

Evidence the ocean is losing less heat in the northern Atlantic and the AMOC has started to slowly weaken

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Article

Keywords: Atlantic Meridional Overturning Circulation, net surface heat fluxes, climate change

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10854125/v1>

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Additional Declarations: There is **NO** Competing Interest.

Evidence the ocean is losing less heat in the
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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is widely expected to weaken this century, with potentially large impacts on Europe, but the strength and timing of the weakening is still uncertain. Using validated, satellite-based, energy-balanced estimates of net surface heat fluxes, we show that from **1985 to 2023** the heat lost by the Atlantic ocean between **26.5 °N** and **70 °N** reduced by about **$18 \pm 10\%$** (**95%** confidence interval). Such large changes in ocean heat loss over a **40**-year period are rare in CMIP6 pre-industrial control simulations, suggesting the change is a consequence of forced climate change. Using correlations between trends in this heat loss and the AMOC in CMIP6 climate change simulations, we calculate the AMOC at **26.5 °N** reduced by **$14.2 \pm 13.9\%$** over the last **30** years. These findings are probably more robust than those from other AMOC proxies, because the reduction in heat loss is the fundamental mechanism for AMOC weakening under global warming.

Keywords: Atlantic Meridional Overturning Circulation, net surface heat fluxes, climate change

28 August 2026

1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) transports warm near-surface waters northward and colder deep water southward in the Atlantic [1–3]. The warm water brought northward loses heat to the atmosphere which keeps Europe much warmer than it otherwise would be [4, 5]. The AMOC is an important element of the ocean’s global overturning circulations which redistribute heat, carbon, oxygen and other tracers and as such play a key role in global climate [6]. These circulations involve complex, time-varying currents [7] which are controlled by subtle combinations of drivers and processes [8–10].

The AMOC at a given latitude is defined by the net volume transport through the meridional section across the Atlantic basin above the depth (or density) where the net transport integrated from the surface is a maximum. There is strong evidence that, at least for zonal sections near 26.5°N, the AMOC is strongly correlated with the

net poleward ocean heat flux through that section [11–13], and that fluctuations with periods of less than 2-3 years are mainly driven by variations in surface wind stresses whilst longer period fluctuations are mainly associated with fluctuations in surface buoyancy fluxes to the north of the section [14, 15]. Carefully designed experiments [16] suggest that changes in the AMOC under climate warming are mainly associated with reductions in the net upward surface heat fluxes (NUSHFs) from the ocean to the atmosphere in the northern Atlantic.

The AMOC at 26.5 °N has been well observed by the RAPID array since 2004 [17–19]. The latest report of the Intergovernmental Panel on Climate Change [20] concluded that the observation record of the AMOC from the RAPID array since 2004 is too short for the evaluation of a long-term trend given the decadal scale internal variability and, whilst it is very likely that AMOC will decline in the 21st century, there is low confidence in the projected timing and magnitude of the decline because of the lack of agreement in its simulation between climate models.

Many studies have attempted to extend the observed AMOC timeseries back in time from 2004 using different observational proxies. A sea surface temperature (SST) fingerprint has been used in many studies because of the potentially long observational records [21–26]. These SST fingerprints have suggested a weakening of the AMOC over the last century. However, several studies [27–30] have shown that the relationship between SST and the AMOC differs depending on external forcing and that observational uncertainty can affect the fingerprint [31, 32], casting doubt on the robustness of the proxy. Other variables have also been used as proxies, including subsurface temperatures and heat content [21, 33], sea level [34], heat fluxes [35, 36], salinity [37], sea surface height [38] and the Bernoulli function [39]. There is disagreement between the proxies about the weakening since the mid 1900s [33–35], leading to uncertainty in whether an ongoing trend in the AMOC has been detected.

83 Since the 1990s there has been greater observational coverage allowing additional
84 proxies to be used, however on these shorter timescales variability has a larger role
85 and trends indicated by proxies for the subtropical and subpolar North Atlantic can
86 differ. A review of recent variability [40] suggested that the subpolar AMOC had a
87 maximum in the 1990s followed by a weakening, though it has been unclear how much
88 of this weakening is due to internal variability rather than anthropogenic forcing, and
89 whether this weakening will continue [41]. More recent measurements [42] have shown
90 that from 2004 to 2023 the AMOC weakened by about 1.0 Sv per decade (with a 90%
91 confidence interval of 0.4 to 1.6 Sv per decade).

92 Given the large interannual variability in the AMOC measured by the RAPID
93 array, proxies that focus on the mechanisms of longer term change in response to
94 radiative forcing have the potential to better distinguish those longer term changes
95 from interannual noise. With the expected key role of NUSHFs [16], NUSHFs are a
96 particularly attractive candidate as a proxy for long term AMOC change.

97 Based on a strong relationship between the NUSHF in the northern Atlantic and
98 the AMOC, using the NUSHFs obtained directly from atmospheric reanalyses, [35]
99 found no evidence for AMOC decline from 1963 to 2017. The NUSHFs obtained
100 directly from atmospheric reanalyses are however not directly constrained by measure-
101 ments and have been found to be unreliable for many purposes [43–46]. More reliably
102 constrained NUSHFs can be obtained using the DEEP-C method [36, 44, 47–49] (see
103 Methods for more details).

104 The main aims of this paper are: to show that according to these improved methods
105 the heat lost from the ocean to the atmosphere in the northern Atlantic reduced
106 over a recent 39-year period; to show that this reduction is at the outer edge of the
107 distribution of corresponding changes in pre-industrial control (piControl) climate
108 simulations; and to suggest that the reduction in heat loss is likely to be associated
109 with the steady reduction in the strength of the AMOC expected in the 21st century.

2 Results

2.1 NUSHF trends

The large-scale spatial patterns of the DEEP-C trends in the NUSHF from 1985-2023 calculated using ERA5 [50] and JRA55 [51] reanalysis data, respectively (Figs. 1(a) and (b)) agree quite well and are as large as 10 Wm^{-2} per decade. The stippling based on analysis of the residuals after fitting a linear trend at each point (see Methods) suggests that the large-scale patterns of the trends are reliable. Figure 1(c) shows that the DEEP-C timeseries of the integral of the NUSHF in the northern Atlantic between 26.5°N and 70°N (the blue box in panel (a)) calculated from three different atmospheric reanalyses (MERRA2 [52] being the third) are similar and their trends are well captured by best fit linear regressions. Taking the average of the three slopes we estimate that the heat loss has reduced from 0.986 PW by 0.047 PW per decade. This amounts to a reduction of 0.18 PW or 18.5% from the start to the end of the 39-year period. The corresponding rate of reduction of heat loss per unit area (for the blue box region) is 2.15 Wm^{-2} per decade. Assuming the three slopes are independent estimates, the 95% confidence interval for their mean is $-0.047 \pm 0.026 = [-0.021, -0.073] \text{ PW}$ per decade. This interval is reasonably consistent with the minimum (-0.019) and maximum (-0.080) values of the 95% confidence intervals obtained from the residuals of the individual fits (see Methods) displayed on Fig. 1(c). The confidence interval for the fractional reduction in the heat loss is $18.5 \times 0.026/0.047\% = 10.3\%$. The uncertainty in the DEEP-C values across gaps in the satellite timeseries is estimated by [53] to be 0.87 Wm^{-2} . Over four decades this gives an error of 0.22 Wm^{-2} per decade which is small compared to 2.15 Wm^{-2} per decade. We conclude that the trends in Fig 1(c) are probably reliable and significant.

134 Timeseries of the global integral of the NUSHF from the three DEEP-C products
 135 (Fig. 1(d)) by construction agree well with each other and with the satellite measure-
 136 ments of the net downward heat flux at the top of the atmosphere (TOA) (aka the
 137 Earth’s Energy Imbalance). Over the last 20 years the global mean downward TOA
 138 flux has increased at a rate of 0.45 Wm^{-2} per decade. [54]. This puts the almost five
 139 times larger (2.15 Wm^{-2} per decade) 39-year trend in the NUSHF in the much smaller
 140 northern Atlantic in context.

141 The global averages of the NUSHFs obtained directly from the reanalyses are as
 142 large as 10 Wm^{-2} (Fig. 1(h)). Such large values are inconsistent with ocean heat
 143 content calculations based on Argo data [55]. The trends in the global integral of
 144 NUSHF are of the opposite sign to those from the DEEP-C products (Fig. 1(d)) and 2
 145 to 4 times larger in magnitude. The trends in the NUSHF in the northern Atlantic (Fig.
 146 1(g)) also have the opposite sign from those of the DEEP-C products. [36] discuss how
 147 analysis increments to moisture and temporal inhomogeneity in the observing system
 148 could influence these trends particularly in the tropics. Clearly conclusions based on
 149 NUSHFs obtained directly from the reanalyses need to be treated with great caution.

150 **2.2 Correlations between NUSHF and AMOC changes**

151 Strong statistical correlations have been found between the NUSHF north of a given
 152 latitude over the preceding 10-year period and the AMOC at that latitude [35, 56–
 153 58]. Panels (a) and (b) of Fig. 2 show that in three abrupt-4xCO₂ CMIP6 simulations
 154 (in which the CO₂ concentration is abruptly quadrupled) the NUSHF in the northern
 155 Atlantic region (indicated in Fig. 1) reduces abruptly (within the first year or two of
 156 the simulation) from its mean piControl value whereas the AMOC at 26.5 °N initially
 157 remains similar to its piControl value. In subsequent years, to a good approximation,
 158 the NUSHF and AMOC timeseries both decay at an exponential rate toward a reduced
 159 constant value (which is model dependent). Panels (c) and (d) of Fig. 2 confirm that

similar results are obtained for other CMIP6 simulations. A potential explanation of these results is discussed in section 3.

Motivated by these results, Fig. 3 shows correlations between annual mean AMOC timeseries (i.e. the running mean over the previous year) and NUSHF timeseries calculated as the running mean over the preceding 10-years for CMIP6 simulations of climate change (see Methods for details). Fig. 3(a), in which the correlation is very strong ($r^2 = 0.93$), is calculated using 5-year mean differences of these timeseries from their mean value for the first 250 years of the piControl. The correlation between trends in the AMOC and trends in the preceding 10-year average NUSHF depends on the period of the trend (Fig. 3(b) - (d)). For 20-year trends the best fit linear regression for the inference of AMOC from the NUSHF accounts for 58% of the variance and for 30- and 40-year trends, 72% and 75% of the variance are extracted, respectively. The slopes of the regression lines in all the panels agree well, lying between 18.5 and 19.5 Sv/PW. These values are shown to make sense physically in the Methods section.

2.3 Comparisons of simulated and observed NUSHF and AMOC trends

Figure 4 shows how the distributions of trends in the NUSHF from 26.5 °N to 70 °N and in the AMOC at 26.5 °N, in four types of CMIP6 simulations from a wide range of models (see Methods for details), depend on the period of the trend. Figure 4(c) shows that the three DEEP-C trends (calculated using the three different reanalyses and represented by stars) lie at the outer edge of the 40-year NUSHF trends in the piControl simulations (black line). In fact of the 324 piControl trends used in Fig. 4(c), only one has a more negative trend than the ERA5 DEEP-C trend and none has as negative a trend as the JRA55 and MERRA2 DEEP-C trends.

Using regression slopes from Fig. 3, Fig. 4(d) shows that the DEEP-C implied trends in AMOC are also near, but slightly less near, the outer edge of the distribution

186 of the AMOC piControl trends. The mean (red circle) and 95% confidence interval
 187 (red bars) of these 40-year DEEP-C trends is -0.89 ± 0.49 Sv per decade. We note that
 188 the width of the distribution of piControl values is probably somewhat smaller than it
 189 should be as most but not all CMIP3 and CMIP5 simulations probably underestimate
 190 the standard deviation of 10-year AMOC means [59]. Also Figs. 3(b)-(d) use 10-year
 191 mean NUSHFs as inputs so only 30-year trends of this sort can be calculated from the
 192 DEEP-C data.

193 The distribution of 40-year trends from the historical simulations (taken from 1975-
 194 2014) are much more noticeably different from the piControl trends in the NUSHFs
 195 than the AMOC (Figs. 4(c), (d)). The DEEP-C values lie within the range of these
 196 historical trends but all but one of the NUSHF and AMOC trends lie within the upper
 197 quartile of the simulated trends. All of the 40-year ssp245 and ssp585 CMIP6 NUSHF
 198 trends from 2015-2099 and nearly all of the corresponding AMOC trends are negative.
 199 The 40-year DEEP-C trends lie close to the centre of the ssp585 trends.

200 Panels (a) and (b) of Fig. 4, for the corresponding 20-year trends, again show
 201 that the distribution of CMIP6 historical trends is more noticeably different from the
 202 piControl trends for the NUSHF than the AMOC. Of the three (overlapping) 20-year
 203 trends that can be calculated from the DEEP-C products, only one clearly lies near
 204 the outer edge of the distribution of the piControl trends for the NUSHF.

205 Results for 30-year trends in the NUSHFs averaged over the preceding 10 years
 206 (Fig. 4(e)) are similar to those for the 40-year trends (Fig. 4(c)), the DEEP-C trends
 207 again lying outside the distribution of the CMIP6 piControl trends. The mean trend
 208 and its 95% confidence interval for the AMOC inferred from the 30-year DEEP-C
 209 trends is -1.02 ± 0.46 Sv per decade. This mean trend has an additional uncertainty
 210 (not shown in Fig. 4(c)) arising from the standard deviation, $\sigma = 0.456$ Sv per decade,
 211 of the residual from the trend (Fig. 3(c)). Assuming a Gaussian distribution this
 212 uncertainty gives a 95% confidence interval of ± 0.89 Sv per decade. Combining these

two confidence intervals in quadrature gives an overall 95% confidence interval of ± 1.00 Sv / decade. The percentage change over the last 30 years of the average of the three DEEP-C NUSHFs meaned over the preceding 10 years is 14.2% and the 95% confidence interval for this change is $\pm 13.9\%$.

2.4 Comparison with RAPID data

Figure A1 presents comparisons between timeseries of the RAPID array measurements of the AMOC (blue lines) at 26.5°N [60] and the AMOC inferred from the DEEP-C NUSHFs integrated from 26.5°N to 70°N using the mean regression slope of 19 Sv/PW from Fig. 3. The correlation of interannual fluctuations in the AMOC and this NUSHF is very weak, so only the slopes of these timeseries are worthy of comparison. The preceding 10-year average NUSHFs (green lines) agree better with the RAPID timeseries than the annual mean NUSHFs (orange lines) and the slope of the preceding 10-year average DEEP-C ERA5 timeseries for the period 2005 to 2023, -0.63 Sv per decade, agrees reasonably well with that of the RAPID measurements, -0.89 Sv per decade. The 95% confidence interval based on analysis of the residuals after the fit (see Methods) is larger for the AMOC data (1.5 Sv per decade) than it is for the NUSHF data (which lie between 0.1 and 0.5 Sv per decade). The 95% confidence interval arising from the residuals to the fit in Fig. 3(b), ± 1.3 Sv per decade, is more than twice as large as any of the differences between the RAPID and DEEP-C trends. The trends calculated from DEEP-C NUSHFs averaged over the preceding 10 years from all three reanalyses show a larger reduction in net surface heat loss than those using annual mean values, suggesting that the AMOC may not reduce so fast over the next 10 years. The AMOC reduction in the RAPID measurements is slightly larger than that calculated from all the DEEP-C NUSHFs, suggesting that the DEEP-C data are not over-estimating the reductions in net surface heat loss.

238 In summary, this comparison shows that the DEEP-C results are as consistent
239 with the RAPID data as can reasonably be expected.

240 3 Discussion

241 The rapidity of the initial response of the NUSHFs to increased CO₂ in the abrupt-
242 4xCO₂ simulations is striking. The land surface heats up faster and more than the
243 ocean under global warming [61–63] and it has been suggested that this is what leads
244 to the reduced heat loss in the northern Atlantic [64, 65]. This appears to be consistent
245 with the location of the maximum reduction in heat loss in the Atlantic (Fig. 1(c), (d))
246 being just off the Canadian east coast where cold air in winter is advected over warmer
247 seas. This region is particularly poorly simulated by most of the CMIP6 models, their
248 horizontal resolution being insufficient to faithfully represent the steering of the flow
249 by the bathymetry and the large heat loss in this region [66–68]. The patterns of
250 reduced heat loss in the CMIP6 model abrupt-4xCO₂ and historical simulations differ
251 from those of the DEEP-C products in nearly all cases (not shown) and vary greatly.
252 This may be related to the wide variation in the location of the warming hole in the
253 northern Atlantic in the CMIP simulations as the location of maximum reduction
254 in surface heat loss in a given model generally coincides with a warming hole (not
255 shown). The seasonal cycle of the trend in heat loss is worth further study as the main
256 reductions appear to be in the winter months [36], which would maximise their impact
257 on the winters in north-west Europe.

258 4 Concluding summary

259 The net heat loss from the ocean to the atmosphere is expected to play a key role
260 in the response of the AMOC to radiative forcing and is an attractive proxy for
261 the AMOC. All the CMIP6 models investigated show robust 40-year linear trend
262 reductions through the 21st century in the heat lost in the northern Atlantic between

263 26.5 °N and 70 °N in ssp245 and ssp585 simulations (Fig. 4(c)). The trend over the last
264 40 years in the DEEP-C data has a similar linear trend (Figs. 1(a) and 4(c)). That
265 trend is large enough that it occurs in less than 1% of 40-year periods of statistically
266 stable CMIP6 pre-industrial control (piControl) simulations (Fig. 4(c)) suggesting that
267 it is likely to be anthropogenically forced. Following previous work [35], we show that
268 changes in the NUSHF from the mean piControl value between 26.5 °N and 70 °N
269 in historical, ssp245, ssp585 and abrupt-4xCO2 simulations are well correlated with
270 changes in the maximum of the AMOC at 26.5 °N (Fig. 3(a)). We also show that
271 in the abrupt-4xCO2 simulations, the NUSHF reduces markedly in the first year of
272 the simulation (Fig. 2) and note that improved correlations between the AMOC and
273 NUSHFs can be obtained by using averages of the NUSHFs over the preceding 10 years
274 [56–58]. Figure 3(b)-(d) shows that there are strong correlations between 20– to 40-
275 year trends in climate change simulations of the AMOC and the NUSHF averaged over
276 the preceding 10 years. Taken together, the above results suggest that the northern
277 Atlantic heat fluxes have reduced in response to increasing greenhouse gases and that
278 the AMOC has already begun a slow weakening trend.

279 Finally, our study directly targets the change in surface heat loss, because it is the
280 fundamental mechanism for the long-term AMOC weakening seen in climate change
281 projections. For this reason we claim our conclusions are more robust than those of
282 other recent studies that use either indirect AMOC proxies that are subject to non-
283 AMOC confounding factors, or direct AMOC measurements for which the timeseries is
284 too short to detect the long-term trend above year-to-year noise. We therefore believe
285 that our work adds substantially to confidence that a long-term AMOC decline has
286 begun, as well as robustly quantifying the recent rate of change.

287 5 Methods

288 5.1 Data used

289 NUSHFs calculated directly from ERA5 and other reanalyses have been found to be
290 unreliable [44] and exhibit large spurious trends [69, 70]. The methodology used by
291 DEEP-C (Diagnosing Earth’s Energy Pathways in the Climate system) is dedicated
292 to providing more reliable estimates. The DEEP-C version 5.1 data used in this study
293 [53, 71, 72] is derived from reconstructions of the net radiation at the top of the
294 atmosphere calculated using measurements from the ERBE (Earth Radiation Budget
295 Experiment) and CERES (Clouds and the Earth’s Radiant Energy System) satellites,
296 and calculations of the mass-corrected, vertically-integrated, horizontal atmospheric
297 energy flux divergence and rate of change of the atmospheric heat content derived using
298 atmospheric reanalysis data with the techniques described in [44] and [73]. Although
299 atmospheric energy transports from reanalysis products are used in this energy budget
300 approach, these depend upon realistic temperature and moisture gradients and wind
301 fields which are well constrained in the reanalysis products. This provides an obser-
302 vationally constrained estimate in contrast with the surface fluxes calculated within
303 and obtained directly from the reanalyses which are based on short-term model fore-
304 casts using inherently uncertain parameterizations and are not directly constrained
305 by observations. Evaluations of the accuracy of these fluxes, [44, 49] and Supp. Fig.
306 S1 in [45], show that the DEEP-C estimates are more reliable than previous products
307 (including those obtained directly from the reanalyses).

308 The CMIP6 data used were downloaded from the Earth System Grid Federation
309 (ESGF) and are summarised in Table A1. With the exception of CMCC, data from
310 at least one model for each of the contributing institutes were used providing both
311 NUSHF and AMOC data from 300 years of the piControl simulation were available. For
312 each model we used up to five ensemble members from the historical simulations and
313 just one simulation from the piControl, ssp245, ssp585 and abrupt-4xCO2 simulations.

314 The annual means are calculated from January to December. FESOM model data were
 315 not used because we were unable to obtain its NUSHFs on a structured grid. CMCC
 316 data were not used in the plots shown. This choice has an impact on the piControl
 317 distribution in Fig. 4 (see discussion of Fig. 4 below) but little impact on any of the
 318 other figures.

319 The net upward surface heat flux (NUSHF) is equal but opposite to the heat
 320 flux downward at the surface (hfds) generated by CMIP6 simulations and denoted by
 321 NSHF in [74, 75].

322 The RAPID measurements were downloaded from the official website.

323 5.2 Data processing

324 The linear regression trends in all the figures are simple (equally weighted) least square
 325 fits to the timeseries of the form

$$y_i = at_i + b + e_i, \quad (1)$$

326 where t_i is the time of the i th of the N values y_i in the timeseries.

327 Assuming the residuals, e_i , are uncorrelated, the standard error, σ_U , in the ordinary
 328 least square estimate of the slope, $\hat{b}$, is given by

$$\sigma_U^2(\hat{b}) = \frac{s^2}{\sum_{i=1}^N (t_i - \bar{t})^2} \quad , \quad s^2 = \frac{\sum_{i=1}^N e_i^2}{N - 2}, \quad (2)$$

329 $\bar{t}$ representing the mean value of the t_i [76]. The standard error when the residuals
 330 may be correlated is

$$\sigma_{\text{eff}}(\hat{b}) = \sigma_U(\hat{b}) \sqrt{\frac{N - 2}{N_{\text{eff}} - 2}}, \quad (3)$$

where N_{eff} is the effective number of degrees of freedom in the residuals. N_{eff} , can be estimated [77] using

$$N_{\text{eff}}(K) = \frac{N}{1 + 2 \sum_{k=1}^K (1 - k/N) \rho_k} \quad , \quad \rho_k = \frac{\sum_{i=1}^{N-k} e_i e_{i+k}}{\sum_{i=1}^N e_i^2}. \quad (4)$$

Defining $N_{\text{eff}}(0) = N$, the error estimates on the timeseries in Figs. 1 and A1 are set using the minimum value of $N_{\text{eff}}(K)$ for $0 \leq K \leq 19$ and $0 \leq K \leq 9$, respectively. This choice deliberately errs on the side of caution (making the confidence interval wider than it could be). The slopes are displayed as $\hat{b} \pm c_i$ where c_i is the 95% confidence interval,

$$c_i = \sigma_{\text{eff}} S_t(0.975, N_{\text{eff}} - 2), \quad (5)$$

S_t being the Student t-test distribution (approximately equal to 1.96 when N_{eff} is large).

The stippling in the maps in Fig. 1 is calculated using the same formulae except that

$$N_{\text{eff}} = N \min \left[1, \frac{1 - \rho_1}{1 + \rho_1} \right], \quad (6)$$

the expression involving ρ_1 being appropriate for a first order autoregressive process [78]. This choice again deliberately errs on the side of caution. Points are stippled when the magnitude of the NUSHF is larger than c_i .

The least square fits to the abrupt_4xCO₂ simulations of the form $y = A \exp(-ct) + B$ in Fig. 2 were found by normalising the input timeseries and using the Levenberg–Marquardt (LM) method by calling `curve_fit` from `scipy.optimize`.

The differences from the piControl values in Fig. 3(a) correlate much better than the total values and the correlations for individual models are also good (not shown). Subtracting the piControl time-mean values rather than 5-year mean piControl values also strengthened the correlations shown in Fig. 3(a). The high correlation in Fig. 3(a) also partly depends on the improvement to the fit for the first 10-20 years of the

353 AMOC in the abrupt-4xCO₂ simulations obtained using the preceding 10-year average
 354 of the NUSHF (not shown). The much stronger correlation in panel (a) of Fig. 3 than
 355 the other panels can be interpreted from the nature of the change from the piControl
 356 value used in panel (a). Each change is an estimate of the time-integral of the trend
 357 from the start of the simulation. So Fig. 3(a) can be interpreted as being calculated
 358 from trends over many periods, some of the periods being much longer than 40 years
 359 and some of the abrupt-4xCO₂ changes being relatively large. The correlations are
 360 calculated for periods in simulations when radiative forcing is likely to be driving
 361 AMOC changes. Weaker correlations might be obtained in periods when greenhouse
 362 gas forcing has equilibrated.

363 The distribution of linear trends in the simulations presented in Fig. 4 used all
 364 the models listed in Table A1 other than that of CMCC, equally weighted for the
 365 time-periods we succeeded in downloading. For a period of N -years, the trends were
 366 calculated at $N/2$ year intervals (e.g. for 20-year trends they were calculated from
 367 years 0 to 20, 10 to 30, 20 to 40 etc.). The resulting distribution is slightly smoother
 368 but not qualitatively different from calculations at N -year intervals. The mean and
 369 95% confidence intervals for the DEEP-C trends are calculated assuming the trends
 370 are independent estimates following the approach of [79].

371 The AMOC in the CMCC piControl simulation has large amplitude oscillations
 372 with a period of about 100 years. These oscillations are closely related to large vari-
 373 ations in the sea-ice cover in the Labrador Sea and are similar to those investigated
 374 by [80] who concluded that they only occur in models whose piControl simulations
 375 have unrealistically large time-mean sea-ice extents in the Labrador Sea. The AMOC
 376 at both 26.5 °N and 40 °N in the CMCC piControl has linear trends over the first 500
 377 years of simulation which are almost four times larger in magnitude than those in any
 378 of the other models and a very large Top of Atmosphere (TOA) flux imbalance. For

379 these three reasons we have not included the CMCC simulations in the calculation of
380 any of the figures.

381 We obtained similar results to those in Figs. 1-4 using 40 °N instead of 26.5 °N
382 for the southern boundary and/or 60 °N instead of 70 °N for the northern boundary.
383 Investigations of the heat budget showed that the meridional heat flux through 60 °N
384 and its fluctuations are substantially greater than those through 70 °N, so 70 °N
385 is a better choice than 60 °N for this study. Good closure of the heat budget was
386 obtained using the area indicated by the blue boxes in Fig. 1. The correlation between
387 the NUSHF and the rate of change of heat content for this area is very strong for
388 annual means and very weak for 10-year means. Conversely the correlation between
389 the NUSHF and the heat flux through 26.5 °N is very weak for annual means and very
390 strong for 10-year means.

391 5.3 Sense check on regression line slopes

392 The slope of the regression lines in Fig. 3 can be estimated from the difference in
393 potential temperature of the water flowing northward and southward:

$$V_A = \frac{-N}{c_p \Delta T}. \quad (7)$$

394 Here V_A is the volume transport of the AMOC (units kg s^{-1}), N is the NUSHF, c_p
395 is the heat capacity of sea-water, $4 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$, and ΔT is the average difference
396 in potential temperature of the water flowing north and south. A change in potential
397 temperature of -12.5 K gives a regression slope $-(c_p \Delta T)^{-1} = 2 \times 10^{-5} \text{ kg J}^{-1} = 20$
398 Sv/PW similar to that calculated in Fig 3.

399 **Acknowledgements.** Advice and assistance from Alejandro Bodas-Salcedo, John
400 Edwards, David Marshall, Richard Renshaw and Bablu Sinha are gratefully acknowl-
401 edged.

6 Declarations

- Funding: The Met Office authors are supported by the Hadley Centre Climate Programme. Chunlei Liu and Ke Yang are supported by the National Natural Science Foundation of China (42275017, 42075036). M. Mayer was supported by ESA contract ref. 4000145298/24/I-LR (MOTECUSOMA) and ESA Contract ref. 4000147586/I/25-LR (Ocean Surface Heat Flux).
- Conflict of interest/Competing interests (check journal-specific guidelines for which heading to use)
- Ethics approval and consent to participate
- Consent for publication
- Data availability
- Materials availability
- Code availability
- Author contribution

Appendix A

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Name	Atmos	Atm Resoln	Ocean	Ocn Resoln	Sea-ice	Ref.
ACCESS-CM2	UM7.3	135km, 38L	MOM5	1°, 50L	CICE4.1	[81]
CanESM5	CanAM5	T63, 49L	NEMO3.4	ORCA1, 45L	LIM2	[82]
CESM2	CAM6	1°, 70L	POP2	1°, 60L	CICE5	[83]
CMCC-CM2-SR5	CAM5	1°, 30L	NEMO3.6	ORCA1, 50L	CICE4	[84]
CNRM-CM6-1	ARPEGE 6.3	T127, 91L	NEMO3.6	eORCA1, L75	Gelato6	[85]
ECEarth-3	IFS 36r4	T255, L91	NEMO3.6	ORCA1, L75	LIM3	[86]
GFDL-CM4.1	GFDL AM4.1	100km, 49L	MOM6	ORCA05, 75L	SISv2	[87]
GISS-E2-1-G	GISS-E2.1	2°, 40L	GISS O v1	1°, 40L	GISS SI	[88]
HadGEM3-GC3.1 LL	UM7.1	135km, 85L	NEMO3.6	ORCA1, 75L	CICEv5.1	[89]
HadGEM3-GC3.1 MM	UM7.1	60km, 85L	NEMO3.6	ORCA025, 75L	CICEv5.1	[89]
IPSL-CM6A-LR	LMNZ6A	140km, 79L	NEMO3.6	ORCA1, 75L	LIM3.6	[90]
MIROC6	CCSR-NIES	T85, 81L	COCO4.9	ORCA1, 63L	COCO4.9	[91]
MPI-ESM1-2-LR	ECHAM6.3	T63, 47L	MPIOM1.6.3	ORCA04, 40L	MPIOM1.6.3	[92]
MRI-ESM2-0	MRIAGCM3.5	T159, 80L	MRI.COMv4	1°, 60L	MRI.COMv4	[93]
NorESM2-LM	CAM6-Nor	220km, 32L	MICOM	1°, 53L	CICE5.1.2	[94]

Table A1 CMIP6 simulations used. The third column describes the atmosphere grid: Tnn denotes the triangular spectral truncation; $nnnkm$ denotes the approximate latitude grid spacing; nnL denotes the number of levels or layers. The fifth column describes the ocean grid: n° is an n degree lat-lon grid; $ORCAnnn$ is a tri-polar Mercator grid with zonal grid spacing of $n.nn$ degrees at the equator.

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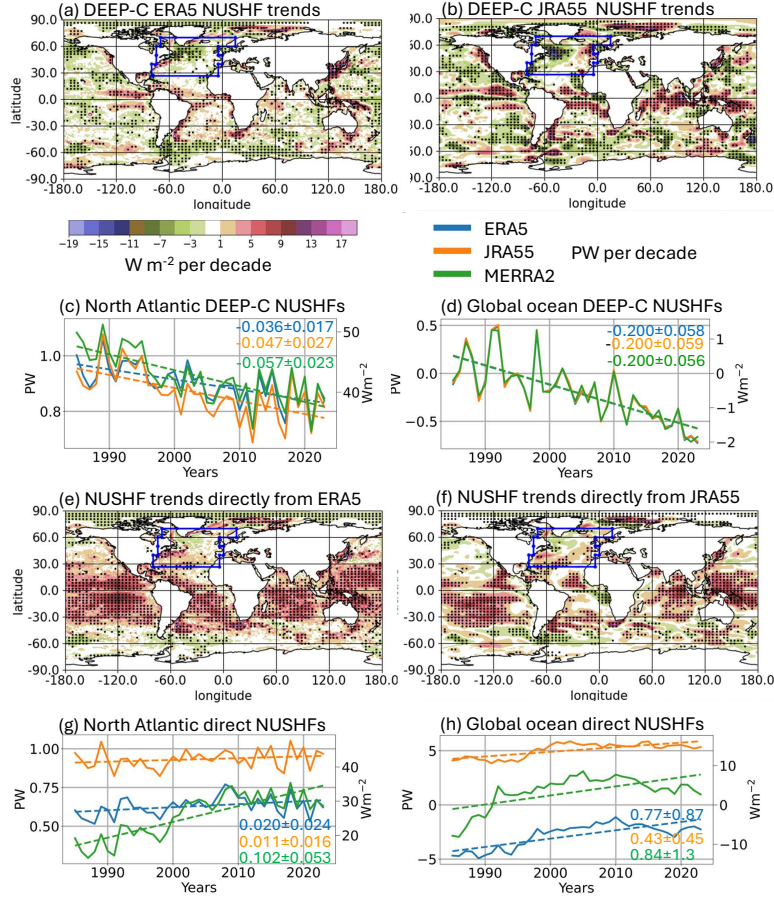


Fig. 1 (a - d): Timeseries and fields inferred from heat budget calculations using the DEEP-C method. (a, b): Geographical maps of the net upward surface heat flux (NUSHF) trends (W m^{-2} per decade) for the period 1985 – 2023 calculated using the DEEP-C method with (a) ERA5 and (b) JRA55 reanalysis data. Stippling indicates where the magnitude of the NUSHF trend is larger than its 95% confidence interval (see Methods). (c, d): Timeseries of the area integrals of the NUSHF into the ocean calculated using DEEP-C products based on ERA5 (blue), JRA55 (orange) and MERRA2 (green) reanalyses for (c) the northern Atlantic area, shown as blue boxes in panels (a), (b), and (d) the global domain. The dashed lines are best fit linear regressions and the numbers are the gradients of these lines and their 95% confidence interval in PW per decade. (e - h) are the same as (a - d) except that (e - h) are calculated using NUSHFs obtained directly from the reanalyses.

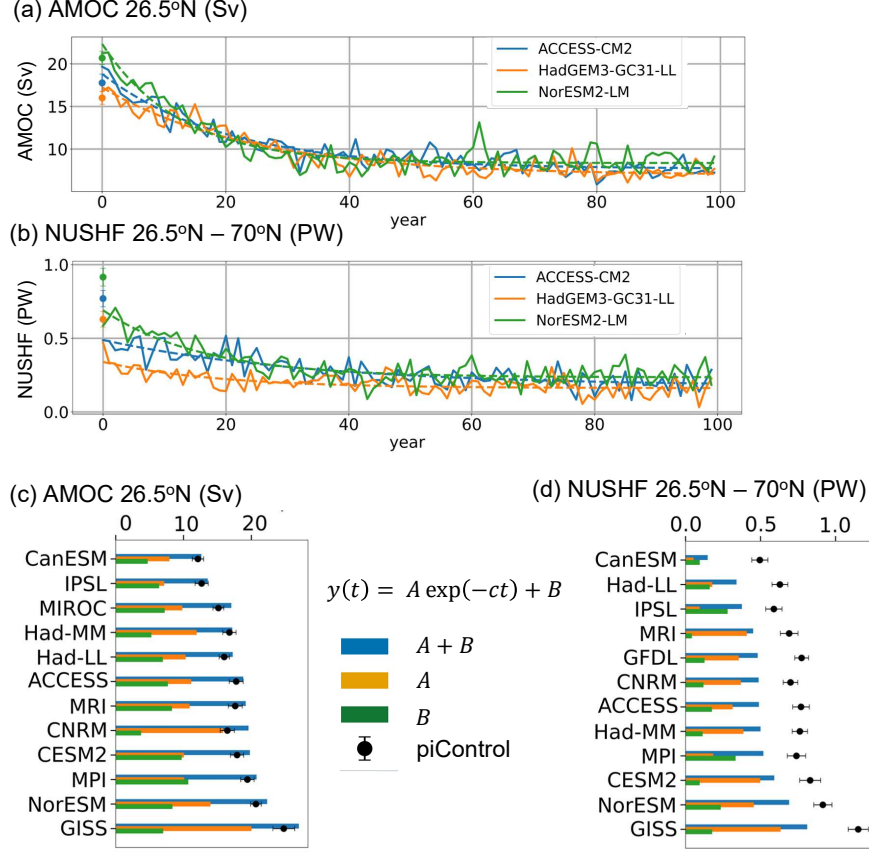


Fig. 2 (a, b): Annual mean timeseries (full lines) from the first 100 years of three abrupt_4xCO₂ simulations; (a) the AMOC at 26.5 °N and (b) the area integral of NUSHF from 26.5 °N to 70 °N. The dashed lines are least square fits of the form $y(t) = A \exp(-ct) + B$ where t is time and A , B and c are allowed to vary. (c, d): The values of A (orange), B (green) and $A + B = y(t = 0)$ (blue) from the least square fits, and the time-means (black circles) and ± 1 standard deviation error bars from the first 500 years of the piControl simulations.

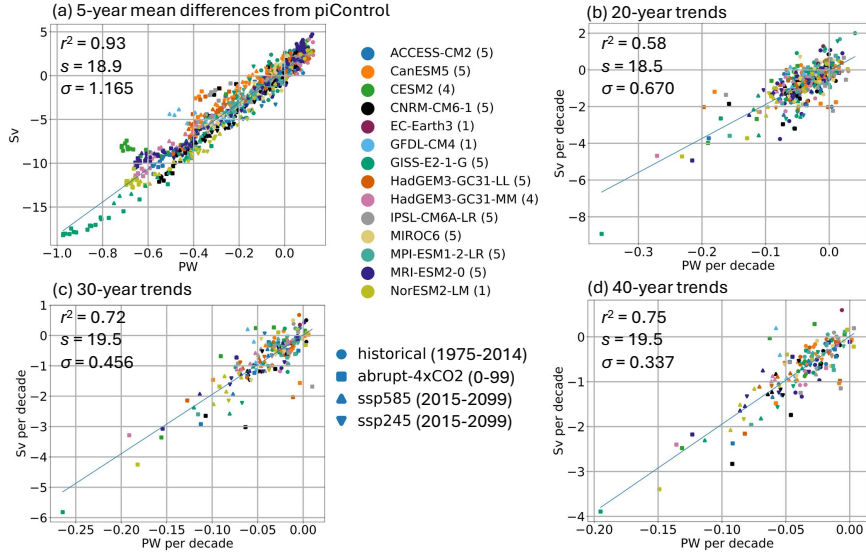


Fig. 3 Scatter plots calculated from a wide range of CMIP6 model simulations of climate change using timeseries of annual mean AMOC at 26.5°N (y -axis) and timeseries of NUSHF for 26.5° to 70°N averaged over the preceding 10 years (x -axis): (a) differences of 5-year means of these timeseries from their time-mean piControl values; (b) 20-year, (c) 30-year and (d) 40-year trends calculated using best fit linear regressions. The units of the slopes, s , are Sv/PW, and those of the standard deviation of the residual to the fit, σ , are the same as the y -axis. The number of historical simulations used for each model is indicated in brackets.

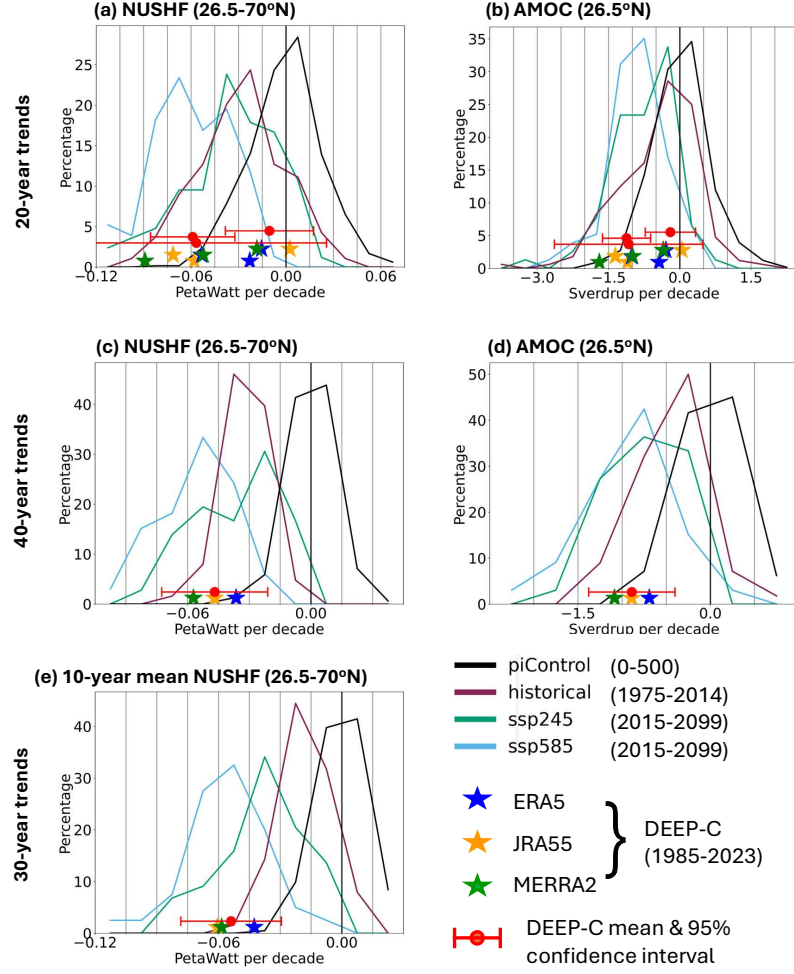


Fig. 4 Histograms showing the distributions in four types of CMIP6 simulations of (a, b) 20-year and (c, d) 40-year linear trends in (a, c) the area integral from 26.5 °N to 70.0 °N of NUSHF (PW per decade) and (b, d) the AMOC (Sv per decade) at 26.5 °N. The linear trends are calculated by least square linear regression fits to annual mean data. (e) 30-year trends in the mean of the NUSHF from the preceding 10 years for the same area integral as (a). Individual DEEP-C trends are plotted as asterisks and mean DEEP-C trends and their 95% confidence intervals as red points and bars, respectively. The three 20-year periods for the DEEP-C data are offset in the vertical (the earliest period is lowest) for both the individual values and the means and confidence intervals. The DEEP-C trends for the AMOC are calculated using the average slope, 19 Sv/PW, from Fig. 3. The faint vertical lines show the bins used to calculate the histograms.

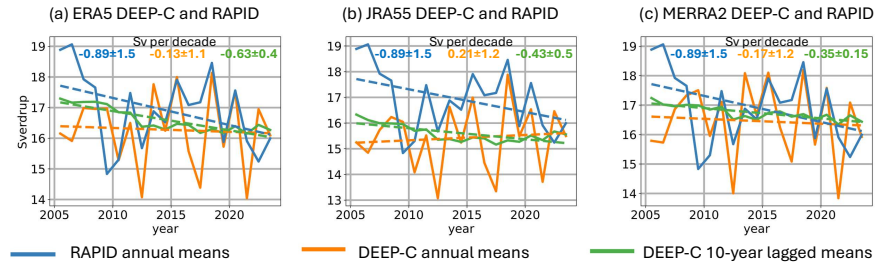


Fig. A1 Comparisons between annual means of the AMOC at 26.5°N based on measurements at the RAPID array (full blue lines) and values based on the NUSHF between 26.5°N and 70°N calculated using the DEEP-C method with a regression slope of 19 Sv/PW (based on Fig. 3) and (a) ERA5 (b) JRA55 and (c) MERRA2 data. The full orange lines are calculated using annual mean NUSHFs whilst the full green lines are obtained using the mean NUSHFs from the preceding 10 years. The dashed lines are least square linear regression fits to the full lines and their slopes and 95% confidence intervals with matching colours are in Sv per decade.