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

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KEY FACTS

What is happening

- Observations of the Atlantic Meridional Overturning Circulation or Gulf Stream System since the 1980s have shown a strengthening in the 1990s and a weakening in the 2000s, with no clear overall trend.

- Shifts in North-east Atlantic circulation, leading to a greater influence of warmer subtropical-origin waters which can impact marine ecosystems and economically important fish species such as mackerel. The changing subpolar ocean circulation is also having impacts on the food supply for deep-sea ecosystems.

- The subpolar gyre recorded its freshest values on record in the 2010s. Ongoing freshwater build-up in the rapidly changing Arctic Ocean may exacerbate this freshening.

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What could happen

- Projections from climate models consistently project a weakening of the Atlantic Meridional Overturning Circulation due to anthropogenic climate change.

- Warming of Atlantic waters is expected to reduce the depth of mixed layers and limit nutrient supply to surface layers.

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 ecosystem-relevant quantities. 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 north-west 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 north-west European shelf are large 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.

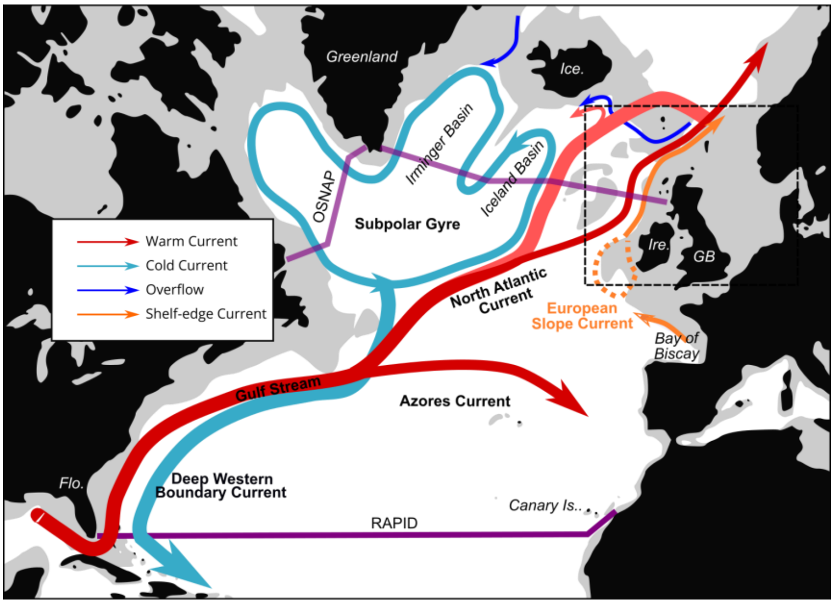


Figure 1. Large-scale circulation in the North Atlantic. A system of warm, northward-flowing currents and cold southward-flowing currents is known as the Atlantic Meridional Overturning

Circulation or Gulf Stream System. The RAPID and OSNAP arrays of moored instruments for observing the AMOC are shown in purple. The dashed box is the area highlighted in Figure 3.

The large-scale North Atlantic circulation consists mainly of the wind-driven gyres and the AMOC which is partly wind-driven and partly driven by differences in density of water masses (mainly dependent on salinity and temperature, Figure 1). Changes in the wind-driven circulation can impact the thermohaline circulation and vice versa. 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 stream function—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. On the eastern boundary of the gyre, at the continental shelf, the European Slope Current flows, with its origins traceable to the Iberian Peninsula and extending all the way around the European shelf towards Scandinavia. On the continental shelf, several coastal currents flow (see Figure 3 for details) that are driven by wind, tides, and thermohaline factors.

The most consistent prediction of ocean circulation change in response to anthropogenic climate change has been AMOC decline. While projections based on climate models are consistent, there are disagreements with observations and between model runs in the historical period. Better understanding of the AMOC has led to a more nuanced consideration of AMOC and not simply as a catch-all for broad-scale ocean circulation change. Understanding different elements of ocean circulation such as the subpolar gyre and shelf circulation are important in understanding how ocean circulation change will impact the 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, health and biodiversity, and sea level.

WHAT IS ALREADY HAPPENING?

Is the AMOC in a weakened state?

A long-term perspective on AMOC change is provided by paleoclimate datasets, specifically indirect past ocean property reconstructions (proxies) which are derived mostly from marine sediments and 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 icesheets.

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, and instead sub-components 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 generally 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 appears to have been relatively stable (Lippold *et al*., 2019). Despite the release of large amounts of meltwater during the early Holocene, 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).

Drawing upon reconstructions in upper ocean properties and the deep western boundary current, several studies suggest that the industrial-era 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 at its weakest for the last millennium (Kilbourne *et al*., 2022; Caesar *et al*., 2022).

In the modern instrumental era (since ~1980), AMOC strength and variability have been measured directly using moored observations, combinations of in-situ hydrographic data with satellite measurements of sea level, or through surface-flux-based proxies. In recent decades (since ~2000), 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 Figure 1 for locations of RAPID and OSNAP). Ocean re-analyses, where ocean models are constrained by ocean and satellite observations, have also been used to assess North Atlantic circulation (Jackson *et al*., 2019).

The expansion of observing arrays for AMOC transport since 2001 has also highlighted significant areas where the community understanding of the AMOC is still developing. 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 Earth Observation 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 compared with the subpolar North Atlantic, with one consequence being that the observed AMOC variability in the subtropics differs from the AMOC variability in the subpolar region.

In summary, there is an increasing amount of data to suggest that certain elements of North Atlantic circulation are in an exceptional state, yet the precise attribution and mechanisms for these long-term trends and the modern AMOC state remain very uncertain. The timing of some of the changes—beginning as early as 1850 CE and then further weakening from the 1950s onwards—may indicate a role for both natural and anthropogenic forcing, and further work is required to attribute these reported changes. In the modern era of AMOC observation 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 (compared to paleo-timescale methods), it is not possible to conclude that the AMOC since 1980 has reduced. However, recent compilations (Jackson *et al*., 2022; Caesar *et al*., 2022) of AMOC records have shown a strengthening of the AMOC in the 1990s, a weakening until the early 2010s, followed by a slight recovery since.

Exceptional change in the subpolar gyre

In the subpolar North Atlantic, polar easterlies in the north and turbulent westerlies with well-established storm tracks in the south drive the anti-clockwise (cyclonic) subpolar gyre. In the south and east the subpolar gyre is flanked by the North Atlantic Current (NAC). The NAC is partly fed by cool and freshwater masses from the western subpolar gyre and partly fed by warm and salty water masses supplied from the subtropical gyre further south as part of the upper limb of the AMOC. The subpolar front marks the boundary between the subpolar cool and fresh and the subtropical warm and saline water masses.

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). 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). In addition, there is also evidence to suggest that the industrial-era surface subpolar gyre is in an exceptional state (e.g., Osman *et al*., 2019, 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).

In the modern instrumental era (since ~1980), 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, 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.

In the 2010s, an intensified, northward-shifted storm track and jet stream (which imply an increased wind forcing over the north-eastern subpolar gyre) 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 values recorded in 120 years (Holliday *et al*., 2020).

Since 2016, 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 AMOC heat transport at 45°N (Desbruyères *et al*., 2019) was observed. This is consistent with a negative feedback mechanism described by (Koul *et al*., 2020). Under persistent positive NAO forcing over several years, positive density anomalies in the western subpolar gyre would be transported southwards and act to strengthen the AMOC. 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.

Influences of the Arctic Ocean circulation 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. Freshwater variations are closely linked to changes in ocean circulation, both as a driver and as a response. On decadal timescales, freshwater variations 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, and a more anti-cyclonic Arctic gyre resulting in an enhanced freshwater accumulation in the Arctic (Proshutinsky and Johnson, 1997; Proshutinsky *et al*., 2015). 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). Consistent with the decadal releases of Arctic freshwater releases, 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*., 2016a; 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). In addition, the atmospheric feedback affects 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*. 2016a; Mecking *et al*. 2019).

On longer timescales, enhanced freshening can influence the AMOC. 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 slowdown of the AMOC. Hydrographic observations from key convective regions (regions of cold, dense water formation) in the subpolar North Atlantic indicate that an increased seasonal freshening shortens the timespan during winter in which freshwater is exported downwards to depth and in which ocean convection occurs (Oltmanns *et al*., 2018).

Currently, the Arctic is warming about twice as fast as the rest of the planet (Serreze *et al*., 2009), losing sea ice and glacial ice (Bamber *et al*., 2018; Carmack, 2000). While there are still many open questions regarding the influences of the Arctic ice loss on the North Atlantic, concurrent with the ice loss, the subpolar region exhibited a significant freshening trend over the last 70 years, superimposed on the decadal cycle associated with Arctic freshwater releases (Figure 2). 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).

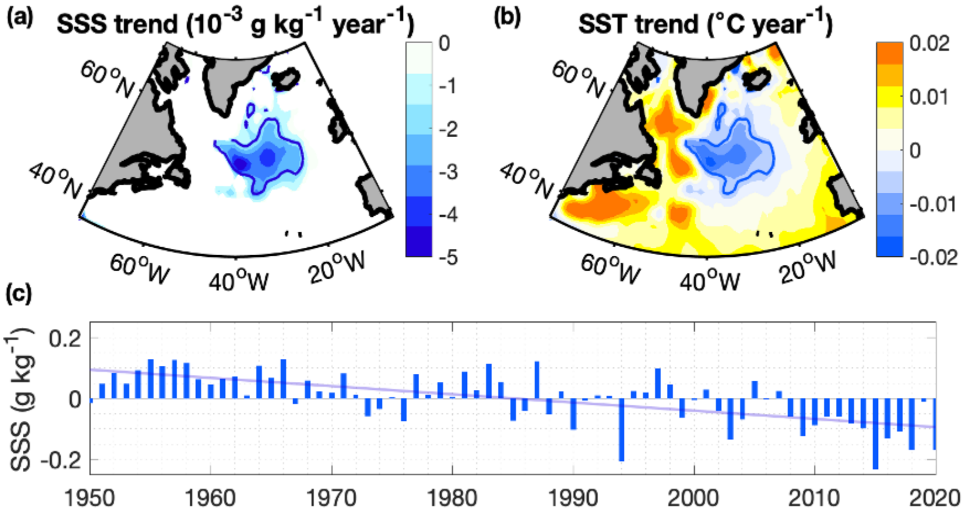


Figure 2. Trend in (a) the sea surface salinity (SSS, in grams of salt per kilogram of freshwater) and (b) the sea surface temperature (SST) over the last 70 years. SSS has been inferred from a mass balance analysis (Oltmanns et al., 2020); SST has been obtained from the UK's Met Office Hadley Centre. Thick contours delineate 95% confidence regions. (c) Variability of the SSS, averaged over the 95% confidence region from (a).

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, and by the land and seabed boundaries. On sub-daily timescales, tidal flows dominate across the north-west European Shelf Seas (hereafter NWESS). Near the coast, circulation patterns may be influenced by riverine sources of freshwater plumes, as well as land-steered surface wind stress. On longer timescales, residual circulation patterns are strongly influenced by density-driven flows and steering by seabed topography and the coastline (Figure 3). The transports of inflows (volume, heat, and salt) from the open ocean, and therefore the relative influence of Atlantic water masses, can then determine changes in the temperature, salinity, and circulation patterns on the shelf.

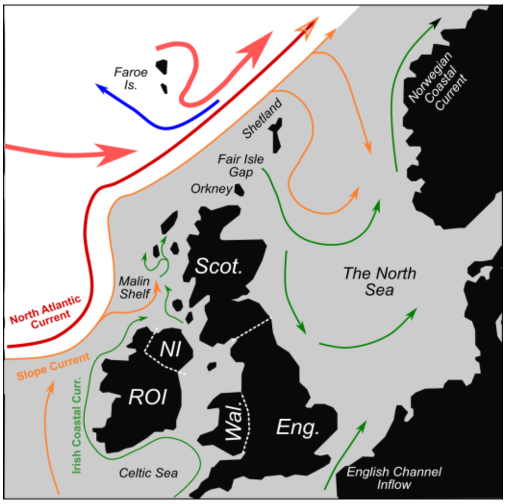


Figure 3. Circulation around the north-west European Shelf. Showing warm (red), cold (blue), shelf-edge (orange), and shelf (green) currents. ROI = Republic of Ireland, NI = Northern Ireland, Wal. = Wales, Eng. = England, Scot. = Scotland.

Though tides dominate instantaneous flows in most locations, mean circulation patterns overall are dominated by the wind (directly or via sea surface height set-up along coasts) and the spatial distribution of density (temperature and/or salinity), which in turn may be strongly influenced by prevailing wind patterns and by synoptic weather systems (Jones *et al*., 2018).

The Atlantic Ocean, and in particular the European Slope Current (Figure 1), sets the density at the seaward edge of the NWESS. Though the shelf edge presents a barrier to large-scale flows which dominate ocean circulation, there exists a host of processes that provide a vigorous but spatially variable exchange of water between 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 NWESS edge, tides (and other motions with periods around one day) dominate the exchange, but their influence is spatially limited to ~10 km from the shelf break. Exchanges by motions of periods more than two days, though variable, are large (Huthnance *et al*. 2022), summing to ~10 Sv (1 Sv = 10^6 m^3 s^{-1}) of exchange across the 5000 km shelf edge between Biscay and north of Shetland.

Exchange at the shelf edge and circulation within the NWESS are thus interrelated. Combined, they determine the residence time of water in the UK shelf seas, which can vary from tens of days in narrower more-exposed shelf areas (e.g. Malin Shelf, Figure 3) to ~400 days for areas in the North Sea. Since exchange with the ocean (~10 Sv) far exceeds total freshwater input from rivers (~0.03 Sv), the majority of shelf sea water remains above 95% of oceanic salinity.

Water flowing onto the shelf from the ocean must ultimately return. Shelf processes transform water properties during their shelf residence. Summer heating plus freshwater inputs, and winter cooling, combine to transform the waters that enter the shelf seas from the ocean. Transformation occurs into both denser water (which returns to the ocean all along the shelf break) and lighter water (which returns to the open ocean predominantly in the Norwegian Coastal Current. In this sense, the NWESS may be viewed as a large double-estuary system, with export from the shelf from two different routes: surface circulation through the Norwegian Current and 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 very 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 transport associated with salinity-driven flow is increased in winter (when Atlantic inflow is principally wind-driven), while temperature-driven flows dominate in summer. On longer timescales, the decadal variability of salinity in the North Sea has been linked to fluctuations in the subpolar gyre (Koul *et al*., 2019; Patsch *et al*., 2020), while the volume inflow is dominated by wind-driven inflow associated with the NAO (Hjollo *et al*., 2009). Slope-current transport variability and source-water provenance are also linked to changes in the subpolar gyre, which drive variability in mid-latitude geostrophic transports that feed the NW European slope current (Clark *et al*., 2022). After 1997 an increase in the significance of warmer (more salty) flow coincides with a reduction in northward transport within the slope current, having major implications for the downstream shelf regions, such as the Northern North Sea. 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.

WHAT COULD HAPPEN IN THE FUTURE?

The future of the AMOC

The IPCC 6th Assessment Report (AR6) report concludes that it is *very likely* that AMOC will decline over the 21st Century as a result of anthropogenic climate change (Figure 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). However, the magnitude of this decline is largely independent of specific future emissions choices until at least 2060. The magnitude of projected AMOC decline in simulations conducted for AR6 is larger than the simulations conducted for AR5 (Collins *et al*., 2013).

Despite this consistent behaviour overall, 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. On average, models with a stronger AMOC over the last century also undergo a larger AMOC decline. By constraining using present-day observations from the RAPID array, this future decline is predicted to be 7±1 Sv by the year 2100 relative to a mean strength of 17–18 Sv (Weijer *et al*., 2020).

Climate model simulations for AR6 suggest an increase in the strength of the AMOC over the previous century (Figure 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 contrasts with that suggested by proxies of past AMOC change as discussed previously. However, the simulated increase in AMOC is sensitive to the anthropogenic aerosol changes (Menary *et al*., 2020) which are still a major source of uncertainty, 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.

One reason for this large spread in simulated AMOC changes is broadly related to questions in how climate models represent the details of AMOC. For example, there is conflicting evidence as to whether the AMOC declines faster in higher-resolution models. However, most of the models used for AR6 had low-resolution ocean components with nominal ocean resolutions of 1 degree. Projected future AMOC decline is likely also sensitive to the simulated locations of deep convection and deep-water formation as well as the subsequent magnitude of the downstream link to the AMOC (Jackson *et al*., 2020). 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. A systematic comparison of these new observations and the climate models used in AR6 has yet to be undertaken. As such, 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.

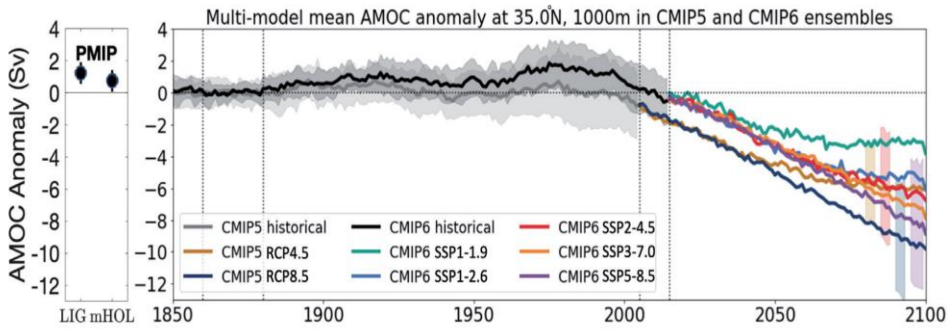


Figure 4. Multimodel mean AMOC anomaly (relative to the period 1860-1880) in CMIP5 and CMIP6 historical ensembles as well as future projections. Taken from IPCC AR6 Ch. 9, fig. 9.10.

Will the AMOC collapse?

Previous studies considering simplified models of the AMOC and studies of paleoclimate have suggested that the AMOC could have two stable states: one with a strong AMOC as in the present day, 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 many coupled climate models have not shown multiple stable states of the AMOC (Stouffer *et al*., 2006), a few studies have shown off or weak states that persist for at least centuries (Liu *et al*., 2017; Jackson and Wood, 2018). The IPCC assesses (with ‘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).

These studies are based on a shift to a weak or off state caused by an input of freshwater into the North Atlantic. However, many studies use freshwater inputs which are much larger than those expected in the future, for example from Greenland ice melt. 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), though Swingedouw *et al*. (2022) have shown that ocean models with very high resolution 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) and Devilliers *et al*. (2021).

Assessments of future AMOC collapse consider the impacts of both increased greenhouse gases and additional freshwater inputs from Greenland melt (which are not usually included in climate model projections). The IPCC AR6 report indicated 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). Bakker *et al*. (2016) found that Greenland melt caused an additional 5–10% weakening by 2100 on top of weakening from projected increases in greenhouse gases and increased the risk of collapse by 2300.

Several studies have tested whether the AMOC is reversible when greenhouse gases are removed, or whether it stays in a weak state. The response is model dependent with some models showing a fast recovery and overshoot, and others a delayed recovery (Jackson *et al*., 2014; Sgubin *et al*., 2017). The AMOC is found to be reversible within centuries (Lee *et al*, in press), however, the path to recovery could have significantly different impacts (Sgubin *et al*., 2017).

Future changes in shelf seas circulation

Future changes will manifest through changes to oceanic source-water properties (temperature, salinity and nutrient load), local surface heating and prevailing wind and storminess patterns. Precipitation changes will likely have only minor localised effects on circulation patterns. Changed wind patterns and storminess may affect up-/down-welling at the shelf edge and higher-frequency wind-forced exchange. Large, episodic exchange and transport events (likely associated with wind-driven processes 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 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 parent models as well as the downscaling methods (e.g., Mathis *et al*., 2018). Seemingly robust signals can be a function of the downscaling, for example, downscaled SST in forced simulations are tightly constrained by the parent model (Mathis *et al*., 2018). Nevertheless, robust signals are reported in SST warming trends (Tinker *et al*., 2020). Though the picture with stratification, being seasonal, is less clear. On one hand, seasonal stratification on the shelf is not projected to strengthen, but its duration is projected to extend (Sharples *et al*., 2020) and on the other hand a close look at subtle changes in the expansivity of seawater are identified as having an amplified effect making enhanced NWESS stratification a robust climate change signal (Holt *et al*., 2022).

For large-scale changes in circulation on the continental shelf, 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). Using downscaled climate projections for the north-west shelf, Holt *et al*. (2018) show that increased freshwater export from the Arctic could lead to a change in oceanic density gradient alongside the NW European shelf, 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 by Mathis *et al*. (2019). However, it is worth noting that while Tinker *et al*. (2016) also suggest a projected reduction in the slope current and changes to circulation within the North Sea, they also demonstrate that there is a large ensemble spread within these projections. The resolution of 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. Traditionally, large-scale ocean circulation is simulated without explicitly representing the tides. In the open ocean, much progress has been made in the field, under these limitations. In the continental shelf seas, the tides are more fundamentally entwined with the regional circulation. Targeting the NW European Shelf, Tinker *et al*. (2022) highlighted the differences in circulation pathways when tidal processes are omitted, at 7 km resolution, and identified tides to be an essential driver for heat and mass circulation. Omitting tides results in non-uniform behaviour with some areas showing increased through-flow and others showing it to be reduced. The consequent biases in the temperature and salinity were of the order of 0.5ºC and 0.5 psu (psu=practical salinity units, approximately 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 is a minimum threshold that is required to capture some of the impacts on circulation. For example, tides in stratified fluid over uneven bathymetry generate internal tides which in turn result in elevated levels of mixing in the pycnocline (Inall *et al*., 2021), with consequences for the strength of the stratification and the fluxes of biological material across it. However, these processes and impacts require an internal tide resolving simulation (the wavelength of an interfacial M2 internal tide for the NWESS is estimated to be over 5 km (Guihou *et al*., 2018), therefore requires at least a kilometric scale resolution simulation for propagation simulation). Kilometric scale simulation resolution is also required to capture the dominant bathymetric and tidal excursion length scales (Polton, 2015), since tidal processes modulate the advection of tracers (and larvae) on these scales.

This resolution requirement is a challenge for wide area regional forecast models, which has only been addressed in the last five years with recent advances (Graham *et al*. 2018b) bringing UK operational forecasting into this regime with 1.5 km resolution. However regional climate models of the NW European Shelf are currently still at 7 km resolution (e.g. Holt *et al*., 2018), and global climate models are coarser still. Consequently, residual circulation in tidally activated global simulations can be expected to under-represent the true tidal contribution to the circulation. Furthermore, the kilometric-scale resolution is likely to be a necessary, rather than sufficient, condition for representing processes that control the circulation. For example, processes that lead to episodic mixing events will likely remain unattainable for wide-area models, yet their contribution must be assessed. In addition to the challenges arising from tides, shelf-sea models also need to accommodate water that is very shallow at the coast, very deep in the open ocean and rapidly transitioning between the two at the shelf break. Terrain following coordinates are typically adopted (e.g, Song and Haidvogel, 1994) to retain vertical resolution across the simulated depth ranges. However, these model grids generate spurious currents in regions of steep bathymetry (e.g. along the shelf break) which can have anomalous northwards transports. Refined versions of terrain following coordinates exist (Bruciaferri *et al*., 2018) and are reviewed in Wise *et al*. (2021) for application in the NWESS.

For better knowledge of NWESS circulation, a coordinated program of observations would provide an effective way forward. Agencies in England, the Republic of Ireland, Wales, Northern Ireland and Scotland could agree to each occupy one or two hydrographic sections at least annually and invest in autonomous systems (Gliders or ASVs) and ‘smart’ moorings, perhaps combining 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.

Ocean circulation as the key to unlocking decadal forecasts

Decadal predictions attempt to provide more useful information on timescales 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). Unlocking the skill in these forecasts offers the potential for improved forecasts of climate on timescales relevant for decision making. While the added value of these forecasts is not obvious in all regions, the North Atlantic, due largely to the climatic importance of its ocean circulation, is an exception to this. Studies on the predictability of the North Atlantic system and especially of the AMOC have been undertaken for more than 25 years as it is considered as a predictable component on decadal scales of the North Atlantic system (Griffies and Bryan, 1997).

The availability of observations like the RAPID-MOCHA at 26.5°N (Moat *et al*., 2022) as a reference made it possible to validate predictions of monthly mean values of AMOC for up to four years in advance (Matei *et al*., 2012a). The results were criticised by Vecchi *et al*. (2012) as they did not exceed the ‘prediction skill’ stemming from a climatological annual cycle in their analysis. Longer observational time-series data allowed an extension for up to five years significant prediction skill (Müller *et al*., 2017). Nevertheless, it has been demonstrated that initial conditions are essential for the quality of the prediction (Dunstone and Smith, 2010). Without relying on direct observations but verifying against assimilated model runs, Pohlmann *et al*. (2013) showed in a multi-model system that predictions for the AMOC variability at 45° N are possible for up to five years, and they find significant skill for means of 3–6 years. Similar results were shown by Yeager and Robson (2017), who argued that the predictability of AMOC in density space cannot be translated to the depth space formulation of AMOC. Menary *et al*. (2016) and Menary and Hermanson (2018) indicated that prediction skill depends on the physical consistency between the prediction system and reference. Menary and Hermanson (2018) demonstrated large differences within the models in terms of drifts, variability, and model-specific biases when predicting the

AMOC. Although there is uncertainty in the current predictability of the AMOC, the initialisation of the AMOC is crucial to deliver skill in AMOC-related variables such as ocean heat content and SST (Pohlmann *et al*., 2004, 2006; Yeager and Robson 2017). SST in the North Atlantic is predictable on 6 to 10 year timescales, when the models are initialised with subsurface observations constraining the AMOC at initialisation (Matei *et al*., 2012b). AMOC initialisation and the interaction of AMOC with natural forcings are also an important factor for the prediction of the subpolar gyre (Robson *et al*., 2012; Borchert *et al*., 2020). From the prediction of ocean heat content, we also know that prediction skill likely depends on the state of the ocean at the point of initialisation (Borchert *et al*., 2018).

Impacts of ocean circulation change

The potential impacts of AMOC decline have widespread implications for global climate, with a weakened AMOC causing: widespread cooling in the North Atlantic; large changes in precipitation patterns including a shift in the Intertropical Convergence Zone; changes in mid-latitude circulation patterns; and delaying the timing of an ice free Arctic (Jackson *et al*., 2015; Bellomo *et al*., 2021; Liu *et al*., 2020). It is worth noting that 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, although a collapse of the AMOC remains unlikely, it may have the potential to induce a cascade of abrupt events (Collins *et al*., 2019). In the present report we focus on the impacts of AMOC decline relevant to the UK and north-western Europe.

Although a collapse of the AMOC before 2100 has been judged unlikely, the impacts of a collapse would be substantial, including for the UK and Europe (Jackson *et al*., 2015). For example, the loss of UK arable farming and agricultural output in response to changes in temperature and precipitation patterns associated with a collapsed AMOC could be an order of magnitude greater under climate change with an AMOC collapse than without (Ritchie *et al*., 2020).

Multiple studies (e.g. Jackson *et al*., 2015) show changes in Atlantic SSTs lead to widespread decreases in surface air temperatures across the Northern Hemisphere including cooling by several degrees in the UK. For a gradual weakening of AMOC under anthropogenic climate change, this decrease in surface air temperatures would likely delay the full extent of global warming (Liu *et al*., 2020).

Changes to atmospheric circulation which can influence the UK climate in winter and summer also result from AMOC change. Liu *et al*. (2020) and

Bellomo *et al*. (2021) find a weakened AMOC displaces the mid-latitude jet poleward in winter, resulting in a stronger and eastward extension of the storm track over the UK and northern Europe (Jackson *et al*., 2015). 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). Meanwhile, an eastward extension of the storm track could increase snowfall rates, snow depths and snow cover duration in winter (Jackson *et al*., 2015).

In summer there is a general decrease in precipitation in northern Europe in response to a weakened AMOC due to reduced evaporation which reinforces the climate signal. However, local increases in summer precipitation are expected in parts of southern Europe (Jackson *et al*., 2015; Liu *et al*., 2020). There is also an increased probability of heatwaves over Europe in summer in response to cold Atlantic SST anomalies (Duchez *et al*., 2016b; Rousi *et al*., 2021). Heatwaves and drier conditions in the UK could increase drought impacts.

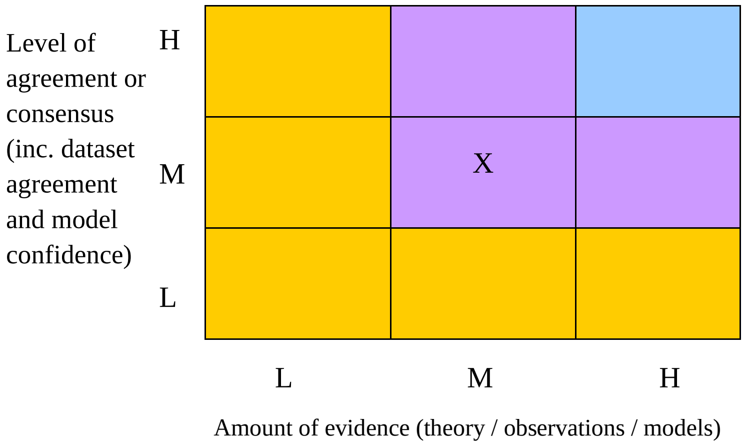
Ocean circulation change also has impacts in the marine realm, where it can influence biogeographic shifts through different mechanisms. First, direct impacts may occur when circulation affects the trajectory or dispersal of marine species (predominantly eggs or larvae). For example, when considering larval dispersal during early life stages, circulation patterns will determine the connectivity (the connection of distant local populations by currents) or recruitment of marine species. Understanding the influence of circulation on larval dispersal is 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).

Second, biogeographic shifts may 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 North-east 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, shifts in the circulation of the North-east Atlantic that cause a westward retreat of subpolar water and a greater influence of warmer subtropical-origin waters, impact 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 North-east Atlantic (Payne *et al*., 2017). On the shelf, the relative changes in temperature, salinity and nutrient 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 (Reid *et al*., 2001a; 2001b; Beaugrand, 2004). Understanding each of these relative processes, as well as the behaviour and adaptability of marine species, will be necessary to predict any future biogeographical shifts.

The economic impacts of ocean circulation change, potentially including an AMOC slow-down, on human systems, including fisheries and agriculture, are not well understood and existing studies are limited (Kopits *et al*., 2014; Bouwer *et al*., 2022).

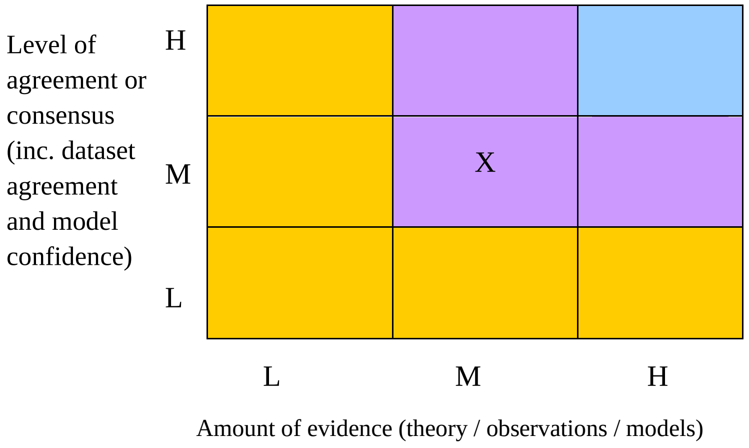
CONFIDENCE ASSESSMENT

What is already happening?



Overall confidence is medium (evidence and agreement). There is an increasing amount of data to suggest that certain elements of North Atlantic circulation are in an exceptional state, yet the precise attribution and mechanisms for these long-term trends and the modern AMOC state remain very uncertain. For better knowledge of North-West European Shelf Seas circulation, a co-ordinated program of observations is needed. The largest unknowns are perhaps related more to the biogeochemistry and productivity and annual cycle measurements of carbon, nitrogen and phosphorus cycles are needed.

What could happen in the future?



Overall confidence is medium (evidence and agreement). This takes consideration of a range of factors, including general agreement that the AMOC in the 21st century will be weaker than during the 20th century (medium evidence and agreement), that predictions of an AMOC slowdown by 2100 are robust (high agreement and evidence), ocean circulation is unlikely to pass a tipping point before 2100 (medium agreement and evidence).

For shelf circulation, changes will manifest through oceanic source-water property changes, which require more sustained coordinated observations. Predictions of changes in shelf circulation are also subject to uncertainty due to deficiencies in current models.

KEY CHALLENGES AND EMERGING ISSUES

Changes in the AMOC

- Reconciling AMOC reconstructions and climate simulations is a key challenge to underpin confidence in future projections
- Focus of understanding circulation change should not focus solely on AMOC with elements such as the subpolar gyre and its driving processes being key to emerging understanding
- Accumulation of Arctic freshwater is a concern 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
- 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
- Weather and biogeographical impacts of ocean circulation change have been studied but the economic impacts of these changes are not well-understood

Changes in shelf sea circulation

- 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
- Projections of shelf sea circulation and exchange in future climates needs to be improved through model improvement
- Observations on the shelf need to be sustained and coordinated to validate model simulations and fill fundamental gaps in understanding

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