A robust statistical link between Atlantic Multidecadal SST variability and the Meridional Overturning circulation in the MPI Grand Ensemble

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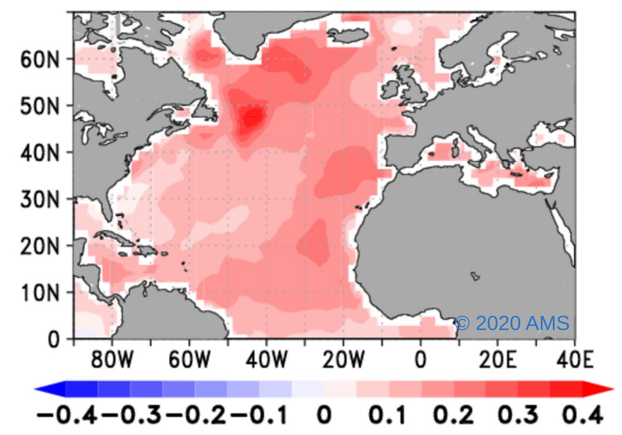
1. Motivation & Introduction

- There is an ongoing debate whether the Atlantic multi-decadal variability (AMV) is influenced by ocean dynamics:
- Recent publications (e.g. Clement et al. (2015), Cane et al. (2017)) argue that AMV-like ocean variability might only be a result of integrating white noise in the ocean-atmosphere system by the ocean.

- Others (e.g. O'Reilly et al., 2016) point out that the sign of the ocean-atmosphere heat-flux in observations and coupled models, indicate that the AMV is controlled by changes in the ocean heat transport convergence.

AMV pattern observed



➜ **Figure 1:** Observed AMV pattern. Regression of SST (in K, shaded on the standardized AMO index (85°W to 0°, 0° to 60°N).

Key questions:

- What drives the AMV in the coupled ocean-atmosphere system?
- Is there a connection between AMV and ocean variability in MPI-ESM?
- Does the connection between AMV other climate indices change under (strong) external greenhouse gas forcing?

2. Model & Experiments

MPI-ESM-LR earth system model

- Atmosphere: ECHAM6 T63L47
- Ocean: MPIOM GR15L40

MPI Grand Ensemble

100 x 155 years historical

- Transient historical greenhouse gas and aerosol forcing.

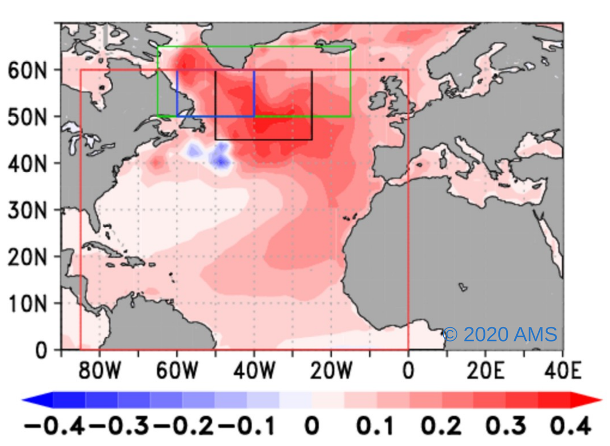
100 x 150 years +1% CO_2/year

- CO2 gradually increasing by 1%/year set to (constant) pre-industrial values.

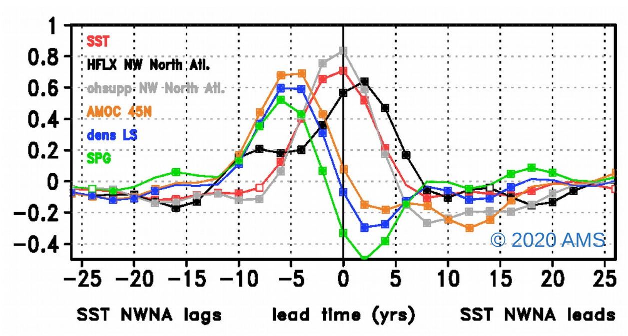
3. Results (1): A robust correlation between the AMV, AMOC and ocean heat supply

historical

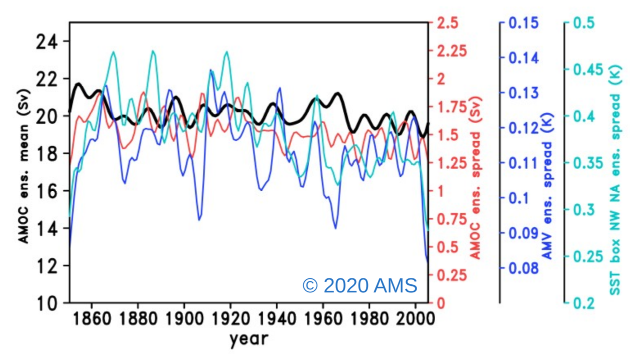
(a) AMV pattern



(c) lag cross-correlation

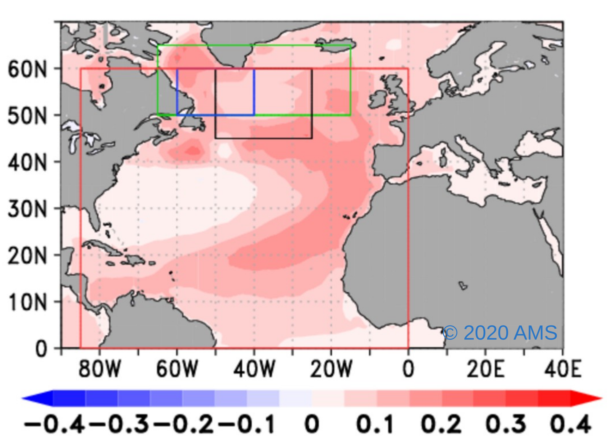


(e) Ens. mean & spread

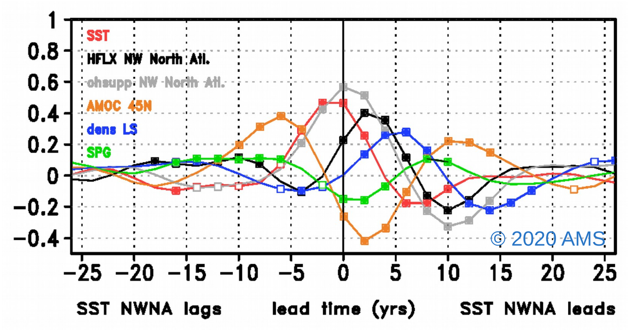


+1% CO_2/year

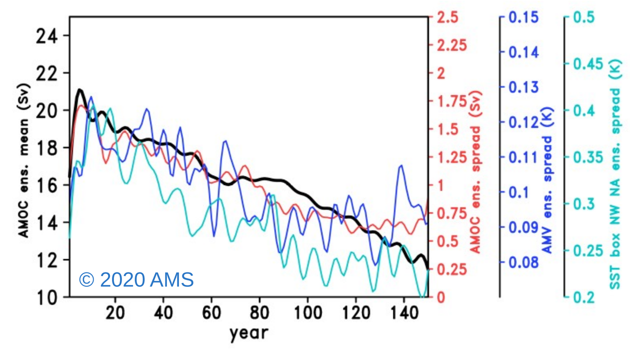
(b) AMV pattern



(d) lag cross-correlation



(f) Ens. mean & spread



← **Figure 2:**
Left: Spatial structure of the AMV in **(a)** the historical ensemble and **(b)** the ensemble with an incrental CO2 increase by +1%/year. Regression of the SST on the normalized field average (85°W-0°, 0°-60°N) of SST (in K/standard deviation). For detrending, the ensemble mean was removed and a 10-year lowpass-filter was applied. The rectangular boxes indicate the regions for computing the spatially averaged climate indices used in the following figures.
Middle: Lag-correlation of the SST in the Northwest North Atlantic with the AMV index (red) and different ocean indices for **(c)** the historical ensemble and **(d)** the last 50 years of the ensemble with an incremental CO 2 increase by +1%/year. Colors indicate correlation with the ocean-atmosphere turbulent heat flux in the Northwest North Atlantic region (black, positive upwards), the ocean heat supply as the residual between the ocean heat content change integrated over the Northwest North Atlantic region minus the turbulent flux to the atmosphere over the same region (grey), the AMOC (as the overturning streamfunction at 1000 m depth) at 45°N (orange), the potential density (w.r.t. 2000m) averaged for the deep ocean in the Labrador Sea convection region (60-40°W, 50-60°N, 1500-3000m depth) … (continued in the next column)

Figure 2 (continued):
...and the Subpolar Gyre strength (green) as the fieldmean of the barotropic streamfunction in the SPG region (multiplied by -1 to get positive values for a stronger SPG in the historical ensemble. Non-filled (filled) markers indicate significance at the 98% (99%) confidence level. The date were detrended by removing the ensemble mean of each quantity and 10-year low-pass-filtered
Right: AMOC at 45°N mean (black) and ensemble spread (red) and ensemble spread of the AMV (blue) and the Northwest North Atlantic SST (cyan) in **(e)** the historical ensemble and **(f)** the last 50 years of the ensemble with an incremental CO 2 increase by +1%/year. Timeseries are undetrended and 10-year lowpass-filtered.

- The simulated AMV pattern shows strong similarity to the observed AMV pattern for the historical period.
- The pattern shows crucial changes under strong CO2 forcing, particularly in the North West North Atlantic.

- There is a high correlation with several ocean indices in the historical ensemble.
- All correlations decline drastically under strong CO_2 forcing.
- Not shown: the correlation with ocean heat supply also holds for (unfiltered) annual data.

- There is neither an obvious trend in the AMOC and its internal variability in the historical period, nor in the internal variability of the SST indices.
- The ensemble mean AMOC and the ensemble spread of the AMOC decline under strong CO2 forcing. The same accounts for the ensemble spread of the AMV and the North West Atlantic SST.

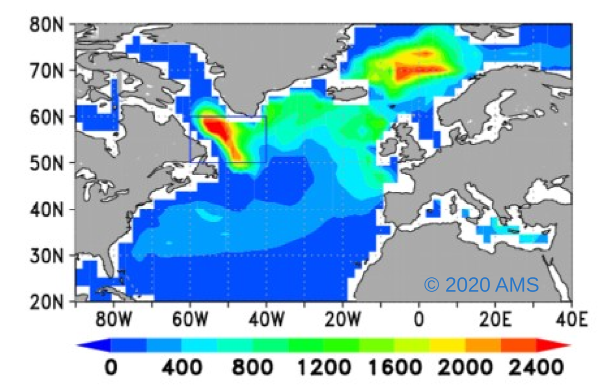
Take Home Message (1)

- **The AMV pattern shows remarkable changes under strong CO2 forcing.**
- **There are strong correlations between North West north Atlantic SSTs and ocean indices in the historical ensemble.**
- **These correlations decline drastically under strong CO_2 forcing.**

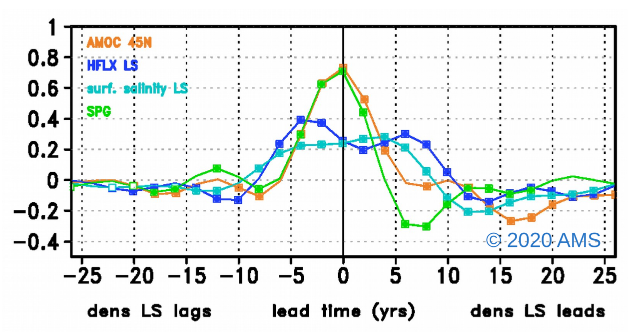
4. Results (2): Decline in variability is linked to Labrador Sea deep ocean density

historical

(a) Mean MLD

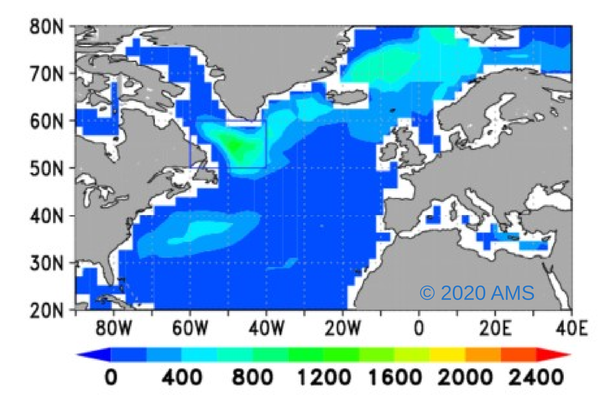


(c) lag cross-correlations

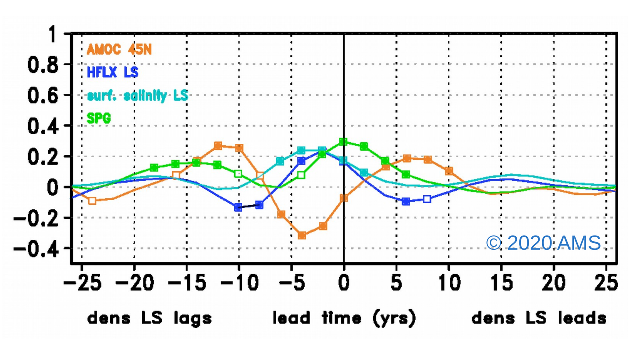


+1% CO_2/year

(b) Mean MLD



(d) lag cross-correlations

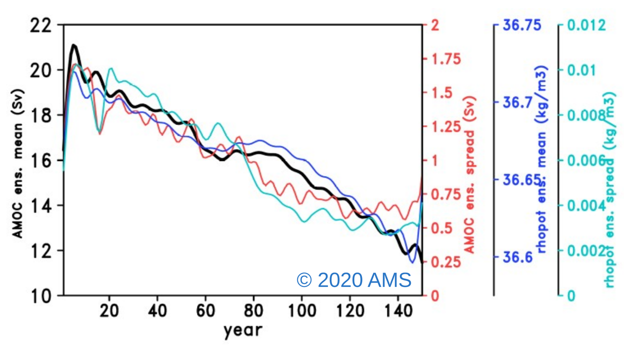


← **Figure 4:**
Left: Temporal and ensemble average of the Mixed-layer depth in March for **(a)** the historical ensemble and **(b)** the last 50 years of the ensemble with an incremental CO 2 increase by +1%/year. The box indicates the Labrador Sea convection region used to compute the density index in (c) & (d).
Right: Lag-correlation of the potential density (w.r.t. 2000m) averaged for the deep ocean in the Labrador Sea convection region (60-40°W, 50-60°N, 1500-3000m depth) and different ocean indices for **(c)** the historical ensemble and **(d)** the last 50 years of the ensemble with an incremental CO 2 increase by +1%/year. The colors indicate the correlation with the AMOC at 45°N (orange), the surface turbulent heat flux averaged over the Labrador Sea (blue), the surface salinity in the Labrador Sea (light blue) and the Subpolar Gyre strength (as previously defined, green). Non-filled (filled) markers indicate significance at the 98% (99%) confidence level. All indices were detrended by removing the ensemblemean of each quantity and 10-year low-pass-filtered.

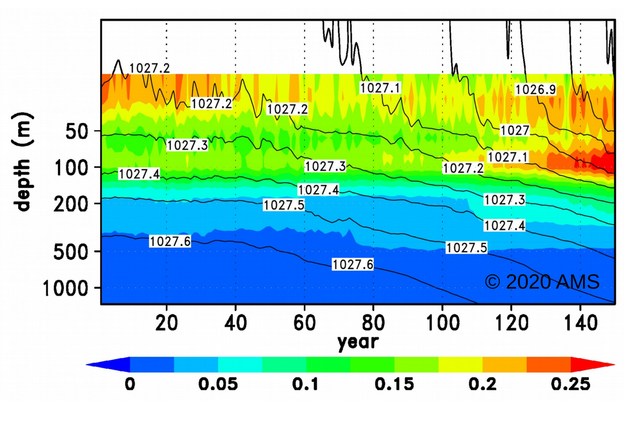
➜ **Figure 5:**
Labrador Sea stratification and deep ocean density in the ensemble with an incremental CO 2 increase by 1%/year.
(a) AMOC at 45°N mean (black) and ensemble spread (red) and the mean (blue) and spread (cyan) of the potential density (w.r.t. 2000m) averaged for the deep ocean in the Labrador Sea convection region (60-40°W, 50-60°N, 1500-3000m depth). Timeseries are undetrended and 10-year lowpass-filtered.
(b) Hovmoeller plot of the vertical profile of the vertical derivative of potential density (shadings, in (kg/m^3)/100m with respect to the surface) in the Labrador Sea convection region (box average for a box 60-40°W, 50-60°N) and potential density (contours, in kg/m^3 with respect to the surface).

+1% CO_2/year

(a) Ens. Mean & spread



(b) Labrador Sea density profile



- Strong CO2 forcing does not affect the localization of ocean convection, but its strength.

- There is a strong correlation between ocean circulation indices and deep ocesn density in the Labrador Sea in the historical ensemble.
- This link vanishes under strong Co_2 forcing.

Take Home Message (2)

Changes in Labrador Sea deep ocean density (and its variability) provide further indication for a role of the ocean circulation in driving the AMV and its simulated changes under strong forcing.
→The changes in ocean circulation and its variability are likely to large extent density driven.

- The decline in AMOC mean and its variability are very similar to that of the AMOC
- Labrador Sea stabilizes under strong CO_2 forcing

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https://doi.org/10.1175/JCLI-D-18-0739.1

References
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Clement, A.., K. Bellomo, L. N. Murphy, M. A. Cane, T. Mauritsen, G. Rädel, and B. Stevens. The Atlantic Multidecadal Oscillation without a role for ocean circulation. Science, 350(6258), 320-324.
O'Reilly, C. H., M. Huber, T. Woollings, and L. Zanna (2016), The signature of low-frequency oceanic forcing in the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 43, 2810–2818.