Review of some proposed mechanisms for decadal to multidecadal AMOC and Atlantic variability

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1. Motivation

2. Observational basis

3. Model based mechanisms of AMOC variability
   - Internal variability (grouping by timescale/physics)
   - Forced variations (SH winds, radiative forcing changes)

4. How can we advance our understanding?
Key motivating goals:

Need to:

(a) understand the mechanisms responsible for observed Atlantic variability over the last century

(b) “improve” predictions of the evolution of the Atlantic over the coming decades to century

- Radiative forcing changes associated with changing greenhouse gases, aerosols
- Internal variability of the coupled ocean-atmosphere-land system
Subtropical drying, including Southern Mexico, the Caribbean, the Mediterranean, and the Sahel region (see Solomon et al. 2007). This apparent difference between the model and observations may be explained by the stronger tropical warming in coupled models, particularly in the Pacific, as discussed above. As shown in previous studies (e.g., Yin 2005), one of the robust responses of the atmospheric circulation to greenhouse forcing is northward-shifted storm tracks, which enhance precipitation in the high latitudes and drying in the subtropics (see also Held and Soden 2006). Figure 7 suggests that this mechanism may not be as advanced in reality as predicted in the coupled models, perhaps because of the lesser warming of the Pacific Ocean in observations compared to the model simulations. Further analysis is needed to confirm such connections.

The internally generated, AMO-related patterns in temperature and precipitation are generally consistent with the findings of previous studies. The temperature pattern (Fig. 7b) is characterized by basinwide warming over the North Atlantic and its surrounding regions. For precipitation (Fig. 7d), the most dominant feature is the positive anomaly over the Sahel associated with the warming phase of the AMO (Knight et al. 2006; Zhang and Delworth 2006), opposite to that associated with the externally forced warming. This is not surprising considering that the Atlantic SST patterns associated with external forcing (Fig. 7a) and the AMO (Fig. 7b) imply different polarities of the Atlantic interhemispheric SST gradient in the warm phase of the AMO and during global warming. The interhemispheric gradient is a key factor in determining the seasonal position of the Atlantic intertropical convergence zone (ITCZ), which governs rainfall over tropical Africa. Thus, when a global warming trend occurs with a cooling trend of the AMO, one would expect the Sahel to experience extreme drying conditions, such as was the case in 1960–70. Other features of the AMO-related precipitation anomalies are less significant, indicating drying of parts of North and South America and Australia and an enhanced Indian monsoon and rainfall over northern Asia.

Another interesting finding in Fig. 7 is the opposite impact of a warm AMO and the externally forced warming trend on South Greenland temperature. Although the externally forced trend is negative along the South Greenland coast, the AMO warming trend there is positive. This is consistent with the simulation of models examined in this study (not shown). A recent study...
In this paradigm, late 20th century North Atlantic SST changes are driven almost exclusively by aerosol indirect effects.

**Critical question:**

*What are the roles of AMOC variability and external radiative forcing in generating the observed multidecadal SST variability in the instrumental record?*
There are only a few directly measured time series available to define the AMO (among them the central England temperature record, which dates back to the second half of the seventeenth century (Fig. 1a). The SSA spectrum (Ghil and Vautard 1991) of this time series (Fig. 1b) indicates that the 20–30-yr variability is caused by internal variability in the North Atlantic climate system. A time scale analysis of multidecadal variability in the North Atlantic climate model (CM2.1) to provide a more detailed picture of the Geophysical Fluid Dynamics Laboratory's Coupled Model (CM2.1) with a focus on the dominant Atlantic exchange processes.

Records from ice cores support the existence of 20-30 year variability

(a) Central England Temperature and Spectrum

(b) Multichannel Spectrum Analysis

Frankcombe and Dijkstra, 2010

Chylek et al., 2012
We therefore conjecture that a quasi-persistent ~55- to 70-year AMO, linked to internal ocean-atmosphere variability, existed during large parts of the Holocene. Our analyses further suggest that the coupling from the AMO to regional climate conditions was modulated by orbitally induced shifts in large-scale ocean-atmosphere circulation.
20-30 year timescale

One postulated mechanism for interdecadal AMOC variability:

Mode of variability characterized by westward propagating thermal anomalies at mid-latitudes.
• The overall timescale is set by the time it takes for a wave to cross the basin.
• The mode can exist without forcing in a highly idealized setting, but often requires stochastic atmospheric driving in a more realistic setting.

A subset of papers discussing this general topic include:

De Verdiere and Huck (1999)
Te Raa and Dijkstra (2002)
Buckley et al. (2012)
Sevellec and Fedorov (2012)

Some other possible mechanisms:
Dong and Sutton (2005)
Msadek and Frankignoul (2009)
Escodier and Mignot (2011)
Fig. 18. Schematic diagram of the oscillation mechanism: a warm anomaly in the north-central part of the basin causes a positive meridional perturbation temperature gradient, which induces a negative zonal overturning perturbation (a). The anomalous upwelling and downwelling associated with this zonal overturning are consistent with westward propagation of the warm anomaly, while a cold anomaly appears in the east (b). Due to the westward propagation of the warm anomaly, the east–west temperature difference decreases and becomes negative, inducing a negative meridional overturning perturbation. The resulting upwelling and downwelling perturbations along the northern and southern boundary reduce the north–south perturbation temperature difference, causing the zonal overturning perturbation to change sign and the second half of the oscillation starts.
Sevellec and Fedorov, 2012

Westward propagation

Spatial pattern of mode

Schematic of propagation

Figure 3: The spatial structure of the least-damped eigenmode of the tangent linear mode: anomalies of (top) upper-ocean temperature and surface currents and (bottom) meridional streamfunction and zonally-averaged temperature for phases A and B of the oscillation. During phase A (left) there exists a strong temperature anomaly in the northern Atlantic with a zero zonal mean, but the AMOC overturning anomaly is close to zero. During phase B (right) there develops a dipole-like temperature anomaly (with a zero zonal mean), associated with a strong AMOC anomaly. The two phases (A and B) are separated by a quarter-period or roughly 6 years. Temperature is given in terms of density. The upper-ocean temperature is averaged over the top 240 m. For the plot of streamfunction: plain, dashed and dotted lines indicate positive, negative and zero values, respectively; contour intervals are 1 Sv. Anomalous velocities reach 6 cm s$^{-1}$.

Note that all variables can be multiplied by an arbitrary factor since we consider a linear problem.

Figure 4: A Hovmöller diagram showing westward propagation of temperature anomalies in the least-damped eigenmode. Temperature has been averaged over the upper 240 m in the latitudinal band 34$^\circ$N to 62$^\circ$N. Contour intervals are 1$^\circ$C.

Figure 5: Schematic of westward propagation of temperature anomalies. Blue and red represent the mean temperature distribution (light colors) and the temperature anomalies in the upper ocean (heavier colors), respectively. (Top) The background meridional temperature gradient and the corresponding eastward geostrophic flow $\mathbf{u}$. (Middle) Phase A of the oscillation with a strong cold temperature anomaly but no change in the meridional overturning. (Bottom) Phase B of the oscillation with a dipole temperature anomaly and a strong anomaly in the overturning associated with the anomalous meridional geostrophic flow $\mathbf{v}'$. The cold temperature anomaly in the middle panel induces cyclonic circulation in the ocean that transports cold water southward along the western flank of the anomaly and warm water northward along the eastern flank. This water transport results in the westward propagation of the original temperature anomaly with the equivalent velocity $\hat{\mathbf{u}}$ (geostrophic self-advection). The net of two velocities ($\hat{\mathbf{u}} + \mathbf{u}$) is westward, as long as $|\hat{\mathbf{u}}| > |\mathbf{u}|$. The $\beta$-effect contributes to the westward propagation as well.
From coupled GCMs, mechanisms are postulated that involve advection or propagation of density anomalies that alter Lab Sea convection, the zonal density gradient and the AMOC.

- Anomalous anticyclonic circulation in midlatitude and cyclonic circulation in high latitude
- Enhanced surface heat flux from ocean to atmosphere

\[\text{(a) Anomalous anticyclonic circulation in midlatitude and cyclonic circulation in high latitude} \]
\[\text{and enhanced surface heat loss into the atmosphere} \]

\[\text{Anomalous cyclonic circulation over the GIN Sea (Preconditions for deep convection)} \]

\[\text{Enhanced subpolar gyre and NAC} \]

\[\text{Enhanced advection of warm and salty water into deep convection region} \]

\[\text{Positive density anomalies in deep convection region} \]

\[\text{MOC maximum} \]

\[\text{AMO-like SST pattern} \]
Escodier and Mignot suggest that active atmosphere-ocean feedbacks are critical to the variability seen in the IPSL model; SLP response that modulates EGC is important.

See also Timmermann et al., 1998 for coupled mode.
Interactions between the North Atlantic and Arctic have also been cited as an important component of AMOC multidecadal variability.

Examples include Delworth et al., 1997; Jungclaus et al., 2005; Frankcombe and Dijkstra, 2011

“The strength of the overturning circulation is related to the convective activity in the deep-water formation regions, most notably the Labrador Sea, and the time-varying control on the freshwater export from the Arctic to the convection sites modulates the overturning circulation. The variability is sustained by an interplay between the storage and release of freshwater from the central Arctic and circulation changes in the Nordic Seas that are caused by variations in the Atlantic heat and salt transport.”

“We conclude that the MOI variability arises from a damped mode of the ocean that is continuously excited by the atmosphere.”

Jungclaus et al., 2005

Figure 4. Illustration of the interaction of the two internal modes. The shorter period mode in the North Atlantic appears as a strengthening/weakening of the AMOC associated with the westward propagation of temperature anomalies near the surface. The longer period mode in the Arctic involves salinity anomalies propagating across the pole.
AMOC oscillation in HADCM3 driven by interaction between AMOC strength and latitudinal position and strength of ITCZ

Menary et al., 2011 suggest this mechanism also operating in Kiel and MPI models

Analyses from 1600 year control simulation of HADCM3: Color shading shows zonally averaged Atlantic salinity anomalies averaged over the top 800 m expressed as as potential density anomalies
For GFDL CM2.1 model, AMOC in North Atlantic has two distinct timescales of variability, but only one timescale in South Atlantic.

In Kiel Climate Model, separate peaks at multidecadal and multi-centennial timescales.

Delworth and Zeng, 2012
Atlantic Meridional Overturning Circulation (AMOC). The interhemispheric ocean heat transport associated with the ability appears to be driven by multi-centennial variations in variability with a timescale of 200 years. This variability is linked to the Northern Hemisphere Extratropical Surface Air Temperature (NHESAT). We have analyzed the output of a 4000-year control simulation of the GFDL CM2.1 model and have shown the existence of a distinct multi-centennial pattern of Northern Hemisphere climate variability.

Summary and Discussion

We have presented evidence that the multi-centennial AMOC variations are driven by salinity anomalies. When positive salinity anomalies reach the subpolar North Atlantic, they increase near-surface density and strengthen the northern boundary current. This leads to a northward propagation of a salinity signal. When this signal reaches the high latitudes of the North Atlantic, it eventually leads to increased salinity in the Southern Ocean, which is transported back to the North Atlantic, eventually leading to enhanced surface salinity at high latitudes. This process involves the propagation of salinity anomalies through the ocean, with a timescale of approximately 0.1 degrees per decade.

The propagation of salinity anomalies through the ocean is associated with coherent hemispheric-scale climate variations. This is illustrated in Figure 5, which shows the zonal integral of the regression coefficients of the AMOC time series against surface salinity at 2500 m depth. The y-axis is latitude, and the x-axis is lag with respect to the time of maximum AMOC. Negative (positive) values on the time axis indicate periods before (after) a maximum AMOC (occurring at lag 0). The propagation time of the salinity anomalies reaches the high latitudes of the North Atlantic, where it is linked to the AMOC. It is important to stress that such a pattern of internal climate variability could have contributed to past climate variations. For example, this simulated multi-centennial variability in the AMOC has potentially significant implications for understanding future climate change.

Mechanism of multi-centennial AMOC variability in GFDL CM2.1 is associated with propagation of salinity signal between high latitudes of the North Atlantic and the Southern Ocean.
AMOC variability in CCSM3 and CCSM4
(Danabasoglu et al, 2012; Kwon and Frankignoul, 2012)

Similarities:
• Spatial pattern
• Relationship to Lab Sea density

Differences
• Timescales (20 years; 50-200 years; red noise)
• Role of overflow parameterization
• Amplitude of AMOC variability

“Such dependence of AMOC variability on these parameterizations has important implications for both AMOC variability characteristics and search for a robust mechanism as they may depend on parameter choices and implementation details of these schemes in various ocean general circulation models.”
Danabasoglu et al., 2012

Fig. 13. Schematic of the sequence of some anomalies with respect to an AMOC maximum event at lag 0. The superscripts + and − refer to approximate peaks of positive and negative anomalies, respectively. AMOC leads for positive lags.
Perspectives ...

(1) “Jungclaus et al (2006) analyze a 500-yr control integration with the ECHAM5-Max Planck Institute Ocean Model (MPI-OM) and find pronounced multidecadal fluctuations in the Atlantic MOC and associated heat transport with a period of 70-80 yr. From a different simulation with the same model (Sterl et al. 2008) it appears that the dominant variability in the AMO Index is in the 20-40 yr band. Variability on the longer time scale (50-80 yr) also exists but is not significant at the 95% level (van Oldenborgh et al 2009).”

- State dependence of variability, and presumably of mechanisms; see also Kwon and Frankignoul, 2012.

(2) Look to analogy with ENSO ...

- far better observed phenomenon
- 30+ years of work on theory and modeling

... and yet while state of the art GCMs generally have some sort of ENSO, they vary greatly in time scale, spatial structure and details of mechanisms.

... further, there can be substantial centennial-scale modulation of simulated ENSO, similar to what we see with AMOC variability (Wittenberg, 2009)

→ With AMOC variability the observational basis is much smaller, and the challenges are formidable.
Enhanced Southern Hemisphere winds can lead to strengthened AMOC – but there may be a dependence of this effect on eddy representation in models.

AMOC changes at 20N in response to artificially strengthening or weakening SH westerly winds.

Strengthened AMOC 70 years after strengthened Southern Annular Mode (SAM)

Marini et al., 2011
Altered Southern Hemisphere winds can influence salt and heat transport into the South Atlantic via Aghulas

Lee et al., 2011

... but presentation from Yeager showed little impact of SAM forcing
External factors: Response of AMOC to changing aerosols

Increased volcanic activity “spins up” the AMOC

For both cases, aerosols weaken upper ocean stratification at high latitudes (colder, saltier in upper ocean) through impacts on surface heat and water fluxes; this leads to stronger AMOC.

Anthropogenic aerosols have similar impact

Stenchikov et al., 2008

Delworth and Dixon, 2006
Increased volcanic activity “spins up” the AMOC

Mignot et al., 2011, further explore these issues with a simulation of the last millennium.

“This study thus stresses the diversity of AMOC responses to volcanic eruptions in climate models and tentatively points to an important role of the seasonality of the eruptions.”

See also Zhong et al., 2010.

Aerosols can also come from natural sources – potential interaction of Saharan dust and Atlantic temperatures on multidecadal scales

Evan et al., 2008; 2011; Wang et al., 2012;

**SOLAR**

*AMOC variability can also be induced by solar variations (Park and Latif, 2011).*

Stenchikov et al., 2008
1. Evidence for multiple time scales in the Atlantic, possibly related to AMOC (20-30 yr, 50-100 yr, multicentennial)

2. Key goal is to assess what role AMOC plays in generating the observed SST variations

3. Evidence that different timescales may be associated with different sets of physical processes
   
   A. No distinct timescale (e.g., last 250 years of CCSM3)
   
   B. Distinctive timescale
      
      a. internal damped ocean mode within North Atlantic (20-30 yrs, sometimes much longer); different types of propagating or advecting signals
      b. coupled air-sea mode within North Atlantic (20-30 yrs, or much longer)
      c. interaction with Arctic (40-80 yrs)
      d. coupled air-sea mode with connections to Tropics (~100 yrs)
      f. Driven from Southern Hemisphere/Aghulas (multidecadal)
      e. Pan-Atlantic mode with connections to Southern Ocean (multicentennial)

4. External radiative driving may also play a role (aerosols, solar, ozone through SH winds)
How can we make progress?

We have different proposed mechanisms – which (if any) occur in Nature?

Some possible pathways to improve understanding:

1. Continued hierarchy of models is crucial.

2. Confronting models with available observations is paramount (both instrumental and paleo data).

3. Improve models so that dependence on uncertain parameterizations is reduced. High resolution is one key component in a hierarchy of models - ocean eddy resolving coupled models are now at hand. Nature of air-sea coupling may be different at very high resolution. Will there be some convergence of mechanisms as models improve?

4. Similar mechanisms in multiple models might imply robustness – but care must be taken due to underlying similarities in model formulations.

5. Can we use the proposed mechanism(s) to predict some previously unknown relationship that can be examined in other models, as well as in instrumental or paleo observations?

6. Analyses can form hypotheses, and then suggest additional model experimentation to test hypotheses. Multi-model testing of such hypotheses is preferable.
GFDL CM 2.6 Ocean Simulation
Sea Surface Salinity
January 15
Practical Salinity Units
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