Title: Consistency of paleo-proxies for the AMOC

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We thank the authors for their comment and welcome the opportunity to respond. Kilbourne et al. (2021) make the argument that if more proxies from the North Atlantic had been considered, the conclusion reached in Caesar et al. [1] would have been different. While it is certainly true that a comprehensive set of paleoceanographic proxy data available in the North Atlantic region shows a complex picture of the evolution of the North Atlantic over the past two millennia [2], most of these proxies are not strongly linked to the strength of the AMOC.

The main objective of Caesar et al. [1] was to compare a range of previously published reconstructions of features that have been linked to the AMOC, which, due to the different proxies used, represent different subsystems/processes related to the AMOC. Our goal was to check the consistency between these reconstructions and to assess the statistical significance of the main changes found.

Kilbourne et al. argue that the AMOC proxies shown in Caesar et al. [1] have substantial caveats that were not discussed and that not all available proxy records potentially related to AMOC variability have been considered. Indeed, the fact that each individual AMOC proxy has influencing factors other than the AMOC (as is the case with all proxy data) was the main motivation for this compilation of multiple proxies. The advantage is that since the proxies come from different locations and with different sources of uncertainties, they have different AMOC-unrelated influencing factors and any common behaviour is therefore likely AMOC-related.

Kilbourne et al. list a number of possible influences on each proxy in addition to the AMOC, including the general global warming signal, changes in atmospheric conditions, the global nitrogen cycle, and shifts in the location of the AMOC's deep currents (figure 1). Like Kilbourne et al. we see those factors as a source of uncertainty for the individual proxy, but we argue that the diverse nature of these additional influencing factors is evidence that the common evolution found in the different proxies is not driven by these factors (as it is unlikely that they all changed contemporaneously) but by the driver that is common to all proxies: the AMOC.

A more detailed look at the individual proxies supports our conclusion that the combination of these proxies is indeed suitable in reconstructing the long-term evolution of the AMOC. For example, the temperature AMOC index by Rahmstorf et al. [3] which is based on *land* data shows the same signal as the *marine* proxy by Thornalley et al. [4] which is based on the analysis of planktic foraminifera. The advantage of foraminiferal-based subpolar temperature proxies is that they typically record subsurface temperatures, and are therefore less subject to seasonal biases [4] as it is known that the AMOC signal on SST is most pronounced during the cold season [5].

To help counteract the problem of a possible non-stationarity of the deep western boundary current that would affect the signal seen in the sortable silt data, Thornalley et al. [4] examined two sites at different depths (1,718m and 2,009m), 41 km apart from each other, and found that the signal of a slowdown is present in both.

Other types of proxy linked to the deep branch of the AMOC are those related to the strength of the Nordic Sea Overflows, which have not been considered in Caesar et al. [1]. There are two reasons for this: 1. We focused on the large-scale overturning in the open Atlantic (e.g. as measured by the RAPID array) and not individual branches feeding into it. 2. The link between AMOC strength and the volume transport at one individual deep water formation site is tenuous because the deep branches of the AMOC are fed by multiple sources in the Labrador Sea, Irminger Sea and Nordic Seas. This is reflected, for example, in the fact that the recent 2004-2012 weakening of the AMOC, which was mainly due to a slowing of the southward deep flow (below 3000m) [6], is not linked to a reduction in the Nordic Overflows [7]. Similarly, while AMOC observations at the RAPID array show strong multi-year variability, overflows across the Greenland-Scotland Ridge do not. To include the overflow data in a meaningful way, one would need a robust reconstruction that can only be provided by a depth transect of cores e.g. [8], but no such suite of records that cover the industrial era has yet been published.

Similarly, we did not include any proxy records from the North Iceland shelf [9] (in contrast to what is indicated in Figure 1 by Kilbourne et al.) as these are not obviously linked to the open Atlantic AMOC, and more prone to local changes and atmospheric influences [10]. Likewise, Keil et al. [11] have shown that decreasing northward heat transport in the AMOC is linked to increasing northward heat transport into the Nordic Seas.

The last point which Kilbourne et al. criticize is that the reconciliation of the proxy data with AMOC observations and reconstructions within the instrumental era given by Caesar et al. [1] is not convincing. We therefore expand this comparison using three indicators for the recent evolution of the AMOC that are independent of the long-term proxy data: The direct AMOC data measured by the RAPID array, a recent reconstruction that combines an empirical model with historical hydrographic data [12] and a reconstruction based on satellite altimetry and cable measurements [13]. These data show decadal-scale variability with an increase in strength from the 90s until about 2005 that has also been seen in other AMOC reconstructions, followed by a strong decline from about 2004-2012 [6] and a slight recovery afterwards. The same evolution is seen in the long-term proxies that extend into the 21st Century (figure 2), increasing our confidence that they are suitable to reconstruct the AMOC strength.

Concluding, we agree with Kilbourne et al. that a more thorough review of all the North Atlantic proxies that could *possibly* be related to the AMOC should be done, with an analysis of the robustness of their link to the AMOC and a detailed analysis of the similarities and differences. But the goal of Caesar et al. [1] was to provide a concise overview of recently published proxy records that have been linked to AMOC strength in the past and to analyze their consistency. And while we cannot rule out that there is an AMOC proxy that does not show the signal of a slowdown over the course of the last century, it remains remarkable that the large variety of proxies presented in Caesar et al. [1] show a very similar behaviour over the last 150 years: the beginning of a first slowdown in the second half of the 19th Century, the start of a second, more rapid one in the mid-20th Century and even consistent variability seen in recent decades. While some climate models have shown this amount of AMOC weakening in response to global warming, the majority shows a lesser or even no weakening up to the present [14] (possibly related to the misrepresentation of relevant drivers like the Greenland meltwater flux). This wide range of model results is a matter of concern which needs to be addressed.

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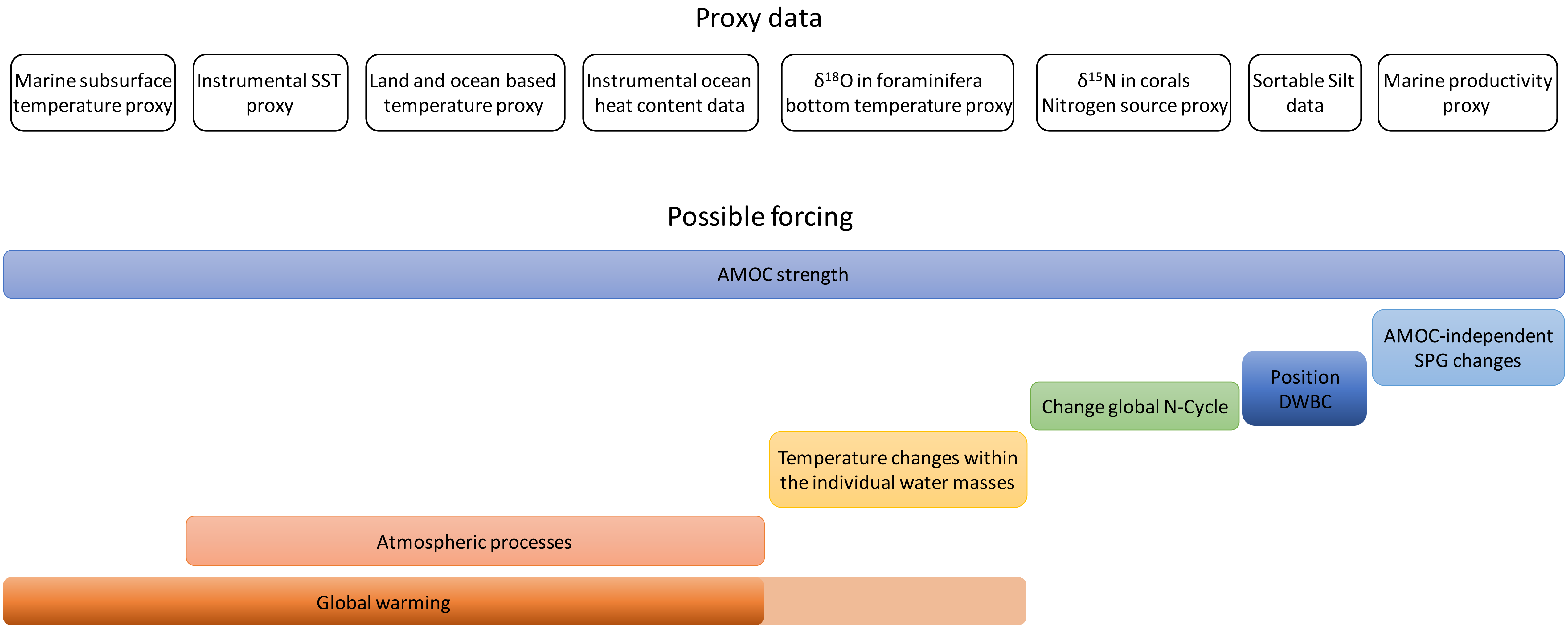
Competing Interests statement

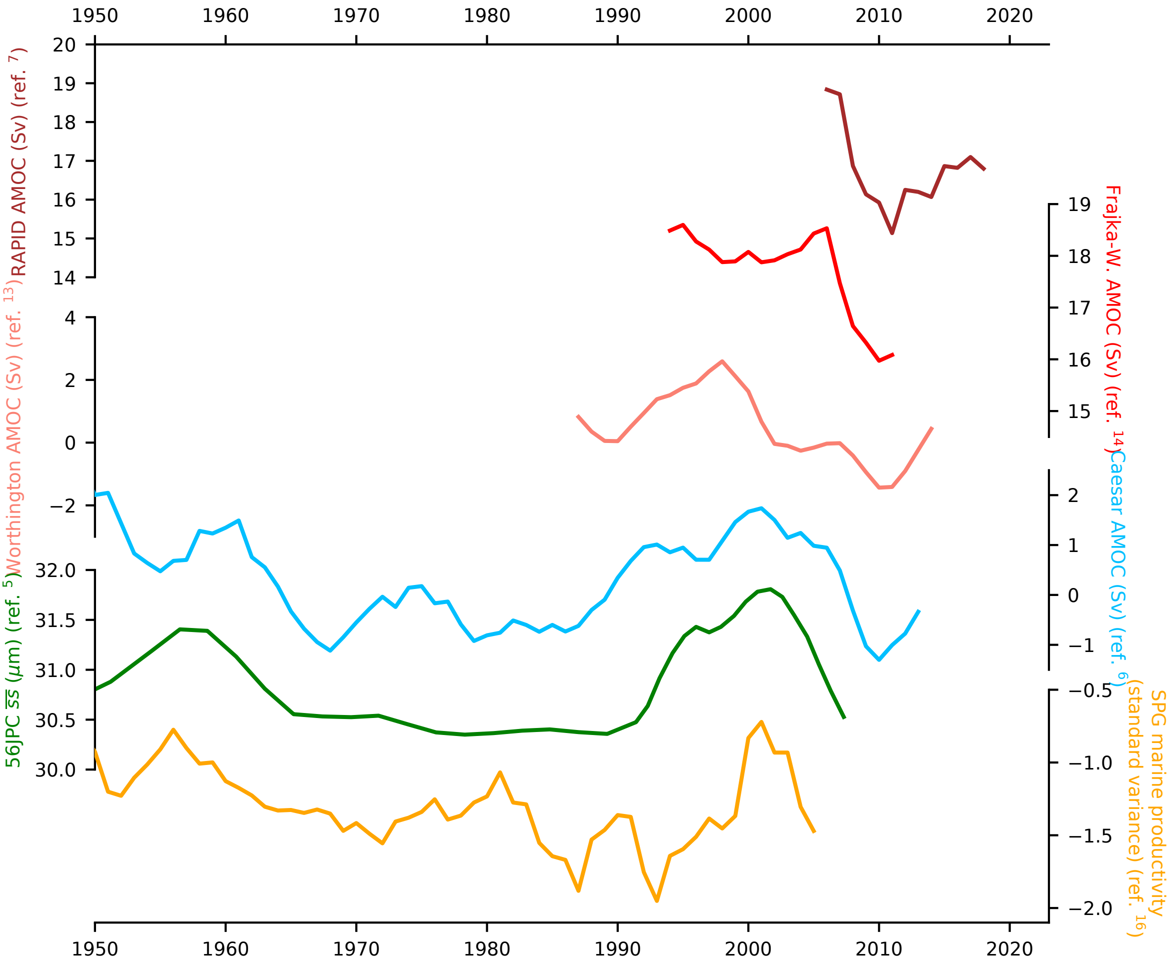
The authors declare no competing interests.

Figure captions

Fig. 1 Overview of the different proxy data and the major climate system forcing that they may be sensitive to. This shows that while some proxies could be sensitive to a certain external forcing, e.g., the general global warming signal (especially those related to upper ocean temperatures and heat content), other proxies are unlikely to be influenced by it. As there is no individual forcing other than the AMOC that influences all proxies, it is likely that their common trend is indeed caused by changes in the AMOC.

Fig. 2 Comparison of direct observational AMOC data [6] and two recent reconstructions [12,13] (all at 26N) to both the SST-based AMOC index (SPG region, 6 yr lag caused by the lagged change in AMOC-related heat transport) as well as two paleo-proxies used in Caesar et al. [1] that extend into the 21st century: the sortable-silt data [4] (DWBC, 6 yr lead, reflecting the modelled lead [4] of the DWBC over AMOC) and the marine productivity data (SPG region, 6 yr lag) [15]. As the hydrographic-based reconstruction is irregularly spaced in time all data is plotted as a 4-year running mean.


Proxy data
Marine subsurface temperature proxy
Instrumental SST proxy
Land and ocean based temperature proxy
Instrumental ocean heat content data
δ^{18}O in foraminifera bottom temperature proxy
δ^{15}N in corals Nitrogen source proxy
Sortable Silt data
Marine productivity proxy
Possible forcing
AMOC strength
AMOC-independent SPG changes
Position DWBC
Change global N-Cycle
Temperature changes within the individual water masses
Atmospheric processes
Global warming


1950
1960
1970
1980
1990
2000
2010
2020
RAPID AMOC (Sv) (ref. 7)
14
15
16
17
18
19
20
Worthington AMOC (Sv) (ref. 13)
−2
0
2
4
56JPC $\overline{ss}$ (μm) (ref. 5)
30.0
30.5
31.0
31.5
32.0
Frajka-W. AMOC (Sv) (ref. 14)
15
16
17
18
19
Caesar AMOC (Sv) (ref. 6)
−1
0
1
2
SPG marine productivity (standard variance) (ref. 16)
−2.0
−1.5
−1.0
−0.5