonos a que dejemos de hipotecar el planeta Tierra para las generaciones futuras.

Palabras clave: circulación meridional Atlántica de retorno; clima global; cambios paleoclimáticos; datos instrumentales; modelos climáticos globales; sistemas complejos; ciencia del sistema terrestre; Tierra viva.

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THE GLOBAL OVERTURNING AND ATLANTIC MERIDIONAL OVERTURNING CIRCULATIONS

We live in a fully non-stop interconnected hydrological cycle, with water reaching near and far sites through a myriad of processes that take place at multiple spatiotemporal scales (UCAR, 2017). The ocean is the central element of this process, as it holds about 97% of all water on Earth, with a relatively long mean residence time of about 3000 years. But ocean water also reaches elsewhere through evaporation-precipitation: a very small fraction (10^{-8}) stays in the atmosphere a mean time of 9 days before falling back to the ocean or over land; liquid water on land has a residence time of less than 100 yrs and accounts for 3 x 10^{-6} of the total, with one-third of it arriving via excess evaporation from the ocean; and the remaining water (about 3%) is found as ice, snow and subsurface freshwaters, with residence times of tens to hundreds of years.

The backstone global- and century-scale driver of the circulatory ocean system is the exchange of near-surface (the upper few hundred metres) and deep (below 2-3 km) ocean waters at planetary scales, in what is now known as the global overturning circulation (GOC). The GOC was originally known as the thermohaline circulation, because the starting limb of this vertical exchange is density-driven, which results from the cooling and salinification of surface waters. It was later called the global conveyor belt (Broecker 1987), because of its non-stop, interconnected nature (Fig. 1). All ocean basins participate in the GOC, but with different roles, the Atlantic Basin acting as a main hall for the start and end of the global deep pathways and the other ocean basins as horizontal and vertical connectors. Indeed, the thermohaline changes that initiate the GOC predominate in the subpolar North Atlantic and around the Antarctic continent, including an Atlantic sector off the Weddell Sea. This is why the Atlantic branch of the GOC—the Atlantic meridional overturning circulation (AMOC)—is of particular importance (Fig. 2).

This review offers an integrated perspective of the GOC and the AMOC. I first set the physical context, focusing on the Atlantic Ocean, followed by some examples illustrative of AMOC palaeoclimatic changes. Then I explain the diverse AMOC monitoring efforts and what they tell us about trends and variability during the last two decades. This is followed by two sections on predictions, the first one based on numerical models and the second on complex-theory

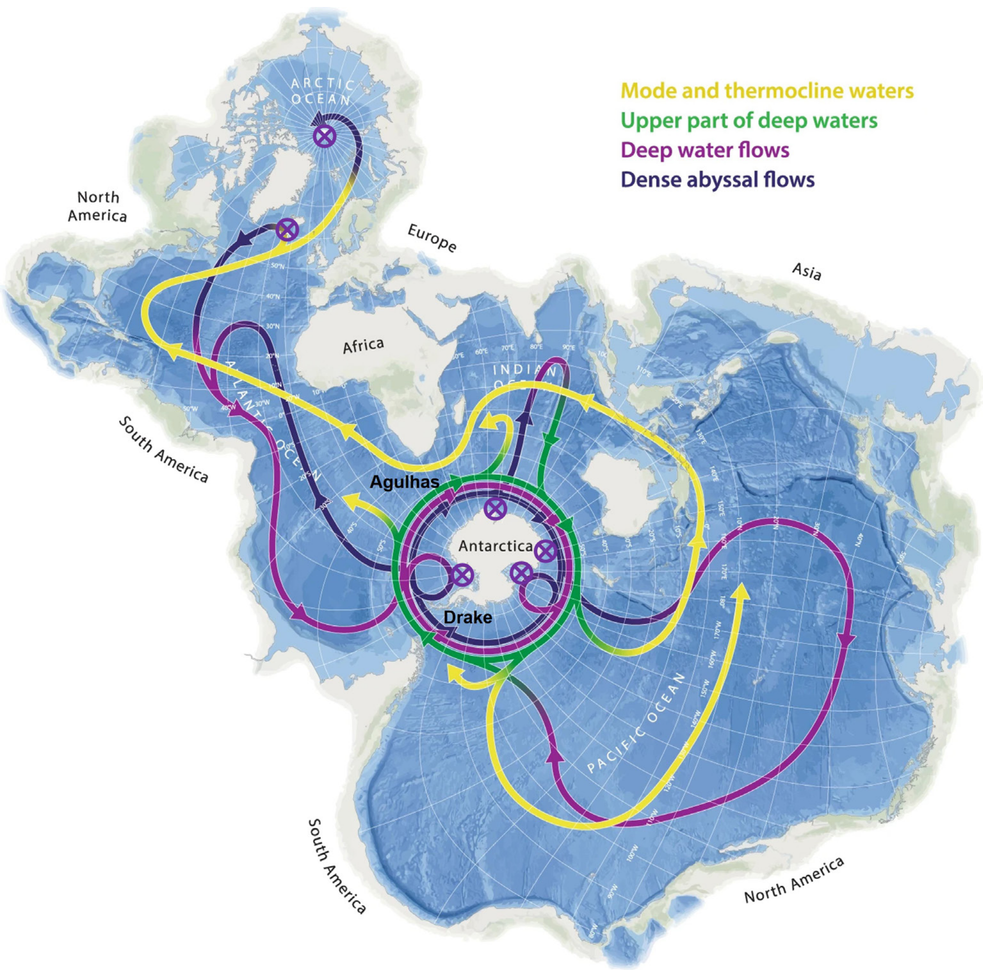

Fig. 1. – Schematics of the predominant GOC circulation, as viewed from the South Pole (Spilhaus projection), adapted from Meredith (2022). The principal regions of deep-water formation are sketched as crossed circles, two in the subpolar North Atlantic and four around Antarctica. The return pathways for surface and intermediate waters into the Atlantic Basin are labelled as Agulhas and Drake, respectively.

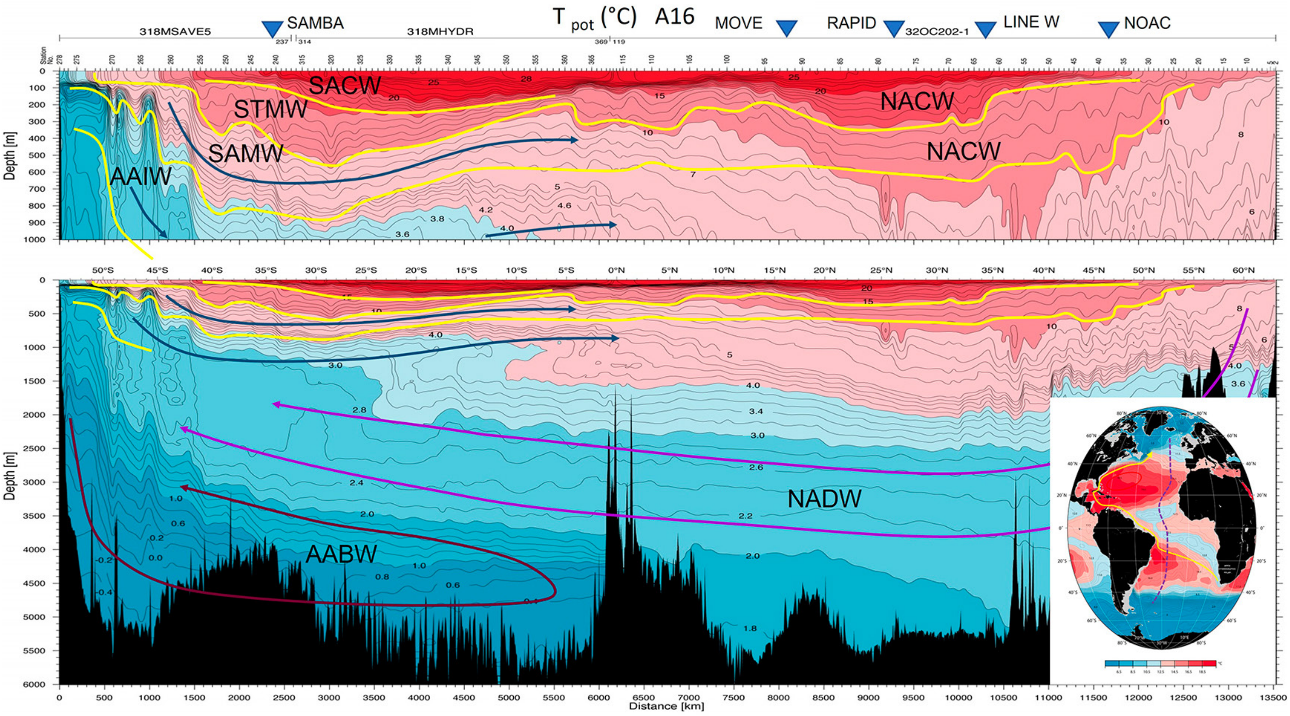

Fig. 2. – Distribution of potential temperature in a meridional Atlantic section, with a sketch of the predominant AMOC pathways. SACW and NACW refer to central waters in the South and North Atlantic, SAMW and AAIW denote mode and intermediate waters in the AMOC returning limb, while NADW and AABW are the deep and bottom water masses that constitute the initial limb of the AMOC. The yellow contours show selected isopycnals (26.0, 26.8, 27.2 and 27.5 kg m^{-3}) that separate upper-ocean water masses. The latitudes of the NOAC, LINE W, RAPID, MOVE and SAMBA arrays are indicated. The inset shows the distribution of temperature at 200 m, a pattern that reflects the extent of the Atlantic thermocline gyres, with the track of the vertical section shown as a latitudinal dashed line and the mean path of the returning limb of the AMOC as a solid yellow line. Both the vertical section and the map are adapted from the WOCE Atlantic Ocean Atlas (Koltermann et al. 2011).

indicators. I continue with a section on the potentially high impacts of the Earth's growing radiative imbalance, and end up with a more personal reflection on our limited skills for predicting the future for the immeasurably complex living Earth, and the urgent need to change our relation with nature. Throughout this review, I will several times recover the physiological analogy, which compares the ocean circulation to the circulatory system in mammals, in terms of similar spatiotemporal patterns and metabolic processes. The perspective presented tries to provide a complementary—and possibly quite personal—perspective of a resilient living Earth being strikingly impacted by anthropogenic forcing. The reader is encouraged to also go to reviews and opinions on the stability and evolution of the AMOC by Buckley and Marshall (2016), Lynch-Stieglitz (2017), Weijer et al. (2019), Liu (2023) and Rahmstorf (2024).

The initial limb of the GOC is a density-driven process that starts during several winter weeks in the subpolar Atlantic regions, creating the pressure difference necessary to transfer the surface waters to the deep ocean and impulse the nascent deep currents. In contrast, the returning limb of the GOC—the return of the deep waters to the near-surface layers—is a long wind-driven process that operates continuously. This circulatory pattern is, in many aspects, comparable to the circulatory system of mammals, with the short systolic period of the heartbeat building the pressure difference that propels blood through the arteries, and the muscle contractions creating the peristaltic pumping that drives the blood back to the heart during the long diastolic phase (Pelegrí 2008, Pelegrí and Duró 2013, Pelegrí et al. 2013, Aloisi 2023). In both cases a central circulatory system progressively bifurcates into smaller and smaller circuits—open circuits for the ocean and closed circuits for mammals—and eventually supplies the essential metabolic properties to the entire living system.

In the subtropical North Atlantic, evaporation exceeds precipitation plus river runoff, so the sea surface layers have a salinity maximum. These subtropical salty surface waters stretch all the way into the subpolar regions via the North Atlantic Current (Schmitt and Blair 2015), causing most of the North Atlantic, including its subpolar waters, to have an unstable vertical salinity profile. However, as a result of solar insolation, these surface waters are also much warmer and less dense than the deep ones, so the water column is vertically stable. This stability breaks down in the boreal winter, when very cold continental westerly winds cool down the surface waters of the subpolar gyre, which turn very dense and sink to the seafloor. The formation of North Atlantic Deep Water (NADW) occurs abruptly over a period of a few weeks, but the volume produced is so large that it corresponds to an annual mean value close to 17-18 Sv (1 Sv = 10^6 m^3 s^{-1}) (see section on "Current state of the Atlantic Meridional Overturning Circulation" below). The NADW fill much of the deep ocean layers and progress south through the entire basin, reaching the Antarctic Circumpolar Current (ACC) in time scales ranging between several years and a few decades (Wett et al. 2023, Frajka-Williams et al. 2018, van Sebille et al. 2012, Garzoli et al. 2015).

During the austral winter, extensive sea-ice formation on the Antarctic continental shelf releases large amounts of salt into the surrounding waters. This process forms very dense open-ocean waters that sink to the bottom layers of the ACC, known as Antarctic Bottom Water (AABW). Antarctic Bottom Water is formed in four regions around Antarctica, which largely determine the target ocean basin: the Weddell Sea supplies the Atlantic, Prydz Bay supplies the Indian Ocean and the Ross Sea and Adelie Land supply the Pacific (Sodoloch et al. 2022, Silvano et al. 2023). The annual mean formation rate is quite uncertain: global northward transports beyond 35°S lie in the 10-20 Sv range (Ganachaud 2003, Lumpkin and Speer 2007, Talley 2013, Lee et al. 2019, Silvano et al. 2023) and transport in the Atlantic sector lies between 5 and 8 Sv (Naveira Garabato et al. 2002, Lumpkin and Speer 2007, Johnson 2008, Palmer et al. 2012, Hernández-Guerra et al. 2019, Kersalé et al. 2020, 2021).

Both NADW and AABW represent the initial limb of the GOC and its principal AMOC branch (Figs 1 and 2), the latter filling the deep Atlantic layers at a total rate of about 22-26 Sv. Most NADW and AABW eventually join the ACC and either upwell along the Southern Ocean in time scales of less than 100 years, via topographically-induced upward spiralling (Tamsitt et al. 2017), or follow a long trip into the Indian and Pacific oceans, which may last between hundreds and a few thousand years, experiencing wind-induced upwelling and vertical mixing before returning to shallow Southern Ocean layers (Lumpkin and Speer 2007, Talley 2013, Cessi 2019, Rousselet et al. 2021). The pathway back into the subpolar North Atlantic is even more complex, as the returning waters reach the Atlantic at intermediate levels via the Drake Passage (south of South America) or as surface leaking waters of the Agulhas Current (south of Africa) and have to travel meridionally across the entire Atlantic, involving an intricate crossing of the anticyclonic subtropical and cyclonic tropical gyres (Fig. 2).

As deep waters in the northern hemisphere are only formed in the Atlantic, the AMOC is central to the entire system. Because of these subpolar northern/southern sources of deep/bottom waters (Fig. 2), in the AMOC we can differentiate between an upper cell linked to NADW and a lower cell associated with AABW formed in the Atlantic sector. However, the reported figures on the intensity of the AMOC usually refer to its upper cell, which is most relevant to the climate of the northern hemisphere and Europe in particular (hereafter, except when specified, all AMOC transports will refer to its upper cell). In particular, the average returning limb of the (upper cell) AMOC is northward at all latitudes of the Atlantic Basin, increasing from about 0.5 PW (1 PW = 10^{15} Watts) at 30°S to a maximum exceeding 1.2 PW at 24°N (Ganachaud and Wusch 2000, Hernández-Guerra et al. 2014, Cabré et al. 2019, Caínzos et al. 2022). As a result, the North Atlantic surface waters are relatively warm all year long, so the predominant high-latitude low-level westerly winds cause temperate winters and year-long precipitation in all of northern Europe.

PALAEO-VARIABILITY IN THE EARTH'S STATE

The GOC is a central element for our living planet as it increases the exchange between deep and surface ocean waters. This planetary vertical exchange allows the transformation of organic into inorganic matter (remineralization) in the deep ocean (Hansell 2013, De La Fuente et al. 2017, Romera-Castillo et al. 2019) and gradually incorporates into the ocean system the properties coming from the underlying lithosphere (Giraud et al. 2008, Ardyna et al. 2019, Syverson et al. 2021). Both processes lead to a continuous recovery of the deep reservoir of inorganic nutrients, which eventually return to the surface photic layers and allow for non-stop global (new) primary production. In terms of global metabolism, defined as the net autotrophic community production (Pelegrí et al. 2008, 2013), we may again use the physiological analogy to compare the GOC with the basal circuit of the circulatory system in mammals, which is responsible for replenishing the fluid with nutrients that will hence sustain the surface ocean primary production. The second major circuit is the relatively swift thermocline circulation, characterized by ocean–atmosphere gas exchange, which has been compared with the pulmonary circuit in mammals (Pelegrí 2008).

As in any living being, the GOC requires major changes in the rate of circulation in order to reinitialize the system and maximize the flow of properties (Bejan 1997, 2000, Reis and Bejan 2006, Pelegrí 2008). A well-known major cyclic pattern is the seasonal cycle. Another one is the glacial–interglacial cycle (Boyle and Keigwin 1982, Labeyrie et al. 1992, Brown and Galbraith 2015, Galbraith et al. 2016), which involves a much deeper resetting: the living Earth switches between glacial "rest" periods characterized by a relatively slow AMOC that allows nutrient reserves to build up in the form of dissolved organic matter (DOM) and interglacial "exercise" periods, when the AMOC becomes more intense to efficiently distribute the reserves and sustain enhanced global primary production (Pelegrí 2008, Pelegrí et al. 2013).

A possibly similar but much faster AMOC transition took place intermittently during the last glacial period, during the relatively warm/cold states of the Dansgaard-Oeschger cycle, known as interstadials and stadials (Lynch-Stieglitz 2017, Malmierca-Vallet et al. 2023). The vertical circulation patterns of these stadials/interstadials possibly resembled those of the glacial/interglacial periods, with the AMOC upper cell intensifying and expanding vertically during the interstadials and weakening and contracting during the stadials (Rahmstorf 2002, Lynch-Stieglitz 2017, Hines et al. 2019, Menviel et al. 2020, Kuniyoshi et al. 2022, Max et al. 2022). Like the glacial-interglacial transition, the Dansgaard-Oeschger transitions were asymmetric, with a very fast stadial-interstadial shift—as short as a

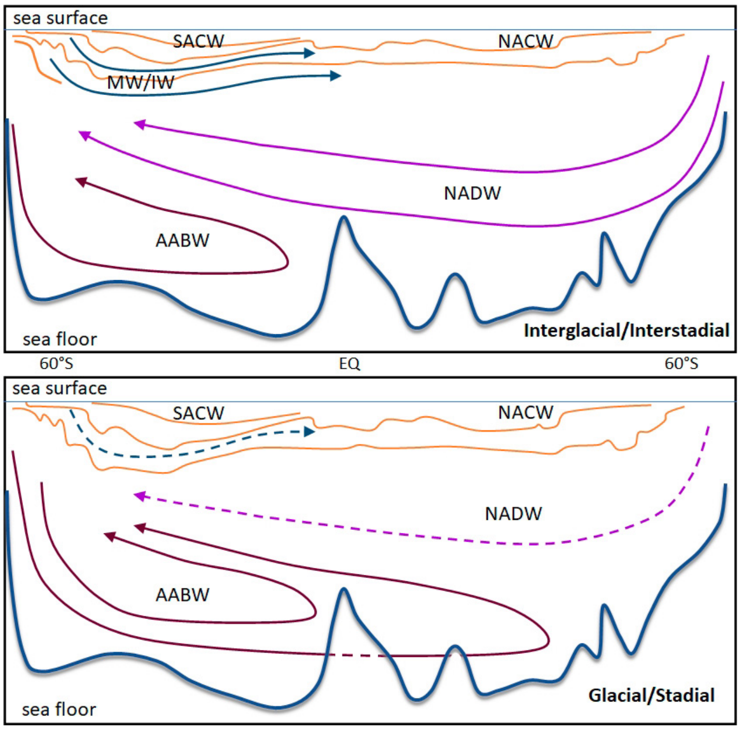

Fig. 3. – Idealized Atlantic vertical sections running from north to south with schematic arrows showing mean latitudinal circulation patterns that correspond to different AMOC states (bathymetry in blue and isopycnals in orange, following Figure 2). SACW and NACW refer to central waters in the South and North Atlantic, MW/IW denote mode and intermediate waters in the AMOC returning limb, NADW and AABW are the deep and bottom water masses that constitute the initial limb of the AMOC. (Bottom panel) During glacial/stadial periods the subtropical gyres are deep and energetic, and the deep ocean is dominated by AABW, while (top panel) during interglacial/interstadial conditions the subtropical gyres become shallow and NADW circulation intensifies. After Sigman and Boyle (2000), Rahmstorf (2002) and Hines et al. (2019).

decade—and a longer stadial cooling that typically took hundreds of years (Fig. 3). The last glacial period was filled with some 25 of these stadial-to-interstadial transitions, when the vertical circulation shifted rapidly to an interglacial-like pattern before slowly returning to the stadial pattern that characterizes most of the glacial period. Some of these stadials, however, showed the presence of events of intense cooling in the North Atlantic, the Heinrich events, when the AMOC upper cell may have collapsed (Fig. 3).

Despite the lack of conclusive evidence on the magnitude and type of variations, there is substantial consensus that major AMOC changes occurred between glacial and interglacial periods, a cycle that has been repeated during the last 3 million years (initially with a 41 kyr cycle and, during the last eight cycles, switching to 100 kyr). A fairly active circulation of deep and bottom waters (NADW and AABW) characterizes the current interglacial period, the Holocene, which started about 12000 yrs ago—apparently with moderate variations during the last millennium (Caesar et al. 2021, 2022, Kilbourne et al. 2022). The use of extensive hydrographic and sea surface temperature (SST) records back to the late 1800s and early 1900s proposes that the AMOC has slowed between 1 and 3 Sv (Caesar et al. 2018, Rossby et al. 2020, Li and Liu 2025), a result that contrasts with a proxy reconstruction that suggests that during the recent decades the AMOC has been at the weakest of the last 1000 years (Caesar et al. 2021).

The possibility of different AMOC states was early shown by Stommel (1961) through a simple two-box nonlinear model, but it did not receive proper attention until much later (Broecker et al. 1985, Paillard 1998, Sigman and Boyle 2000, Paillard and Parrenin 2004, Pelegrí et al. 2013, Watson et al. 2015, Jansen 2016, Hines et al. 2019, Marzocchi and Jansen 2019, Weijer et al. 2019). A major indicator of the glacial-interglacial variations is the atmospheric CO_2 concentration, changing from minimum glacial values of 180 ppm to the interglacial 280 ppm. Several mechanisms have been proposed as drivers of these variations, with an interplay of physical, biological and chemical factors, and with different roles for the northern and southern subpolar regions. However, a major factor is the intensity of the GOC, because it controls the rate of vertical exchange between the deep waters enriched in dissolved inorganic carbon and surface waters that are relatively poor in dissolved inorganic carbon (Fig. 3) (e.g. Sarmiento and Toggweiler 1984, Toggweiler 1999, Paillard and Parrenin 2004, Pelegrí et al. 2013a). The atmospheric CO_2 rises/falls because inorganic carbon establishes partial equilibrium at the ocean–atmosphere interface in response to the increase/decrease in dissolved inorganic carbon at the sea surface.

The high interglacial atmospheric CO_2 reflects an active deep vertical overturning, with an intense initial deep (NADW) and bottom (AABW) limb and a returning limb that reaches back to the Atlantic Basin via Southern Ocean upwelling and the arrival of the Agulhas surface and Drake intermediate waters. In contrast, the low atmospheric

CO_2 glacial concentrations suggest a fairly isolated deep ocean or at least an increased disconnection between the surface and deep layers (Oppo et al. 1993, Sigman and Boyle 2000, Rahmstorf 2002, Lynch-Stieglitz et al. 2007, Brown and Galbraith 2015, Galbraith et al. 2016, Hines et al. 2019; see, however, Böhm et al. 2015), with a weakening of the meridional heat transport and a reduced extension of the temperate regions at the expense of larger tropical-subtropical and subpolar-polar regions (Roca and Pelegrí 2020, Wharton et al. 2024). One consequence would be a sharp transition from the subtropical to the subpolar North Atlantic, creating an intense subtropical gyre that, nevertheless, was unable to proceed to high latitudes.

CURRENT STATE OF THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

Getting to know the far past states of the AMOC relies on seafloor subsurface palaeo-data (geologic cores) along the continental slope and over seamounts. These data become proxies of past water-mass properties ranging from dissolved oxygen and inorganic nutrients to temperature, salinity, foraminifera and radioactive compounds, which are then interpreted in terms of water masses and associated circulation patterns. The situation changed completely with the arrival of instrumental data, initially as hydrographic sections with properly spaced stations that sampled the entire water column to identify water masses and their meridional transports. An early study by Bryden et al. (2005) used five transatlantic sections carried out approximately along 26°N between 1957 and 2004 to propose that the AMOC was weakening. However, the fact that one realization per decade during five decades can lead to biased results sparked a major deployment of instrumented moorings in the North Atlantic along 26°N to gather continuous hydrographic and velocity data (Fig. 4A). This 20-year-old initiative, known as the Rapid Climate Change Programme (RAPID) array, has started providing solid answers about the current state of the AMOC.

The RAPID dataset displays substantial seasonal and interannual changes, with AMOC oscillations at 5-10 Sv (Fig. 4B), showing that the long-term decrease reported by Bryden et al (2005) was within the observed variability and partly caused by seasonality (Kanzow et al. 2010, Fu et al. 2023). The time series displays a 5 Sv decline between about 2006 and 2010, and the level remained low until early 2013, followed by a slow recovery, so by 2018 the AMOC intensity had returned to the 2004–2005 levels (Frajka-Williams et al. 2018, 2019, Fu et al. 2023, Worthington et al. 2021, Wett et al. 2023). The analysis of the continuously updated dataset (https://rapid.ac.uk/) shows that the AMOC remained fairly stable between 2019 and 2024, evidencing a robust AMOC with an average intensity of 17.1 ± 4.4 Sv (monthly standard deviation) in the 2004–2022 period.

In addition to the RAPID array, other initiatives are aimed at estimating the intensity of the AMOC at different latitudes, from near its northern formation region in the subpolar North Atlantic to the South Atlantic (Fig. 4A). These initiatives generally use a more limited set of in situ sensors (moorings with current meters and bottom-mounted pressure-inverted echo-sounders, PIES) that are combined with other field and altimetry data. In particular, since 2000 the Argo programme of drifting profilers (https://argo.ucsd.edu/) has represented a major increase in the amount of hydrographic data in the upper 2000 m of the water column. The northernmost sections are the Overturning in the Subpolar North Atlantic Programme (OSNAP) transoceanic section (since 2016; Lozier et al. 2019) and the Observatoire de la Variabilité Interannuelle et Décennale en Atlantique Nord (OVIDE) section that runs from Greenland to the Iberian Peninsula (since 2000; Mercier et al. 2016). Still in the subpolar region, the 47°N transatlantic Nordic Overturning in the Atlantic Current (NOAC) array represents a combination of PIES since 2006 and moorings since 2017 (Wett et al. 2023). In the western subtropical gyre, LINE W (35°N, since 2005) combines moorings in the deep western boundary current with Argo float and satellite altimetry data across the basin (Toole et al. 2017, Le Bras et al. 2023), and the Meridional Overturning Variability Experiment (MOVE) section has sampled the AMOC along 16°N since 2000, under the assumption that all NADW propagates between the Caribbean Sea and the Mid-Atlantic Ridge (Send et al. 2011, Danabasoglu et al. 2021). In the South Atlantic, the South Atlantic MOC Basin-Wide Array (SAMBA) represents a transoceanic section along 36.5°S that started sampling the boundaries in 2010 and has progressively reached the deep ocean (Meinen et al. 2018, Chidichimo et al. 2023).

All the North Atlantic systems provide very consistent mean values of 17-18 Sv for the intensity of the (upper cell) AMOC. Regardless of the different lengths of the diverse time series (Fig. 4B) the reported values are fairly well constrained: 17 Sv at RAPID (as calculated in https://rapid.ac.uk/ with data up to early 2024), 18.1 Sv at OVIDE (Mercier et al. 2015), 16.7 Sv at OSNAP (Fu et al. 2023), 17.2 Sv at NOAC (Wett et al. 2023) and 14.7/17.0 Sv at LINE W in vertical/isopycnal coordinates (Le Bras et al. 2023). The time series for the deep western boundary current that carries NADW southwards shows mean values about 5 Sv higher, as these values do not include any possible deep-water recirculation in the entire basin: 22.6 Sv at MOVE (Danabasoglu et al. 2021) and 22.8 Sv for the boundary sector of LINE W (Toole et al. 2017). Furthermore, this southward NADW flow takes a couple of years to cross the North Atlantic Basin: NOAC (47°N) and RAPID (26°N) are significantly correlated with a southward time delay of about a year (Wett et al. 2023), and RAPID and MOVE (16°N) maintain this correlation with an additional seven-month delay (Frajka-Williams et al. 2018).

The AMOC in the South Atlantic is more complex, comprising not only the upper vertical cell of southward-flowing NADW and returning intermediate and surface waters, but also the lower cell of equatorward-flowing AABW and its poleward recirculation beneath the NADW (Fig. 2). Nevertheless, the available data of the SAMBA array (36°S) gives an upper cell mean value between 14.7 Sv for the entire 2009-2017 period (with a 2011-2013

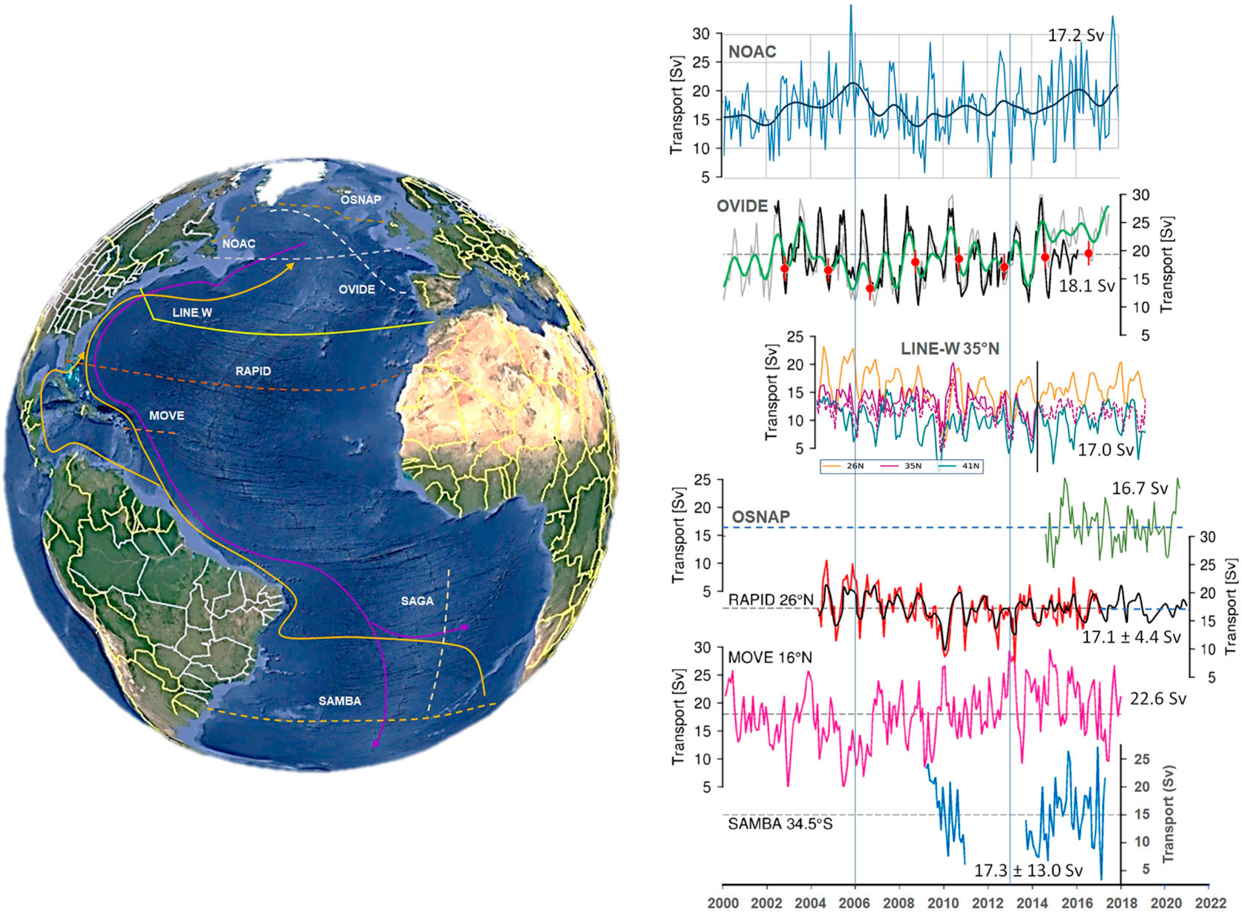

Fig. 4. – (Left panel) Location of eight observational arrays used to sample the AMOC. The purple arrows sketch the path of the initial limb of the AMOC (NADW), while the orange arrows trace the return routes of the intermediate and surface waters. (Right panels) Monthly time series of AMOC intensity as estimated from the arrays (coloured lines) together with their mean values during the observation period (values in Sv; the monthly standard deviations are indicated for the RAPID and SAMBA arrays); notice that several panels also include further smoothed time series. Adapted from Wett et al. (2023) (NOAC time series), Mercier et al. (2016) (OVIDE time series with red dots for hydrographic cruises, see also Mercier et al. 2015), Le Bras et al. (2023) (LINE-W, orange line), and Frajka-Williams et al. (2019, 2023) (OSNAP, RAPID, MOVE and SAMBA time series; for the SAMBA array see also Meinen et al. 2018). The OSNAP monthly time series has been extended using the data in Fu et al. (2023), and the RAPID time series also shows the 90-day smoothed values (solid black line) extended until late 2020 using data available at https://rapid.ac.uk/. The solid vertical lines denote the period between 1 January 2006 and 31 December 2012.

gap) and 17.3 ± 13.0 Sv (monthly standard deviation) for the 2013-2017 period, the latter with enhanced resolution near the lateral boundaries (Meinen et al. 2018, Kersalé et al. 2020, 2021; Fig. 4), which are very consistent with the intensity of the North Atlantic AMOC (Fig. 4). The striking feature is the high variability in the South Atlantic, with daily peak values ranging between 11.2 Sv southward and 43.4 Sv northward (Meinen et al. 2018) and monthly standard deviation three times larger than in the RAPID array (Frajka-Williams et al. 2019, Kersalé et al. 2021).

The high variability of the AMOC signal in the South Atlantic reflects the complexity of this basin, which extends beyond the presence of southern AABW (Chidichimo et al. 2023). A partial cause of variability is the intermittent shedding and propagation of Agulhas rings (4–9 per year) from the Indian Ocean, with a mean contribution of about 10 Sv (Schouten et al. 2000, Richardson 2007, Casanova-Masjoan et al. 2017, Kersalé et al. 2021). Another possible cause is the fact that a substantial fraction of the water that enters the South Atlantic as part of the (northern basin) AMOC returning limb, either through the Drake Passage or as part of the Agulhas leakage (Fig. 1), recirculates in the subtropical and tropical South Atlantic gyres at intermediate and near-surface levels (Cabré et al. 2019, Olivé Abelló et al. 2024a), which likely affects the actual northward transfer to a much greater degree than in the North Atlantic (Tooth et al. 2024). Another important cause is the complexity of the pathway followed by this returning limb in the South Atlantic. In the North Atlantic, both the initial limb (NADW via a deep western boundary current) and the returning limb (upper-ocean western boundary Gulf Stream and its North Atlantic Current extension into the subpolar gyre) of the AMOC follow a predominant latitudinal pathway along the American continent. By contrast, in the South Atlantic a large fraction of the deep AMOC is routed through fracture zones in the Mid-Atlantic Ridge (Garzoli et al. 2015), and the returning AMOC follows a zonal pathway between the tropical and subtropical gyres

(Cabré et al. 2019, Olivé Abelló et al. 2024a). To capture this zonal corridor, the South Atlantic GAteway array (SAGA) was installed in 2021 along 10°W (Pelegrí et al. 2021). The original array extended between 19.5°S and 34.5°S, with four PIES and three moorings, but in 2023 the moorings were recovered and an additional PIES was installed at 14.5°S (Fig. 4); the PIES and data were recently recovered (May 2025) and are currently being processed.

In contrast to the relatively well-established AMOC transport in the North Atlantic, the AABW transport is much less known, with values in the 10-20 Sv range. Recently, Auger et al. (2025) showed the potential use of sea surface altimetry to continuously monitor these bottom-water formations. The contribution of the Atlantic sector to the formation of AABW is not well known, but it appears that Weddell Sea Deep Water and Weddell Sea Bottom Water, which are the main Atlantic sources of AABW, could possibly account for somewhere between one-third and half of the total (Lumpkin and Speer 2007, Naveira Garabato et al. 2014, Solodoch et al. 2022, Silvano et al. 2023). In particular, the SAMBA array has been used to estimate the intensity of the lower vertical cell of the AMOC at 7.8 SV (Kersalé et al. 2020, 2021), while an array of moorings deployed in the Orkney Passage, a deep passage in the South Scotia Ridge, has estimated a 5-8 Sv input of Weddell Sea Deep Water into the ACC (Abrahamsen et al. 2019, Silvano et al. 2023, Auckland et al. 2024).

The observed variability in AABW formation may reflect a lack of data, the existence of interannual or long-term internal feedbacks, or an actual reduction in bottom-water formation since 1990 (Abrahamsen et al. 2019, Jullion et al. 2013, Purkey and Johnson, 2012, 2013, Strass et al. 2020). This reduction could possibly be due to increased input of meltwater around Antarctica (Li et al. 2023a) and to changes in the Southern Ocean westerlies, which modify the amount of ice, the intensity of the Weddell Sea gyre and the hydraulics of the Orkney Passage (Auckland et al. 2024). Lee et al. (2023) found substantial changes in the Southern Ocean overturning cells since the mid-1970s, with a strengthening and expansion of the upper branch and a weakening and contraction of the lower branch, which they attributed to an increase in both the westerlies and meltwater discharge. This change is consistent with results by Olivé Abelló et al. (2024b) in the South Scotia Sea, which suggest that, during the last two decades, natural carbon has outgassed in the southernmost cold sector at a rate comparable to the incorporation of anthropogenic carbon.

MODEL PREDICTIONS FOR THE 21ST CENTURY

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) carefully reviewed the diverse AMOC predictions for the 21st century (Fox-Kemper et al. 2021, Lee et al. 2021). The report considers outputs of atmosphere–ocean and Earth system models, the latter including diverse biogeochemical cycles, with special emphasis on experiments that are part of the standardized Coupled Model Intercomparison Project (CMIP; https://wcrp-cmip.org/). The high-complexity models explore the mean state, variability and response of the AMOC to different scenarios of carbon dioxide emissions to the atmosphere (socio-economic shared pathways, SSP), and the results are referenced to both the 1850–1900 and 1995–2014 periods.

The multi-model results (23 models and 55 outputs, including 17 reanalysis) from the sixth phase of CMIP (CMIP6) predict that the AMOC will weaken by an average value of about 5 Sv over the 21st century (Fig. 5) (Fox-Kemper et al. 2021, Lee et al. 2021); note that CMIP is currently in phase CMIP7 (Dunne et al. 2025). However, there is a striking spread in the individual simulations, with the outputs approximately grouped in a bimodal distribution around a decrease of either 3 or 8 Sv. It is noteworthy that the AMOC reduction is fairly independent of the SSP scenario, with mean projected declines by 2100 of 24% for SSP1-2.6 (ranging from 4% to 46%) and 39% for SSP5-8.5 (ranging from 17% to 55%). Weijer et al. (2020) explored the outputs of 27 CMIP6 models and—considering only those models that have a significant linear relationship with AMOC measurements—observed a reduction of 6 Sv (34%) for SSP1-2.6 and 8 Sv (45%) for SSP5-8.5. These authors also observed a relationship between AMOC changes and the sensitivity of models to warming, with those models more prone to large warming experiencing the highest reduction. Baker et al. (2025) recently evaluated the outputs of 34 CMIP6 climate models for two scenarios of extreme greenhouse and freshwater forcing and observed a substantial weakening of the AMOC by the end of the century (mean reductions of 56% and 61%, respectively, in both cases with very large spreading) but not a collapse. These authors further observe that the weakening is compensated by the appearance of an upper overturning cell in the Pacific Ocean.

A comparison of the CMIP6 model outputs and the observations reveals substantial differences that deserve consideration (Figs 4 and 5). For the period 2010–2020 the multi-model mean output predicts a minor decrease in AMOC transport (Fig. 5), while observations from the NOAC, OVIDE, RAPID and MOVE arrays show a small increase (Fig. 4). A more detailed analysis of the individual model outputs shows limited ability to accurately reproduce both the intensity of deep-water formation in different areas of the subpolar North Atlantic and the observed interannual to multi-decadal variability (Fox-Kemper et al. 2021). The limited modelling skill may be due to several factors, such as the omission of meltwater release from the Greenland ice sheet and the difficulty of accurately simulating the depth of the surface mixed layer, which results in unrealistic values of NADW formation (Collins et al. 2019). Because of these uncertainties in the realism of simulations and the large discrepancy between modelled and reconstructed AMOC values, the IPCC concluded that the AMOC will very likely decline in the 21st century, though confidence in the magnitude and timing of this decline remains low (Collins et al. 2019, Fox-Kemper et al. 2021, Lee et al. 2021).

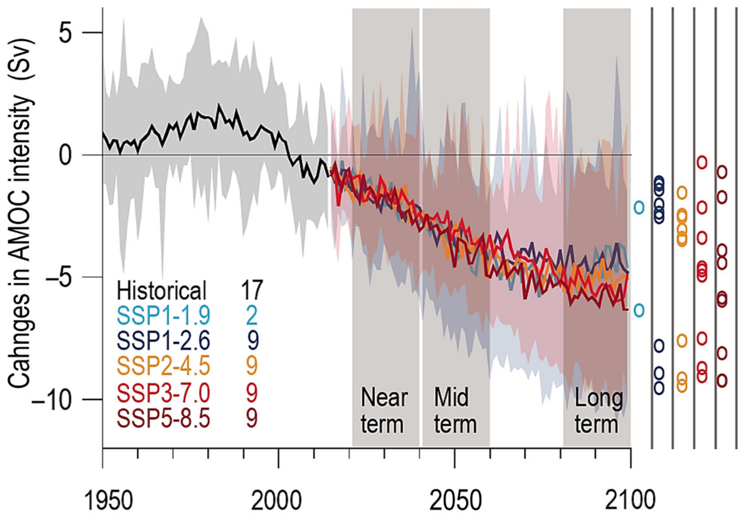

Fig. 5. – Changes in the intensity of the AMOC at 26°N (the latitude of the RAPID array) relative to the 1995–2014 average, as calculated from CMIP6 simulations for different SSP scenarios. The curves show ensemble averages for diverse scenarios (as coloured) and the shadings represent the SSP1-2.6 (grey) and SSP3-7.0 (red) 5%–95% ranges; the coloured circles show the 2081–2100 average final anomalies for each simulation. Reproduced from Lee et al. (2021).

The wide range of projections for the upper branch of the AMOC reflect the complex mechanisms that control NADW formation and climate change. The most obvious effects are the freshening through ice melt and warming of the surface ocean layers, particularly intense at high northern latitudes, which lighten these layers and may thereby inhibit deep-water formation. However, there may be negative feedback processes. One such feedback would arise from the fact that most Gulf Stream waters—which carry the returning limb of the AMOC—will travel the North Atlantic subtropical gyre several times before stretching into the subpolar gyre via the North Atlantic Current (Pelegrí et al. 2019, Tooth et al. 2024). Berglund et al. (2022) showed that these subtropical transiting waters have a net gain in both depth and density, so they rejoin the Gulf Stream at a greater depth in the permanent thermocline. This is highly relevant, as the Gulf Stream waters entering the subpolar gyre are precisely these subsurface thermocline layers (Pelegrí et al. 1996, 2006, Williams and Follows, 1998, Williams et al. 2006, Bower et al. 2009, Burkholder and Lozier 2011, Jacobs et al. 2019). Since the subtropical gyre is gaining both heat and salt (Bates and Johnson 2021), the challenge is to understand how this density-gain mechanism will evolve in time. However, the marked differential increase in the surface salinity of the subtropical North Atlantic (Lu et al. 2024) suggests that the negative feedback mechanism may increase.

Large-scale feedbacks, in the form of zonal and meridional atmospheric teleconnections, may also drive large-scale changes in precipitation and wind patterns as well as in heat transport and storage (Orihuela-Pinto et al. 2023, An et al. 2024). The most obvious relation possibly takes place at interannual scales between the intensity of the AMOC and the sea-level pressure difference between the North Atlantic subpolar low and subtropical high, an index known as the North Atlantic Oscillation (NAO) (Eden and Willebrand 2001). An inspection of the RAPID AMOC time series (Fig. 4) shows the existence of a seasonal cycle, with peak values occurring in late winter and early spring, following the formation of the NADW (Fu et al. 2023), but it also shows substantial interannual differences. One example of this interannual variability is the alteration of the seasonality in late 2009 and through 2010, with values well below the average and an early recovery in the autumn of 2010 (Fig. 4). This weakened AMOC began during an intense NAO negative phase (the subpolar-subtropical pressure difference decreases and the westerly winds weaken) between June 2009 and January 2011 (NOAA, 2025). The mechanisms behind these large-scale interannual NAO-AMOC interactions are not sufficiently known and/or represented, as shown by the large discrepancy of results among CMIP6 models (Kim et al. 2023), but it is plausible that a negative NAO leads to less positive Ekman pumping in the subpolar region and a weakening of the subtropical gyre, ultimately reducing the penetration of the subsurface Gulf Stream waters into the subpolar gyre (McClain and Firestone, 1993, Williams and Follows 1998, Pelegrí et al. 2006, Williams et al. 2006).

There may also be significative local feedbacks, possibly also related to basin-wide processes, such as changes in sea-ice extent (a decrease could potentially increase the size of winter convection regions) and in surface wind intensity. The evolution of the cold winter winds of continental origin is particularly relevant as they are the main cause of deep-water formation. The critical preconditioning of the winter surface waters occurs largely via mixing, either vertically as a result of the wind-induced deepening of the surface mixed layer (Nobre et al. 2023) or laterally via Atlantic–Arctic exchange (Dey et al. 2024).

Interdecadal and centennial variability have also been related to changes in ocean–atmosphere heat fluxes, and to how and where buoyancy and energy is stored in the ocean (Ren et al. 2025), though there is a notable lack of consensus and ample recognition that much of the variability is model-dependent (Buckley and Marshall 2016). Changes at interdecadal scales appear to be generated in the western boundary of the North Atlantic, with heat anomalies propagating southwards from near the subtropical–subpolar boundary (Buckley et al. 2012, Polo et al. 2014) or possibly affecting the rate of deep water formation in the subpolar region (Ferster et al. 2021, 2025). At centennial scales, the main driver may be changes in subpolar surface salinity, either propagating from the tropical Atlantic (Ferster et al. 2021) or resulting from freshwater exchanges with the Arctic (Mehling et al. 2024). Ferster et al. (2025) observe that centennial variability is related to salinity in the western subpolar region but largely model-dependent. These results indeed point to the complexity of the system, with multiple feedback processes acting at very diverse spatiotemporal scales, leading to the extraordinary difficulty of making a consistent forecast.

OPTIMAL STATES AND TIPPING POINTS

Complex systems have many interacting components with multiple linear and non-linear combinations of positive and negative feedbacks that grant the system resilience near some mean conditions, known as the system attractor (e.g. Nicolis and Prigonini 1989, Thurner et al. 2018). Complex systems, however, are also characterized by the presence of high variability around the attractor, so, under sufficient internal or external forcing, the system may either move slowly (driven by an internal non-linear mechanism) or switch abruptly (responding to substantial external forcing) to a different state.

Earth system science (ESS) deals with the Earth as a complex system, possibly the best example we know of resilience and adaptation. ESS includes humankind as a major economic and social global player, with the potential to not only produce global changes but also to generate new adaptive characteristics of the Earth system (Ives et al. 2003, Ehlers and Krafft 2006, Dakos et al. 2008, Scheffer et al. 2009, Lenton 2011, Weijer et al. 2019, Steffen et al. 2020). Through both observation and modelling (from process to high-complexity models), and by incorporating social and economic aspects of human activity while recognizing the challenges posed by technological and societal dynamics, ESS seeks to predict the evolution of the Earth system.

As for any resilient complex system, the Earth remains in a relatively stable, near-optimal state, with its conditions orbiting near a system attractor, but it may also shift to a different state. The Earth's attractor may be thought as a combination of global-mean thermodynamic and metabolic conditions, the former referring to the inputs/outputs, distribution and storage of mass and energy, and the latter referring to the production/use, distribution and storage of inorganic and organic matter. A key element, as proposed by constructal theory, is that a resilient Earth is characterized by spatial and temporal patterns that optimize the transfer of properties, in particular energy (Bejan 1997, 2000, Reis 2006, Pelegrí 2008, Bejan and Lorente 2011, Pelegrí et al. 2013, Roca and Pelegrí 2020). As the system's complexity increases, its self-regulative capacity also expands, which includes tipping between different states. Back to the physiological analogy, such a pulsating reinitialization (periodic or intermittent) is a characteristic of all living beings, switching between phases of rest (recovery of energy reserves) and exercise (the energy reserves are used) in order to optimize overall productivity.

The application of complex-theory statistical techniques to long-enough time series of significant variables should give an early warning of the (in)stability of the system, providing information on the proximity of critical thresholds that precede abrupt transitions—also known as catastrophic bifurcations or tipping points—toward one or more different states (Dakos et al. 2008, 2024, Scheffer et al. 2009, Lenton 2011, Gaffrey and Steffen 2017). Two main properties of these time series are variance and autocorrelation: perturbations that may potentially take the system away from its state of near-equilibrium must be sufficiently large (high variance) and persist long enough to overcome the temporal memory of the system (high autocorrelation or a low restoring rate).

In exploring palaeo-conditions, a principal challenge is to identify proxies that can be indicators of the global conditions of the Earth. With the start of the instrumental era, the challenge remains but is now focused on identifying which time series reflect basin-wide or global variability, particularly those that recognize indicators or fingerprints of AMOC strength. Several recent works have proposed these fingerprints and have then analysed their time series through statistical techniques to suggest that the AMOC is approaching a tipping point and may collapse in the coming decades, in clear contradiction with the AR6 conclusions (Fox-Kemper et al. 2021, Lee et al. 2021). Boers (2021) used a 150-year-long reanalysis of SST and sea surface salinity (SSS) in the Atlantic Ocean to find a substantial increase in the variance and restoring rate (70-year window) for eight selected time series, concluding that the AMOC is approaching a critical transition. Ditlevsen and Ditlevsen (2023) also used a 150-year time series of SST anomalies in the Atlantic subpolar gyre to calculate the trend of the variance (50-year window), which they then fitted to an idealized model that simulates how the system moves away from equilibrium. They concluded that the AMOC transition will occur between 2025 and 2095 with 95% confidence. Michel et al. (2022) used an optimized proxy reconstruction for the multidecadal variability in the North Atlantic circulation during the last millennium and concluded that the temporal memory of this variability has increased significantly during the last century, attributing this change to AMOC variations.

Van Westen et al. (2024) used the Community Earth System Model to explore how the strength of the AMOC would change under increased freshwater input in the North Atlantic between 20°N and 50°N, with greenhouse gases fixed at preindustrial levels. They ran the model for 1800 years, progressively increasing the freshwater forcing, and found that an addition of 0.6 Sv of freshwater (about 80 times the current melt rate of the Greenland ice sheet) leads to a collapse of the AMOC. Van Westen et al. (2024) further reported that the statistics of the AMOC strength and the SST subpolar anomalies are not comparable, so they do not support the fingerprint chosen by Ditlevsen and Ditlevsen (2023). Instead, Van Westen et al. (2024) propose a physics-based tipping-point indicator: the freshwater leaving the Atlantic Basin at 34°S (essentially equivalent to salt entering the Atlantic northwards through this latitude), which they argue is currently decreasing and will reach a minimum in some unknown future, some 25 years before the AMOC collapse.

The model-based statistical approach can indeed be useful for exploring the mechanisms affecting the response of the North Atlantic Ocean, but their early-warning skills have several limitations. Ben-Yami et al. (2024) pointed that using historical time series involves major uncertainties, mostly related to the assumption that the tipping point may be identified through a stationary time series of one simple fingerprint, in addition to the uncertainties in the preprocessing and significance of the available data. Additionally, both the coupled Global Community Earth System model and the specific simulations rely on substantial over-simplifications of a very complex system, calibrated on the basis of past forcing and responses. One such simplification is the setting of a constant greenhouse forcing (Van Wasten et al. 2024): SSS and SST have increased in most of the North Atlantic and will continue doing so because the ocean is the principal recipient of the surplus solar radiation, and hence the excess evaporation that results from rising greenhouse gases (von Schuckmann et al. 2023, Hansen et al. 2025). Another example is the unrealistic freshwater input required for the AMOC to collapse, which is often justified in terms of well-known CMIP limitations in modelling the salinity fluxes into and out of the Atlantic Basin (Van Westen and Dijkstra, 2024).

RADIATIVE IMBALANCE AND HEAT STORAGE

During the last 3 million years, glacial-interglacial changes have been triggered by orbital changes (Hays et al. 1976, Berger 1978, Williams et al. 1998, Paillard and Parrenin 2004). These changes led to internal feedback processes—such as via the intensity of the AMOC—that changed the amount of dissolved inorganic carbon in the surface ocean layers and hence the partial-pressure equilibrium of atmospheric CO_2. In this way, greenhouse gas became the main driver for the natural changes in climate, raising the global-mean surface temperatures from about 8°C during the last glacial maximum to a peak value of 13.8°C in the 19th century preindustrial period. In the absence of anthropogenic forcing, the GOC and its associated high thermodynamic-metabolic state—in particular, the global mean surface temperature—would have slowly decreased until the next glacial maxima, to occur some 80 kyrs after the present (Oppo et al. 1993, Sigman and Boyle 2000, Rahmstorf 2002, Lynch-Stieglitz et al. 2007, Brown and Galbraith 2015, Galbraith et al. 2016, Hines et al. 2019), when a shift towards interglacial conditions would have been triggered by a maximum in boreal insolation (e.g. Paillard 1998, Sigman and Boyle 2000, Paillard and Parrenin 2004, Weijer et al. 2019). However, the continuous emission of greenhouse gases to the atmosphere—combined with their long atmospheric lifetime, e.g. carbon dioxide removal takes between decades and millennia (Archer et al. 2009, Ciais et al. 2013)—will very likely extend the current interglacial period and delay the following glacial-interglacial transition (Loutre and Berger 2000, Mysak 2008, Herrero et al. 2014). The predictions largely depend on the accumulated global carbon emissions, which determine the magnitude of the peak atmospheric CO_2. According to Herrero et al (2014), under preindustrial CO_2 conditions the current interglacial would have lasted some 10 kyr and the next interglacial-glacial shift would have taken place in some 75 kyr, while for atmospheric CO_2 peak concentrations between 450 and 560 ppt the current interglacial will actually last some 45 kyr and the subsequent glacial will stretch until about 232 kyr after the present (hence missing three boreal insolation maxima).

A major challenge is to decipher how the living Earth—a robust yet transient system—will behave during this anthropogenically-induced long interglacial. The large anthropogenic input of greenhouse gases to the atmosphere strongly suggests that the natural non-linear internal planetary mechanisms will be substantially modified. Because of the greenhouse effect, the amount of radiative energy effectively entering the Earth system has increased by nearly 3 Watts m^{-2} since preindustrial times (Lee et al. 2021, Hansen et al. 2025), and the long residence time of atmospheric CO_2 ensures that this energy excess will continue to arrive for decades and centuries even if we stop fossil fuel consumption. Further, largely because of a 0.5% decrease in the Earth's albedo in the last two decades, there has been a substantial increase in the difference between the incoming and outgoing radiative fluxes at the top of the atmosphere: this Earth energy imbalance, or difference between the absorbed solar radiation (ASR) and the outgoing longwave radiation (OLR), has risen from 0.37 W m^{-2} at the beginning of the century to 1.37 W m^{-2} at present (Hansen et al. 2025) (Fig. 6, left panel). This means that the Earth's surface is not warming enough to reach a radiative equilibrium: the 1.4°C rise in the surface temperature of the Earth since preindustrial times is not sufficient to ensure that the OLR equals the ASR. About 90% of the heat surplus has gone into the ocean even though the temperature of the vertically averaged water column has barely increased by about 0.1°C (Fox-Kemper et al. 2021, Cheng et al. 2022, Li et al. 2023b, von Schuckmann et al. 2023, Allan and Merchant 2025). A fraction of this excess energy is stored in the surface mixed layer and the upper few hundred metres of the water column, which will fairly rapidly contribute to an increase in OLR, but the core of the Earth's energy imbalance is being slowly incorporated into the intermediate and deep ocean layers, thus causing a time lag of decades and centuries before a proportionate OLR rise.

An increased radiative forcing and a reduced AMOC will likely have opposite effects in the evolution of SST in the North Atlantic subpolar gyre. A good example of these counteracting effects are the surface changes in the eastern subpolar gyre, with warming until 2008 followed by cooling until 2016 and warming thereafter (Drijfhout et al. 2012, Robson et al. 2016, Desbruyères et al. 2021). Surface warming should be the direct outcome of the shortwave radiative increase, but the cooling period, known as the North Atlantic Warm Hole, has been related to variations in the northeastward penetration of the subtropical waters via the North Atlantic Current (Liu et al. 2020, Desbruyères et al. 2021, Li and Liu 2025). Indeed, the subpolar cooling closely matches the AMOC weakening between 2006 and 2012, as sampled in the subtropical LINE W and RAPID arrays (Fig. 4), with 2–4 years delay likely related to the accumulative effect of subtropical-subpolar advection.

High-complexity coupled global models—most of them having a reduced AMOC (Fig. 5)—forecast sustained global warming of the surface ocean, yet with substantial spatial variability and anomalously low values in the subpolar North Atlantic Warm Hole region (Fig. 6, right panels). However, the intensity of this subpolar North Atlantic anomaly differs greatly depending on the model and forcing, with some studies showing that it will only reduce the rate of warming or cause mild cooling (<0.5°C) (Liu et al. 2020, Bellomo and Mehling 2024, Park et al. 2024), other ones showing intermediate cooling (1–2°C) (Swingedouw et al. 2021) and still others predicting substantially greater cooling (2–10°C) (Vellinga and Wood 2002, Liu et al. 2017, Orihuela-Pinto et al. 2022). The multi-model IPCC average predicts that the subpolar North Atlantic will cool by the middle of this century and will only warm slightly (<1°C) by the end of the century, but the wide range of results gives these projections low confidence (Lee et al. 2021).

The difficulty of delivering a precise AMOC forecast—and its effect on high-latitude surface temperature, winds and precipitation—is largely related to feedbacks between subsurface heat storage and heat distribution by ocean currents, acting at interannual and interdecadal scales. Heating of the subsurface layers occurs via a combination of vertical diffusion and along-isopycnal advection-diffusion, two processes that may well compete and whose relative strength is often poorly constrained. A weakening of the AMOC would imply greater heat storage in the subtropics, possibly through an expansion and intensification of the subtropical gyre (McCarthy et al. 2015, Roberts et al. 2020, Fox-Kemper et al. 2021) (Fig. 7, right panel), but this enhanced latitudinal heat partition would also involve greater available potential energy that could lead to greater heat distribution via mesoscalar and submesoscalar features.

The dependence of energy storage and distribution on ocean circulation makes it difficult to obtain reliable projections of heat partitioning in the subsurface ocean for diverse SSP climatic scenarios. In particular, AMOC changes—which have proved very hard to model (Fig. 4)—can lead to substantial changes in subsurface heat content for the subpolar North Atlantic (Fig. 7, left panels) (Bronselaer and Zanna 2020, Fox-Kemper et al. 2021). Other AMOC-related variations are yet possible, linked either to further changes in ocean-atmosphere coupling—

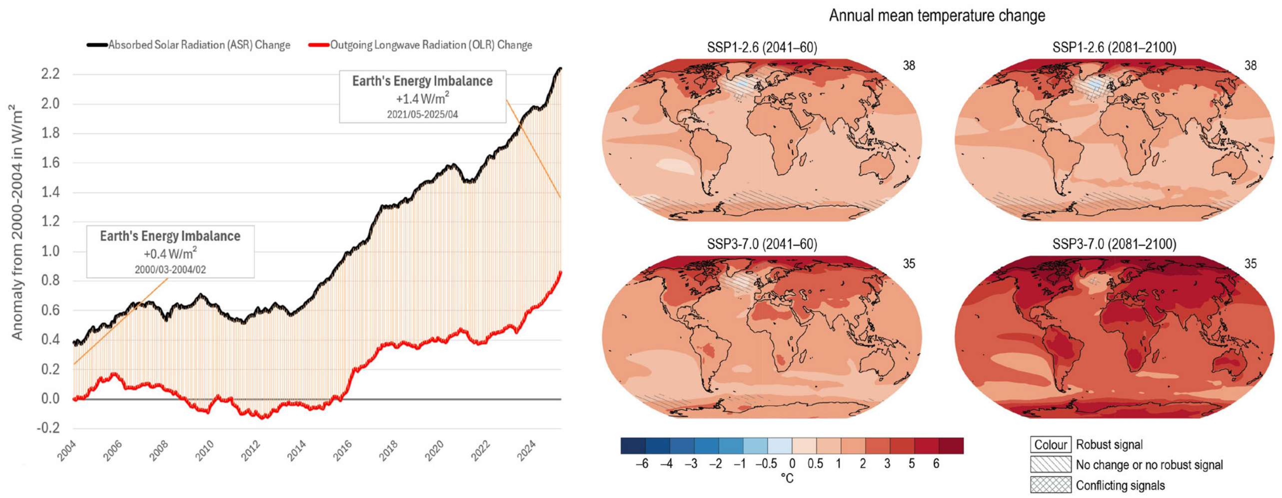

Fig. 6. – (Left panel) Global-mean absorbed solar radiation (black line), outgoing longwave radiation (red line) and resulting Earth energy imbalance. Values are calculated with a four-year running mean relative to the mean value between March 2000 and February 2004. Reproduced from Simons (2025). (Right panel) Multi-model mean projections of changes in near-surface air temperature (°C) in (left) 2041-2060 and (right) 2081-2100 relative to 1995-2014, for the (top) SSP1-2.6 and (bottom) SSP3-7.0 scenarios; for each case, the number of models used to obtain the mean is shown at the top-right. Diagonal lines show regions with non-robust results (<66% of models show changes less than internal variability) and crossed lines indicate regions with conflicting results (>66% show changes greater than internal variability but <80% of the models agree on the sign of this variability). Reproduced from Lee et al. (2021).

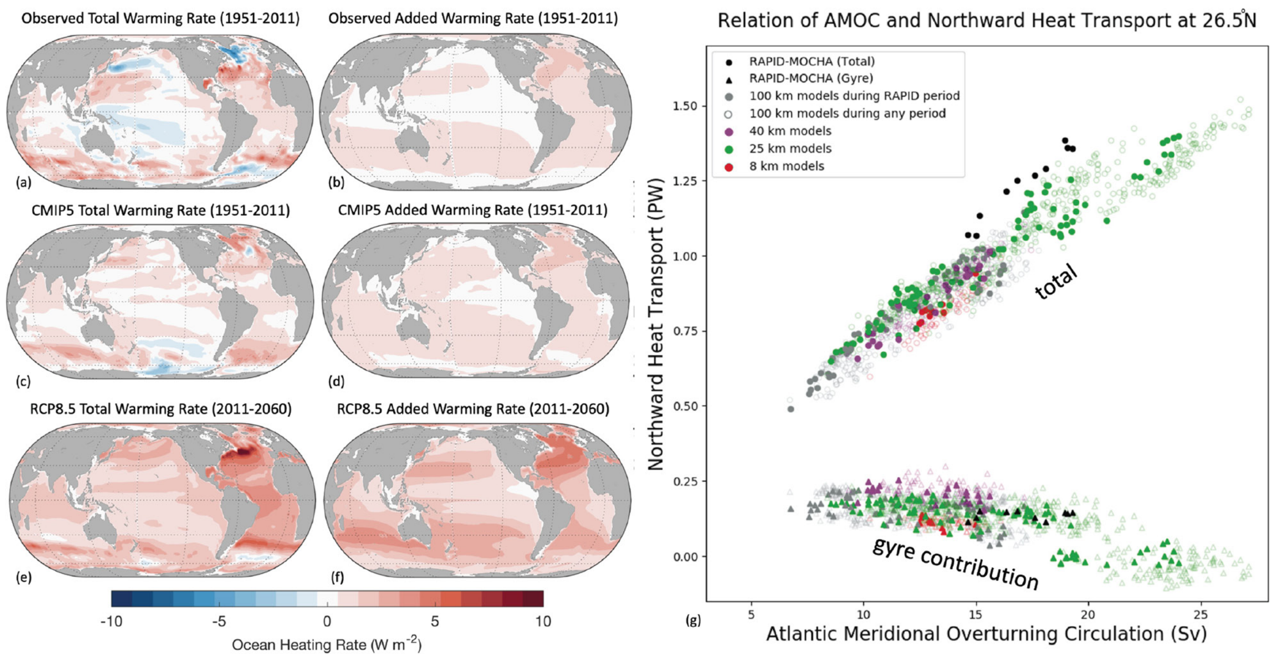

Fig. 7. – (Left panels) Projections of rates of change in heat content in the top 2000 m of the water column over the historical period (1972–2011), including changes in radiative warming but maintaining the historical circulation fields (*added warming rate*, right column) and the total allowing the circulation fields to evolve (*total warming rate*, left column). Reproduced from Fox-Kemper et al. (2021), after Bronselaer and Zanna (2020). (Right panel) Total RAPID-observed (2004–2018) and 26°N modelled (1950–2050) northward heat transport in the Atlantic and the respective subtropical gyre contribution as a function of AMOC intensity; the horizontal resolution of the various models is indicated. Reproduced from Fox-Kemper et al. (2021).

such as how a high subtropical-subpolar heat gradient could intensify the westerly winds and cause more frequent extreme storms (Hermoso et al. 2024)—or to changes in biogeochemical processes, such as how the blocking of the Gulf Stream would affect the input of inorganic nutrients that sustain the North Atlantic spring bloom (Pelegrí et al. 2019).

UNCHARTED WATERS FOR THE LIVING EARTH

The ocean is indeed the predominant global heat regulator, but we still do not know how fast and deep the excess radiative heat will be incorporated into the ocean in the coming decades and centuries—whether it will be progressive or whether there will be major regional or global adjustments—and how this input will affect the AMOC (Lee et al. 2025). Several reanalyses of 150 years of data and direct observations during the last 20 years show that, despite the increased freshwater input, the AMOC intensity has remained fairly unchanged since preindustrial times. However, we know that the AMOC can change; it has done so in the past and our best coupled global models suggest that it will weaken in the future, yet without collapsing during the 21st century. Nevertheless, our discussion has shown that there are indicators that this collapse may happen earlier than expected, even during the coming decades, although these are based on simple fingerprints of the AMOC and idealized models that involve significant uncertainties. While major palaeoclimatic transitions have been largely driven by AMOC variations, current climate change is primarily due to the significant radiative changes that result from the rising atmospheric greenhouse gases. AMOC changes would not drive climate change but rather be its consequence, as is the case with other key global indices of Earth (e.g. Ripple et al. 2024), likely generating significant feedback loops. The strong interconnection among these shifting global variables (Steffen et al. 2018) should alert us that the Earth may already be on a path to a different climatic/metabolic state.

I end up with a personal reflection on our predictive limits and an urgent requirement to follow the principle of prevention. ESS is based on a finite number of interactions between a finite number of components, each of them responding in potentially very intricate yet (statistically) predictable manners to external or internal forcing. The current phase of the high-complexity CMIP models, aided by the huge possibilities arising from artificial intelligence, will undoubtedly produce more robust and reliable projections. However, ESS will never be able to fully simulate the living Earth and its intelligent natural evolution. The living Earth extends far beyond the reaches of ESS, to a practically infinite number of components interacting among themselves in an infinite number of ways that are impossible to conceive and even less to model, giving rise not only to adaptive but also to evolutive responses, as shown by the palaeo-evolution of the Earth. The living Earth paradigm recognizes that the socio-economic global imprint of humankind is a major actor in the Earth's evolution at human scales, from decades to centuries. It also sustains that it is the unperceivable and inexplicable natural intelligence of our planet—acting at all scales, from the short scales that characterize all microcosms to the long scales determined by the huge regulatory capacity of the ocean and beyond—that will determine the future of planet Earth.

Our current knowledge delivers a stark warning: humankind—led by the developed and some developing countries (Lin and Wackernagel 2024)—is overexploiting the Earth and driving it into unexplored territories with poorly predictable consequences (Steffen et al. 2018), disproportionately affecting the most vulnerable populations and placing a heavy burden on the coming generations. Certainly, we cannot be optimistic, but equally we must not be pessimistic, because both options lead to inaction. We must be realistic and express hope, which involves, first, increased knowledge of the causes and consequences of our actions and, second, the engagement and mobilization of citizens towards a fully sustainable lifestyle, based on equity and justice with people and nature (Pelegrí et al. 2025, UN 2025).

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The author of this article declares that he has no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

AUTHORSHIP CONTRIBUTION STATEMENT

Josep L. Pelegrí: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing.

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