On the role of the ocean in the Atlantic Multi-decadal Oscillation

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Key Points:

- Tracer-decomposed North SST anomalies show weak atmosphere-forced but strong ocean-forced multi-decadal variability.
- The fully-coupled surface heat flux variability has a dominant fingerprint of the ocean-forced SST anomaly component.
- The reduced multi-decadal power of the fully-coupled AMO is due to the damping of the ocean-forced variability by strong air-sea coupling.

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Abstract

The relative roles of the ocean and the atmosphere in driving the Atlantic Multi-decadal Oscillation (AMO) are investigated by isolating the AMO components forced by anomalous surface heat fluxes and ocean dynamics in a fully- and partially-coupled experiments. The impact of the ocean-dynamics-forced SST on air-sea interaction is disabled in the partially-coupled experiment in order to isolate the atmosphere-forced variability. In the partially-coupled experiment, the ocean-forced AMO component exhibits a strong multi-decadal variability (25- to 50-yr periods), while the atmosphere-forced component has weak multi-decadal variability. This ocean-forced variability is imprinted on the fully-coupled surface heat fluxes, which however, damp the ocean-forced SST variability inducing them, so that the fully-coupled AMO multi-decadal power is only slightly stronger than that forced by the atmosphere alone. Our results suggest that the multi-decadal variability of the AMO is largely driven by ocean dynamics, but its power is also determined by the strength air-sea coupling.

1 Introduction

Observations and fully-coupled models show that North Atlantic sea surface temperatures (SSTs) exhibit decadal to multi-decadal variability, which is known as the Atlantic Multi-decadal Oscillation (AMO) [Kushnir, 1994; Frankcombe et al., 2010; Zhang and Wang, 2013]. However, the relative roles of the atmosphere and ocean in driving this variability remains uncertain. This uncertainty is heightened by the demonstrated ability of both the atmosphere and ocean to drive decadal to multi-decadal AMO variability. The notion of an atmosphere-forced AMO is supported by the similarity between the spectra and predictable components of the AMO in slab ocean models, without an interactive ocean circulation, and those of the fully-coupled models with an interactive ocean dynamics [Clement et al., 2015; Srivastava and DelSole, 2017; Cane et al., 2017]. Interactive ensemble experiments wherein the variability is forced by atmospheric noise and only the ensemble mean surface fluxes feed back to the atmosphere, similarly suggest an atmosphere-forced variability [Schneider and Fan, 2012; Fan and Schneider, 2012; Chen et al., 2016]. On the other hand, several other studies have demonstrated a dominant role for the ocean by showing that the slowly varying Atlantic Meridional Overturning Circulation (AMOC) can drive the AMO decadal to multi-decadal variability [Knight et al., 2005; Msadek and Frankignoul, 2009; Zhang and Wang, 2013; Gulev et al., 2013; O'Reilly et al., 2016; Zhang, 2017].
The conceptual model of the ocean mixed layer temperature tendency have been used to evaluate the roles of the atmosphere and ocean [Frankignoul, 1985; Frankignoul et al., 2002; Zhang, 2017]:

\[
\rho c_p h \frac{\partial T'}{\partial t} = Q'_{\text{net}} + Q'_{\text{O}} = -\lambda_A T' + q'_A - \lambda_O T' + q'_O, \tag{1}
\]

where \(Q'_{\text{net}}\) is the net anomalous surface heat flux, consisting of an atmospheric forcing term, \(q'_A\), and the surface damping of the total ocean temperature anomaly, \(\lambda_A T'\); and \(Q'_{\text{O}}\) is the net ocean heat convergence, consisting of an oceanic forcing term, \(q'_O\), and an ocean damping of the total ocean temperature anomaly, \(\lambda_O T'\). The ocean heat convergence term \((Q'_{\text{O}})\), can be diagnosed from fully-coupled models as the difference between the mixed layer heat content tendency \((\rho c_p h \frac{\partial T'}{\partial t})\) and the anomalous surface heat flux \((Q'_{\text{net}})\). Zhang et al. [2016] showed that the fully-coupled AMO index is positively correlated with the diagnosed \(Q'_{\text{O}}\), but anti-correlated with \(Q'_{\text{net}}\), suggesting an ocean-forced variability, whereas slab models show a positive correlation between the AMO and \(Q'_{\text{net}}\). Using a stochastic model based on (1), with the atmospheric forcing \((q'_A)\) represented as white noise, O’Reilly et al. [2016] showed that it is necessary to include a periodic low frequency \(Q'_{\text{O}}\) term, in order to reproduce the anti-correlation between surface turbulent heat fluxes (THF) and the AMO index, found in fully-coupled models and observations.

Clement et al. [2016] and Cane et al. [2017], on the other hand, also use a stochastic model to show that the THF-AMO anti-correlation can also be reproduced when both the atmospheric forcing, \(q'_A\) and ocean heat convergence, \(Q'_{\text{O}}\), are represented as white noise. The representation of \(Q'_{\text{O}}\) as white noise is based on the spectra of the \(Q'_{\text{O}}\) diagnosed from fully-coupled models. They further point out that the surface and ocean heat terms simply balance each other out on long timescales, and thus cannot be used to ascribe causality. The foregoing arguments, therefore, suggest that the inferences on the driving mechanism of the AMO based on the \(Q'_{\text{net}}\) and \(Q'_{\text{O}}\) terms are uncertain. We can see the reason why from equation (1), both \(Q'_{\text{net}}\) and \(Q'_{\text{O}}\) are functions of the total temperature \((T')\) which includes both atmosphere- and ocean-forced components, due to the forcing terms, \(q'_A\) and \(q'_O\). Therefore, in order to understand the roles of the atmospheric noise forcing and ocean circulation variability in generating decadal to multi-decadal AMO variability, it is necessary to isolate the atmosphere- and ocean-forced components of \(T'\). Isolating these components will also clarify questions such as: are both the atmosphere-forced and ocean-forced mechanisms active in
low-frequency AMO variability? If both are involved, how might these mechanisms interact with each other through coupling?

In this study, we explicitly isolate the North Atlantic SST anomaly components due to the atmospheric and oceanic forcings. We employ the passive tracer temperature decomposition method used in global warming experiments [Banks and Gregory, 2006; Xie and Vallis, 2012; Bouttes et al., 2014; Garuba and Klinger, 2016; Gregory et al., 2016; Garuba et al.] to decompose ocean temperature variability into parts forced by the surface heat flux and ocean circulation variability. Following the partial coupling approach in Garuba et al., we further isolate the atmosphere-forced variability from the ocean-forced one, by preventing the ocean-forced component from coupling with the atmosphere in a partially-coupled experiment. Further analysis of the spectra AMO index and its components, and their correlation with the THF in the partially-coupled and fully-coupled simulations are used to show how the interactions between the atmosphere- and ocean-forced components generate the fully-coupled AMO variability.

2 Model and experimental design

We use the fully-coupled version of the community Earth System Model version1.1 (CESM 1.1 and CESM-SOM). The fully-coupled CESM consists of the following active components: Community Atmospheric Model version 5 (CAM5) [Neale et al., 2010], Parallel Ocean Program version 2 (POP2) [Danabasoglu et al., 2012], Community Land Model version 4 (CLM4) [Oleson et al., 2010], and the Community Ice CodE (CICE) [Hunke et al., 2010]. In the CESM-SOM, the ocean model POP is replaced by a slab ocean model [SOM; see Bitz et al., 2012]. CAM5 and CLM4 use a 2.5°X 1.9° horizontal resolution, with 30 vertical levels in CAM5. CICE, POP, and SOM run on a nominally-1° resolution, displaced-pole grid (with the north pole singularity centered over Greenland); POP has 61 vertical levels.

The fully-coupled and partially-coupled experiments are 200-year long experiments with preindustrial radiative forcing. The AMO index is defined as the detrended, area averaged SST anomalies over the North Atlantic region (0°N-60°N), or alternatively over the sub-polar North Atlantic region (40°N-60°N). SST anomalies are monthly averaged SSTs with monthly mean climatology removed at each grid point. The spatially averaged time-series is detrended by subtracting the global-mean SST anomaly time-series, following Tren-
berth and Shea [2006]. The AMO component indices are obtained in the same way as the AMO index, but by using the decomposed components of the SST anomalies.

### 2.1 Fully-coupled decomposition

We employ the tracer decomposition method used in Banks and Gregory [2006], Xie and Vallis [2012], Marshall et al. [2015], Bouttes et al. [2014], Gregory et al. [2016], and Garuba and Klinger [2016]; Garuba et al., except here to decompose ocean temperature anomalies due to internal variability rather than those due to CO2 forcing in these earlier studies. The decomposition is based on the temperature anomaly evolution equation:

\[
\frac{DT'}{Dt} = Q'_{net} - v' \cdot \nabla T
\]  

(2)

Here, overbars represent the monthly climatological mean variables, primes denote anomalies from the climatology, and \( \frac{D}{Dt} = \frac{d}{dt} + v \cdot \nabla \) (i.e, the total derivative following the ocean circulation, \( v = \bar{v} + v' \)). Equation (2) is decomposed into parts forced by surface flux anomalies \( Q'_{net} \), and the redistribution of the background climatology temperature, \( \tilde{T} \), by the circulation change \( v' \), that is, "surface-forced" \( T'_{AF} \) and "redistributive" \( T'_{RF} \); also referred to here as "dynamics-forced") components (subscript “F” denotes fully-coupled components), that is:

\[
\frac{DT'_{AF}}{Dt} = Q'_{net} = -\lambda A T' + q'_A
\]  

(3)

\[
\frac{DT'_{RF}}{Dt} = -v' \cdot \nabla \tilde{T}
\]  

(4)

and

\[
T' = T'_{AF} + T'_{RF}
\]  

(5)

The decomposition into the "surface-forced" and "ocean-dynamics-forced" or "redistributive" components is realized by implementing two temperature-like passive tracers formulated the same way as those in Xie and Vallis [2012] and Garuba and Klinger [2016] (See Supplementary information for details of tracer implementation). The monthly mean clima-
ology of surface heat fluxes and ocean temperature, derived from a 200-yr control simulation replicating the fully-coupled simulation, are used as forcings for the tracers.

Comparing equations (2) and (1) shows: $Q_{net}'$ is equivalent in both equations, including both the atmospheric forcing and surface damping terms ($q'_A$ and $\lambda_A T'$); $v' \cdot \nabla \bar{T}$ is equivalent to the ocean forcing term ($q'_O$), due to ocean circulation variability; $v \cdot \nabla T'$ in $\frac{DT'}{Dt}$ could be thought of as the ocean damping term ($\lambda_O T'$), since it involves the removal or addition of the surface-forced or ocean-forced temperature anomalies by the ocean advective, diffusive or mixing processes [Frankignoul et al., 2002].

The ocean dynamics-forced (redistributive) component ($T'_{RF}$) in (4) isolates the ocean-forced temperature anomaly, since it consists of an ocean forcing term and the ocean damping of only this ocean-forced component. The surface-forced component ($T'_{AF}$), however, does not yet isolate the atmosphere-forced temperature anomaly. According to equation (3), $Q_{net}'$ the forcing for $T'_{AF}$, includes both an atmospheric forcing term and the surface damping term of the total ocean temperature anomaly ($T'$), which also includes an ocean-dynamics-forced component.

### 2.2 Partially-coupled decomposition

The atmosphere-only-forced temperature variability is isolated using the partial coupling method introduced in Garuba et al.. Like in the fully-coupled experiment, the partially-coupled ocean temperature anomaly is decomposed using tracers into the surface-forced and redistributive components using passive tracers ($T'_{AP}$ and $T'_{RP}$ respectively; subscript “P” denotes partially-coupled components). However, the partially-coupled total ocean temperature anomaly ($T'_p$) is not used for computing the surface fluxes. The partially-coupled surface fluxes are computed using only the surface-forced temperature anomaly, thereby, preventing the ocean dynamics-forced temperature anomaly from interacting with the atmosphere (See Garuba et al. for details on the experimental design). As a result, the partially-coupled surface heat flux ($Q'_p$) and the passive surface-forced temperature anomaly ($T'_{AP}$) it forces, are atmosphere-forced only. The equations governing the partially-coupled surface-forced and redistributive temperature anomalies, therefore, can be written as:

$$\frac{DT'_{AP}}{Dt} = Q'_p = -\lambda_A T'_{AP} + q'_A$$ (6)
\[ \frac{DT_R''}{Dt} = -v'_P \cdot \nabla \bar{T} \]  

(7)

\[ T_P'' = T_{AP}' + T_{RP}' \]  

(8)

The impact of ocean circulation variability on the fully-coupled air-sea interaction is evident from comparing the surface heat fluxes or surface-forced temperature anomaly variability between the partially- and fully-coupled experiments. Like its fully-coupled analog, the partially-coupled ocean dynamics-forced temperature anomaly \( T_{RP}' \) is due only to the ocean forcing. However, the partially-coupled ocean forcing is different from the fully-coupled one, because it excludes the impact of the ocean-induced surface fluxes on the ocean circulation variability, that is, the difference between \( v' \) and \( v'_P \) (compare (4) and (7)). This uncoupled ocean dynamics-forced component thus reveals a pure ocean-forced variability.

The partially-coupled experiment here shares some similarities with the slab experiments: Both the slab and the partially-coupled surface-forced temperature anomalies, exclude the feedback from the ocean-forced temperature anomaly in surface interaction. However, unlike the slab temperature anomaly, the partially-coupled surface-forced temperature anomaly includes the damping effect due to the transport by the ocean advective, diffusive or mixing processes, that is, \( v \cdot \nabla T_{AP}' \). The partially-coupled experiment also reveals an additional uncoupled ocean-forced temperature anomaly which will provide further insight into ocean-forced variability in the fully-coupled experiment.

3 Results

3.1 AMO components pattern and spectra

We consider first the AMO pattern and index and those of its surface-forced (SF) and ocean dynamics-forced (DF) components, defined over 0-60°N, in the partially- and fully-coupled experiments (Fig 1). Despite non-linear behavior of the temperature anomaly, the decomposition holds for the spatially-averaged indices in this region, as shown by the the sum of the AMO components and the actual AMO index. In both experiments, the indices show a dominant DF component in the AMO index (Fig 1g and h). The AMO index often has the same sign as the DF component, while the SF components are often out-of-phase with both the AMO and DF components (Fig 1g and h). This is more obvious in the partially-coupled simulation where the DF component has a much larger amplitude than the SF com-
ponent. Nevertheless, the SF components show similar patterns to the fully-coupled AMO, like the similarity found in slab and fully-coupled AMO patterns (Fig 1a, d and f; compare also Fig 1a and b in Clement et al. [2015]), while the patterns of the dominant DF components are distinct from the AMO pattern (compare Fig 1b and e with c and f).

Figure 1. Pattern of the surface-forced (SF) and ocean dynamics-forced (DF) components and the AMO in the partially-coupled (a,b and c), and fully-coupled (d, e and f); AMO index (black) and its SF (blue) and DF (red) components and their sum (cyan) in the partially-coupled (g), and fully-coupled (h) experiments.

To see their relationship quantitatively, we examine the spectra of the AMO index and its components in both experiments, but focus on the 40°N to 60°N region (Box in Fig 1a). This region is often used to study the dynamics of the AMO because of the stronger decadal to multi-decadal SST variability here [Gulev et al., 2013; Zhang et al., 2016; O’Reilly et al.,]
2016], compared to the more damped AMO defined over the 0 - 60°N region (compare Figs S1 and 2a). This alternative AMO index is, however, strongly correlated with the AMO index defined over entire North Atlantic, and therefore does not change the conclusions we will show.

The spectra of the AMO and its components show significant peaks at the 16, 25 and 50 periods (Fig 2a), which captures the 20-to-30, and 50-to-80 year timescales found in observational studies and historical simulations [Frankcombe et al., 2010; Zhang and Wang, 2013; Gulev et al., 2013]. The partially-coupled AMO has a large and significant multi-decadal power (25 and 50 yr periods), which evidently comes from its much stronger DF component. The partially-coupled DF component spectrum shows a very strong multi-decadal power increasing at lower frequencies, while the partially-coupled SF component has very weak multi-decadal power, but more power at higher frequencies (Fig 2a; compare with the indices in Fig 1g). In the fully-coupled experiment, however, the multi-decadal power of the AMO is much weaker than in the partially-coupled experiment, with its 50-yr peak about ten times weaker than in the partially-coupled experiment and its 25-peak becoming insignificant (Fig 2b). This reduced multi-decadal variability of the fully-coupled AMO is due to the spectral change in both its components. Though it is still the dominant component, the fully-coupled DF component is much weaker than in the partially-coupled experiment (about half the partially-coupled power at the 50-year period). The fully-coupled SF component, on the other hand, is a lot stronger than that in the partially-coupled experiment on multi-decadal timescales, with a spectrum resembling that of the DF component. Furthermore, in comparison to the partially-coupled AMO components which are only out-of-phase at periods greater than 50 years, the fully-coupled AMO components are completely out-of-phase at all timescales (compare red lines in Fig 2c and d).

The comparison of the fully- and partially-coupled spectra suggests an ocean-driven multi-decadal AMO variability in the fully-coupled simulation. The atmosphere-forced variability shown by the partially-coupled SF component is weak and barely significant on multi-decadal timescales, although stronger at higher frequencies. The ocean-forced component, on the other hand, possesses a much stronger multi-decadal variability, shown by the uncoupled DF component in the partially-coupled experiment. Due to coupling with the atmosphere, however, ocean circulation variability weakens in the fully-coupled simulation, resulting in the weaker spectral power of the fully-coupled DF component. Nevertheless, this ocean-forced SST variability is strongly imprinted on surface heat fluxes and overshad-
Figure 2. Power spectra of the AMO index (black), defined over the sub-polar Atlantic (40°N - 60°N), and its surface-forced (SF; blue) and dynamics-forced (DF; red) components indices, in the partially-coupled (a) and fully-coupled (b) experiments and slab AMO index (cyan); Dashed lines indicate 95% significance level of the spectra. Phase relationship between the: surface-forced and the ocean dynamics-forced AMO components (red); the surface-forced component and the AMO (black) in the partially-coupled (c) and fully-coupled (d).

Owes the purely atmosphere-induced variability therein, as suggested by the much enhanced multi-decadal spectral power of the fully-coupled SF component. The increased phase lag between the fully-coupled AMO components results from the dominant fingerprint of the ocean-forced SST component on the surface heat fluxes; the surface heat fluxes and the SF component it forces, are opposite in sign to the ocean-forced SST anomaly inducing them. The result of the relatively weaker ocean-forced variability and the stronger surface damping of it, is the much weaker multi-decadal variability of the fully-coupled AMO, which nevertheless, remains significant because its ocean-forced component is still dominant.

The analysis here offers an insight into the reasons for the similarity in the AMO spectra and pattern between fully-coupled and slab models, which has been used as evidence to
support an atmospheric noise-driven mechanism for the AMO [Clement et al., 2015; Cane et al., 2017]. Like the slab AMO, the partially-coupled SF component variability is atmosphere-forced only (see section 2.2), and likewise shows stronger spectral peaks at higher frequencies, and similar pattern and significant multi-decadal peaks comparable to the fully-coupled AMO. We point out that the slab AMO spectrum is much stronger than that of the partially-coupled SF component, due to the lack of ocean damping of the surface-forced SSTa in the slab model (cyan line in Fig 2a). The fully-coupled AMO and SF components show similar patterns in both simulations, suggesting that these patterns merely reflects the advection of passive temperature anomalies forced by surface heat fluxes by the ocean circulation (consistent with the horse shoe shape of the anomalies). Furthermore, the comparable multi-decadal power of the fully-coupled AMO and that of the partially-coupled SF component, (even weaker than the multi-decadal power of the slab AMO), is the result of the strong damping by surface heat fluxes which masks the strong multi-decadal variability forced by the ocean in the fully-coupled AMO. These results therefore, suggest a need for caution in equating similarities between the slab and fully-coupled AMO patterns and spectra to similar mechanisms.

### 3.1.1 Correlation with surface heat fluxes

The mechanism of AMO variability is further investigated using the correlation of the AMO index and its components with surface heat fluxes in the partially- and fully-coupled experiments. We first compare the spectra of the radiative and turbulent components of the surface heat fluxes. The turbulent heat fluxes (THF) shows much more spectral power than the radiative fluxes, and accordingly, the impact of ocean circulation variability (the difference between their fully-coupled and partially-coupled spectra) is also more evident in the THF spectrum, especially at the 25 and 50 year periods (Fig 3a and b). This suggests that the ocean-driven spectral-change of the fully-coupled SF component is largely due to the turbulent component rather than the radiative component of the surface heat fluxes (note that the SF temperature anomaly is forced by the total surface heat fluxes, radiative plus turbulent). Because the THF component is dominant, we will focus on the correlation between THF and the AMO index and its components in the following discussion.

In both simulations, the DF component has a positive correlation with the THF, while the SF component has a negative correlation (Fig 3c and f). We adopt the sign convention that surface heat fluxes into the ocean are negative, therefore, the negative SF-THF correla-
Figure 3. (a) Power spectra of the surface radiative and turbulent heat fluxes averaged over the sub-polar Atlantic (40 -60N) in the fully-coupled (red) and partially-coupled (blue) simulation; Dashed lines indicate 95% significance level of the spectra; Correlation of the sub-polar Atlantic area averaged indices of surface turbulent heat fluxes (THF) with the AMO index (black), its SF (blue) and DF (red) components in the partially-coupled (c, d and e) and fully-coupled (f, g and h) experiments; correlation using 10-yr running mean filtered indices (c and f), using 30-yr running mean filtered indices (d and g), and using 10-30-yr band-pass filtered indices (e and h).

...tion is consistent with the warm passive temperature response (positive SF anomalies) expected from surface heat fluxes into the ocean (negative THF anomalies). The AMO-THF correlation, however, takes on the positive sign of the DF-THF correlation because the DF component is dominant (note that correlation values are normalized by the variance; thus, the stronger component dominates the correlation). In the partially-coupled simulation, the AMO-THF correlation is more positive due to a more dominant DF anomaly in the AMO index. In the fully-coupled simulation due to the surface coupling with the dominant DF component, the SF anomaly is stronger and shows greater negative correlation with the THF,
especially when the SF component leads, and so the fully-coupled DF anomaly becomes less
dominant than that in the partially-coupled experiment (compare the indices in Fig 1g and
h). As a result, the positive correlation between the fully-coupled AMO and THF becomes
weaker, especially when the AMO leads (Fig 3c and f, black lines). This weakening of the
positive AMO-THF correlation by a stronger SF component in the fully-coupled experiment,
gives a plausible explanation for the weaker positive AMO-THF correlation in fully-coupled
models compared to that found in observations [Gulev et al., 2013; O’Reilly et al., 2016].
The positive AMO-THF correlation here, depends on the relative magnitudes of the SF and
DF anomalies, which in turn depends on the strength of the surface coupling. Stronger sur-
face coupling means a stronger SF anomaly, and also a less dominant DF anomaly and weaker
positive AMO-THF correlation. Therefore, the strength of the surface coupling in fully-
coupled models might be stronger than in observation, thus reducing the dominance of the
strong positive DF-THF correlation component in the full AMO-THF relationship.

When the AMO-THF correlation is decomposed into the inter-decadal (10-30-yr pe-
riod) and multi-decadal (>30-yr period) timescales, it is evident that the positive AMO-
THF correlation comes from a stronger positive AMO-THF correlation on multi-decadal
timescales, in both experiments (compare Fig 3c, with d and e; f, with g and h). This strong
positive multi-decadal AMO-THF correlation is due to a stronger positive multi-decadal
DF-THF correlation and an even more dominant DF anomaly in the AMO index, in both
experiments. As their spectra show, the partially- and fully-coupled DF anomalies have the
strongest variance and dominance at the 50 yr period, and are more in phase with the AMO
index at periods greater than 30 years (compare Fig 2a and b and 2c and d black lines). On
the other hand, on inter-decadal timescales, the AMO-THF correlation is not significant,
due to a weaker DF-THF correlation and a much less dominant DF component in the AMO,
resulting in the cancellation of its positive correlation with THF by the negative SF-THF
correlation, in both experiments (compare Fig 3 g and h). In fact, unlike the multi-decadal
timescale, the partially-coupled SF-THF correlation is dominant in the AMO-THF corre-
lation, and the AMO index is more in phase with the SF component in both experiments at
these inter-decadal timescales (compare Fig 2c and d, black lines).

Furthermore, the lead-lag correlation pattern of AMO components on the multi-decadal
timescale shows a dominant DF component in surface interactions. The partially-coupled
SF-THF correlation sign is negative at all time lags, and is maximum when the THF leads
the SF component by one year, indicating the SF component is largely driven by the sur-
face fluxes (Fig 3d). However, in the fully-coupled experiment, the negative multi-decadal
SF-THF correlation is stronger especially when the SF component leads (maximum at 8
years lead; Fig 3g). This stronger fully-coupled SF-THF correlation when the SF component
leads, is not caused by SF anomalies driving THF anomalies, as the negative correlation sug-
gest, rather it points again to the the fact that the SF anomaly is driven by surface heat fluxes
which are largely forced by the DF component. In the partially-coupled experiment, the SF
component shows maximum correlation with the DF component at a lead of about 8 years,
and becomes even more strongly correlated with the DF component in the fully-coupled ex-
periment at the 8 year lead time (see Fig S2). This suggests that SF anomalies induce DF
anomalies, which in turn induce THF anomalies due to the coupling in the fully-coupled
experiment. As a result, the SF anomaly indirectly drives THF anomalies through the DF
anomalies it induces in the fully-coupled experiment (compare Fig 3d and f with Fig S2).

Unlike the multi-decadal timescale, the inter-decadal timescale lead-lag correlation
pattern of the partially-coupled SF-THF correlation is negative when the THF leads by about
one year, but positive when the SF component leads for about 10 years (Fig 3e and h). In-
terestingly, this inter-decadal lead-lag correlation pattern of the partially-coupled SF compo-
nent is similar to that found in slab models on timescales longer than 11 years in the study of
O’Reilly et al. [2016] and Cane et al. [2017], where it is shown to forced by atmospheric
noise with a stochastic model. The negative correlation when THF leads suggests that it
drives warm SST anomalies within one year. However, due to the longer memory of the
ocean, the ocean eventually becomes warmer than the atmosphere over a longer time; as a
result, the warmer SST anomalies drive positive THF anomalies, shown by the positive SF-
THF correlation when the SF component leads. The partially-coupled AMO-THF correla-
tion takes on this atmosphere-forced correlation pattern, though very weak due to a simi-
lar but opposite-signed DF-THF correlation pattern. This correlation pattern, however, is
not found in the fully-coupled AMO-THF correlation due to the coupling with DF compo-
nent. The fully-coupled atmosphere, unlike the partially-coupled one, sees the total SST,
which includes SF and DF anomalies of opposite signs, induced by the atmosphere-forced
surface heat fluxes in the partially-coupled simulation (compare Fig 3e, red and blue line).
The fully-coupled atmosphere, therefore, sees the sum of warm SF and cool DF anomalies,
thus does not warm up enough to drive positive THF anomalies like the partially-coupled
SF-component when the SF component leads THF.
The timescale separation here, suggests that different mechanisms are active at these different timescales, the ocean-forced mechanism is active on the multi-decadal timescales while the atmosphere-forced mechanism of the slab models is active on the inter-decadal timescale. However, the atmosphere-forced mechanism is damped out ocean-forced anomalies, therefore, is much weaker than the ocean-forced mechanism on the multi-decadal timescales. These results suggest that the improvement of the positive AMO-THF correlation with greater smoothing in observations and fully-coupled models, is not merely an artifact of time-filtering as suggested in Cane et al. [2017]. Time filtering only isolates the multi-decadal timescale in which the DF component is very dominant in the AMO index causing the AMO-THF correlation to reflect the strongly positive DF-THF correlation.

4 Discussion and Summary

We investigate the mechanism of the AMO variability, by decomposing North Atlantic SST variability into components forced by the surface heat flux (surface-forced; SF) and ocean dynamics variability (dynamics-forced; DF), in fully- and partially-coupled experiments. In order to remove the impact of ocean dynamics on surface fluxes and isolate pure atmosphere-driven SST anomalies from ocean-driven ones, the DF component is removed from coupling in a partially-coupled experiment. The comparison of the partially- and fully-coupled SF and DF components and their correlation with surface turbulent heat fluxes (THF) reveals that the atmosphere drives weak multi-decadal variability, while the ocean by itself (when uncoupled) drives a strong North Atlantic SST multi-decadal variability. However, when coupled to the atmosphere, the ocean-driven multi-decadal variability is strongly damped by the SF component through the impact of the ocean-forced SST anomaly on the THF variability in the fully-coupled experiment. As a result, the multi-decadal variability of the fully-coupled AMO is much reduced and only slightly stronger than the pure atmosphere-driven SF component. Further decomposition into inter-decadal and multi-decadal timescales, shows that the atmosphere-driven mechanism is active on inter-decadal timescales but strongly damped and weak in the fully-coupled experiment, while the ocean-driven mechanism is active on the dominant on the multi-decadal timescales.

The explicit decomposition of ocean temperature anomalies into atmosphere- and ocean-forced component in this study clears up the uncertainty surrounding the ocean-driven mechanism of the AMO demonstrated in earlier studies [O’Reilly et al., 2016; Gulev et al., 2013; Zhang et al., 2016]. The balance between the surface heat flux terms and the ocean
heat convergence term diagnosed from fully-coupled models, as well as, its almost white
spectrum, makes the role of the ocean more uncertain [Clement et al., 2015; Cane et al.,
2017]. The ocean heat convergence diagnosed from coupled models is due to the total tem-
perature, which is the residual of the opposite-signed atmosphere- and ocean-forced temper-
ature components, and therefore, does not show the strong multi-decadal variability forced
by the ocean. The ocean-forced component decomposed here, however, shows a strong and
dominant multi-decadal variability, confirming earlier results that surface heat fluxes damp
rather than force SST anomalies in fully-coupled models. Through the decomposed partially-
coupled SF component on the inter-decadal timescales, we also show that the atmosphere-
forced mechanism is also present in the fully-coupled AMO, but weaker compared to the
ocean-forced mechanism on multi-decadal timescales, due to interaction with opposite-
signed ocean-forced anomaly. Our study further reveals a useful insight on more accurately
simulating the observed decadal to multi-decadal variability in fully-coupled models: that the
power in the low frequency variability of the AMO depends on the strength of the coupling
in the models.

The results presented here, however, only examine the interaction between the ocean-
forced and atmosphere-forced components in one model. The relative strength of these com-
ponents in other models will depend on other factors, such as the resolution, the strength of
ocean circulation variability, and the strength of air-sea coupling. Finally, we point out that
we have yet to examine the mechanisms behind the strong ocean-forced multi-decadal vari-
ability. For instance, why is there a strong correlation between the atmosphere-forced surface
heat fluxes and the ocean-forced temperature anomaly in the partially-coupled experiment,
despite being decoupled from each other by design. What roles do momentum and fresh wa-
ter fluxes play in driving the ocean-forced component, or why ocean circulation variability
weakens in the fully-coupled simulation. The relative roles of the AMOC and sub-polar gyre
circulation in driving the strong ocean-forced variability also needs to be explored further.
This study however, show that ocean circulation variability drives the AMO regardless of
where the ocean circulation variability originates, and gives an insight on how better simu-
late the observed AMO in fully-coupled models.

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