The AMO in Complex Models and a Very, Very Simple Model

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- and to our Critics.

Jacob Riis Park, New York City
Conclusions

Low frequency balances are not indicative of causality.

Most Atlantic Multidecadal Variability is most probably forced by noise, mostly from the atmosphere.

- So say the models. Unequivocally. But they could be wrong.
The AMO is associated with societally important climate variations. The **AMO Index** is the average SST over the entire North Atlantic. Usually it is detrended and low-passed.

Upper figure shows the regression of SST, SLP and winds on the AMO Index. Lower figure is the time series.
**Coupled** models (CMIP pre-industrial multimodel mean) reproduce this pattern!
So do the same atmosphere models coupled to a **slab ocean**.
From Clement et al 2015 *Science*
How do the temporal characteristics compare with and without interactive ocean dynamics?

- Slab and coupled CMIP3, 5 have the same variance.
- All look like red noise, without a multidecadal peak.

AMO in CMIP3 slab models (red) and CMIP3 coupled models (blue)

AMO in CMIP3 coupled models (blue) and CMIP5 coupled models (purple)
The clear implication is that the ocean circulation is not necessary for the AMO.

The AMOC Empire strikes back:

- Zhang et al 2016
- O’Reilly et al 2016
- Drews and Greatbatch 2016

- Gulev et al 2013
North Atlantic control on surface turbulent heat flux (STHF) on multidecadal timescales

Gulev et al. (2013, Nature)

The Bjerknes hypothesis:

Low Frequency
The ocean heats the atmosphere

High Frequency
The atmosphere heats the ocean

Based on VOS reports from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, version 2.5) for 1880-2007
To interpret this correctly, consider the heat equation for the mixed layer:

\[ rC_p\frac{d[hT]}{dt} = Q_a + Q_o; \]

Take \( h = \text{constant} \):

\[ \frac{dT}{dt} = -\alpha T + q_a + q_o \]

-\( \alpha T \) is the turbulent flux (latent + sensible) damping

\( q_a \) are the other atmospheric fluxes – radiative, non-feedback turbulent fluxes

\( Q_s = -\alpha T + q_a \) is the total surface flux– the total heat exchange with the atmosphere

\( q_o \) is the ocean heat flux convergence
At Low Frequency – e.g. if low pass filtered – $dT/dt \ll \alpha T$:

\[ \frac{dT}{dt} = -\alpha T + q_a + q_o \]

Q_s

1) $Q_s \approx -q_o$  Atmosphere and Ocean Fluxes balance.
2) $\alpha T \approx (q_a + q_o)$  Damping balances all other forcing.

Implications

• These are balances and so not indicative of causality.
• $\rho(Q_s,T) \leq 0$ and $= 0$ iff there is no ocean forcing ($q_o=0$):
  
  • $E\{Q_s,T\} \approx -E\{q_o,T\}$  because 1) $Q_s \approx -q_o$,
  • $\approx -\alpha^{-1}E\{q_o, (q_a + q_o)\}$  2) $T \approx (q_a + q_o)/\alpha$
  • $\approx -\alpha^{-1}E\{q_o, q_o\} \leq 0$  $E\{q_o, q_a\} \approx 0$
In response to GCMs, we go very simple:

**Noise Forced Model (NFM)**

\[
dT/dt = -\alpha T + q_a + q_o
\]

- $-\alpha T$ is the turbulent flux (latent + sensible) damping
- $q_a$ are the other atmospheric fluxes – radiative, non-feedback turbulent fluxes
- $Q_s = -\alpha T + q_a$ is the total surface flux– the total heat exchange with the atmosphere
- $q_o$ is the ocean heat flux convergence

We now take $q_a$ and $q_o$ to be uncorrelated **white noise** forcing:

Is the NFM *relevant* for GCMs and reality?
But are the ocean and atmosphere fluxes white?

Spectra of Fluxes in the Coupled Model (CESM-CAM5)

\[ Q_s = \text{Surface Heat Flux} \]
\[ \text{Residual} = \frac{dT}{dt} - Q_s = Q_{\text{ocean}} \]

All quantities are averages over the AMO_mid region (60-20W, 40-55N)
Comparison of AMO_mid from Pre-industrial runs of two Coupled Models (GFDL CM2.1, CCSM) with functions of the Filter Autocorrelation $R(t)$ from white noise forced theory

$R(t)/R(0)$
$r(T,T)$

$R_t(t)/[-R_{tt}(0)R(0)]^{1/2}$
$r(dT/dt,T)$

$-R_{tt}(t)/[-R_{tt}(0)]$
$r(dT/dt, dT/dt)$

ACF of LP white noise (pink) and ACF of LP AMO-mid coupled models

Correctly scaled first derivative of ACF of noise; $r(dT/dt,T)$ for coupled models

Second derivative of ACF of noise; $r(dT/dt,dT/dt)$ for coupled models
Correlation $r(dT/dt, T)$ with varying filter cutoff periods of 5, 10, 20, 30 years

White Noise Forced Model (NFM)

Periodic Forcing $T = \sin(2\pi/60 \text{ years})$
North Atlantic control on surface turbulent heat flux (STHF) on multidecadal timescales

Gulev et al. (2013, Nature)

AMV vs. STHF correlations

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Based on VOS reports from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, version 2.5) for 1880-2007
Correlation of Qs and T at lead/lag=0 as a function of % of forcing from the atmosphere according to noise model analysis.

\[ a^2 = \text{Fraction of the total forcing from the Atmosphere} \]
Zhang et al 2016:

Low Pass Regressions on the (4 year lagged) AMO index

Fully Coupled Models

Regression of Tendency of LF SST (4-yr lead) on AMO (1/yr) (W/m²)

Slab-Ocean Models

Regression of LF Net Surface Heatflux (4-yr lead) on AMO (W/m²)

Regression of LF Diagnosed Ocean Heat Transport Convergence (4-yr lead) on AMO (W/m²)

Note Change of Scale

\[ \frac{d(SST)}{dt} \]

\[ Q_s \]

Surface Heat Flux

Residual aka Ocean Heat Flux

\[ \rho \]

\[ C \]

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 \( \rho \) and \( C \) are the

\[ \text{Zhang et al 2016:} \]

\[ \text{Low Pass Regressions on the (4 year lagged) AMO index} \]
Lead-Lag Correlations

Simple Noise Forced Model (NFM)
85% Atmosphere

Coupled Model (CESM)
(40-55N, 60-20W)

$\text{Simple Noise Forced Model (NFM)}$

85% Atmosphere

$\text{Coupled Model (CESM)}$

(40-55N, 60-20W)
Conclusions

Low frequency balances are not indicative of causality.

Most Atlantic Multidecadal Variability is most probably forced by noise, mostly from the atmosphere
- So say the models. Unequivocally. But they could be wrong.
- The real AMV is probably forced externally by GHGs, aerosols, volcanos, solar.

If you are going to use a low pass filter, it’s a good idea to check first and see if there is a real low frequency signal.
Thank You

Jacob Riis Park, New York City
GFDL slab model (red) and coupled model (blue)

ENSO in the tropics
An active subpolar gyre
Arises from subpolar variability.

Red: AGCM-slab ocean

Blue: Fully coupled models

Slab has *more* power. Is the ocean circulation damping?
Is the impact of the ocean circulation apparent only at low frequencies?

- **Coupled unfiltered**
- **Coupled Low Pass filtered**
- **Slab unfiltered**
- **Slab Low Pass filtered**

All are CMIP multi-model means
Conclusion:
The AMO is a response to stochastic atmospheric forcing. But thermal coupling (WES) is active in the tropics, generating a wind (and SST) signal there.
No spectral peak in long model simulations (Ba et al. 2014)

Fig. 2 The spectra of detrended AMV Indices in ten coupled general circulation models (CGCMs). The AR1 red noise fit is the mean of the AR1 red noise fits from ten models. Due to the varying autocorrelation for the models, the individual red-noise spectra are not shown.
The fact that the coupled and slab results are so similar is a surprise, and creates a puzzle: How can the Atmosphere + (constant depth) Ocean Mixed Layer generate the same AMO patterns as a model with fully active ocean dynamics?

- There is an ocean circulation and it surely transports heat and salt.
- In the current prevailing paradigm, the ocean circulation (usually the AMOC) is considered essential for Atlantic Multidecadal Variability.
Lead-Lag Correlations

Simple Noise Forced Model (NFM)

\[ a^2 = 1.0, \quad b^2 = 0, \quad a = 13 \text{W/m}^2/\text{K} \]

- \( r(T,T) \) unfiltered 20 yr LP
- \( r(dT/dt,T) \) dT/dt leads T leads
- \( r(dT/dt,Q_s) \) dT/dt leads Qs leads
- \( r(Q_s,T) \) Qs leads T leads

Slab Ocean Model (SOM)

(40-55N, 60-20W)

- \( r(T,T) \) unfiltered 20 yr LP
- \( r(dT/dt,T) \) dT/dt leads T leads
- \( r(dT/dt,Q_s) \) dT/dt leads Qs leads
- \( r(Q_s,T) \) Qs leads T leads
Zhang et al 2016:

**Low Pass Regressions on the (4 year lagged) AMO index**

- **d(SST)/dt**
- **$Q_s$**
  - Surface Heat Flux
- **Residual**
  - aka Ocean Heat Flux

**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) pre-industrial control fully coupled and slab-ocean models as listed in Table 1 in Clement et al. (1).

- (A,C,E) Multi-model ensemble mean of 10 fully coupled models (CGCM).
- (B,D,F) Multi-model ensemble mean of 10 slab-ocean models (SOM).

The GISS slab-ocean model has an unrealistic discontinuity of longwave surface fluxes at year 101, so only the first 100 years of GISS slab-ocean model are used.

- (A,B) Regression of LF SST tendency ($\partial \theta / \partial t$) ($C,D$) Regression of LF net surface heat flux ($F$), positive sign denotes downward heat flux into the ocean ($E,F$) Regression of LF diagnosed ocean heat transport convergence ($\bar{OHTC}$), $\bar{h}$ is 50m for slab-ocean models, and $\bar{h}$ 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 $\rho$ and $C_\beta$ are the...
In response to GCMs, we go very simple:

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$\mathcal{E}\{q_a, q_a\} = a^2, \mathcal{E}\{q_o, q_o\} = b^2, \quad a^2 + b^2 = 1$

$a^2$ is the fraction of forcing variance from the atmosphere

$b^2$ is the fraction of forcing variance from the ocean

We now take $q_a$ and $q_o$ to be **white noise** forcing.
North Atlantic control on surface turbulent heat flux (STHF) on multidecadal timescales

Gulev et al. (2013, Nature)

AMV vs. STHF correlations

AMO_{mid} index (40N-55N, 60W-20W)

Low frequency

High frequency

Based on VOS reports from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, version 2.5) for 1880-2007

CESM1

15-yr Low-pass Filtered

High-frequency (raw - low-freq)

Courtesy of Gokhan Danabasoglu