Climate change impacts on ocean circulation relevant to the UK and Ireland

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KEY FACTS

What is happening:

1. The AMOC, which plays an important role in the climate of northwest Europe, has been mostly stable through the last 12,000 years apart from a disputed weakening in the late 19th century (Confidence: medium evidence, medium agreement).

2. Overall weakening of AMOC through the instrumental period (since 1950) depends on proxy data and sparse measurements leading to low confidence in this trend (Confidence: Low evidence, low agreement).

3. The AMOC underwent a strengthening in the 1990s, a weakening until the early 2010s, followed by a slight recovery, before a return to weakening in recent years (Confidence: High evidence, high agreement).

4. Freshwater fluxes from Arctic and Greenland sources have influenced the subpolar North Atlantic, and the enhanced release of freshwater could have an increasing impact on the AMOC in the future (Confidence: Medium evidence, medium agreement).

What could happen:

1. Predictions of an AMOC weakening by 2100 are robust and consistent in magnitude with the observed trend in the AMOC since 2004 of 1 Sv/decade (Confidence: medium evidence, high agreement).

2. There have been increased numbers of studies highlighting the risk of AMOC passing a tipping point in this century, but large uncertainty remains around the robustness of the metrics and data used to assess this (Confidence: Low confidence, low agreement).

3. Future changes in shelf circulation are uncertain but will result from both local climate impacts and exchanges with the open ocean (Confidence: Low confidence, low agreement). Understanding these changes is important as

they are likely to have a direct impact on fisheries and aquaculture, sediment transport, marine biodiversity and sea level.

SUPPORTING EVIDENCE

Introduction

Ocean circulation, including ocean currents and *systems* of ocean currents, such as ocean gyres and the Meridional Overturning Circulation, play a key role in the climate system through the redistribution of heat, freshwater, carbon, and nutrients. Some of these systems of ocean currents are on a large spatial scale and of global climate relevance. For example, the basin scale Atlantic Meridional Overturning Circulation (AMOC) plays an important role in the climate of northwest Europe (Bellomo et al., 2021; McCarthy et al., 2015). Other ocean circulation features are on a smaller spatial scale and still have an important climate relevance. For example, the regional-scale exchanges across the northwest European shelf are large (Huthnance et al., 2022) and enable a disproportionately large carbon transport that plays an important role in the ocean's sequestration of anthropogenic carbon (Legge et al. 2020). How these systems will change as the climate changes is a key focus of research.

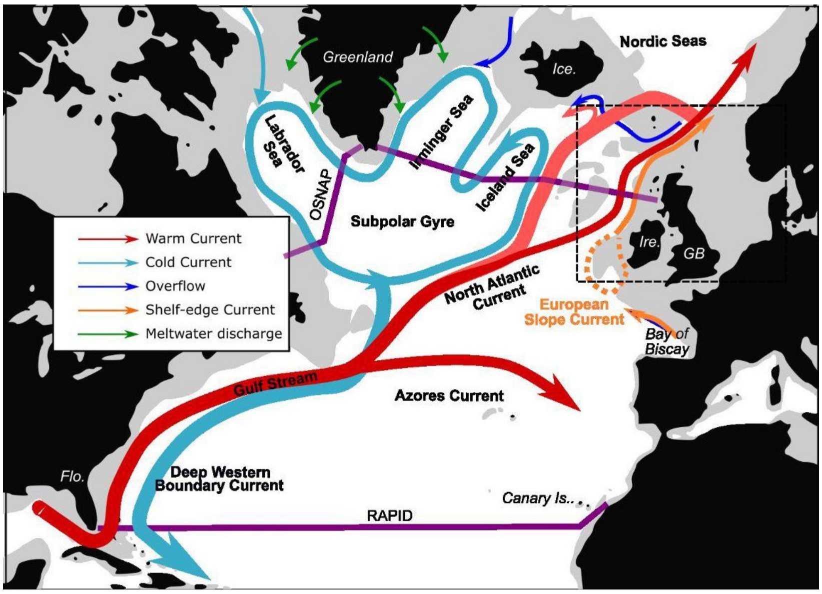

Figure 1: Large-scale circulation in the North Atlantic. A system of warm, northward flowing currents and cold southward flowing currents is known as the Atlantic Meridional Overturning Circulation or Gulf Stream System. The RAPID and OSNAP arrays of moored instruments for observing the AMOC are shown in purple. Named ocean currents, freshwater input, and geographic features are also highlighted. Dashed box is the area highlighted in Fig. 4.

The large-scale North Atlantic circulation mainly consists of the wind-driven gyres and the AMOC which is partly wind-driven and partly driven by differences in density of water masses (Fig. 1). This overlap of drivers makes distinct definitions of AMOC and subpolar gyre strength impossible. Traditionally, the AMOC has been defined by the maximum of the overturning streamfunction—the maximum balance of upper water flowing to the north balanced by deeper water flowing south, which occurs in the subtropics. In the subpolar North Atlantic, warmer water flows northwards on the eastern side of the basin and colder water flows southwards at the western side of the basin. At these subpolar latitudes, a more appropriate measure of the overturning is the overturning streamfunction in density space (Lozier et al., 2019). In climate models, such as the CMIP6 models used in the IPCC 6th Assessment Report, the metric of the maximum overturning streamfunction in depth space—typically at 30ºN—is used. Key to the choice of metric is the climate relevance of the metric. For example, the maximum of streamfunction in depth space captures 90% of the heat transport of the ocean in the subtropics (Johns et al., 2011).

On the eastern boundary of the gyre, at the continental shelf edge, flows the European Slope Current, with its origins traceable to the Iberian Peninsula and extending all the way around the European shelf towards Scandinavia. While the steep change in bathymetry restricts large-scale currents flowing onto the shelf, various processes can lead to exchange between the open ocean and shelf seas (Huthnance et al. 2022). Circulation and conditions on the continental shelf can then be influenced by both the open ocean as well as exchange across the shelf edge. On the continental shelf, a number of coastal currents exist that are also driven by local wind, tides, and thermohaline factors. These distribute heat, salt and nutrients across the shelf seas.

A consistent prediction of ocean circulation change in response to anthropogenic climate change has been that the AMOC will weaken. Since the mid-1980s, the earliest climate models first predicted that an AMOC slowdown would result from an increase in atmospheric $CO2$ (Stouffer et al., 1989)—a projection that has been repeated in successive IPCC reports in the intervening 40 years. While projections based on climate models are consistent, there are disagreements with observations and between model runs in the historical period (McCarthy and Caesar, 2023) and questions remain about the inability of climate models to simulate abrupt change (Valdes, 2011). Better understanding of the AMOC has led to a more nuanced consideration of the AMOC and not simply as a catch-all for all broad-scale ocean circulation change. Understanding different elements of ocean circulation such as the subpolar gyre, boundary currents, and shelf circulation are important to understand the impact on climate and ecosystems. For example, uncertain future changes in shelf sea circulation and dynamics are likely to have a direct impact on fisheries and aquaculture, sediment transports, biodiversity, and sea level.

WHAT IS ALREADY HAPPENING

Is the AMOC in a weakened state?

A long-term perspective, beyond modern observations, on AMOC change is provided by paleoclimate datasets, specifically indirect past ocean property reconstructions (proxies) which are mostly derived from marine sediments and long-lived organisms recovered from the seafloor (Moffa-Sánchez et al. 2019). These paleoclimate datasets can be used to help identify natural and anthropogenic changes in circulation, and to test the performance of climate models through comparisons with relevant previous climate states—such as past warmer climates, or periods of enhanced melting of ice sheets.

Paleoclimate proxy data have associated caveats: (i) they are limited in their spatial extent; (ii) proxies contain multiple secondary controls that add uncertainty to the interpretation of the data; (iii) they are unable to reconstruct the overall paleo-AMOC directly, particularly in the most recent timescales. Instead, sub-components (e.g. different currents) or ‘fingerprints’ of the AMOC system need to be examined and inferences then made on the AMOC as a whole; (iv) these paleo-data are sometimes validated in a numerical model framework and thus rely on models correctly capturing the causal connections between AMOC and the diagnostic in question (Thornalley et al. 2018).

During the current warm interglacial period of the last 11,700 years—the Holocene—the AMOC has been relatively stable (Lippold et al. 2019). Despite the release of large amounts of meltwater during the early Holocene (11,000-8,000 years ago), as Ice Age ice-sheets melted, there was likely only a minor, or even no weakening of the AMOC (Lippold et al., 2019), suggesting that the Holocene AMOC was not close to a meltwater-induced tipping point. In contrast, climate model simulations of this time period display a larger AMOC decline, suggesting that some models may be over-sensitive to this type of meltwater forcing (He and Clark 2022).

Studies drawing upon reconstructions in upper ocean properties and the deep western boundary current suggest that the post-1850 AMOC is in an anomalously weak state compared to the previous 1000 years (Thornalley et al. 2018; Caesar et al. 2018, 2021). Yet, this change is not observed in all proxy datasets and differences exist across locations and methods used (Moffa-Sánchez et al. 2019). Therefore, there remains ongoing debate as to whether the AMOC is currently at the weakest on millennial timescales (Kilbourne et al. 2022; Caesar et al. 2022).

In contrast with climate observations, such as global surface temperature that are reported from the mid-19th century, observations of the AMOC are much more recent. In spite of a number of early expeditions such as that of the Challenger or Meteor, no direct observations of the AMOC exist before the 1950s. Observational estimates from 1950s to the 1980s rely on reconstructions from in-situ shipboard data (e.g. Fraser and Cunningham, 2021; Rossby et al., 2020) or are reconstructed from instrumental proxy data (e.g. Caesar et al., 2018; Terhaar et al., 2025). Many of these reconstructions show a weak AMOC in the 1960s and 1970s (Fraser and Cunningham, 2021; Caesar et al., 2018), in line with paleo reconstructions (Thornalley et al. 2018). However, the overall trend in these reconstructions does not conclusively support an overall weakening and many of these studies conclude there has been no overall slowdown in the AMOC (Fraser and Cunningham, 2021; Rossby et al., 2020; Terhaar et al., 2025) or a weak slowdown (Pontes and Menviel, 2024). This contrasts with the paleo and SST reconstructions that do show a weakening in this timeperiod (Caesar et al., 2018; Thornalley et al. 2018).

Since the 1980s, AMOC strength and variability have been measured directly using moored observations, combinations of in situ hydrographic data with satellite measurements of sea level (since 1993), or through surface-based proxies. These records have shown growing agreement (Fig. 2). Since the 2000s, measurements in the subpolar and subtropical North Atlantic, the OSNAP (Lozier et al., 2019), RAPID (Moat et al., 2020), and MOVE (Send et al., 2011) arrays, have provided a detailed look at the strength and variability of the AMOC (see Fig. 1 for locations of RAPID and OSNAP). Ocean reanalyses, where ocean models assimilate observations, have also been used to assess North Atlantic circulation (Jackson et al., 2019, Fig. 2). Since 1980, the AMOC has strengthened through the 1990s, and overall weakened thereafter, with the RAPID observations showing a 1 Sv/decade trend over the 20 years of observations since they began in 2004 (Volkov et al., 2024, McCarthy et al., 2025).

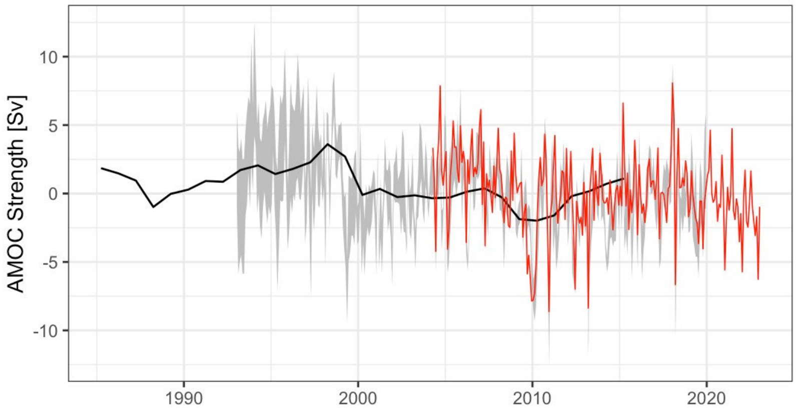

Figure 2. Examples of different AMOC estimates during the modern instrumental era (since 1980) from a dedicated observing system RAPID (red, Moat et al., 2024), an ensemble average of reanalysis products (grey, Copernicus Marine), and reconstruction from hydrography (black, Worthington et al., 2021).

The expansion of AMOC transport observing arrays since 2001 has also highlighted significant areas where the community understanding of the AMOC is still developing (Frajka-Williams et al., 2023). These areas include methods of observation and how to apply reference level adjustments to geostrophic transport (Danabasoglu et al. 2021) and how to incorporate distributed measurements like Argo float profiles and satellite observations into transport estimates (Desbruyères et al. 2019). The AMOC at a single latitude does not necessarily capture the same processes as at another latitude: Jackson et al. (2022) highlight that atmospheric forcing has different relative importance in the subtropical North Atlantic versus the subpolar North Atlantic, with one consequence being that the observed AMOC variability in the subtropics is typically dominated by interannual timescale variability whereas decadal variability dominates in the subpolar region. This differing behaviour highlights the complexity around the continuity of the AMOC, in particular, across the subpolar-subtropical gyre boundaries. Mechanisms explaining the differences include additional Ekman pumping (Fraser et al., 2025) and differing timescales of connectivity from the Labrador Sea to the subtropics (Kostov et al., 2022).

In summary, while observational estimates of AMOC have broadly converged since the 1980s, the precise attribution and mechanisms for these long-term trends and the modern AMOC state remain very uncertain. Since 1980, due to the variability in the AMOC at different latitudes, the variations in methods of measurement, and the relatively short duration of the records, it is not possible to conclude that the AMOC since 1980 has weakened. Recent compilations (Jackson et al. 2022; Caesar et al. 2022) of AMOC records have consistent behaviour: a strengthening of the AMOC in the 1990s, a weakening until the early 2010s, followed by a slight recovery, before a return to weakening in recent years (Volkov et al., 2024, McCarthy et al., 2025). The overall weakening in the RAPID observations since 2004 of 1 Sv/decade is only just statistically significant (Volkov et al., 2024) and remains small in comparison to the shorter timescale variability (McCarthy et al., 2025). Nonetheless, a 1 Sv/decade weakening matches the projected weakening from AR6.

Given the uncertainties in model predictions of AMOC weakening and their predictions of the transitions to an AMOC tipping point (or collapse), it is critical that North Atlantic AMOC observational arrays are maintained into the future. This will lead to better understanding of the dynamics of the subpolar region, extend the AMOC record in the subtropics which will increase our present understanding of AMOC impacts in Europe.

Changes in the subpolar gyre

In the subpolar North Atlantic, polar easterlies in the north and turbulent westerlies in the south drive the cyclonic (anti-clockwise) subpolar gyre. In the south, the subpolar gyre is flanked by the North Atlantic Current (NAC). The NAC marks the boundary between the subpolar cool and fresh and the subtropical warm and saline water masses. As such, the NAC is partly fed by cool and fresh water masses from the western subpolar gyre further north, and by warm and salty water masses supplied from the subtropical gyre further south.

Although the AMOC has been relatively stable over the current interglacial (Lippold et al., 2019), last millennium centennial-scale climate events such as the Medieval Climate anomaly and Little Ice Age have been linked to changes involving variability in the strength of the subpolar gyre, driven by variability in Arctic waters reaching the subpolar North Atlantic and/or through externally forced atmosphere-ocean feedbacks (Moreno-Chamarro et al. 2017; Moffa-Sánchez and Hall 2017; Arellano-Nava et al., 2022). There is evidence to suggest that the industrial-era surface subpolar gyre is in an exceptional state (e.g. Spooner et al., 2020a), contracted towards the western basin with increased northward penetration of warmer waters into the Iceland Basin, Nordic Seas and Arctic (Spielhagen et al. 2011; Tesi et al. 2021). However, there is little evidence that these multi-centennial ocean surface changes were accompanied by changes in the integrated strength of the AMOC and/or deep AMOC changes (Mjell et al. 2016; Moffa-Sanchez et al. 2015; Thornalley et al. 2018) and there is low confidence that AMOC changes on decadal to multidecadal timescales are significantly influenced by ocean surface changes and by anthropogenic forcing (Eyring et al., 2021).

Decadal to multidecadal changes in the subpolar gyre are driven by natural internal variability of the ocean (Moat et al. 2024), externally forced atmosphere-ocean feedback such as greenhouse gas forcing (Lee et al. 2021) and aerosol emissions (Hassan et al. 2021; Robson et al. 2022), and naturally forced atmosphere-ocean feedback such as solar radiation (Ye et al. 2023) and volcanic eruptions (Marshall et al. 2022; Paik et al. 2023). Since the 1980s, changes in wind over the subpolar North Atlantic have changed the strength and extension of the subpolar gyre circulation, which is associated with changes in the position of the subpolar front. In the mid to late 1990s, the subpolar gyre contracted towards the western basin, at a period of AMOC strengthening, associated with a westward shift of the subpolar front that allowed the NAC to transport more water of subtropical origin northward (Häkkinen et al. 2011a; Häkkinen and Rhines 2004). These anomalous wind patterns have been associated with modes of variability such as the North Atlantic Oscillation (NAO) (Koul et al. 2020) and the East Atlantic Pattern (Häkkinen et al. 2011b)—the first and second modes of atmospheric variability respectively. Furthermore, the AMOC fingerprint and gyre index are two metrics used to infer these changes that have been subject to recent debate considering the complexity of inferring dynamic changes from property variability that is driven by multiple oceanic and atmospheric mechanisms (Chafik & Lozier, 2025).

In the 2010s, an intensified, northward shifted storm track and jet stream led to a stronger gyre circulation, which advected more cold and fresh polar water in the subpolar gyre and simultaneously reduced the import of warm, saline subtropical water into the subpolar gyre, leading to the freshest upper ocean recorded in 120 years (Holliday et al. 2020). The freshening of the upper subpolar gyre propagated at depth through entrainment of the salinity anomaly and led to a rapid freshening of the deep overflow layer 2 years later (Devana et al., 2021). A consequence of the freshening signal in the subpolar gyre is a decrease in the Deep Western Boundary Current transport since 2016 (Koman et al., 2024).

Following a period of cold subpolar gyre, a prevailing positive NAO enhanced transport of warm and saline subtropical waters into the Subpolar North Atlantic (Desbruyères et al. 2021) associated with a strengthening of the heat transport at 45°N (Desbruyères et al. 2019) was observed since around 2016. Indeed, under persistent positive NAO forcing over several years, positive density anomalies in the western subpolar gyre are transported southward along the western boundary and act to strengthen the AMOC at these timescales (Chafik et al., 2023). A strengthened AMOC is concomitant with the westward contraction of the subpolar gyre and the enhanced transport of subtropical water into the subpolar North Atlantic. This warming phase observed in the upper ocean of the subpolar gyre is not observed at depth where, on the contrary, the deep overflow layer undergoes a warming-to-cooling reversal in 2014, possibly dominated by entrainments of surrounding waters at the Greenland-Iceland-Scotland ridge (Desbruyeres et al., 2022).

Influences of freshwater fluxes on the North Atlantic

In the subpolar North Atlantic, freshwater variations are of particular importance as they affect, and are affected by, the large-scale climate (Fig. 3). Freshwater variations are closely linked to changes in the ocean circulation, both as a driver and as a response. On decadal timescales, freshwater variations in the subpolar North Atlantic have been connected to changes in the Arctic Ocean circulation, with a more cyclonic Arctic gyre resulting in an enhanced freshwater export into the subpolar region, which is the current state of the Arctic Ocean circulation since about 2015 (Lin et al., 2023; Nishino et al., 2023), and a more anti-cyclonic Arctic gyre resulting in an enhanced freshwater accumulation in the Arctic (Proshutinsky & Johnson, 1997; Proshutinsky et al., 2015; Solomon et al., 2021). Yet, there are many open questions regarding the exact pathways and timescales of the freshwater export from the Arctic into the subpolar region. In addition, it is not clear what drives the atmospheric circulation over the Arctic that triggers the decadal switches in the Arctic Ocean circulation regimes.

An enhanced freshening of the subpolar region increases the stratification of the water column. Thus, it requires a stronger surface cooling for the water to become dense enough to be mixed down. Large freshwater events can thus lead to pronounced cold anomalies (Oltmanns et al. 2020; Oltmanns et al., 2024). Consistent with the decadal releases of Arctic freshwater, the North Atlantic exhibited a pronounced decadal cycle of subpolar cold anomalies over the last century, linked to change in the ocean and atmospheric circulations (Årthun et al. 2021; Zhang et al. 2019). These cold anomalies are associated with increased gradients in the sea surface temperature (SST), triggering changes in the large-scale atmospheric circulation. The resulting atmospheric feedbacks, in turn, lead to further changes in the subpolar gyre circulation, increasing the import of cold and fresh polar water (Oltmanns et al. 2020), intensifying the surface fluxes (Duchez et al. 2016; Josey et al. 2018), and increasing the residence times and recirculation of the cold and freshwater masses in the subpolar gyre (Fox et al., 2022). An open question remains regarding the relative importance of air-sea heat fluxes in the subpolar North Atlantic (Josey et al., 2019) and ocean processes of freshwater inflow in generating cold anomalies in the subpolar North Atlantic, if this differs between timescales and if this would change in the coming years to decades in a context of enhanced ice loss (Josey et al., 2018). In addition, the atmospheric feedbacks affect the weather over the continents surrounding the North Atlantic, resulting in more storms in winter (Oltmanns et al. 2020) and heatwaves and droughts over Europe in summer (Duchez et al. 2016; Mecking et al. 2019).

On longer timescales, enhanced freshening can influence the AMOC (Haine et al., 2023). By increasing stratification, large freshwater releases into the subpolar North Atlantic can potentially disconnect the northward flowing branch at the surface from the southward flowing branch at depth and trigger a weakening of the AMOC. Hydrographic observations from key convective regions (regions of cold, dense water formation such as the Labrador, Irminger, and Nordic Seas) in the subpolar North Atlantic indicate that an increased seasonal freshening shortens the time span during winter in which freshwater is exported downward to depth and in which ocean convection occurs (Oltmanns et al. 2018).

Surface freshening in the subpolar North Atlantic is mainly driven by changes in the subpolar gyre circulation (Holliday et al., 2020) and Arctic Ocean circulation (Proshutinsky et al., 2015) on interannual to decadal timescales. An increasingly important driver of recent surface freshwater and cold anomalies (since ~1995) is seasonal runoff and melting of sea ice and Greenland ice sheet in the subpolar region (Oltmanns et al., 2024). The accelerated melting of Greenland ice sheet is releasing additional freshwater into the subpolar North Atlantic (Shepherd et al., 2021) and, for long-lasting increase of freshwater discharge, could reduce deep convection by strengthening the upper ocean stratification (Dukhovskoy et al., 2021). Ocean model experiments show that the Greenland meltwater discharge enhances the density gradient along the boundary current, which increases current velocities and modify the deep convection regimes in the subpolar North Atlantic, with shallower mixed layers in the Labrador Sea and deeper mixed layer in the Irminger Sea (Illana Shiller-Weiss et al., 2024). Changes in the Labrador Sea deep convection is dependent on the resolution of the model considered: high resolution models are associated with thinner boundary current and finer representation of eddies, which leads to larger changes in the deep convection (Swingedow et al., 2022). The Greenland meltwater discharge and Arctic Ocean freshwater inflow are also mainly responsible for the density compensation of the AMOC observed over the Labrador Sea (Zou et al., 2020), with a strong sensitivity of the density compensation to the entry location of the freshwater fluxes (Bebieva & Lozier, 2023). The residence time of Greenland freshwater anomalies are strongly dependent on their entry location in the subpolar North Atlantic (Dukhovskoy et al., 2021). This suggests that enhanced meltwater in the subpolar North Atlantic can impact the mechanisms of density compensation in the Labrador Sea and affect the AMOC.

Currently, the Arctic is warming about twice as fast as the rest of the planet (Rantanen et al. 2022), contributing to an enhanced ice loss from Greenland and Arctic glaciers (Bamber et al., 2018). There are still many open questions regarding the role of the North Atlantic on the Arctic and, in turn, the role of the Arctic ice loss on the North Atlantic. However, we do know that the subpolar region exhibited a significant freshening trend over the last 70 years, superimposed on the decadal cycle associated with Arctic freshwater releases (Oltmanns et al., 2024). The trend, in turn, was accompanied by a cooling signal in the subpolar North Atlantic, which has been linked to a slowdown of the large-scale Atlantic Meridional Overturning Circulation (Caesar et al., 2018, 2021). It was further shown that the density and depth of the AMOC lower limb is critically dependent on the strength of interior mixing between waters of Atlantic and Arctic origins in the vicinity of Denmark Strait (Dey et al., 2024).

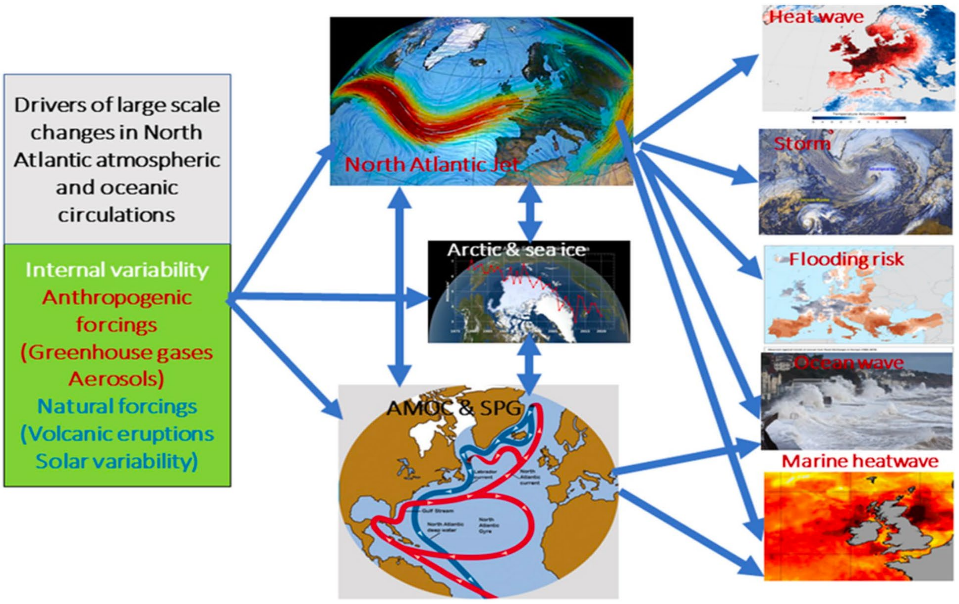

Figure 3: Schematic from Dong et al. (2025) summarizing the links between the drivers (left panels) of ocean and atmospheric circulation changes (middle panels) and their impacts over the North Atlantic (right panels).

Linking the Open Ocean to the European Shelf Seas

Due to their shallow nature, shelf seas are influenced to a far greater extent than the open ocean by tides and wind, as well as the land and seabed boundaries. On sub-daily time scales, tidal flows dominate across the northwest European Shelf Seas (hereafter NWESS). However, on longer timescales, the mean circulation patterns are strongly influenced by wind and density driven flows and steering by seabed topography and the coastline (Fig. 4). The Atlantic Ocean, and particularly the European Slope Current, sets the density at the seaward edge of the NWESS. Transport from the open ocean onto the shelf then determines the relative influence of Atlantic water masses, and therefore the temperature, salinity, and circulation patterns across the shelf. This on-shelf transport can in turn be strongly influenced by prevailing weather patterns (Jones et al. 2018). Near the coast, circulation patterns may also be influenced by riverine sources of freshwater plumes, as well as land-steered surface wind stress.

Though the continental shelf edge presents a barrier to large-scale ocean currents, a host of processes drive exchange of water between the open ocean and shelf seas (including tides, internal tides, topographic deviations of along-slope flow, eddies, and Ekman transports in the wind-driven surface and bottom boundary layers). Along the 5000 km shelf edge from Biscay to north of Shetland, these are estimated to sum to ~ 10 Sv (1 Sv = 10^6 m^3 s^{-1}), with variability in exchange as well as circulation on the shelf having implications for the residence time of water in UK shelf seas (Huthnance et al. 2022). This can vary from tens of days in narrower more exposed shelf areas (e.g. Malin Shelf, Fig. 3), to ~400 days for areas in the North Sea. Export from the shelf then occurs from two different routes: surface circulation through the Norwegian Current or export at depth along the length of the shelf edge.

Unlike transects used for the AMOC across the Atlantic Ocean, long-term monitoring of transport pathways across the NWESS is limited. Data from the Joint North Sea Information System (JONSIS) hydrographic section in the northern North Sea (Berx et al. 2018) captures the main inflows of Atlantic Water to the North Sea, which is important for the hydrography and ecology of the Northern North Sea. It is one of the few long-term observation programs on the NWESS dating from 1981. Sheehan et al. (2017) found that, although inflow in predominantly wind-driven, transport associated with salinity-driven flow is increased in winter, while, in the summer, temperature-driven flows dominate. On shorter timescales, Sheehan et al. (2020) used glider observations in the Northern North Sea to study weekly variability of transports and found thermohaline flows focused into narrow jets which cannot be captured by traditional transects, highlighting the importance of high spatial and temporal resolution data.

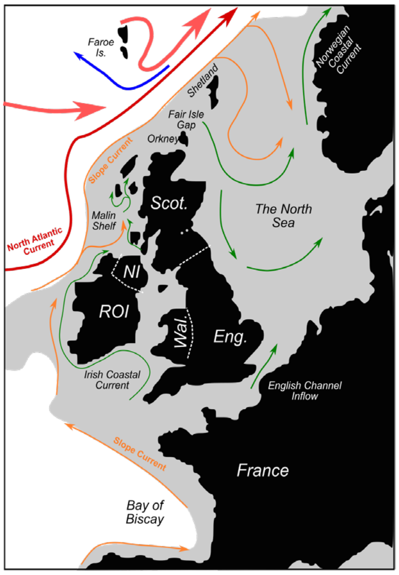

Figure 4: Circulation around the northwest European Shelf (grey = 200 m isobath). Showing warm (red), cold (blue), shelf-edge (orange), and shelf (green) currents. ROI = Republic of Ireland, NI = Northern Ireland, Wal. = Wales, Eng. = England, Scot. = Scotland.

Variability in shelf water properties can be influenced by both the volume of exchange with open ocean as well as changes in open ocean properties. Slope current transport variability and source water provenance are both linked to changes in the subpolar gyre, which drives variability in circulation that feed the NW European slope current (e.g., Clark et al. 2022; Daly et al. 2024). Decadal variability of salinity in the North Sea has also been linked to fluctuations in the subpolar gyre (Koul et al., 2019; Patsch et al., 2020), while the volume of inflow is dominated by wind-driven inflow associated with the NAO (Hjollo et al., 2009). The source water properties of water masses will influence nutrient content as well as physical properties on the NWESS. For example, observations from the OSNAP array in the eastern subpolar North Atlantic have shown variability in different nutrient concentrations between 2017 and 2020, with potentially significant implications for the downstream shelf regions, such as the Northern North Sea (Johnson et al. 2024). Daly et al. (2024) also highlight the potential impact of variability of variability in the European Slope Current and surrounding region for understanding species distribution and habitat suitability over different timescales.

Future changes in the NWESS circulation are strongly linked to changes in the wider North Atlantic. Wind patterns and storminess may affect exchange at the shelf edge through both changes in Ekman transport as well as impacts on the slope current. Large, episodic exchange and transport events (likely associated with wind and storm events) might play an important role for maintaining the continental shelf carbon pump on the NWESS through resupply of oceanic origin nutrients and flushing of dissolved organic carbon (Sharples et al. 2019). Overall, Atlantic warming is expected to increase stratification and shoal the mixed layer, limiting the supply of nutrients into the surface layer. However, under certain conditions, mixing at the shelf-break can then connect the shelf seas to the deeper, nutrient-rich, Atlantic waters (Mathis and Mikolajewicz 2020).

Robust climate projections for shelf circulation can be challenging, as uncertainties can arise from both the large scale models as well as the downscaling methods necessary for resolving the processes in the shelf seas (e.g., Mathis et al., 2018). Downscaled model scenarios have suggested there could be significant changes to circulation within the North Sea (e.g., Holt et al. 2018; Tinker et al., 2016). Holt et al. (2018) show that increased freshwater export from the Arctic could lead to a change in oceanic density gradient alongside the NWESS, resulting in a significant reduction to the slope current and therefore reduced inflow into the North Sea (from 1.2-1.3 Sv to 0.0-0.6 Sv). Such changes in circulation would lead to a reduced inflow of nutrients, and therefore reduction in primary production, consistent with projections also presented in Mathis et al. (2019). However, more recent projections from Tinker et al. (2024) suggest that while the residual circulation may decrease in the North Sea, there is no large-scale change in circulation patterns. Consistent with results from Holt et al. (2018), Tinker et al. (2024) suggest that the response seen within the North Sea may be sensitive to the resolution of the driving global ocean circulation model. Tinker et al. (2024) also show that the change in residual circulation may differ across the shelf, with opposing changes seen between the southern and northern stretches of the slope current, and therefore between the Celtic Sea and North Sea. However, the resolution of NWESS models used in each of these studies to date also do not resolve key processes within the slope current or exchanges across the shelf break (e.g., Graham et al., 2018a), therefore significant uncertainties remain around these downscaled simulations and circulation responses on the continental shelf.

Integrating the shelf seas into climate models to place changes on the shelf in the context of climate change remains a challenge. Global ocean circulation is typically simulated without explicitly representing the tides. However, in continental shelf seas the tides are more fundamentally entwined with the regional circulation. For the NWESS, Tinker et al. (2022) highlighted the differences in circulation pathways when tidal processes are omitted and identified tides as an essential driver for heat and mass circulation. Omitting tides results in non-uniform behaviour with some areas showing increased throughflow and others showing reduced throughflow. The consequent biases in temperature and salinity were of order 0.5ºC and 0.5 psu (practical salinity units ~ g/kg). Excluding tides from coupled ocean-atmosphere simulations has also shown to have impacts for the local atmospheric circulation and seasonality around the UK (Arnold et al. 2021), so may be critical for understanding longer term climate scenarios.

Even when tides are explicitly included in simulations, there are additional small-scale processes that can be a challenge to capture in coarser resolution models. For example, the interaction between tides and complex bathymetry can generate internal tides, with significant impacts for stratification and mixing in shelf seas (Inall et al. 2021). These processes as well as other tidal circulations can only begin to be resolved with kilometric scale grid spacing (e.g., Guihou et al. 2018; Polton 2015). This challenge of resolution has only been addressed for UK operational ocean forecasting within the past 10 years (Graham et al. 2018b). However, the significant computational expense means that regional climate projections of the NWESS are currently still at 7 km resolution (e.g., Tinker et al. 2024), and global climate models are coarser still. Therefore, residual circulation in tidally activated global simulations can be expected to under-represent the true tidal contribution to the circulation.

For better knowledge of NWESS circulation, a coordinated program of observations would provide an effective way forward. This could include occupying one or two hydrographic sections at least annually and investing in autonomous systems (Gliders or ASVs) and 'smart' moorings, in combination with existing buoyancy or offshore structures. The largest unknowns are perhaps related more to the biogeochemistry and productivity of NWESS. Annual cycle measurements of carbon, nitrogen and phosphorus cycles are needed. Autonomous systems (gliders) are now capable of such measurement and require further investment.

WHAT COULD HAPPEN IN THE FUTURE

Future ocean circulation

The IPCC 6th Assessment Report (hereafter AR6) report concludes that it is *very likely* that AMOC will decline over the 21st Century as a result of anthropogenic climate change (Fig. 4). According to simulations undertaken with different levels of forcings for CMIP6 the AMOC is expected to decline by -24% to -32% by 2100 for low and high emissions scenarios, SSP1-2.6 and SSP5-7.0 respectively (Fox-Kemper et al., 2021). The magnitude of this decline is largely independent of specific future emissions choices until at least 2060 and may be related to competing changes in near-term climate forcings across scenarios (Hassan et al, 2022). The magnitude of projected AMOC decline in simulations conducted for AR6 was larger than the simulations conducted for AR5 (Collins et al. 2013). A broadscale revisiting of the AMOC projections will be undertaken as part of the IPCC's forthcoming 7th Assessment report when CMIP7 models will be used.

Despite the consistent ensemble-mean decline in CMIP6 future scenario simulations, it is important to emphasise that there remains a large spread between models in terms of how large and how fast the AMOC decline will be. Specifically, AMOC decline by 2100 ranges from -5% to -40% for low emission scenarios. Similar uncertainties are also seen in extreme climate change simulations, with the range of AMOC reduction spanning ~20-80% in abrupt quadrupling of atmospheric CO2 concentration (Bellomo et al, 2021; Baker et al, 2025). Baker et al. (2025) highlight that there is a weak, but robust, overturning circulation even in CMIP6 models where the AMOC reduces substantially due to sustained Southern Ocean winds. Using this result, Baker et al, (2025) inferred that a complete collapse (defined in the paper as a weakening to below 6 Sv) is unlikely this century even under a high emissions scenario. However, the AMOC continues to decline when extending simulations beyond 2100 and a reduction of AMOC below 6 Sv is seen as more likely when examining changes on timescales to 2300 (Drijfout et al, 2025). On average, models with a stronger AMOC over the last century undergo a larger AMOC decline (Gregory et al, 2005; Weijer et al, 2020). Observational constraints have also been used to constrain future projections (Weijer et al, 2020; Bonan et al, 2025). By constraining the mean state using present day observations from the RAPID array, Weijer et al, (2020) constrained the future decline to be 7±1 Sv by the year 2100, equivalent to approximately 40% decline or a decline of approximately 1 Sv/decade. More recently Bonan et al, 2025 used overturning depth and the rapid array, and concluded the largest declines in AMOC are "very unlikely" with an expected AMOC decline by 2100 of 5+-2Sv.

Climate model simulations for AR6 suggest an increase in the strength of the AMOC over the previous century (Fig 4), with an anthropogenic aerosol driven increase in AMOC of ~10% for the multi-model mean by ~1985 and a subsequent AMOC decline (Fox-Kemper et al., 2021). This historical increase in AMOC is in contrast to that suggested by proxies of past AMOC change (McCarthy and Caesar, 2023). However, the simulated increase in AMOC is sensitive to the anthropogenic aerosol changes (Menary et al., 2020; Robson et al., 2022) which are a still a major source of uncertainty, and so we have more confidence in the climate models' ability to faithfully represent the response to greenhouse gases (dominant in the future) than to aerosols (which played a significant role over the last century). In addition, various proxy-based estimates of AMOC variability over the last century are themselves uncertain. Therefore, we have greater confidence in future AMOC downward trends.

There is a broad range of physical processes that are thought to contribute to the spread in AMOC projections across climate models. For example, the projected future AMOC decline is likely sensitive to the simulated locations of deep convection and deep water formation as well as the subsequent magnitude of the link between deep water formation and the AMOC (Jackson et al., 2020). Lin et al. (2023) emphasize the role of Labrador Sea stratification, showing that weaker stratification allows deeper penetration of surface warming, which in turn reduces subsurface density and contributes to AMOC weakening. Baker et al. (2023) highlight the importance of Indo-Pacific upwelling pathways, demonstrating that models with stronger present-day return flow tend to exhibit greater AMOC weakening. Additionally, Levermann et al. (2007) underscore the influence of northern sea-ice cover, suggesting that initial sea ice extent modulates oceanic heat loss and thus affects the magnitude of AMOC decline. There is also conflicting evidence as to whether the AMOC declines faster in higher resolution models (Roberts et al., 2020; Shan et al., 2024). However, most of the models used for AR6 had low resolution ocean components with nominal ocean resolutions of 1 degree.

Recent observational studies from the OSNAP project (Lozier et al. 2019) have questioned the strength of the link between Labrador Sea convection and the AMOC and instead highlighted the relative importance of the eastern North Atlantic subpolar gyre. The structure and magnitude of the AMOC from coupled models generally agree well with OSNAP observations: a majority of the AMOC occurs at the eastern subpolar gyre rather than over the Labrador Sea (Oldenburg et al. 2022; Yeager et al 2021; Menary et al 2020; Petit et al 2023) in the mean. However, the impact of resolution is still unclear, with some models showing a simulated subpolar AMOC closer to observations at low resolution (Petit et al., 2023) and others at high resolution (Oldenburg et al., 2022; Yeager et al., 2021). Furthermore, the specific mechanistic pathways linking anthropogenic climate change and AMOC decline are currently not fully constrained. Nonetheless, the overall effect of increased heat and high-latitude freshwater input driving AMOC decline remains well understood.

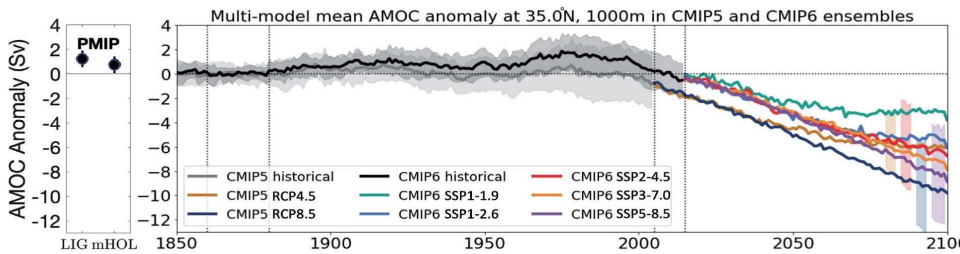

Figure 5: Multimodel mean AMOC anomaly (relative to the period 1860-1880) in CMIP5 and CMIP6 historical ensembles as well as future projections. Taken from IPCC AR6 Ch. 9, Fig. 9.10.

Will the AMOC pass a tipping point?

There is a growing number of studies that conclude that the AMOC is approaching or has passed a tipping point (e.g. van Westen and Dijkstra, 2023; Diltlevsen and Ditlevsen, 2023; van Westen et al., 2024, Boers, 2021; Michel et al., 2022), but the evidence remains inconclusive. Observational proxies of AMOC, typically based on SST, show that, over the last century, the AMOC may have evolved from relatively stable conditions to a point close to a critical transition as indicated by a critical slowing down (Boers, 2021; Michel et al., 2022; Diltlevsen and Ditlevsen, 2023). Others argue that the current uncertainties are too high to robustly predict the timing of any potential AMOC collapse (Ben-Yami et al., 2024) and that critical slowing down indicators may not always be reliable when applied to complex systems like the AMOC (Zimmerman et al., 2025).

Evidence that the AMOC has a tipping point come from previous studies that consider simplified models of the AMOC and studies of paleoclimate that have suggested that the AMOC could have two stable states: one with a strong AMOC as in the present day (an 'on' state), and one with an 'off state' or reversed AMOC (Rahmstorf et al. 2015; McManus et al. 2004; Weijer et al. 2020). This raises the question of whether there is the potential for a collapse of the AMOC in the future. Although in the past it has been difficult to demonstrate multiple stable states of the AMOC in coupled climate models (Stouffer et al. 2006), several climate models have now shown off or weak states that persist for at least centuries (Mecking et al., 2016; Liu et al. 2017; Jackson et al., 2023; van Westen and Dijkstra, 2023). The IPCC also assessed (medium confidence) that model biases could be making climate models overly stable (Valdes 2011; Liu et al. 2017; Mecking et al. 2017; Weijer et al. 2020).

Many studies that show the AMOC passing a tipping point are based on a shift to a weak or off state caused by an input of freshwater into the North Atlantic (Kim et al., 2022; van Westen et al., 2024; Willeit and Ganopolski, 2024). However, typically studies use freshwater inputs which are much larger than those expected in the future from, for example, Greenland ice melt (e.g. van Westen et al., 2024). More realistic rates of freshwater input over the next century show little AMOC weakening from freshwater input alone (Martin et al. 2022; van den Berk and Drijfhout 2014). In contrast, Swingedouw et al. (2022) has shown that models with a very high-resolution ocean may be more sensitive to Greenland melt. Applying updated estimates of Greenland melt over the last few decades, they found a larger impact of Greenland melt in a very high-resolution ocean model, than had been found in earlier studies such as (Böning et al. 2016; Devilliers et al. 2021). Bakker et al. (2016) found that Greenland melt increased the risk of collapse by 2300.

The IPCC AR6 report has found that although the AMOC is very likely to decline before 2100, there is medium confidence of no collapse. For longer timescales a collapse has been found to be as likely as not before 2300 in high emission scenarios (Collins et al, 2019). While there has been an increase in the number of papers indicating that a tipping point in AMOC is imminent, many questions remain around the validity of the metrics, the timing of a tipping, and the underlying data that informs AMOC strength. The gold standard of AMOC observations, the RAPID array, shows a weakening in line with projected weakening from AR6 (approx. 1 Sv/decade) and not in line with a mid-20th century collapse (which would require a 4 Sv/decade weakening, McCarthy et al., 2025). However, this doesn't mean that the AMOC hasn't passed a tipping point. Given the magnitude of the impacts associated with an AMOC collapse (see later section), in particular for northwestern Europe, a letter from scientists in 2024 urged "the Council of Nordic Ministers to (a) initiate an assessment of this significant risk to the Nordic countries and (b) take steps to minimize this risk as much as possible". While the science in this area is evolving rapidly, assessing the risks associated with AMOC collapse should not be postponed.

Ocean circulation as the key to unlocking decadal forecasts

Decadal predictions aim to predict climate on time-scales relevant to decision making by forecasting how the slower components of the Earth System change from years to decades ahead. They do this by using the current state of the ocean circulation (i.e., the initial conditions) and by taking account of changes in external forcings like greenhouse gases (i.e., the boundary conditions). The North Atlantic is a region where initialising the ocean circulation is key to unlocking the skill of these forecasts (Yeager and Robson, 2017; Smith et al, 2019). On annual-to-decadal timescales, changes in the strength of the AMOC and the subpolar gyre drive large scale changes in North Atlantic SSTs, sea surface height and salinity (Yeager, 2020; Fan et al, 2023), which have been linked to a wide variety of impacts, including regional rainfall variability, atmospheric circulation, Arctic sea ice, and fisheries (Zhang et al, 2019). Therefore, successful prediction of the AMOC and subpolar gyre on annual-to-decadal timescales brings substantial societal benefits.

Although direct observations of ocean circulation only cover a relatively short period, there is evidence that both the AMOC and subpolar gyre circulation can be predicted successfully. For example, by verifying against assimilated model runs, previous studies have shown in a multi-model system that decadal predictions of AMOC variability at 45° N is possible up to five years (Pohlmann et al. 2013; Yeager, 2020). Changes in the subpolar gyre strength are also apparently predictable for a number of years (Wouters et al., 2013; Yeager, 2020). The prediction skill likely depends on the state of the ocean at the point of initialisation (Borchert et al. 2018). However, the correct initialisation of the AMOC is difficult and current decadal prediction systems show a variety of drifts that affect skill in predicting the subpolar gyre temperatures (Menary and Hermanson, 2018; Polkova et al, 2023). Additionally, Menary and Hermanson (2018) showed that the uncertainty in past decadal variability of salinity in the Labrador Sea is so large that the choice of observational reference data set decides which models are most skilful.

Annual-to-decadal predictions of the AMOC are made operationally and are available from the WMO Lead Centre for Annual-to-Decadal Climate Prediction (www.wmolc-adcp.org, Hermanson et al., 2022). Understanding the dynamics and predictability of the AMOC and the subpolar gyre is an active research topic and improvements in annual-to-decadal predictions from better understanding and representation of ocean circulation is likely to quickly translate into societal benefits.

Future regional impacts of ocean circulation change

The potential impacts of AMOC decline have widespread implications for global climate, with a weakened AMOC causing: relative cooling in the North Atlantic; large changes in precipitation patterns including a shift in the Intertropical Convergence Zone; changes in mid-latitude atmospheric circulation patterns; and delaying the timing of an ice free Arctic (Jackson et al. 2015; Liu et al. 2020; Bellomo et al. 2021; Orihuela-Pinto et al. 2022; van Westen et al. 2024). It is worth noting the detailed patterns and exact magnitude of potential impacts depend on the extent of AMOC decline (gradual weakening versus collapse) (Bellomo et al. 2021) and may also vary with different climate models and emission scenarios (Jackson et al. 2015; Liu et al. 2020). For example, whilst a collapse of the AMOC remains unlikely, it may have the potential to induce a cascade of abrupt events (Collins et al. 2019). The impacts of an AMOC collapse would be substantial, influencing global and regional climate (Jackson et al. 2015; van Westen et al. 2024). Here we will focus on the impacts of AMOC weakening relevant to the region encompassing the UK, Ireland, and northwestern Europe.

To isolate the effects of AMOC weakening from other drivers of climate change, studies artificially weaken the AMOC using large freshwater inputs (known as hosing runs). Whilst useful for understanding the impacts of AMOC weakening, caution is required in interpreting results as the impacts of AMOC weakening depend on background climate state (Bellomo and Mehling, 2024). For example, AMOC hosing runs show decreased annual mean temperatures (Jackson et al. 2015) and annual mean precipitation rates (Bellomo et al., 2023; Bellomo and Mehling, 2024; Zhang et al. 2024) over the UK due to a weakened AMOC. However, Bellomo and Mehling (2024) compare 4xCO2 experiments, with a pre-industrial AMOC strength, to hosing runs that are extrapolated to 4xCO2 climate. They show the hosing runs predict much stronger cooling and more drying over the UK than the 4xCO2 runs.

Temperature

The duration of winter cold spells over the UK varies spatially. A weakened AMOC increases the strength of the jet stream, reducing atmospheric blocking and the duration of cold spells over Ireland and Southern UK. There is also a moderate but not robust increase in cold spell duration over Northern UK (Meccia et al. 2024). However, as impacts depend on the position of the jet stream and climate models struggle to resolve jet stream position, regional impacts should be treated with caution. In the case of AMOC collapse, van Westen and Baatsen (2025) indicate cold events may become more extreme in both the UK and Ireland. This scenario can occur under the intermediate warming scenario RCP4.5, when an AMOC collapse in CESM simulations run sufficiently far into the future (beyond 2300).

Observational studies show cold Atlantic SSTs prior to most extreme European heatwaves since the 1980s, suggesting an increased probability of heatwaves over Europe in summer in response to cold Atlantic SST anomalies (Duchez et al. 2016). But hosing runs show atmospheric blocking decreases in summer, leading to less frequent extreme warm events (when identified by fixed temperature thresholds) over the UK (Meccia et al. 2024).

Multiple studies (e.g. Jackson et al. 2015; Orihuela-Pinto et al. 2022; van Westen et al. 2024) show regional changes in Atlantic SSTs in response to an AMOC collapse lead to a seesaw pattern in surface air temperatures, with relative decreases (increases) across the Northern (Southern) Hemisphere including cooling by several degrees in northwest European waters. Impacts due to a gradual AMOC weakening may be less severe. For example, van Westen et al. (2024) find no significant trend in global mean surface temperature or global sea ice area. In addition, any changes in surface air temperature in response to AMOC strength, occur in the context of background global warming.

Precipitation

Multiple studies show a decrease in annual mean precipitation over the UK due to a weakened AMOC (Bellomo et al. 2023; Bellomo and Mehling 2024; Zhang et al. 2024). However, this signal varies seasonally. For example, Jackson et al. (2015) find a weakened AMOC leads to increases in snowfall rates, snow depth and snow cover duration in winter and Bellomo et al. (2023) find an increased number of wet days over Northern Europe associated with an increased frequency of wintertime NAO positive phase. Increases in high pressure circulation over the UK in summer, due to AMOC weakening, lead to increased dry spells, posing substantial drought risks (Rousi et al., 2021). In the case of AMOC collapse, precipitation change could lead to the loss of UK arable farming (Ritchie et al. 2020).

Storminess

A weakening AMOC has been shown to impact storm tracks through changing Atlantic SST gradients (Brayshaw et al. 2009; Howard et al. 2024). Liu et al. (2020) and Bellomo et al. (2021) find a weakened AMOC displaces the mid latitude jet poleward in winter—a finding that is supported by observational evidence (Hallam et al., 2022). Whilst Jackson et al. (2015) find a strengthening and eastward extension of the storm track over the UK and northern Europe. A stronger storm track may: increase the number and strength of storms over Europe (Hansen et al. 2016); increase precipitation and mean wind speeds when the storms make landfall; and enhance the maritime effect in winter (Jackson et al. 2015). The latter may also reduce the cooling signature over Europe in winter (Yamamoto and Palter 2016).

Extreme water levels

AMOC weakening affects sea level extremes directly through sea surface height and indirectly through storm surges, a major contributor to coastal flooding in the UK, due to changes in the North Atlantic storm track (Howard et al. 2024). Howard et al. (2024) find up to a 25% increase in the annual maximum meteorological component of UK storm surges due to AMOC weakening, although this varies spatially around the UK. The greatest projected increases are expected at some west coast sites, consistent with a strengthening of westerly winds, whereas south-eastern coastlines see smaller or negative changes.

Biogeographical shifts

Ocean circulation change also has impacts in the marine ecosystem, where it can influence biogeographic shifts through different mechanisms. Firstly, direct impacts may occur when circulation affects the trajectory or dispersal of marine species (predominantly eggs or larvae). For example, when considering larval dispersal during early life stages, circulation patterns will determine the connectivity (the connection of distant local populations by currents) and survival of marine species. Understanding the influence of circulation on larval dispersal is then crucial for understanding the resilience of marine species to any changes in the marine environment. Multiple controls may have a combined impact on larval dispersal, such as changing circulation patterns combining with temperature, food and ocean acidity induced changes in the behaviour and fitness of larvae. Models suggest changes in the AMOC can impact larval dispersal but, for cold water coral species, changes in connectivity are relatively small. Larval behaviour has a much greater impact on connectivity, which needs to be considered in connectivity models and conservation planning (Gary et al. 2020). There is considerable uncertainty in future changes in connectivity, given the multiple factors that may influence larval behaviour, as well as likely changes in species habitats and migration.

Biogeographic shifts may also occur when changes in circulation lead to changes in heat, salt, nutrient and chemical fluxes (such as dissolved oxygen), or relative locations of boundaries between water masses (and their associated properties). In the Northeast Atlantic, shifts in the extent of subpolar waters linked to subpolar gyre dynamics have been linked to biogeographical shifts in marine life at all levels of different ecosystems including plankton, fish, seabirds, tuna, billfish and pilot whales (Hátún et al. 2009). The impacts of changes in subpolar gyre also extend beyond the immediate area and have a clear impact on the productivity of cod in the Barents Sea for example (Årthun et al. 2018). Similarly, long-term industrial-era shifts in the circulation of the Northeast Atlantic are causing a westward retreat of subpolar water and a greater influence of warmer subtropical-origin waters, impacting marine ecosystems including economically important fish species such as mackerel (Spooner et al. 2020). The changing subpolar ocean circulation is also leading to heterogeneous impacts on deep-sea ecosystems, likely caused by changes in the surface-to-deep ocean supply of food (O'Brien et al. 2021). Where spatial distributions of marine species have been shown to be influenced by temperature or salinity, predicting such changes in ocean circulation has already been shown to have potential applications for fisheries management in the northeast Atlantic (e.g., Payne et al. 2017; Townhill et al. 2023). However, on the shelf, the relative changes in temperature, salinity and nutrients will also be affected by local surface or riverine forcing, as well as the larger scale circulation patterns. Indeed, the regime shifts in the North Sea pelagic food webs and plankton populations in the late 1980s were driven by changes in wind intensity, SSTs and oceanic inflow (all associated with changes in the North Atlantic Oscillation) plus changes in biogeographical boundaries (e.g., Reid et al. 2001; Beaugrand 2004). Understanding each of these relative processes, as well as the behaviour and adaptability of marine species, will then be necessary to predict any future biogeographical shifts.

KEY CHALLENGES AND EMERGING ISSUES

AMOC

- Reconciling AMOC reconstructions and climate simulations is a key challenge to underpin confidence in future projections
- Focus of understanding circulation change should not be solely on AMOC with elements such as the subpolar gyre and its driving processes being key to emerging understanding
- Additional freshwater from the Arctic and Greenland is concerning since its release could have major consequences for the stability of the AMOC
- Projections consistently show a weakening of the AMOC in the future, but concern exists about whether current models could overlook the possibility of AMOC collapse
- Further work is also required to understand the timescales for when impacts occur following an AMOC decline.

Shelf seas

- Features on the continental shelf often have shorter timescales and smaller spatial scales than the open ocean, which causes a challenge for their observation and simulation
- Observations on the shelf need to be sustained and coordinated to validate model simulations and fill fundamental gaps in understanding
- Projections of shelf sea circulation and exchange in future climates should be improved through model development as well as validation with observations

Supporting decision making

- Ocean circulation is the key to predictability on decadal timescales and the leveraging of this skill offers the potential for policy-relevant timescales of forecasting
- Climate and biogeographical impacts of ocean circulation change have been studied but the economic impacts of these changes are not well-understood

References

Arellano-Nava, B., Halloran, P. R., Boulton, C. A., et al. (2022). Destabilisation of the Subpolar North Atlantic prior to the Little Ice Age. *Nature Communications, 13*, 5008. https://doi.org/10.1038/s41467-022-32653-x

Arnold, A. K., Lewis, H. W., Hyder, P., Siddorn, J., & O'Dea, E. (2021). The sensitivity of British weather to ocean tides. *Geophysical Research Letters, 48*, e2020GL090732. https://doi.org/10.1029/2020GL090732

Årthun, M., Bogstad, B., Daewel, U., Keenlyside, N. S., Sandø, A. B., Schrum, C., & Ottersen, G. (2018). Climate based multi-year predictions of the Barents Sea cod stock. *PLoS One, 13*, e0206319. https://doi.org/10.1371/journal.pone.0206319

Årthun, M., Wills, R. C. J., Johnson, H. L., Chafik, L., & Langehaug, H. R. (2021). Mechanisms of decadal North Atlantic climate variability and implications for the recent cold anomaly. *Journal of Climate, 34*, 3421–3439. https://doi.org/10.1175/JCLI-D-20-0464.1

Baker, J. A. et al. Overturning pathways control AMOC weakening in CMIP6 models. (2023). Geophys. Res. Lett. 50, e2023GL103381.

Baker, J. A., Bell, M. J., Jackson, L. C., Vallis, G. K., Watson, A. J., & Wood, R. A. (2025). Continued Atlantic overturning circulation even under climate extremes. *Nature, 638*(8052), 987-994.

Bakker, P., et al. (2016). Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters, 43*, 12,252-12,260. https://doi.org/10.1002/2016GL070457

Bamber, J. L., Tedstone, A. J.,King, M. D., Howat, I. M., Enderlin, E. M.,van den Broeke, M. R., & Noel, B.(2018). Land ice freshwater budget ofthe Arctic and North Atlantic Oceans:1. Data, methods, and results. Journalof Geophysical Research: Oceans, 123,1827–1837. https://doi.org/10.1002/2017JC013605

Beaugrand, G. (2004). The North Sea regime shift: evidence, causes, mechanisms and consequences, *Progress in Oceanography, 60*, 245-262. https://doi.org/10.1016/j.pocean.2004.02.018

Bebieva, Y., & Lozier, M. S. (2023). Fresh water and atmospheric cooling control on density-compensated overturning in the Labrador Sea. *Journal of Physical Oceanography*. https://doi.org/10.1175/jpo-d-22-0238.1

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nature Communications, 12*.

https://doi.org/10.1038/s41467-021-24015-w

Bellomo, K., Meccia, V. L., D'Agostino, R., et al. (2023). Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model. *Climate Dynamics, 61*, 3397–3416. https://doi.org/10.1007/s00382-023-06754-2

Bellomo, K., & Mehling, O. (2024). Impacts and state-dependence of AMOC weakening in a warming climate. *Geophysical Research Letters, 51*, e2023GL107624. https://doi.org/10.1029/2023GL107624

Ben-Yami, M., Morr, A., Bathiany, S., & Boers, N. (2024). Uncertainties too large to predict tipping times of major Earth system components from historical data. *Science Advances*, *10*(31), eadl4841.

Berx, B., Hindson, J., & Marine Scotland Science Oceanography Group. (2018). Temperature and salinity on the Joint North Sea Information System (JONSIS) Standard Hydrographic Section. https://doi.org/10.7489/12060-1

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nature Climate Change, 11*, 680–688. https://doi.org/10.1038/s41558-021-01097-4

Bonan, D. B., Thompson, A. F., Schneider, T., Zanna, L., Armour, K. C., & Sun, S. (2025). Observational constraints imply limited future Atlantic meridional overturning circulation weakening. Nature Geoscience, 1-9.

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K., & Bamber, J. L. (2016). Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience, 9*. https://doi.org/10.1038/ngeo2740

Borchert, L. F., Muller, W. A., & Baehr, J. (2018). Atlantic Ocean heat transport influences interannual-to-decadal surface temperature predictability in the North Atlantic region. *Journal of Climate, 31*.

Bouwer, L. M., Cheong, S. M., Jacot Des Combes, H., Frölicher, T. L., McInnes, K. L., Ratter, B. M. W., & Rivera-Arriaga, E. (2022). Risk management and adaptation for extremes and abrupt changes in climate and oceans: Current knowledge gaps. *Frontiers in Climate, 3*, 184. https://doi.org/10.3389/FCLIM.2021.785641

Brayshaw, D. J., Wooling, T., & Vellinga, M. (2009). Tropical and extratropical responses of the North Atlantic atmospheric circulation to a sustained weakening of the MOC. *Journal of Climate, 22*, 3146–3155. https://doi.org/10.1175/2008JCLI2594.1

Bryan, K., & Spelman, M. J. (1985). The ocean's response to a CO2-induced warming. *Journal of Geophysical Research: Oceans, 90*, 11,679–11,688. https://doi.org/10.1029/JC090iC06p11679

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature, 556*, 191.

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nature Geoscience, 14*, 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2022). Reply to: Atlantic circulation change still uncertain. *Nature Geoscience, 15*, 168–170. https://doi.org/10.1038/s41561-022-00897-3

Chafik, L., & Lozier, M. S. (2025). When simplification leads to ambiguity: A look at two ocean metrics for the subpolar North Atlantic. *Geophysical Research Letters, 52*(3). https://doi.org/10.1029/2024GL112496

Chafik, L., Holliday, N. P., Bacon, S., Baker, J. A., Desbruyères, D., Frajka-Williams, E., & Jackson, L. C. (2023). Observed mechanisms activating the recent subpolar North Atlantic warming since 2016. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 381*(2262). https://doi.org/10.1098/rsta.2022.0183

Clark, M., Marsh, R., & Harle, J. (2022). Weakening and warming of the European Slope Current since the late 1990s attributed to basin-scale density changes. *Ocean Science, 18*(2), 549-564.

Collins, M., et al. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. http://www.climatechange2013.org/report/reports-graphic/ch12-graphics/

Collins, M., Sutherland, M., Bouwer, L., Cheong, S. M., Frolicher, T., Jacot Des Combes, H., Mathew Koll, R., Losada, I., McInnes, K., Ratter, B., & Rivera-Arriga, E. (2019). IPCC special report on the ocean and cryosphere in a changing climate. *Extremes. Abrupt Changes and Managing Risks, 6*, 589-655.

Daly, E., Nolan, G., Berry, A., Büscher, J.V., Cave, R.R., Caesar, L., Cronin, M., Fennell, S., Lyons, K., McAleer, A., McCarthy, G.D., McGovern, E., McGovern, J.V., McGrath, T., O'Donnell, G., Pereiro, D., Thomas, R., Vaughan, L., White, M., Cusack, C. (2024). Diurnal to interannual variability in the Northeast Atlantic from hydrographic transects and fixed time-series across the Rockall Trough, *Deep Sea Research, 204*, 104233, https://doi.org/10.1016/j.dsr.2024.104233.

Danabasoglu, G., Castruccio, F. S., Small, R. J., Tomas, R., Frajka-Williams, E., & Lankhorst, M. (2021). Revisiting AMOC transport estimates from observations and models. *Geophysical Research Letters, 48*, e2021GL093045. https://doi.org/10.1029/2021GL093045

Desbruyères, D., Chafik, L., & Maze, G. (2021). A shift in the ocean circulation has warmed the subpolar North Atlantic Ocean since 2016. *Communications Earth & Environment, 2*, 1–9. https://doi.org/10.1038/s43247-021-00120-y

Desbruyères, D. G., Mercier, H., Maze, G., & Daniault, N. (2019). Surface predictor of overturning circulation and heat content change in the subpolar North Atlantic. *Ocean Science, 15*, 809–817. https://doi.org/10.5194/os-15-809-2019

Desbruyères, D. G., Bravo, E. P., Thierry, V., Mercier, H., Lherminier, P., Cabanes, C., Biló, T. C., Fried, N., & De Jong, M. F. (2022). Warming-to-cooling reversal of overflow-derived water masses in the Irminger Sea during 2002–2021. *Geophysical Research Letters, 49*(10), 1–10.

https://doi.org/10.1029/2022GL098057

Devilliers, M., Swingedouw, D., Garric, G., & Ocean, M. (2021). A realistic Greenland ice sheet and surrounding glaciers and ice caps melting in a coupled climate model. https://doi.org/10.21203/rs.3.rs-401895/v1

Devana, M. S., Johns, W. E., Houk, A., & Zou, S. (2021). Rapid freshening of Iceland Scotland overflow water driven by entrainment of a major upper ocean salinity anomaly. *Geophysical Research Letters*, 1–11. https://doi.org/10.1029/2021GL094396

Dey, D., Marsh, R., Drijfhout, S., Josey, S. A., Sinha, B., Grist, J., & Döös, K. (2024). Formation of the Atlantic Meridional Overturning Circulation lower limb is critically dependent on Atlantic-Arctic mixing. *Nature Communications, 15*(1), 7341. https://doi.org/10.1038/s41467-024-51777-w

Ditlevsen, P., & Ditlevsen, S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications, 14*, 4254. https://doi.org/10.1038/s41467-023-39810-w

Drijfhout, S., Angevaare, J., Mecking, J. V., van Westen, R., & Rahmstorf, S. (2025). Shutdown of northern Atlantic overturning after 2100 following deep mixing collapse in CMIP6 projections. Environmental Research Letters.

Duchez, A., et al. (2016). Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters, 11*. https://doi.org/10.1088/1748-9326/11/7/074004

Dukhovskoy, D. S., Yashayaev, I., Chassignet, E. P., Myers, P. G., Platov, G., & Proshutinsky, A. (2021). Time scales of the Greenland freshwater anomaly in the subpolar North Atlantic. *Journal of Climate, 34*, 8971–8987. https://doi.org/10.1175/JCLI-D-20-0610.1

Eyring, V., Gillett, N. P., Rao, K. M. A., et al. (2021). Human influence on the climate system. In V. Masson-Delmotte et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 423–552). Cambridge University Press.

Fan, H., Borchert, L. F., Brune, S., et al. (2023). North Atlantic subpolar gyre provides downstream ocean predictability. *npj Climate and Atmospheric Science, 6*, 145. https://doi.org/10.1038/s41612-023-00469-1

Frajka-Williams, E., Foukal, N., & Danabasoglu, G. (2023). Should AMOC observations continue: how and why? *Philosophical Transactions of the Royal Society A, 381*(2262), 20220195.

Fraser, N. J., Fox, A. D., & Cunningham, S. A. (2025). Impact of Ekman pumping on the meridional coherence of the AMOC. *Geophysical Research Letters, 52*(1), e2024GL108846.

Fraser, N. J., & Cunningham, S. A. (2021). 120 years of AMOC variability reconstructed from observations using the Bernoulli inverse. *Geophysical Research Letters, 48*(18), e2021GL093893.

Fox, A. D., Handmann, P., Schmidt, C., Fraser, N., Rühs, S., Sanchez-Franks, A., Martin, T., Oltmanns, M., Johnson, C., Rath, W., Holliday, N. P., Biastoch, A., Cunningham, S. A., & Yashayaev, I. (2022). Exceptional freshening and cooling in the eastern subpolar North Atlantic caused by reduced Labrador Sea surface heat loss. *Ocean Science, 18*, 1507–1533. https://doi.org/10.5194/os-18-1507-2022

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., & Yu, Y. (2021). Ocean, cryosphere and sea level change. In V. Masson-Delmotte et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1211–1362). Cambridge University Press. https://doi.org/10.1017/9781009157896.011

Gary, S. F., Fox, A. D., Biastoch, A., Roberts, J. M., & Cunningham, S. A. (2020). Larval behaviour, dispersal and population connectivity in the deep sea. *Scientific Reports, 10*, 1–12. https://doi.org/10.1038/s41598-020-67503-7

Graham, J. A., Rosser, J. P., O'Dea, E., & Hewitt, H. T. (2018a). Resolving shelf break exchange around the European Northwest Shelf. *Geophysical Research Letters, 45*, 12,386-12,395. https://doi.org/10.1029/2018GL079399

Graham, J. A., O'Dea, E., Holt, J., Polton, J., Hewitt, H. T., Furner, R., Guihou, K., Brereton, A., Arnold, A., Wakelin, S., Castillo Sanchez, J. M., & Mayorga Adame, C. G. (2018b). AMM15: A new high-resolution NEMO configuration for operational simulation of the European north-west shelf. *Geoscientific Model Development, 11*, 681-696. https://doi.org/10.5194/gmd-11-681-2018

Gregory, J. M., Dixon, K. W., Stouffer, R. J., Weaver, A. J., Driesschaert, E., Eby, M., ... & Thorpe, R. B. (2005). A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration. *Geophysical Research Letters*, *32*(12).

Guihou, K., Polton, J. A., Harle, J., Wakelin, S., O'Dea, E., & Holt, J. (2018). Kilometric scale modeling of the North West European Shelf Seas: Exploring the spatial and temporal variability of internal tides. *Journal of Geophysical Research: Oceans, 123*, 688-707. https://doi.org/10.1002/2017JC012960

Haine, T. W. N., Siddiqui, A. H., & Jiang, W. (2023). Arctic freshwater impact on the Atlantic Meridional Overturning Circulation: Status and prospects. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 381*(2262). https://doi.org/10.1098/rsta.2022.0185

Häkkinen, S., & Rhines, P. B. (2004). Decline of subpolar North Atlantic circulation during the 1990s. *Science, 304*, 555–559.

Häkkinen, S., Rhines, P. B., & Worthen, D. L. (2011a). Warm and saline events embedded in the meridional circulation of the northern North Atlantic. *Journal of Geophysical Research: Oceans, 116*, C03006. https://doi.org/10.1029/2010JC006275

Häkkinen, S., Rhines, P. B., & Worthen, D. L. (2011b). Atmospheric blocking and Atlantic multidecadal ocean variability. *Science, 334*, 655–659.

Hassan, T., Allen, R. J., Liu, W., & Randles, C. A. (2021). Anthropogenic aerosol forcing of the Atlantic meridional overturning circulation and the associated mechanisms in CMIP6 models. *Atmospheric Chemistry and Physics, 21*(8), 5821–5846. https://doi.org/10.5194/acp-21-5821-2021

Hallam, S., Josey, S. A., McCarthy, G. D., & Hirschi, J. J. M. (2022). A regional (land–ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011. *Climate Dynamics, 59*(7), 1897-1918.

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., & Velicogna, I. (2016). Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming is highly dangerous. *Atmospheric Chemistry & Physics Discussions, 15*(15).

Hassan, T., Allen, R.J., Liu, W. et al. (2022) Air quality improvements are projected to weaken the Atlantic meridional overturning circulation through radiative forcing effects. Commun Earth Environ 3, 149. https://doi.org/10.1038/s43247-022-00476-9

Hátún, H., et al. (2009). Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography*. https://doi.org/10.1016/j.pocean.2009.03.001

He, F., & Clark, P. U. (2022). Freshwater forcing of the Atlantic Meridional Overturning Circulation revisited. *Nature Climate Change, 12*(5), 449–454. https://doi.org/10.1038/s41558-022-01328-2

Hermanson, L., and Coauthors, 2022: WMO Global Annual to Decadal Climate Update: A Prediction for 2021–25. Bull. Amer. Meteor. Soc., 103, E1117–E1129, https://doi.org/10.1175/BAMS-D-20-0311.1.

Hjøllo, S. S., Skogen, M. D., & Svendsen, E. (2009). Exploring currents and heat within the North Sea using a numerical model. *Journal of Marine Systems, 78*(1), 180-192.

Holliday, N. P., et al. (2020). Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. *Nature Communications, 11*(1), 1–15. https://doi.org/10.1038/s41467-020-14474-y

Holt, J., et al. (2018). Climate-driven change in the North Atlantic and Arctic Ocean can greatly reduce the circulation of the North Sea. *Geophysical Research Letters, 45*, 11,827-11,836. https://doi.org/10.1029/2018GL078878

Howard, T., Palmer, M. D., Jackson, L. C., & Yamazaki, K. (2024). Storm surge changes around the UK under a weakened Atlantic meridional overturning circulation. *Environmental Research Communications, 6*, 035026. https://doi.org/10.1088/2515-7620/ad3368

Huthnance, J., et al. (2022). Ocean shelf exchange, NW European shelf seas: Measurements, estimates and comparisons. *Progress in Oceanography, 202*, 102760. https://doi.org/10.1016/J.POCEAN.2022.102760

Inall, M., Toberman, M., Polton, J., Palmer, M., Green, J., & Rippeth, T. (2021).

Shelf seas baroclinic energy loss: Pycnocline mixing and bottom boundary layer dissipation. *Journal of Geophysical Research: Oceans, 126*(8). https://doi.org/10.1029/2020JC016528

Jackson, L. C., Alastrué De Asenjo, E., Bellomo, K., Danabasoglu, G., Haak, H., Hu, A., Jungclaus, J., Lee, W., Meccia, V. L., Saenko, O., Shao, A., & Swingedouw, D. (2023). Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project. *Geoscientific Model Development, 16(7),* 1975–1995. https://doi.org/10.5194/GMD-16-1975-2023,

Jackson, L. C., Schaller, N., Smith, R. S., Palmer, M. D., & Vellinga, M. (2014). Response of the Atlantic meridional overturning circulation to a reversal of greenhouse gas increases. *Climate Dynamics, 42*, 3323–3336. https://doi.org/10.1007/S00382-013-1842-5

Jackson, L. C., Roberts, M. J., Hewitt, H. T., Iovino, D., Koenigk, T., Meccia, V. L., Roberts, C. D., Ruprich-Robert, Y., & Wood, R. A. (2020). Impact of ocean resolution and mean state on the rate of AMOC weakening. *Climate Dynamics, 55*(7), 1711-1732.

Jackson, L. C., Dubois, C., Forget, G., Haines, K., Harrison, M., Iovino, D., Köhl, A., Mignac, D., Masina, S., Peterson, K. A., & Piecuch, C. G. (2019). The mean state and variability of the North Atlantic circulation: A perspective from ocean reanalyses. *Journal of Geophysical Research: Oceans, 124*(12), 9141-9170.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*. https://doi.org/10.1007/s00382-015-2540-2

Jackson, L. C., Biastoch, A., Buckley, M. W., Desbruyères, D. G., Frajka-Williams, E., Moat, B., & Robson, J. (2022). The evolution of the North Atlantic Meridional Overturning Circulation since 1980. *Nature Reviews Earth & Environment, 3*, 241–254. https://doi.org/10.1038/s43017-022-00263-2

Johnson, C., Fraser, N., Cunningham, S., Burmeister, K., Jones, S., Drysdale, L., et al. (2024). Biogeochemical properties and transports in the North East Atlantic. Journal of Geophysical Research: Oceans, 129, e2023JC020427. https://doi.org/10.1029/2023JC020427

Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S. A., Kanzow, T., Bryden, H. L., Hirschi, J. J. M., et al. (2011). Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N. *Journal of Climate, 24*(10), 2429-2449.

Jones, S., Cottier, F., Inall, M., & Griffiths, C. (2018). Decadal variability on the Northwest European continental shelf. *Progress in Oceanography*. https://doi.org/10.1016/j.pocean.2018.01.012

Josey, S. A., de Jong, M. F., Oltmanns, M., Moore, G. K., & Weller, R. A. (2019). Extreme variability in Irminger Sea winter heat loss revealed by Ocean Observatories Initiative mooring and the ERA5 reanalysis. *Geophysical Research Letters, 46*(1), 293–302. https://doi.org/10.1029/2018GL080956

Josey, S. A., Hirschi, J. J. M., Sinha, B., Duchez, A., Grist, J. P., & Marsh, R. (2018). The recent Atlantic cold anomaly: Causes, consequences, and related phenomena. *Annual Review of Marine Science, 10*(1), 475–501.

https://doi.org/10.1146/annurev-marine-121916-063102

Kilbourne, K. H., Wanamaker, A. D., Moffa-Sanchez, P., Reynolds, D. J., Amrhein, D. E., Butler, P. G., ... & Whitney, N. M. (2022). Atlantic circulation change still uncertain. *Nature Geoscience, 15*(3), 165-167.

Kim, SK., Kim, HJ., Dijkstra, H.A. et al. Slow and soft passage through tipping point of the Atlantic Meridional Overturning Circulation in a changing climate. npj Clim Atmos Sci 5, 13 (2022). https://doi.org/10.1038/s41612-022-00236-8

Koman, G., Bower, A. S., Holliday, N. P., Furey, H. H., Fu, Y., & Biló, T. C. (2024). Observed decrease in Deep Western Boundary Current transport in subpolar North Atlantic. *Nature Geoscience*. https://doi.org/10.1038/s41561-024-01555-6

Kopits, E., Marten, A., & Wolverton, A. (2014). Incorporating 'catastrophic' climate change into policy analysis. *Climate Policy, 14*, 637–664. https://doi.org/10.1080/14693062.2014.864947

Kostov, Y., Messias, M. J., Mercier, H., Johnson, H. L., & Marshall, D. P. (2023). Fast mechanisms linking the Labrador Sea with subtropical Atlantic overturning. *Climate Dynamics*, *60*(9), 2687-2712.

Koul, V., Schrum, C., Düsterhus, A., & Baehr, J. (2019). Atlantic inflow to the North Sea modulated by the subpolar gyre in a historical simulation with MPI-ESM. *Journal of Geophysical Research: Oceans, 124*(3), 1807-1826.

Koul, V., et al. (2020). Unraveling the choice of the North Atlantic subpolar gyre index. *Scientific Reports, 10*, 1–12. https://doi.org/10.1038/s41598-020-57790-5

Lee, J. Y., Marotzke, J., Bala, G., et al. (2021). Future global climate: Scenario-based projections and near-term information. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 553–672). Cambridge University Press. https://doi.org/10.1017/9781009157896.006

Legge, O., et al. (2020). Carbon on the Northwest European Shelf: Contemporary budget and future influences. *Frontiers in Marine Science, 7*, 143. https://doi.org/10.3389/FMARS.2020.00143/BIBTEX

Levermann, A., Mignot, J., Nawrath, S., & Rahmstorf, S. (2007). The role of northern sea ice cover for the weakening of the thermohaline circulation under global warming. Journal of Climate, 20(16), 4160-4171.

Lobelle, D., Beaulieu, C., Livina, V. N., Sévellec, F., & Frajka-Williams, E. (2020). Detectability of an AMOC decline in current and projected climate changes. *Geophysical Research Letters, 47*, e2020GL089974. https://doi.org/10.1029/2020GL089974

Lippold, J., et al. (2019). Constraining the variability of the Atlantic Meridional Overturning Circulation during the Holocene. *Geophysical Research Letters, 46*, 11338–11346. https://doi.org/10.1029/2019GL084988

Lin, P., Pickart, R. S., Heorton, H., et al. (2023). Recent state transition of the Arctic Ocean's Beaufort Gyre. *Nature Geoscience*.

https://doi.org/10.1038/s41561-023-01184-5

Lin, Y.-J., Rose, B. E. & Hwang, Y.-T. (2023). Mean state AMOC affects AMOC weakening through subsurface warming in the Labrador Sea. J. Clim. 36, 3895–3915.

Liu, W., Xie, S.-P., Liu, Z., & Zhu, J. (2017). Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances, 3*, e1601666.

Liu, W., Fedorov, A. V., Xie, S. P., & Hu, S. (2020). Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Science Advances, 6*. https://doi.org/10.1126/SCIADV.AAZ4876

Lozier, M. S., et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science*. https://doi.org/10.1126/science.aau6592

Marshall, L. R., Maters, E. C., Schmidt, A., et al. (2022). Volcanic effects on climate: Recent advances and future avenues. *Bulletin of Volcanology, 84*, 54. https://doi.org/10.1007/s00445-022-01559-3

Martin, T., Biastoch, A., Lohmann, G., Mikolajewicz, U., & Wang, X. (2022). On timescales and reversibility of the ocean's response to enhanced Greenland ice sheet melting in comprehensive climate models. *Geophysical Research Letters, 49*, e2021GL097114. https://doi.org/10.1029/2021GL097114

Mathis, M., Elizalde, A., & Mikolajewicz, U. (2018). Which complexity of regional climate system models is essential for downscaling anthropogenic climate change in the Northwest European Shelf? *Climate Dynamics, 50*, 2637–2659. https://doi.org/10.1007/s00382-017-3761-3

Mathis, M., Elizalde, A., Mikolajewicz, U. (2019). The future regime of Atlantic nutrient supply to the Northwest European Shelf, *Journal of Marine Systems, 189*, 98-115, https://doi.org/10.1016/j.jmarsys.2018.10.002.

Mathis, M., & Mikolajewicz, U. (2020). The impact of meltwater discharge from the Greenland ice sheet on the Atlantic nutrient supply to the northwest European shelf. *Ocean Science, 16*, 167–193. https://doi.org/10.5194/OS-16-167-2020

McCarthy, G. D., Gleeson, E., & Walsh, S. (2015). The influence of ocean variations on the climate of Ireland. *Weather, 70*(8), 242-245.

McCarthy, G. D., & Caesar, L. (2023). Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past? *Philosophical Transactions of the Royal Society A, 381*(2262), 20220193.

McCarthy, G. D., Hug, G., Smeed, D. A., Morris, K. J., & Moat, B. I. (2025). Signal and noise in the Atlantic Meridional Overturning Circulation at 26°N. *Geophysical Research Letters, 52*(7), e2025GL115055.

McManus, J. F., Francois, R., Gherardi, J. M., Kelgwin, L., & Drown-Leger, S. (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature, 428*, 834–837. https://doi.org/10.1038/NATURE02494

Meccia, V. L., Simolo, C., Bellomo, K., & Corti, S. (2024). Extreme cold events in Europe under a reduced AMOC. *Environmental Research Letters, 19*, 014054. https://doi.org/10.1088/1748-9326/ad14b0

Meccia, V. L., Simolo, C., Bellomo, K., & Corti, S. (2025). The impact of a weakened AMOC on European heatwaves. *Environmental Research Letters, 20*, 024005. https://doi.org/10.1088/1748-9326/ada3e7

Mecking, J. V., Drijfhout, S. S., Hirschi, J. J. M., & Blaker, A. T. (2019). Ocean and atmosphere influence on the 2015 European heatwave. *Environmental Research Letters, 14*, 114035. https://doi.org/10.1088/1748-9326/AB4D33

Mecking, J. V., Drijfhout, S. S., Jackson, L. C., & Andrews, M. B. (2017). The effect of model bias on Atlantic freshwater transport and implications for AMOC bi-stability. *Tellus A: Dynamic Meteorology and Oceanography, 69*, 1299910. https://doi.org/10.1080/16000870.2017.1299910

Mecking, J. V., Drijfhout, S. S., Jackson, L. C., & Graham, T. (2016). Stable AMOC off state in an eddy-permitting coupled climate model. *Climate Dynamics, 47,* 2455-2470. https://doi.org/10.1007/s00382-016-2975-0

Menary, M.B. and L. Hermanson (2018) Limits on determining the skill of North Atlantic Ocean decadal predictions, *Nature Communications* 9, 1694, https://doi.org/10.1038/s41467-018-04043-9

Menary, M. B., Hermanson, L., & Dunstone, N. J. (2016). The impact of Labrador Sea temperature and salinity variability on density and the subpolar AMOC in a decadal prediction system. *Geophysical Research Letters, 43*, 12,217-12,227. https://doi.org/10.1002/2016GL070906

Menary, M. B., Jackson, L. C., & Lozier, M. S. (2020). Reconciling the relationship between the AMOC and Labrador Sea in OSNAP observations and climate models. *Geophysical Research Letters, 47*(18), e2020GL089793. https://doi.org/10.1029/2020GL089793

Michel, S. L., Swingedouw, D., Ortega, P., Gastineau, G., Mignot, J., McCarthy, G., & Khodri, M. (2022). Early warning signal for a tipping point suggested by a millennial Atlantic Multidecadal Variability reconstruction. *Nature Communications, 13*(1), 5176.

Mjell, T. L., Ninnemann, U. S., Kleiven, H. F., & Hall, I. R. (2016). Multidecadal changes in Iceland Scotland Overflow Water vigor over the last 600 years and its relationship to climate. *Geophysical Research Letters, 43*, 2111–2117. https://doi.org/10.1002/2016GL068227

Moat, B. I., Smeed, D. A., Frajka-Williams, E., Desbruyères, D. G., Beaulieu, C., Johns, W. E., Rayner, D., Sanchez-Franks, A., Baringer, M. O., Volkov, D., Jackson, L. C., & Bryden, H. L. (2020). Pending recovery in the strength of the meridional overturning circulation at 26°N. *Ocean Science, 16*(4), 863-874. https://doi.org/10.5194/os-16-863-2020

Moat, B. I., Sinha, B., Berry, D. I., Drijfhout, S. S., Fraser, N., Hermanson, L., Jones, D. C., Josey, S. A., King, B., Macintosh, C., Megann, A., Oltmanns, M., Sanders, R., & Williams, S. (2024). Ocean heat convergence and North Atlantic multidecadal heat content variability. *Journal of Climate, 37*(18), 4723–4742. https://doi.org/10.1175/JCLI-D-23-0370.1

Moffa-Sanchez, P., Hall, I. R., Thornalley, D. J. R., Barker, S., & Stewart, C. (2015). Changes in the strength of the Nordic Seas overflows over the past

3000 years. *Quaternary Science Reviews, 123*, 134–143. https://doi.org/10.1016/J.QUASCIREV.2015.06.007

Moffa-Sánchez, P., & Hall, I. R. (2017). North Atlantic variability and its links to European climate over the last 3000 years. *Nature Communications, 8*(1), 1–9. https://doi.org/10.1038/s41467-017-01884-8

Moffa-Sánchez, P., et al. (2019). Variability in the Northern North Atlantic and Arctic Oceans across the last two millennia: A review. *Paleoceanography and Paleoclimatology, 34*, 1399–1436. https://doi.org/10.1029/2018PA003508

Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., & Jungclaus, J. H. (2017). An abrupt weakening of the subpolar gyre as trigger of Little Ice Age-type episodes. *Climate Dynamics, 48*, 727–744. https://doi.org/10.1007/S00382-016-3106-7

Nishino, S., Jung, J., Cho, K. H., et al. (2023). Atlantic-origin water extension into the Pacific Arctic induced an anomalous biogeochemical event. *Nature Communications, 14*, 6235. https://doi.org/10.1038/s41467-023-41960-w

O'Brien, C. L., et al. (2021). Exceptional 20th century shifts in deep-sea ecosystems are spatially heterogeneous and associated with local surface ocean variability. *Frontiers in Marine Science, 8*, 1376. https://doi.org/10.3389/FMARS.2021.663009

Oldenburg, D., Wills, R. C. J., Armour, K. C., & Thompson, L. (2022). Resolution dependence of atmosphere–ocean interactions and water mass transformation in the North Atlantic. *Journal of Geophysical Research: Oceans, 127*(4), 1–18. https://doi.org/10.1029/2021JC018102

Oltmanns, M., Karstensen, J., & Fischer, J. (2018). Increased risk of a shutdown of ocean convection posed by warm North Atlantic summers. *Nature Climate Change*. https://doi.org/10.1038/s41558-018-0105-1

Oltmanns, M., Karstensen, J., Moore, G. W. K., & Josey, S. A. (2020). Rapid cooling and increased storminess triggered by freshwater in the North Atlantic. *Geophysical Research Letters, 47*, e2020GL087207. https://doi.org/10.1029/2020GL087207

Oltmanns, M., Holliday, N. P., Screen, J., Moat, B. I., Josey, S. A., Evans, D. G., & Bacon, S. (2024). European summer weather linked to North Atlantic freshwater anomalies in preceding years. *Weather and Climate Dynamics, 5*(1), 109-132. https://doi.org/10.5194/wcd-5-109-2024

Orihuela-Pinto, B., England, M. H., & Taschetto, A. S. (2022). Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation. *Nature Climate Change, 12*, 558-565. https://doi.org/10.1038/s41558-022-01380-y

Paik, S., Min, S.-K., Son, S.-W., Lim, E.-P., McGregor, S., An, S.-I., Kug, J.-S., & Yeh, S.-W. (2023). Impact of volcanic eruptions on extratropical atmospheric circulations: Review, revisit and future directions. *Environmental Research Letters, 18*(6), 063003. https://doi.org/10.1088/1748-9326/acd5e6

Pätsch, J., Gouretski, V., Hinrichs, I., & Koul, V. (2020). Distinct mechanisms underlying interannual to decadal variability of observed salinity and nutrient concentration in the northern North Sea. *Journal of Geophysical Research: Oceans, 125*(5), e2019JC015825.

Payne, M. R., et al. (2017). Lessons from the first generation of marine ecological forecast products. *Frontiers in Marine Science, 4*, 289. https://doi.org/10.3389/FMARS.2017.00289/BIBTEX

Petit, T., Robson, J., Ferreira, D., & Jackson, L. C. (2023). Understanding the sensitivity of the North Atlantic subpolar overturning in different resolution versions of HadGEM3-GC3.1. *Journal of Geophysical Research: Oceans, 128*, e2023JC019672. https://doi.org/10.1029/2023JC019672

Pohlmann, H., Smith, D.M., Balmaseda, M.A. *et al.* Predictability of the mid-latitude Atlantic meridional overturning circulation in a multi-model system. *Clim Dyn* **41**, 775–785 (2013). https://doi.org/10.1007/s00382-013-1663-6

Polkova, I., Swingedouw, D., Hermanson, L., Köhl, A., Stammer, D., Smith, D., Kröger, J., Bethke, I., Yang, X., Zhang, L., Nicolì, D., Athanasiadis, P. J., Karami, M. P., Pankatz, K., Pohlmann, H., Wu, B., Bilbao, R., Ortega, P., Yang, S., Sospedra-Alfonso, R., Merryfield, W., Kataoka, T., Tatebe, H., Imada, Y., Ishii, M., & Matear, R. J. (2023). Initialization shock in the ocean circulation reduces skill in decadal predictions of the Atlantic subpolar gyre. *Frontiers in Climate, 5*, 2624-9553. https://doi.org/10.3389/fclim.2023.1273770

Polton, J. A. (2015). Tidally induced mean flow over bathymetric features: A contemporary challenge for high-resolution wide-area models. *Geophysical and Astrophysical Fluid Dynamics, 109*, 207–215. https://doi.org/10.1080/03091929.2014.952726

Pontes, G. M., & Menviel, L. (2024). Weakening of the Atlantic Meridional Overturning Circulation driven by subarctic freshening since the mid-twentieth century. *Nature Geoscience, 17*, 1291–1298. https://doi.org/10.1038/s41561-024-01568-1

Proshutinsky, A. Y., & Johnson, M. A. (1997). Two circulation regimes of the wind-driven Arctic Ocean. *Journal of Geophysical Research: Oceans, 102*(C6), 12493-12514.

Proshutinsky, A., Dukhovskoy, D., Timmermans, M. L., Krishfield, R., & Bamber, J. L. (2015). Arctic circulation regimes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 373*(2052), 20140160.

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*. https://doi.org/10.1038/nclimate2554

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment, 3*(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Reid, P.C., Holliday, P.N., Smyth, T.J. (2001). Pulses in the eastern margin current and warmer water off the north west European shelf linked to North Sea ecosystem changes, *Marine Ecology Progress Series, 215*, 283-287, https://doi.org/10.3354/meps215283

Ritchie, P. D. L., et al. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. *Nature Food, 1*(1), 76–83. https://doi.org/10.1038/s43016-019-0011-3

Roberts, M. J., Jackson, L. C., Roberts, C. D., Meccia, V., Docquier, D., Koenigk, T., et al. (2020). Sensitivity of the Atlantic Meridional Overturning Circulation to model resolution in CMIP6 HighResMIP simulations and implications for future changes. *Journal of Advances in Modeling Earth Systems, 12*, e2019MS002014. https://doi.org/10.1029/2019MS002014

Robson, J., Menary, M. B., Sutton, R. T., Mecking, J., Gregory, J. M., Jones, C., Sinha, B., Stevens, D. P., & Wilcox, L. J. (2022). The role of anthropogenic aerosol forcing in the 1850–1985 strengthening of the AMOC in CMIP6 historical simulations. *Journal of Climate, 35*(20), 6843-6863.

Rossby, T., Chafik, L., & Houpert, L. (2020). What can hydrography tell us about the strength of the Nordic Seas MOC over the last 70 to 100 years?. *Geophysical Research Letters*, *47*(12), e2020GL087456.

Rousi, E., Selten, F., Rahmstorf, S., & Coumou, D. (2021). Changes in North Atlantic atmospheric circulation in a warmer climate favor winter flooding and summer drought over Europe. *Journal of Climate, 34*(6), 2277-2295.

Send, U., Lankhorst, M., & Kanzow, T. (2011). Observation of decadal change in the Atlantic meridional overturning circulation using 10 years of continuous transport data. *Geophysical Research Letters, 38*(24).

Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y., & Bennabi, A. (2017). Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications*. https://doi.org/10.1038/ncomms14375

Sharples, J., Mayor, D. J., Poulton, A. J., Rees, A. P., & Robinson, C. (2019). Shelf Sea Biogeochemistry: Nutrient and carbon cycling in a temperate shelf sea water column. *Progress in Oceanography, 177*, 102182.

Sheehan, P. M. F., Berx, B., Gallego, A., Hall, R. A., Heywood, K. J., & Hughes, S. L. (2017). Thermohaline forcing and interannual variability of northwestern inflows into the northern North Sea. *Continental Shelf Research, 138*, 120–131. https://doi.org/10.1016/J.CSR.2017.01.016

Sheehan, P. M. F., Berx, B., Gallego, A., Hall, R. A., Heywood, K. J., & Queste, B. Y. (2020). Weekly variability of hydrography and transport of northwestern inflows into the northern North Sea. *Journal of Marine Systems, 204*, 103288. https://doi.org/10.1016/J.JMARSYS.2019.103288

Shan, X., Sun, S., Wu, L., et al. (2024). Role of the Labrador Current in the Atlantic Meridional Overturning Circulation response to greenhouse warming. *Nature Communications, 15*, 7361. https://doi.org/10.1038/s41467-024-51449-9

Shepherd, S. T. A., McMillan, M., Leeson, A., Gilbert, L., Muir, A., et al. (2021). Increased variability in Greenland Ice Sheet runoff from satellite observations. *Nature Communications, 12*(1), 6069. https://doi.org/10.1038/s41467-021-26229-4

Schiller-Weiss, I., Martin, T., & Schwarzkopf, F. U. (2024). Emerging Influence of

Enhanced Greenland Melting on Boundary Currents and Deep Convection Regimes in the Labrador and Irminger Seas. Geophysical Research Letters, 51(9). https://doi.org/10.1029/2024GL109022

Smith, D. M., et al. (2019). Robust skill of decadal climate predictions. *npj Climate and Atmospheric Science, 2*, 13. https://doi.org/10.1038/s41612-019-0071-y

Solomon, A., Heuzé, C., Rabe, B., et al. (2021). Freshwater in the Arctic Ocean 2010–2019. *Ocean Science, 17*(4), 1081–1102. https://doi.org/10.5194/os-2020-113

Spielhagen, R. F., et al. (2011). Enhanced modern heat transfer to the Arctic by warm Atlantic Water. *Science, 331*, 450–453. https://doi.org/10.1126/SCIENCE.1197397

Spooner, P., D. Thornalley, S. Cunningham, J. M. Roberts, and D. Sorm, 2020: *Changing ocean state and its impact on natural capital*.

Stouffer, R. J., Manabe, S., & Bryan, K. (1989). Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO2. *Nature, 342*, 660–662. https://doi.org/10.1038/342660a0

Stouffer, R. J., et al. (2006). Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *Journal of Climate, 19*, 1365–1387. https://doi.org/10.1175/JCLI3689.1

Swingedouw, D., Houssais, M. N., Herbaut, C., Blaizot, A. C., Devilliers, M., & Deshayes, J. (2022). AMOC recent and future trends: A crucial role for oceanic resolution and Greenland melting? *Frontiers in Climate, 4*, 32. https://doi.org/10.3389/FCLIM.2022.838310

Terhaar, J., Vogt, L., & Foukal, N. P. (2025). Atlantic overturning inferred from air-sea heat fluxes indicates no decline since the 1960s. *Nature Communications, 16*(1), 222.

Tesi, T., et al. (2021). Rapid Atlantification along the Fram Strait at the beginning of the 20th century. *Science Advances, 7*, 2946.

Thornalley, D. J. R., et al. (2018). Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*. https://doi.org/10.1038/s41586-018-0007-4

Tinker, J., Lowe, J., Pardaens, A., Holt, J., Barciela, R. (2016) Uncertainty in climate projections for the 21st century northwest European shelf seas, *Progress in Oceanography, 148,* 56-73, https://doi.org/10.1016/j.pocean.2016.09.003.

Tinker, J. P., Howes, E. L., Wakelin, S., Menary, M., Kent, E., & Berry, D. (2020). The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review, 2020*, 1-30.

Tinker, J., Polton, J. A., Robins, P. E., Lewis, M. J., & O'Neill, C. K. (2022). The influence of tides on the Northwest European Shelf winter residual circulation. *Frontiers in Marine Science, 9*. https://doi.org/10.3389/fmars.2022.847138

Tinker, J., Palmer, M. D., Harrison, B. J., O'Dea, E., Sexton, D. M. H., Yamazaki, K., & Rostron, J. W. (2024). Twenty-first century marine climate projections for the NW European shelf seas based on a perturbed parameter ensemble.

Ocean Science, 20, 835-885. https://doi.org/10.5194/os-20-835-2024

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. *Fish and Fisheries*. https://doi.org/10.1111/faf.12773

Valdes, P. (2011). Built for stability. *Nature Geoscience*. https://doi.org/10.1038/ngeo1200

van den Berk, J., & Drijfhout, S. S. (2014). A realistic freshwater forcing protocol for ocean-coupled climate models. *Ocean Modelling, 81*, 36–48. https://doi.org/10.1016/J.OCEMOD.2014.07.003

Volkov, D. L., Smith, R. H., & Garcia, R. F. (2024). Florida Current transport observations reveal four decades of steady state. *Nature Communications, 15*, 7780. https://doi.org/10.1038/s41467-024-51879-5

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 models predict significant 21st century decline of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters, 47*, e2019GL086075. https://doi.org/10.1029/2019GL086075

Willeit, M., & Ganopolski, A. (2024). Generalized stability landscape of the Atlantic meridional overturning circulation. *Earth System Dynamics*, *15*(6), 1417-1434.

van Westen, R. M., & Dijkstra, H. A. (2023). Asymmetry of AMOC hysteresis in a state-of-the-art global climate model. *Geophysical Research Letters, 50*, e2023GL106088. https://doi.org/10.1029/2023GL106088

van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on a tipping course. *Science Advances, 10*(6). https://doi.org/10.1126/sciadv.adk1189

Van Westen, R. M., & Baatsen, M. L. J. (2025). European Temperature Extremes Under Different AMOC Scenarios in the Community Earth System Model. Geophysical Research Letters, 52(12), e2025GL114611. https://doi.org/10.1029/2025GL114611

Wett, S., Rhein, M., Kieke, D., Mertens, C., & Moritz, M. (2023). Meridional connectivity of a 25-year observational AMOC record at 47°N. *Geophysical Research Letters, 50*, e2023GL103284. https://doi.org/10.1029/2023GL103284

Wouters, B., W. Hazeleger, S. Drijfhout, G. J. van Oldenborgh, and V. Guemas (2013), Multiyear predictability of the North Atlantic subpolar gyre, *Geophys. Res. Lett.*, 40, 3080-3084 doi:10.1002/grl.50585.

Yamamoto, A., & Palter, J. B. (2016). The absence of an Atlantic imprint on the multidecadal variability of wintertime European temperature. *Nature Communications, 7*, 1–8. https://doi.org/10.1038/ncomms10930

Ye A, Zhu Z, Zhang R, Xiao Z, Zhou L (2023) Influence of solar forcing on multidecadal variability in the Atlantic meridional overturning circulation (AMOC). Front Earth Sci 11. https://doi.org/10.3389/feart.2023.1165386

Yeager, S. (2020). The abyssal origins of North Atlantic decadal predictability. *Climate Dynamics, 55*, 2253–2271. https://doi.org/10.1007/s00382-020-05382-4

Yeager, S. G., Castruccio, F., Chang, P., Danabasoglu, G., Maroon, E., Small, J., et al. (2021). An outsized role for the Labrador Sea in the multidecadal variability of the Atlantic overturning circulation. *Science Advances, 7*, 1–25. https://doi.org/10.1126/sciadv.abh3592

Yeager, S. G., & Robson, J. I. (2017). Recent progress in understanding and predicting Atlantic decadal climate variability. *Current Climate Change Reports, 3*(2), 112–127.

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y. O., Marsh, R., Yeager, S. G., Amrhein, D. E., & Little, C. M. (2019). A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic multidecadal variability and associated climate impacts. *Reviews of Geophysics, 57*, 316–375. https://doi.org/10.1029/2019RG000644

Zhang, X., Waugh, D. W., Mitevski, I., Orbe, C., & Polvani, L. M. (2024). Decreased northern hemisphere precipitation from consecutive CO2 doublings is associated with significant AMOC weakening. *Environmental Research: Climate, 3*, 041005. https://doi.org/10.1088/2752-5295/ad929c

Zimmerman, C. C., Wagner, T. J., Maroon, E. A., & McNamara, D. E. (2025). Slowed response of Atlantic meridional overturning circulation not a robust signal of collapse. *Geophysical Research Letters*, *52*(2), e2024GL112415.

Zou, S., Lozier, M. S., Li, F., Abernathey, R., & Jackson, L. (2020). Density-compensated overturning in the Labrador Sea. *Nature Geoscience, 13*(2), 121–126. https://doi.org/10.1038/s41561-019-0517-1