Multidecadal Oscillation of the Atlantic Meridional Overturning Circulation in CMIP5 Models

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1. Research Goal

The low frequency variation of the Atlantic meridional overturning circulation (AMOC) is a major component of the natural climate variability in the North Atlantic from decadal to centennial time scales. However, the physical mechanisms of the AMOC variability have yet to be understood. Current state-of-the-art climate simulations show that the AMOC can oscillate on a wide range of frequencies and amplitudes in different models. It is important to identify the oscillation mechanisms and the causes of model dependency. In this study, we systematically examine the physical processes associated with the AMOC oscillations in several preindustrial simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5).

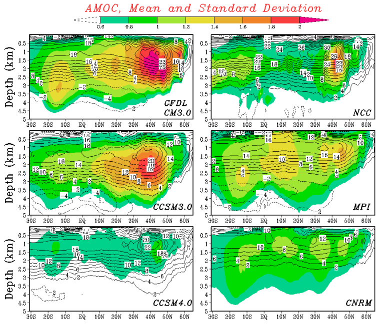
2. Data and Method

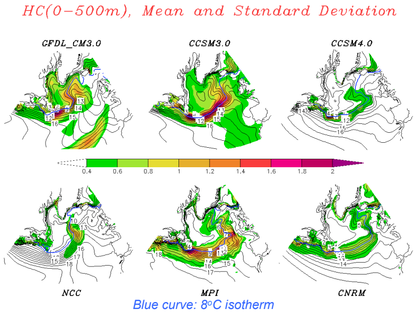
The annual mean ocean-atmosphere fields from five CMIP5 preindustrial simulations are analyzed, including the Geophysical Fluid Dynamics Laboratory climate model, version 3.0 (GFDL CM3.0), Community Climate System Model, version 4.0 (CCSM4.0), the Max-Planck-Institut für Meterologie earth system model, medium resolution (MPI), the Norwegian Climate Centre's earth system model (NCC) and Centre National de Recherches Météorologiques / Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique climate model, version 5 (CNRM). The CMIP3 simulation from CCSM3.0 is also analyzed. The lengths of the simulations range from 500 to 1000 years.

The multichannel singular spectrum analysis (MSSA) is used to identify the leading modes of the AMOC oscillation with characteristic time scale and temporal-spatial structure in each of these climate models.

A phase composite procedure based on the time series of an identified oscillatory mode is used to reconstruct its composite lifecycle and examine the evolution of various variables throughout this lifecycle.

3. Climatology



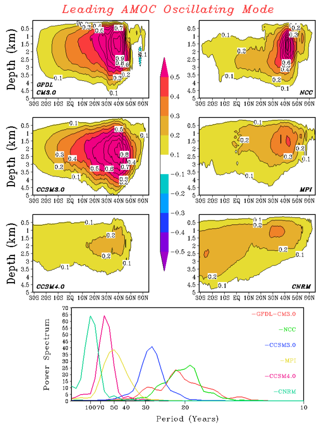


Blue curve: 8°C isotherm

Mean: Contour; Standard deviation: Shading

1) Mean AMOC stream functions show different strengths among models, ranging from 14 to 30 Sv.
2) In most models, maximum AMOC standard deviations appear near the turning point from downwelling to lower AMOC branches (1500-2000m and 40°N-50°N). The intensity of fluctuation is not directly linked to the mean AMOC strength.
3) According to the upper ocean heat content (HC, averaged temperature in upper 500m), the subpolar gyre strengths vary in different models, as measured by the HC gradient intensity associated with the Gulf Stream extension and the North Atlantic Current (NAC), as well as the area encompassed by the 8°C isotherm.
4) Major HC variations (high standard deviation) appear en route the Gulf Stream extension and the NAC, which are characterized by the 8°C isotherm.

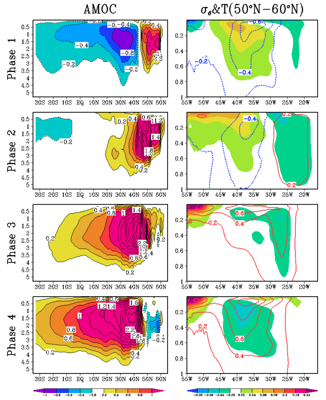
4. MSSA Modes



1) A leading oscillating mode of the AMOC stream function is identified by MSSA analysis for each of the simulations. These modes account for 23% of the domain total variance for GFDL-CM3.0, 19% for CCSM3.0, 12% for NCC, 11% for CNRM, 7% for CCSM4.0, 5% for MPI.
2) The main spatial patterns of these modes (left panels), as derived from the 1st EOFs of the MSSA modes, are dominated by an anomalous deep overturning center around 40°N, reaching a few kilometers with its core located at 1000 to 2000m.
3) The oscillations, though intermittent (not shown), are of characteristic time scales. Based on the power spectrum of the MSSA PC1 (lower left panel), the periods are model-dependent, ranging from 20 to 100 years.
4) Models with intensive subpolar gyres confined in a smaller domain tend to generate stronger oscillations with higher frequencies.

5. Composite AMOC Lifecycle, GFDL-CM3

Buoyancy Driving of AMOC



T: contour
σ_θ: shading

Composite Construction

A composite lifecycle is constructed from an oscillation phase index defined by MSSA PC1, varying cyclically from 0 to 2π. The full cycle includes eight phases, each π/4 long.

Half Cycle for GFDL-CM3

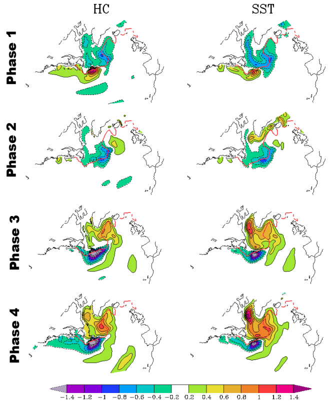
Phase 1: Cold HC/SST anomalies (HCA/SSTA) occupy most of the subpolar gyre. Positive North Atlantic Oscillation (NAO) is developing. AMOC is weak in mid-latitudes. A positive AMOC anomaly develops between 50°-60°N, driven by the positive local subsurface density anomalies between 200-600m.

Phase 2: Center of positive AMOC anomaly migrates to 40°N and intensifies, associated with strong NAO. Cold HCA/SSTA migrates to mid-latitudes, replacing local warm remnants there. Warm HCA/SSTA is initiated in the north.

Phase 3: Positive AMOC matures. Warm (cold) HCA/SSTA is enhanced along the track of NAC (Gulf Stream extension). Sea level pressure (SLP) is reduced over warm SSTA. Surface heat flux (evaporation) damps SSTA but enhances surface salinity anomaly.

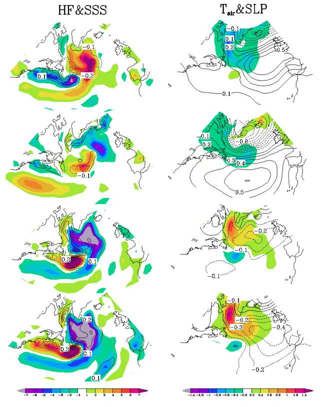
Phase 4: Warm HCA/SSTA peaks and circulates through subpolar gyre. Negative subsurface density anomalies below 200m initiate negative AMOC anomaly between 50°-60°N. Negative NAO phase starts to develop.

Subsurface Influence



Red curve: 8°C HC isotherm

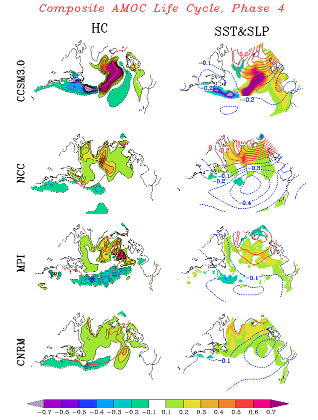
Ocean-Atmosphere Feedback



SSS: contour
HF: shading

SLP: contour
T_{air}: shading

6. Other Model Composites



Red curve: 8°C HC isotherm

SLP: contour
SST: shading

Following a strong AMOC, there are warm HC and SST anomalies, as well as a weak NAO, in northern North Atlantic.

7. Summary

Multidecadal AMOC oscillations appear in CMIP5 climate models, centered at 40°-50°N, with different amplitudes and frequencies in different models.

The frequency and strength seem to be dependent upon the extent of subpolar gyre (area surrounded by the 8°C HC isotherm), as well as the strength of the Gulf Stream extension and NAC.

The transition of phases is driven by subsurface density anomalies in northern North Atlantic, induced by temperature anomalies.

A strong AMOC generates strong warm HCA near the NAC. The advection transports these warm HCA throughout the subpolar gyre.

HCA forces SSTA. Warm SSTA in northern North Atlantic weakens NAO, which feedbacks to ocean.

Surface evaporation damps SSTA but enhances sea surface salinity, offsetting or overwriting the temperature influence on surface density.