

TECHNICAL RESPONSE

OCEAN VARIABILITY

Response to Comment on “The Atlantic Multidecadal Oscillation without a role for ocean circulation”

Amy Clement,^{1*} Mark A. Cane,² Lisa N. Murphy,¹ Katinka Bellomo,² Thorsten Mauritsen,³ Bjorn Stevens³

Zhang *et al.* interpret the mixed-layer energy budget in models as showing that “ocean dynamics play a central role in the AMO.” Here, we show that their diagnostics cannot reveal the causes of the Atlantic Multidecadal Oscillation (AMO) and that their results can be explained with minimal ocean influence. Hence, we reaffirm our findings that the AMO in models can be understood primarily as the upper-ocean thermal response to stochastic atmospheric forcing.

In their Comment on Clement *et al.* (1), Zhang *et al.* (2) show that several years before the peak of the AMO (Atlantic Multidecadal Oscillation) in coupled models, the net surface heat flux in parts of the subpolar North Atlantic is out of the ocean and into the atmosphere. They interpret this signal as indicative that ocean dynamics is the leading cause of the AMO.

We do not share this interpretation, foremost because cause and effect cannot be inferred from this budget. At low frequencies (long time scales), the heat storage in the upper ocean, $\rho C_p h dT/dt$, is negligible; hence, the heat fluxes, which must balance on such time scales, do not inform a causal analysis. This is apparent in the maps shown in Zhang *et al.*, where there is almost complete cancellation between the net surface heat flux [figure 1C in (2)] and what they call the ocean residual [figure 1E in (2)]. The ocean residual may or may not have caused the warming, but the equilibrium heat budget is not informative about how this state came about. In addition, the ocean residual in their calculation should not be called the ocean heat transport convergence because it also includes the effect of local mixed-layer physics.

The problem with the budget approach is illustrated by the analysis shown in Fig. 1. Following Zhang *et al.*, we calculate average quantities for the region 40° to 55°N, 20° to 60°W, a region of the subpolar ocean that they argue contains the seed of the AMO warming. The main finding of Zhang *et al.* is recovered in this analysis (here based on correlation values rather than regression coefficients so as to give equal weight when averaging across models). The multimodel mean correlation of net surface heat flux is slightly negative leading the temperature (Fig. 1C, heavy blue line), and the ocean residual is slightly positive

(Fig. 1D, heavy blue line). However, the same relationships are also found at positive lags, when the temperature is cooling (dT/dt is negative) (Fig. 1B). Following the logic of Zhang *et al.*, we would be forced to the opposite conclusion, that the atmosphere is driving the temperature. This serves to illustrate the difficulty of inferring causality from such an analysis.

Zhang *et al.*'s diagnostic does show that the net effect of the ocean at low frequencies is not zero in some regions of the subpolar gyre and Labrador sea, in contrast to what is found in the slab-ocean models. The net ocean influence is zero in the slab-ocean models by design. Hence, the net surface heat flux is approximately zero (to within 0.5 W/m²), as shown in figure 1D in (2) (note the change of color scale in that panel), as required by the lack of heat storage on these time scales. Just because the AMO is correlated with a coherent pattern of surface fluxes in models where it is not forced to be zero does not mean that the ocean is the leading cause of the AMO.

To further illustrate this point, a comparison of the GCM results with a simple stochastically forced model is instructive. Assume that

$$dT/dt = -\alpha T + aN_a + bN_o \quad (1)$$

where N_a and N_o are the atmosphere and ocean forcing, respectively, and $-\alpha T + aN_a$ can be interpreted as the net surface heat flux, Q_s in this model. Here, both N_a and N_o are unit amplitude white noise and uncorrelated with each other. The parameter α is set to 4 year⁻¹, which is the best fit to the multimodel mean, and is consistent with observed values (3). We take $a^2 + b^2 = 1$, which means that a^2 and b^2 are the fractions of forcing variance contributed by the atmosphere and ocean. A case with strong atmospheric driving is shown in Fig. 1, where $a^2 = 0.9$ (which is 90% atmosphere forcing and only 10% ocean). The sign of the relationship between Q_s and dT/dt predicted by this model (Fig. 1, B and C) is the same as in the multi-

model mean with negative values of heat flux both leading and lagging temperature. The sign of the ocean residual (Fig. 1D) also matches the multimodel mean.

This example illustrates that the multimodel mean results and the findings of Zhang *et al.* can be explained with a small amount of ocean noise. Zhang *et al.*'s analysis does not show that the ocean is necessary for the AMO but rather that a particular diagnostic has some influence from the ocean. This is consistent with the main findings of Clement *et al.*. The virtue of that study was to show that eliminating variations in the ocean heat transport convergence, in the manner of the usual process attribution studies (turn off some process and see how the result changes), did not change the AMO space and time characteristics. Thus, while ocean processes may be doing something to the mixed-layer energy budget in parts of the subpolar gyre and Labrador Sea in coupled models, its effect on the AMO is small compared with the stochastic atmospheric forcing.

Although the AMO is defined as the average SST in the entire North Atlantic, it is worth remembering that over most of the North Atlantic, the net surface heat flux is as negligible in the coupled models as it is in the slab-ocean models [figure 1, C and D, in (2)]. Zhang *et al.* confine their discussion to the subpolar gyre, which they assert is “the key region for generating the AMO.” Because of its implications for prediction studies, this idea is an attractive one, but this is far from settled science. Studies of the AMO are commonly motivated by the effects on rainfall and temperature patterns on land around the Atlantic, and many studies—e.g., (4)—have shown that these effects originate in the tropical North Atlantic. Both Clement *et al.* and previous studies cited therein showed that in this region the atmosphere is strongly influenced by the ocean through thermal coupling. If the subpolar gyre is important for warming the rest of the Atlantic basin and associated effects, then its influence must be communicated through the atmosphere. Notwithstanding the studies cited by Zhang *et al.*, other studies come to different conclusions, and as recently reviewed by Buckley and Marshall (5), the debate remains contentious. The finding in Clement *et al.* is another challenge to the idea that the subpolar gyre is the hinge on which the whole Atlantic swings.

Finally, all of the “coherent multidecadal variability in multiple variables” mentioned by Zhang *et al.* as “associated” with the AMO can be accounted for as additional responses to the same atmospheric forcing that we find to be responsible for the AMO in models. As ever, neither association nor correlation implies causality.

REFERENCES AND NOTES

1. A. Clement *et al.*, *Science* **350**, 320–324 (2015).
2. R. Zhang *et al.*, *Science* **352**, 1527 (2016).
3. S. Park, C. Deser, M. A. Alexander, *J. Clim.* **18**, 4582–4599 (2005).
4. R. T. Sutton, D. L. Hodson, *Science* **309**, 115–118 (2005).
5. M. W. Buckley, J. Marshall, *Rev. Geophys.* **54**, 5–63 (2016).

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation Climate and Large-Scale Dynamics and Paleo Perspectives on

¹Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, USA. ²Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA. ³Max Planck Institute for Meteorology, Hamburg, Germany. *Corresponding author. Email: aclement@rsmas.miami.edu

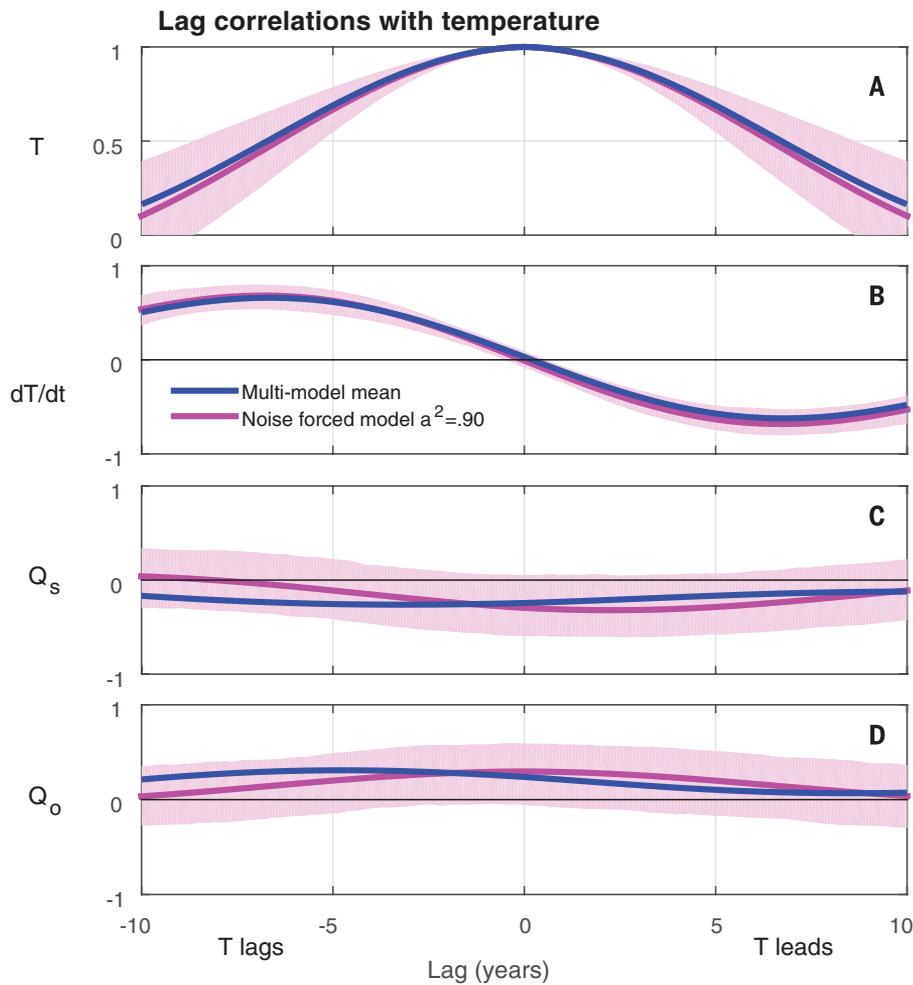


Fig. 1. Lead-lag relationships with the AMO index. Here, we reproduce similar diagnostics as in Zhang *et al.* for the region 40° to 55°N, 20° to 60°W, with eight of the CMIP3 fully coupled models that were used in their comment and in Clement *et al.*, along with the same quantities calculated from the simple noise-forced model from Eq. 1. (We limit our analysis to 55°N to avoid the effects of sea ice on the mixed-layer heat budget.) We exclude two models (mri_cgcm2_3_2a and miroc3_2_hires_coupled_40_55N_20_60W) because their published data contain less than 200 years. We analyze only the last 300 years of the model time series to remove any effect of adjustment (and the last 200 years in the hadgem1). Data are detrended and then low-pass filtered, with a 20-year cutoff Butterworth fourth-order filter. The multi-model mean is shown in heavy blue for (A) the autocorrelation of temperature, (B) the lag correlation of dT/dt and temperature, (C) the lag correlation of net surface heat flux (defined as positive downward) and temperature, and (D) the lag correlation of the “ocean residual” (defined as positive for convergence of heat) and temperature. Superimposed on these curves are the results from the simple noise-forced model, with $a^2 = 0.9$ (pink lines). The pink shading shows the 5% and 95% confidence intervals based on a nonparametric estimation using 500 300-year long realizations of the noise-forced model.

Climate Change programs. M.A.C. was supported by Office of Naval Research grant N00014-12-1-0911. We thank Y. Kushnir for comments. We acknowledge the contributors to the Coupled Model Intercomparison Project phase 3 (CMIP3) archive. The CMIP3 data are available at <http://cmip-pcmdi.llnl.gov/>.

3 February 2016; accepted 16 May 2016
10.1126/science.aaf2575



Response to Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation"
Amy Clement, Mark A. Cane, Lisa N. Murphy, Katinka Bellomo,
Thorsten Mauritsen and Bjorn Stevens (June 23, 2016)
Science **352** (6293), 1527. [doi: 10.1126/science.aaf2575]

Editor's Summary

This copy is for your personal, non-commercial use only.

- Article Tools** Visit the online version of this article to access the personalization and article tools:
<http://science.sciencemag.org/content/352/6293/1527.2>
- Permissions** Obtain information about reproducing this article:
<http://www.sciencemag.org/about/permissions.dtl>

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2016 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.