Atmospheric response to the natural variability of the Atlantic meridional overturning circulation

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Abstract

The influence of the natural variability of the Atlantic meridional overturning circulation (AMOC) on the atmosphere is studied in 7 climate models, using Maximum Covariance Analysis (MCA). A significant but weak influence of the AMOC changes is found during winter, when the ocean leads the atmosphere by a few years. In all models but CCSM3, an intensification of the AMOC is followed by a negative phase of the North Atlantic Oscillation (NAO). For CCSM3, no atmospheric response is detected in the first half of the simulation when the AMOC is in an oscillatory state, but a positive NAO response is found when the AMOC variability has a red-noise like behavior. The signal amplitude is typically 0.5 hPa. It only explains about 10% of the yearly fluctuations of the NAO, but a larger fraction at lower frequencies.

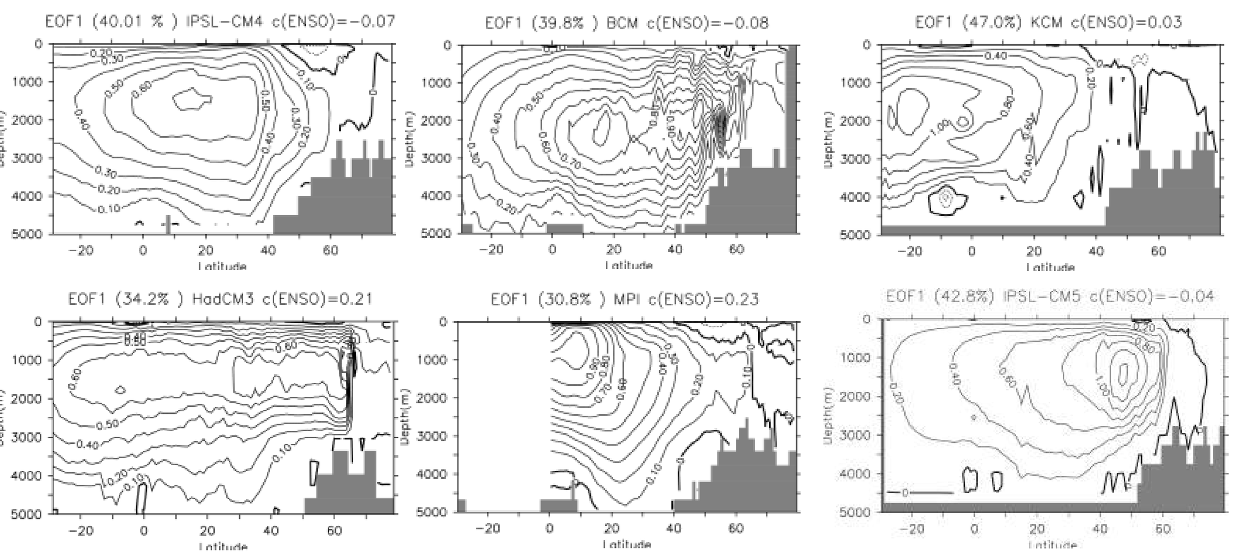
The negative NAO response seems to be primarily due to an increase of the heat loss along the North Atlantic Current (NAC) and the subpolar gyre associated with an AMOC-driven warming. Stronger heating decreases and shifts southward the baroclinicity and the eddy activity in the North Atlantic storm track. In the red-noise regime of the AMOC in CCSM3, the warming mostly occurs in the eastern portion of the NAC, which reinforces the storm track and shifts it northward, resulting in a positive NAO response. In the oscillatory regime, there is an additional cooling along the western part of the NAC and the storm track is only slightly weakened.

Models

- **Preindustrial control** simulations using low resolution (2-3° atmosphere, 1-2° ocean) coupled models (EU project THOR):

Model	*Reference*	*Duration*	*Mean AMOC max*
MPI-ESM,	Jungclaus et al. (2010),	1000 yr	~16 Sv
BCM,	Otterå et al. (2010),	700 yr	~18 Sv
CCSM3,	Danabasoglu (2008),	700 yr	~22 Sv
KCM,	Park et al. (2009),	1000 yr	~12 Sv
IPSL-CM4,	Marti et al (2010),	1000 yr	~10 Sv
IPSL-CM5,	Dufresne et al. (2010),	1000 yr	~10 Sv
HadCM3,	Vellinga and Wu (2004),	700 yr	~18 Sv

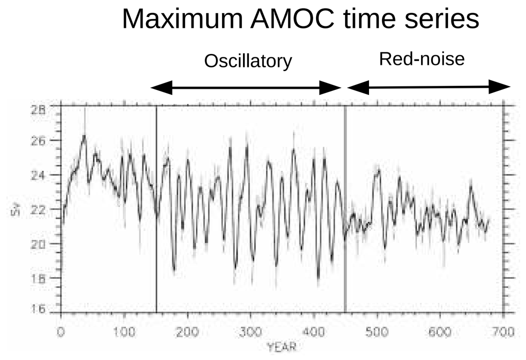
EOF1 of yearly mean meridional streamfunction (Sv)



- Mean AMOC within the range of uncertainties of other coupled models,
- EOF1 shows :
  - maximum over the tropical regions for IPSL-CM4, MPI-ESM,
  - maximum over the Nordic Seas for HadCM3, IPSL-CM5, BCM,
  - maximum over the Southern Hemisphere for KCM.
- PC1 with a red-noise like spectrum for most models, except IPSL-CM5 that has a strong 20-yr cycle.

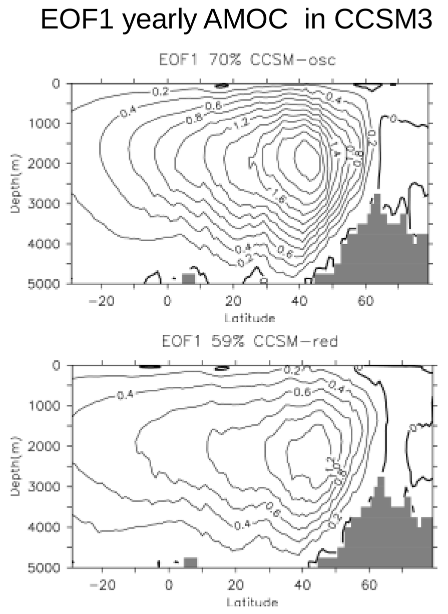
CCSM3 – oscillatory and red noise behavior

Maximum AMOC time series



(from Danabasoglu, 2008)

EOF1 yearly AMOC in CCSM3



- The variability of the AMOC shows two different behaviors

Method

Maximum Covariance Analysis (MCA) between the AMOC and the Sea Level Pressure (SLP):

1. Covariance matrix

$$C_{MOC\ SLP}(x,y,\tau) = MOC_{YR}(y,t-\tau) \, . \, SLP_{Seasonal}(x,t)$$

Yearly — Seasonal JFM, AMJ,JAS or OND

2. ENSO removed using the first PCs of the SST in the equatorial Pac. Ocean

3. MCA gives the patterns of covariability

$$C_{MOC\ SLP}(x,y,\tau) = 1/n \; U(x) \; A^T(t) \; B(t-\tau) \; V(y)$$

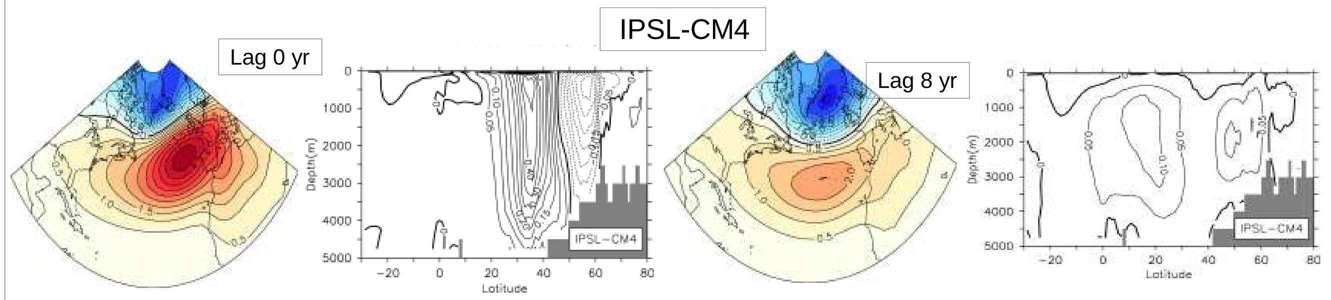
Left singular vector — Left time series — Right time series — Right singular vector

4. Significance test with Monte Carlo Analysis

AMOC response to atmosphere

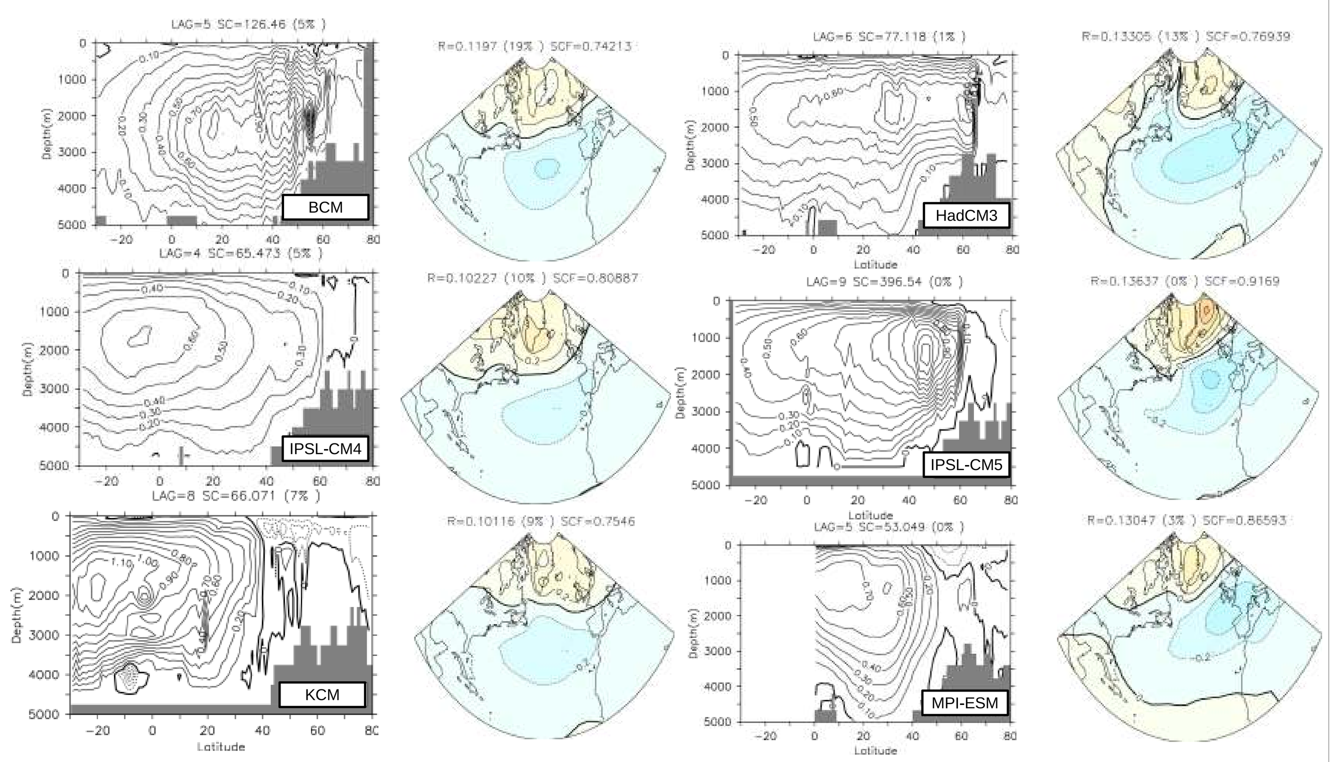
- Atmospheric stochastic forcing of the AMOC during the cold-season (OND-JFM),
- When atmosphere and ocean are in phase,it reflects the NAO and the Ekman pumping deep return flow.

Heterogeneous AMOC (Sv) and homogeneous SLP (hPa), 1st MCA mode, atmosphere leads



Atmospheric Response to AMOC

Homogeneous AMOC (Sv) and heterogeneous SLP (hPa), 1st MCA mode, ocean leads (by 5, 6, 8 or 9 yr)



- A SLP dipole similar to a negative NAO follows an AMOC intensification, with a time lag from 1 yr to 10 yr.
- The atmospheric response is equivalent barotropic (not shown),
- The AMOC explains 10% of the NAO interannual variability (weak but significant).

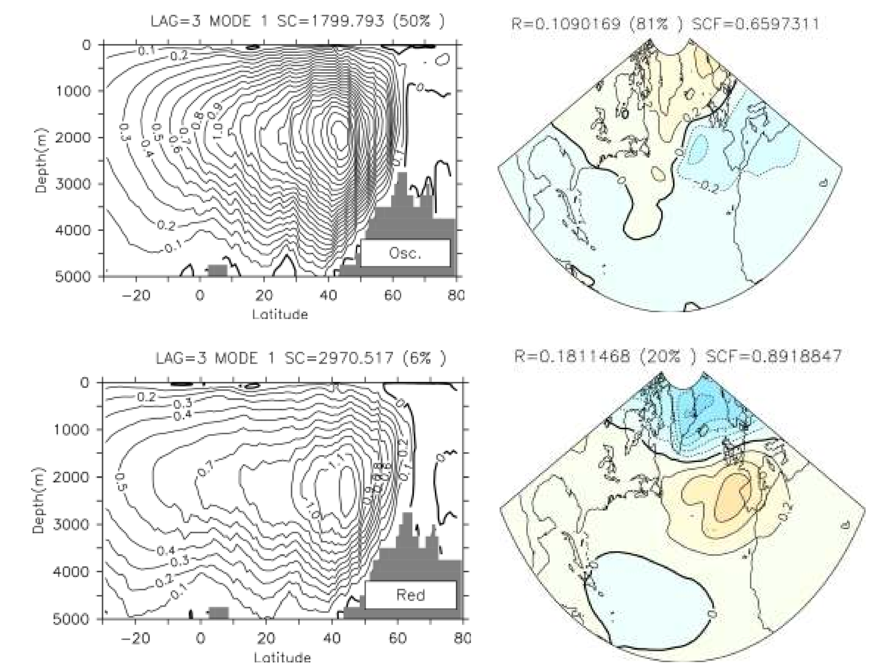
Homogeneous AMOC (Sv) and heterogeneous SLP (hPa), 1st MCA mode CCSM3 results

Oscillatory period :

- weak negative NAO signal OND, no signal in JFM.

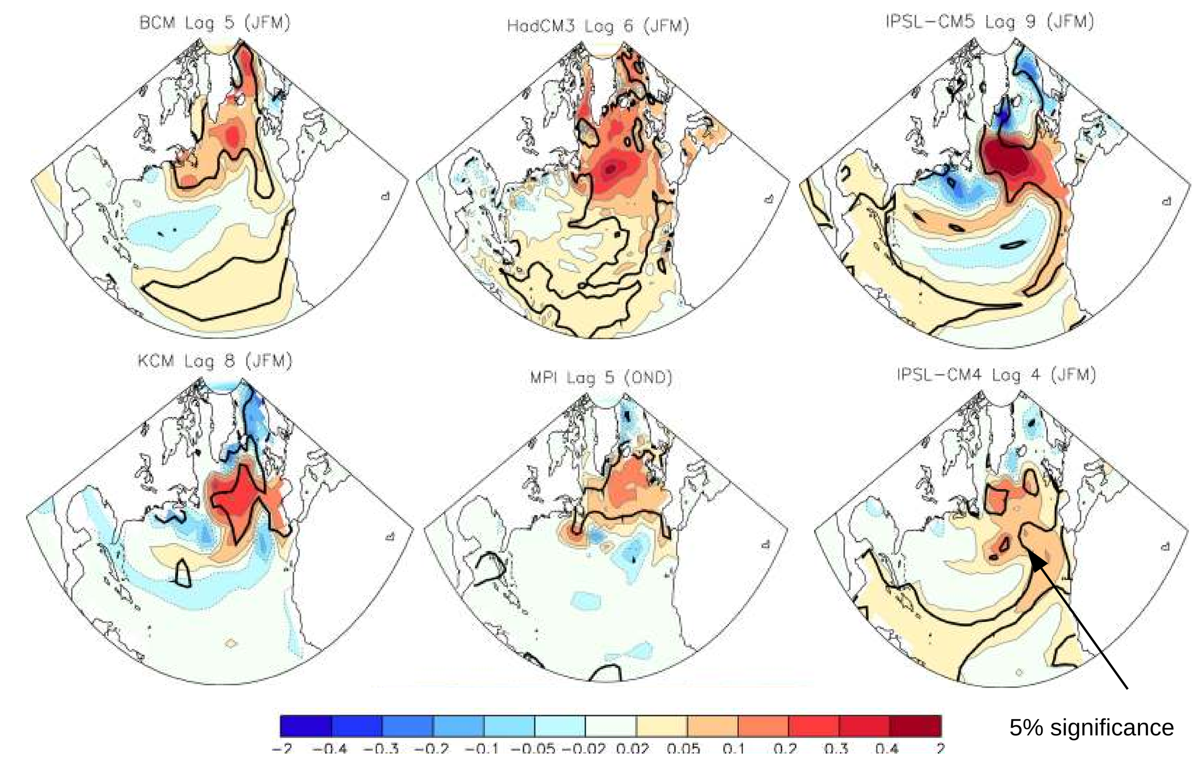
Red-noise like period :

- weak positive NAO signal in JFM.



Mechanism of the AMOC response

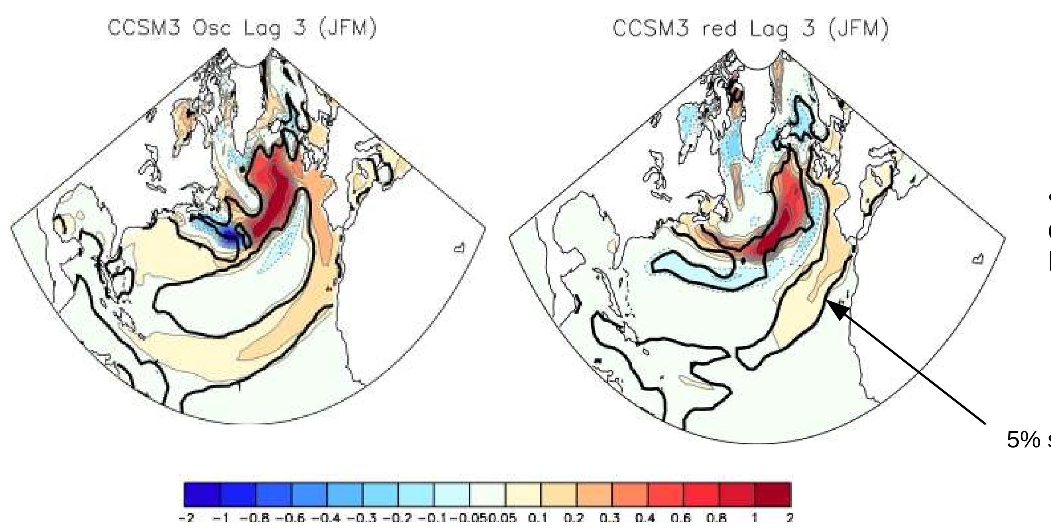
Regression of the SST(K) onto MOCy, MOCy leads by 5,6, 8 or 9 yr



MOCy = AMOC index from the MCA 1st mode (similar to PC1)

- SST anomalies mainly in the subpolar gyre,
- SST anomalies similar to the AMO (Atlantic Multidecadal Oscillation).

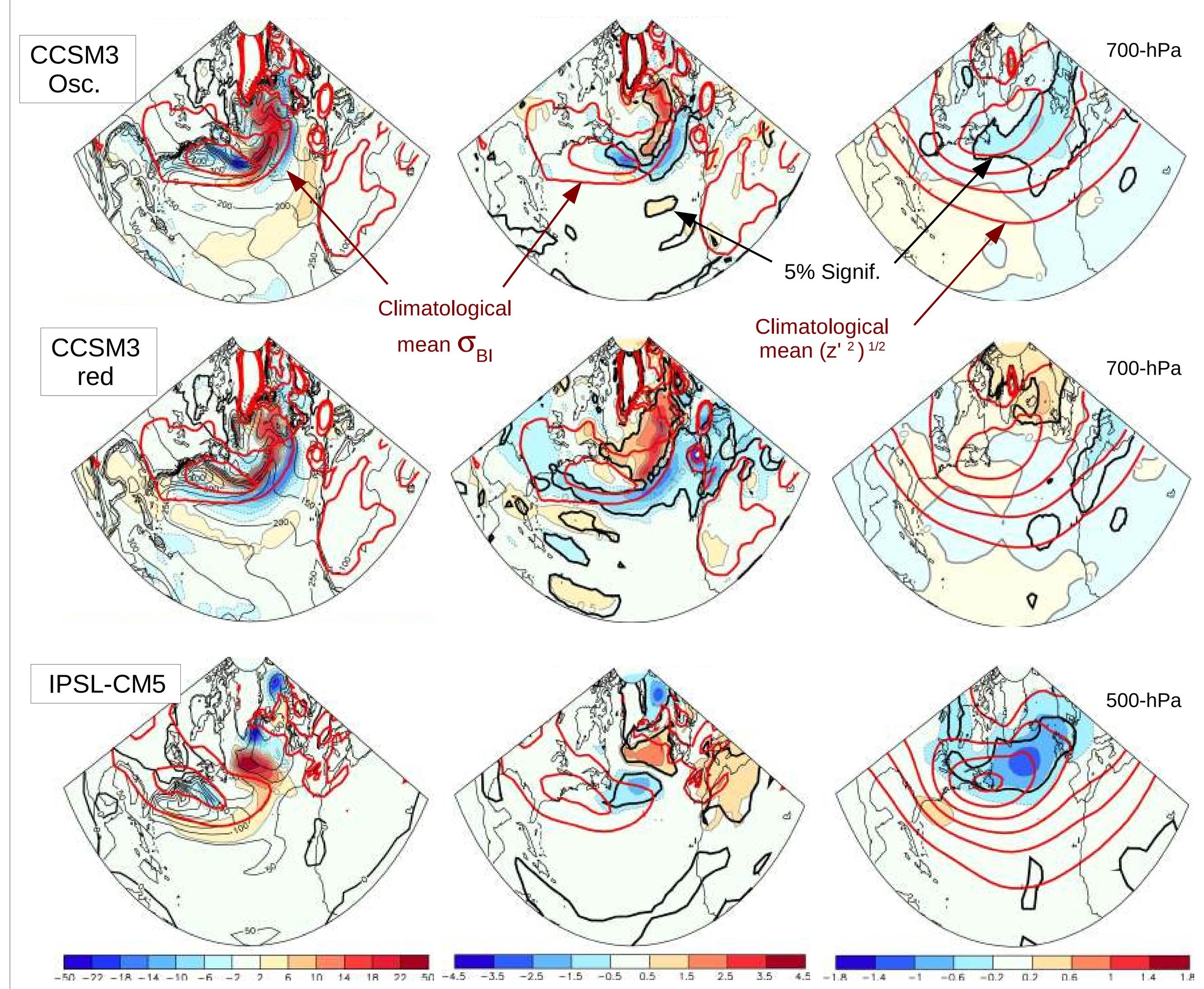
Regression of the SST(K) onto AMOC-PC1, AMOC-PC1 leads by 3 yr CCSM3 results



- SST signature different over the NAC region

Regressions onto AMOC-PC1, AMOC-PC1 leads by 3 yr (CCSM3) or 9 yr (IPSL-CM5)

Heat flux, Q (W m^{2}), positive upward — σ_{BI} in day^{-1} — Band pass $(z'^2)^{1/2}$, in m



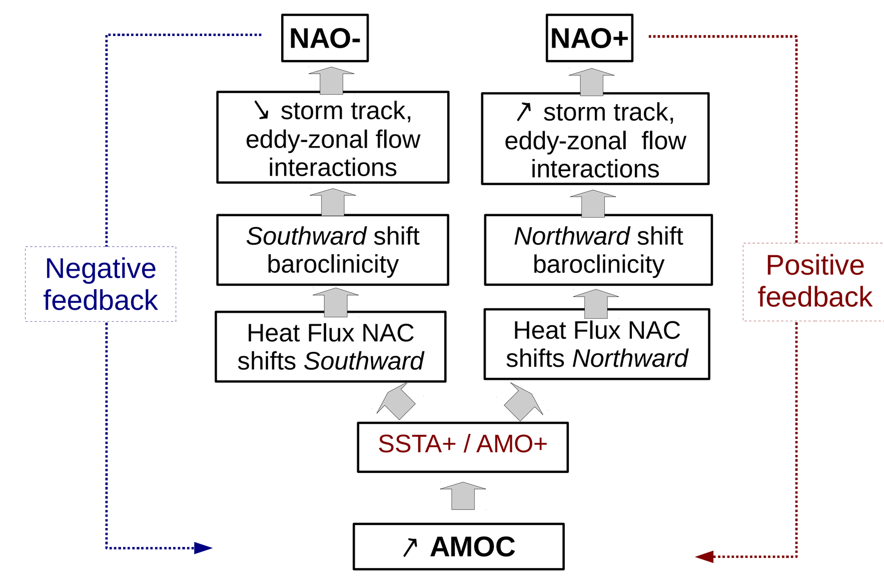
In most models, when AMOC leads, during the cold-season:

- southward shift of the heat flux over the Gulf Stream/NAC region,
- southward shift of the baroclinicity upstream of the storm track,
- weakening of the storm track,
- consistent with **negative NAO**.

For CCSM3, and the red noise period:

- northward shift of the heat flux and baroclinicity over the Gulf Stream/NAC,
- strengthening of storm track and **positive NAO**.

Summary



- AMOC explains 10-15% of the NAO interannual variability, but 20-30% of the decadal variability,
- For CCSM3, the atmospheric response is different when the AMOC regime changes, it may contribute to amplify the AMOC low-frequency variability in the red-noise regime.

Reference

Gastineau, G. and C. Frankignoul (2011) Cold-season atmospheric response to the natural variability of the Atlantic meridional overturning circulation. *Climate Dynamics. Online first.*

Danabasoglu, G., 2008: On multidecadal variability of the Atlantic Meridional Overturning Circulation in the Community Climate System Model version 3. *Journal of Climate*, 21 (**21**), 5524–5544.

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