Effects of climate change on the Atlantic Heat Conveyor relevant to the UK

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EXECUTIVE SUMMARY

- The Atlantic Heat Conveyor or Atlantic Meridional Overturning Circulation (AMOC) is a major factor in maintenance of the climate and marine environment of the UK.
- The AMOC is predicted to weaken in the coming century due to climate change.
- The AMOC is currently in a weakened state and the subpolar North Atlantic appears to be entering a cool (and fresh) state. However, record cold temperatures in 2015 were found to be driven largely by air–sea heat loss rather than reduced AMOC.
- Large biogeographical and climatic shifts are expected in response to this shift to cooler conditions.
- There is little support for the idea that the AMOC will abruptly shut down despite new ideas suggesting more plausible mechanisms related to a shutdown.
- Skill in predicting climate on decadal timescales can be derived from correct initialisation of AMOC in prediction systems hence increasing the capacity to manage, mitigate, and adapt to AMOC related climate changes.

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1. INTRODUCTION

The Atlantic Heat Conveyor or Atlantic Meridional Overturning Circulation (AMOC) describes a system of ocean currents associated with the exchange of warm and cold water. Here, we focus on the North Atlantic sector that has the largest influence on the UK and North-Western Europe. We consider two regions: the subtropical North Atlantic and the subpolar North Atlantic (Figure 1). The nature of the AMOC in these two regions is fundamentally different. In the subtropical North Atlantic, the overturning is a classic overturning in depth, a 'conveyor belt' where warm water is moved northwards in the upper ocean by, predominantly, the Gulf Stream and cold water is returned southwards at depth mainly by the Deep Western Boundary Current, consisting of the upper and lower branches of North Atlantic Deep Water (NADW). The Gulf Stream leaves the coast of North America at Cape Hatteras (37ºN) and flows eastwards, first as the Gulf Stream Extension and then as the North Atlantic Current (east of the Grand Banks). The path of the Gulf Stream Extension and North Atlantic Current approximately marks the boundary between the subtropical and subpolar gyres. The inflow of warm water into the subpolar gyre occurs from a proportion of the North Atlantic Current flowing north into the eastern subpolar gyre. This is balanced by the outflow of cold water from the western subpolar gyre that feeds the cold deep flow. In the subpolar gyre, this circulation is not an overturning in *depth* space, but in *density* space, with the key exchanges of warm and cold water taking place in the horizontal rather than the vertical.

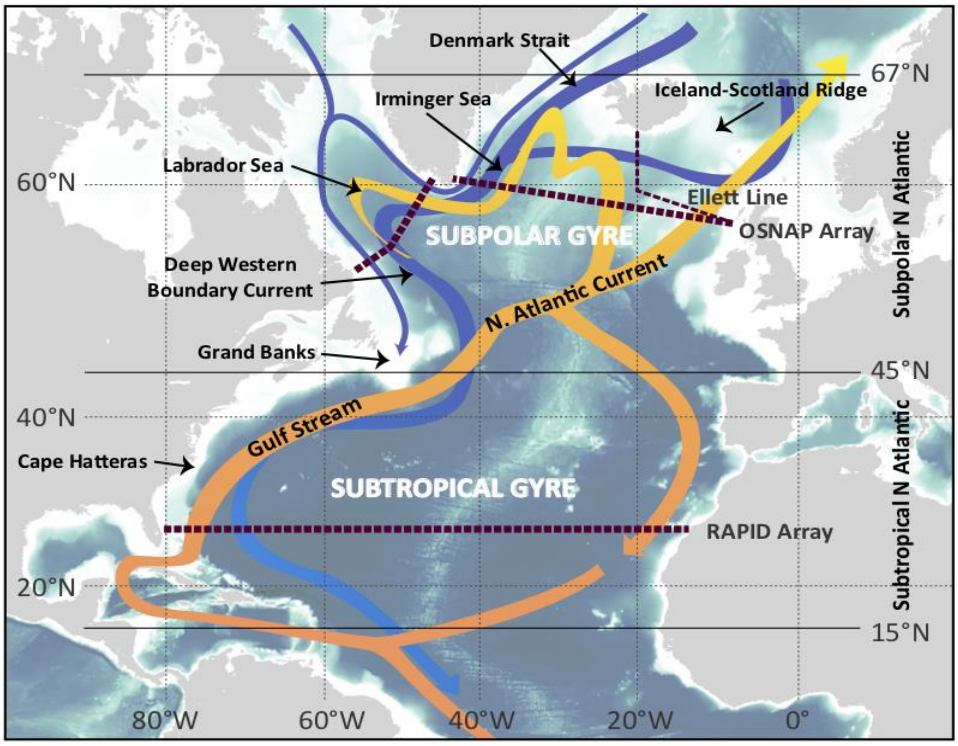


Figure 1: Schematic showing the main warm water (orange) and cold-water pathways in the North Atlantic. (From Robson et al.*, 2018.)*

The AMOC is the engine of heat transport in the Atlantic. The largest heat transport of any ocean of 1.3 PW (1 PW = 10^{15} W) occurs at approximately 30ºN in the North Atlantic (Johns *et al*., 2011; McCarthy *et al*., 2015a), just north of the RAPID array at 26ºN. This heat is released from the ocean to the atmosphere north of 30ºN and by 57°N at the OSNAP array the heat transport has reduced to 0.45 PW (Lozier *et al*., 2019), implying a heat flux to the atmosphere of 0.85 PW. This heat is carried by the atmosphere in the direction of North-West Europe by prevailing south-westerly winds, leading

to a milder climate than other maritime climates at similar latitudes (McCarthy *et al*., 2015b).
This dynamic role of ocean heat transport associated with the AMOC also yields a vulnerability for the climates dependent on it. Were the ocean to act as a simple heat sink or storage heater, absorbing heat in the summer and releasing it in winter, North-Western Europe climate would not be subject to the same risks as it is. However, the AMOC is known to have varied dramatically in the past, with evidence for AMOC changes associated with dramatic changes in climate during and at the end of the last glacial period (Lynch-Stieglitz, 2017); and the AMOC is predicted to weaken in the coming century due to climate change, with the Intergovernmental Panel for Climate Change (IPCC) ranking as *very likely* (>90% likelihood) the prospect of the AMOC weakening.

This review looks at updates to the state of knowledge of the AMOC since the last MCCIP Report Card (McCarthy *et al*., 2017) and addresses the impacts of these changes.

2. WHAT IS ALREADY HAPPENING?

The AMOC is currently in a reduced state, but the timing of when this reduction started and whether the reduction is due to decadal variability or anthropogenic forcing is disputed (Smeed *et al*., 2018; Thornalley *et al*., 2018; Caesar *et al*., 2018). Thornalley *et al*. (2018) used a proposed relationship between the size of silt particles in sediment cores taken in the Deep Western Boundary Current of the North Atlantic to the strength of the AMOC to assert that the AMOC has been weaker in the past 150 years than in the previous 1500 years. Caesar *et al*. (2018) built upon a subpolar Sea-Surface Temperature (SST) proxy for AMOC strength (Rahmstorf *et al*., 2015) to assert that the AMOC has been weakening since the mid-20th century. Smeed *et al*. (2018), using results from direct observations of the AMOC from the RAPID programme at 26ºN in the North Atlantic showed that the multi-year averages from 2008–2011 and 2012–2016 were weaker than the period 2004–2007 by 2.5 Sv and 3.0 Sv respectively. While this new evidence all points to a weakened AMOC currently, these studies propose very different answers on when the weakening began and whether it is part of a long-term slowdown.

The OSNAP array at 57°N was deployed in summer 2014. The following two winters were characterised by strongly positive North Atlantic Oscillation (NAO) state and saw a return of deep convection in the Labrador Sea to levels not seen since the early to mid-1990s. Expectations that significant AMOC variability would be driven by the new production were confounded as the OSNAP array did not observe significant export of new Labrador Sea Water or of overflow waters to the south of the section in 2014 or 2015 (Zantopp *et al*., 2017; Lozier *et al*., 2019).

Certainly, there is a growing body of evidence that the Atlantic is entering a cool phase associated with a weakened AMOC (Robson *et al.*, 2014; Smeed *et al*., 2018; Caesar *et al.*, 2018). The Atlantic is a region of large multi-decadal variability. This is most prominently manifested in Atlantic Multidecadal Variability (AMV) where SSTs in the North Atlantic, focused on the subpolar gyre, show periods of multiple decades of anomalous warmth or coolness relative to the global average (Sutton *et al*., 2017). The leading hypothesis for AMV is that AMOC-driven heat transport controls the phases of the AMV by controlling the export of heat into the subpolar gyre. The AMV was in a relatively cool period through the 1970s and 1980s, before rapidly warming during the 1990s (Robson *et al*., 2012). There is growing evidence that this warm period came to an end in the mid-2000s with the reversal of warming (salinifying) trends to cooling (freshening) trends focused on the subpolar gyre (Robson *et al*., 2016; Frajka-Williams *et al*., 2017). In addition the direct observations from the RAPID array that support a declining AMOC (Smeed *et al*., 2014, 2018), indirect measurements of the AMOC based on a combination of sea surface height and either Argo data at 41ºN (Willis 2010; Baringer *et al*., 2018) or Florida Straits transport at 26.5º (Frajka-Williams, 2015) support a decline in the AMOC since the mid-2000s. Ocean reanalysis data from the UK Met Office also support a decline in the AMOC (Jackson *et al*., 2016), although there is a low level of agreement between ocean reanalysis products for earlier periods (Karspeck *et al*., 2017). An apparent contradiction to this picture arises from the MOVE array at 16º N, where observations are showing a strengthening of the AMOC from the mid-2000s (Baringer *et al*., 2018). However, (Frajka-Williams *et al*., 2018) highlighted the consistent density changes at both MOVE (Send *et al*., 2002) and RAPID, implying that the difference is likely to be methodological. Therefore, there is broad agreement that the AMOC has weakened since the mid-2000s with most literature pointing to this being part of a multi-decadal cycle that could potentially be superimposed on a long-term decline that is predicted due to climate change.

One of the most dramatic manifestations of Atlantic climate variability in recent years was the 2015 cold anomaly. Record cold SSTs were recorded south of Greenland in 2015 (Figure 2a). These cold anomalies persisted through 2016 and disappeared in 2017. It is now established that these extreme cold anomalies were a combination of extreme heat loss and ocean re-emergence (Josey *et al*., 2018) (Figure 2b). The atmospheric domination of this interannual cold event in the subpolar gyre was notably different from the cool anomalies in the subtropical gyre in 2009–10, which were dominated by AMOC variations (Bryden *et al*., 2014; Cunningham *et al*., 2013). Atmospheric control of this recent interannual event in the subpolar gyre does not contradict the decadal timescale cooling and slowdowns that have been observed in the Atlantic, but does serve as a note of caution for interpreting SST variability as being solely due to AMOC variations.

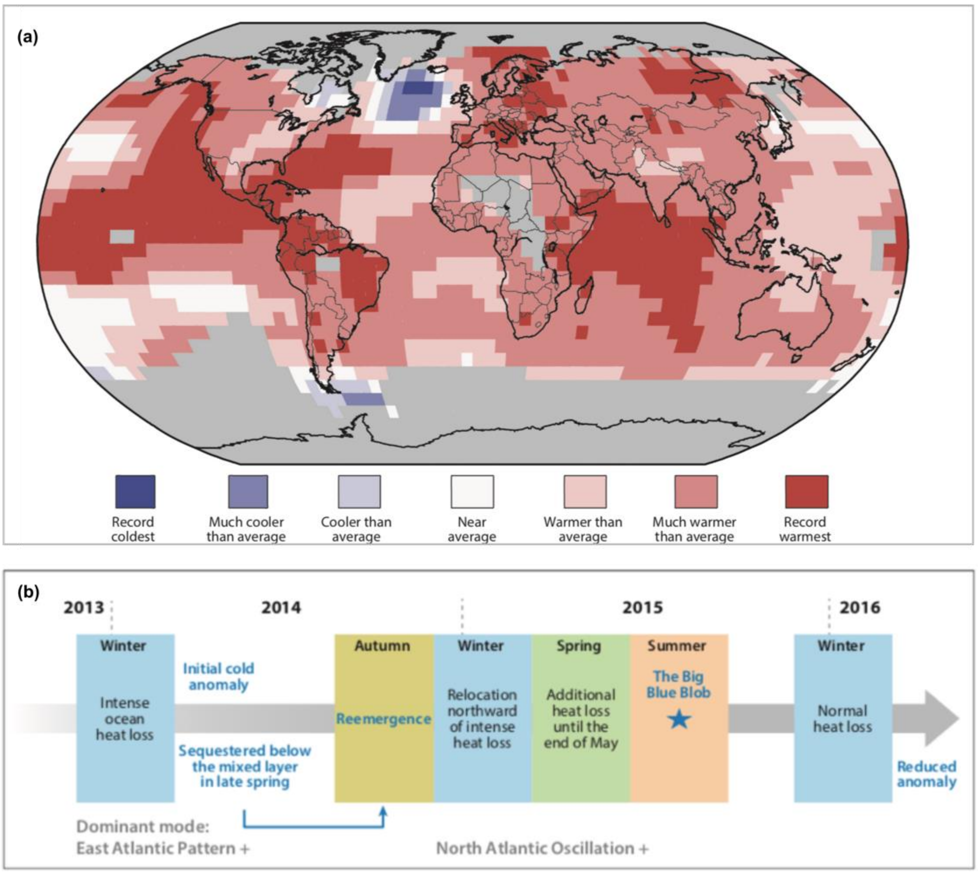


Figure 2: (a) Land and ocean temperature percentiles for 2015. Record coldest (warmest) indicates those grid cells in which the annual mean temperature is the lowest (highest) in the period 1880–2015. Regions with less than 80% coverage since 1880 are shaded grey. (b) Schematic timeline showing the development of the cold anomaly with associated major heat loss events and dominant atmospheric modes. (Reproduced from Josey et al., *2018.*)

No less dramatic, but receiving less attention, is the fresh anomaly in the eastern subpolar gyre. Since 2010, freshening has been noted throughout the eastern subpolar gyre. Along the Ellett line between Scotland and Iceland, a freshening from 0.15 g/ kg in the Iceland basin to 0.1 g/ kg in the Rockall trough. This freshening has in many cases been in concert with a cooling ranging from 1.0ºC in the Iceland Basin to 0.5ºC in the Rockall trough. Salinity in the core of the Atlantic water in the Faroe Current was observed to be the freshest on record. A summary of these findings is available in the IROC 2016 report (Gonzáles-Pola *et al.*, 2018). Analysis of the origin of this freshening trend is ongoing (N.P. Holliday, pers. comm.), however, it is instructive to compare with previous large-scale shifts in salinity in the subpolar gyre. Most famous of these is the so-called ‘Great Salinity Anomaly’ (GSA) in the late 1960s/early 1970s (Dickson *et al.*, 1988). The GSA was a widespread fresh anomaly through much of the subpolar gyre. The region stayed relatively fresh for the following 20 years. This fresh period ceased in the mid-1990s and widespread increase in salinity was observed (Holliday *et al.*, 2008). Indications are that this period of salinity increase has now also ended. The salinity changes in the subpolar North Atlantic have broadly varied in line with the AMV, with cool periods of AMV coinciding with lower salinities. This decrease in salinity in the eastern subpolar gyre is further evidence that the Atlantic is entering a cool phase associated with a weakened AMOC, and therefore weakened northwards transport of heat and salt. The OSNAP observations will provide the necessary basin integrated view to interpret such changes in the future.

The temperature and salinity of the eastern subpolar North Atlantic are also influenced by the circulation of the subpolar gyre, and specifically changes in the eastward spread of cooler, fresher water from the west (Hátún *et al*., 2005). It has been suggested that the cold, freshwater spreads farther east when the gyre circulation is enhanced in response to buoyancy forcing or wind stress curl (Häkkinen and Rhines, 2004). A subpolar gyre index, based on the leading Empirical Orthogonal Function (EOF) derived from satellite altimetry, was developed as a tool for expressing the strength and extent of the gyre (Häkkinen and Rhines, 2004). The index suggested that the subpolar gyre slowed and contracted during the rapid warming of the 1990s (Häkkinen and Rhines, 2004), and expanded during periods of low salinity (cooler) in the 1970s and early 1990s (Hatun *et al*., 2005). However, recent updates to subpolar gyre index (Berx and Payne, 2017) have been dominated by a long-term trend and have not described the same decadal-scale amplitude of the original gyre. Foukal and Lozier (2016) challenged the idea that contractions in the subpolar gyre are associated with warm Atlantic periods. (Hátún and Chafik, 2018) suggests that characteristics of the index are sensitive to satellite data set choices and assert that the gyre index is no longer based on the leading EOF but is contained in the second EOF (Figure 3). This highlights a lack of dynamical understanding stemming from this statistical method, and Hátún and Chafik (2018) suggest that more-physically based metrics may be required to characterise subpolar gyre shape and dynamics.

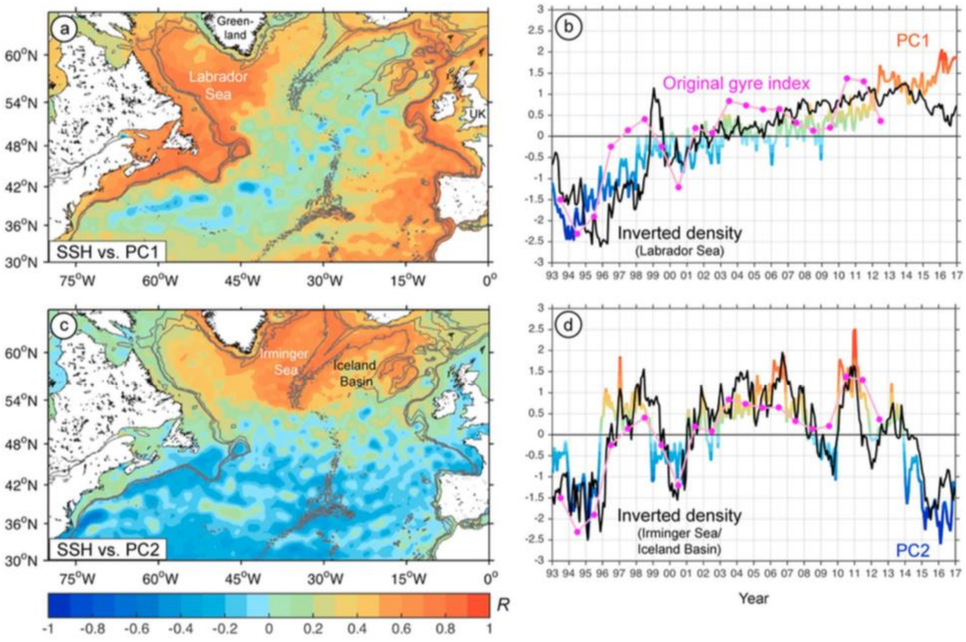


Figure 3: The two leading EOF modes derived from the DUACS 2014 altimetry data set (1993–2016). (a) Correlations between the first principal component and the sea surface height (SSH) field; (b) PC1 (coloured), the inverted deep Labrador Sea density anomaly (σ2 averaged over the 1000–2500-m layer in the Labrador Sea; black); (c) correlations between PC2 and the SSH field; and (d) PC2 (coloured) and the inverted density anomaly (σ1 averaged over the top 1000-m layer in the vicinity of the Reykjanes ridge; black). The original gyre index is from Hakkinen and Rhines (2004), annual averages, pink) is added to (b) and (d). None of the time series are to scale. For the domain included, the first and second EOF (Empirical Orthogonal Function) explain 18.5 and 7%, respectively, of the total variance. An analysis based on a re-mapped coarser resolution (1° latitude × 1° longitude) SSH data set gave a very similar result. (Figure and caption from Hátún and Chafik, 2018.)

Returning to the boundary between the subtropical and subpolar North Atlantic, changes have been noted in the Gulf Stream Extension region. On leaving the coast of North America at Cape Hatteras, the Gulf Stream becomes the Gulf Stream Extension. This is the region of the Gulf Stream North Wall (GSNW) where there is a sharp boundary between warm subtropical waters and cold subpolar waters. Since 2005, the region from approximately 70ºW to 55ºW has become much more unstable and eddy-filled (Andres, 2016), leading to a broadening of the Gulf Stream in this region (McCarthy *et al*., 2018). Two relationships are commonly cited between the AMOC and this section of the Gulf Stream: (1) a northward (southward) shift in the GSNW associated with a weakening (strengthening) of the AMOC (Joyce and Zhang, 2010; Zhang and Vallis, 2007), and (2) a warming (cooling) north of the Gulf Stream Extension in the Northern Recirculation Gyre associated with a weakening (strengthening) of the AMOC (Zhang, 2008). Since 2005, there is evidence of a northward shift in the GSNW consistent with a declining AMOC, but only west of 70ºW (Smeed *et al*., 2018; McCarthy *et al*., 2018). There is also evidence of warming north of the Gulf Stream Extension between 70ºW and 55ºW but this is not due a northward shift in the Gulf Stream position but related to increased Gulf Stream warm-core rings entering the Northern Recirculation Gyre north of the Gulf Stream Extension.

The Atlantic shift towards a weaker AMOC and a cooler subpolar phase has global consequences. Controversially, Chen and Tung (2018) claimed that a shift to a weaker AMOC could lead to a surge in global temperatures, arguing that the role of a weakened AMOC in reducing the rate of sequestration of heat in the deep ocean could lead to a rise in global surface temperatures. This assertion is contrary to conventional wisdom and the large body of model experiments on the subject, which associate a decline in the overturning circulation with a reduction in surface temperatures (e.g. Jackson *et al*., 2015; Drijfhout, 2015; Shi *et al*., 2018).

The regional consequences of a shift towards weaker AMOC and cooler subpolar North Atlantic are less clear. The connection between broad Atlantic changes and the North-Western European shelf is not altogether obvious. Indications are that there is an influence of broad Atlantic changes (Jones *et al*., 2018) but local factors complicate the issue.

Large biogeographical shifts (movement of biological organisms) have been associated with large-scale circulation in the subpolar gyre in the past (Hátún *et al*., 2009). There is evidence that the same is occurring again with the shift towards colder and fresher conditions. For example, blue whiting is a fish whose extent depends on the salinity of the water. With the return of fresher conditions in the eastern subpolar gyre, the distribution of blue whiting has shifted to a narrow band in the eastern Rockall trough (Figure 4). With the re-establishment of a cold subpolar gyre, much of the biogeographical shifts associated with the rapid warming of the 1990s (Hátún *et al*., 2016) may well be expected to reverse.

3. WHAT COULD HAPPEN IN THE FUTURE?

The IPCC AR5 report (Stocker *et al*., 2014) predicts that it is *very likely* that the AMOC will decline by 2100 and approximates the likely rate of decline at 11% under an RCP2.5 emissions scenario, and 34% under an RCP8.5 emissions scenario. Under the RC8.5 scenario a weakening of the AMOC is a common response in the CMIP5 models during the twenty-first century (Figure 5), (Heuzé *et al*., 2015). The IPCC SR1.5 (IPCC, 2018) report states there is little difference in amplitude of AMOC weakening for a 1.5ºC warming scenario compared to a 2ºC warming scenario.

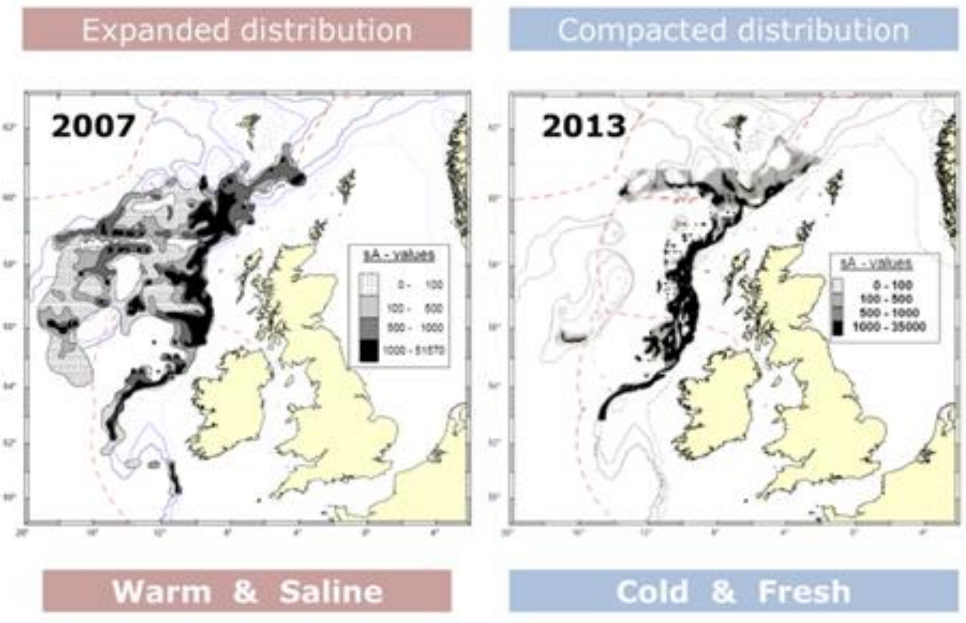


Figure 4: Spatial distributions of blue whiting from the International Blue Whiting Spawning Stock Survey. Two years characterized by different oceanographic conditions (2007 and 2013) are shown. (Reproduced with permission from M. Payne.) (https://rpubs.com/markpayne/WGS2D_01_blue_whiting_spawning).

In the last couple of years new understanding about AMOC projections has been gained from a couple of papers. (Sévellec *et al*., 2017) demonstrated a new mechanism for AMOC weakening where Arctic sea ice loss exposes more of the sea surface to the atmosphere and hence enables more heat uptake. This warming then reduces the density and weakens the AMOC. Also, Liu *et al*. (2017) claimed that the AMOC can weaken more strongly under anthropogenic climate change once biases are accounted for. The wintertime retreat of sea ice in the Greenland and Iceland Seas has significantly reduced the magnitude of air–sea heat fluxes in the regions (Moore *et al*., 2015). At the same time, the sea-ice retreat has exposed Atlantic origin water returning southwards along east Greenland to severe heat loss (Våge *et al*., 2018). These changes to surface heat fluxes have the potential to modify the properties of Denmark Strait overflow and hence thereby impact the lower limb of the AMOC (Moore *et al*., 2015; Sévellec *et al*., 2017; Våge *et al*., 2018).

Various theories, simple models and paleo evidence have suggested the potential of the AMOC to become unstable leading to an abrupt collapse (Rahmstorf, 1996; Rahmstorf *et al*., 2005; McManus *et al*., 2004). Apart from a few exceptions, however, coupled climate models have not shown abrupt collapses or bi-stability of the AMOC (Hawkins *et al*., 2011; Liu and Liu, 2012). One such exception is Jackson and Wood (2018) who found that the AMOC in a higher resolution climate model had a threshold beyond which the AMOC did not recover within a couple of centuries. There have been suggestions that the AMOC in many current climate models may be too stable because of biases (Liu and Liu, 2012; Mecking *et al*., 2017), although flux corrections to remove biases may themselves have impacts on the stability (Gent, 2018; Gnanadesikan *et al*., 2018). Although there are still uncertainties in this area, nothing has so far contradicted the AR5 conclusion that an AMOC collapse before 2100 is unlikely (Collins *et al*., 2013; see also Good *et al*. (2018) for a more-recent review of AMOC stability).

One potential tipping point that has been highlighted is that of convective collapse (Sgubin *et al*., 2017). This differs from a collapse of the AMOC in that it refers to a cessation of deep convection in a limited region of the subpolar gyre, resulting in abrupt changes in surface temperatures. Recent melting of the Greenland Ice Sheet in summer has been linked to inhibiting convection and potentially leading to convective collapse (Oltmanns *et al*., 2018).

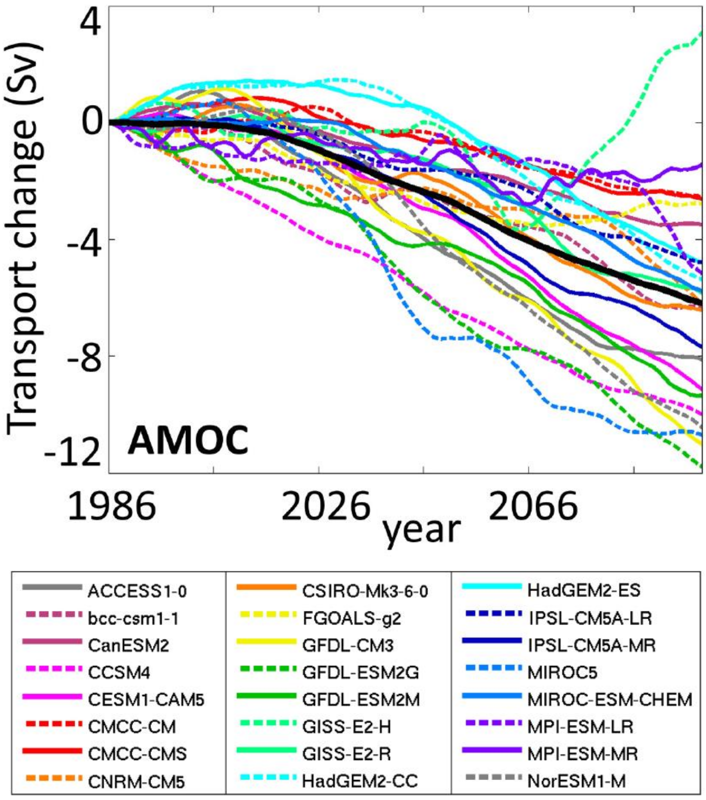


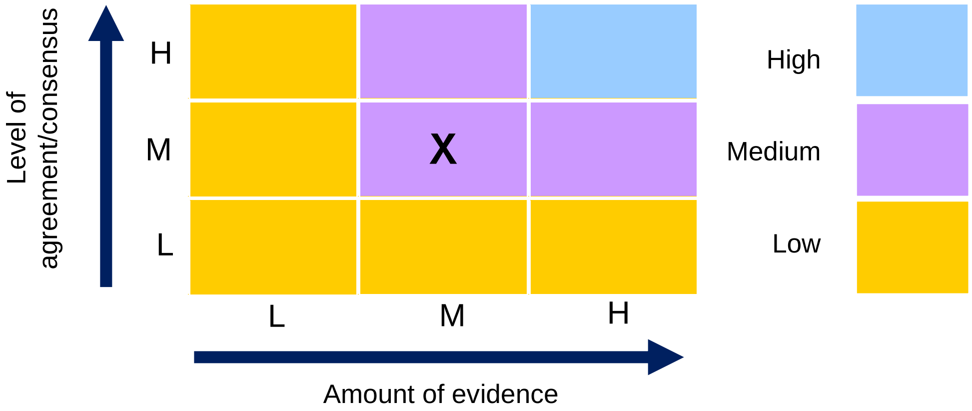
Figure 5: RCP8.5 time series of the change in AMOC at 30ºN from the 1986 value for each model after removal of the model control drift and 15-yr low-pass filtering. The black line indicates the multi-model mean change. The apparent increase in AMOC from 2066 in in the GISS-E2-H model is due to variation in the control simulation rather than an increase in the scenario simulation.

An area of research that has advanced apace in recent years is the field of near-term climate predictions or decadal predictions. Decadal predictions differ from climate projections by being initialised from observations. In this sense, they are more like a weather forecast run over long periods of time. The origin of predictability on these timescales arises from the ocean where slow advective processes are a key origin of predictability (Yeager and Robson, 2017). One area where decadal predictions are consistently more skilful than uninitialized projections is the North Atlantic (Yeager *et al*., 2018), with the strength of the heat conveyor a useful predictor (Borchert *et al*., 2018). This predictive skill arises from the response of the ocean to initialisation of an anomalous AMOC, rather than an ability to predict the onset of an anomalous AMOC itself (Yeager and Robson, 2017). Predictability is much higher in models with stronger low-frequency AMOC variability and lower in models with weaker AMOC variability (Yan *et al*., 2018).

Predictions of a cooling Atlantic have been made by a number of authors (Klower *et al*., 2014; Hermanson *et al*., 2014). The prediction length or forward run of these models is seldom more than 5–10 years and so cannot tell whether this ongoing cooling is a long term, potentially anthropogenically-forced, slow down or part of a multi-decadal oscillation. From the perspective of climate projections, climate models consistently show a long-term slow down, but most do not show the magnitude of multi-decadal variability that we would expect from observations (Roberts *et al*., 2014; Yan *et al*., 2018).

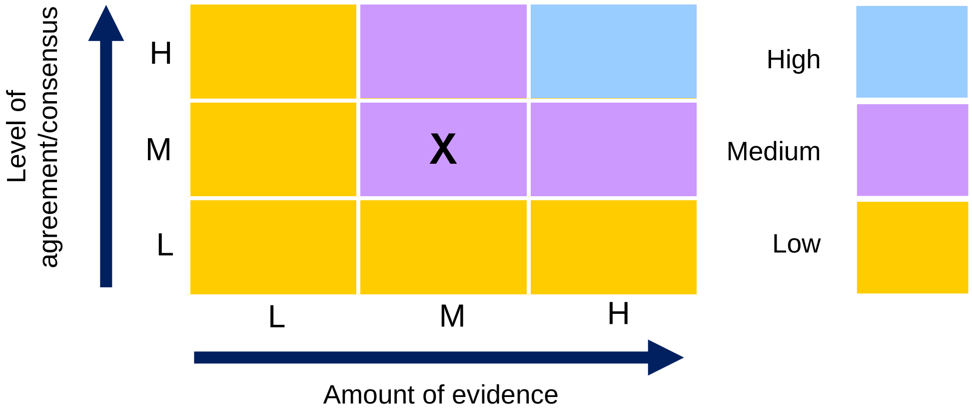
4. CONFIDENCE ASSESSMENT

The AMOC is in a weakened state



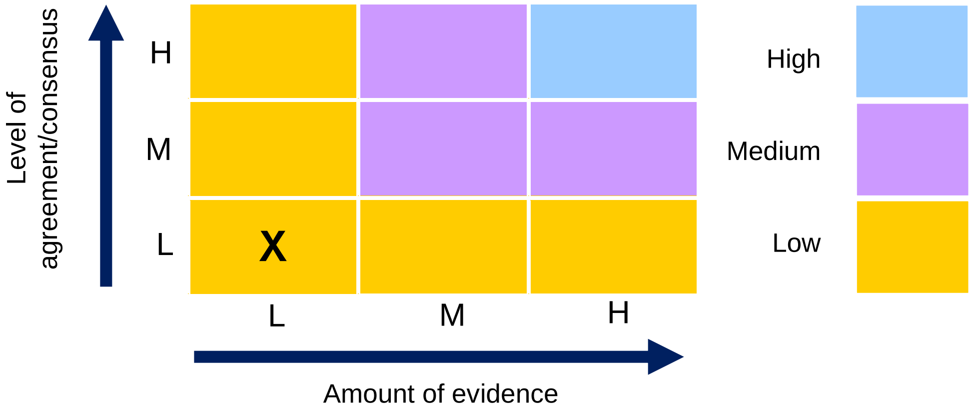
Half of the authors felt that there was medium agreement and medium amount of evidence that the AMOC was in a weakened state. One author each voted for each of the medium and high boxes. No author thought there was low agreement or low amount of evidence. This is no change from previous reports.

Current AMOC weakening is consistent with multi-decadal variability



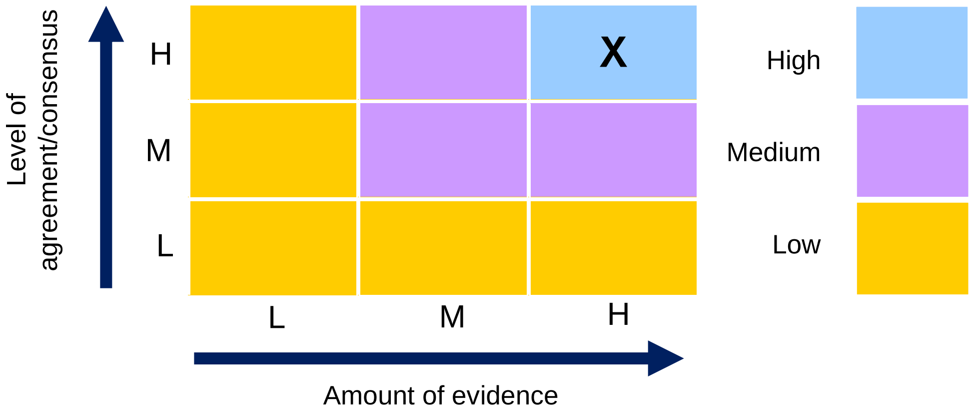
Half of the authors felt that there was medium agreement and medium amount of evidence that the AMOC was in a weakened state. There was no real pattern with the remaining votes. This question was not posed in previous assessments.

Current AMOC weakening is due to anthropogenic factors



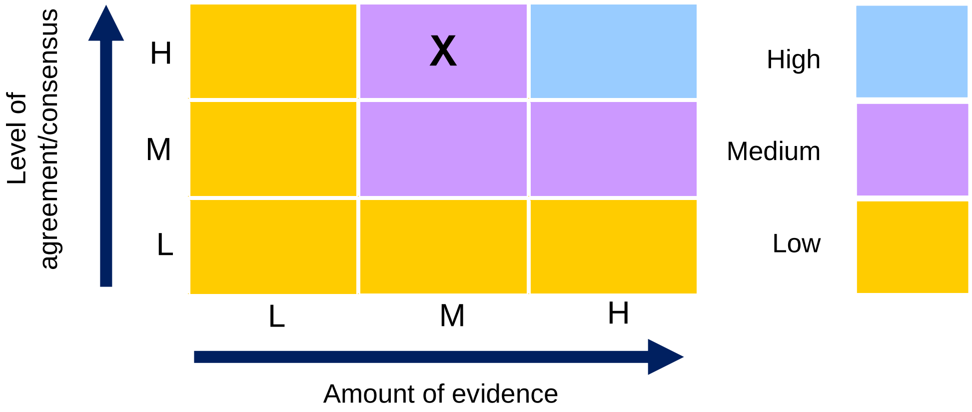
Half of the authors felt there was low agreement and little evidence that the current weakening is due to anthropogenic factors. The remaining authors either voted for little evidence and medium consensus, or medium amounts of evidence and low consensus. This question was not posed in previous reviews.

Predictions of an AMOC slowdown by 2100 are robust



Half of the authors felt there was high agreement and high levels of evidence for this statement. The remaining authors all voted for either medium amounts of evidence and high agreement, or high amounts of evidence and medium agreement. This is a stronger statement than in previous report cards.

The AMOC is unlikely to collapse before 2100



Half of the authors felt there was medium amounts of evidence and high levels of agreement. The remaining authors all voted for medium agreement with varying levels of evidence. This question was not posed in previous report cards.

5. KEY CHALLENGES AND EMERGING ISSUES

The largest current issue for AMOC science is understanding whether the ongoing decline is part of a multidecadal cycle or part of a long-term decline in the AMOC associated with anthropogenic climate change. Crucial to understanding this issue is sustaining the direct observations of the AMOC. In addition to the RAPID programme, the OSNAP array at approximately 57ºN (Lozier *et al.*, 2019) and the NOAC array at 47ºN (M. Rhein, *pers. comm.*) are at the cusp of producing additional direct observations of the AMOC that will help us to better understand the AMOC throughout the North Atlantic. Efforts to observe the AMOC in the South Atlantic are also ongoing at the SAMBA array near 35ºS (Meinen *et al*., 2018) and the TSAA array at 11ºS (Hummels *et al*., 2015). It is crucial to maintain and optimise these arrays to understand the changes that are ongoing in the AMOC.

Understanding the question of the duration of the decline is a challenge for modelling. Climate projections from CMIP5 predict a decline through the 21st century, but do not show the multi-decadal variability expected. Initialised decadal predictions are capable of capturing multi-decadal variations but the skill in these predictions beyond a decade is not established. Further work is needed for future projections or predictions to resolve the transition from multi-decadal variability to long term decline. Model bias is the greatest impediment to improved decadal predictions (Yeager and Robson, 2017; Cassou *et al*., 2018).

Finally, the changes ongoing in the North Atlantic in the last decade, including a cooling of the subpolar gyre, a freshening in the eastern subpolar gyre, and increased instability in the Gulf Stream, may be linked by changes in the AMOC system as a whole. However, the AMOC is not a catch-all and understanding the individual ocean process (including wind-driven circulation variations, deep water formation processes, etc.) and the links between them are key to understanding Atlantic variability, particularly in the context of a changing climate.

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