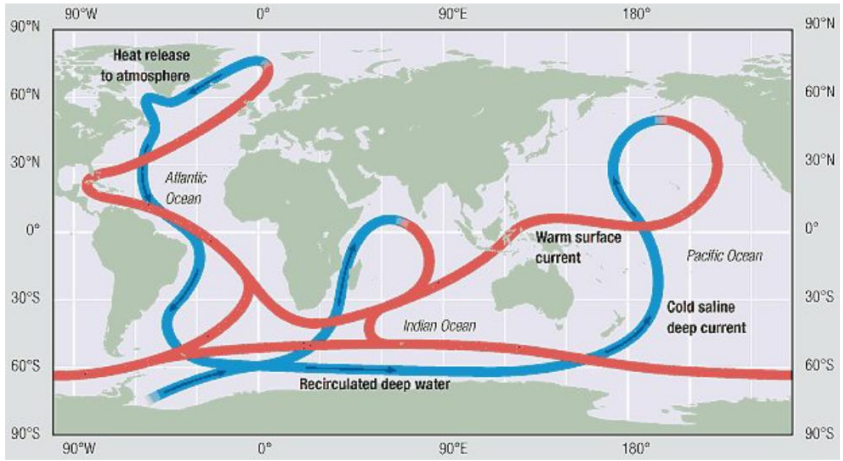
Inter-model differences in the representation of the AMOC forcing of the NAO

Rein Haarsma (1,2) Sybren Drijfhout (2)

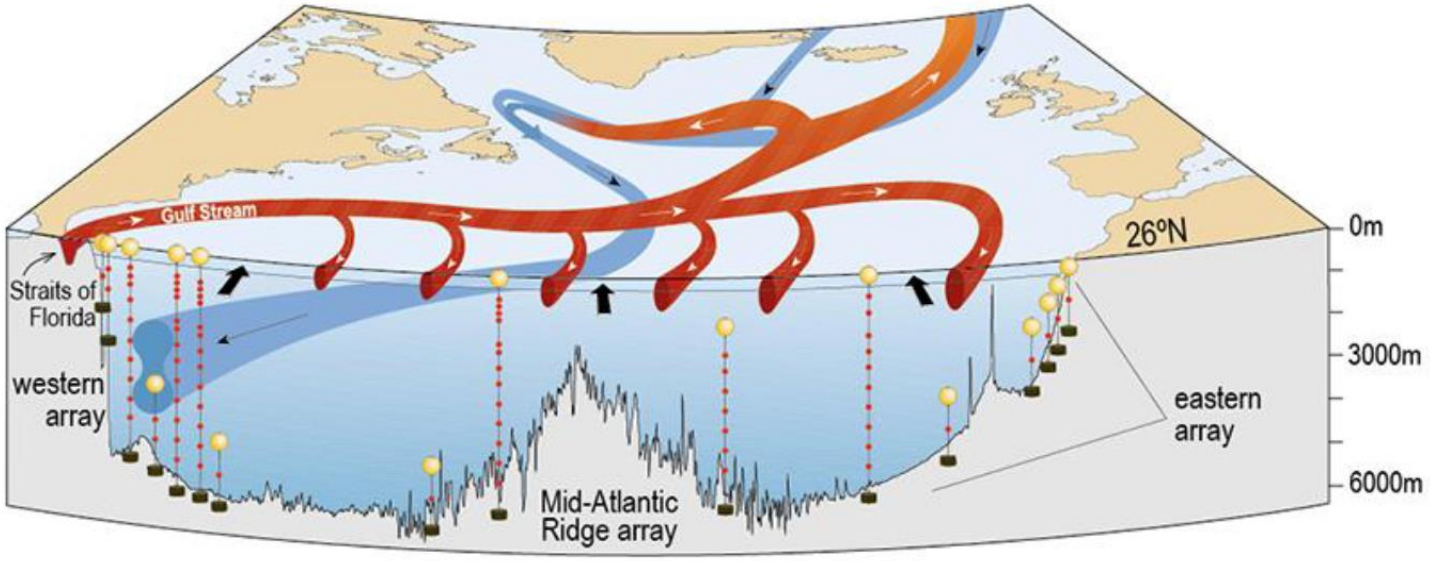
(1)Barcelona Supercomputing Center (BSC), Barcelona, Spain
(2)Royal Dutch Meteorological Institute (KNMI), De Bilt, The Netherlands

Thermohaline Circulation (THC)



Atlantic Meridional Overturning Circulation (AMOC)

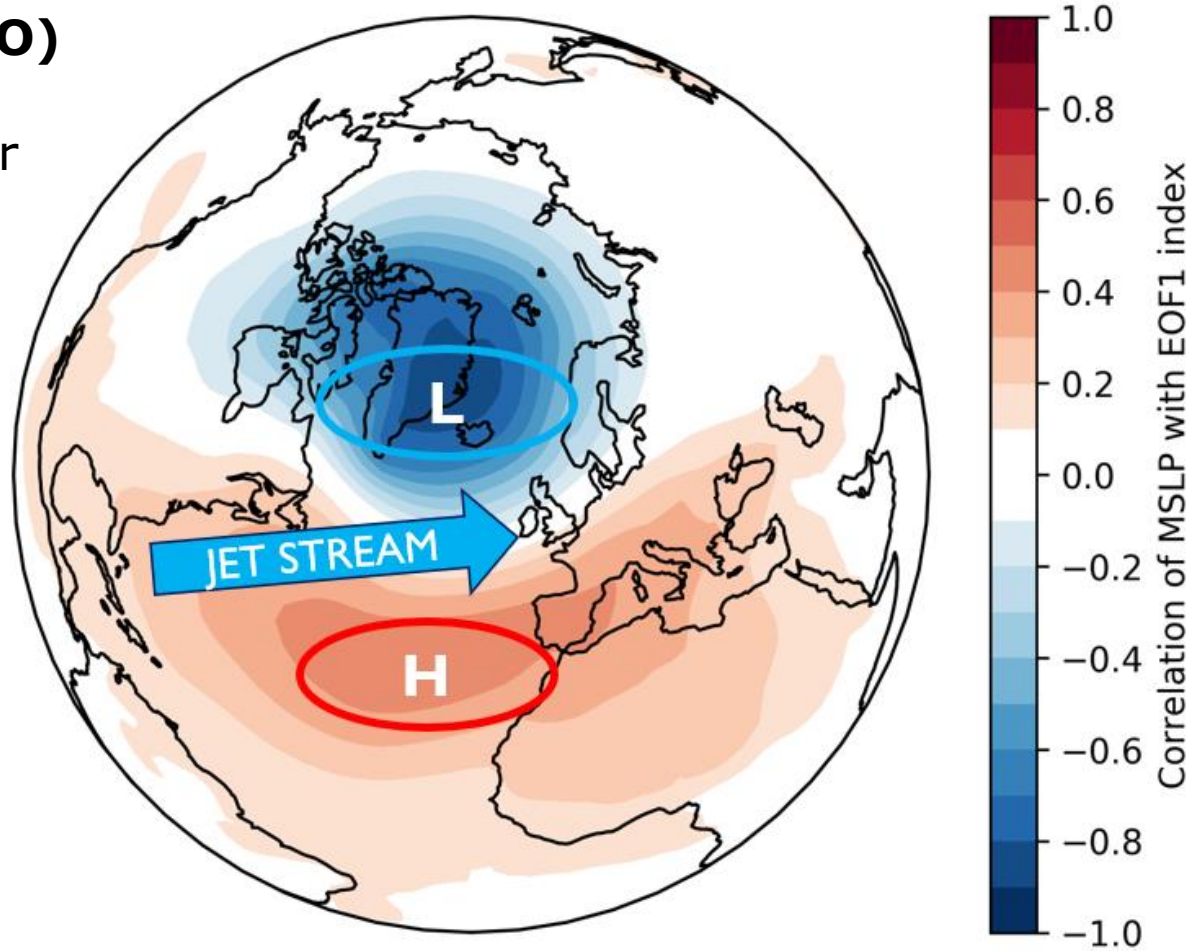
RAPID array monitoring AMOC strength at 26N since 2004



North Atlantic Oscillation (NAO)

Dominant mode of variability over the North Atlantic

Observations based on ERA5 reanalysis



MSLP correlation with Nov-Mar NAO index 1979-2019

15 HighResMIP models

100-year control simulations

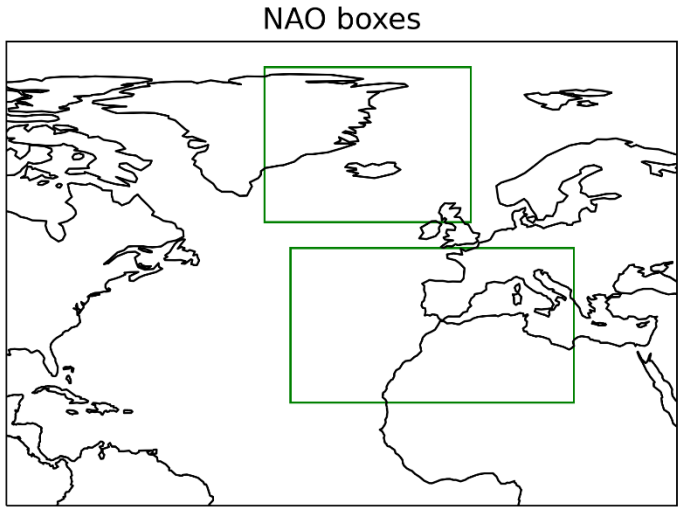
1950's conditions

RAPID-ERA5 2004-2022

ERA5 1941-2023

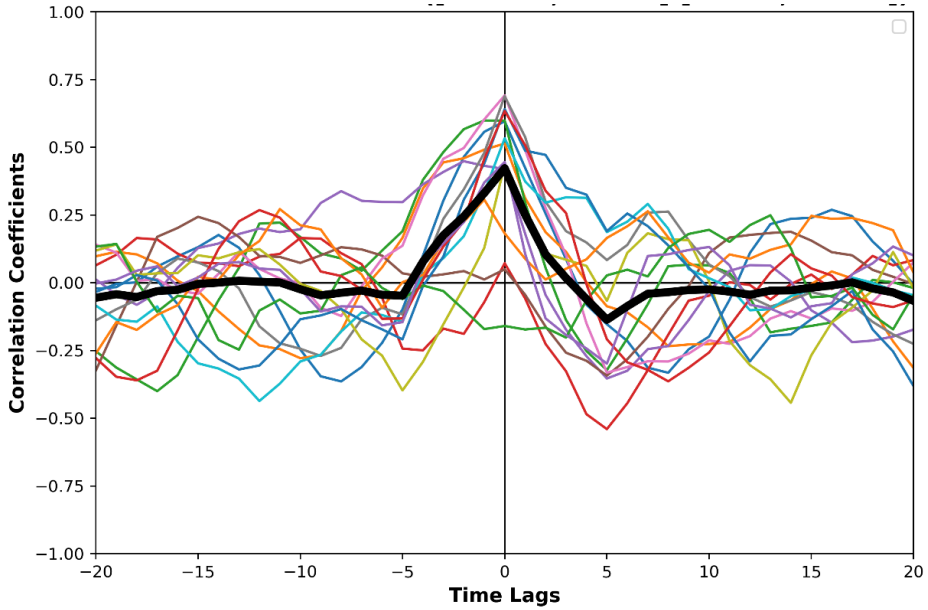
Model-Version	L_{eff} (km)	L_{nom} (km)	O_{res} (degrees)
HadGEM3-GC31-LL	**≥625**	250	1
HadGEM3-GC31-MM	364	100	1/4
HadGEM3-GC31-HM	185	50	1/4
HadGEM3-GC31-HH	**≤185**	50	1/12
CMCC-CM2-HR4	571	100	1
CMCC-CM2-VHR4	182	25	1/4
ECMWF-IFS-LR	253	50	1
ECMWF-IFS-MR	**≥185**	50	1/4
ECMWF-IFS-HR	185	25	1/4
EC-Earth3	351	100	1
EC-Earth3-HR	238	50	1/4
MPIESM-1-2-HR	364	100	1
MPIESM-1-2-XR	256	50	1/4
CNRM-CM6-0	**≥625**	250	1
CNRM-CM6-0-HR	313	50	1/4

- Winter season (DJF)
- Nonlinear detrended
- AMOC index: strength at 26N in Sv
- Different lags using 5 year running means
  - Negative lag: atmosphere is before ocean
  - Positive lag: atmosphere is lagging ocean



Large spread among PRIMAVERA models especially at positive lags

NAO MSLP response lag correlated with AMOC



correlation

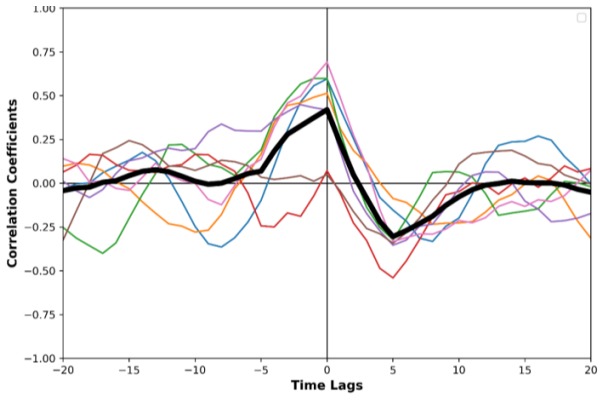
Lag in years

5 years running mean

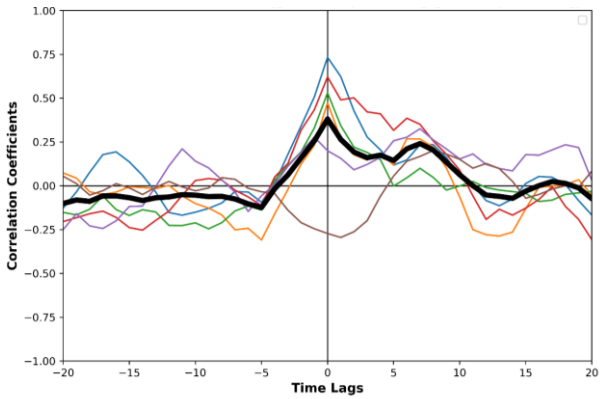
NAO MSLP response lag correlated with AMOC

Separation between models according to their response at lag +5

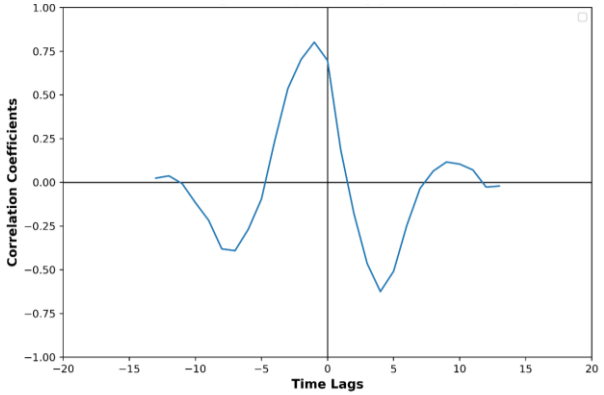
neg. NAO models



pos. NAO models



RAPID – ERA5



NAO0 models

HadGEM - MM
MPI - HR

Ecmwf - HR
HadGEM - HH
HadGEM - HM
CMCC - VHR
CMCC - HR
HadGEM- LL
CNRM - LR

ECMWF - MR
ECMWF - LR
CNRM - HR
EC-Earth - HR
EC-Earth - LR
MPI - XR

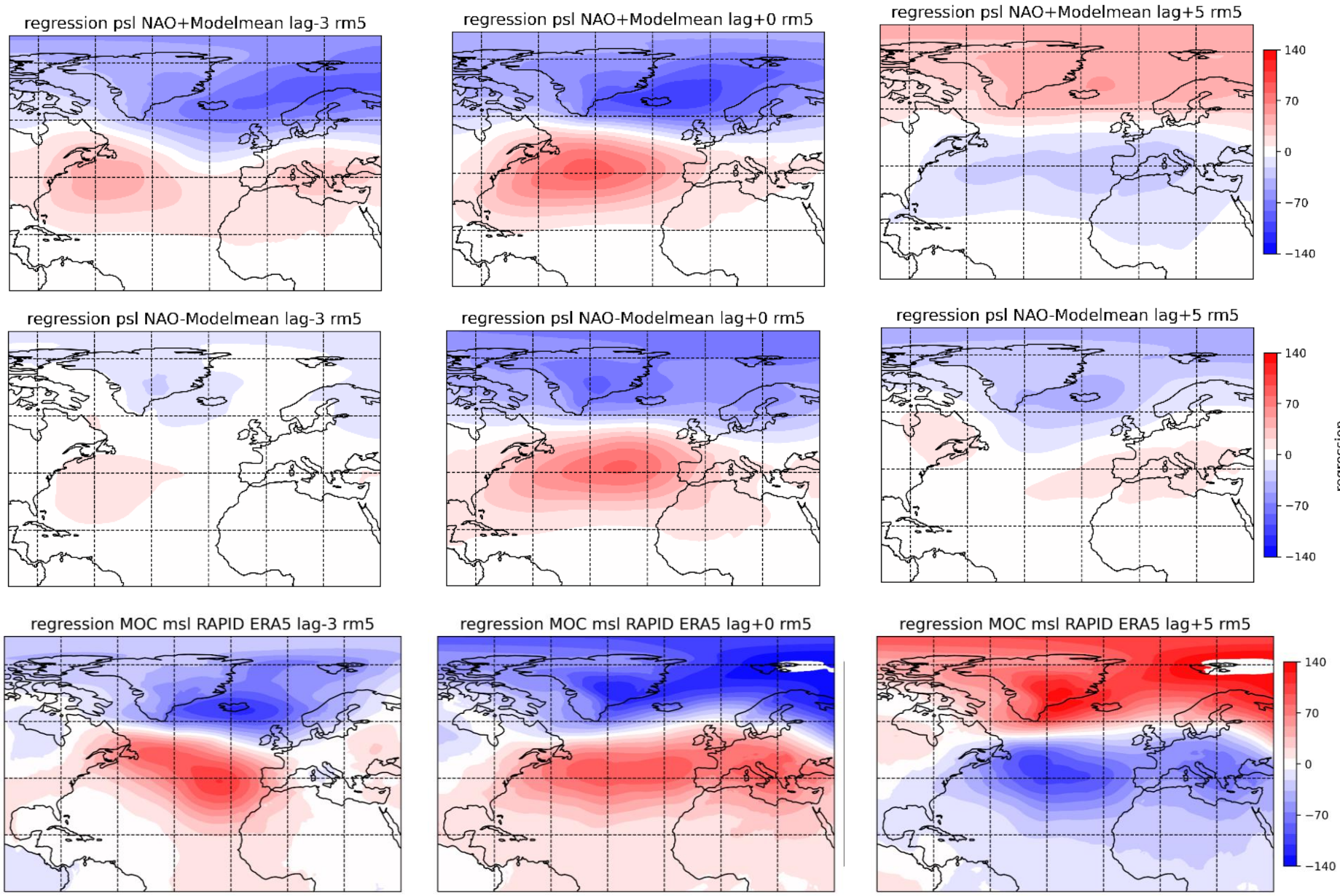
Smith et al. 2020 "*North Atlantic climate far more predictable than models imply*"

Regression MSLP on AMOC

Lag -3

Lag 0

Lag +5



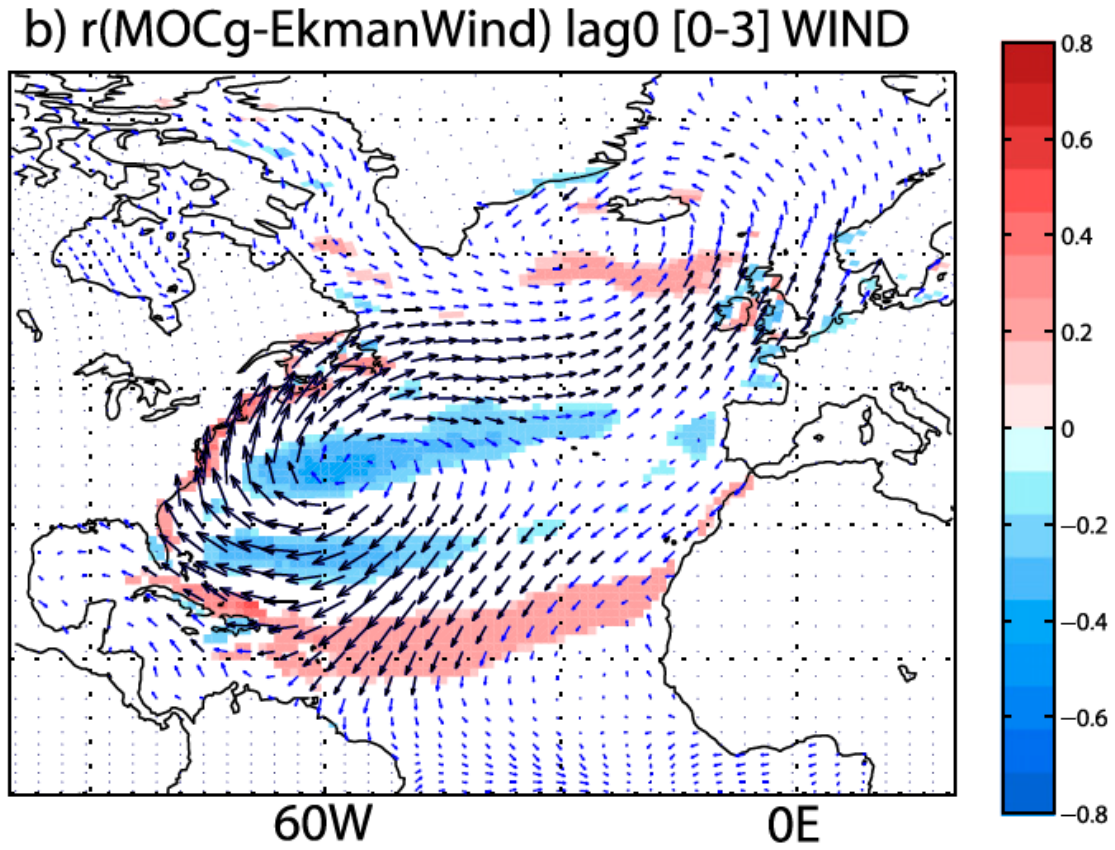
Neg. NAO models
Model mean

Pos. NAO models
Model mean

RAPID-ERA5
2004-2022

At lag 0 the AMOC response is dominated by the Ekman transport

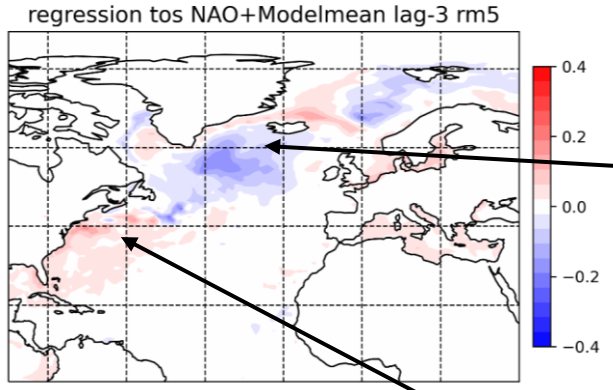
Polo et al. 2014. Ocean model forced with ERA-40 winds

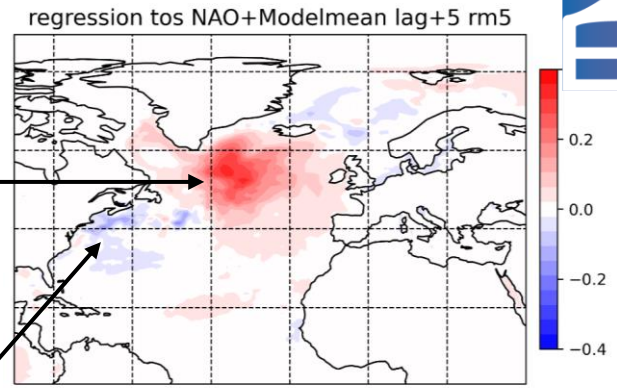


Regression SST on AMOC

Lag -3

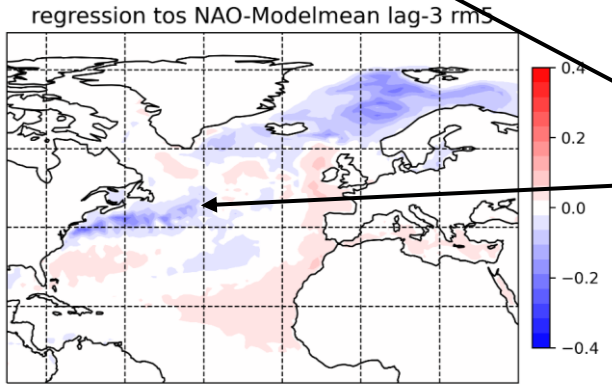
Lag +5

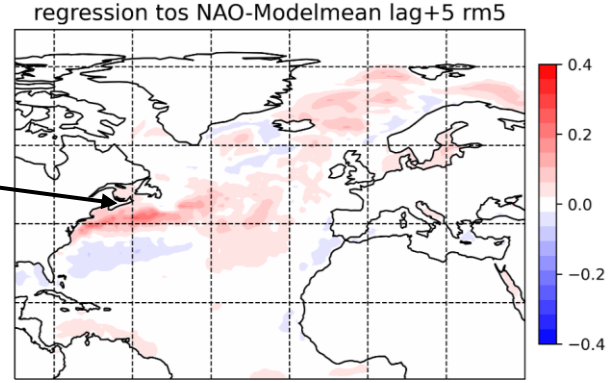




SPG signal

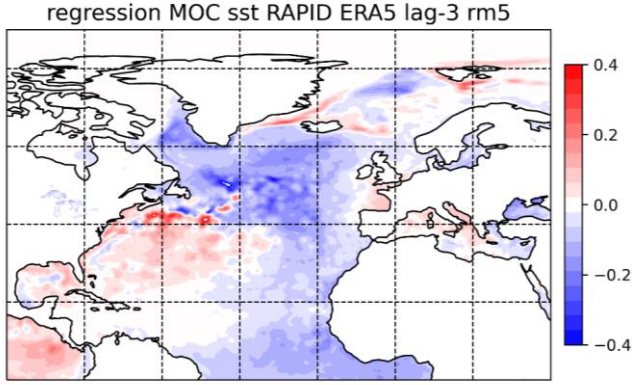
Neg. NAO models

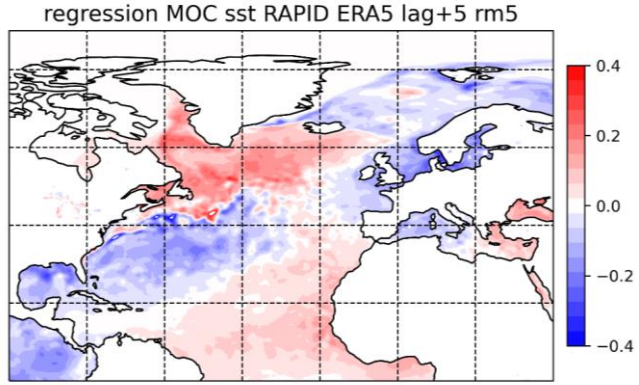




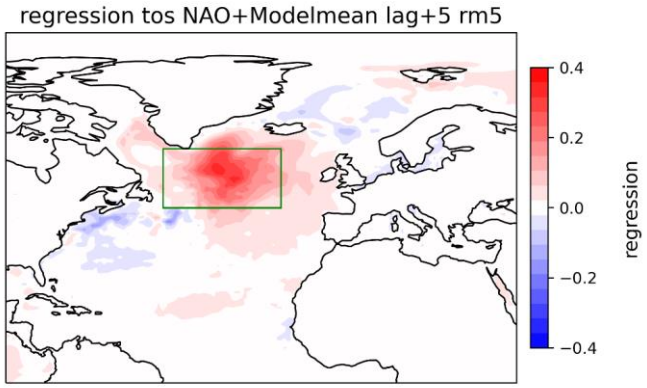
Gulfstream signal

Pos. NAO models



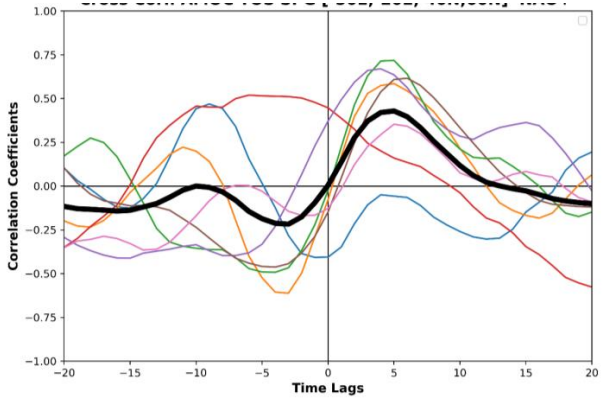


RAPID-ERA5



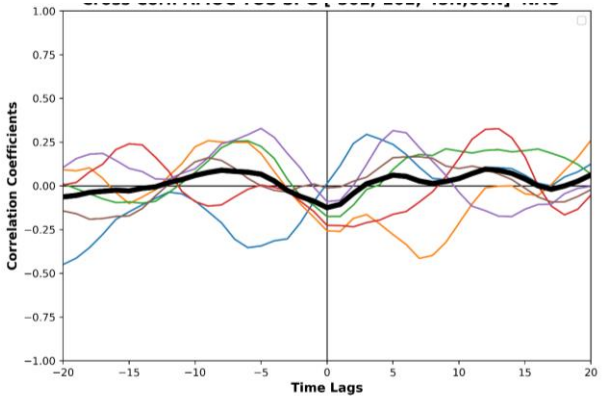
SST averaged over SPG box regressed on AMOC

Neg. NAO models



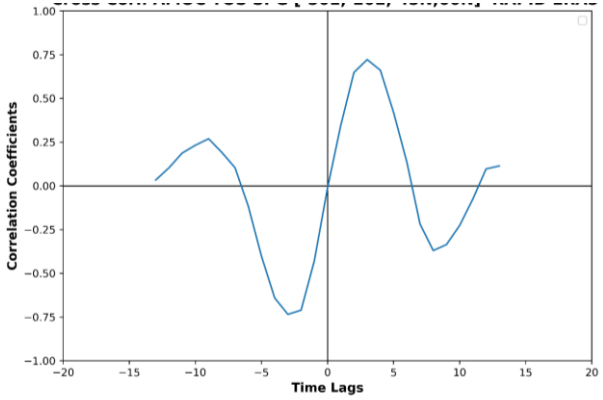
Lag in years

Pos. NAO models



Lag in years

RAPID-ERA5



Lag in years

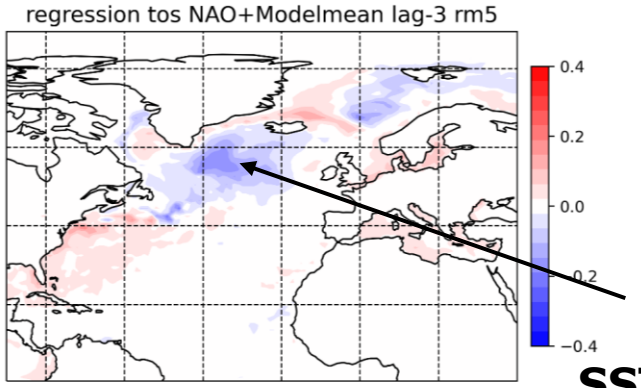
Correlation

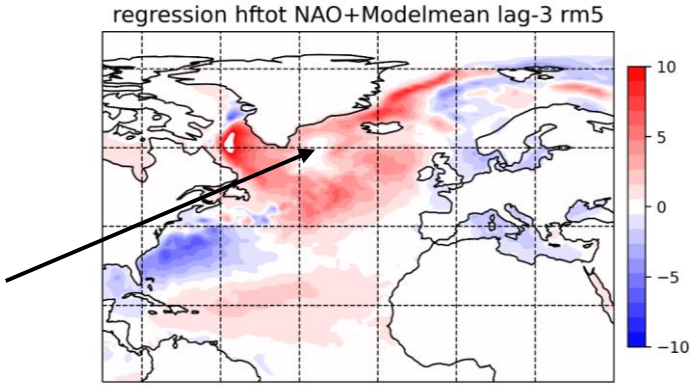
Regression SST on AMOC

Neg. NAO models

Regression turbulent heat flux on AMOC (positive upward)

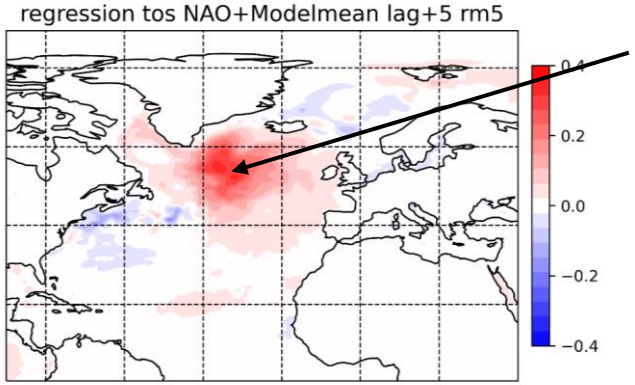
Lag -3

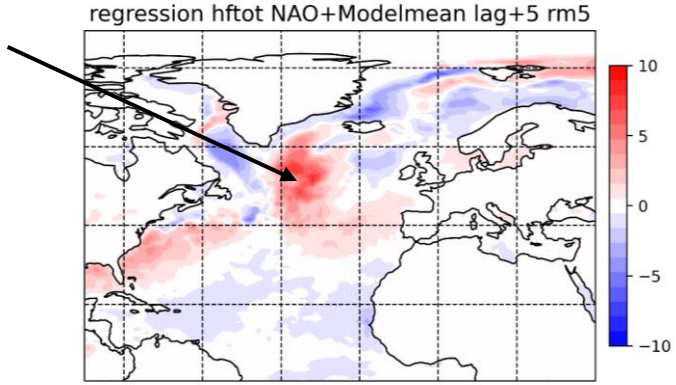




SST SPG is forced by ocean

Lag +5



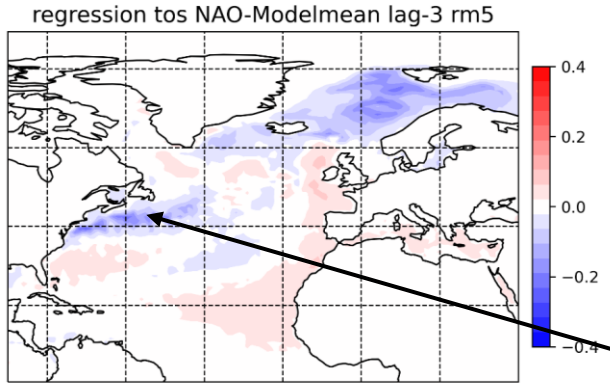


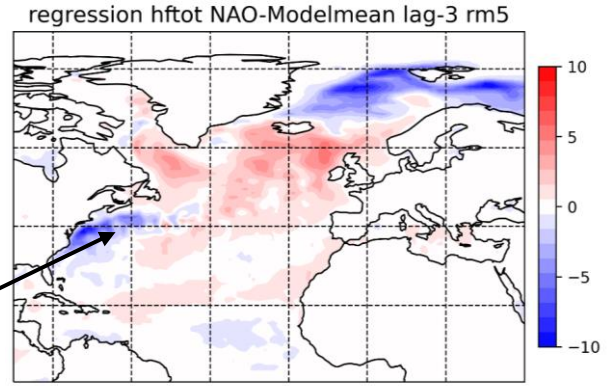
Regression SST on AMOC

Pos. NAO models

Regression turb. heatflux on AMOC

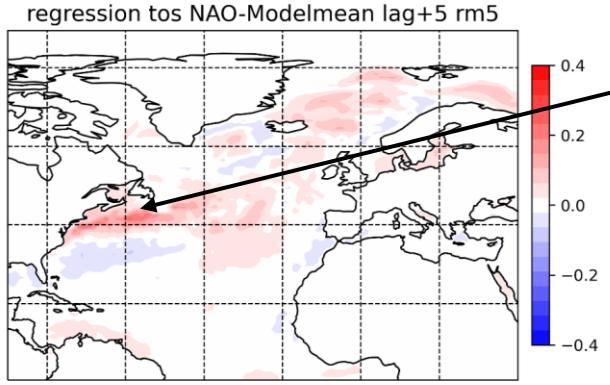
Lag -3

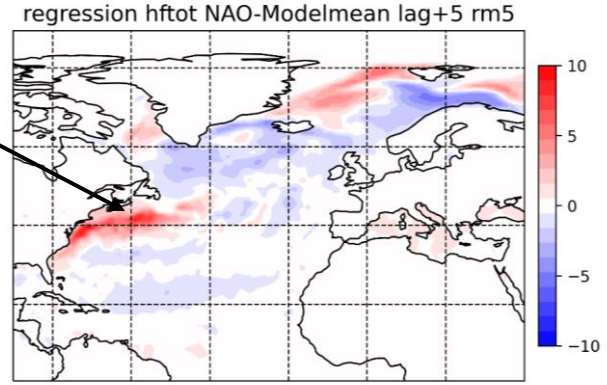




SST Gulfstream is forced by AMOC

Lag +5



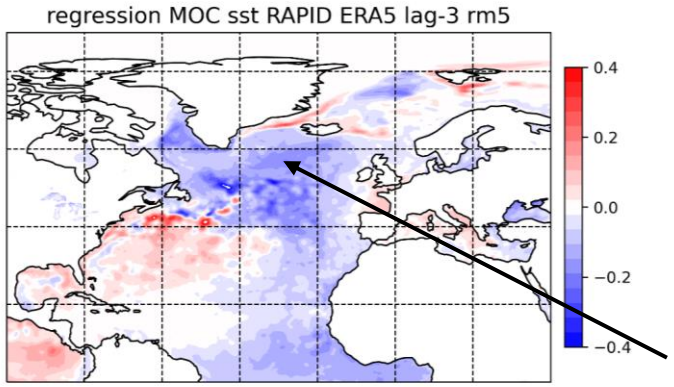


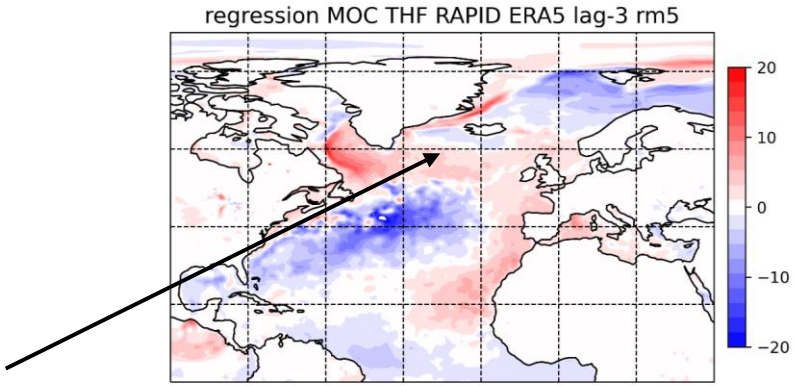
Regression SST on AMOC

Regression turb. heatflux on AMOC

Rapid – ERA5

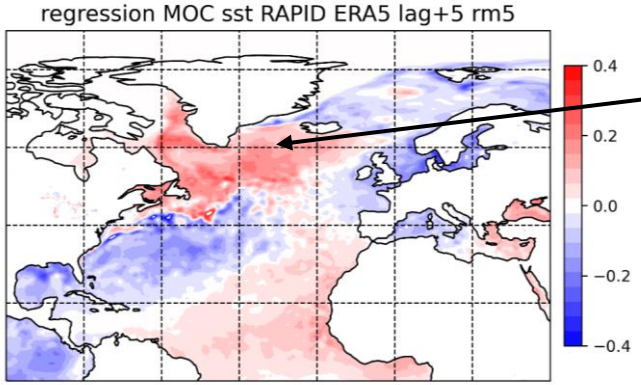
Lag -3

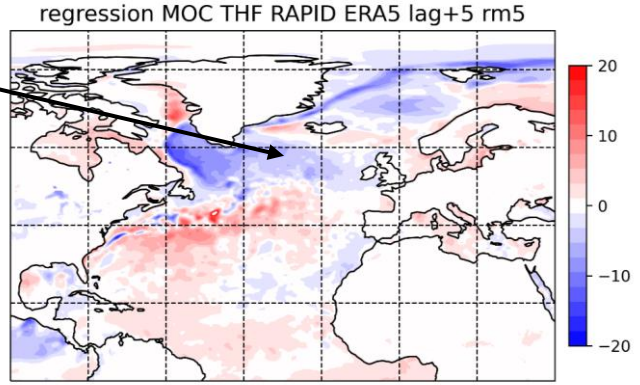




Forcing SPG SST by AMOC is suggested

Lag +5

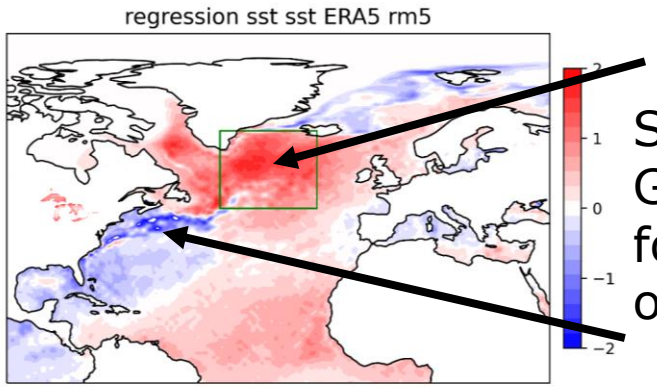




ERA5 1981-2023
5 yr running mean

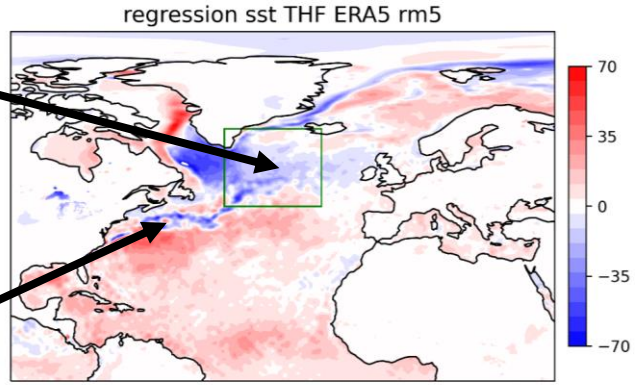
Regression SST SPG box on SST, THF and MSLP

SST

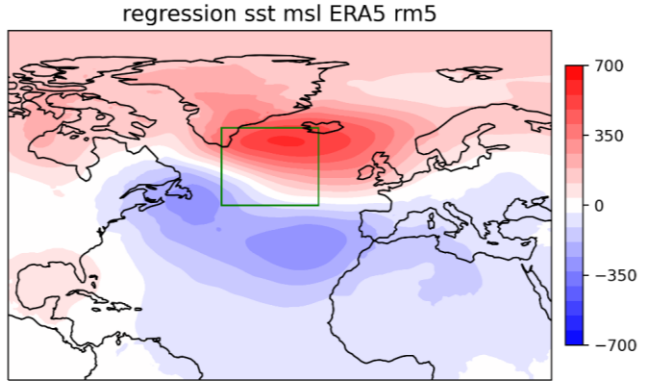


SPG and Gulfstream forced by ocean

THF



MSLP



How is the atmosphere forced by the lagged SST response?

Regression T850 hPa on AMOC

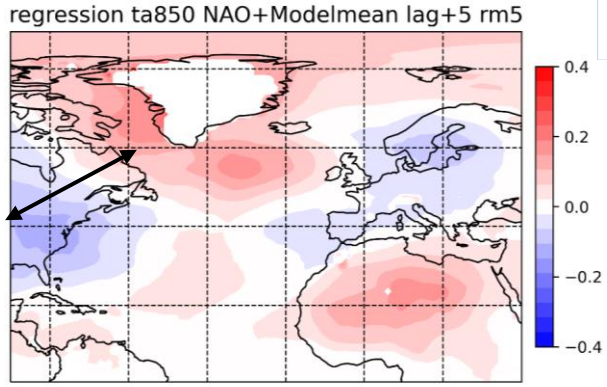
Lag +5

For *neg. NAO* models and *RAPID-ERA5* reduced meridional T850 hPa gradient

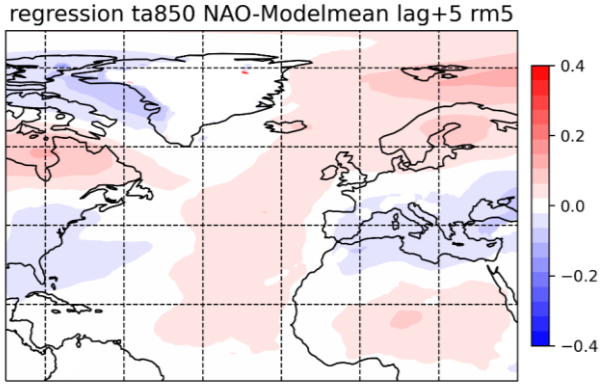
Reduced baroclinic instability

Weakened storm track

neg. NAO response



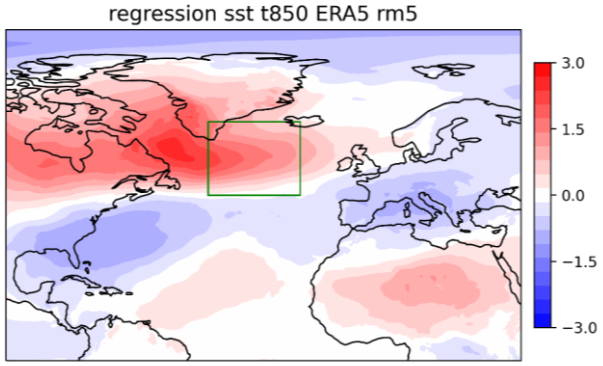
Neg. NAO models

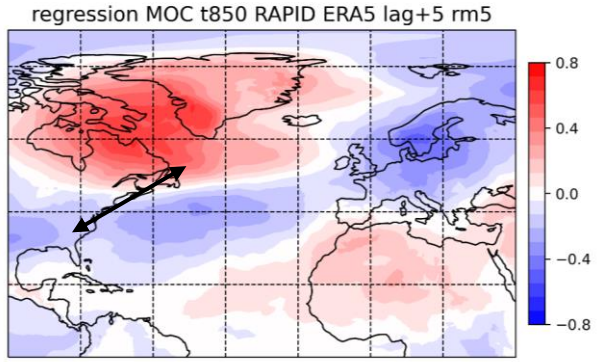


Pos. NAO models

Regression T850 on SST

ERA5 1981- 2023





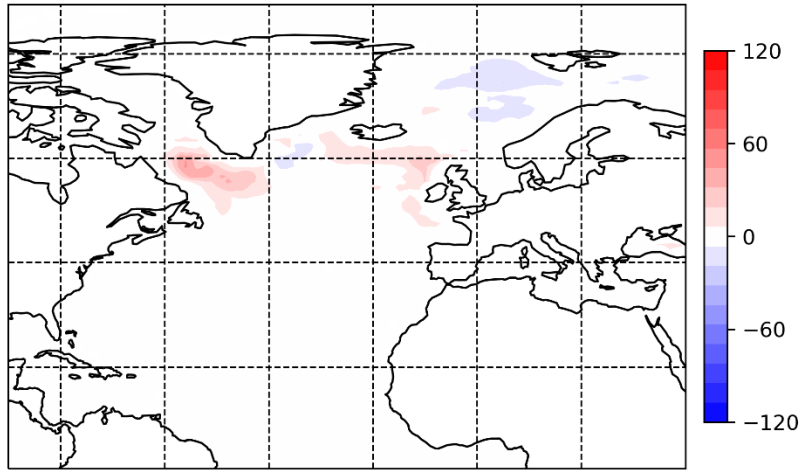
RAPID-ERA5

AMOC forcing and evolution of SSTs

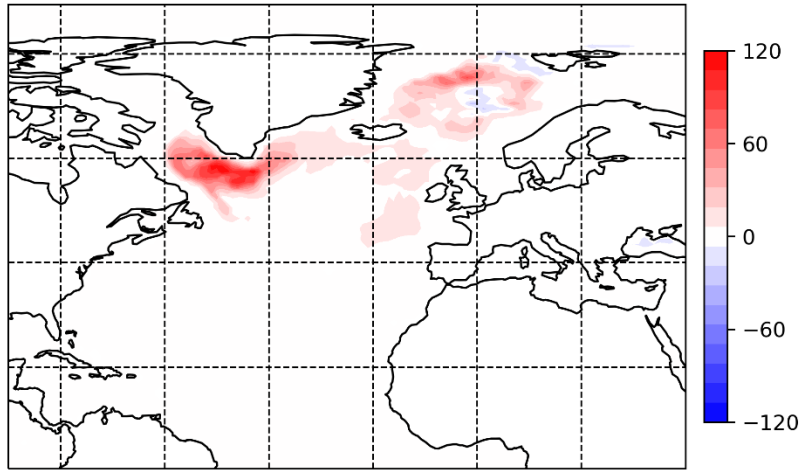
Mixed Layer Depth

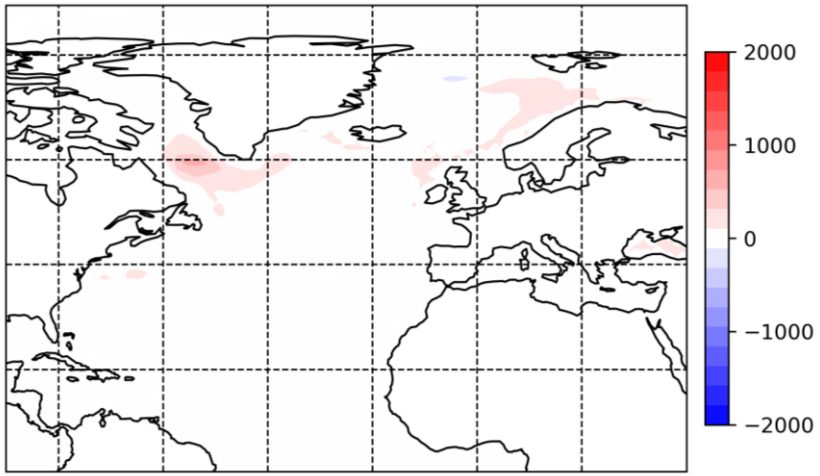
Pos. NAO models

Neg. NAO models

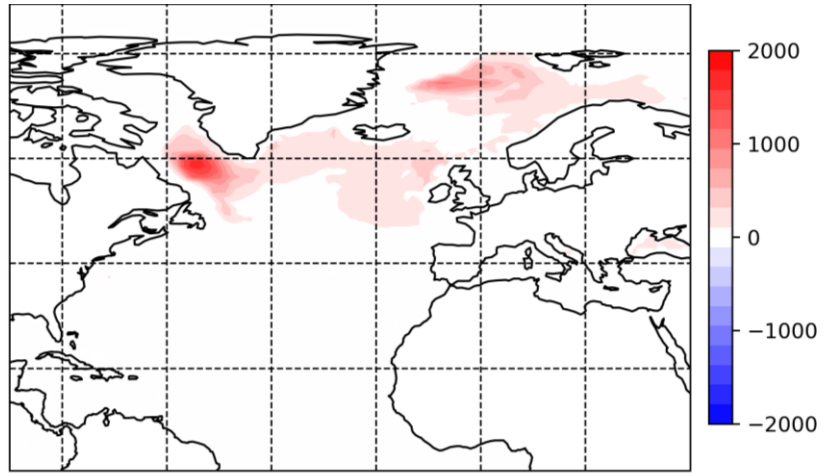


Regression with AMOC at Lag -3



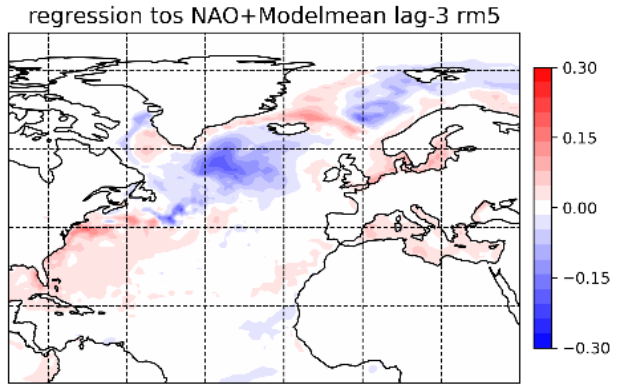


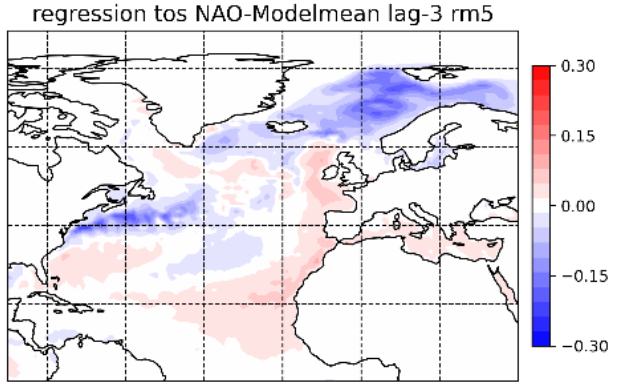
Bias

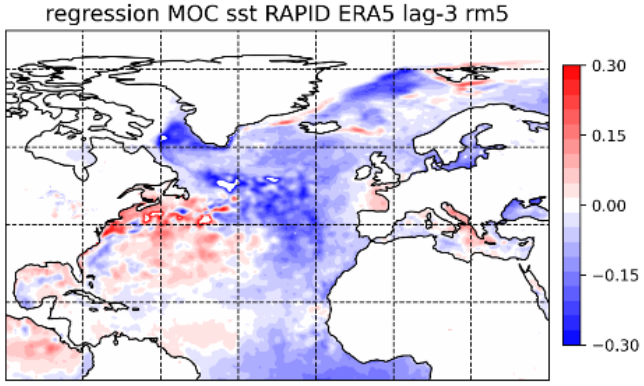


Regression SST with AMOC

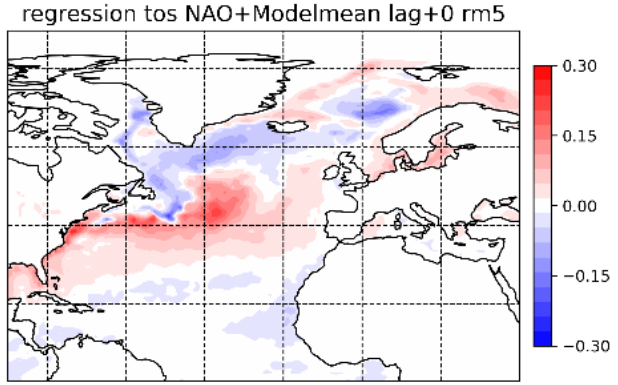
Lag -3

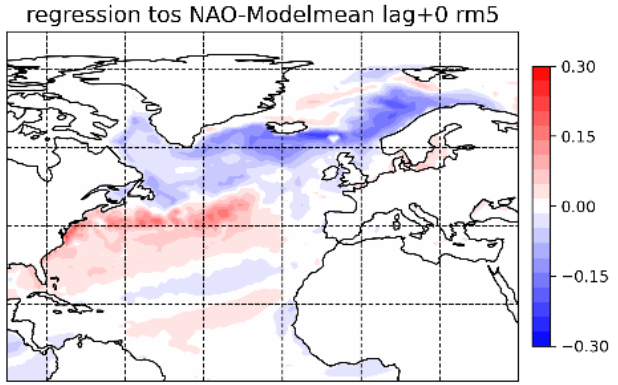


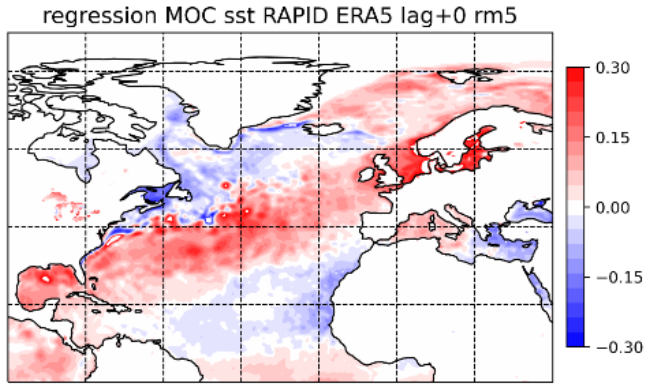




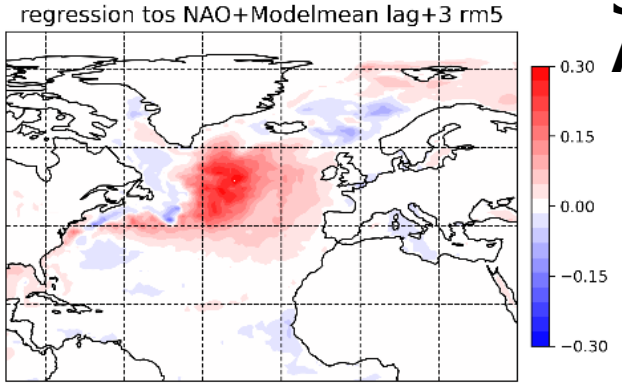
Lag 0

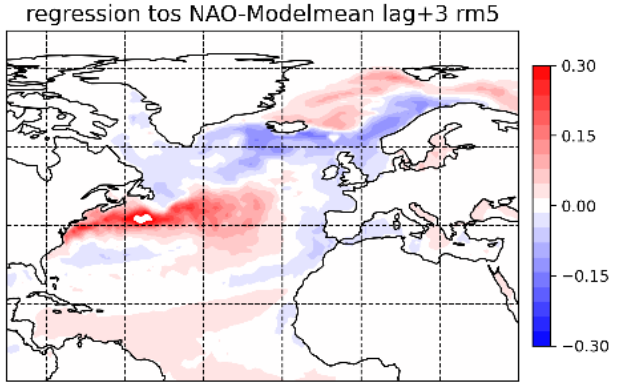


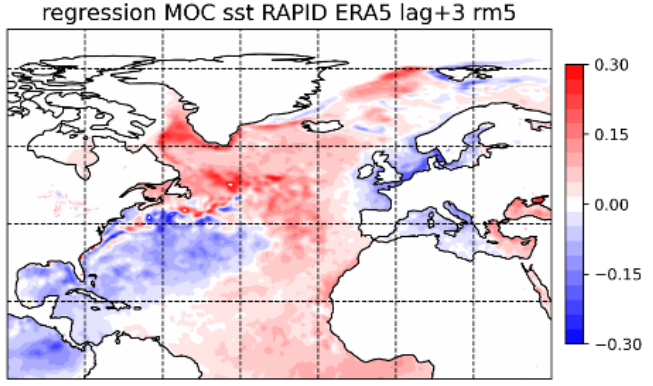




Lag +3







Neg. NAO

Pos. NAO

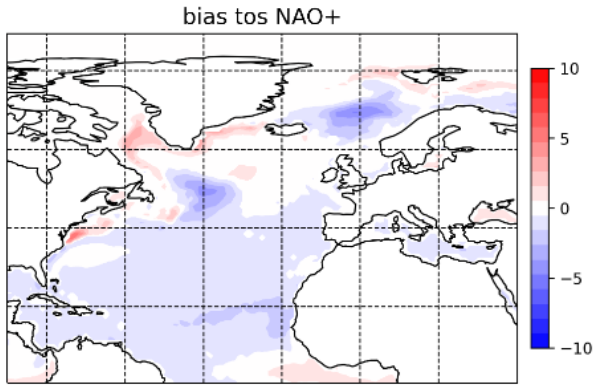
RAPID-ERA

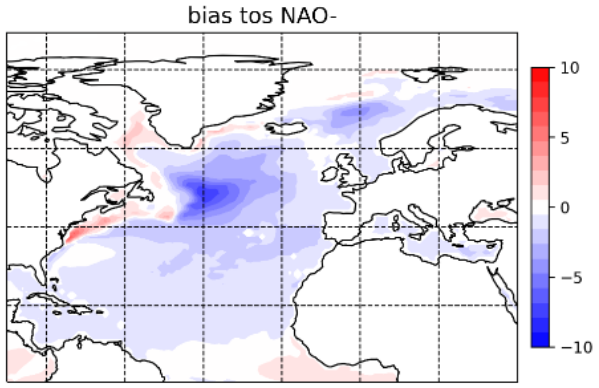
What determines the difference between the neg. NAO and pos. NAO models?

- **Bias**
- **Resolution**

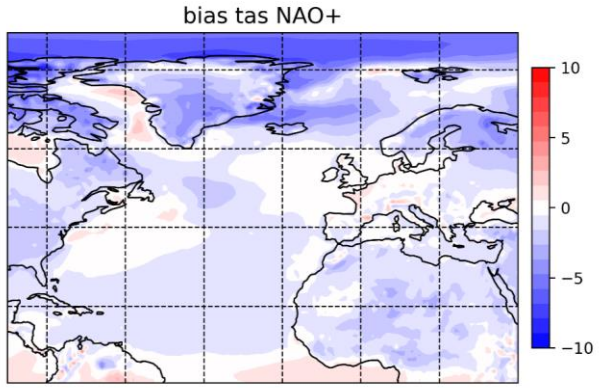
Bias

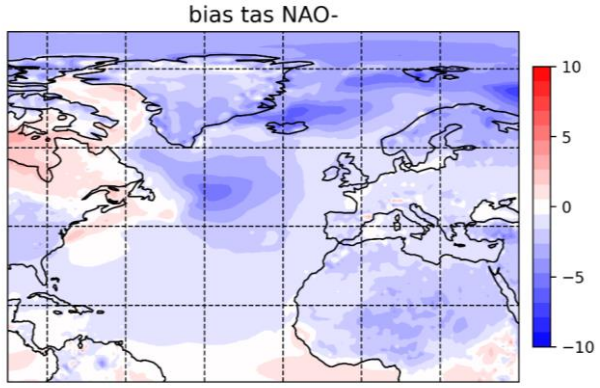
SST



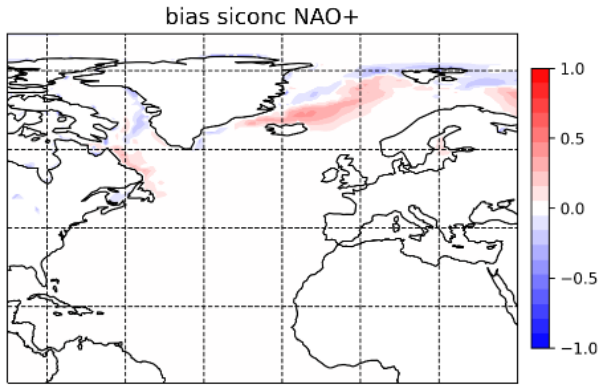


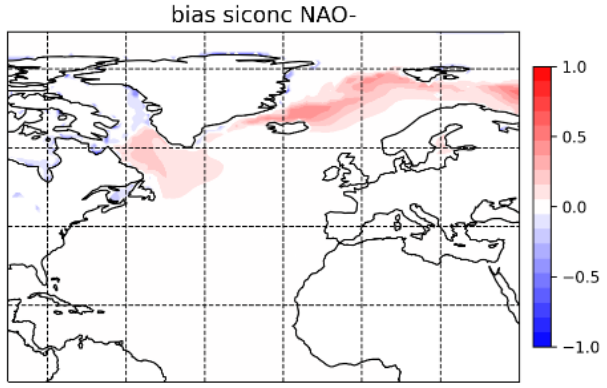
T2m





Sea-ice conc.



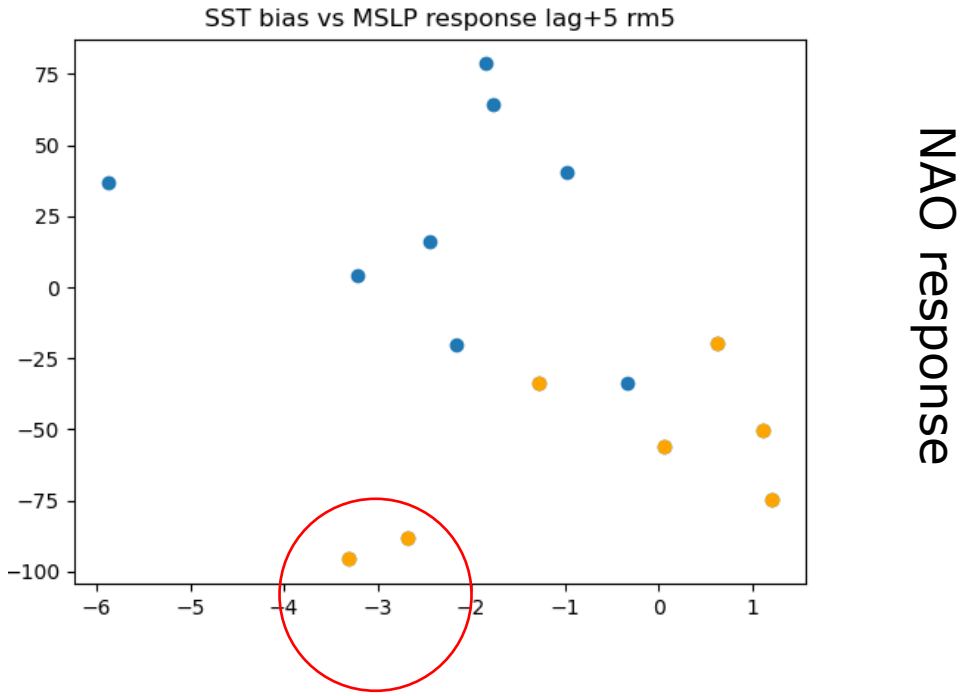


Neg. NAO models

Pos. NAO models
larger bias than
Neg. NAO models

Pos. NAO models

SPG bias ⟷ NAO response at lag +5

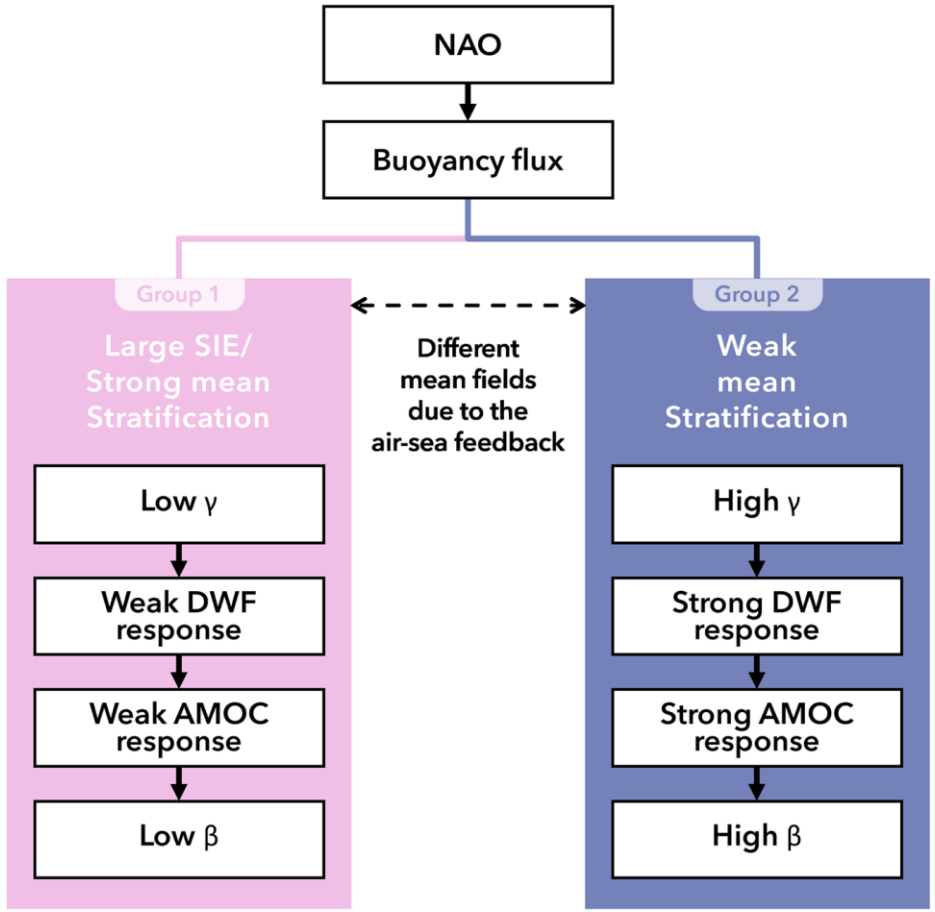


Neg. NAO models
Other models

Kim et al. 2023

γ: sensitivity of deep water formation to buoyancy flux

β: sensitivity of AMOC response to NAO forcing



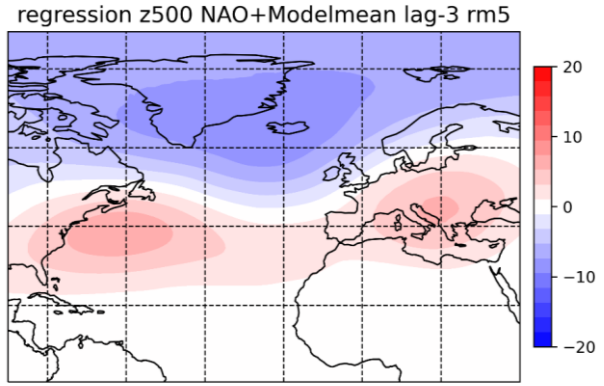
strong bias

weak bias

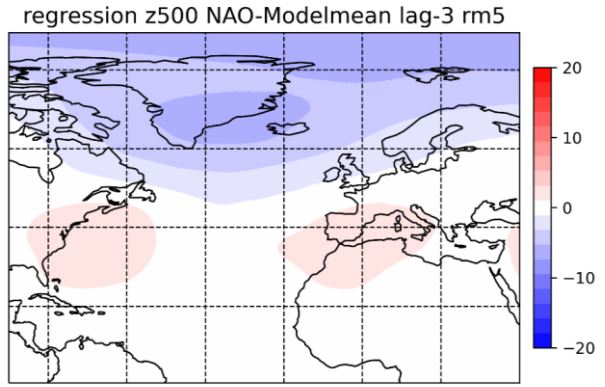
Neg. NAO models

Pos. NAO models

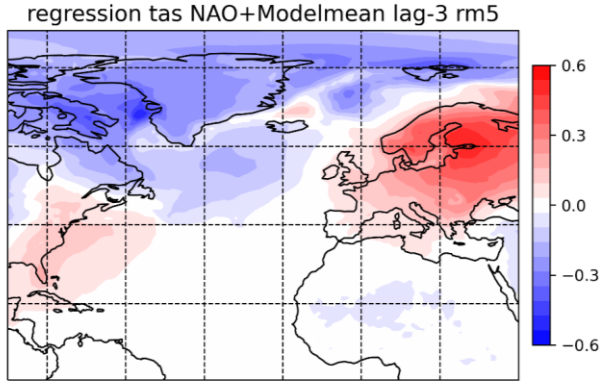
Z500



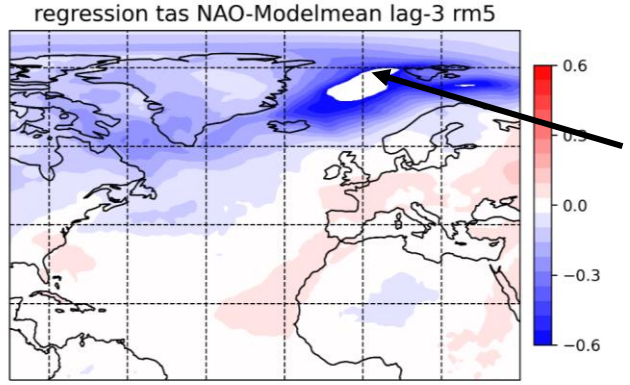
Regression on AMOC at lag -3



T2m

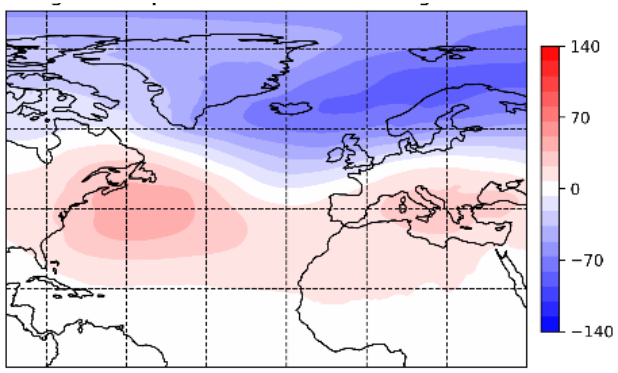


At lag-3 T2m response seems to affect MSLP response

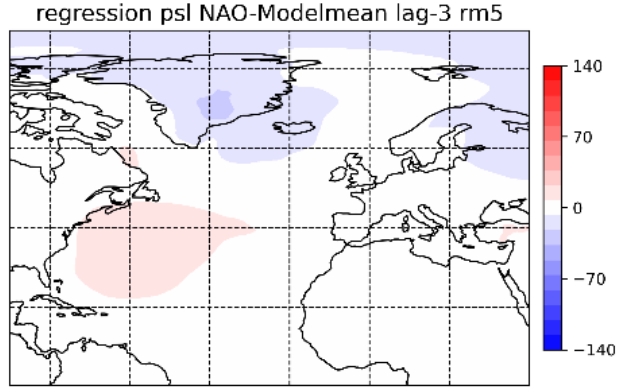


Impact of sea-ice response

MSLP



Cold – High
Warm – Low
mechanism



Effective resolution atmosphere models
(Klaver et. al 2020)

High Ocean (0.25°)		Low Ocean (1°)	
V High Res (≤ 185 km)	High Res (185-256 km)	Low Res (256-364 km)	V Low Res (≥ 364 km)

model	group	SPG SST bias
ECMWF HR	Neg. NAO	-1.3
HadGEM HH	Neg. NAO	+0.6
HadGEM HM	Neg. NAO	+0.1
CMCC-VHR	Neg. NAO	+1.1

model	group	SP SST bias
ECMWF MR	Pos. NAO	-1.0
MPI XR	Pos. NAO	-3.2
ECMWF LR	Pos. NAO	-5.9
EC-Earth HR	Pos. NAO	-1.8

model	group	SPG SST bias
CNRM HR	Pos. NAO	-5.9
HadGEM MM	NAO0	-0.3
MPI HR	NAO0	-2.2
EC-Earth LR	Pos. NAO	-2.4

model	group	SPG SST bias
HadGEM LL	Neg. NAO	-3.3
CMCC HR	Neg. NAO	+1.2
CNRM LR	Neg. NAO	-2.7

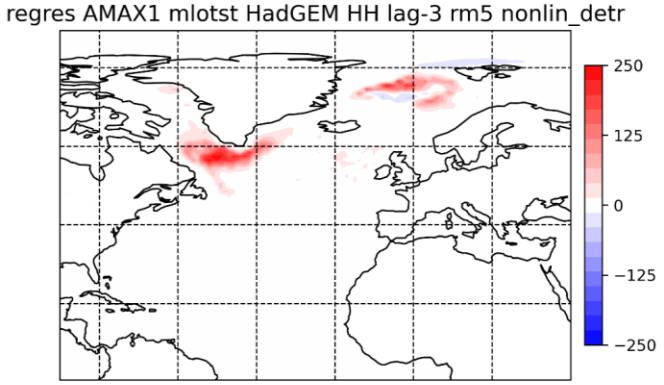
SPG SST bias is averaged over SPG box in °C

Neg. NAO response for very high and very low-resolution models

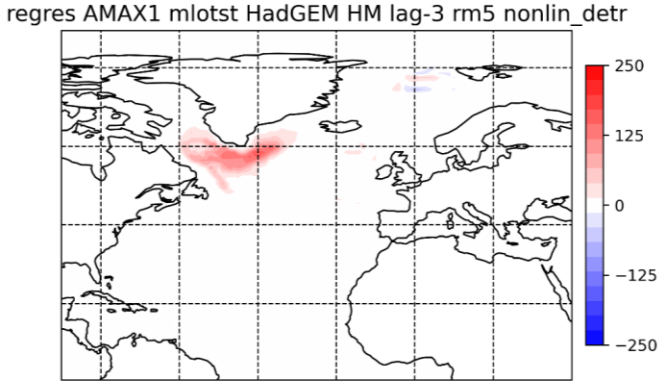
Very low-resolution models well-tuned?

DWF for a few models at lag -3

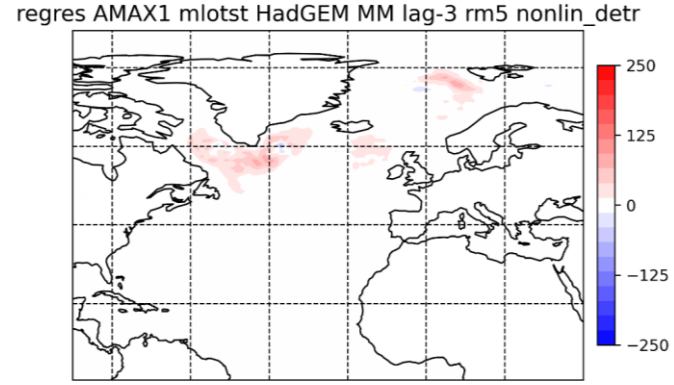
HadGEM HH



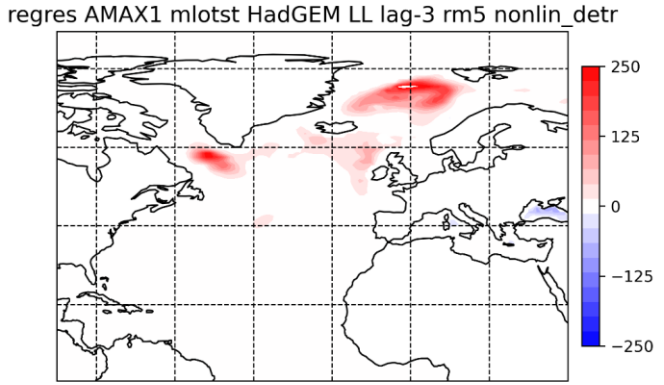
HadGEM HM



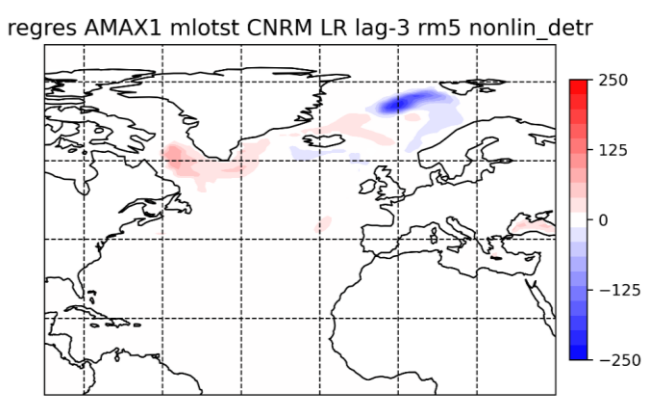
HadGEM MM



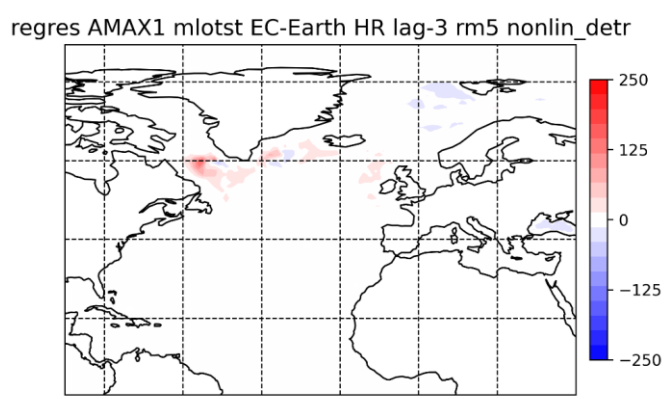
HadGEM LL

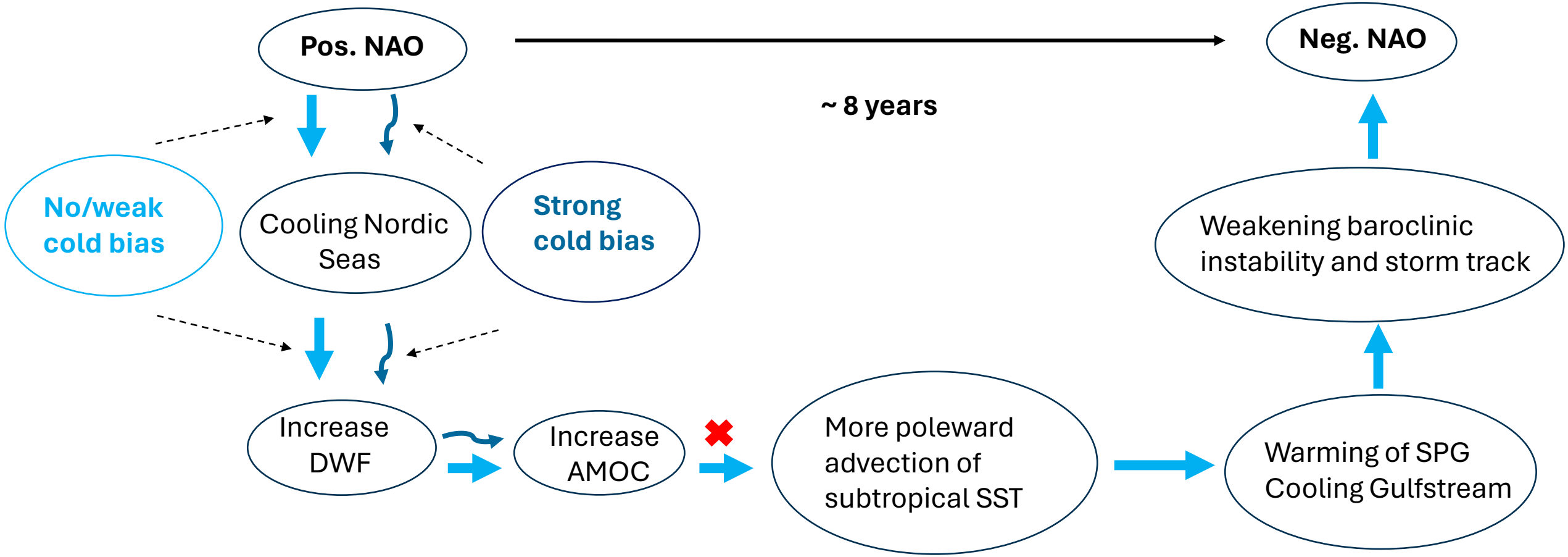


CNRM LR



EC-Earth HR

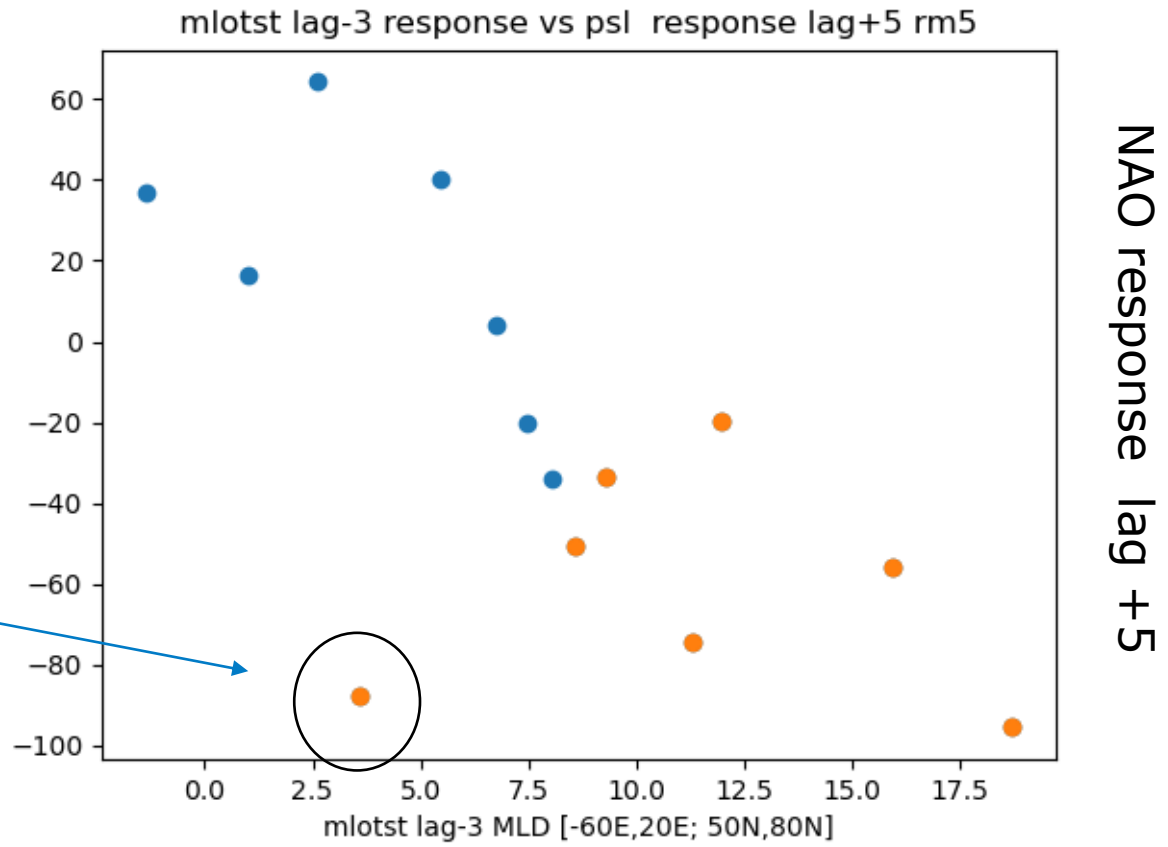




NAO – AMOC feedback

Scatter plot DWF lag -3 with NAO response at lag +5

CNRM LR: Enhanced DWF in Labrador sea is compensated by reduced DWF in Gin sea

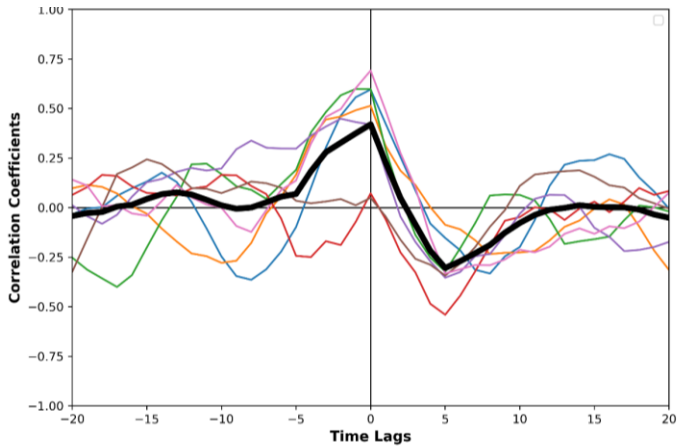


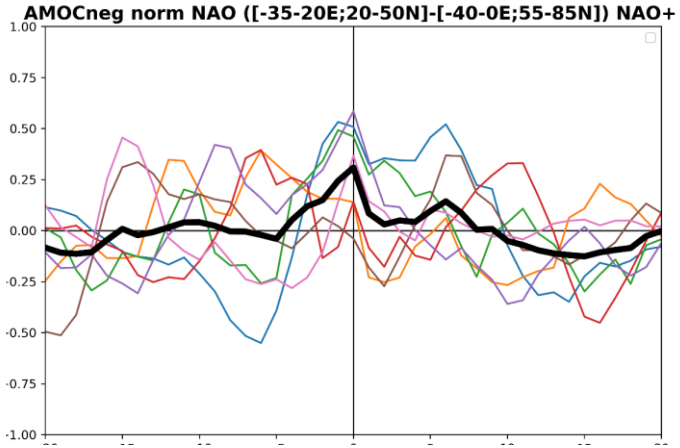
NAO – AMOC feedback is non-linear

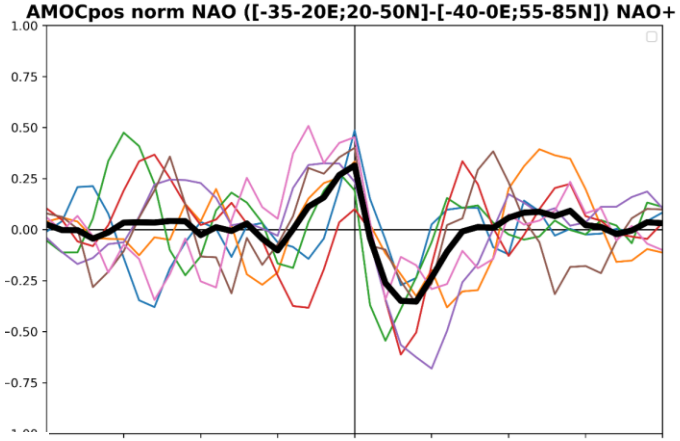
All AMOC

Neg. AMOC

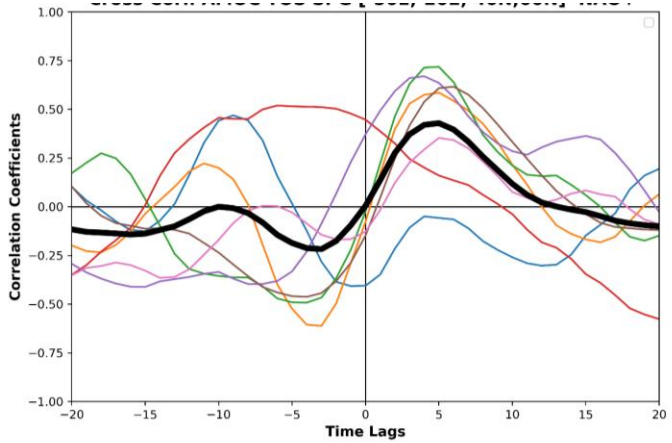
Pos. AMOC

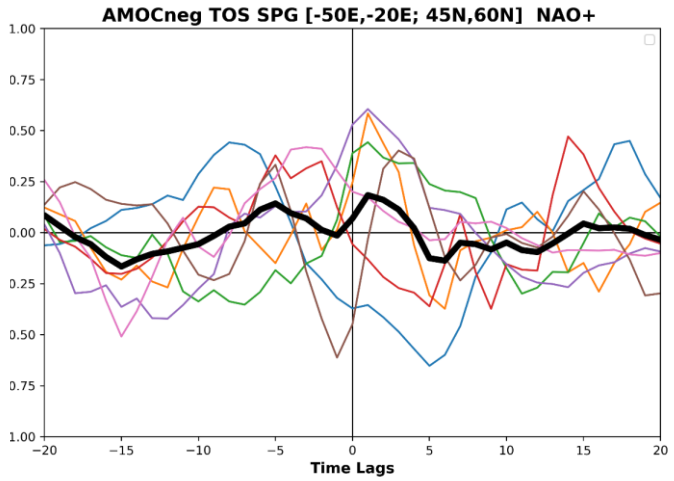


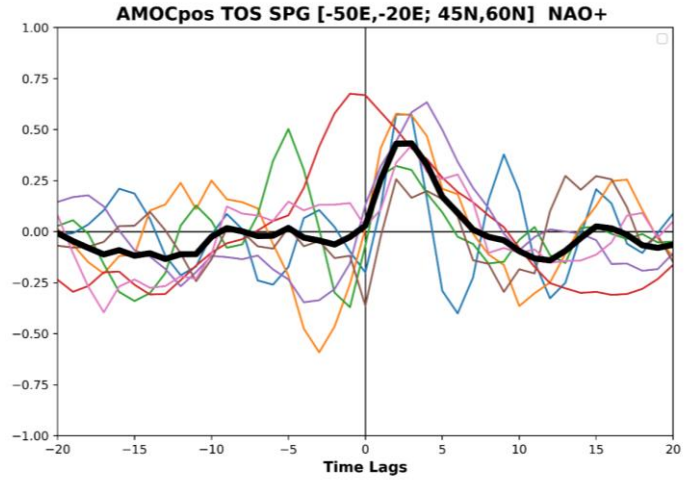




NAO







SST

Conclusions

- Different behaviour of PRIMAVERA models with respect to AMOC-NAO interaction
- SST bias in the SPG appears to be the main cause for the different behaviour. Resolution is important to reduce the bias. Tuning can compensate errors.
- Models with small bias simulate a switch from positive to negative NAO at positive lags of the AMOC
- RAPID – ERA5 and ERA5 support the forcing of a negative NAO by the AMOC at positive lags

Discussion

For reliable decadal predictions:

- Crucial to reduce the SST-bias in the SPG and the sea-ice bias in the GIN sea
- Use flux correction to reduce the bias?

EERIE funding

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101081383

All UK Partners in EERIE are funded by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant numbers 10057890, 10049639, 10040510, 10040984).

ETH Zürich's contribution to EERIE is funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract #22.00366.

END