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REPLY

Reply to Comment on 'On the relationship between Atlantic meridional overturning circulation slowdown and global surface warming'

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Abstract

In their comment on our paper (Caesar *et al* 2020 *Environ. Res. Lett.* **15** 024003), Chen and Tung (hereafter C&T) argue that our analysis, showing that over the last decades Atlantic meridional overturning circulation (AMOC) strength and global mean surface temperature (GMST) were positively correlated, is incorrect. Their claim is mainly based on two arguments, neither of which is justified: first, C&T claim that our analysis is based on 'established evidence' that was only true for preindustrial conditions—this is not the case. Using data from the modern period (1947–2012), we show that the established understanding (i.e. deep-water formation in the North Atlantic cools the deep ocean and warms the surface) is correct, but our analysis is not based on this fact. Secondly, C&T claim that our results are based on a statistical analysis of only one cycle of data which was furthermore incorrectly detrended. This, too, is not true. Our conclusion that a weaker AMOC delays the current surface warming rather than enhances it, is based on several independent lines of evidence. The data we show to support this covers more than one cycle and the detrending (which was performed to avoid spurious correlations due to a common trend) does not affect our conclusion: the correlation between AMOC strength and GMST is positive. We do not claim that this is strong evidence that the two time series are in phase, but rather that this means that the two time series are not anti-correlated.

In July 2018 Chen and Tung (C&T) published a letter in *Nature* claiming that 'Global surface warming (is) enhanced by (a) weak Atlantic overturning circulation' (Chen and Tung 2018). As we came to the conclusions that this central claim of the article is incorrect and not supported by the evidence provided, we submitted a comment to *Nature* (*Nature's* Matters Arising) demonstrating that a weaker Atlantic meridional overturning circulation (AMOC) did not enhance global surface warming over the last decades. Our comment as well as a reply by Chen and Tung were peer-reviewed, with the conclusion that (Chen and Tung 2018) present a controversial perspective on the role of the AMOC in global surface warming which should be challenged in the conventional literature rather than a formal reply. This is what we have done with our ERL publication.

In Caesar *et al* (2020) we show that the observed changes in AMOC strength, global mean surface temperature (GMST) and ocean heat content in Atlantic and Southern Ocean can all be explained with the common understanding that the deep-water formation in the North Atlantic associated with the AMOC releases heat to the atmosphere, thereby balancing the net heat uptake occurring over large areas in the ocean (Drijfhout 2015). Our paper neither claimed that any two time series are 'in phase', nor 'strong evidence' for anything. Rather, we examined the hypothesis by C&T that a weak AMOC enhances surface warming, which would be supported by a negative correlation between AMOC strength and surface temperature, and we found the correlation to be positive. We therefore concluded that the data presented by C&T in support of their hypothesis (albeit without quantitative analysis), do in fact not support their hypothesis when subjected to a quantitative analysis. We further found that the data they presented are explained by the established view that a weak AMOC reduces global surface warming, and by the expected changes in horizontal rather than vertical heat transport.

1. Correlation analysis of AMOC strength and GMST change

To determine the relationship between AMOC strength and global surface warming, a correlation analysis of the observed changes in the GMST (adjusted to account for radiative forcing) and several indices of the AMOC strength was performed. Here, C&T criticize that we apply evidence based on preindustrial conditions to the present. This is not true. We use the same observational data (1947–2012) for GMST and AMOC strength for which C&T concluded that they show that a weakened AMOC leads to a period of more rapid surface warming (Chen and Tung 2018, figure 3). We use a simple correlation analysis to demonstrate that the opposite appears to be true. Therefore, our data analysis is consistent with and supports the previous understanding that the deep-water formation associated with the AMOC cools the deep ocean and warms the surface. This established understanding is also not solely based on preindustrial conditions (as claimed by C&T), it is rather based on years of research (e.g. Winton 1995, Drijfhout 2015) as well as the physical basis of deep-water formation, as explained in the following. The AMOC is sustained by two main drivers: deep-water formation in the North Atlantic (e.g. Jungclaus *et al* 2005, Swingedouw *et al* 2007) and Ekman pumping in the Southern Ocean (e.g. Toggweiler and Samuels 1998, Kuhlbrodt *et al* 2007). With the latter dominating, it is theoretically possible for the AMOC to be thermally indirect and to pump heat downward into the deeper ocean (Zika *et al* 2013), yet for the period of interest (1947–2012) a weaker AMOC coincides with a strengthening of the Southern Ocean westerly winds (Swart *et al* 2015), suggesting that, for this period, the dominating factor for AMOC variability is the thermally driven deep-water formation in the North Atlantic. Of course, C&T are correct in saying that new results do not have to be conform with previous evidence. But new results must be supported by proper evidence and they have to be consistent. With our analysis we showed that C&T's claim that an AMOC slowdown would act to increase surface warming is inconsistent with the observed data, including the data they presented in support of their claims but without providing any statistical analysis in their original publication (Chen and Tung 2018).

In contrast, our analysis includes a statistical evaluation of the relationship between AMOC strength and global surface warming. To account for the fact that the GMST is influenced by other factors, most of all the increase in CO_2, the GMST was adjusted to subtract the effect of radiative forcing. The forcing correction was done in two different ways: (a) 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 (b) by using a simple equation for the global mean energy balance (Trenberth *et al* 2010, Brown *et al* 2014):

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

with T the GMST, c_m 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 (Brown *et al* 2014).

C&T question the validity of this analysis on several points, which are examined in the following. First, C&T argue that we are using an incorrect simplification of the equation for the Earth's energy budget (Brown *et al* 2014) to account for the changes in the radiative forcing. Their argument is based on an order-of-magnitude analysis comparing $c_m\, dT/dt$ to $\lambda\, \Delta T$, concluding that, when looking at decadal variations, the former is larger than $\lambda\, \Delta T$ by a factor of 3. However, they fail to understand that this is a global mean heat budget equation, for which a mixed layer depth of 200 m is far too large and a factor of 0.7 is required to account for the fraction of Earth covered by ocean. Thus the effective heat capacity of the mixed layer is defined as (Brown *et al* 2014)

$$\mathrm{c_m} = 0.7 * \rho\, \mathrm{C_p\, D}$$

with $\rho = 1030$ kg m^{-3}, $C_p = 4180$ J kg^{-1} K^{-1} and $D \sim 75$ m, therefore $c_m = 2.3 \times 10^8$ J m^{-2} K^{-1}, yielding a value of about 0.3–0.7 W m^{-2} K^{-1} for decadal variations (10–30 years). This is smaller by a factor of 2–10 than the range of values for the feedback parameter λ considered in Caesar *et al* (2020) (1.3–3.0 W m^{-2} K^{-1}, with a best estimate of 2.3 W m^{-2} K^{-1} for the considered time period (Gregory and Andrews 2016)). Empirical studies have furthermore shown that the time lag between forcing change and temperature response in the mixed layer, which is caused by the transient term $c_m\, dT/dt$, is far shorter than decadal (Foster and Rahmstorf 2011) and therefore not significant for this analysis.

Yet, the conclusion of Caesar *et al* (2020) does not depend on the analysis described above (where the relationship between the GMST evolution and AMOC strength is evaluated while accounting for the variability in GMST due to changes in the radiative forcing as well as feedback processes in the Earth system). Caesar *et al* (2020) also revisit the analysis of Chen and Tung (2018) where the radiative forcing is taken into account simply by detrending the data (with both a linear trend and the

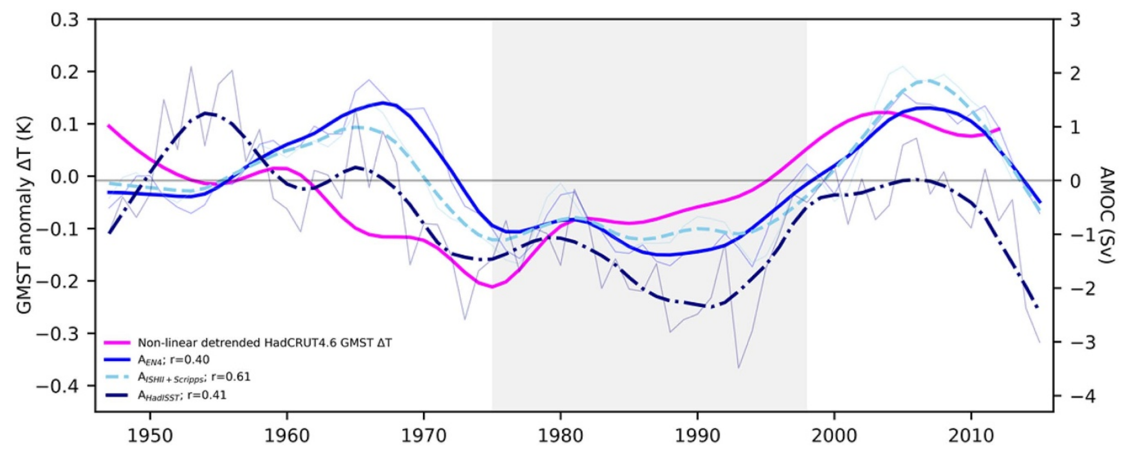

Figure 1. Time evolution of the multidecadal variability of the AMOC compared to the global mean surface temperature for the time period 1947–2012. In grey the time period from 1975 to 1998 is marked during which the AMOC was in a relatively weak state. Proxies for the AMOC are the salinity based proxies $A_{ISHIIS+Scripps}$, A_{EN4} and the temperature based proxy $A_{HadISST}$ (shades of blue). The global mean temperature deviation is based on HadCRUT4.6 data and is corrected for secular trend as done by Chen and Tung (2018) (ΔT, magenta). Thin lines are annual values; thick lines are 10 year LOWESS smoothed values.

same secular trend C&T used), yielding very similar results (the code can be found at www.pik-potsdam.de/~caesar/AMOC_OHC/—showing that we did not apply a second detrending as C&T claim). Figure 1 compares the smoothed, multidecadal variability of the GMST (following Chen and Tung 2018) compared to the smoothed AMOC strength, and the positive correlation is clearly visible (as it is in figure 3 of the comment by Chen and Tung, especially when looking at the time periods 1960–1975 and 1990 onwards).

C&T now argue that a trend removal in general is incorrect when only one cycle of data is considered. Yet the 1947–2012 shows clearly more than one cycle, and the removal of the trend is done to ensure that no spurious correlations due to a common trend occurs. Furthermore, the results of the analysis are not sensitive to the trend removal. Table 1 list the correlation coefficients for both the energy balance approach and the secular trend removal after Chen and Tung (2018) for the case that the AMOC indices are not linearly detrended as well as the results for the case that none of the time series is detrended (which also means that no radiative forcing correction is done on the GMST evolution).

Most of the correlation coefficients remain positive. The largest negative value of −0.1 describes the relationship between the sea surface temperature (SST)-based AMOC index (Caesar *et al* 2018) and the GMST with no trend removed. This is not surprising as the latter shows a clear warming signal, while the former shows a slowdown over the time period 1947–2012. The resulting correlation coefficient therefore does not represent how the decadal variability of AMOC strength and GMST are related, but rather how global warming will affect the AMOC in the long term, i.e. by slowing it down (Maroon *et al* 2018). This also shows us that the period of 1947–2012 is long enough to study the relationship between the decadal variability of AMOC and GMST and even hints at the reverse in this relationship as continued global warming will eventually lead to a slowdown of the overturning circulation.

The fact that most of the calculated correlation coefficients are not significant (something we pointed out in our paper) does not call into question any of our conclusions. What we conclude is that the negative relationship claimed by C&T is not supported by the data. For that it logically suffices that the correlation analysis does not show a negative correlation; there is no need to show that the positive correlation found is statistically significant.

We would also like to stress here that we never claimed that the positive correlation between AMOC and GMST means that the two time series are in phase. We show that the time series are *not anti-correlated,* which would be the case if a reduced AMOC leads to an increased surface warming as claimed by C&T.

2. Changes in the ocean heat content

Overall, C&T spend most of their comment on discussing why their 2018 paper is (in their opinion) correct, which seems not appropriate for a comment. Nevertheless, we explain in the following why the data they present do not disagree with the results of Caesar *et al* (2020).

Figure 5 of the comment is supposed to show 'that more heat and salinity are transported down below the mixed layer, to 900 m, when AMOC is stronger' and C&T claim that it provides 'definitive observational evidence'. However, there is no analysis of downward transport in this figure. It merely shows heat and salinity anomalies regardless of what process

Table 1. Results of the sensitivity analysis of the correlation values without linearly detrending the data. The correlation values were calculated for the whole time period (1947–2012) and are given for different values of the feedback parameter λ as well as the case that the radiative forcing is either not taken into account ('no trend removed') or considered by removing a secular trend (taking the data from Chen and Tung 2018).

λ in W K^{-1} m^{-2} AMOC proxy	1.3	1.5	1.9	2.3	3	No trend removed	Secular warming trend removed
ISHII + Scripps	−0.08	−0.05	0.00	0.09	0.35	0.42	0.61
EN4	0.09	0.12	0.17	0.24	0.45	0.23	0.40
HadISST	0.38	0.39	0.41	0.45	0.52	−0.10	0.41

caused these; a warm anomaly at depth could arise from anomalous warmth at the surface being mixed down regardless of any anomaly in AMOC strength (i.e. due to the strong SST anomaly rather than due an AMOC anomaly), or it could also arise from horizontal transport. That it is due to an AMOC anomaly is thus pure speculation (by the way their unit on the heat graph is nonsensical because red shading cannot show an amount of heat in Joules; presumably it is something like Joules per unit of depth). There is also confusion in the time dimension here since 'more heat being transported down' would correspond to a high rate of increase in heat at depth. However, just around peak AMOC strength this rate of warming appears to be very low (roughly horizontal contours)—so their graph does not even show deep warming coinciding with strong AMOC, let alone the mechanism by which it might occur if it actually did occur. We would also like to point out that the global temperature anomaly graph in figure 5(a) looks different from established global mean temperature data and also stops in 2012, though we are now in 2020. As a result the red smooth apparently does not account for the post-2012 data, so the last portion of this smooth is just based on using some boundary assumption (which is a way of producing a smooth curve—though with large uncertainty—when data are missing, but in fact the post-2012 data are available, of course). The near-constant temperatures for the last 10 years in this graph are an artefact of the cherry-picked end date and inappropriate smoothing (this so-called 'hiatus' has been thoroughly refuted in ERL (e.g. Lewandowsky *et al* 2018)).

What figure 5 really shows is that there is a heat peak in the mixed layer during the AMOC maximum in 2006 which *coincides* with a heat peak at all depths down to 1200 m. That is exactly the signal one would expect from *horizontal* transport (i.e. the classic view of the AMOC as argued in our paper). If the reasoning of C&T were correct, the *heat peak at the surface would coincide with a maximum heating rate and be followed by a maximum heat peak* at depth which is not the case. Instead, the temperatures at depth start cooling during (and below 900 m even before) peak warmth near the surface and peak AMOC (around the year 2004).

Therefore, C&T provide no evidence for their claim that there is more downward heat transport during a time of strong AMOC; rather they provide evidence that there is more horizontal heat transport into the northern Atlantic during a time of strong AMOC, exactly as we argued in our paper and as is commonly understood.

3. Related literature

To support their findings, C&T cite the study by Kostov *et al* (2014). This is misleading as Kostov *et al* do not deal with the questions of whether the AMOC transports warm or cold surface waters to the deep ocean, it rather shows that a model with a strong mean AMOC has a larger ocean heat capacity (better ocean ventilation) and thus more thermal inertia. This can then delay global surface warming as it enables the ocean to better take up excess heat but is not related to the process we analyse in this paper, i.e. how the decadal variability of the AMOC is related to the GMST. The results of Kostov *et al* (2014) are furthermore based on a simulation where the CO_2 concentration in the atmosphere was instantly quadrupled—a situation that is not even remotely comparable to the current climate change. Nevertheless, we would like to stress again that our conclusion that a weakening of the AMOC cools the surface only holds for the present and the near future. It is very likely that anthropogenic warming will eventually lead to a weakening of the AMOC causing a negative relationship between AMOC strength and GMST on longer time scales (Maroon *et al* 2018). Maroon *et al* also differentiated between the effects of forced and unforced AMOC variability on surface temperatures concluding about the latter that 'there is a positive relationship between global surface warming and AMOC strength' (their figure 4(b) shows the correlation of AMOC and global warming with the ensemble mean removed, i.e. the correlation of the unforced variability), which is in contrast to the findings of C&T.

4. Conclusion

Due to the number of processes involved it is very difficult to determine the relationship between AMOC strength and GMST at a given time(scale). Our study does not aim at the precise determination of this relationship, we merely show that the data provided by after Chen and Tung (2018) do not support their hypothesis that over the last decades a slowdown of the AMOC has led to increased surface warming. We acknowledge that this relationship depends on both the considered time scale and period, and may change in the future, yet the observed data of the last decades supports the understanding that the effect of a slower AMOC on surface warming is a cooling effect.

Data availability statement

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

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