
The evolution of the North Atlantic Meridional Overturning Circulation since 1980

Jackson Laura C. ^{1,*}, Biastoch Arne ^{2,3}, Buckley Martha W. ⁴, Desbruyères Damien ⁵,
Frajka-Williams Eleanor ⁶, Moat Ben ⁶, Robson Jon ⁷

¹ Met Office, Hadley Centre, Exeter, UK

² GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

³ Kiel University, Kiel, Germany

⁴ Atmospheric, Oceanic and Earth Sciences, George Mason University, Fairfax, VA, USA

⁵ Ifremer, University of Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale, Plouzané, France

⁶ National Oceanography Centre, Southampton, UK

⁷ National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK

* Corresponding author : Laura C. Jackson, email address : laura.jackson@metoffice.gov.uk

Abstract :

The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the climate through its transport of heat in the North Atlantic Ocean. Decadal changes in the AMOC, whether through internal variability or anthropogenically forced weakening, therefore have wide-ranging impacts. In this Review, we synthesize the understanding of contemporary decadal variability in the AMOC, bringing together evidence from observations, ocean reanalyses, forced models and AMOC proxies. Since 1980, there is evidence for periods of strengthening and weakening, although the magnitudes of change (5–25%) are uncertain. In the subpolar North Atlantic, the AMOC strengthened until the mid-1990s and then weakened until the early 2010s, with some evidence of a strengthening thereafter; these changes are probably linked to buoyancy forcing related to the North Atlantic Oscillation. In the subtropics, there is some evidence of the AMOC strengthening from 2001 to 2005 and strong evidence of a weakening from 2005 to 2014. Such large interannual and decadal variability complicates the detection of ongoing long-term trends, but does not preclude a weakening associated with anthropogenic warming. Research priorities include developing robust and sustainable solutions for the long-term monitoring of the AMOC, observation–modelling collaborations to improve the representation of processes in the North Atlantic and better ways to distinguish anthropogenic weakening from internal variability.

Introduction

15 The Atlantic Meridional Overturning Circulation (AMOC; Box 1) is a system of ocean currents in the Atlantic that move warmer,
16 upper waters northwards and cooler, deeper waters southwards. Accordingly, the AMOC is a major source of northward heat
17 transport, accounting for 20-30% of total atmospheric and oceanic heat transport into the mid-latitudes¹. The AMOC, therefore,
18 has a key role in governing the climate of the North Atlantic region and beyond, influencing European air temperatures and
19 precipitation, the frequency of Atlantic hurricanes and winter storms, spatial patterns of sea level and tropical monsoons^{2,3}, and
20 the global carbon budget⁴.

21 The strength of the AMOC is typically ~ 17 Sv (Sv=Sverdrup; $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$)⁵. However, both observations and models
22 indicate that the AMOC exhibits substantial variability on daily to multi-decadal timescales. Coupled climate models suggest
23 decadal variability can arise naturally due to internal interactions within the climate system⁶⁻⁸. The AMOC is also expected to
24 respond to external forcing, including anthropogenic aerosols, volcanic eruptions and solar changes^{9,10}, as well as anthropogenic
25 greenhouse gas emissions¹¹. Indeed, observations, reanalyses, models and proxies¹²⁻¹⁶ indicate substantial contemporary
26 decadal-scale changes in AMOC strength. The RAPID array at 26.5°N ^{5,17}, for example, revealed a statistically significant
27 weakening from 2004 (ref^{18,19}), likely representing decadal variability rather than ongoing long-term weakening²⁰⁻²². There
28 are indications that the AMOC might be recovering in strength¹².

29 Despite evidence of decadal variability, many questions remain. For example, high-quality continuous observations, like the
30 RAPID array, are short and sparse, making it difficult to assess longer-term AMOC variability and determine whether decadal
31 changes are representative of those across the wider Atlantic. Moreover, there is uncertainty about the relative roles of internal
32 variability and forced variability, owing to diverse AMOC variability^{8,23} and externally-forced AMOC trends^{10,24} in models.
33 Indeed, the AMOC might have already weakened over the 20th Century^{25,26}, potentially implying that it is more sensitive to
34 external forcing than previously thought. Understanding how and why the AMOC has changed on decadal timescales is thus
35 crucial to not only understand the AMOC's role in shaping the climate of the North Atlantic relative to other influences^{27,28},
36 but also to constrain predictions of future changes and AMOC impacts^{2,29}.

37 In this Review, we bring together and critically assess multiple lines of evidence to understand decadal-scale changes

38 in the AMOC since 1980, the time period selected owing to greater data availability. Given that decadal-scale variability
39 likely has a larger impact on ocean temperatures than variability at shorter timescales²⁸, we focus discussion on multiannual
40 and decadal timescales. We begin by reviewing current knowledge about the mechanisms driving AMOC variability and the
41 methods and tools available to estimate it. We then outline and compare estimates of AMOC variability from the subtropical
42 and subpolar North Atlantic regions, including indirect evidence from observed changes in the North Atlantic Ocean. We follow
43 by discussing these changes in a longer term context, before ending with recommendations for future research.

44 **AMOC variability**

45 The AMOC exhibits substantial variability on intra-annual and seasonal timescales³⁰ (order 100% of its mean value) and
46 much smaller variability on interannual to decadal timescales^{7,30} (order 10-30%). Mechanisms of interannual-decadal AMOC
47 variability depend strongly on the region of interest. In the subtropics, high-frequency (sub-annual to interannual) wind
48 forcing dominates AMOC variability, with buoyancy forcing also contributing at low frequencies^{28,31} (Fig 1). In contrast,
49 low frequency variability (interannual to decadal) dominates the subpolar AMOC, with both wind and buoyancy forcing
50 considered important³²⁻³⁵. The AMOC responds strongly to the North Atlantic Oscillation (NAO), the dominant mode of
51 atmospheric variability in the North Atlantic, which leads to both wind-induced and buoyancy-induced AMOC variations²⁸.
52 The mechanisms driving AMOC variability are now discussed.

53 **Wind forcing**

54 Wind stress forcing creates AMOC anomalies through two mechanisms: Ekman transports and wind-induced geostrophic
55 currents. Wind stress anomalies drive surface currents (Ekman transports) perpendicular to the wind, so zonal wind stress
56 anomalies create meridional currents. To conserve mass, these Ekman transports must be balanced by a return flow in the
57 opposite direction, creating a meridional overturning³⁶. Spatial variations in Ekman transports also cause convergence and
58 divergence, leading to downwelling and upwelling, respectively. These vertical velocities move the thermocline up or down
59 (heaving), generating density anomalies and, thus, wind-induced geostrophic currents.

60 While the AMOC responds locally and instantaneously to wind-forcing through Ekman transports and heaving, the ocean
61 also has slow and remote responses. Wind-induced thermocline variations propagate westward as baroclinic Rossby waves and
62 can lead to western boundary density, and hence AMOC, anomalies in both subtropical^{37,38} and subpolar latitudes³⁹. The time
63 taken for these waves to propagate varies from about a year in the subtropics to many decades in subpolar regions.

64 Wind-driven variations of the AMOC depend on the local winds, and so variability can differ by latitude⁴⁰⁻⁴³. However,
65 given that a large portion of wind-driven variability results from the NAO, spatially coherent NAO-driven AMOC changes are
66 often observed. Specifically, a positive NAO results in anomalous westerly winds over the subpolar North Atlantic and easterly
67 winds over the subtropical North Atlantic (and vice versa for a negative NAO), driving AMOC variability of opposite sign
68 between the subtropical and subpolar regions⁴⁴.

69 **Buoyancy forcing**

70 Buoyancy forcing (changes in surface density through surface heat and freshwater fluxes) results in water mass transforma-
71 tion^{45,46} and densification of waters in the subpolar North Atlantic. The densest waters are formed in the Labrador Sea and
72 the Nordic seas, with the reduction in stratification preconditioning deep convection. Model experiments suggest that large,
73 decadal-scale AMOC variability in the North Atlantic primarily arises from buoyancy fluxes over subpolar regions associated
74 with low frequency NAO variability^{33,47-50}. In particular, a positive NAO results in stronger winds over the subpolar North
75 Atlantic and, hence, increased heat loss to the atmosphere and greater dense water formation; a negative NAO has the opposite
76 effect. Numerous model simulations indicate that anomalies of deep convection and subsurface density anomalies in the
77 subpolar North Atlantic precede AMOC anomalies^{6,51-54}.

78 However, understanding of the connections between overturning, water mass formation and convection are thought to be
79 incomplete. For example, observations have been unable to show direct links between Labrador Sea Water formation⁵⁵⁻⁵⁸
80 and AMOC variability⁵⁹. Instead, changes in Labrador Sea Water formation rates might only change the volume or density
81 of Labrador Sea Water within the subpolar North Atlantic rather than its export^{60,61}. However, longer time averages (decade
82 or longer) might be required to see a direct correspondence between formation rates and export^{12,62,63}. Moreover, observa-
83 tions suggest that AMOC mean strength and sub-annual variability are dominated by variations east of Greenland^{12,64-66},
84 whereas models frequently highlight the Labrador Sea as a key region for deep water formation and originator of AMOC
85 variability^{23,50,67}. Yet, some coupled models do show agreement with observations⁶⁸⁻⁷⁰ and suggest AMOC variability can
86 be dominated by the eastern subpolar region while still having strong correlations between the AMOC and Labrador Sea
87 properties⁶⁹. The interpretation of model results might therefore be flawed rather than the models themselves.

88 **Oceanic processes and AMOC feedbacks**

89 AMOC anomalies can be generated by purely oceanographic processes. For example, baroclinic instability can spontaneously
90 generate ocean eddies, adding chaotic-intrinsic variability to the AMOC⁷¹⁻⁷³, as well as force baroclinic Rossby waves^{39,72,74-76}.
91 Both eddies and Rossby waves modify the east-west density difference, thus contributing to AMOC anomalies^{37,75}.

92 AMOC variability can also involve ocean or coupled feedbacks that amplify (positive feedback) or dampen (negative
93 feedback) the initial perturbation. For example, AMOC-related heat and freshwater transport changes can modify advection
94 and thus subpolar density, in turn impacting the AMOC^{51,77-79}. AMOC-driven SST anomalies can also change atmospheric
95 circulation, perturbing the NAO⁸⁰⁻⁸². However, the importance of both these processes in explaining decadal AMOC variability
96 is unclear. For instance, coupled models simulate a range of advective feedbacks with differing roles for heat and freshwater
97 transports^{51,77-79,83}, and the atmospheric response to AMOC-related SST anomalies is often weak and inconsistent across
98 models^{84,85}.

99 **Southward communication of AMOC anomalies**

100 While many AMOC anomalies remain localized, some are communicated meridionally to give rise to large-scale AMOC
101 variations. Large-scale AMOC anomalies are thought to be generated in the subpolar gyre and communicated southward
102 into the subtropical gyre^{32,86} either slowly through advection of deep subpolar density anomalies⁸⁷, or more quickly through
103 boundary waves^{86,88,89}. There is strong mixing of these dense waters before reaching the subtropics⁹⁰⁻⁹², meaning only large
104 and persistent AMOC anomalies might succeed in being communicated southward^{93,94}.

105 **Measuring and modelling the AMOC**

106 As the AMOC varies on different timescales, it is important to have continual measurements of its strength. Estimates come
107 from direct observations, models, reanalyses and proxy records, and when used together, can improve the understanding of the
108 robustness of signals.

109 **Observations**

110 Historically, measurements of AMOC strength come from longitude-depth temperature and salinity measurements at particular
111 times; these measurements are converted to AMOC strength by applying the thermal wind relationship (which relates zonal
112 density gradients with vertical gradients in meridional velocity)⁹⁵, sometimes using box inverse models²². While such AMOC
113 estimates provide key benchmarks for validating time series obtained from time-continuous measurements⁹⁶, they suffer from
114 aliasing of large monthly and interannual variability, and are likely inadequate to examine decadal changes in ocean transport⁹⁷.

115 The RAPID/MOCHA/WBTS 26.5°N array^{5,98} (Box 1) has measured AMOC variability since 2004, delivering an in-depth
116 view of its circulation¹⁷. The array consists of moorings near the Bahamas and Canary Islands which make continuous
117 measurements of temperature and salinity to compute relative velocities in the interior ocean. AMOC strength is calculated
118 from the full velocities, requiring the addition of a reference level velocity (obtained by setting the total volume transport
119 through the section), and combining with near-surface Ekman transport from wind stress in atmospheric reanalyses and Gulf
120 Stream transport from a submarine cable⁵. The OSNAP (Observing the subpolar North Atlantic program) array started in 2014
121 (ref⁶⁵), although is not yet long enough to examine interannual or decadal variability. While mooring-derived calculations (such
122 as RAPID⁹⁸) are the most valuable method for measuring the AMOC, they still suffer from data gaps (in particular surface
123 layers and continental slopes) and from difficulty in robustly determining the reference velocity.

124 Other observation-based methodologies complement these arrays and extend AMOC estimates back in time or to other
125 latitudes. The most common methodology uses alternative data sets (shipboard hydrographic sections or Argo profiling floats⁹⁹)
126 to generate gridded fields of temperature and salinity at monthly resolutions from which relative velocities can be computed.
127 These relative velocities are then combined with a reference level velocity (obtained from satellite-based measurements of
128 surface currents or directly estimated from float displacements near 1000m depth) and Ekman wind stress using atmospheric
129 reanalyses^{12,96,100}. Arrays using such methods, including at A25-OVIDE⁹⁶, 41°N¹⁰⁰ and 45°N¹², have additional uncertainties
130 owing to irregular and limited data distribution, notably along basin margins where strong and narrow boundary currents are
131 insufficiently sampled.

132 At 26.5°N, an additional reconstruction has extended the AMOC timeseries using Gulf Stream cable measurements
133 and sea-level anomalies measured by satellite altimetry¹⁰¹, with an updated reconstruction taking into account the vertical
134 structure¹⁰². Building on a clear relationship between western boundary sea-level anomalies and upper mid-ocean geostrophic
135 transport changes, these reconstructions recover a large fraction of the directly-observed AMOC interannual variability¹⁰¹.
136 Although these methodologies provide key multi-decadal records, they rely on a fragile linear and time-invariant relationship
137 between sea-level anomalies and interior density changes.

138 An alternative methodology relies on a balance between the northward import of light waters, their densification through
139 air-sea buoyancy fluxes, and their southward export as dense waters^{45,103,104}. Accordingly, it becomes possible to reconstruct

140 an AMOC time series from surface observations alone¹². This estimate is expected to lead AMOC variability observed
141 downstream of water mass transformation sites by several years owing to the time of advection of buoyancy anomalies by the
142 mean circulation. While providing an independent measure of the AMOC, such relationships between transformation and the
143 AMOC might only hold on longer (decadal) timescales and neglect diapycnal mixing.

144 **Models and reanalyses**

145 AMOC changes can also be assessed using numerical models, either with forced ocean models^{105,106} (ocean models forced
146 with historical atmospheric conditions) or ocean reanalyses¹⁰⁷ (forced ocean models that assimilate observations). Models
147 and reanalyses provide more complete, physically consistent views of the ocean, both spatially and temporally. However,
148 both rely on imperfect ocean models; insufficient resolution often incorrectly simulates processes such as eddies, convection
149 and overflows¹⁰⁸, resulting in different AMOC strength compared to eddy-rich models^{109,110}. Ensembles of forced ocean
150 models^{14,111} are generally able to reproduce the mean structure of the AMOC^{68,110,111} and interannual variability, given that
151 interannual variability is mainly wind-driven and the forcing sets are well-constrained by satellite winds^{112,113}. However,
152 AMOC trends and decadal variability can be affected by uncertainties in surface fluxes and the different methods used to impose
153 and correct them^{112,114,115}.

154 Ocean reanalyses are ocean models further constrained by observations such as SST, sea ice concentration and sea surface
155 height from satellites, and subsurface observations of temperature and salinity. These constraints potentially have the advantage
156 of providing a more observationally-consistent estimate of the AMOC, but the assimilation itself can generate spurious
157 effects. Reanalyses vary substantially with different data assimilation strategies (from nudging to adjoint methods¹⁰⁷) and
158 the observations that are assimilated. In particular, there has been a large increase in available observations from satellite
159 measurements (since the early 1990s) and Argo profiling floats¹¹⁶ (since the early 2000s). Reanalyses focusing on earlier periods
160 have little agreement in AMOC variability^{112,117}. However, the agreement is much stronger since the mid 90s, particularly for
161 reanalyses, which use the wide variety of observational constraints available since 1993 (ref¹³).

162 Coupled models are simulations of the oceans and atmosphere, where instead of applying historical atmospheric conditions
163 to force the ocean, both the ocean and atmosphere are free to evolve and interact. They are important tools for understanding
164 the spectrum and mechanisms of AMOC variability on a range of timescales. However, as AMOC variability is not constrained
165 by atmospheric fluxes and observed ocean properties, coupled models are not expected to represent the observed internal
166 variability of specific time periods. Nevertheless, they can be used to examine the forced response of the AMOC to historical
167 greenhouse gas and aerosol changes.

168 **Indirect evidence**

169 In addition to observations, models and reanalyses, estimates of the AMOC can be determined by considering changes in the
170 North Atlantic Ocean that are mechanistically and statistically associated with the AMOC^{118,119}. Such proxies can be used
171 to reconstruct AMOC timeseries, and are often developed using relationships derived from models owing to limited direct
172 observations. An understanding of the robustness of these relationships is needed. For example, because models indicate
173 causal relationships between the AMOC and North Atlantic ocean temperatures, and because there are long records of upper
174 ocean temperatures, proxies based on SSTs and subsurface temperatures have been proposed^{120–123}. These relationships occur
175 because changes in the AMOC affect ocean heat transport, which, in turn, affects the rate of change of heat content. Hence, an
176 SST signal would be expected to lag the AMOC by a few years^{7,122}, though results are sensitive to the latitude of the AMOC
177 index.

178 Other proxies have made use of relationships between the AMOC and subsurface density in the Labrador sea^{15,124} and
179 with sea level records along the eastern seaboard of North America^{125,126}. Paleoclimate data potentially provides very long
180 records. Although most cannot resolve decadal variability, sortable silt¹²⁷, a proxy for deep western boundary current speeds,
181 has sufficient temporal resolution to estimate variability since the 1980s.

182 **Changes in the AMOC**

183 The multitude of AMOC observations, reconstructions and models offer opportunities to assess and compare contemporary
184 AMOC changes for both the subpolar and the subtropical North Atlantic (Fig 2, 3), where variability and drivers can differ.
185 AMOC variability since 1980 (when consistent records are available) is now discussed.

186 **Subpolar AMOC**

187 Since 1980, evidence suggests the subpolar AMOC strengthened to the mid-90s, weakened from the mid-90s to 2010s, with
188 some indications for strengthening since 2010.

189 The initial strengthening from the 80s to the mid-90s is evident in several data sets. The forced ensemble¹⁰⁶, the only
190 reconstruction extending back to 1980, reveals an AMOC strengthening of ~ 2 Sv (Fig 2e), consistent with that of an earlier

191 forced ensemble¹¹². Proxy reconstructions of subpolar North Atlantic density^{15,124}, sortable silt¹²⁷ and sea level anomalies¹²⁵
192 further depict increases to the mid 1990s (Fig.3a-c). Although the sortable silt proxy is measured at 35°N (in the subtropics), it
193 represents the deep western boundary current speed and, thus potentially, the propagation of changes from the subpolar North
194 Atlantic.

195 All reconstructions and the subpolar proxies subsequently suggest a weakening of the AMOC from the mid 1990s (Fig 2a-e
196 and Fig.3a-c), in agreement with previous results^{32,33,48}. For example, from 1993-2013, statistically significant trends ($P < 0.05$)
197 of -0.26 Sv/year, -0.15 Sv/year, -0.14 Sv/year, -0.06 Sv/year and -0.18 Sv/year are evident from AMOC estimates at 45°N
198 (in depth and density space), from surface fluxes, reanalyses and forced models, respectively. At OVIDE, however, the -0.13
199 Sv/year AMOC reduction is not statistically significant. Hence there is strong evidence for a weakening AMOC at subpolar
200 latitudes following the mid 1990s, but the magnitude of this weakening remains uncertain. Although these reconstructions
201 differ in whether the AMOC was computed in density or depth space, and whether the wind-driven Ekman component was
202 included, such differences do not explain the range of trends found.

203 Long-term moorings of the western boundary current system at 53°N also provide evidence of a ~ 10% decline in deep
204 water export since 1998 (ref^{128,129}). Yet further north, the export of dense water across the Greenland-Scotland ridge has
205 remained stable since the early 1990s¹³⁰. Accordingly, the source of decadal variability originates south of the overflows but
206 north of 45°N¹², consistent with observations of dense anomalies and enhanced deep convection in the west subpolar North
207 Atlantic (south of the overflows) in the mid-90s^{15,57}.

208 Following this mid-90s to early 2010s AMOC weakening, there have been some indications of potential strengthening¹². In
209 particular, there has been an increase in density and deep convection in the subpolar North Atlantic^{15,57,58}, and an increase
210 in the AMOC from observational reconstructions (Fig 2a-c) and sub-polar density and sea level proxies (Fig.3a,c). However,
211 this strengthening is not present in reanalyses or forced models (though both show a cessation of a weakening trend), and the
212 magnitudes and timing of this strengthening vary across the different observational reconstructions and proxies.

213 These decadal changes in subpolar AMOC have been attributed to low-frequency atmospheric variability and associated
214 buoyancy forcing^{32,33,48,131}. In particular, persistent and intense positive winter NAO in the early 1990s, a subsequent
215 weakening of the winter NAO index until ~2010 and strengthening thereafter¹³², are all broadly consistent with with observed
216 AMOC variability. However, salinity changes are thought to also have contributed to subpolar AMOC changes. For example,
217 there is evidence that a small long-term freshening trend contributed to the very low subsurface density anomalies observed in
218 the Labrador Sea post-2000 (ref^{15,133}), with suggestions that melting from Greenland ice sheets might have contributed¹³⁴.
219 Variability in Arctic export of fresh water has led to "great salinity anomalies" in the subpolar North Atlantic in the 70s, 80s and
220 90s, though the impact these salinities might have had on the AMOC is uncertain¹³⁵⁻¹³⁷.

221 Subtropical AMOC

222 The subtropical AMOC exhibits different variability from that of the subpolar AMOC, with purported strengthening from
223 2001-2005 and weakening from 2005-2014. Although there is agreement between different reconstructions on interannual
224 variability, there is uncertainty on changes over longer timescales.

225 The longest estimate for the subtropical AMOC is from the ensemble of forced models, which reveals an AMOC strength-
226 ening to around 1998 and weakening thereafter (Fig 2j). These features are also seen in other forced model ensembles^{14,112},
227 including eddy-rich models^{109,110} (Supplementary Fig. 1), though no obvious influence of resolution on the response to forcing
228 was found^{109,110}. Although the weakening in the forced models is statistically significant from 1998-2018, it is not apparent in
229 other subtropical AMOC reconstructions (Fig 2g,h,i), and is, thus, uncertain.

230 There is, however, agreement on multi-annual AMOC changes and the decadal AMOC weakening observed by the
231 RAPID array. Over 1993-2015, all subtropical AMOC reconstructions (Fig 2g-j) are significantly correlated ($P < 0.05$) (other
232 than between the 41°N reconstruction and the forced ensemble), leading to confidence in the estimates of variability. The
233 observational reconstruction at 41°N is close to the inter-gyre boundary between subtropical and subpolar regions²⁸. Although
234 this reconstruction has previously been assumed to be representative of the subpolar North Atlantic¹³⁸, the variability at
235 41°N bears more resemblance to observational reconstructions in the subtropical North Atlantic (Fig 2h), suggesting that the
236 inter-gyre boundary is north of 41°N.

237 All reconstructions suggest a 0.21-0.69 Sv/year increase in subtropical AMOC strength from 2001-2006. However, these
238 trends are only statistically significant for the AMOC reconstruction at 26.5°N (Fig 2g) and the ensemble mean of the reanalyses
239 (Fig 2i). All individual reanalyses also illustrate a strengthening over this period¹³.

240 Following this strengthening, the RAPID array shows a weakening of 0.4 Sv/year from 2005-2014¹⁸ (Fig. 2f). This decadal
241 weakening is statistically significant even when neglecting the temporary 2009-2010 dip¹⁸, and is consistent with decadal
242 variability in climate models^{21,139}. Other reconstructions similarly capture a decadal weakening at this time, although trends of
243 the order 0.23-0.27 Sv/year are somewhat weaker. Since 2014 the AMOC has been steady, or slightly increasing, although this
244 increase is not statistically significant³⁰.

245 There is uncertainty about the drivers of these changes. Most of the monthly and interannual variability can be attributed
246 to wind forcing, including the negative NAO-related dip in 2009/10^{113,140-142}. There is also evidence of a buoyancy forced
247 contribution to the decadal weakening from 2005-2014 (ref^{31,142}), in particular through warming and freshening of the deep
248 waters (below 1200 m) at the western boundary¹⁴³. Although these signals were found in waters associated with North
249 Atlantic deep water (formed in the subpolar North Atlantic), there is no observational evidence of subpolar-to-subtropical signal
250 propagation or consensus on how subpolar changes might have influenced subtropical AMOC variability. For example, the
251 strong subtropical AMOC in 2004-2006 has been linked to the strong subpolar AMOC in the mid 1990s through decadal
252 propagation of subpolar dense anomalies²⁰. However, the strong subpolar AMOC in the mid 1990s has also been linked to a
253 strong subtropical AMOC in the late 1990s, with a faster propagation time^{30,112}. While some models also suggest meridional
254 linkages of AMOC variability⁸⁶⁻⁸⁸, the processes and timescales vary, and it might be that some subpolar signals do not reach
255 the subtropics^{90,91,93}.

256 **Impacts on heat and freshwater**

257 AMOC variability can impact Atlantic Ocean heat and freshwater content. Hence, observations of temperature and salinity
258 patterns can be used to infer AMOC changes if other contributions to heat and freshwater budgets are assumed to be small.
259 Between the early-1990s and the mid-2000s, upper ocean temperature increased in the subpolar North Atlantic and in the
260 tropics, but decreased along the Gulf Stream path (Fig 4). This pattern is consistent with Atlantic Multidecadal Variability
261 (AMV)³, which in models, is linked to an increase in the AMOC^{51,78,80,125}. After 2007, these trends reversed, cooling the
262 subpolar North Atlantic and warming the western subtropics^{3,15,144,145} (Fig 4). Since 2015, upper subpolar North Atlantic
263 layers warmed by around 0.2-1°C, with salinity also increasing^{15,145} by 0.02-0.1 PSU (Fig 4). The similarity in temperature and
264 salinity patterns provides evidence for changes in advection affecting both heat and freshwater transports. These temperature
265 and salinity changes are consistent with subpolar AMOC variability: a strong AMOC in the mid 1990s (leading to greater heat
266 and salt transports across 45/50°N, hence warming and salinification of the subpolar North Atlantic and cooling and freshening
267 of the subtropics), a weak AMOC around 2010 (leading to a reversal in the pattern), and a stronger AMOC since 2015.

268 Several proxies representing AMV^{120,121}, subpolar North Atlantic SSTs¹²³ and subpolar North Atlantic subsurface
269 temperatures^{146,147}, also illustrate an AMOC increase from the mid-90s to the mid-2000s, followed by a decrease (Fig.3d-f).
270 This variability is closer to that seen in the subtropical AMOC reconstructions than the subpolar reconstructions. However,
271 ocean temperature changes can lag the AMOC by several years¹⁴⁷, and lags can differ across models^{7,122} and depend on
272 the latitude the AMOC is measured at¹²². Hence, there is some uncertainty as to which aspects of the AMOC these proxies
273 represent.

274 Changes in temperature and salinity can be driven by a number of processes. Although some cooling in 2014 can be related
275 to surface fluxes¹⁴⁸, observed heat budget reconstructions^{12,16,48} suggest that temperature trends cannot be fully explained by
276 variations in surface heat fluxes alone, and are rather due to the varying magnitude of ocean heat transport convergence resulting
277 from changes in the AMOC and horizontal gyre circulations¹⁴⁴. In particular, the 2007-2015 cooling (and freshening) of the
278 subpolar North Atlantic results from weak heat (and salt) transports across 45°N¹⁴⁵, consistent with the reduced strength of the
279 AMOC at 45°N¹². Likewise, the latest cooling-to-warming reversal was likely driven by changes in ocean heat advection from
280 the subtropics with a lesser (yet non-negligible) role of air-sea heat fluxes¹⁴⁹, consistent with a strengthening of the subpolar
281 AMOC since 2010 (Fig. 2a-c).

282 While AMOC variability is an important driver of North Atlantic temperature and salinity, as suggested by models^{3,87} and
283 observations¹⁵⁰, uncertainties about its relative contribution exist. Indeed, other processes can also be important, including
284 local atmospheric forcing^{151,152} and external forcing^{2,153}. Furthermore, coupled models tend to underestimate the magnitude
285 of decadal SST variability in the North Atlantic compared to observations¹⁵⁴, so the dominant mechanisms of decadal SST
286 variability might differ between models and observations.

287 **Long term context**

288 In addition to internal variability, the AMOC can also vary owing to external forcing such as changing greenhouse gas
289 concentrations or aerosols (Fig 1). Externally-forced AMOC changes, historical evolution and future projections are now
290 discussed.

291 **Forced changes**

292 Given that ensemble averaging cancels out internal variability leaving only an externally-forced response, ensemble means of
293 climate models can be used to examine the impact of external forcing on the AMOC. Generally, increased greenhouse gases are
294 expected to weaken the AMOC through warming-related reductions in subpolar density^{155,156}, exacerbated by freshening from
295 increased precipitation, sea ice loss and ice sheet melting¹⁵⁷. Anthropogenic aerosol increases also cause a strengthening of the
296 AMOC in models. Differing mechanisms have been proposed to explain this connection, including cooling through modified

297 heat fluxes¹⁵⁸ and increases in salinity through changes in evaporation and precipitation^{131,159}. In addition to this mechanistic
298 uncertainty, historical anthropogenic forcing itself remains uncertain¹⁶⁰. As such, the extent that aerosol forcing has driven
299 historical AMOC changes remains an open question.

300 An ensemble mean of historical (1850–2014) CMIP6 simulations (Fig 5) reveals a 10% strengthening of the AMOC
301 to a maximum around 1980, followed by a weakening (-1.2 ± 0.2 Sv over 2004–2014 minus 1974–1984)²⁴. This AMOC
302 strengthening is attributed to changes in anthropogenic aerosol concentrations, with a small overall weakening from increases
303 in greenhouse gases¹⁰. However, there is evidence that CMIP6 models with the strongest aerosol forcing overestimate its
304 impact^{10,161}, and hence uncertainty around the historical forced response. The forced weakening since 1980 from CMIP6
305 simulations (Fig 5) is not seen in estimates of subpolar or subtropical AMOC changes (Fig 2), but the small magnitude of this
306 forced change in comparison to the decadal and interannual variability of the AMOC would make it difficult to detect.

307 **Linking to the past**

308 There are substantial uncertainties in how the AMOC might have changed over the past few centuries. In particular, while
309 model ensembles indicate a 20th century strengthening, salinity¹⁶² and sea level¹⁶³ proxies, along with palaeoclimate
310 records^{26,123,127,164}, all indicate a weakening, albeit with variations in timing and magnitude. Proxy observations reveal
311 a region of reduced warming (a “warming hole”) developing over the last century in the subpolar North Atlantic that some
312 model simulations suggest is related to a weakened AMOC and ocean heat transports. Indeed, a proxy for AMOC strength
313 using the difference between warming hole SSTs and global mean SSTs^{25,123} suggests a 3 ± 1 Sv AMOC weakening since the
314 middle of the twentieth century. However, the interpretation of this proxy for AMOC changes^{10,119,164,165} and its applicability
315 to the historical period^{10,165} have substantial uncertainties. Although it has been suggested that this weakening is the result of
316 fresh water from melting glaciers¹²³ (which climate models represent poorly or not at all), such impacts are not yet considered
317 large enough to influence the AMOC^{166,167}. Apparent model-proxy conflicts over the historical AMOC record might arise
318 from proxies being unable to capture AMOC variations, particularly in the presence of large changes in forcing over different
319 periods, or because of model deficiencies in the response of the AMOC to forcing.

320 **Future projections and predictions**

321 To understand how the AMOC might evolve in the future, climate models must be used. Over the next century, a long term
322 weakening of the AMOC is expected owing to increased greenhouse gases^{11,24}. However, there is substantial uncertainty in
323 the magnitude of this weakening arising from differences in how individual models respond to forcing^{24,168,169}. Nevertheless,
324 a relationship between the present-day AMOC strength and projected weakening in CMIP6 models provides an emergent
325 constraint, suggesting a 6-8 Sv (34-45%) decrease in AMOC strength by 2100 (ref²⁴). Differences in the mean climate state,
326 in particular the locations of water mass transformation, can also affect AMOC projections. For example, in some models, a
327 higher resolution ocean impacts the climate state and leads to a greater projected AMOC weakening¹⁷⁰, but different models
328 have different responses¹⁷¹.

329 In contrast to the longer-term weakening, AMOC variability over the next decade or two is likely to be caused by a mix of
330 long-term forced decline and internal variability. On these timescales, the internal variability is of similar magnitude to the
331 forced changes (Fig 5). Thus, internal AMOC variability could oppose or reinforce the long-term trend making it difficult to
332 detect (Fig 5). There is potential for predictability using a multimodel mean¹⁷². For example, predictions made in 2020 using
333 7 near-term prediction systems suggest the AMOC will be weaker in 2021–2025 than the 1981–2010 average, but there is
334 considerable uncertainty in these predictions¹⁷³ and weak skill in the subtropics¹⁷⁴. Although a long-term AMOC weakening is
335 considered very likely in the future, a temporary strengthening related to decadal variability is possible. Predicting the evolution
336 of the AMOC over the next decade or so is, thus, a major goal.

337 **Summary and future perspectives**

338 Having critically assessed decadal AMOC variability since 1980, both models and observations indicate that the AMOC
339 varies on interannual and decadal timescales, with differences between the subpolar and subtropical North Atlantic. For the
340 subpolar AMOC, there is strong evidence for a buoyancy forced increase in AMOC strength from at least 1980 to the mid
341 1990s, a weakening over the following 20 years^{15,32,33,48}, and emerging evidence of strengthening at 45°N since the early
342 2010s¹²; this latter strengthening is not yet apparent in all lines of evidence, and the relative magnitude of this strengthening
343 varies substantially. In the subtropics, by contrast, there is some evidence of an AMOC strengthening from 2001–2005, strong
344 evidence (including from direct measurement at the RAPID array) of a decadal AMOC weakening from around 2005, and
345 relative stability since the early 2010s^{18,30}. It is difficult to determine any coherence between AMOC variability in the subpolar
346 and subtropical regions, specifically the propagation of signals from the former to the latter. Although a long-term weakening
347 of AMOC has previously been suggested, there is no evidence for such changes in the subpolar or subtropical AMOC from
348 1980 to the present day, in agreement with modelling results^{22,175}. However, a gradual long-term weakening could be obscured

349 by the large interannual and decadal variability. Hence, these changes are not inconsistent with a weakening over a much longer
350 period, such as that expected from anthropogenic warming^{11,24}.

351 Despite understanding of decadal-scale AMOC changes, there are still many unknowns and challenges. For instance,
352 existing observational mooring arrays are expensive and lack sustainable funding. Thus, low-cost approaches to AMOC
353 monitoring are required, perhaps through reduced complexity arrays (for example with fewer instruments or moorings), with
354 their accuracy being tested with numerical models. Such long-term monitoring is required at both subtropical and subpolar
355 latitudes.

356 In addition to long-term observations, there is scope to develop alternative methods for monitoring the AMOC. Alternative
357 approaches that make use of existing observations, such as observational reconstructions, proxies and reanalyses, should be
358 further explored: data science techniques might provide new methodologies for combining observations. Given uncertainties in
359 different monitoring strategies we recommend using multiple, independent estimates of the AMOC to increase confidence in
360 results.

361 Climate and ocean models also offer opportunities to better understand the AMOC, and to provide predictions and
362 projections of its future evolution. However, certain processes, such as mixing by mesoscale eddies, transports in narrow
363 boundary currents, mixing in overflows, deep convection and atmosphere-ocean feedbacks are often inadequately represented¹⁰⁸.
364 These deficiencies can lead to model biases, impacting how the simulated AMOC evolves¹⁷⁰. Therefore, understanding and
365 constraining the causes of model error is an important route to improving AMOC simulations and predictions. It is also crucial
366 to better understand the causal relationships between processes such as surface buoyancy forcing, deep convection, sinking and
367 the AMOC, and whether these interactions are correctly represented in models^{59,65,69}. Unravelling these causal relationships
368 requires improved understanding from both detailed observations and high-resolution process studies, especially given that
369 small scale processes are likely to be key. Long term measurements remain important in this regard^{19,59,176,177}, and increasing
370 sampling in less observed regions of the North Atlantic, such as the deep ocean and in boundary currents, is vital¹⁷⁸. Increasing
371 the resolution might also be an important route for improving the representation of the AMOC in coupled models, but resolving
372 all these processes will be difficult to achieve for the foreseeable future owing to the computational expense. Technical solutions
373 to improve resolution where it is needed, such as nested models or unstructured grids, might be an alternative, though improved
374 representations of unresolved processes will still likely be needed through improved parameterisations. Doing so requires
375 collaborations across observational, process-modelling and climate modelling communities.

376 Finally, there needs to be better understanding of how to separate forced trends (from greenhouse gases and aerosols) and
377 internal variability in order to detect weakening from anthropogenic climate change. One approach might be to use large
378 ensembles of simulations to quantify how individual drivers and variability imprint on the AMOC and wider ocean patterns, and
379 to examine where they differ. Understanding how robust these patterns are in different models and scenarios might also help to
380 reconcile historical changes implied by proxies and climate models^{10,26,164,165}. Partial coupling or coupled data assimilation
381 might close the gap between forced ocean models and climate models, offering the opportunity to understand historical AMOC
382 drivers while still correctly representing coupled processes. Improvements to predict and quantify the AMOC evolution of the
383 coming decades is a major goal and requires a better understanding of the processes and model improvements.

384 References

- 385 1. Trenberth, K. E., Zhang, Y., Fasullo, J. T. & Cheng, L. Observation-based estimates of global and basin ocean meridional
386 heat transport time series. *J. Clim.* **32**, 4567–4583 (2019).
- 387 2. Bellomo, K., Angeloni, M., Corti, S. & von Hardenberg, J. Future climate change shaped by inter-model differences
388 in atlantic meridional overturning circulation response. *Nat. Commun.* **12**, 3659, DOI: [10.1038/s41467-021-24015-w](https://doi.org/10.1038/s41467-021-24015-w)
389 (2021).
- 390 3. Zhang, R. *et al.* A review of the role of the atlantic meridional overturning circulation in atlantic multidecadal variability
391 and associated climate impacts. *Rev. Geophys.* **57**, 316– 375, DOI: [10.1029/2019RG000644](https://doi.org/10.1029/2019RG000644) (2019).
- 392 4. Sarmiento, J. L. & Le Quere, C. Oceanic carbon dioxide uptake in a model of century-scale global warming. *Science* **274**,
393 1346–1350 (1996).
- 394 5. McCarthy, G. D. *et al.* Measuring the Atlantic meridional overturning circulation at 26°N. *Prog. Oceanogr.* **130**, 91–111,
395 DOI: [10.1016/j.pocean.2014.10.006](https://doi.org/10.1016/j.pocean.2014.10.006) (2015).
- 396 6. Danabasoglu, G. On multidecadal variability of the Atlantic Meridional Overturning Circulation in the Community
397 Climate System Model Version 3. *J. Clim.* **21**, 5524–5544, DOI: [10.1175/2008JCLI2019.1](https://doi.org/10.1175/2008JCLI2019.1) (2008).
- 398 7. Ba, J. *et al.* A multi-model comparison of Atlantic multidecadal variability. *Clim. Dyn.* **43**, 2333–2348, DOI: [10.1007/
399 s00382-014-2056-1](https://doi.org/10.1007/s00382-014-2056-1) (2014).

- 400 8. Wills, R. C., Armour, K. C., Battisti, D. S. & Hartmann, D. L. Ocean–atmosphere dynamical coupling fundamental to the
401 atlantic multidecadal oscillation. *J. Clim.* **32**, 251–272 (2019).
- 402 9. Otterå, O. H., Bentsen, M., Drange, H. & Suo, L. External forcing as a metronome for atlantic multidecadal variability.
403 *Nat. Geosci.* **3**, 688–694 (2010).
- 404 10. Menary, M. B. *et al.* Aerosol-forced amoc changes in cmip6 historical simulations. *Geophys. Res. Lett.* DOI: [10.1029/
405 2020GL088166](https://doi.org/10.1029/2020GL088166) (2020).
- 406 11. Collins, M. *et al.* Long-term Climate Change: Projections, Commitments and Irreversibility. In Stocker, T. F. *et al.* (eds.)
407 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of
408 the Intergovernmental Panel on Climate Change*, DOI: [10.1017/CBO9781107415324.025](https://doi.org/10.1017/CBO9781107415324.025) (Cambridge University Press,
409 Cambridge, United Kingdom and New York, NY, USA., 2013).
- 410 12. Desbruyères, D., Mercier, H., Maze, G. & Daniault, N. Surface predictor of overturning circulation and heat content
411 change in the subpolar north atlantic. *Ocean. Sci.* **15**, 809–817, DOI: [10.5194/os-15-809-2019](https://doi.org/10.5194/os-15-809-2019) (2019).
- 412 13. Jackson, L. C. *et al.* The mean state and variability of the north atlantic circulation: A perspective from ocean reanalyses.
413 *J. Geophys. Res. Ocean.* **124**, 9141–9170, DOI: <https://doi.org/10.1029/2019JC015210> (2019).
- 414 14. Tsujino, H. *et al.* Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the
415 Ocean Model Intercomparison Project phase 2 (OMIP-2). *Geosci. Model. Dev. Discuss.* **2020**, 1–86, DOI: [10.5194/
416 gmd-2019-363](https://doi.org/10.5194/gmd-2019-363) (2020).
- 417 15. Robson, J., Ortega, P. & Sutton, R. A reversal of climatic trends in the North Atlantic since 2005. *Nat. Geosci.* **9**, 513–517,
418 DOI: [10.1038/ngeo2727](https://doi.org/10.1038/ngeo2727) (2016).
- 419 16. Bryden, H. L. *et al.* Reduction in ocean heat transport at 26°n since 2008 cools the eastern subpolar gyre of the North
420 Atlantic ocean. *J. Clim.* **33**, 1677–1689, DOI: [10.1175/JCLI-D-19-0323.1](https://doi.org/10.1175/JCLI-D-19-0323.1) (2020).
- 421 17. Srokosz, M. A. & Bryden, H. L. Observing the Atlantic meridional overturning circulation yields a decade of inevitable
422 surprises. *Science* **348**, 1255575, DOI: [10.1126/science.1255575](https://doi.org/10.1126/science.1255575) (2015).
- 423 18. Smeed, D. A. *et al.* Observed decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean. Sci.* **10**,
424 29–38, DOI: [10.5194/os-10-29-2014](https://doi.org/10.5194/os-10-29-2014) (2014).
- 425 19. Smeed, D. A. *et al.* The North Atlantic Ocean Is in a State of Reduced Overturning. *Geophys. Res. Lett.* **45**,
426 2017GL076350+, DOI: [10.1002/2017gl076350](https://doi.org/10.1002/2017gl076350) (2018).
- 427 20. Jackson, L. C., Peterson, K. A., Roberts, C. D. & Wood, R. A. Recent slowing of Atlantic overturning circulation as a
428 recovery from earlier strengthening. *Nat. Geosci.* **9**, 518–522, DOI: [10.1038/ngeo2715](https://doi.org/10.1038/ngeo2715) (2016).
- 429 21. Latif, M., Park, T. & Park, W. Decadal atlantic meridional overturning circulation slowing events in a climate model.
430 *Clim. Dyn.* **53**, 1111–1124, DOI: [10.1007/s00382-019-04772-7](https://doi.org/10.1007/s00382-019-04772-7) (2019).
- 431 22. Fu, Y., Li, F., Karstensen, J. & Wang, C. A stable atlantic meridional overturning circulation in a changing north atlantic
432 ocean since the 1990s. *Sci. Adv.* **6**, eabc7836, DOI: [10.1126/sciadv.abc7836](https://doi.org/10.1126/sciadv.abc7836) (2020).
- 433 23. Danabasoglu, G., Landrum, L., Yeager, S. G. & Gent, P. R. Robust and nonrobust aspects of Atlantic Meridional
434 Overturning Circulation variability and mechanisms in the Community Earth System Model. *J. Clim.* **32**, 7349–7368,
435 DOI: [10.1175/JCLI-D-19-0026.1](https://doi.org/10.1175/JCLI-D-19-0026.1) (2019).
- 436 24. Weijer, W., Cheng, W., Garuba, O. A., Hu, A. & Nadiga, B. T. CMIP6 Models Predict Significant 21st Century Decline
437 of the Atlantic Meridional Overturning Circulation. *Geophys. Res. Lett.* **47**, DOI: [10.1029/2019GL086075](https://doi.org/10.1029/2019GL086075) (2020).
- 438 25. Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. & Saba, V. Observed fingerprint of a weakening atlantic ocean
439 overturning circulation. *Nature* **556**, 191–196, DOI: [10.1038/s41586-018-0006-5](https://doi.org/10.1038/s41586-018-0006-5) (2018).
- 440 26. Caesar, L., McCarthy, G., Thornalley, J., Cahill, N. & Rahmstorf, S. Current atlantic meridional overturning circulation
441 weakest in last millennium. *Nat. Geosci.* **14**, 118–120, DOI: [10.1038/s41561-021-00699-z](https://doi.org/10.1038/s41561-021-00699-z) (2021).
- 442 27. Booth, B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. & Bellouin, N. Aerosols implicated as a prime driver of
443 twentieth-century north atlantic climate variability. *Nature* **484**, 228–232 (2012).
- 444 28. Buckley, M. W. & Marshall, J. Observations, inferences, and mechanisms of the Atlantic Meridional Overturning
445 Circulation: A review. *Rev. Geophys.* **54**, 2015RG000493+, DOI: [10.1002/2015rg000493](https://doi.org/10.1002/2015rg000493) (2016).
- 446 29. Yeager, S. G. & Robson, J. I. Recent progress in understanding and predicting atlantic decadal climate variability. *Curr.*
447 *Clim. Chang. Reports* **3**, 112–127, DOI: [10.1007/s40641-017-0064-z](https://doi.org/10.1007/s40641-017-0064-z) (2017).

- 448 **30.** Moat, B. I. *et al.* Pending recovery in the strength of the meridional overturning circulation at 26°N. *Ocean. Sci.* **16**,
449 863–874, DOI: [10.5194/os-16-863-2020](https://doi.org/10.5194/os-16-863-2020) (2020).
- 450 **31.** Kostov, Y. *et al.* Distinct sources of interannual subtropical and subpolar Atlantic overturning variability. *Nat. Geosci.*
451 DOI: [10.1038/s41561-021-00759-4](https://doi.org/10.1038/s41561-021-00759-4) (2021).
- 452 **32.** Biastoch, A., Böning, C. W., Getzlaff, J., Molines, J.-M. & Madec, G. Causes of interannual–decadal variability
453 in the Meridional Overturning Circulation of the midlatitude North Atlantic Ocean. *J. Clim.* **21**, 6599–6615, DOI:
454 [10.1175/2008JCLI2404.1](https://doi.org/10.1175/2008JCLI2404.1) (2008).
- 455 **33.** Yeager, S. & Danabasoglu, G. The Origins of Late-Twentieth-Century Variations in the Large-Scale North Atlantic
456 Circulation. *J. Clim.* **27**, 3222–3247, DOI: [10.1175/jcli-d-13-00125.1](https://doi.org/10.1175/jcli-d-13-00125.1) (2014).
- 457 **34.** Pillar, H. R., Heimbach, P., Johnson, H. L. & Marshall, D. P. Dynamical attribution of recent variability in Atlantic
458 Overturning. *J. Clim.* **29**, 3339–3352, DOI: [10.1175/JCLI-D-15-0727.1](https://doi.org/10.1175/JCLI-D-15-0727.1) (2016).
- 459 **35.** Larson, S. M., Buckley, M. W. & Clement, A. C. Extracting the buoyancy-driven Atlantic meridional overturning
460 circulation. *J. Clim.* DOI: [10.1175/JCLI-D-19-0590.1](https://doi.org/10.1175/JCLI-D-19-0590.1) (2020).
- 461 **36.** Baehr, J., Hirschi, J., Beismann, J.-O. & Marotzke, J. Monitoring the meridional overturning circulation in the north
462 Atlantic: A model-based array design study. *J. Mar. Res.* **62**, 283–312, DOI: [doi:10.1357/0022240041446191](https://doi.org/10.1357/0022240041446191) (2004).
- 463 **37.** Clément, L., Frajka-Williams, E., Szuts, Z. B. & Cunningham, S. A. Vertical structure of eddies and Rossby waves, and
464 their effect on the Atlantic meridional overturning circulation at 26.5°N. *J. Geophys. Res. Ocean.* **119**, 6479–6498, DOI:
465 [10.1002/2014JC010146](https://doi.org/10.1002/2014JC010146) (2014).
- 466 **38.** Polo, I., Robson, J., Sutton, R. & Bamaseda, M. The importance of wind and buoyancy forcing of the boundary
467 density variations and the geostrophic component of the AMOC at 26°N. *J. Phys. Oceanogr.* **44**, 2387–2408, DOI:
468 [10.1175/JPO-D-13-0264.1](https://doi.org/10.1175/JPO-D-13-0264.1) (2014).
- 469 **39.** Buckley, M. W., Ferreira, D., Campin, J.-M., Marshall, J. & Tulloch, R. On the relationship between decadal buoyancy
470 anomalies and variability of the Atlantic Meridional Overturning Circulation. *J. Clim.* **25**, 8009–8030, DOI: [10.1175/
471 JCLI-D-11-00505.1](https://doi.org/10.1175/JCLI-D-11-00505.1) (2012).
- 472 **40.** Bingham, R., Hughes, C., Roussenov, V. & Williams, R. Meridional coherence of the North Atlantic meridional
473 overturning circulation. *Geophys. Res. Lett.* **34**, L23606, DOI: [10.1029/2007GL031731](https://doi.org/10.1029/2007GL031731) (2007).
- 474 **41.** Mielke, C., Frajka-Williams, E. & Baehr, J. Observed and simulated variability of the AMOC at 26°N and 41°N. *Geophys.*
475 *Res. Lett.* DOI: [10.1002/grl.50233](https://doi.org/10.1002/grl.50233) (2013).
- 476 **42.** Wunsch, C. & Heimbach, P. Two decades of the Atlantic Meridional Overturning Circulation: Anatomy, variations,
477 extremes, prediction, and overcoming its limitations. *J. Clim.* **26**, 7167–7186, DOI: [10.1175/JCLI-D-12-00478.1](https://doi.org/10.1175/JCLI-D-12-00478.1) (2013).
- 478 **43.** Gu, S., Liu, Z. & Wu, L. Time scale dependence of the meridional coherence of the Atlantic Meridional Overturning
479 Circulation. *J. Geophys. Res. Ocean.* **125**, e2019JC015838, DOI: [10.1029/2019JC015838](https://doi.org/10.1029/2019JC015838) (2020).
- 480 **44.** Lozier, M., Roussenov, V., Reed, M. & Williams, R. Opposing decadal changes for the north Atlantic meridional
481 overturning circulation. *Nat. Geosci.* **3**, 728–734, DOI: [10.1038/ngeo947](https://doi.org/10.1038/ngeo947) (2010).
- 482 **45.** Groeskamp, S. *et al.* The water mass transformation framework for ocean physics and biogeochemistry. *Annu. Rev. Mar.*
483 *Sci.* **11**, 271–305, DOI: [10.1146/annurev-marine-010318-095421](https://doi.org/10.1146/annurev-marine-010318-095421) (2019). PMID: 30230995.
- 484 **46.** Xu, X., Rhines, P. & Chassignet, E. On mapping the diapycnal water mass transformation of the upper north Atlantic
485 ocean. *J. Phys. Ocean.* **48**, 2233–2258, DOI: [10.1175/JPO-D-17-0223.1](https://doi.org/10.1175/JPO-D-17-0223.1) (2018).
- 486 **47.** Böning, C. W., Scheinert, M., Dengg, J., Biastoch, A. & Funk, A. Decadal variability of subpolar gyre transport and its
487 reverberation in the North Atlantic overturning. *Geophys. Res. Lett.* **33**, DOI: [10.1029/2006GL026906](https://doi.org/10.1029/2006GL026906) (2006).
- 488 **48.** Robson, J., Sutton, R., Lohmann, K., Smith, D. & Palmer, M. D. Causes of the Rapid Warming of the North Atlantic
489 Ocean in the Mid-1990s. *J. Clim.* **25**, 4116–4134, DOI: [10.1175/jcli-d-11-00443.1](https://doi.org/10.1175/jcli-d-11-00443.1) (2012).
- 490 **49.** Delworth, T. L. & Zeng, F. The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic
491 Meridional Overturning Circulation. *J. Clim.* **29**, 941–962, DOI: [10.1175/JCLI-D-15-0396.1](https://doi.org/10.1175/JCLI-D-15-0396.1) (2016).
- 492 **50.** Kim, W. M., Yeager, S. & Danabasoglu, G. Atlantic Multidecadal Variability and associated climate impacts initiated by
493 ocean thermohaline dynamics. *J. Clim.* **33**, 1317–1334, DOI: [10.1175/JCLI-D-19-0530.1](https://doi.org/10.1175/JCLI-D-19-0530.1) (2019).
- 494 **51.** Delworth, T., Manabe, S. & Stouffer, R. J. Interdecadal variations of the thermohaline circulation in a coupled ocean-
495 atmosphere model. *J. Clim.* **6**, 1993–2011, DOI: [10.1175/1520-0442\(1993\)006<1993:IVOTTC>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<1993:IVOTTC>2.0.CO;2) (1993).

- 496 **52.** Kwon, Y.-O. & Frankignoul, C. Stochastically-driven multidecadal variability of the Atlantic meridional overturning
497 circulation in CCSM3. *Clim. Dyn.* **38**, 859–876, DOI: [10.1007/s00382-011-1040-2](https://doi.org/10.1007/s00382-011-1040-2) (2012).
- 498 **53.** Danabasoglu, G. *et al.* Variability of the Atlantic Meridional Overturning Circulation in CCSM4. *J. Clim.* **25**, 5153–5172,
499 DOI: [10.1175/JCLI-D-11-00463.1](https://doi.org/10.1175/JCLI-D-11-00463.1) (2012).
- 500 **54.** Roberts, C. D., Garry, F. K. & Jackson, L. C. A multimodel study of sea surface temperature and subsurface density
501 fingerprints of the Atlantic Meridional Overturning Circulation. *J. Clim.* **26**, 9155–9174, DOI: [10.1175/JCLI-D-12-00762.](https://doi.org/10.1175/JCLI-D-12-00762.1)
502 **1** (2013).
- 503 **55.** Vage, K. *et al.* Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007-2008. *Nat.*
504 *Geosci* **2**, 67–72 (2009).
- 505 **56.** Rhein, M. *et al.* Deep water formation, the subpolar gyre, and the meridional overturning circulation in the subpolar
506 North Atlantic. *Deep. Sea Res. Part II: Top. Stud. Oceanogr.* **58**, 1819–1832, DOI: [10.1016/j.dsr2.2010.10.061](https://doi.org/10.1016/j.dsr2.2010.10.061) (2011).
- 507 **57.** Yashayaev, I. & Loder, J. W. Recurrent replenishment of Labrador Sea Water and associated decadal-scale variability. *J.*
508 *Geophys. Res. Ocean.* **121**, 8095–8114, DOI: [10.1002/2016jc012046](https://doi.org/10.1002/2016jc012046) (2016).
- 509 **58.** Yashayaev, I. & Loder, J. W. Further intensification of deep convection in the Labrador Sea in 2016. *Geophys. Res. Lett.*
510 **44**, 2016GL071668+, DOI: [10.1002/2016gl071668](https://doi.org/10.1002/2016gl071668) (2017).
- 511 **59.** Li, F. *et al.* Subpolar north atlantic western boundary density anomalies and the meridional overturning circulation. *Nat*
512 *Commun* **12**, 3002, DOI: [10.1038/s41467-021-23350-2](https://doi.org/10.1038/s41467-021-23350-2) (2021).
- 513 **60.** Mauritzen, C. & Häkkinen, S. On the relationship between dense water formation and the “Meridional Overturning Cell” in
514 the North Atlantic ocean. *Deep. Sea Res. Part I: Oceanogr. Res. Pap.* **46**, 877–894, DOI: [10.1016/S0967-0637\(98\)00094-6](https://doi.org/10.1016/S0967-0637(98)00094-6)
515 (1999).
- 516 **61.** Deshayes, J., Frankignoul, C. & Drange, H. Formation and export of deep water in the Labrador and Irminger Seas in a
517 GCM. *Deep. Sea Res. Part I: Oceanogr. Res. Pap.* **54**, 510 – 532, DOI: [10.1016/j.dsr.2006.12.014](https://doi.org/10.1016/j.dsr.2006.12.014) (2007).
- 518 **62.** Grist, J. P., Marsh, R. & Josey, S. A. On the relationship between the north atlantic meridional overturning circulation and
519 the surface-forced overturning streamfunction. *J. Clim.* **22**, 4989 – 5002, DOI: [10.1175/2009JCLI2574.1](https://doi.org/10.1175/2009JCLI2574.1) (2009).
- 520 **63.** Josey, S. A., Grist, J. P. & Marsh, R. Estimates of meridional overturning circulation variability in the north atlantic from
521 surface density flux fields. *J. Geophys. Res. Ocean.* **114**, DOI: <https://doi.org/10.1029/2008JC005230> (2009).
- 522 **64.** Chafik, L. & Rossby, T. Volume, heat, and freshwater divergences in the Subpolar North Atlantic suggest the Nordic
523 Seas as key to the state of the Meridional Overturning Circulation. *Geophys. Res. Lett.* **46**, 4799–4808, DOI: [10.1029/
524 2019GL082110](https://doi.org/10.1029/2019GL082110) (2019).
- 525 **65.** Lozier, M. S. *et al.* A sea change in our view of overturning in the subpolar North Atlantic. *Science* **363**, 516, DOI:
526 [10.1126/science.aau6592](https://doi.org/10.1126/science.aau6592) (2019).
- 527 **66.** Petit, T., Lozier, M. S., Josey, S. A. & Cunningham, S. A. Atlantic deep water formation occurs primarily in the Iceland
528 Basin and Irminger Sea by local buoyancy forcing. *Geophys. Res. Lett.* **47** (2020).
- 529 **67.** Feucher, C., Garcia-Quintana, Y., Yashayaev, I., Hu, X. & Myers, P. G. Labrador Sea Water Formation rate and its impact
530 on the local meridional overturning circulation. *J. Geophys. Res. Ocean.* **124**, 5654–5670, DOI: [10.1029/2019JC015065](https://doi.org/10.1029/2019JC015065)
531 (2019).
- 532 **68.** Hirschi, J. J. *et al.* The Atlantic Meridional Overturning Circulation in High-Resolution Models. *J. Geophys. Res. Ocean.*
533 **125**, DOI: [10.1029/2019JC015522](https://doi.org/10.1029/2019JC015522) (2020).
- 534 **69.** Menary, M. B., Jackson, L. C. & Lozier, M. S. Reconciling the relationship between the AMOC and Labrador Sea in
535 OSNAP observations and climate models. *Geophys. Res. Lett.* **47**, DOI: <https://doi.org/10.1029/2020GL089793> (2020).
- 536 **70.** Oldenburg, D., Wills, R., Armour, K., Thompson, L. & Jackson, L. Mechanisms of low-frequency variability in north
537 atlantic ocean heat transport and amoc. *J Clim* (2021).
- 538 **71.** Hirschi, J. J.-M. *et al.* Chaotic variability of the meridional overturning circulation on subannual to interannual timescales.
539 *Ocean. Sci.* **9**, 805–823, DOI: [10.5194/os-9-805-2013](https://doi.org/10.5194/os-9-805-2013) (2013).
- 540 **72.** Grégorio, S. *et al.* Intrinsic variability of the Atlantic Meridional Overturning Circulation at interannual-to-multidecadal
541 time scales. *J. Phys. Oceanogr.* **45**, 1929–1946, DOI: [10.1175/JPO-D-14-0163.1](https://doi.org/10.1175/JPO-D-14-0163.1) (2015).
- 542 **73.** Leroux, S. *et al.* Intrinsic and atmospherically forced variability of the AMOC: Insights from a large-ensemble ocean
543 hindcast. *J. Clim.* **31**, 1183–1203, DOI: [10.1175/JCLI-D-17-0168.1](https://doi.org/10.1175/JCLI-D-17-0168.1) (2018).

- 544 **74.** Frankcombe, L. M., von der Heydt, A. & Dijkstra, H. A. North Atlantic multidecadal climate variability: An investigation
545 of dominant time scales and processes. *J. Clim.* **23**, 3626–3638, DOI: [10.1175/2010JCLI3471.1](https://doi.org/10.1175/2010JCLI3471.1) (2010).
- 546 **75.** Sévellec, F. & Fedorov, A. V. The leading, interdecadal eigenmode of the Atlantic Meridional Overturning Circulation in
547 a realistic ocean model. *J. Clim.* **26**, 2160–2183, DOI: [10.1175/JCLI-D-11-00023.1](https://doi.org/10.1175/JCLI-D-11-00023.1) (2012).
- 548 **76.** Huck, T., Arzel, O. & Sévellec, F. Multidecadal variability of the overturning circulation in presence of eddy turbulence.
549 *J. Phys. Oceanogr.* **45**, 157–173, DOI: [10.1175/JPO-D-14-0114.1](https://doi.org/10.1175/JPO-D-14-0114.1) (2014).
- 550 **77.** Rahmstorf, S. & Willebrand, J. The role of temperature feedback in stabilizing the thermohaline circulation. *J. Phys.*
551 *Oceanogr.* **25**, 787–805, DOI: [10.1175/1520-0485\(1995\)025<0787:TROTFI>2.0.CO;2](https://doi.org/10.1175/1520-0485(1995)025<0787:TROTFI>2.0.CO;2) (1995).
- 552 **78.** Jungclauss, J., Haak, H., Latif, M. & Mikolajewicz, U. Arctic–north atlantic interactions and multidecadal variability of
553 the meridional overturning circulation. *J. Clim.* **18**, 4013 – 4031, DOI: [10.1175/JCLI3462.1](https://doi.org/10.1175/JCLI3462.1) (2005).
- 554 **79.** Deshayes, J., Curry, R. & Msadek, R. Cmp5 model intercomparison of freshwater budget and circulation in the north
555 atlantic. *J. Clim.* **27**, 3298 – 3317, DOI: [10.1175/JCLI-D-12-00700.1](https://doi.org/10.1175/JCLI-D-12-00700.1) (2014).
- 556 **80.** Timmermann, A., Latif, M., Voss, R. & Groetzner, A. Northern hemispheric interdecadal variability: a coupled air-sea
557 mode. *J. Clim.* **11**, 1906–1931 (1998).
- 558 **81.** Dima, M. & Lohmann, G. A hemispheric mechanism for the Atlantic Multidecadal Oscillation. *J. Clim.* **20**, 2706–2719,
559 DOI: [10.1175/JCLI4174.1](https://doi.org/10.1175/JCLI4174.1) (2007).
- 560 **82.** Menary, M. B., Hodson, D. L. R., Robson, J. I., Sutton, R. T. & Wood, R. A. A mechanism of internal decadal Atlantic
561 Ocean variability in a high-resolution coupled climate model. *J. Clim.* **28**, 7764–7785, DOI: [10.1175/JCLI-D-15-0106.1](https://doi.org/10.1175/JCLI-D-15-0106.1)
562 (2015).
- 563 **83.** Menary, M. B. *et al.* Exploring the impact of cmip5 model biases on the simulation of north atlantic decadal variability.
564 *Geophys. Res. Lett.* **42**, 5926–5934, DOI: <https://doi.org/10.1002/2015GL064360> (2015). <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015GL064360>.
- 566 **84.** Peings, Y., Simpkins, G. & Magnusdottir, G. Multidecadal fluctuations of the North Atlantic Ocean and feedback
567 on the winter climate in CMIP5 control simulations. *J. Geophys. Res. Atmospheres* **121**, 2571–2592, DOI: [10.1002/2015JD024107](https://doi.org/10.1002/2015JD024107)
568 (2016). [2015JD024107](https://doi.org/10.1002/2015JD024107).
- 569 **85.** Martin, T., Reintges, A. & Latif, M. Coupled north atlantic subdecadal variability in cmip5 models. *J. Geophys. Res.*
570 *Ocean.* **124**, 2404–2417, DOI: <https://doi.org/10.1029/2018JC014539> (2019). <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JC014539>.
- 572 **86.** Zhang, R. Latitudinal dependence of Atlantic meridional overturning circulation (AMOC) variations. *Geophys. Res. Lett.*
573 **37**, L16703, DOI: [10.1029/2010GL044474](https://doi.org/10.1029/2010GL044474) (2010).
- 574 **87.** Ortega, P. *et al.* Labrador sea sub-surface density as a precursor of multi-decadal variability in the north atlantic: a
575 multi-model study. *Earth Syst. Dynam. Discuss. [preprint]* DOI: [10.5194/esd-2020-83](https://doi.org/10.5194/esd-2020-83) (2020).
- 576 **88.** Hodson, D. & Sutton, R. The impact of resolution on the adjustment and decadal variability of the Atlantic meridional
577 overturning circulation in a coupled climate model. *Clim. Dyn.* **39**, 3057–3073, DOI: [10.1007/s00382-012-1309-0](https://doi.org/10.1007/s00382-012-1309-0) (2012).
- 578 **89.** Getzlaff, J., Böning, C., Eden, C. & Biastoch, A. Signal propagation related to the North Atlantic overturning. *Geophys.*
579 *Res. Lett.* **32**, DOI: [10.1029/2004GL021002](https://doi.org/10.1029/2004GL021002) (2005).
- 580 **90.** Bower, A. S., Lozier, M. S., Gary, S. F. & Böning, C. W. Interior pathways of the North Atlantic meridional overturning
581 circulation. *Nature* **459**, 243–247, DOI: [10.1038/nature07979](https://doi.org/10.1038/nature07979) (2009).
- 582 **91.** Gary, S. F., Lozier, M. S., Biastoch, A. & Böning, C. W. Reconciling tracer and float observations of the export pathways
583 of Labrador Sea Water. *Geophys. Res. Lett.* **39**, DOI: [10.1029/2012GL053978](https://doi.org/10.1029/2012GL053978) (2012).
- 584 **92.** Rhein, M., Kieke, D. & Steinfeldt, R. Advection of North Atlantic Deep Water from the Labrador Sea to the southern
585 hemisphere. *J. Geophys. Res. Ocean.* **120**, 2471–2487, DOI: [10.1002/2014JC010605](https://doi.org/10.1002/2014JC010605) (2015).
- 586 **93.** Zou, S. & Lozier, M. S. Breaking the linkage between Labrador Sea Water production and its advective export to the
587 subtropical gyre. *J. Phys. Oceanogr.* **46**, 2169–2182, DOI: [10.1175/JPO-D-15-0210.1](https://doi.org/10.1175/JPO-D-15-0210.1) (2016).
- 588 **94.** Li, F. *et al.* Local and downstream relationships between Labrador Sea Water volume and North Atlantic Meridional
589 Overturning Circulation variability. *J. Clim.* **32**, 3883–3898, DOI: [10.1175/JCLI-D-18-0735.1](https://doi.org/10.1175/JCLI-D-18-0735.1) (2019).
- 590 **95.** Bryden, H. L., Longworth, H. R. & Cunningham, S. A. Slowing of the Atlantic meridional overturning circulation at
591 25°N. *Nature* **438**, 655–657, DOI: [10.1038/nature04385](https://doi.org/10.1038/nature04385) (2005).

- 592 **96.** Mercier, H. *et al.* Variability of the meridional overturning circulation at the greenland–portugal ovide section from 1993
593 to 2010. *Prog. Oceanogr.* **132**, 250 – 261, DOI: <https://doi.org/10.1016/j.pocean.2013.11.001> (2015).
- 594 **97.** Kanzow, T. *et al.* Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N. *J. Clim.* **23**, 5678–5698,
595 DOI: [10.1175/2010JCLI3389.1](https://doi.org/10.1175/2010JCLI3389.1) (2010).
- 596 **98.** Frajka-Williams, E. *et al.* Atlantic meridional overturning circulation observed by the rapid-mocha-wbts (rapid-meridional
597 overturning circulation and heatflux array-western boundary time series) array at 26n from 2004 to 2020 (v2020.1), DOI:
598 [10.5285/cc1e34b3-3385-662b-e053-6c86abc03444](https://doi.org/10.5285/cc1e34b3-3385-662b-e053-6c86abc03444) (2021).
- 599 **99.** Rayner, N. A. *et al.* Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late
600 nineteenth century. *J. Geophys. Res.* **108**, 4407, DOI: [10.1029/2002JD002670](https://doi.org/10.1029/2002JD002670). (2003).
- 601 **100.** Willis, J. K. Can in situ floats and satellite altimeters detect long-term changes in atlantic ocean overturning? *geophys.*
602 *res. lett.*, **37**, 106602, doi:10.1029/2010gl042372. *Geophys. Res. Lett.* **37**, L06602, DOI: [10.1029/2010GL042372](https://doi.org/10.1029/2010GL042372) (2010).
- 603 **101.** Frajka-Williams, E. Estimating the Atlantic overturning at 26°N using satellite altimetry and cable measurements.
604 *Geophys. Res. Lett.* **42**, 2015GL063220+, DOI: [10.1002/2015gl063220](https://doi.org/10.1002/2015gl063220) (2015).
- 605 **102.** Sanchez-Franks, A., Frajka-Williams, E., Moat, B. I. & Smeed, D. A. A dynamically based method for estimating the
606 atlantic meridional overturning circulation at 26n from satellite altimetry. *Ocean. Sci.* **17**, 1321–1340, DOI: [10.5194/
607 os-17-1321-2021](https://doi.org/10.5194/os-17-1321-2021) (2021).
- 608 **103.** WALIN, G. On the relation between sea-surface heat flow and thermal circulation in the ocean. *Tellus* **34**, 187–195, DOI:
609 <https://doi.org/10.1111/j.2153-3490.1982.tb01806.x> (1982).
- 610 **104.** Marsh, R., Josey, S. A., de Nurser, A. J. G., Cuevas, B. A. & Coward, A. C. Water mass transformation in the north
611 atlantic over 1985-2002 simulated in an eddy-permitting model. *Ocean. Sci.* **1**, 127–144, DOI: [10.5194/os-1-127-2005](https://doi.org/10.5194/os-1-127-2005)
612 (2005).
- 613 **105.** Large, W. G. & Yeager, S. The global climatology of an interannually varying air-sea flux data set. *Clim. Dyn.* **33**,
614 341–364 (2009).
- 615 **106.** Tsujino, H. *et al.* JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do). *Ocean. Model.* **130**,
616 79–139, DOI: [10.1016/j.ocemod.2018.07.002](https://doi.org/10.1016/j.ocemod.2018.07.002) (2018).
- 617 **107.** Storto, A. *et al.* Ocean reanalyses: Recent advances and unsolved challenges. *Front. Mar. Sci.* **6**, 418, DOI: [10.3389/
618 fmars.2019.00418](https://doi.org/10.3389/fmars.2019.00418) (2019).
- 619 **108.** Fox-Kemper, B. *et al.* Challenges and prospects in ocean circulation models. *Front. Mar. Sci.* **6**, DOI: [10.3389/fmars.
620 2019.00065](https://doi.org/10.3389/fmars.2019.00065) (2019).
- 621 **109.** Chassignet, E. P. *et al.* Impact of horizontal resolution on global ocean–sea ice model simulations based on the
622 experimental protocols of the ocean model intercomparison project phase 2 (omip-2). *Geosci. Model. Dev.* **13**, 4595–4637,
623 DOI: [10.5194/gmd-13-4595-2020](https://doi.org/10.5194/gmd-13-4595-2020) (2020).
- 624 **110.** Biastoch, A. *et al.* Regional imprints of changes in the atlantic meridional overturning circulation in the eddy-rich ocean
625 model viking20x. *Ocean. Sci.* **17**, 1177–1211, DOI: [10.5194/os-17-1177-2021](https://doi.org/10.5194/os-17-1177-2021) (2021).
- 626 **111.** Danabasoglu, G. *et al.* North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II).
627 Part I: Mean states. *Ocean. Model.* **73**, 76–107, DOI: [10.1016/j.ocemod.2013.10.005](https://doi.org/10.1016/j.ocemod.2013.10.005) (2014).
- 628 **112.** Danabasoglu, G. *et al.* North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II).
629 Part II: Inter-annual to decadal variability. *Ocean. Model.* **97**, 65–90, DOI: [10.1016/j.ocemod.2015.11.007](https://doi.org/10.1016/j.ocemod.2015.11.007) (2016).
- 630 **113.** Blaker, A. *et al.* Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning
631 circulation at 26°N. *Clim. Dyn.* **44**, 457–473, DOI: [10.1007/s00382-014-2274-6](https://doi.org/10.1007/s00382-014-2274-6) (2015).
- 632 **114.** Griffies, S. M. *et al.* Coordinated Ocean-ice Reference Experiments (COREs). *Ocean. Model.* **26**, 1–46, DOI: [10.1016/j.
633 ocemod.2008.08.007](https://doi.org/10.1016/j.ocemod.2008.08.007) (2009).
- 634 **115.** Behrens, E., Biastoch, A. & Böning, C. W. Spurious AMOC trends in global ocean sea-ice models related to subarctic
635 freshwater forcing. *Ocean. Model.* **69**, 39–49, DOI: [10.1016/j.ocemod.2013.05.004](https://doi.org/10.1016/j.ocemod.2013.05.004) (2013).
- 636 **116.** Riser, S. C. *et al.* Fifteen years of ocean observations with the global Argo array. *Nat. Clim. Chang.* **6**, 145–153, DOI:
637 [10.1038/nclimate2872](https://doi.org/10.1038/nclimate2872) (2016).
- 638 **117.** Karspeck, A. R. *et al.* Comparison of the Atlantic meridional overturning circulation between 1960 and 2007 in six ocean
639 reanalysis products. *Clim. Dyn.* 1–26, DOI: [10.1007/s00382-015-2787-7](https://doi.org/10.1007/s00382-015-2787-7) (2015).

- 640 **118.** Roberts, C. D. & Palmer, M. D. Detectability of changes to the Atlantic Meridional Overturning Circulation in the Hadley
641 Centre Climate Models. *Clim. Dyn.* **39**, 2533–2546, DOI: [10.1007/s00382-012-1306-3](https://doi.org/10.1007/s00382-012-1306-3) (2012).
- 642 **119.** Jackson, L. & Wood, R. Fingerprints for early detection of changes in the amoc. *J. Clim.* **33**, 7027–7044, DOI:
643 [10.1175/JCLI-D-20-0034.1](https://doi.org/10.1175/JCLI-D-20-0034.1) (2020).
- 644 **120.** Latif, M. *et al.* Reconstructing, monitoring, and predicting multidecadal-scale changes in the north atlantic thermohaline
645 circulation with sea surface temperature. *J. Clim.* **17**, 1605–1614, DOI: [10.1175/1520-0442\(2004\)017<1605:RMAPMC>](https://doi.org/10.1175/1520-0442(2004)017<1605:RMAPMC>2.0.CO;2)
646 [2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1605:RMAPMC>2.0.CO;2) (2004).
- 647 **121.** Msadek, R., Dixon, K. W., Delworth, T. L. & Hurlin, W. Assessing the predictability of the atlantic meridional overturning
648 circulation and associated fingerprints. *Geophys. Res. Lett.* **37**, L19608, DOI: [10.1029/2010GL044517](https://doi.org/10.1029/2010GL044517) (2010).
- 649 **122.** Zhang, L. & Wang, C. Multidecadal North Atlantic sea surface temperature and Atlantic meridional overturning circulation
650 variability in CMIP5 historical simulations. *J. Geophys. Res. Ocean.* **118**, 5772–5791, DOI: [10.1002/jgrc.20390](https://doi.org/10.1002/jgrc.20390) (2013).
- 651 **123.** Rahmstorf, S. *et al.* Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nat. Clim. Chang.*
652 **5**, 475–480, DOI: [10.1038/nclimate2554](https://doi.org/10.1038/nclimate2554) (2015).
- 653 **124.** Robson, J., Hodson, D., Hawkins, E. & Sutton, R. Atlantic overturning in decline? *Nat. Geosci.* **7**, 2–3, DOI:
654 [10.1038/ngeo2050](https://doi.org/10.1038/ngeo2050) (2013).
- 655 **125.** MacCarthy, G. D., Haigh, I. D., Hirschi, J. J.-M., Grist, J. P. & Smeed, D. A. Ocean impact on decadal atlantic climate
656 variability revealed by sea-level observations. *Nature* **521**, 508–510 (2015).
- 657 **126.** Diabaté, S. T. *et al.* Western boundary circulation and coastal sea-level variability in northern hemisphere oceans. *Ocean.*
658 *Sci.* **17**, 1449–1471, DOI: [10.5194/os-17-1449-2021](https://doi.org/10.5194/os-17-1449-2021) (2021).
- 659 **127.** Thornalley, D. J. R. *et al.* Anomalously weak labrador sea convection and atlantic overturning during the past 150 years.
660 *Nature* **556**, 227–230, DOI: [10.1038/s41586-018-0007-4](https://doi.org/10.1038/s41586-018-0007-4) (2018).
- 661 **128.** Zantopp, R., Fischer, J., Visbeck, M. & Karstensen, J. From interannual to decadal: 17 years of boundary current
662 transports at the exit of the Labrador Sea. *J. Geophys. Res. Ocean.* **122**, 1724–1748, DOI: [10.1002/2016JC012271](https://doi.org/10.1002/2016JC012271) (2017).
- 663 **129.** Handmann, P. *et al.* The Deep Western Boundary Current in the Labrador Sea From Observations and a High-Resolution
664 Model. *J. Geophys. Res. Ocean.* **123**, 2829–2850, DOI: [10.1002/2017JC013702](https://doi.org/10.1002/2017JC013702) (2018).
- 665 **130.** Osterhus, S. *et al.* Arctic Mediterranean exchanges: a consistent volume budget and trends in transports from two decades
666 of observations. *Ocean. Sci.* **15**, 379–399, DOI: [10.5194/os-15-379-2019](https://doi.org/10.5194/os-15-379-2019) (2019).
- 667 **131.** Delworth, T. L. & Dixon, K. W. Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the north
668 atlantic thermohaline circulation? *Geophys. Res. Lett.* **33**, L02606, DOI: [10.1029/2005GL024980](https://doi.org/10.1029/2005GL024980) (2006).
- 669 **132.** Robson, J., T, S. R., Archibald, A. & et al. Recent multivariate changes in the north atlantic climate system, with a focus
670 on 2005- 2016. *Int J Clim.* DOI: [10.1002/joc.5815](https://doi.org/10.1002/joc.5815) (2018).
- 671 **133.** Holliday, N. *et al.* Ocean circulation causes the largest freshening event for 120 years in eastern subpolar north atlantic.
672 *Nat. Comms* **11**, 585 (2020).
- 673 **134.** Rühls, S. *et al.* Changing spatial patterns of deep convection in the subpolar North Atlantic. *J. Geophys. Res. Ocean.* **126**,
674 e2021JC017245, DOI: [10.1029/2021jc017245](https://doi.org/10.1029/2021jc017245) (2021).
- 675 **135.** Häkkinen, S. A simulation of thermohaline effects of a great salinity anomaly. *J. Clim.* **12**, 1781 – 1795, DOI:
676 [10.1175/1520-0442\(1999\)012<1781:ASOTEO>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<1781:ASOTEO>2.0.CO;2) (1999).
- 677 **136.** Haak, H., Jungclaus, J., Mikolajewicz, U. & Latif, M. Formation and propagation of great salinity anomalies. *Geophys.*
678 *Res. Lett.* **30**, 1473, DOI: <https://doi.org/10.1029/2003GL017065> (2003).
- 679 **137.** Kim, W. M., Yeager, S. & Danabasoglu, G. Revisiting the causal connection between the great salinity anomaly of
680 the 1970s and the shutdown of labrador sea deep convection. *J. Clim.* **34**, 675–696, DOI: [10.1175/JCLI-D-20-0327.1](https://doi.org/10.1175/JCLI-D-20-0327.1)
681 (2021).
- 682 **138.** Chen, X. & Tung, K. Global surface warming enhanced by weak atlantic overturning circulation. *Nature* **559**, 387–391,
683 DOI: [/10.1038/s41586-018-0320-y](https://doi.org/10.1038/s41586-018-0320-y) (2018).
- 684 **139.** Roberts, C. D., Jackson, L. & McNeill, D. Is the 2004-2012 reduction of the Atlantic meridional overturning circulation
685 significant? *Geophys. Res. Lett.* **41**, 3204–3210, DOI: [10.1002/2014gl059473](https://doi.org/10.1002/2014gl059473) (2014).
- 686 **140.** McCarthy, G. *et al.* Observed interannual variability of the Atlantic MOC at 26.5°N. *Geophys. Res. Lett.* **39**, L19609,
687 DOI: [10.1029/2012GL052933](https://doi.org/10.1029/2012GL052933) (2012).

- 688 **141.** Roberts, C. D. *et al.* Atmosphere drives recent interannual variability of the Atlantic meridional overturning circulation at
689 26.5°N. *Geophys. Res. Lett.* **40**, 5164–5170, DOI: [10.1002/grl.50930](https://doi.org/10.1002/grl.50930) (2013).
- 690 **142.** Zhao, J. & Johns, W. Wind-forced interannual variability of the atlantic meridional overturning circulation at 26.5°n. *J.*
691 *Geophys. Res. Ocean.* **119**, 2403–2419, DOI: <https://doi.org/10.1002/2013JC009407> (2014).
- 692 **143.** Frajka-Williams, E., Lankhorst, M., Koelling, J. & Send, U. Coherent Circulation Changes in the Deep North Atlantic
693 From 16N and 26N Transport Arrays. *J. Geophys. Res. - Ocean.* <https://doi.org/10.1029/2018JC013949> (2018).
- 694 **144.** Picuch, C. G., Ponte, R. M., Little, C. M., Buckley, M. W. & Fukumori, I. Mechanisms underlying recent decadal changes
695 in subpolar north atlantic ocean heat content. *J. Geophys. Res. Ocean.* **122**, 7181–7197, DOI: [10.1002/2017JC012845](https://doi.org/10.1002/2017JC012845)
696 (2017).
- 697 **145.** Tesdal, J.-E. & Haine, T. W. N. Dominant terms in the freshwater and heat budgets of the subpolar north atlantic
698 ocean and nordic seas from 1992 to 2015. *J. Geophys. Res. Ocean.* **125**, e2020JC016435, DOI: <https://doi.org/10.1029/2020JC016435> (2020).
- 700 **146.** Zhang, R. Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophys. Res. Lett.*
701 **35**, L20705+, DOI: [10.1029/2008gl035463](https://doi.org/10.1029/2008gl035463) (2008).
- 702 **147.** Zhang, J. & Zhang, R. On the evolution of atlantic meridional overturning circulation fingerprint and implications for
703 decadal predictability in the north atlantic. *Geophys. Res. Lett.* **42**, 5419–5426, DOI: [10.1002/2015GL064596](https://doi.org/10.1002/2015GL064596) (2015).
- 704 **148.** Josey, S. A. *et al.* The recent atlantic cold anomaly: Causes, consequences, and related phenomena. *Annu. Rev. Mar. Sci.*
705 **10**, 475–501, DOI: [10.1146/annurev-marine-121916-063102](https://doi.org/10.1146/annurev-marine-121916-063102) (2018). PMID: 28934597.
- 706 **149.** Desbryères, D., Chafik, L. & Maze, G. A shift in the ocean circulation has warmed the subpolar north atlantic ocean
707 since 2016. *Nat. Commun Earth Environ* **2**, 48, DOI: [10.1038/s43247-021-00120-y](https://doi.org/10.1038/s43247-021-00120-y) (2021).
- 708 **150.** Moat, B. *et al.* Insights into decadal North Atlantic sea surface temperature and ocean heat content variability from an
709 eddy-permitting coupled climate model. *J. Clim.* **32**, 6137–6149, DOI: [10.1175/JCLI-D-18-0709.1](https://doi.org/10.1175/JCLI-D-18-0709.1) (2019).
- 710 **151.** Clement, A. *et al.* The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science* **350**, 320–324
711 (2015).
- 712 **152.** Cane, M. A., Clement, A. C., Murphy, L. N. & Bellomo, K. Low-pass filtering, heat flux, and Atlantic multidecadal
713 variability. *J. Clim.* **30**, 7529–7553, DOI: [10.1175/JCLI-D-16-0810.1](https://doi.org/10.1175/JCLI-D-16-0810.1) (2017).
- 714 **153.** Murphy, L. N., Bellomo, K., Cane, M. & Clement, A. The role of historical forcings in simulating the observed atlantic
715 multidecadal oscillation. *Geophys. Res. Lett.* **44**, 2472–2480, DOI: <https://doi.org/10.1002/2016GL071337> (2017).
- 716 **154.** Yan, X., Zhang, R. & Knutson, T. R. Underestimated AMOC Variability and Implications for AMV and Predictability in
717 CMIP Models. *Geophys. Res. Lett.* **45**, 4319–4328 (2018).
- 718 **155.** Gregory, J. M. *et al.* A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing
719 atmospheric CO₂ concentration. *Geophys. Res. Lett.* **32**, DOI: [10.1029/2005GL023209](https://doi.org/10.1029/2005GL023209) (2005).
- 720 **156.** Marshall, J., Donohoe, A., Ferreira, D. & McGee, D. The ocean’s role in setting the mean position of the Inter-Tropical
721 Convergence Zone. *Clim. Dyn.* **42**, 1967–1979, DOI: [10.1007/s00382-013-1767-z](https://doi.org/10.1007/s00382-013-1767-z) (2014).
- 722 **157.** Sévellec, F., Fedorov, A. & Liu, W. Arctic sea-ice decline weakens the atlantic meridional overturning circulation. *Nat.*
723 *Clim Chang.* **7**, 604–610, DOI: [10.1038/nclimate3353](https://doi.org/10.1038/nclimate3353) (2017).
- 724 **158.** Hassan, T., Allen, R. J., Liu, W. & Randles, C. A. Anthropogenic aerosol forcing of the atlantic meridional overturning
725 circulation and the associated mechanisms in cmip6 models. *Atmospheric Chem. Phys.* **21**, 5821–5846, DOI: [10.5194/](https://doi.org/10.5194/acp-21-5821-2021)
726 [acp-21-5821-2021](https://doi.org/10.5194/acp-21-5821-2021) (2021).
- 727 **159.** Menary, M. B. *et al.* Mechanisms of aerosol-forced amoc variability in a state of the art climate model. *J. Geophys. Res.*
728 *Ocean.* **118**, 2087–2096, DOI: [10.1002/jgrc.20178](https://doi.org/10.1002/jgrc.20178) (2013).
- 729 **160.** Smith, C. J. *et al.* Energy budget constraints on the time history of aerosol forcing and climate sensitivity. *J. Geophys. Res.*
730 *Atmospheres* **126**, e2020JD033622, DOI: <https://doi.org/10.1029/2020JD033622> (2021). E2020JD033622 2020JD033622,
731 <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020JD033622>.
- 732 **161.** Wang, C., Soden, B. J., Yang, W. & Vecchi, G. A. Compensation between cloud feedback and aerosol-cloud interaction
733 in cmip6 models. *Geophys. Res. Lett.* **48**, e2020GL091024, DOI: <https://doi.org/10.1029/2020GL091024> (2021).
734 E2020GL091024 2020GL091024, <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020GL091024>.
- 735 **162.** Zhu, C. & Liu, Z. Weakening atlantic overturning circulation causes south atlantic salinity pile-up. *Nat. Clim. Chang.*
736 DOI: [10.1038/s41558-020-0897-7](https://doi.org/10.1038/s41558-020-0897-7) (2020).

- 737 **163.** Piecuch, C. Likely weakening of the florida current during the past century revealed by sea-level observations. *Nat*
738 *Commun* **11**, DOI: [10.1038/s41467-020-17761-w](https://doi.org/10.1038/s41467-020-17761-w) (2020).
- 739 **164.** Moffa-Sánchez, P. *et al.* Variability in the northern north atlantic and arctic oceans across the last two millennia: A review.
740 *Paleoceanogr. Paleoclimatology* **34**, 1399–1436, DOI: [10.1029/2018PA003508](https://doi.org/10.1029/2018PA003508) (2019).
- 741 **165.** Little, C. M., Zhao, M. & Buckley, M. W. Do surface temperature indices reflect centennial-timescale trends in atlantic
742 meridional overturning circulation strength?. *Geophys. Res. Lett.* **47**, e2020GL090888, DOI: [10.1029/2020GL090888](https://doi.org/10.1029/2020GL090888)
743 (2020).
- 744 **166.** Boning, C. W., Behrens, E., Biastoch, A., Getzlaff, K. & Bamber, J. L. Emerging impact of Greenland meltwater on
745 deepwater formation in the North Atlantic Ocean. *Nat. Geosci.* **9**, 523–527, DOI: [10.1038/ngeo2740](https://doi.org/10.1038/ngeo2740) (2016).
- 746 **167.** van den Berk, J. & Drijfhout, S. A realistic freshwater forcing protocol for ocean-coupled climate models. *Ocean. Model.*
747 **81**, 36–48, DOI: <https://doi.org/10.1016/j.ocemod.2014.07.003> (2014).
- 748 **168.** Reintges, A., Martin, T., Latif, M. & Keenlyside, N. Uncertainty in twenty-first century projections of the Atlantic
749 Meridional Overturning Circulation in CMIP3 and CMIP5 models. *Clim. Dyn.* 1–17, DOI: [10.1007/s00382-016-3180-x](https://doi.org/10.1007/s00382-016-3180-x)
750 (2016).
- 751 **169.** Liu, W., Xie, S.-P., Liu, Z. & Zhu, J. Overlooked possibility of a collapsed atlantic meridional overturning circulation in
752 warming climate. *Sci. Adv.* **3**, e1601666, DOI: [10.1126/sciadv.1601666](https://doi.org/10.1126/sciadv.1601666) (2017). [https://www.science.org/doi/pdf/10.1126/](https://www.science.org/doi/pdf/10.1126/sciadv.1601666)
753 [sciadv.1601666](https://www.science.org/doi/pdf/10.1126/sciadv.1601666).
- 754 **170.** Jackson, L. C. *et al.* Impact of ocean resolution and mean state on the rate of amoc weakening. *Clim. Dyn.* **55**, 1711–1732,
755 DOI: [10.1007/s00382-020-05345-9](https://doi.org/10.1007/s00382-020-05345-9) (2020).
- 756 **171.** Chang, P. *et al.* An unprecedented set of high-resolution earth system simulations for understanding multiscale interactions
757 in climate variability and change. *J. Adv. Model. Earth Syst.* **12**, e2020MS002298, DOI: [https://doi.org/10.1029/](https://doi.org/10.1029/2020MS002298)
758 [2020MS002298](https://doi.org/10.1029/2020MS002298) (2020).
- 759 **172.** Pohlmann, H. *et al.* Predictability of the mid-latitude Atlantic meridional overturning circulation in a multi-model system.
760 *Clim. Dyn.* **41**, 775–785, DOI: [10.1007/s00382-013-1663-6](https://doi.org/10.1007/s00382-013-1663-6) (2013).
- 761 **173.** Global annual to decadal climate update. Tech. Rep., World Meteorological Organisation, Geneva, Switzerland (2020).
- 762 **174.** Yeager, S. The abyssal origins of north atlantic decadal predictability. *Clim. Dyn.* **55**, 2253–2271, DOI: [10.1007/](https://doi.org/10.1007/s00382-020-05382-4)
763 [s00382-020-05382-4](https://doi.org/10.1007/s00382-020-05382-4) (2020).
- 764 **175.** Worthington, E. L. *et al.* A 30-year reconstruction of the atlantic meridional overturning circulation shows no decline.
765 *Ocean. Sci.* **17**, 285–299, DOI: [10.5194/os-17-285-2021](https://doi.org/10.5194/os-17-285-2021) (2021).
- 766 **176.** Cunningham, S. A. *et al.* Atlantic Meridional Overturning Circulation slowdown cooled the subtropical ocean. *Geophys.*
767 *Res. Lett.* **40**, 2013GL058464+, DOI: [10.1002/2013gl058464](https://doi.org/10.1002/2013gl058464) (2013).
- 768 **177.** Zou, S., Lozier, M., Li, F., Abernathy, R. & Jackson, L. Density-compensated overturning in the labrador sea. *Nature.*
769 *Geosci.* **13**, 121–126, DOI: [10.1038/s41561-019-0517-1](https://doi.org/10.1038/s41561-019-0517-1) (2020).
- 770 **178.** Frajka-Williams, E. *et al.* Atlantic meridional overturning circulation: Observed transport and variability. *Front. Mar. Sci.*
771 **6**, DOI: [10.3389/fmars.2019.00260](https://doi.org/10.3389/fmars.2019.00260) (2019).
- 772 **179.** Good, S. A., Martin, M. J. & Rayner, N. A. EN4: Quality controlled ocean temperature and salinity profiles and monthly
773 objective analyses with uncertainty estimates. *J. Geophys. Res.* **118**, 6704–6716 (2013).
- 774 **180.** Spall, M. A. Boundary currents and watermass transformation in marginal seas. *J. Phys. Ocean.* **34**, 1197–1213, DOI:
775 [10.1175/1520-0485\(2004\)034<1197:BCAWTI>2.0.CO;2](https://doi.org/10.1175/1520-0485(2004)034<1197:BCAWTI>2.0.CO;2) (2004).
- 776 **181.** Sayol, J.-M., Dijkstra, H. & Katsman, C. Seasonal and regional variations of sinking in the subpolar north atlantic from a
777 high-resolution ocean model. *Ocean. Sci.* **15**, 1033–1053, DOI: [10.5194/os-15-1033-2019](https://doi.org/10.5194/os-15-1033-2019) (2019).
- 778 **182.** Marshall, J. & Speer, K. Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nat.*
779 *Geosci* **5**, 171–180, DOI: [10.1038/ngeo1391](https://doi.org/10.1038/ngeo1391) (2012).

780 **Acknowledgements**

781 LCJ was supported by the Met Office Hadley Centre Climate Programme funded by BEIS and Defra (GA01101). MWB
782 gratefully acknowledges the support from the NOAA ESS Program (NA20OAR4310396) and the NASA Physical Oceanog-
783 raphy Program (80NSSC20K0823). JR was supported by NERC through NCAS, and through the NERC ACSIS project
784 (NE/N018001/1), and the UKRI-NERC WISHBONE (NE/T013516/1) and SNAP-DRAGON (NE/T013494/1) projects. EFW
785 and BM were supported by the UK Natural Environment Research Council RAPID-AMOC programme at 26.5°N. BM was
786 also supported by the European Union Horizon 2020 research and innovation programme BLUE-ACTION (Grant 727852).
787 The authors thank Herlé Mercier, Alejandra Sanchez-Franks and Gerard McCarthy for providing updated time series for the
788 AMOC at A25-Ovide, AMOC at 26.5°N, and sea level proxy respectively.

789 **Author contributions**

790 LCJ led the writing, coordinated the contributions and made the figures. All authors discussed the content and contributed to
791 the writing of the manuscript.

792 **Competing interests**

793 The authors declare no competing interests.

794 **Peer review information**

795 *Nature Reviews Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work.

796 **Supplementary information**

797 Supplementary information is available for this paper at <https://doi.org/10.1038/s415XX-XXX-XXXX-X>

798 **Publishers note**

799 Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

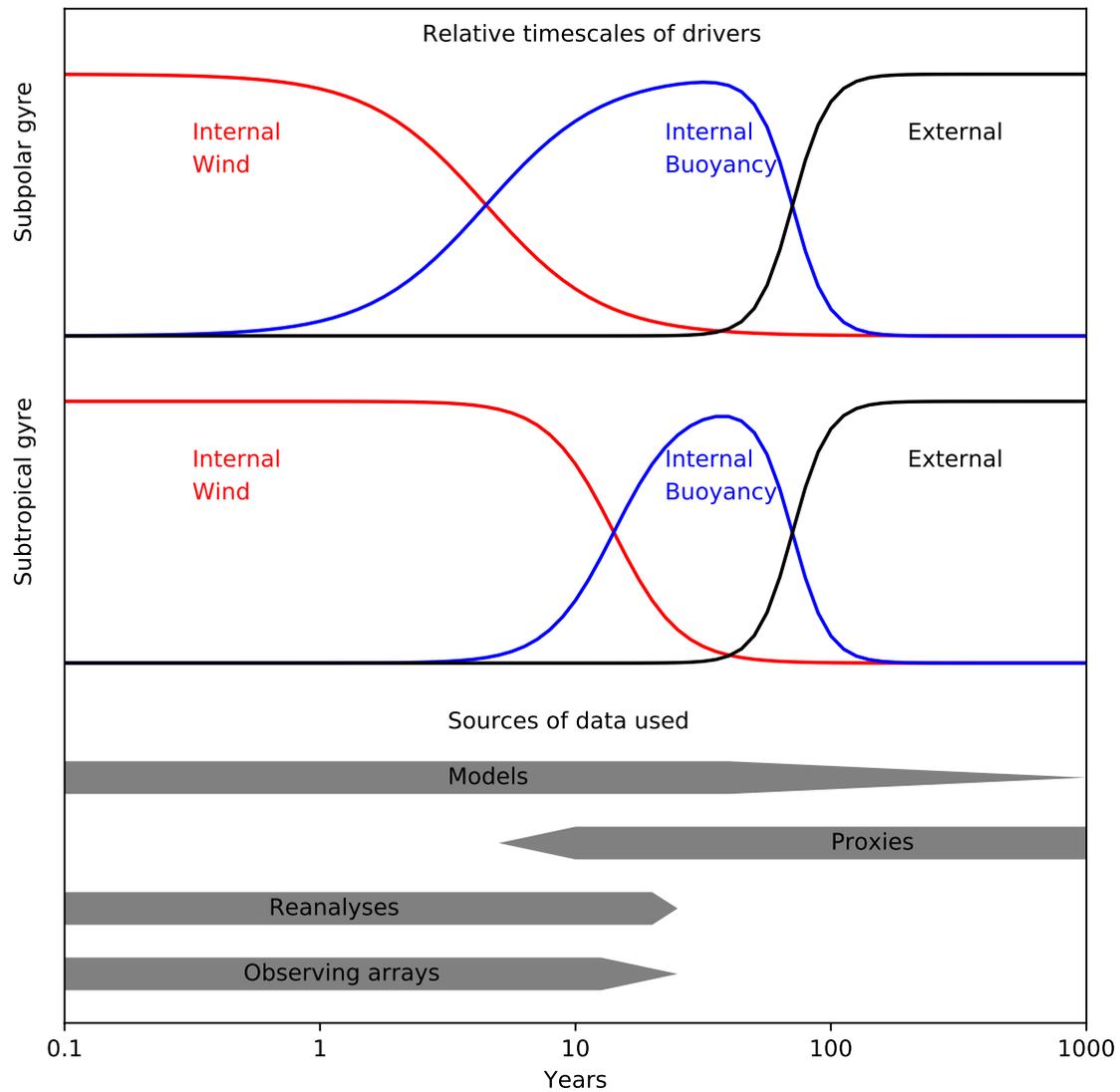


Figure 1. Schematic of AMOC timescales. a) Relative contributions of internal wind, buoyancy forcing and external forcing for AMOC changes in the subpolar North Atlantic. b) As in a, but for the subtropical North Atlantic. c) Timescale over which different data sources are able to distinguish AMOC variability based on their length (see Supplementary Information), and assuming that proxies used do not represent higher frequency AMOC variability. Drivers of AMOC variability differ depending on timescales, and different data sources are appropriate for different timescales.

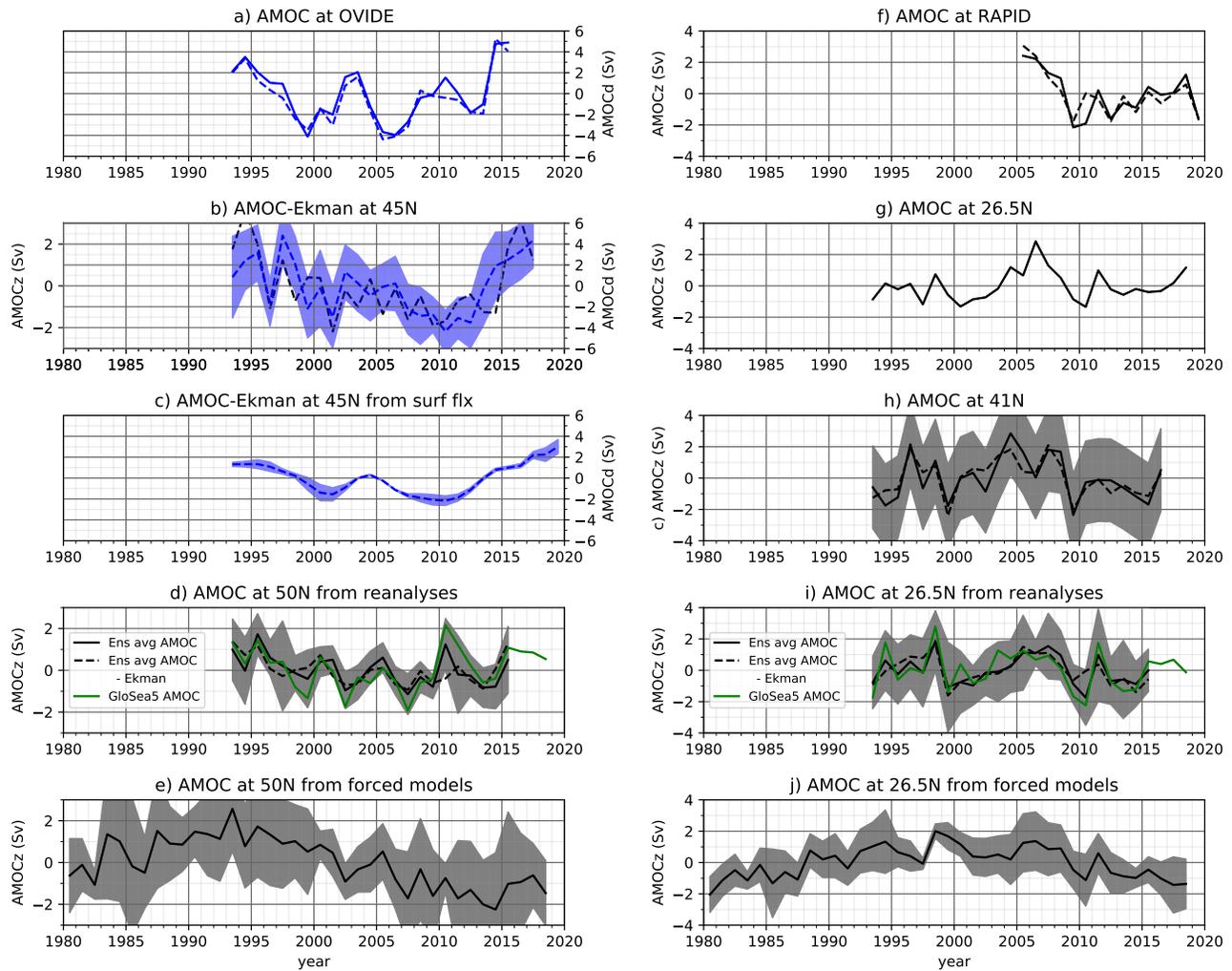


Figure 2. Timeseries of AMOC anomalies. Reconstructed AMOC in the subpolar North Atlantic (left): a) AMOC from observations along the Portugal-Greenland A25-OVIDE line⁹⁶; b) AMOC from observations at 45°N¹²; c) Implied overturning in density space from observed surface fluxes¹²; d) AMOC at 50°N from an ensemble mean of ocean reanalyses¹³ (black) and GloSea5 reanalysis²⁰ (green); e) AMOC at 50°N from forced models participating in OMIP2 (ref¹⁴). Reconstructed AMOC in the subtropical North Atlantic (right): f) AMOC at 26.5°N from the RAPID array⁹⁸; g) AMOC from observations at 26.5°N¹⁰²; h) AMOC from observations at 41°N¹⁰⁰; i) as in d but for the AMOC at 26.5°N; j) as in e but for the AMOC at 26.5°N. AMOC is either the maximum of the overturning in density space (blue, right axis) or the maximum in depth space (black, left axis). Dashed lines indicate those timeseries wherein the wind-driven Ekman component is excluded. Shading indicates observational uncertainties for b, c and h, or 2 times the standard deviation for d, e, i and j. See Supplementary Information for more detail on data sources. AMOC timeseries in the subpolar and subtropical North Atlantic show changes on interannual to decadal timescales.

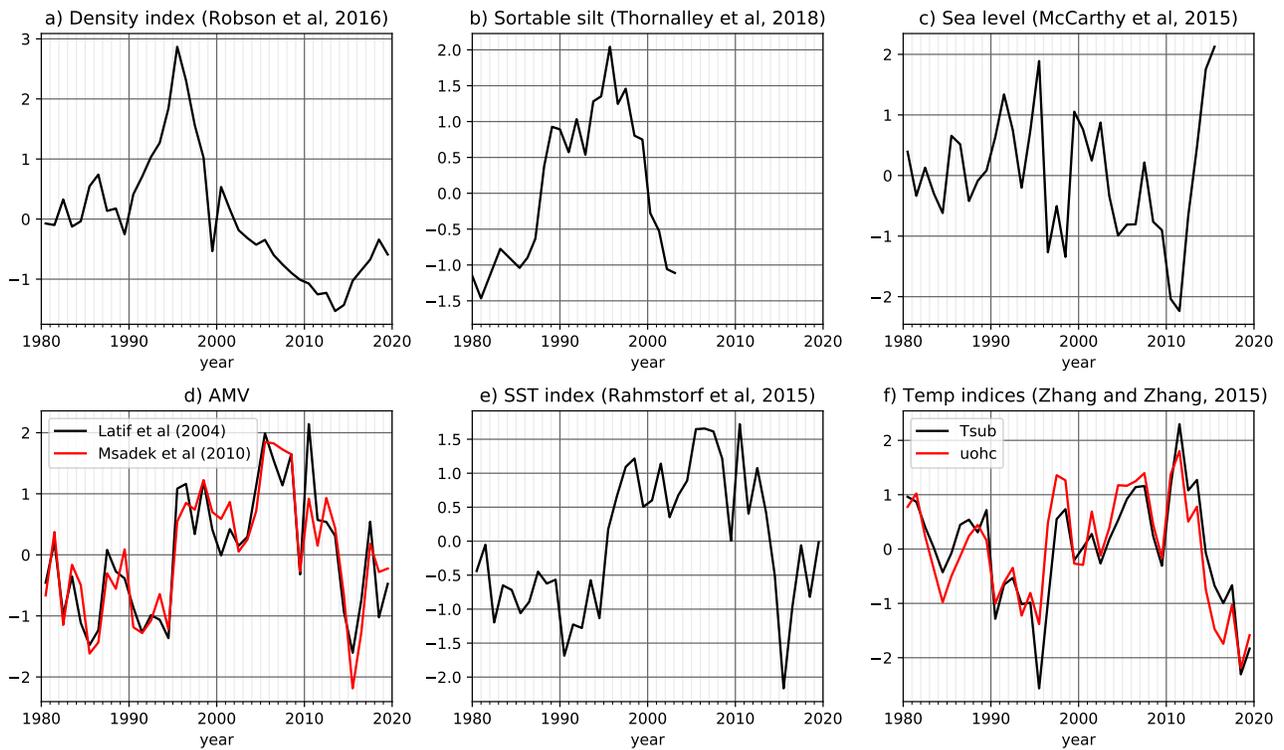


Figure 3. AMOC proxy records from 1980. a) Labrador Sea density proxy¹⁵; b) Sortable silt (proxy of deep boundary current speed)¹²⁷; c) Sea level proxy^{125,126}; d) Indices of Atlantic Multidecadal Variability from ref¹²⁰ (black) and ref¹²¹ (red); e) Subpolar sea surface temperature (SST) proxy¹²³; f) Temperature indices, including temperature at 400 m (T_{sub} ; black) and ocean heat content over the top 700 m (uohc; red)¹⁴⁷. All proxies are presented as standardised anomalies (see Supplementary Information). AMOC proxies support a strong subpolar AMOC in the mid 90s and weak in the early 2010s.

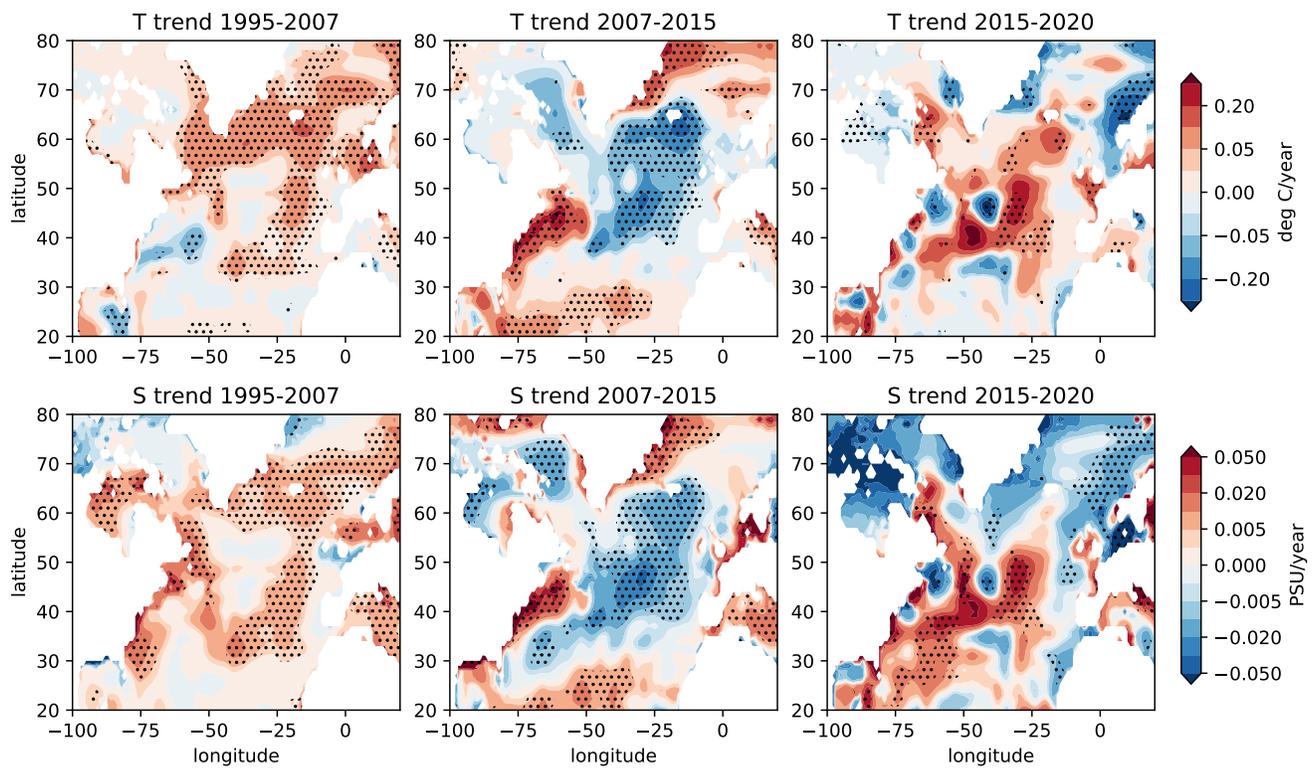


Figure 4. North Atlantic temperature and salinity trends. Trends of temperature averaged over the top 700 m for years 1995–2007 (panel a), 2007–2015 (panel b) and 2015–2020 (panel c). Trends of salinity averaged over the top 700 m for years 1995–2007 (panel d), 2007–2015 (panel e) and 2015–2020 (panel f). Stippling indicates statistically significant trends ($P < 0.05$). Analysis and regions adapted from ref¹⁵ and calculated from EN4 data¹⁷⁹. Atlantic temperature and salinity trends reveal periods of warming and salinification (1995–2007, 2015–2020) and cooling and freshening (2007–2015).

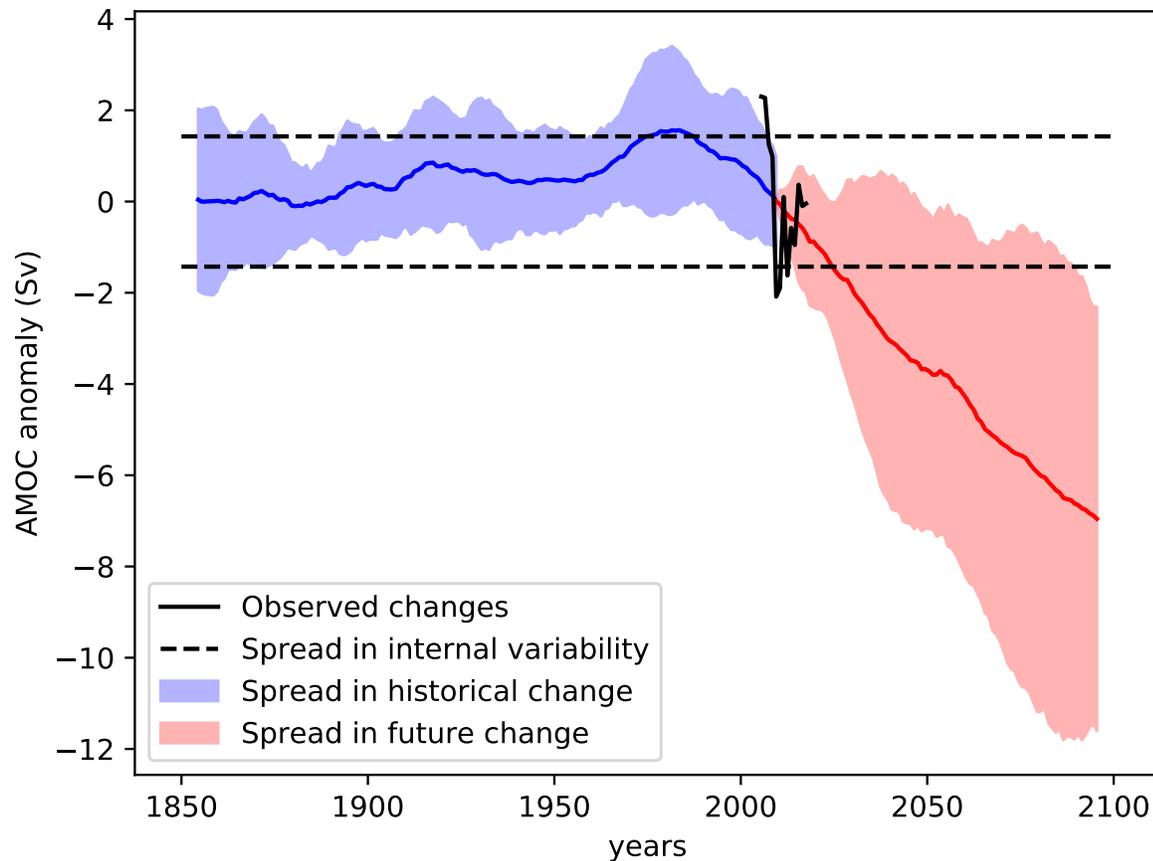


Figure 5. Past and future AMOC changes from climate models. Annual mean observed AMOC anomalies from RAPID⁹⁸ (black). The ensemble mean and spread (2*standard deviation) of 10 year running mean AMOC anomalies in the CMIP6 historical scenario (blue line and shading). The ensemble mean and spread (2*standard deviation) of 10 year running mean AMOC projections for the scenario SSP585 from CMIP6 (red line and shading). For modelled scenarios, the mean illustrates the forced response to changes in greenhouse gases and aerosols, and the spread includes differences in forced response and internal variability. See Supplementary Information for more detail on data sources. The black horizontal lines indicates internal variability of the AMOC, calculated as two times the ensemble mean standard deviation of 10 year mean AMOC in the CMIP6 preindustrial control experiment. The AMOC is projected to weaken in the future, however internal variability could obscure this signal.

800 **BOX: Introduction to the AMOC**

801 The Atlantic Meridional Overturning Circulation (AMOC) is a system of currents in the North Atlantic, whose net effect is
802 to transport warmer upper waters (above 1000 m) northwards and colder deep waters (1000–3000 m) southwards (see dark
803 and light grey arrows on Figure, respectively). The Gulf Stream and its extension into the North Atlantic current are major
804 contributions to the upper limb of the AMOC, as are the recirculations in oceanic gyres and transports by mesoscale eddies
805 (typical currents shown in upper and front faces of Figure). As light, upper waters are transported north from the tropics, they
806 lose heat and hence become denser. Once the waters have reached the Irminger, Labrador or Greenland-Iceland-Norwegian
807 Seas, stratification between upper and lower waters is reduced enough to trigger deep convection in winter, generating sinking
808 along the continental slopes^{180,181} and the formation of North Atlantic Deep Water. This deep water is transported southwards
809 in the Atlantic deep western boundary current and dispersive interior pathways⁹⁰. The deep waters recirculate round the
810 Southern Ocean and the rest of the global oceans, with the circulation being closed through wind-driven upwelling in the
811 Southern Ocean¹⁸² and mixing of dense waters globally.

812 Since currents in the Atlantic tend to transport upper waters northwards and deeper waters southwards, the circulation is
813 often visualised in a two dimensional plane of latitude and depth or density, creating an "overturning streamfunction". The
814 AMOC streamfunction (right hand face of Figure) is calculated by integrating the meridional (north-south) velocity across the
815 Atlantic basin and cumulatively in depth. The strength at a given latitude is the maximum value in depth. The AMOC can also
816 be calculated in density coordinates (where the northwards and southwards branches are defined in lighter and denser waters
817 respectively) to better account for heat and buoyancy redistribution in the ocean. These two vertical coordinates give similar
818 estimates of overturning in the subtropics where light waters overlay dense waters, but they differ at higher latitudes where the
819 light inflow and dense outflow are found at similar depths⁸⁶.

820 **ToC blurb**

821 The Atlantic Meridional Overturning Circulation (AMOC) has a key role in the climate system. This Review documents
822 AMOC variability since 1980, revealing periods of decadal-scale weakening and strengthening that differ between sub-polar
823 and sub-tropical regions.

