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Absence of an internal multidecadal oscillation in the North Atlantic has consequences for anticipating the future of marine ecosystems

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Abstract :

The North Atlantic marine ecosystem has been expected to adjust imminently to a negative phase of the Atlantic Multidecadal Oscillation (AMO). Recent results suggest, however, that the AMO is not a regular internal source of variability, but has been driven by both volcanism and sulphate aerosol emissions that have influenced temperature negatively, and a period of greenhouse gas accumulation causing temperatures to be higher than normal. The demise of the AMO removes the expected and imminent cyclical change from the current warm phase to a negative cool phase in the North Atlantic. Here, we discuss the implications of this new finding for the near-future of North Atlantic marine ecosystems in a context of rapid climate warming.

Keywords : Climate change, Russell Cycle, Bluefin tuna, Sea surface temperature, AMO

Main text

For centuries, humans have tried to recognise patterns in natural systems and determine their controlling mechanisms, not least in marine ecosystems (Cheung et al. 2009, Rombouts et al. 2012, Raybaud et al. 2013, Schickele et al. 2021) where it helps to enhance predictability and especially, with regard to commercial fisheries, *e.g*. the European herring Bohuslän periods (Alheit & Hagen 1997) or the multidecadal fluctuations of sardines and anchovies in different oceans *(Chavez et al. 2003)*.

Until now, an inherent large-scale oceanic phenomenon called the AMO was thought to explain periodic changes observed in key physical and biological systems in the North Atlantic, with a periodicity of ~60 years (Mann et al. 1995, Kerr 2000, Enfield et al. 2001, Edwards et al. 2013). Climate change biologists have documented significant correlations between the cyclical nature of the AMO index and North Atlantic biological systems to try to understand the ecosystem and how it might evolve, even postulating that the next negative AMO phase could alleviate or momentarily reverse the current warming trend (Frajka-Williams et al. 2017). For example, in the English Channel, the Russell Cycle that describes an alternation of periods dominated by cold-water (i.e. herring, *Clupea harengus,* and the chaetognath *Sagitta elegans)* and warm-water species (i.e. pilchard, *Sardina pilchardus*, and the chaetognath *S. setosa)* has been related to the AMO (Russell et al. 1971, Edwards et al. 2013). Sardine (and *S. setosa*) dominates during positive phases and herring (and *S. elegans*) during negative phases of the AMO. In the North Atlantic, bluefin tuna has been shown to exhibit a long-term, quasi-cyclical, north to south, seesaw-like population movement and changes in abundance driven by climatic variation that correlates with the AMO: when the AMO phase is positive or negative, bluefin tuna are distributed further north or further south, respectively (Faillettaz et al. 2019).

While previous studies attributed the AMO to internal climatic processes, a recent study by Mann *et al*. (Mann et al. 2021) showed that positive (warm) and negative (cool) phases of the AMO have been due to external forces, such as volcanic activity, sulphate aerosol cooling, and greenhouse-gas-induced warming. The last negative AMO phase was mostly caused by the negative forcing exerted by the increasing sulphate aerosol emission, and the current warm phase by the predominant effect of increasing greenhouse gases at a time of diminishing sulphate aerosol emission (Mann et al. 2021). The AMO-like pattern has therefore, never been governed fully by internal hydro-climatic variability and this new knowledge is of profound importance for our understanding of the regional climate and marine ecosystems.

To illustrate the strong influence of multidecadal changes in temperature on extra-tropical North Atlantic marine resources, we have updated a previous Principal Component Analysis (PCA) on Sea Surface Temperature (SST) (Beaugrand et al. 2002) for the region 20°N-65°N and 100°W-20°E using SST data from the COBE interpolated 1°x1°dataset from 1891 to 2020 (Ishii et al. 2005). Expectedly, this analysis shows two cold and two warm phases superimposed on a long-term positive SST trend for most areas of the North Atlantic except for the central and south-western regions (Figure 1a-b). Detrending the first principal component (PC1, 49.8% of the total variance) gives a pattern similar to the classic AMO index, albeit the AMO index is usually based on a larger area than the one we considered here (Enfield et al. 2001, Mann et al. 2021, Murphy et al. 2021).

When we include long-term changes in an index of phytoplankton concentration in the North Sea (Reid et al. 1998), Norwegian spring spawning herring (Toresen & Østvedt 2008) and bluefin tuna distribution in the north-east Atlantic (Faillettaz et al. 2019), we see that changes across three trophic levels in different regions correlate with long-term changes in North Atlantic SST, exhibiting a clear oscillation (Fig. 1c-e). High North Sea phytoplankton concentration, high Norwegian Sea herring and north-east Atlantic tuna abundance are observed during a positive (warm) phase of the AMO and inversely. Because the AMO is considered to cause these changes in addition to other factors (e.g. overfishing of North-east Atlantic tuna and Norwegian Spring-Spawning herring at the beginning of the 1960s) (Lorentzen & Hannesson 2004, Fromentin et al. 2014, Cort & Abaunza 2015), and because the nature of the phenomenon was cyclical, a reversal of the AMO was soon expected to occur (Frajka-Williams et al. 2017) with its putative consequences for the marine ecosystem and its exploited resources. Results from Mann et al. (Mann et al. 2021) imply that an imminent reversal to a cool period is now unlikely and so we should not expect an imminent shift in the North Atlantic marine ecosystem and provisioning services.

While overfishing has been an important component of the collapse of North-east Atlantic tuna or Norwegian Spring-Spawning herring and so management actions may have played an important role in the rebuilding of the different stocks (Lorentzen & Hannesson 2004, Toresen & Østvedt 2008, Fromentin et al. 2014, Cort & Abaunza 2015), it often interplayed with changing environmental conditions (Beaugrand et al. 2003, Faillettaz et al. 2019). A shift in the state of the AMO from positive to negative could have caused another rapid retreat of bluefin tuna southwards as was observed notoriously at the beginning of the 1960s together with another biological shift in the Russel cycle bringing a new period of high productivity to the English Channel. So, while the demise of the AMO does not negate the climatic modulation of North

Atlantic biology, it does have significant implications for our understanding of the drivers of change and how ecosystems and provisioning services may change in the future. Consequently, the recent northward shift of bluefin tuna is likely due to greenhouse gas-induced global warming and the well-known Russell Cycle is not necessarily a cycle anymore (McManus et al. 2016), and there is now, no *a priori* reason that the North Atlantic region will return soon to the negative AMO phase that has been anticipated (Frajka-Williams et al. 2017, Mann et al. 2021).

The latest IPCC report includes the influence of anthropogenic and volcanic activity on Atlantic multidecadal variability (Masson-Delmotte et al. In press). Climatologists now also use the term Atlantic Multidecadal Variability (AMV) instead of the AMO because multidecadal variability in the Atlantic may result from broad, low-frequency signals (Lapointe et al. 2020, Murphy et al. 2021, Masson-Delmotte et al. In press). The AMV includes the influence of the North Atlantic Oscillation (NAO) that is a natural source of atmospheric variability (Hurrell 1995) and which interacts with the AMOC, although the mechanisms involved and their relative strengths are still unclear (Masson-Delmotte et al. In press). As a result, we also think it is better to replace the AMO by AMV in climate change biology and to therefore recognise that the oscillatory behaviour of Atlantic multidecadal variability observed during the last two centuries may not continue. Consequently, we cannot predict a return to a lower temperature regime with all that entails, i.e. rapid shift in the marine ecosystems with its consequences for exploited resources.

A fundamental question in ecology is, why is what where? (Berry 1989). Sea surface temperature is a key determinant of the abundance and distribution of marine pelagic species. Of course, knowing that an anticipated and imminent climate reversal in the North Atlantic will not now occur due to the AMO neither invalidates previous environment-driven, cyclical variation seen in species such as bluefin tuna (Faillettaz et al. 2019) nor helps predict the future direction of marine ecosystems, but it does help us focus on those drivers of change that are important. While climatic surprises remain possible (*e.g*. the slow-down of the Atlantic Meridional Overturning

Circulation and its negative influence on North-east Atlantic climate (Boers 2021, Caesar et al. 2021)), if the results of Mann et al. (Mann et al. 2020, Mann et al. 2021) are confirmed, and recent works suggest, at least in part, that they are (Murphy et al. 2021, Masson-Delmotte et al. In press), they have now eliminated the AMO as one variable thereby simplifying a complex world where ecosystem shifts are moving towards a warmer dynamic regime in response to anthropogenic climate change (Beaugrand et al. 2002).

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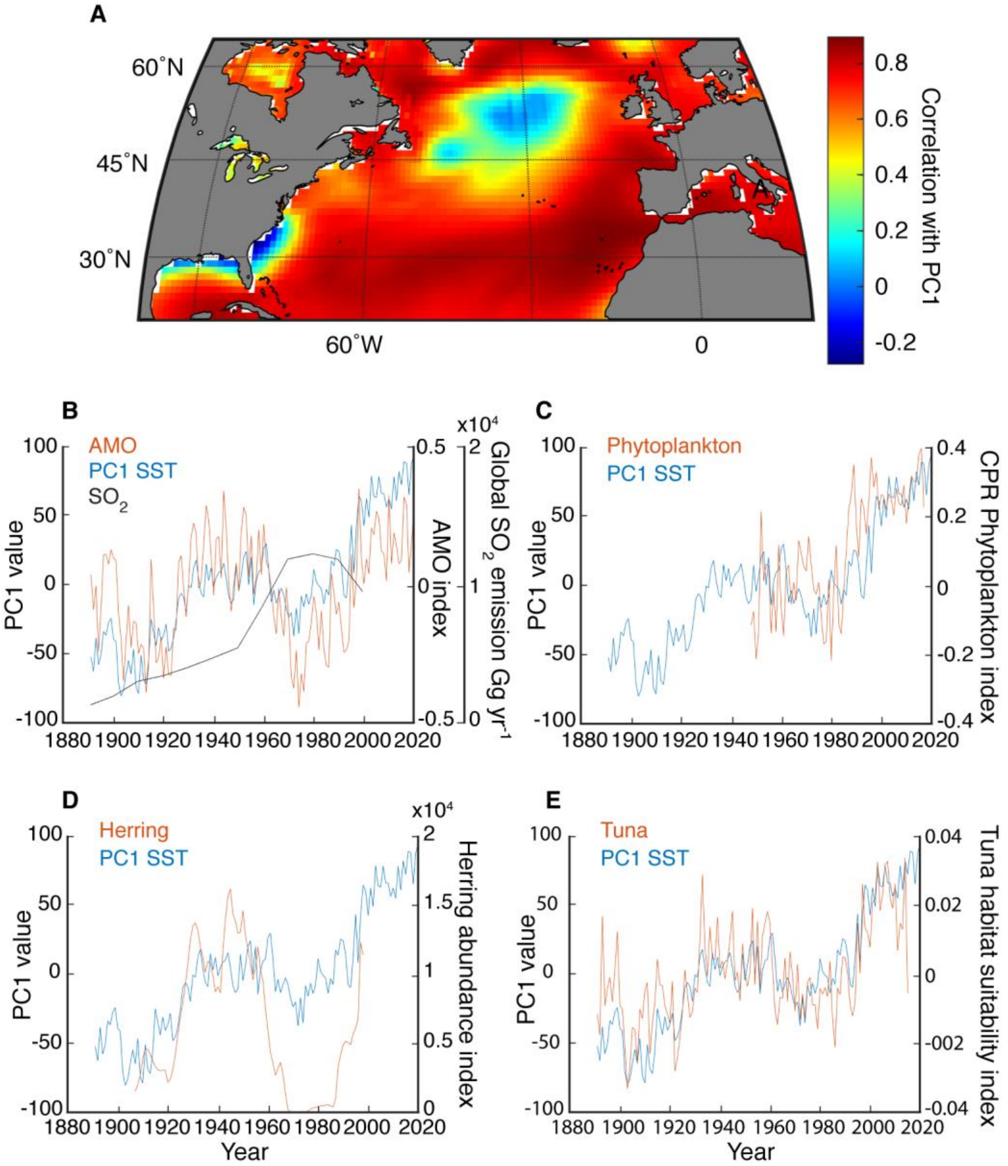
Figure legend

Figure 1. Relationships between changes in North Atlantic annual SST and pelagic life. A) First standardised eigenvector (49.8% of the total variance) showing the long-term changes in annual SST and the first principal component (SST PC1). B) The long-term changes in SST PC1 and an AMO index (Spearman correlation r_{sp} 0.68, $p<0.01$), and long-term changes in global sulphate aerosol emissions. C) The long-term changes in SST PC1 and the CPR phytoplankton colour index (PCI) in the North Sea (r_{sp} 0.66, $p<0.01$) (Reid & Hunt 1998). D) The long-term changes in SST PC1 and Norwegian spring spawning herring (r_{sp} 0.43, $p<0.01$) (Toresen & Østvedt 2008). E) The long-term changes in SST PC1 and a bluefin tuna occurrence index (r_{sp} 0.75, $p<0.01$) (Faillettaz et al. 2019). Although based on temperature, the occurrence index has been validated with the observed changes in tuna abundance that took place in the North-east Atlantic (Faillettaz et al. 2019). The given r_{sp} is the coefficient of Spearman correlation and values are based upon a Montecarlo test with 10,000 simulations.


A
60˚N
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0
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Correlation with PC1
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Global SO2 emission Gg yr⁻¹
100
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1880 1900 1920 1940 1960 1980 2000 2020
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PC1 SST
PC1 value
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Herring abundance index
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Tuna
PC1 SST
PC1 value
Tuna habitat suitability index
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