TECHNICAL COMMENT

OCEAN VARIABILITY

Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation"

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Clement *et al*. (Reports, 16 October 2015, p. 320) claim that the Atlantic Multidecadal Oscillation (AMO) is a thermodynamic response of the ocean mixed layer to stochastic atmospheric forcing and that ocean circulation changes have no role in causing the AMO. These claims are not justified. We show that ocean dynamics play a central role in the AMO.

Without analyzing the Atlantic Multidecadal Oscillation (AMO) mechanisms in fully coupled general circulation models (CGCMs) that include ocean dynamics, Clement *et al*. (*1*) conclude that the AMO in CGCMs is generated by the same mechanism as in slab-ocean models (SOMs), which lack ocean dynamics. They suggest that the AMO is a direct response of the ocean mixed layer to stochastic surface heat fluxes without a role for ocean heat transport/circulation changes.

Here, we show that the above conclusions are not justified. Any claims about the mechanisms governing the AMO, such as those in (*1*), must be based on direct analyses of these mechanisms. It is not possible to make robust inferences about mechanisms causing the AMO from a simple analysis of sea surface temperature (SST) patterns and power spectra. We refute the claims in (*1*) through analyses of the same models employed in (*1*) and show that the mechanism causing the AMO in CGCMs is different from that in SOMs—i.e., time-varying ocean heat transport convergence is a leading cause of the AMO in CGCMs (Figs. 1 and 2).

Figure 1, A and B, shows the SST tendency ($\frac{dSST'}{dt}$) at low frequencies regressed on the AMO index with a 4-year lead time. The AMO index used for regression analyses should be the "low-pass filtered" detrended North Atlantic basin–averaged SST anomalies (SST′) to reflect the "multidecadal" variability that gives the AMO its name (*2*). The 4-year lead time is not chosen arbitrarily. With 10-year low-pass filtering, the AMO tendency ($\frac{dAMO}{dt}$) leads the AMO index by 4 years at their maximum correlation in all CGCMs, and the multimodel mean lead time for SOMs is 3 to 4 years. The SST tendency ($\frac{dSST'}{dt}$) at low frequencies has a similar pattern to the simulated AMO pattern [figure S1 in (*1*)], with the largest amplitude in the subpolar region. At low frequencies, the positive SST tendency in SOMs (Fig. 1B) is induced mainly by reduced upward sensible heat flux (not shown) leading to a positive net surface heat flux anomaly ($F'_{Net} = \rho C_p h \frac{dSST'}{dt} > 0$, where the positive sign denotes downward heat flux into the ocean) (Fig. 1D). In contrast, in CGCMs the positive SST tendency in the subpolar region (Fig. 1A) is induced by enhanced ocean heat transport convergence (Fig. 1E) (OHTC′, diagnosed approximately as $OHTC' \approx \rho C_p h \frac{dSST'}{dt} - F'_{Net}$, where h is 50 m for SOMs and is the thickness of the top ocean model layer for each CGCM (not a constant across models). The residual term $\rho C_p h \frac{dSST'}{dt}$ is negligible, compared with F'_{Net} that is almost in balance with OHTC′ (Fig. 1, C and E). Consistent with observations (*3*), the enhanced turbulent heat fluxes (not shown) and negative net surface heat flux ($F'_{Net} < 0$)(Fig. 1C) damp the surface warming induced by positive OHTC′ in the subpolar region at low frequencies.

Similar regression patterns also appear at other lead times (Fig. 2, A to D) and at zero-lag. With 20- or 30-year low-pass filtering, the multimodel mean correlation between $\frac{dAMO}{dt}$ and the AMO peaks at longer lead times (8 or 10 to 11 years, respectively) due to the broad AMO spectra in CGCMs. The SOM simulations are too short to apply longer low-pass filtering cutoff periods, but in SOMs the same mechanism holds at all frequencies. Our results are robust for a wide range of lead times and different low-pass filtering cutoff periods, and our conclusions about causality are not a consequence of the filtering. The leading role of ocean dynamics that we identify in CGCMs is consistent with a wealth of evidence that the AMO is associated with coherent multidecadal variability in multiple variables (ocean heat/salt content, overturning circulation and heat transport, and ocean-driven surface turbulent heat fluxes) (*3*–*11*). Our results (Figs. 1 and 2) refute the claims in (*1*) that "the current generation models analyzed here do not support the idea that ocean circulation drives the AMO" and "simulations of the AMO using fully coupled atmosphere-ocean models…are essentially indistinguishable from those produced by the equivalent slab-ocean model versions." They are clearly distinguishable if one examines the mechanisms, even if the models have similar SST patterns and power spectra.

Curiously, Clement *et al*. comment at the end of their Report that "Our analysis does not rule out that the ocean circulation may contribute to low-frequency variability in parts of the ocean, such as the subpolar gyre." This curious statement contradicts their central claim that "the AMO is the response to stochastic forcing from the mid-latitude atmospheric circulation" in which "ocean circulation changes would be largely a response to, not a cause of, the AMO". Our analyses demonstrate that in the subpolar region, ocean dynamics is the leading cause of the AMO, whereas the varying surface heat fluxes are a passive response to, not a cause of, the AMO, contrary to the claims in (*1*) (Fig. 2, E and F). The largest low-frequency SST anomalies in the observed AMO pattern are in the subpolar region (*12*). The simulated AMO in CGCMs [figure S1 in (*1*)] is dominated by the subpolar gyre variability induced by ocean dynamics. The weaker low-latitude AMO signal responds to the stronger subpolar AMO signal through combined oceanic and atmospheric teleconnections (including changes in the Hadley circulation, wind-evaporation-SST feedback, and cloud feedback) (*12*–*15*) (Fig. 2E). Changes in the subpolar ocean state also induce tropical North Atlantic subsurface temperature variations through the oceanic teleconnection, which are anticorrelated with the tropical AMO signal (*5*, *7*, *13*) (Fig. 2E). If the tropical AMO signal were forced by stochastic F'_{Net}, as in SOMs, its anticorrelation with oceanic-driven tropical subsurface temperature variations found in both observations and CGCMs (*5*, *7*, *13*) would not exist (Fig. 2, E and F). The climate impacts associated with the tropical AMO have high decadal predictability only when the subpolar ocean state is initialized (*14*). The successful decadal predictions (*9*–*11*), with initialized observed ocean states, suggest that ocean dynamics is the leading cause of the AMO (Fig. 2E). The mechanism in SOMs implies no decadal predictability other than simple persistence (Fig. 2F). Our results show that the subpolar gyre is the key region for generating the AMO and that our most realistic models indicate that ocean circulation indeed plays a leading role in driving this variability.

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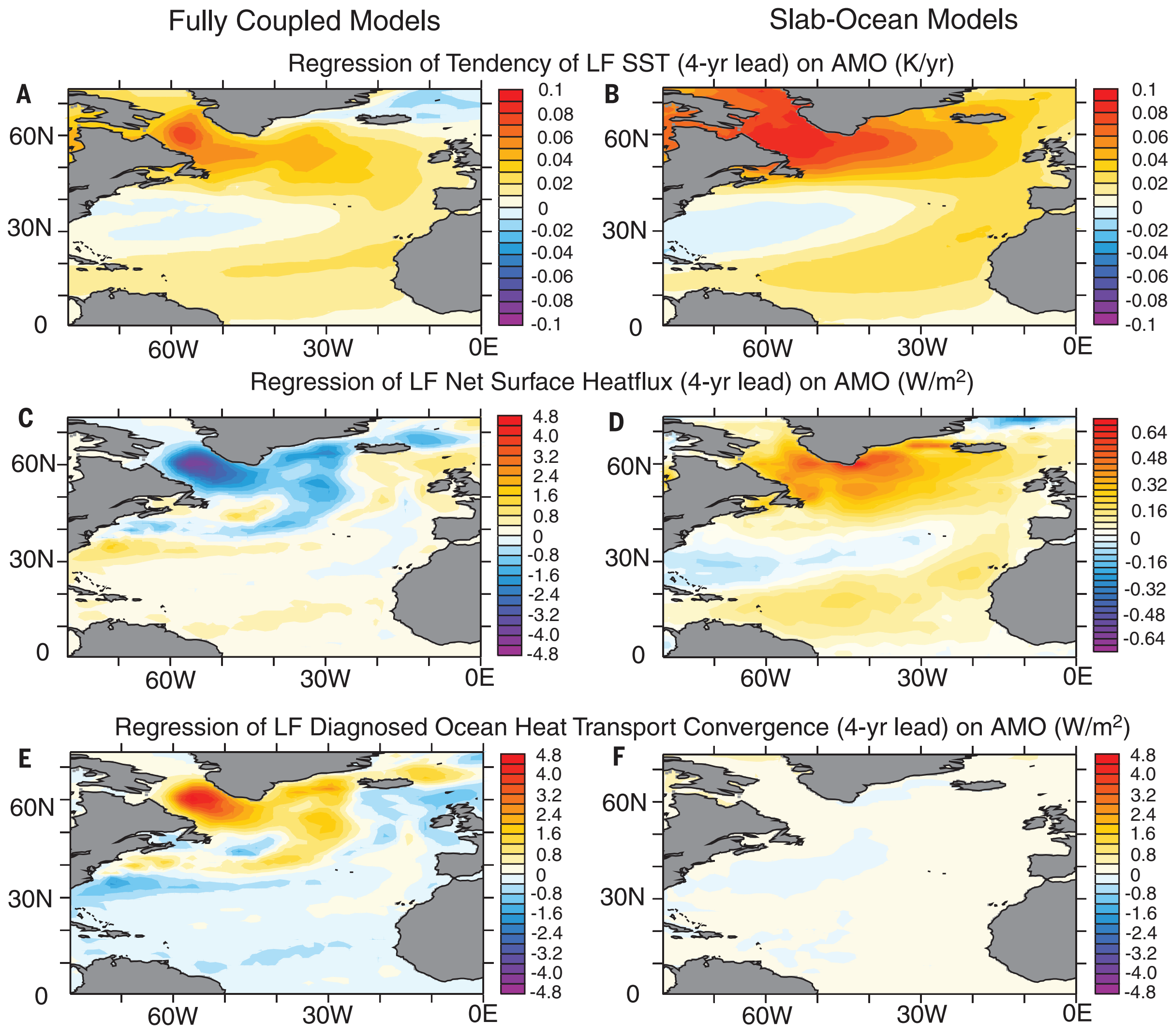

Fig. 1. Regression of 10-year low-pass filtered (LF) variables on the standardized AMO index when the variables lead the AMO index by 4 years, using the same 10 Coupled Model Intercomparison Project phase 3 (CMIP3) preindustrial control fully coupled and SOMs, as listed in table 1 in Clement *et al.* (*1*). (**A**, **C**, and **E**) Multimodel ensemble mean of 10 fully coupled models (CGCMs). (**B**, **D**, and **F**) Multimodel ensemble mean of 10 SOMs. (The GISS SOM has an unrealistic discontinuity of longwave surface fluxes at year 101, so only the first 100 years of GISS SOM are used.) [(A) and (B)] Regression of tendency of LF SST ($\frac{dSST'}{dt}$). [(C) and (D)] Regression of LF net surface heat flux (F'_{Net}, positive sign denotes downward heat flux into the ocean). [(E) and (F)] Regression of LF diagnosed ocean heat transport convergence ($OHTC' \approx \rho C_p h \frac{dSST'}{dt} - F'_{Net}$). h is 50 m for SOMs and is the thickness of the top ocean model layer to calculate SST (top ocean model layer temperature) heat budget for each fully coupled model (h is not a constant across models), and ρ and C_p are the density and heat capacity of ocean water. Regression values correspond to one standard deviation of the AMO index. The AMO index is defined as 10-year LF basin–averaged SST anomalies in the North Atlantic (80°W to 0°, 0° to 60°N). All variables are detrended.

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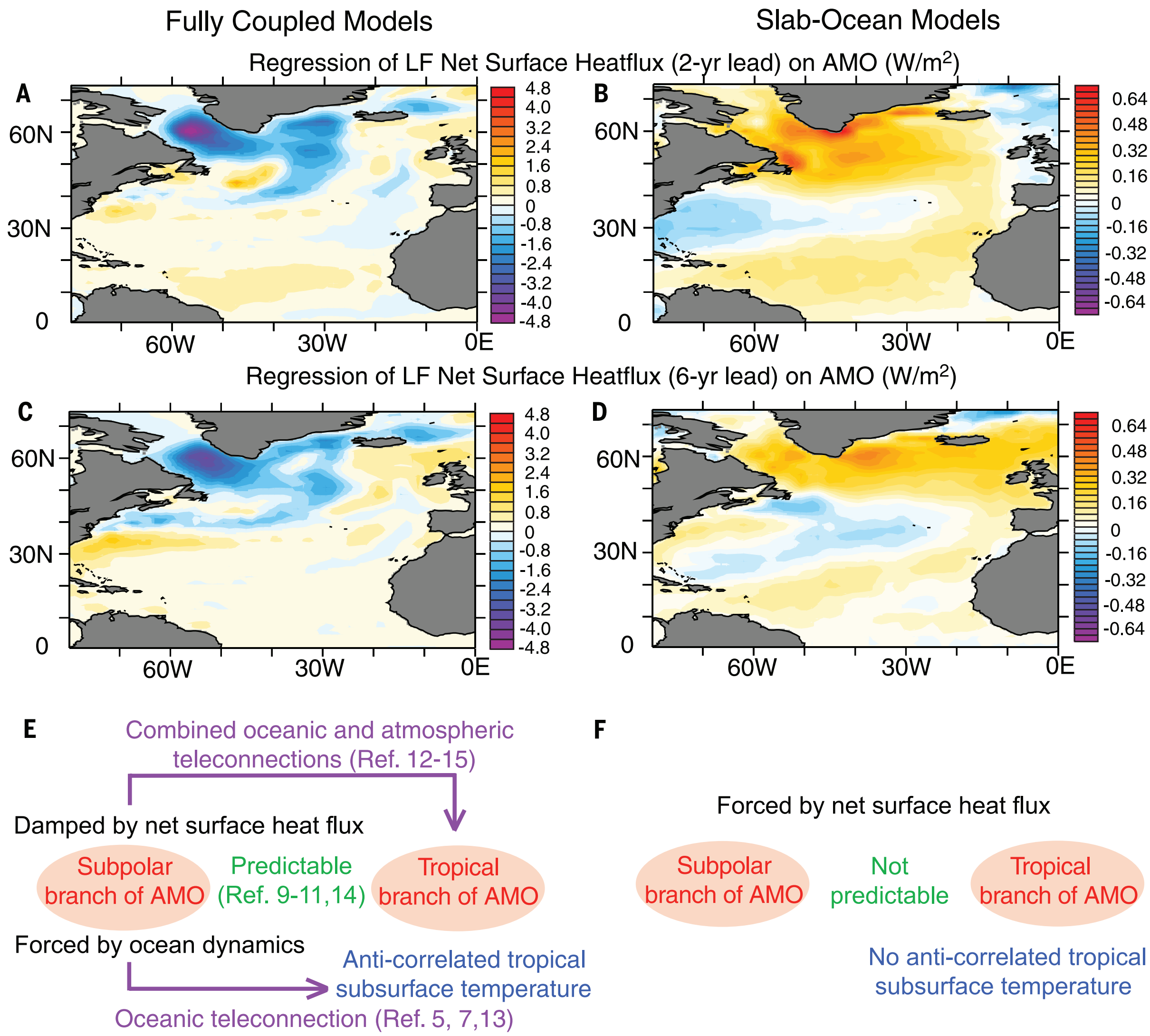

Fig. 2. Regression of 10-year LF net surface heat flux on the standardized AMO index when the heat flux leads by 2 and 6 years and schematic mechanisms of the AMO. (**A** and **C**) Multi-model ensemble mean of 10 fully coupled models (CGCMs). (**B** and **D**) Multimodel ensemble mean of 10 SOMs. (**E** and **F**) Schematic diagrams of different mechanisms of the AMO. In fully coupled models (E), the subpolar AMO is forced by time-varying ocean heat transport convergence and damped by net surface heat flux anomalies. The weaker tropical AMO responds to the stronger subpolar AMO through combined oceanic and atmospheric teleconnections (*12–15*). Changes in the subpolar North Atlantic ocean state also induce tropical North Atlantic subsurface temperature variations through oceanic teleconnection, which is anticorrelated with the tropical AMO, suggesting that the tropical AMO is linked to subpolar oceanic variability (*5*, *7*, *13*). The subpolar AMO and the climate impacts associated with the tropical AMO have decadal predictability when initializing the subpolar North Atlantic ocean state (*9–11*, *14*). In SOMs (F), both subpolar and tropical AMO branches are forced by stochastic net surface heat flux anomalies and thus have no decadal predictive skill other than simple persistence. The mechanism in SOMs cannot explain the anticorrelation between the tropical AMO and tropical North Atlantic subsurface temperature variations found in both observations and fully coupled models.