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LETTER

On the relationship between Atlantic meridional overturning circulation slowdown and global surface warming

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Abstract

According to established understanding, deep-water formation in the North Atlantic and Southern Ocean keeps the deep ocean cold, counter-acting the downward mixing of heat from the warmer surface waters in the bulk of the world ocean. Therefore, periods of strong Atlantic meridional overturning circulation (AMOC) are expected to coincide with cooling of the deep ocean and warming of the surface waters. It has recently been proposed that this relation may have reversed due to global warming, and that during the past decades a strong AMOC coincides with warming of the deep ocean and relative cooling of the surface, by transporting increasingly warmer waters downward. Here we present multiple lines of evidence, including a statistical evaluation of the observed global mean temperature, ocean heat content, and different AMOC proxies, that lead to the opposite conclusion: even during the current ongoing global temperature rise a strong AMOC warms the surface. The observed weakening of the AMOC has therefore delayed global surface warming rather than enhancing it.

Social Media Abstract: The overturning circulation in the Atlantic Ocean has weakened in response to global warming, as predicted by climate models. Since it plays an important role in transporting heat, nutrients and carbon, a slowdown will affect global climate processes and the global mean temperature. Scientists have questioned whether this slowdown has worked to cool or warm global surface temperatures. This study analyses the overturning strength and global mean temperature evolution of the past decades and shows that a slowdown acts to reduce the global mean temperature. This is because a slower overturning means less water sinks into the deep ocean in the subpolar North Atlantic. As the surface waters are cold there, the sinking normally cools the deep ocean and thereby indirectly warms the surface, thus less sinking implies less surface warming and has a cooling effect. For the foreseeable future, this means that the slowing of the overturning will likely continue to slightly reduce the effect of the general warming due to increasing greenhouse gas concentrations.

1. Introduction

Variations in the Atlantic meridional overturning circulation (AMOC) can change Northern Hemisphere and even global surface temperatures (Knight *et al* 2005, Stolpe *et al* 2018). Most model studies have shown that an AMOC decline, in response to increased CO_2 concentrations, weakens the poleward ocean heat transport, increases the ocean heat uptake (Rugenstein *et al* 2013) and therefore diminishes global warming. Yet a recent study, analysing observations of the last decades (Chen and Tung 2018), challenged this finding and came to the conclusion that a weak AMOC can lead to more rapid surface warming. In the following we show that the observational and reanalyses data analysed in this study are fully consistent with the previously established understanding, i.e. that the correlation between AMOC strength and global surface warming is (at inter-annual to decadal timescales) negative and that over the last decades a weaker AMOC likely acted to delay global surface warming.

Chen and Tung (2018) base their idea that global surface warming in the next decades may be enhanced by a weaker AMOC on the concept that as a consequence of an AMOC weakening less heat can be carried into the deep ocean via deep convection. This central claim was supported by a visual comparison of the time series for AMOC strength and global surface warming over the last decades (Chen and Tung (2018), figure 3) and rests primarily on the period from 1975 to 1998, during which the AMOC was in a relatively weak state, which coincided with a period of rapid surface warming. They conclude that in recent decades a weakened AMOC warmed the surface by bringing less heat into the deep North Atlantic. Furthermore they argue that this mechanism explains why the trend in ocean heat content in the North Atlantic Ocean went from positive to negative when comparing two time spans of an increasing (1993–2004) and a decreasing (2005–2016) AMOC, explaining this change in the ocean heat content by a change in the vertical heat transport into the ocean driven by the AMOC: 'Deep convections can now carry more heat downward' (Chen and Tung 2018). This suggested mechanism is unlikely to operate in the northern Atlantic, since convection there is thermally driven: convective mixing results from static instability due to colder water overlying warmer water. It therefore transports heat upwards in the water column, not downward, balancing the oceanic heat uptake occurring over large areas of the ocean by turbulent diffusion (e.g. Winton 1995, Drijfhout 2015).

To investigate the relationship between overturning strength and changes in the global mean surface temperature (GMST), we perform a correlation analysis of the two time series. We therefore revisit the analysis of Chen and Tung (2018) and investigate the relationship between the detrended GMST evolution and different indices for the AMOC strength. This correlation analysis shows that the data they present do not support the conclusion that an AMOC weakening currently enhances global surface warming. We furthermore extend the analysis with a second method that accounts for the variability of the radiative forcing as well as feedback processes in the Earth system, yielding very similar results. These results are in agreement with the understanding that a weaker AMOC *in*creases the global ocean heat uptake and therefore has a cooling effect on the global surface temperature. Additional support to this conclusion is provided by the fact that the recent decline of the AMOC (Smeed *et al* 2014) coincided with an increase in the ocean heat uptake rate.

2. Data

To ensure that differences in the results between this study and that of Chen and Tung (2018) are not due to differences in the underlying data we used the same global mean temperature time series, the same AMOC proxies and the same time series for the ocean heat content (OHC). The latter is extended by the improved OHC estimates by Cheng *et al* (2017).

2.1. Global mean surface temperature, forcing time series and feedback parameter

We start by considering the temperature evolution in the light of the global energy balance. For this purpose we use the median of the HadCRUT4.6 data (Morice *et al* 2012) that provides an estimate of the global mean surface temperature anomaly since 1850 with respect to 1961–1990. For the changes in the radiative forcing we use a time series that combines the known individual forcing data sets (greenhouse gases, ozone, solar irradiance, land use, snow albedo, orbital parameters, direct and indirect effect of tropospheric aerosols and volcanic aerosols) that are used to drive the CMIP5 historical simulations and represents all changes in both the natural and anthropogenic forcing from 1850 until 2012 (Miller *et al* 2014). For our analysis we need to consider the temperature difference ΔT relative to the preindustrial equilibrium state. Therefore, both GMST and forcing anomaly are given relative to the year 1850. Since we also account for the feedback response of the Earth system to an initial temperature change, we need to estimate the strength of this response, i.e. the feedback parameter λ. As a best estimate we chose a feedback parameter of $\lambda = 2.3 \pm 0.7\,\mathrm{W\,K^{-1}\,m^{-2}}$ that was determined for the period 1979–2008 across an ensemble of 19 AGCMs (Gregory and Andrews 2016). However, there is a growing understanding that the Earth's climate sensitivity is time-scale dependent, as the different climate feedbacks act on different time scales. An ensemble study based on the analysis of a modified energy balance model, constrained by observations and the outputs from the CMIP5 models, give a feedback parameter of $1.9 \pm 0.3\,\mathrm{W\,K^{-1}\,m^{-2}}$ for intra-annual scales that decreases to around $1.5 \pm 0.3\,\mathrm{W\,K^{-1}\,m^{-2}}$ and $1.3 \pm 0.3\,\mathrm{W\,K^{-1}\,m^{-2}}$ on response time scales of 10 and 100 years, respectively (Goodwin 2018). We therefore tested the correlation between AMOC changes and surface warming with the following values for the feedback parameter: $\lambda = 1.3, 1.5, 1.9, 2.3, 3.0\,\mathrm{W\,K^{-1}\,m^{-2}}$ as well as for a counterfactual case where we neglect all radiatively forced surface temperature changes.

2.2. AMOC indices and ocean heat content

Due to the lack of long-term AMOC measurements, the evolution of the AMOC over the last century has to be reconstructed from proxy data. To cover the uncertainty of the reconstruction we base our analysis on three different AMOC indices. The first two indices are based on the upper (0–1500 m) subpolar ocean salinity with salinity values taken either from ISHII and Scripps ($A_{ISHIIS+Scripps}$) or from EN4 (A_{EN4}) data (Chen and Tung 2018). The third is the sea surface temperature (SST) based index as defined by Caesar *et al* (2018) based on the HadISST data ($A_{HadISST}$). To determine the trend in the ocean heat uptake (OHU) over the last decade, the ocean heat content based on the ISHII and Scripps datasets (Chen and Tung 2018) is used. It is a time series of the 0–1500 m OHC from mid-2000 until mid-2014. We further analyse the OHC distribution over the different ocean basins using the improved OHC estimates by Cheng *et al* (2017) that are given until a depth of 2000 m.

3. Method and results

First, we study the relationship between AMOC strength and the forcing corrected global surface warming with a correlation analysis over the whole length of the time series for which all data is available (1948–2012). The forcing correction is done in two different ways: on the one side by just removing the long-term warming signal (either by removing the linear trend or by removing a nonlinear trend as done by Chen and Tung (2018)) and on the other side by using a simple equation for the global mean energy balance. This will answer the question whether the opposing course of the two variables between 1975–1998, as identified by Chen and Tung (2018) (their figure 3(b)), is also valid during other time periods. While this correlation analysis will not suffice to determine the contribution of different processes to global temperature changes, it is sufficient to identify whether periods of a weaker AMOC over the last decades had a distinct cooling, warming or close to no effect on the global surface temperature.

Second, we investigate the trend reversal in the ocean heat content in the North Atlantic Ocean from positive, during a time period of increasing AMOC strength (2000–2004), to negative, during a time period of a decreasing AMOC (2005–2016), considering the role of the AMOC in transporting heat horizontally from the Southern Ocean into the Atlantic.

3.1. Energy budget and the influence on the vertical ocean heat transport

Global mean surface temperature changes—i.e. the lower atmosphere and upper ocean, which are well-mixed and thermally tightly coupled—are forced by radiative forcing from the top and heat exchange with the deep ocean below (Trenberth *et al* 2010, Brown *et al* 2014):

$$c_m \, dT/dt = \Delta Q_{rad} - \Delta Q_{ocean} - \lambda \, \Delta T. \qquad (1)$$

Here, T is the global mean surface temperature, c_m is the effective heat capacity of the system (dominated by the ocean mixed layer), Q_{rad} the radiative forcing and Q_{ocean} the vertical heat transport across the bottom of the ocean mixed layer e.g. through diffusion (fluxes are positive downward) (Brown *et al* 2014). Δ indicates differences to a previous equilibrium state (e.g. preindustrial). The term $\lambda \, \Delta T$ represents the equilibrium response ΔT of the surface temperature to the forcing anomaly, which depends on the climate feedback parameter λ. The equation holds for the global mean temperature, therefore horizontal transport processes play no role. Solved for ΔQ_{ocean} this equilibrium is:

$$\Delta Q_{ocean} = \Delta Q_{rad} - \lambda \Delta T. \qquad (2)$$

Since we are looking at temperature changes at multidecadal timescales we can assume that the mixed layer is close to equilibrium and thus neglect the transient term on the left hand side in equation (1). This term would lead to some delay of the surface temperature response to forcing changes, yet empirical correlation shows that the lag of the global surface temperature response to a change in the radiative forcing, e.g. the 11 year solar cycle, is of the order of a month (Foster and Rahmstorf 2011), so for our purposes this lag is not significant.

With given time series for ΔT and ΔQ_{rad} (both with respect to the preindustrial equilibrium state of 1850) and the different estimates for the feedback parameter λ we can now use equation (2) to test how AMOC variations (represented by the AMOC indices) correlate with the part of surface temperature changes that are not directly radiatively forced (i.e. the right hand side of the equation (2)).

The correlation values (figure 1) are positive (with $r = 0.49$, 0.57 or 0.22 depending on the AMOC proxy) with particularly warm GMST anomalies coinciding with a strong AMOC. This is in direct contradiction to the idea that a strong AMOC acts to cool the surface and in full agreement with the established understanding of the AMOC's role in vertical heat transport (Drijfhout 2015). We use the smoothed time series to determine the influence of the AMOC since the short-term fluctuations in the ocean heat uptake in the North Atlantic are dominated by atmospheric variability (Gulev *et al* 2013).

While the exact values of the correlation coefficients depend on the choice of the feedback parameter and the AMOC index, they are positive in all cases (i.e. between 0.01 and 0.65, see table 1) and therefore do not support the hypothesis that a weak AMOC enhances surface warming by decreasing the ocean heat uptake (in that case the correlation coefficients would be negative). The fact that most of the correlation values are not significant at the 5% level (this was tested using amplitude-adjusted Fourier transform (AAFT) surrogates (Donges *et al* 2015)) is also irrelevant for deducing that an AMOC weakening does not enhance surface warming, as it is sufficient to show

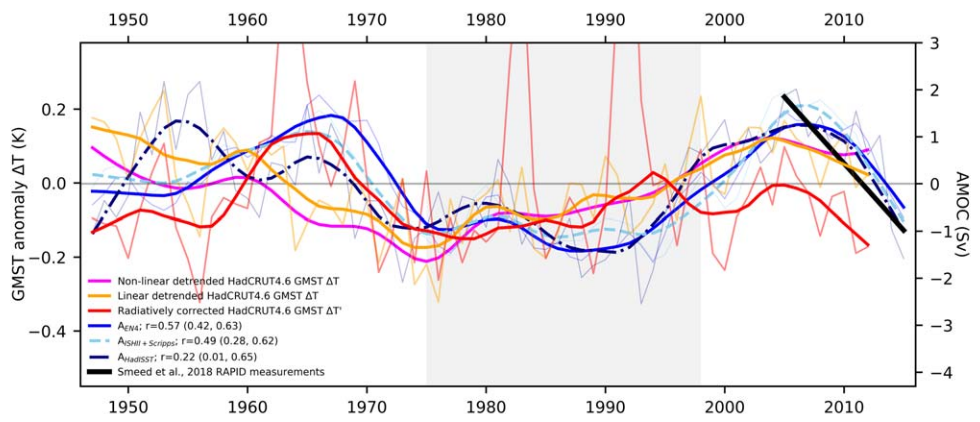

Figure 1. Time evolution of the multidecadal variability of the AMOC compared to the global mean surface temperature adjusted by the historical forcing for the time period 1948–2012. In grey the time period from 1975 to 1998 is marked during which the AMOC was in a relatively weak state. Proxies for the AMOC are the salinity based proxies $A_{ISHIIS+Scripps}$, A_{EN4} and the temperature based proxy $A_{HadISST}$ (shades of blue), which are compared to the linear trend of the 2005–2015 measurements form the RAPID array (thick black line). The global mean temperature deviation is based on HadCRUT4.6 data and is corrected for the linear, long-term warming trend (ΔT, orange), the nonlinear trend as done by Chen and Tung (2018) (ΔT, magenta) or adjusted by the historical forcing used for CMIP5 ($\Delta T' = \Delta T - 1/\lambda\, \Delta Q_{rad}$, red line). The default value for the feedback parameter is $\lambda = 2.3 \pm 0.7$ W K^{-1} m^{-2} and the numbers in brackets give the range of correlation coefficients resulting from other values for λ that are additionally shown in table 1. Thin lines are annual values; thick lines are 10 year LOWESS smoothed values. The LOWESS (Locally Weighted Scatterplot Smoothing) filter fits a regression curve to a scatterplot using weighted local linear regressions depending on the smoothing span, in this case 10 years (Cleveland 1979). The correlation coefficients r were calculated with the smoothed time series. (To remove any correlations due to common trends the time series were first linearly detrended.)

Table 1. Results of the sensitivity analysis of the correlation values considering the uncertainties of the feedback parameter λ. The correlation values were calculated for the whole time period (1947–2012). Values that are significant at the 5%-level are shown in boldface.

λ in W K^{-1} m^{-2} AMOC proxy	1.3	1.5	1.9	2.3	3	Linear warming trend removed	Nonlinear warming trend removed
ISHII + Scripps	0.28	0.34	0.40	0.49	**0.62**	0.62	0.57
EN4	0.45	0.49	0.53	**0.57**	**0.63**	0.42	0.39
HadISST	0.01	0.07	0.12	0.22	0.37	0.65	0.61

that the coefficients are not negative. As can be seen in figure 1 there is no apparent lag between the adjusted surface warming and the AMOC strength, consistent with our assumption that the ocean's mixed layer and the atmosphere are responding to the changes in forcing within a year. This was verified with a lag-correlation analysis that showed no significant time lag between the two.

Our analysis takes the role of radiative forcing in affecting GMST as a given and looks at any additional effect of the AMOC. Alternatively, the internal climate variability can be estimated by removing the warming trend from the original time series. This is the approach taken by Chen and Tung (2018) who removed a nonlinear secular trend (their figure 3) that is very similar to the 100 year linear trend. In the case that we remove either a linear warming trend or a nonlinear trend (using the exact same data as Chen and Tung (2018)) we get even larger positive correlation values with $r = 0.62$, 0.42, 0.65 for the linear warming trend removed and $r = 0.57$, 0.39, 0.61 when removing the nonlinear trend (for $A_{ISHIIS+Scripps}$, A_{EN4} and $A_{HadISST}$, see right columns of tables 1 and 2).

Even if we consider only the period after 1975, on which Chen and Tung rested their argument, we find mostly positive correlation values (see table 2). While certain combinations of λ and AMOC proxy yield a negative correlation (especially for smaller values for the feedback parameter), the correlation between AMOC strength and GMST variability is still positive when the radiative forcing is taken into account by removing the linear or nonlinear trend from the data (right columns of table 2).

These results are consistent with several model studies which likewise found a positive correlation with no lag between the AMOC strength and global as well as northern hemisphere temperature (e.g. Knight *et al* 2005, Maroon *et al* 2018). It is also in alignment with the fact that the decline of the AMOC over the last decade (Smeed *et al* 2014), for which direct AMOC measurements exist, coincided with an increase in the rate of ocean heat uptake (figure 2), not a decrease.

3.2. Basin shift or the influence on the horizontal ocean heat transport

Since the Argo era, ocean heat content measurements have increased in quality and extent in particular considering the deep ocean (Cheng *et al* 2017). The data show that there is a large shift in the regional ocean heat content between the period 2000–2004 and

Table 2. Results of the sensitivity analysis of the correlation values considering the uncertainties of the feedback parameter λ. The correlation values were calculated for the time period 1975–2012, values in brackets for the time period 1975–1998.

λ in W K^{-1} m^{-2} AMOC proxy	1.3	1.5	1.9	2.3	3	Linear warming trend removed	Nonlinear warming trend removed
ISHII + Scripps	−0.14	0.00	0.14	0.29	0.48	0.84	0.82
	(−0.30)	(−0.24)	(−0.18)	(−0.09)	(0.03)	(0.50)	(0.75)
EN4	−0.15	−0.01	0.12	0.27	0.47	0.84	0.84
	(0.06)	(0.11)	(0.05)	(0.06)	(0.11)	(0.33)	(0.73)
HadISST	−0.15	−0.02	0.09	0.24	0.43	0.83	0.83
	(−0.03)	(0.01)	(−.08)	(−0.07)	(−.02)	(0.30)	(0.68)

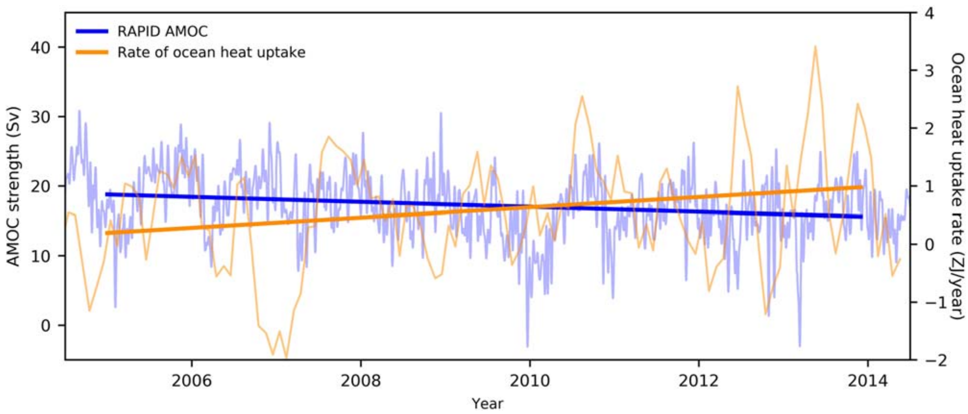

Figure 2. Relationship between ocean heat uptake rate and AMOC strength for the decade 2005–2014. Shown is the temporal evolution of the ocean heat uptake rate, derived from the ISHII and Scripps datasets with a linear increase of 0.088 ZJ yr^{-1}, compared to the AMOC strength as measured by the RAPID array with a linear decrease of 0.35 Sv yr^{-1}. The two time series have opposing trends over the time period for which both data exist, i.e. 2005–2014.

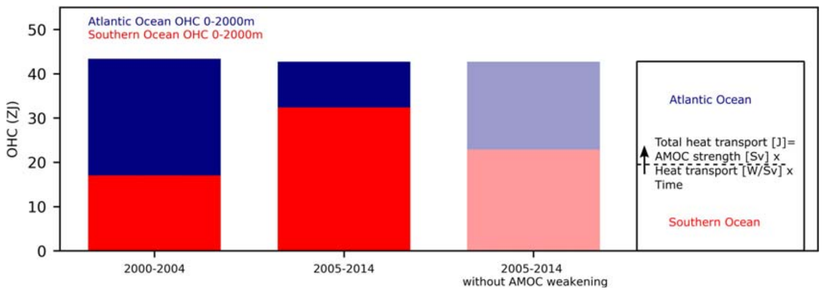

Figure 3. Changes in ocean heat content distribution between two recent periods of different AMOC strength (as analysed by Chen and Tung (2018)). Shown is the division of the global ocean increase in heat storage (0–2000 m) between the Atlantic (30°S–65°N) and the Southern Ocean (70°S–30°S) in the periods 2000–2004 and 2005–2014. A hypothetical division for 2005–2014 for the case that the AMOC did not slow down between the two periods is shown in lighter shading. Here we added the calculated shift of 9.5 ZJ in the heat transport due to the weaker AMOC in the later period to the Atlantic Ocean heat content.

2005–2014 from the Atlantic to the Southern Ocean (see figure 3) as identified by Chen and Tung (2018). As there have only been very few ARGO measurements prior to 2005 (especially in the Southern Ocean) it is uncertain how accurate the magnitude of this shift is. However, the fact that the Southern Ocean has been experiencing the greatest warming of all oceans since 1998 is robust (Cheng *et al* 2017). While Chen and Tung (2018) explain this shift with a change in the vertical heat transport into the ocean driven by the AMOC, we show that it can largely be explained within the established understanding that AMOC variations cause a change in the horizontal heat transport in the Atlantic.

As the AMOC carries relatively warm, saline water from the low-latitudes and Southern Ocean to the polar North Atlantic and returns cold, deep water southwards, it accounts for about 90% of the maximum meridional heat transport in the Atlantic of about 1.3 PW (Johns *et al* 2011, Xu *et al* 2016) occurring in the subtropics. AMOC variations lead therefore to a change in the meridional heat transport. A statistical analysis of expendable bathythermograph (XBT) data suggests that a 1 Sv weaker AMOC leads to a decrease of 0.04 ± 0.02 PW in the associated meridional heat transport at 35°S either due to less import of warm surface waters like the Agulhas Current, a reduced export of colder subsurface waters or a combination of the two (Garzoli *et al* 2013).

Between the periods 2000–2004 and 2005–2014 the AMOC decreased by about 1.5 Sv (Caesar *et al* 2018). Neglecting short term variability, a constant AMOC strength can be taken for the years 2000–2004, followed by a linear decline of 1.5 Sv until the year 2014. This means that the mean strength of the AMOC in the years 2005–2014 was 0.75 Sv weaker than in the years before. This leads to a cumulative change of $0.75\ \mathrm{Sv} \cdot 10\ \mathrm{yr} \cdot 0.04\ \mathrm{PW/Sv} = 9.5\ \mathrm{ZJ}$ in the meridional heat transport over the duration of these 10 years. Thus, the AMOC decline is estimated to cause a shift of about 9.5 ZJ of heat from the Atlantic Ocean to the Southern Ocean over this period. Taking the reduced heat transport due to the weaker AMOC into account, the changes in the division in ocean heat uptake between the two basins can largely be explained in terms of horizontal transport rather than surface heat uptake change (see figure 3).

4. Discussion

The statistical evaluation of the observed global mean temperature, ocean heat content, and different AMOC proxies, presented in this study, yields a positive correlation between GMST changes and changes in AMOC strength. This supports the understanding that the deep water formation related to the AMOC transports cold surface water downwards and that the recent weakening of the AMOC has therefore delayed global surface warming.

Even though we find this positive correlation between AMOC strength and global mean temperatures, indicating a cooling effect of an AMOC slowdown on GMST, the relatively moderate correlation values suggest that, at least for the considered time period (1948–2012) and timescale (intra-annual to decadal), AMOC variability is not dominant in explaining changes in ocean heat uptake. This is not surprising as there are other processes that cause variations in the ocean heat uptake. For example England *et al* (2014) showed that a pronounced strengthening of the Pacific trade winds over the last two decades cooled the tropical Pacific and significantly increased the ocean heat uptake which can at least partly explain the slowdown in the observed surface warming since 2001. At the same time there are other mechanisms than changes in ocean heat uptake through which AMOC variability influences global surface temperatures. The reduced meridional heat transport following an AMOC weakening leads to a cooling in the Northern Hemisphere and a warming in the Southern Hemisphere. Although this just changes the distribution of heat on the planet, climate feedbacks that selectively amplify the cooling response in the Northern Hemisphere can lead to a decrease in the global mean temperature (Drijfhout 2015). One example of such a feedback is that a cooling in the subpolar North Atlantic can increase the sea-ice cover and thus lead to a further decrease in GMST through enhanced reflection of solar radiation (Drijfhout 2018). Another feedback is that a strong decline in AMOC strength can enhance the meridional SST gradients in the North Atlantic, leading to stronger Northern Hemisphere storm tracks, as shown in a model simulation of an AMOC shutdown (Jackson *et al* 2015). Stronger storm tracks allow for a greater lower cloud coverage in the high latitudes (Trossman *et al* 2016). Thus, the enhanced shortwave cloud feedback cools the surface (Rose *et al* 2014).

Additionally, we would like to stress the importance of differentiating between the relationship between AMOC and GMST when considering the response of the global mean temperature to an AMOC change (where a weaker AMOC cools the surface) and the forced response of the AMOC to changes in GMST (where a warming leads to a weaker AMOC) as discussed in Maroon *et al* (2018). Anthropogenic warming will very likely lead to a weakening of the AMOC which among other things due to the reduced ocean heat release associated with a weaker deep convection will dampen the original warming signal and therefore acts as a negative feedback. Figure 1 suggests that this cooling response is of the order of 0.1 °C per Sverdrup.

In summary, we find that the observed changes in AMOC and global mean surface temperature over the last decades are fully consistent with the established understanding that a strong AMOC cools the deep ocean, and that this continues to be the case under the current situation of global warming. The observed, recent weakening of the AMOC has therefore delayed global surface warming rather than enhancing it.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Brown P T, Li W, Li L and Ming Y 2014 Top-of-atmosphere radiative contribution to unforced decadal global temperature variability in climate models *Geophys. Res. Lett.* **41** 5175–83

Caesar L, Rahmstorf S, Robinson A, Feulner G and Saba V 2018 Observed fingerprint of a weakening Atlantic Ocean overturning circulation *Nature* **556** 191–6

Chen X and Tung K K 2018 Global surface warming enhanced by weak Atlantic overturning circulation *Nature* **559** 387–91

Cheng L, Trenberth K E, Fasullo J, Boyer T, Abraham J and Zhu J 2017 Improved estimates of ocean heat content from 1960 to 2015 *Sci. Adv.* **3** e1601545

Cleveland W S 1979 Robust locally weighted regression and smoothing scatterplots *J. Am. Stat. Assoc.* **74** 829–36

Donges J F *et al* 2015 Unified functional network and nonlinear time series analysis for complex systems science: the pyunicorn package *Chaos* **25** 113101

Drijfhout S 2015 Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance *Sci. Rep.* **5** 14877

Drijfhout S 2018 The relation between natural variations in ocean heat uptake and global mean surface temperature anomalies in CMIP5 *Sci. Rep.* **8** 7402

England M H, Mcgregor S, Spence P, Meehl G A, Timmermann A, Cai W, Gupta A S, Mcphaden M J, Purich A and Santoso A 2014 Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus *Nat. Clim. Change* **4** 222

Foster G and Rahmstorf S 2011 Global temperature evolution 1979–2010 *Environ. Res. Lett.* **6** 044022

Garzoli S, Baringer M, Dong S, Perez R and Yao Q 2013 South Atlantic meridional fluxes *Deep Sea Res.* I **71** 21–32

Goodwin P 2018 On the time evolution of climate sensitivity and future warming *Earth's Future* **6** 1336–48

Gregory J M and Andrews T 2016 Variation in climate sensitivity and feedback parameters during the historical period *Geophys. Res. Lett.* **43** 3911–20

Gulev S K, Latif M, Keenlyside N, Park W and Koltermann K P 2013 North Atlantic Ocean control on surface heat flux on multidecadal timescales *Nature* **499** 464

Jackson L C, Kahana R, Graham T, Ringer M A, Woollings T, Mecking J V and Wood R A 2015 Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM *Clim. Dyn.* **45** 3299–316

Johns W E *et al* 2011 Continuous, array-based estimates of atlantic ocean heat transport at 26.5°N *J. Clim.* **24** 2429–49

Knight J R, Allan R J, Folland C K, Vellinga M and Mann M E 2005 A signature of persistent natural thermohaline circulation cycles in observed climate *Geophys. Res. Lett.* 32

Maroon E A, Kay J E and Karnauskas K B 2018 Influence of the atlantic meridional overturning circulation on the northern hemisphere surface temperature response to radiative forcing *J. Clim.* **31** 9207–24

Miller R L *et al* 2014 CMIP5 historical simulations (1850–2012) with GISS ModelE2 *J. Adv. Modeling Earth Syst.* **6** 441–78

Morice C P, Kennedy J J, Rayner N A and Jones P D 2012 Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set *J. Geophys. Res.: Atmos.* 117

Rose B E J, Armour K C, Battisti D S, Feldl N and Koll D D B 2014 The dependence of transient climate sensitivity and radiative feedbacks on the spatial pattern of ocean heat uptake *Geophys. Res. Lett.* **41** 1071–8

Rugenstein M A A, Winton M, Stouffer R J, Griffies S M and Hallberg R 2013 Northern high-latitude heat budget decomposition and transient warming *J. Clim.* **26** 609–21

Smeed D A *et al* 2014 Observed decline of the Atlantic meridional overturning circulation 2004–2012 *Ocean Sci.* **10** 29–38

Stolpe M B, Medhaug I, Sedláček J and Knutti R 2018 Multidecadal variability in global surface temperatures related to the atlantic meridional overturning circulation *J. Clim.* **31** 2889–906

Trenberth K E, Fasullo J T, O'dell C and Wong T 2010 Relationships between tropical sea surface temperature and top-of-atmosphere radiation *Geophys. Res. Lett.* **37** n/a-n/a

Trossman D S, Palter J B, Merlis T M, Huang Y and Xia Y 2016 Large-scale ocean circulation-cloud interactions reduce the pace of transient climate change *Geophys. Res. Lett.* **43** 3935–43

Winton M 1995 Why is the deep sinking narrow? *J. Phys. Oceanogr.* **25** 997–1005

Xu X, Rhines P B and Chassignet E P 2016 Temperature–salinity structure of the North Atlantic circulation and associated heat and freshwater transports *J. Clim.* **29** 7723–42