Diagnosing and Understanding the AMOC Biases in NorESM

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NorESM

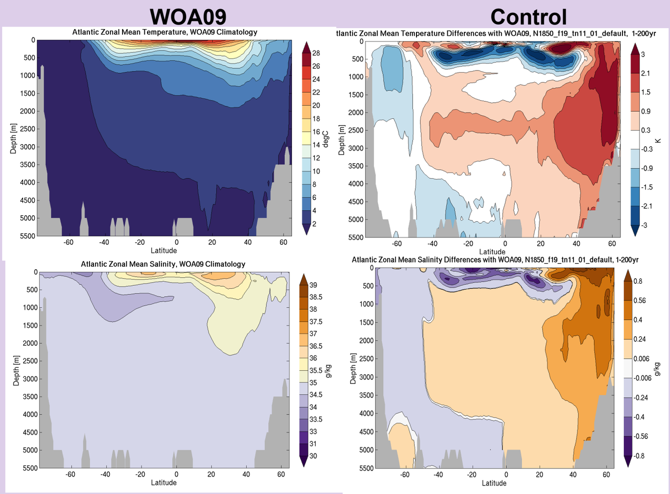
The Norwegian Earth System Model (NorESM) version 1 is based on the Community Earth System Model version 1.0 (CESM1.0) featuring atmospheric chemistry by Oslo University, Norway and Miami Isopycnic Coordinate Ocean Model (MICOM) by Uni Research Ltd., Bergen, Norway (Bentsen et al., 2013). Some of the sub-grid scales parameterizations in the ocean model are : the isopycnal thickness eddy diffusivity by Eden & Greatbatch (2008) and Mixed Layer Eddy (MLE) parameterization by Fox-Kemper et al., 2008.

Grid: CAM and CLM are on regular longitude-latitude grid with ~1.9°x2° horizontal resolution and 26 vertical levels in the atmosphere. MICOM and CICE are on tripole grid ~1° horizontal resolution and 53 isopycnal levels in the ocean.

Integration period: Each of the experiments below have bee integrated for 200 years.

Termohaline Stratification

WOA09 **Control**



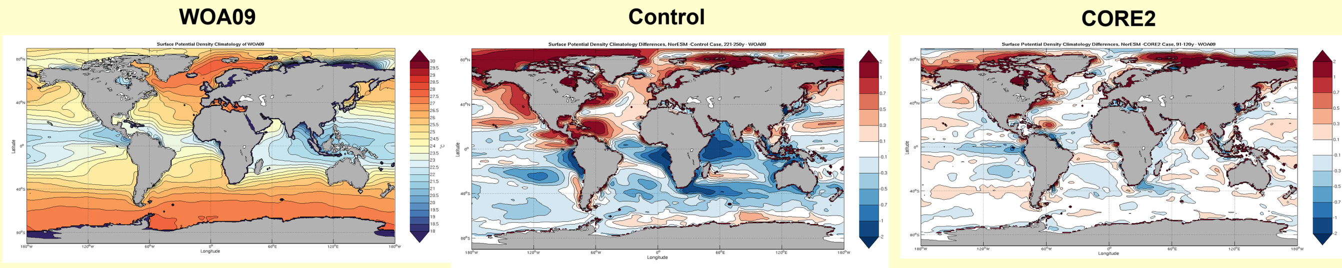
To the left are compared the Atlantic zonal mean vertical sections of temperature and salinity of the CMIP5 set-up of NorESM (Control Exp.) and World Ocean Atlas, 2009 (WOA09) climatologies. Some of the major biases in the model are the cool and fresh bias in the upper thermocline (500m), warm and salty bias at the surface, and in the intermediate layers 1500-3000m in North Atlantic, and cold and fresh bias in Southern Ocean. Range of the biases are for Temp. -0.3 – 0.3 °C and for Sal. -0.8 – 0.8 g/kg.

Water Mass Formation

To understand further the origins of the model biases in the thermohaline structure and their relation to the vigorous AMOC, we analyzed the processes of water mass formation as diagnosed from the surface buoyancy forcing and evaluated them against observational estimates. Below are shown comparison of the surface potential density in the Control run and WOA09 observations and surface heat and fresh water fluxes to the NOC1.1a (UK National Oceanographic Center) observational data. Besides to the observed estimates we compared the results from the fully-coupled "Control" run to "CORE2" forced ocean simulation, where surface salinity restoring has been applied.

Potential Density

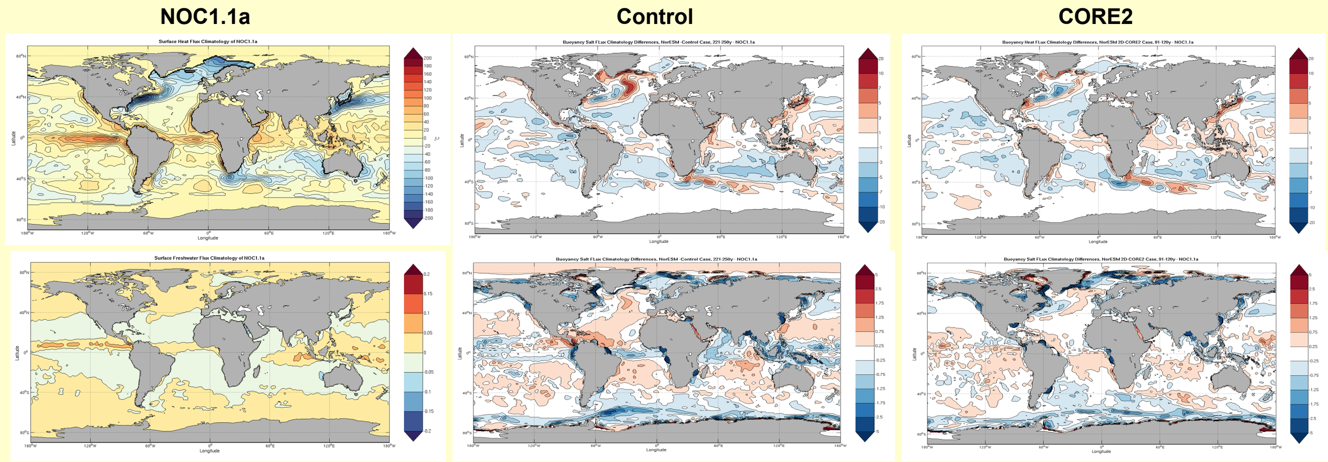
WOA09 **Control** **CORE2**



The model (Control) differences with the observations (WOA09) reveal a dipole PD anomaly bias in the Tropics which might be responsible for creating a pressure gradient and consequently intensification of the MOC. In CORE2 Experiment the bias is controlled.

Surface Heat and Fresh Water Fluxes

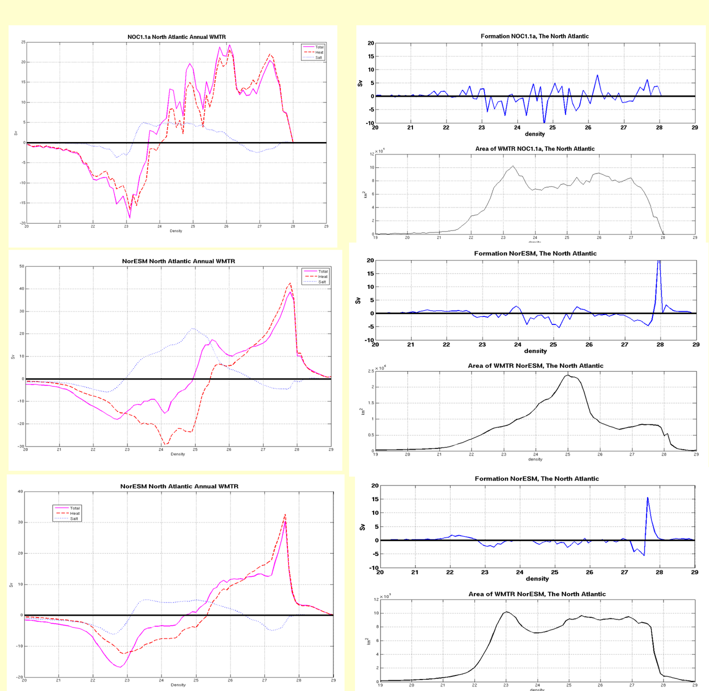
NOC1.1a **Control** **CORE2**



Above are shown the models (Control and CORE2) differences with NOC1.1a observational product of Surface Heat Flux (SHF) and Surface Fresh Water Flux (SFWF). Generally the biases in the SHF remain the same in the two simulations with exception of the NW corner in NA. There is an overall improvement in the SFWF in CORE2, particularly in the equatorial, tropical and sub-tropical areas.

Water Mass Transformation Rates

To the right are shown water mass transformation rates (WMTR) as defined by Speer&Tziperman, 1992. They indicate the amount of water formed in a certain density range at the surface due to the surface buoyancy forcing. There are two major water types in North Atlantic – Sub-tropical Mode Water (STMW, σ_θ=26) and Sub-polar Mode Water (SPMW, σ_θ=26.9-27.75) well defined in the observed (NOC1.1a) estimates. In the model (Control) there is a tendency of excessive production of SPMW and the STMW is formed in a rather lighter density classes and smaller rates. The salinity restoring in the forced simulation (CORE2) seems to fix the mismatch in the STMW density, but still the simulation has a tendency to overestimate SPMW formation.

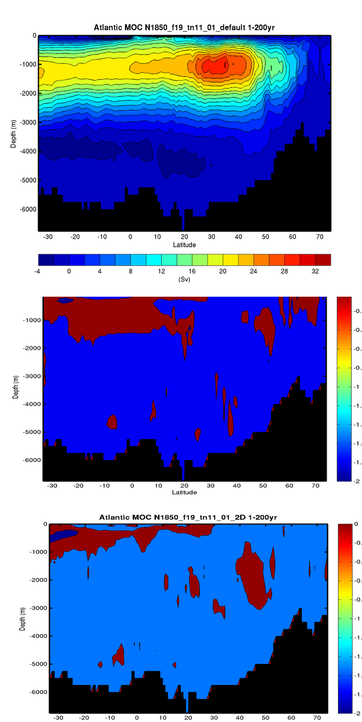


SUMMARY

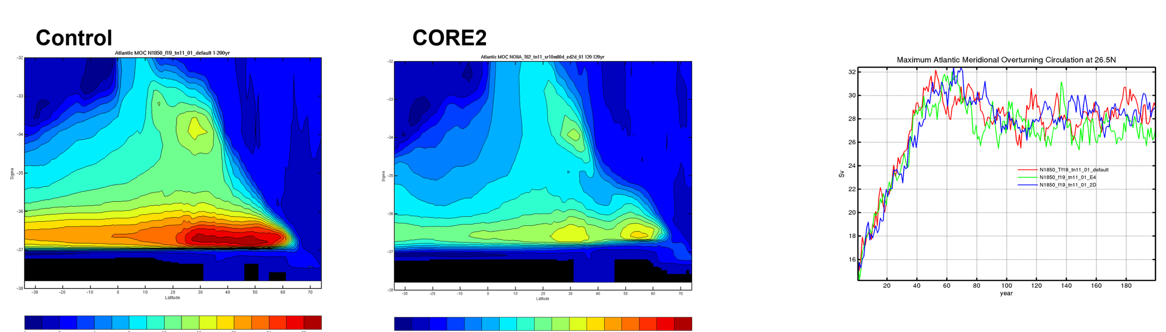
We investigate the Atlantic Meridional Overturning Circulation (AMOC) in the Norwegian Earth System Model (NorESM) featuring isopycnal ocean component (MICOM). The Coupled Model Intercomparison Phase 5 (CMIP5) NorESM historical simulations showed a decline of the AMOC after 1980 concurring with the recent observations from RAPID-MOCHA program. The NorESM future projections predict reduction of the AMOC with 12 to 30% under different warming (RCP2.6-RCP8.5) scenarios. In the CMIP5 model intercomparison project, the NorESM ocean component demonstrated an intense AMOC and took place in the upper end of the AMOC magnitudes model range. The NorESM AMOC strength was found to be sensitive to oceanic grid resolution and whether coupled or uncoupled configuration is used. However, the AMOC tends to be on the strong side in all configurations. In order to find the causes of this vigorous AMOC we carried out a careful diagnostics of the AMOC and explored possible relationship to the model biases found in the Atlantic thermohaline structure, and water mass formation. Several processes has been investigated to understand further their connection and significance to the AMOC strength and variability: 1) The North Atlantic Mode Waters Formation (STMW and SPMW); 2) The Labrador Sea Water Mass formation and variability. Furthermore, the AMOC sensitivity to sub-grid scale physical parameterizations such as isopycnal eddy mixing and the impact of model resolution on the representation of overflows is examined.

AMOC

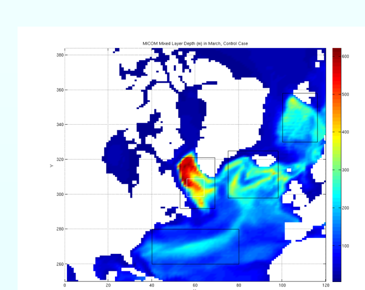
NorESM1 has been found to be on the strong side of AMOC magnitudes among the CMIP5 models with maximum AMOC ~28-30Sv. In a forced simulation of NorESM within the CORE2 protocol experiment the strength of the AMOC was possible to restrain to the observed ~18Sv values via sea surface salinity restoring (see below). In the present study, we explore the sensitivity of the AMOC to the 3-D isopycnal mixing parameterization in the NorESM ocean model based on *Eden and Greatbatch* (2008). By varying the parameters (i.e. maximum diffusivity, ratio of the isopycnal diffusivity to the layer thickness diffusivity) we succeeded to reduce the temperature and salinity biases locally and the AMOC magnitude by 2Sv (Exp. E4, see to the right). The largest improvement in the thermohaline structure biases were achieved by implementing a 2-D version of the parameterization that reduced the biases in the entire water column.



Control **CORE2**

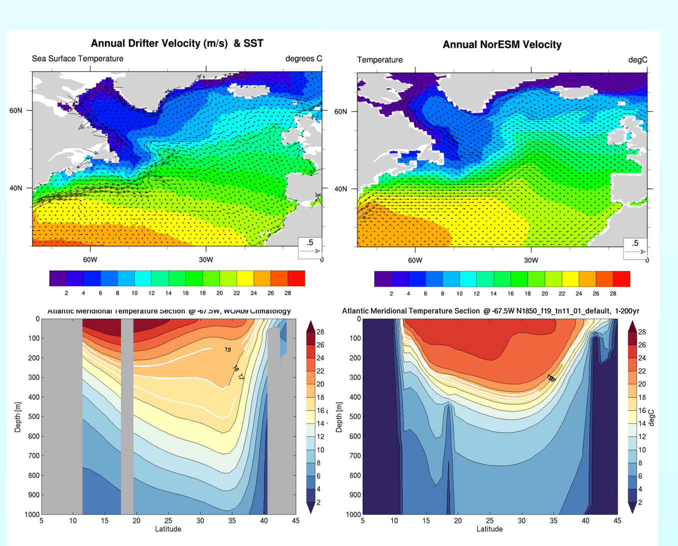


Mode Waters



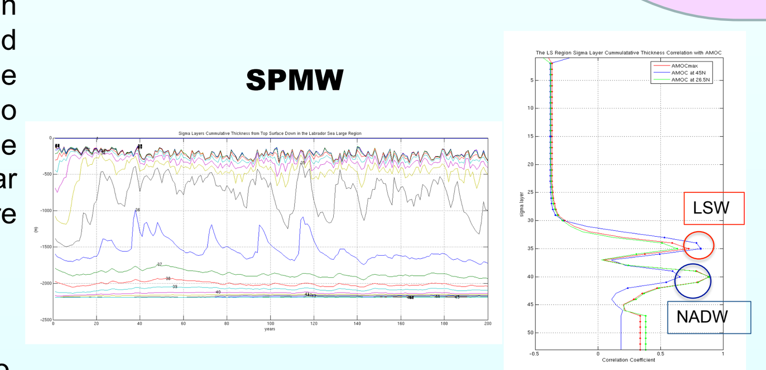
Mode waters are near surface thick layers with homogenous physical properties usually formed during the winter convection (therefore can be located in areas with deep mixed layers) and submerging during the summer season. There are two main mode waters in North Atlantic: the Sub-tropical Mode Water (STMW), also known as 18deg water, forming south of the Gulf Stream in the north-western corner of the sub-tropical gyre, and the Sub-polar Mode Water (SPMW) forming along the periphery of Sub-polar gyre and northern part of the sub-tropical gyre (Hanawa & Talley, 2001).

STMW



The model WMTR have shown that there is no clear formation of STMW at σ_θ=26 which is also supported by the lack of 18°C water layer in the meridional temperature section shown here to the left (compare to WOA09 observations). Instead a significant tick layer of 22°C is formed. One possible reason for this discrepancy in the model can be the misplaced location of the Gulf Stream which in such low resolution models is usually too far offshore and very zonal (see the velocity plots to the left). Another possible candidate is the MLE parameterization in the model which may need further tuning to regulate appropriately the mixing in the surface layers.

SPMW



The time series above of the cumulative (from top to bottom) isopycnic thickness averaged over the Labrador Sea Region (The black box in the Labrador Sea in the MLD plot) reveals that the σ_2~36 which corresponds to the LSW characteristics is the thickest layer. Layers 40-42 (σ_2=36) which most probably represent the NADW originating from the Denmark Overflow also are significantly thicker. The correlation between the time series of the layer thickness with the AMOC at 45°N is significant (>0.8) with LSW layer leading with 2years. This points to the excessive production of LSW (SPMD) as possible explanation for the intense AMOC in the model.

Sensitivity to Isopycnal Mixing

NorESM Isopycnal Mixing parameterization is based on Eden and Greatbach (EG2008) isopycnal thickness diffusivity dependent on the eddy length and time scales:

$$K = cL^2\sigma$$

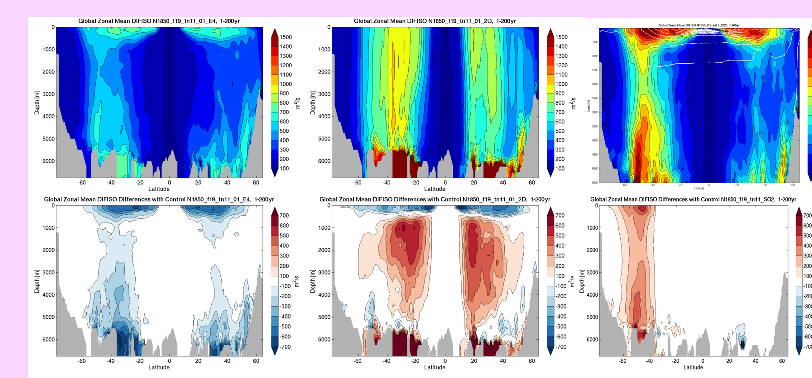
Where **c** – tuning parameter; L – eddy length scale min(L_{Rossby}, L_{Rhines}); σ - inverse time scale.

We conducted suite of experiments to test the sensitivity of the NorESM solution to isopycnal mixing. In 6 of them E1-E5, E12 we varied parameters in the EG2008 isopycnal mixing parameterization, and in 2D we have implemented 2D isopycnal mixing scheme. In the table below: EGC – tuning parameter c; EGMXDF – maximum diffusivity; EGIDFQ – factor relating the isopycnal diffusivity to layer interface diffusivity. We also carried out an experiment where we increased the isopycnal mixing with 1.5 of the original magnitude in the Southern Ocean.

Table 1. Description of the Numerical Experiments

Exp/Param	EGC	EGMXDF	EGIDFQ
Control	1	1.50E+07	1
EXP E1	0.5	1.50E+07	1
EXP E2	0.75	1.50E+07	1
EXP E3	1	1.00E+07	1
EXP E4	1	7.50E+06	1
EXP E5	1	1.50E+07	0.5
EXP E12	0.75	1.00E+07	0.5
EXP 2D	2D parameterization implemented		
Exp SO2	1.5 Increased magnitude of isopycnal diffusivity south of 45S		
Exp CORE2	CORE2 protocol atmospheric forcing		

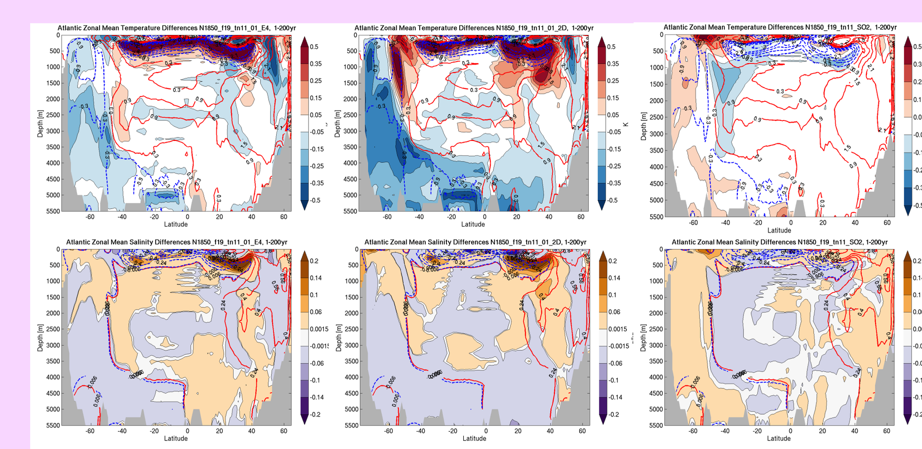
Global Ocean Zonal Mean Vertical Distribution of the Isopycnal Diffusivity Experiments E4, 2D, SO2 (top) and their Differences with Control (bottom)



The ED2008 isopycnal thickness diffusivities. Generally they are large near the surface, the most within the western boundary currents and north flank of ACC and decay with depth. In our experiments E1-E12 we have aimed to decrease the original (Control) set-up of isopycnal mixing in order to reduce the biases in the thermohaline structure.

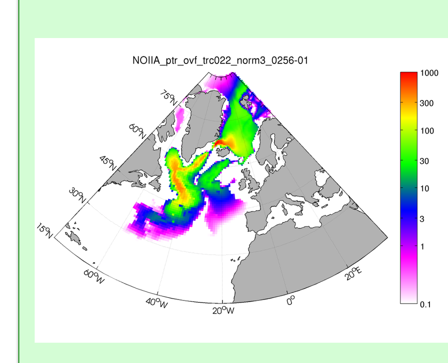
The most improvement we achieved in E4, where we decreased the maximum diffusivity (see the table). Applying 2D parameterization homogenized vertically the isopycnal mixing reducing it in the near-surface layers and increasing it in the intermediate and lower layers, and improved biases in the entire water column. In all of the experiments though the SO cold and fresh bias was increased indicating that we need rather increased mixing there. This was proven in Exp. SO2 where we applied increased by 1.5 magnitude mixing south of 45S which reduced the cold SO bias (see below).

Atlantic Zonalmean Temperature (top) and Salinity (bottom) Differences with the Control Run (color). The contours on top are the Differences of the Control with WOA09 observations.



Overflow Waters

In this CORE2 forced experiment we investigate the representation of the overflow in the 1° NorESM CMIP5 setup by releasing passive tracers. The figure shows the inventory of passive tracer (thickness integration of tracer concentrations below layer 34) after 15 years of its release.



From the figure we can diagnose the pathways of Denmark Strait Overflow Water (DSOW) and Iceland-Scotland Overflow Water (ISOW). The ISOW propagates all the way south to the western European Basin instead of turning westwards across Reykjanes Ridge and at the Charlie Gibbs Fracture Zone (Saunders 1994; Xu et al. 2010). This is because the coarse resolution fails to reproduce inclined isopycnals in the Iceland Basin, hence there is a lack of overflow water on the slope that is important for its cross-ridge transport. This issue, together with the underestimation of DSOW (only a third of the observed), causes lack of overflow waters in the western North Atlantic in this coarse resolution version of the model.