Ocean and Climate Responses to NAO Surface Heat Flux Forcing in Climate Models

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NCAR

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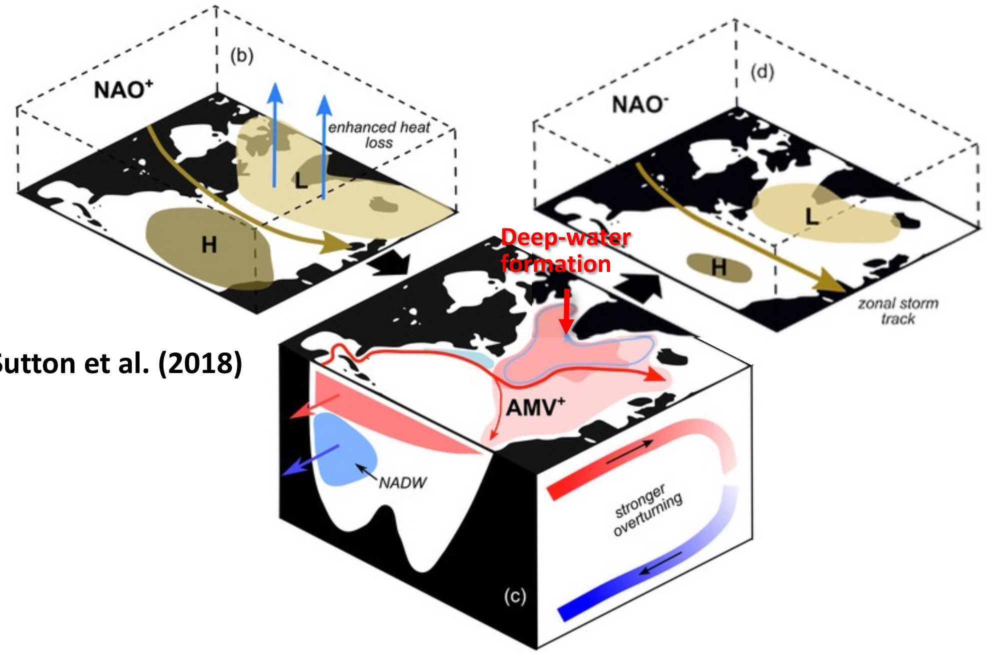
Mechanisms of decadal NA Variability

- North Atlantic Oscillation (NAO) plays a key role for decadal North Atlantic variability
- **Buoyancy-driven ocean dynamics**
- Direct influence through surface fluxes including Ekman heat transport

NAO
↓
Deep water formation
↓
AMOC & Subpolar gyre
↓
SPNA heat and salt contents



Sutton et al. (2018)

Mechanisms of decadal NA Variability

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correlation

NAO
↓
Deep water formation
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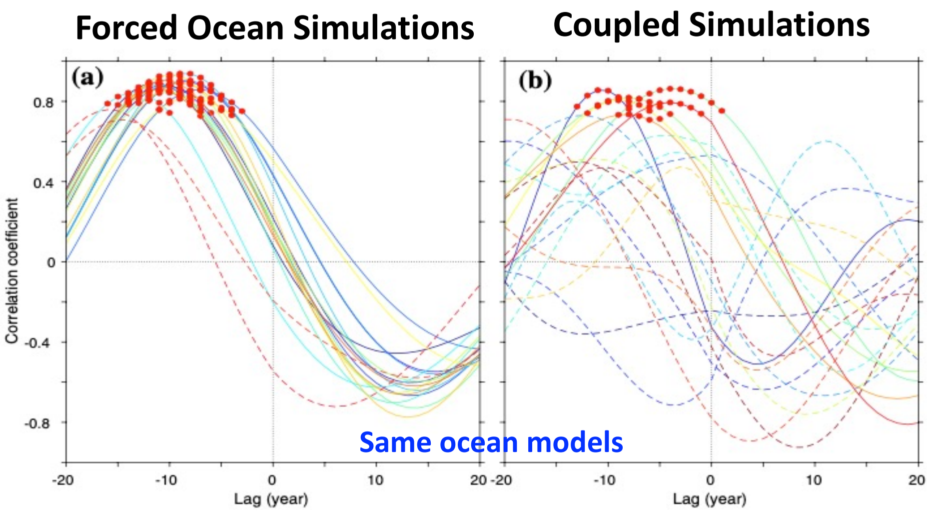
SPNA heat and salt contents



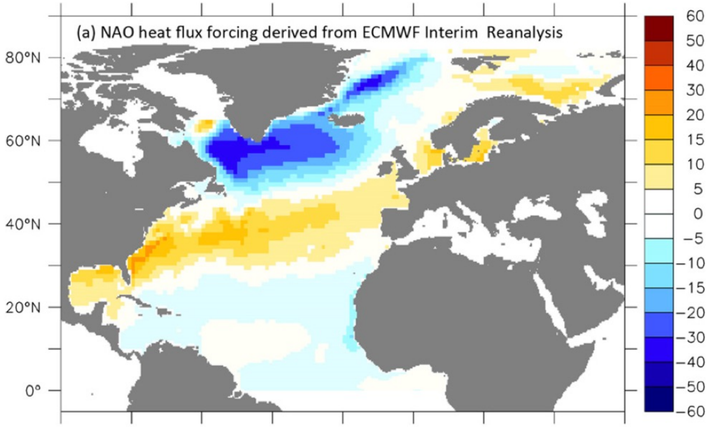
Xu et al. (2019)

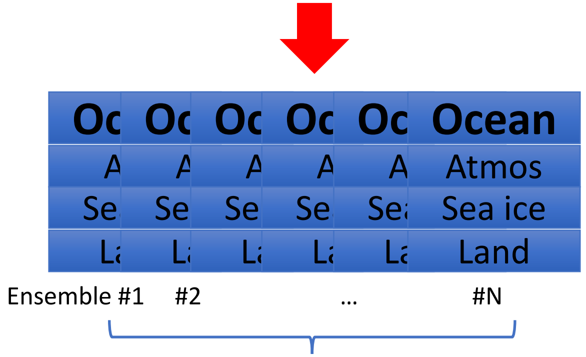
Possible reasons:

- Different representation of surface heat fluxes associated with NAO (eg., pattern and decadal power)
- Different efficacy of NAO buoyancy forcing for driving ocean response due to different mean states

Mechanisms of decadal NA Variability

Delworth & Zeng (2016)

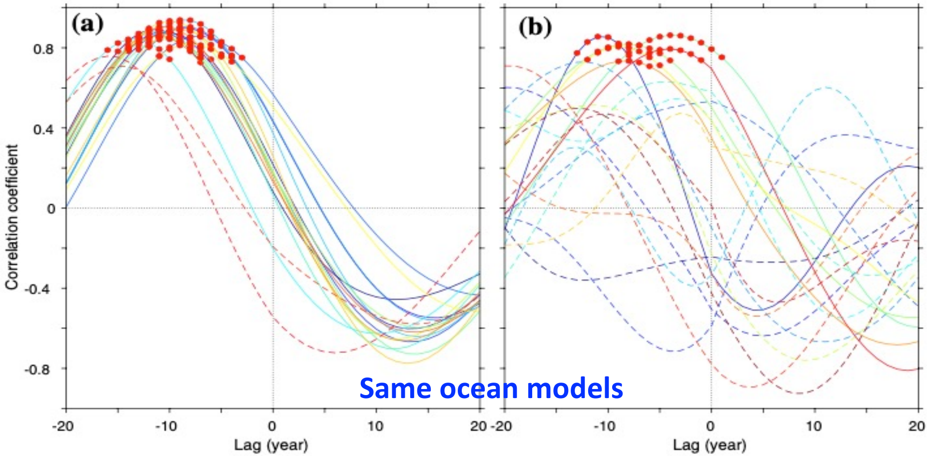




Ensemble mean: response to the forcing

Forced Ocean Simulations

Coupled Simulations



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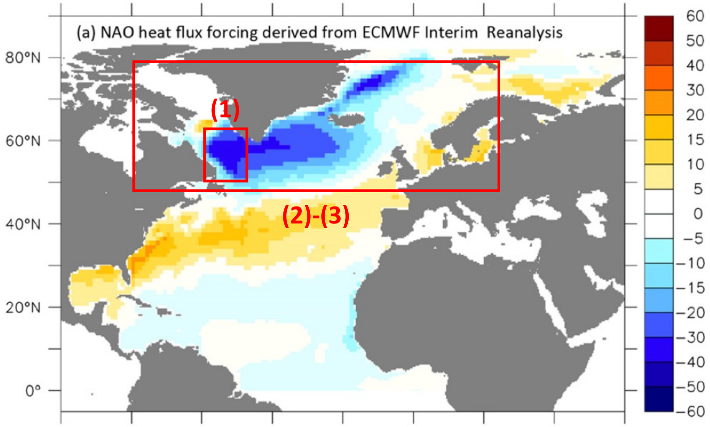
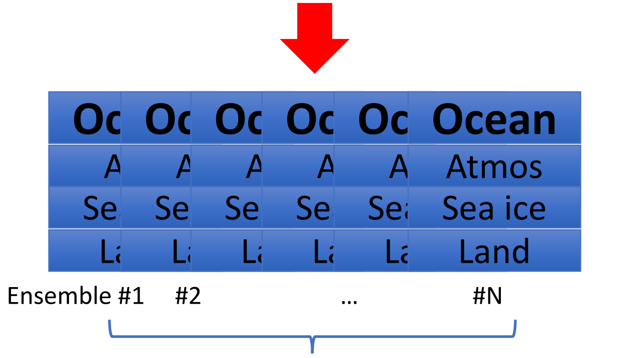
NAO Surface Heat Flux Forcing Experiments

Delworth & Zeng (2016)





Ensemble mean: response to the forcing

1) Lab Sea-only forcing applied in CESM1 (Kim et al. 2020) – **B-LS**
2) Full SPNA forcing applied in CESM2, GC3.1-LL, EC-Earth3P – **B-SPNA**
3) Same as (2), but in high-res ocean-sea-ice models

- Both ±NAO Forcing are applied for **the first 10 years (winter only)**; run for additional 10-20 years without the forcing
- Ensemble size: 10 for each ±B-LS and 20-25 for each ±B-SPNA (3 for high-res experiment)
- Ensemble mean difference between ±experiments

* Forcing over a limited area and "on and off" allow for effective isolation of the response from the forcing

B-LS Experiment

DOI: 10.1175/JCLI-D-19-0530.1

Atlantic Multidecadal Variability and Associated Climate Impacts Initiated by Ocean Thermohaline Dynamics

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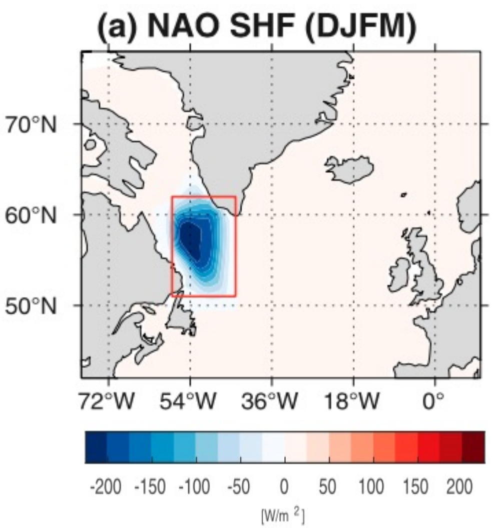
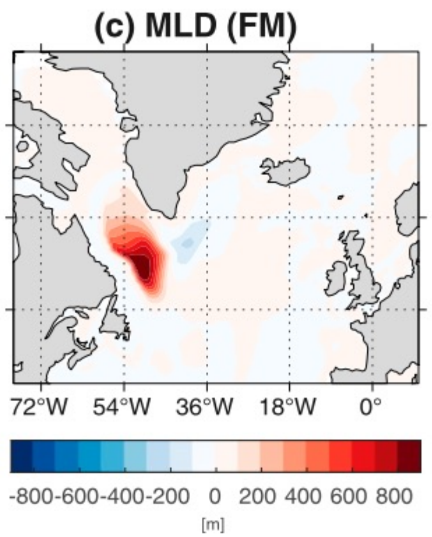
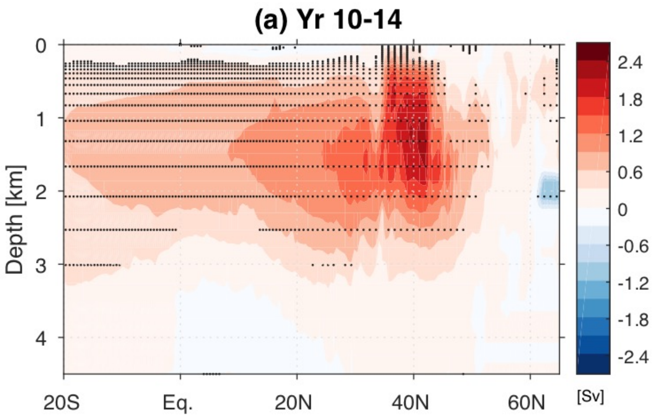
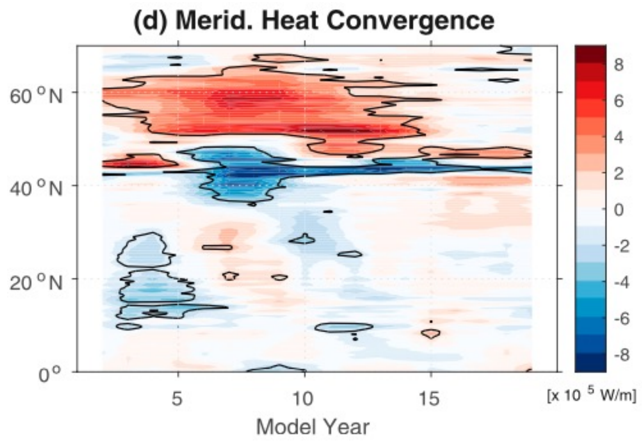
Yr 1-10



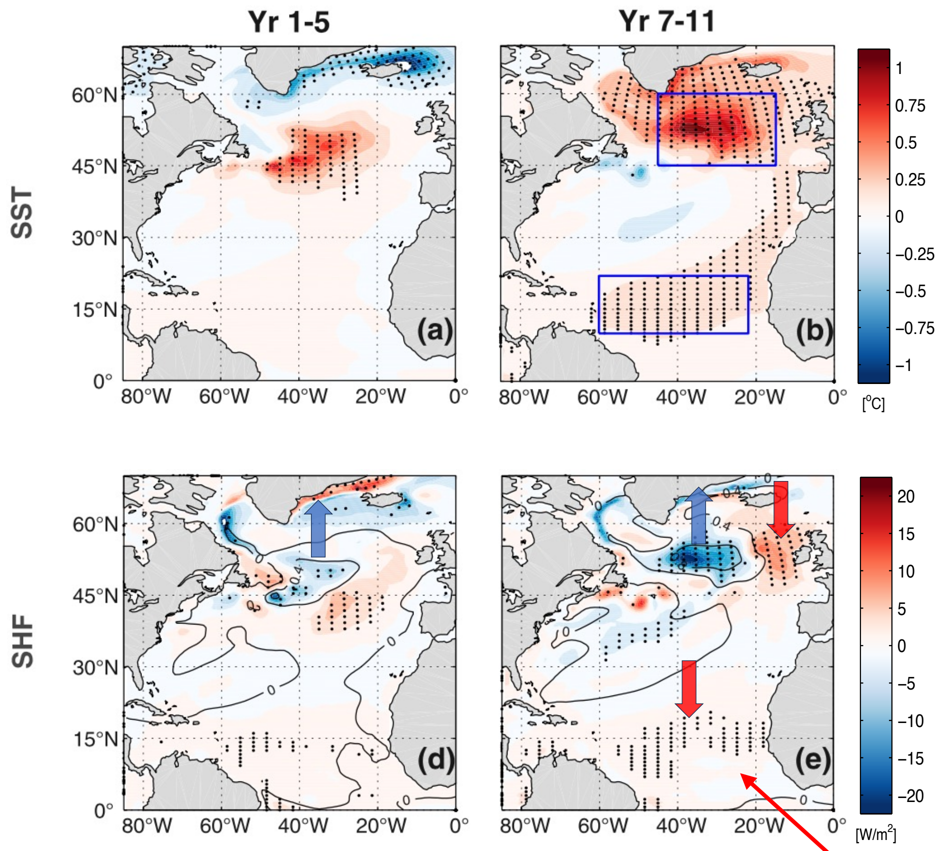


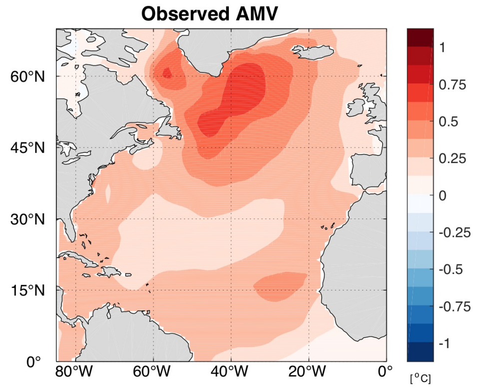
AMOC

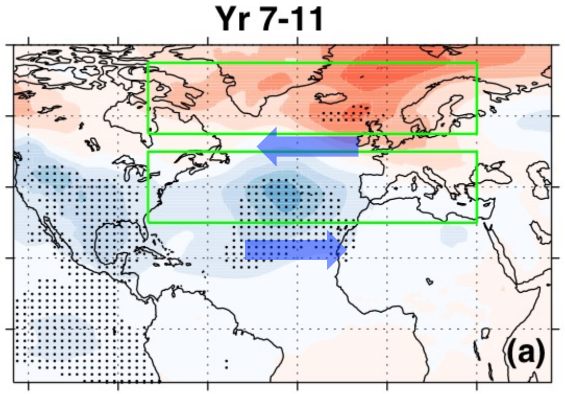




B-LS Experiment – Ocean Response





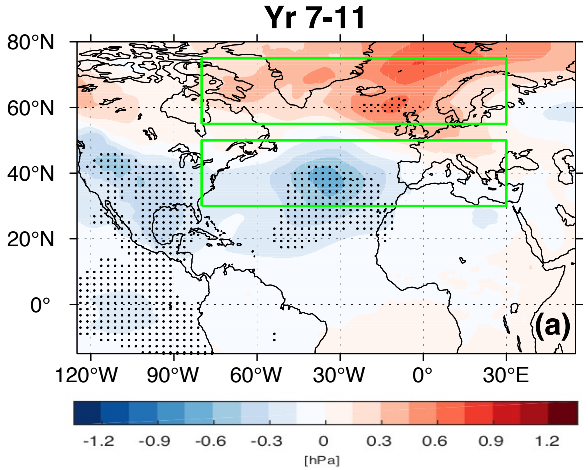


The atmosphere is not heated by the ocean!

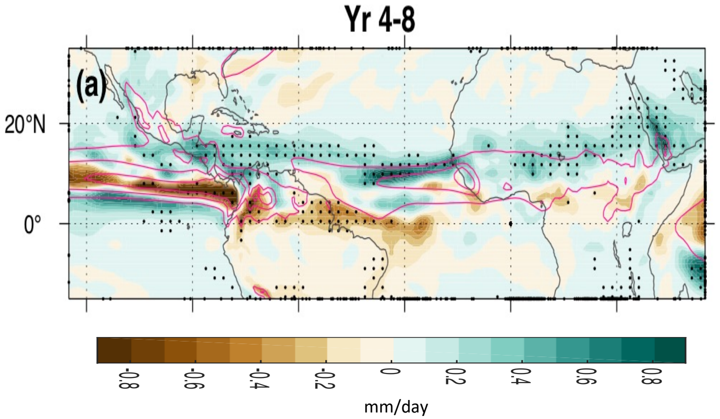
B-LS Experiment – Atmospheric Response

B-LS

Ann SLP

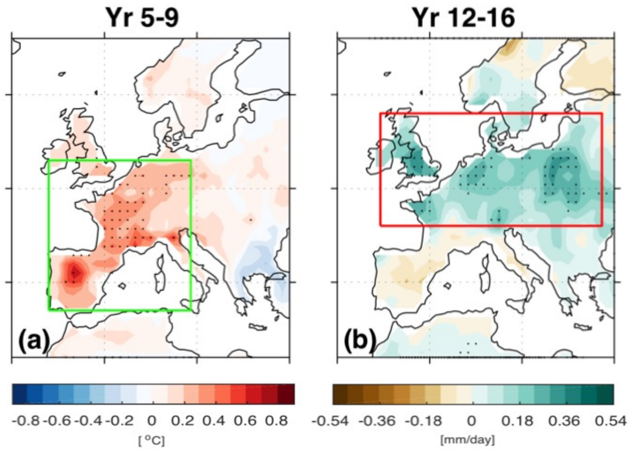


JJAS Precipz

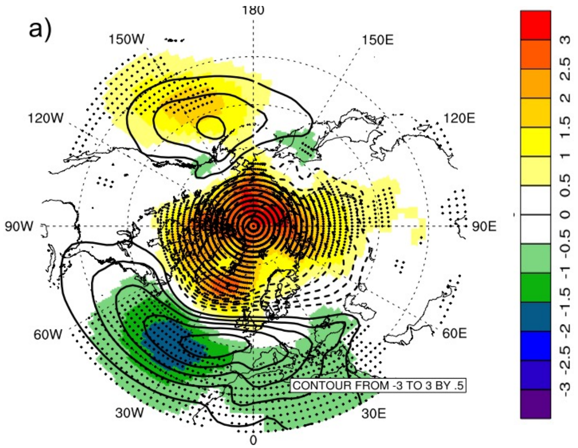


JJAS Ts

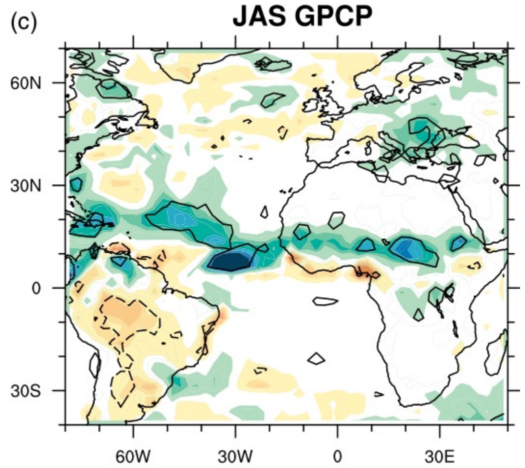
JJAS Precip



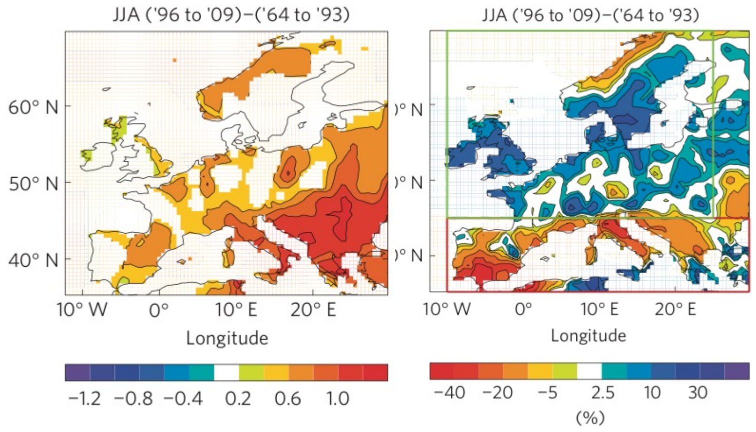
Observational Estimates



Peings & Magnusdottir (2014)

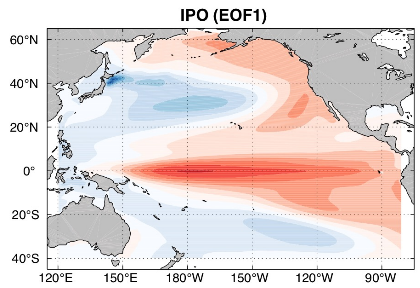


Martin & Thorncroft (2014)

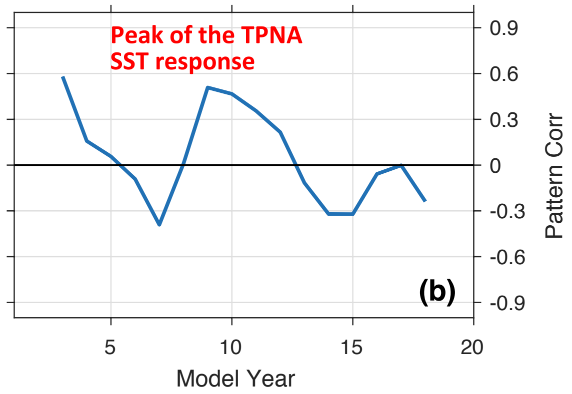


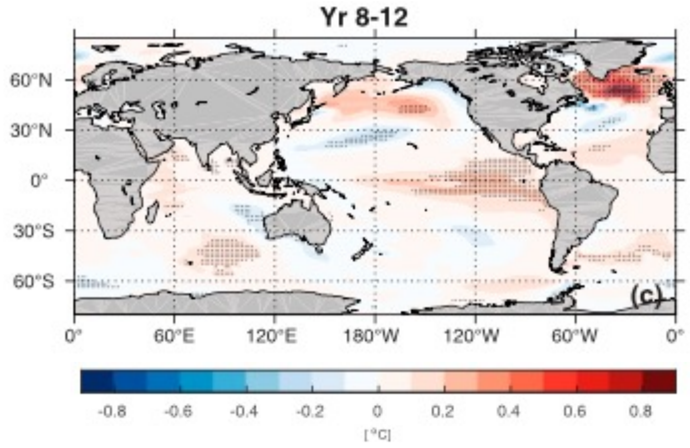
Sutton & Dong (2012)

B-LS Experiment – TBI

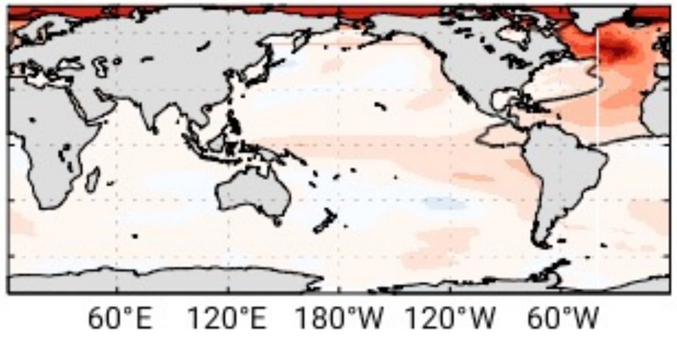


AMV-IPO Relationship

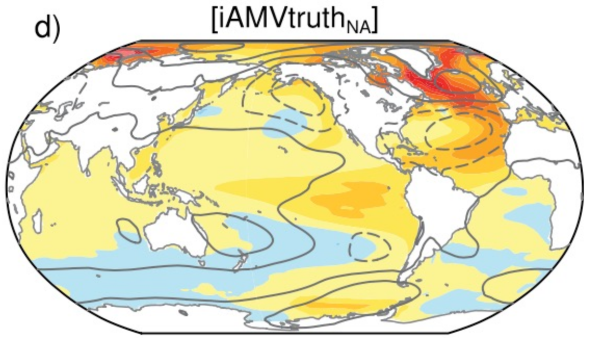




SST Regression on AMV in the CESM1 piControl



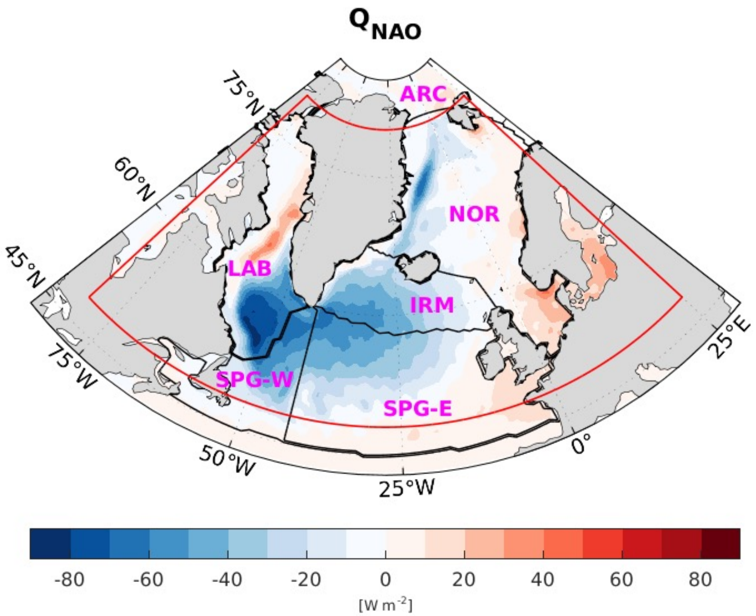
MMM SST Regression on AMV



Deser & Phillips (2023)

No +AMV ➞ –IPO link is found likely because the tropical North Atlantic does not drive the overlying atmosphere (see also O'Reilly et al. 2023)

B-SPNA Experiment



10-yr +NAO

10-yr –NAO

CESM2
(10 + 20 yr x 20 mem)

HadGEM-GC3.1-LL
(10 + 10 yr x 20 mem)

EC-Earth3P
(10 + 20 yr x 25 mem)

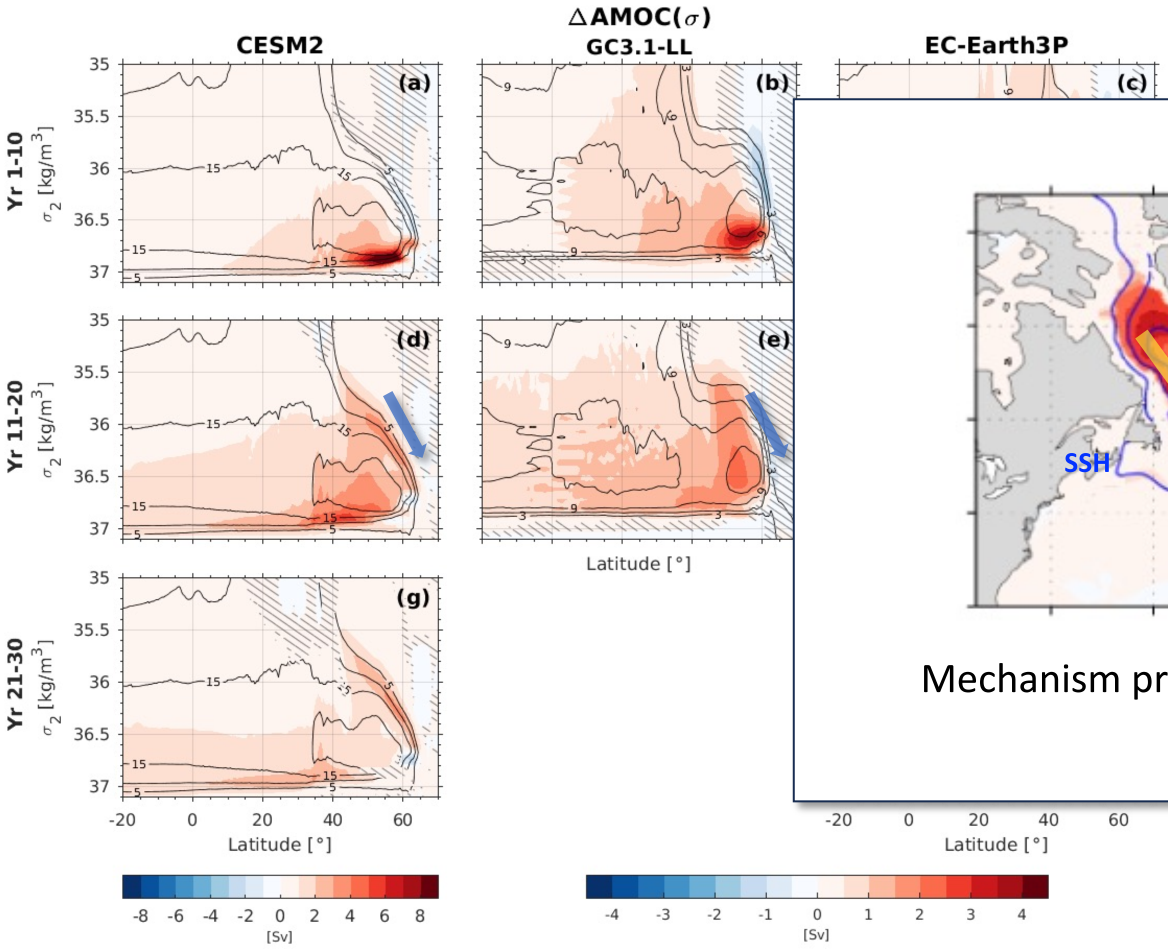
Questions: Is the mechanism of ocean response to NAO surface heat flux forcing robust across the models?

* Manuscript (Kim et al.) submitted to *J. Clim.*

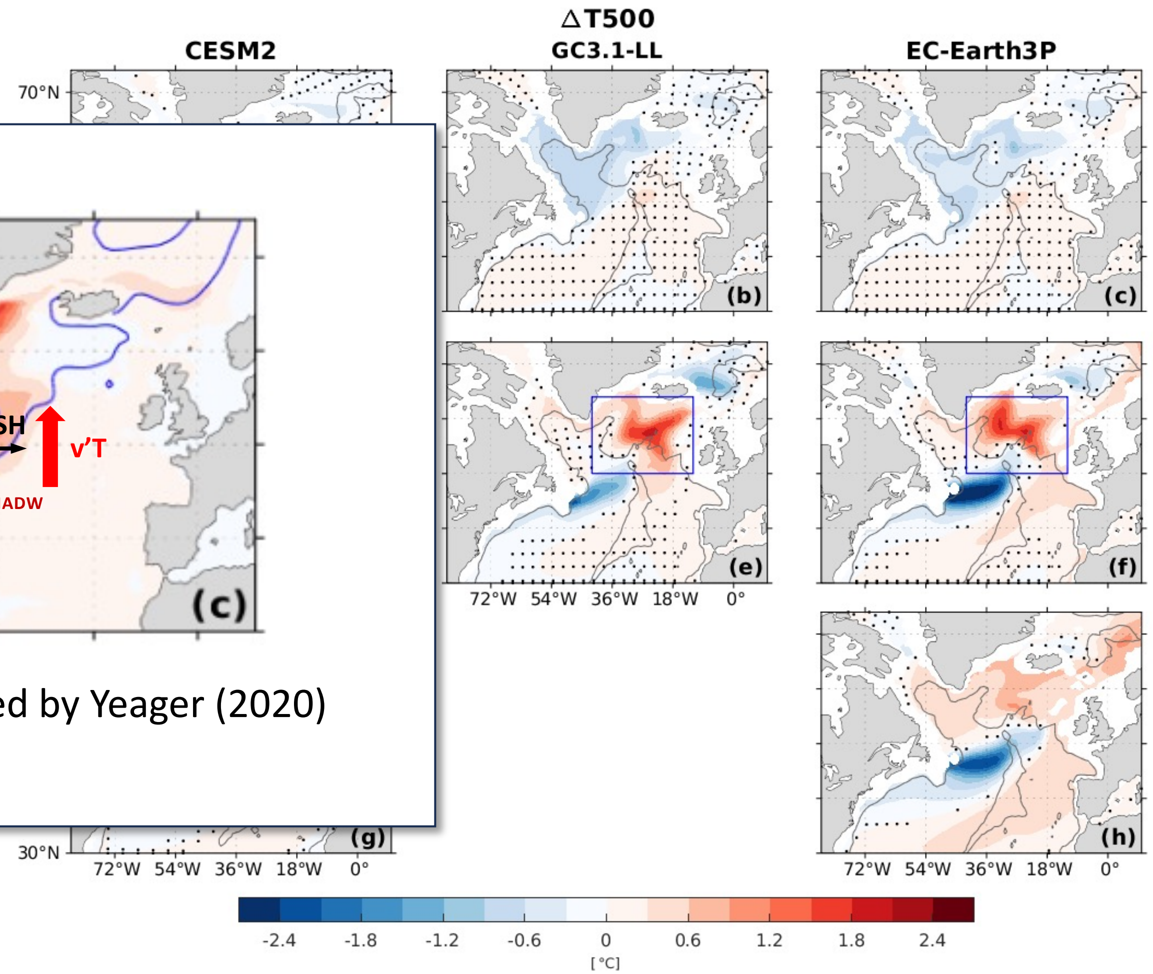
Wider Impact of Subpolar North Atlantic Decadal Variability on the Ocean and Atmosphere

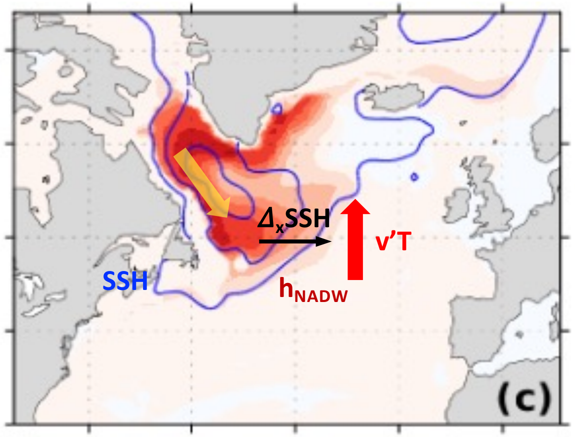
B-SPNA Experiments – NA Response

AMOC (σ)



Upper 500m Temperature





Mechanism proposed by Yeager (2020)

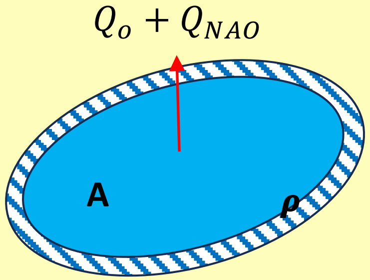
Responses are generally consistent, but the amplitude of the AMOC response is stronger (∼2x) in CESM2

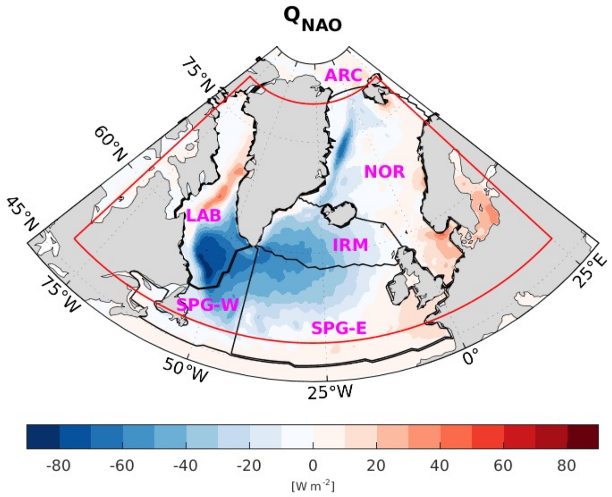
B-SPNA Experiments – WMT Response

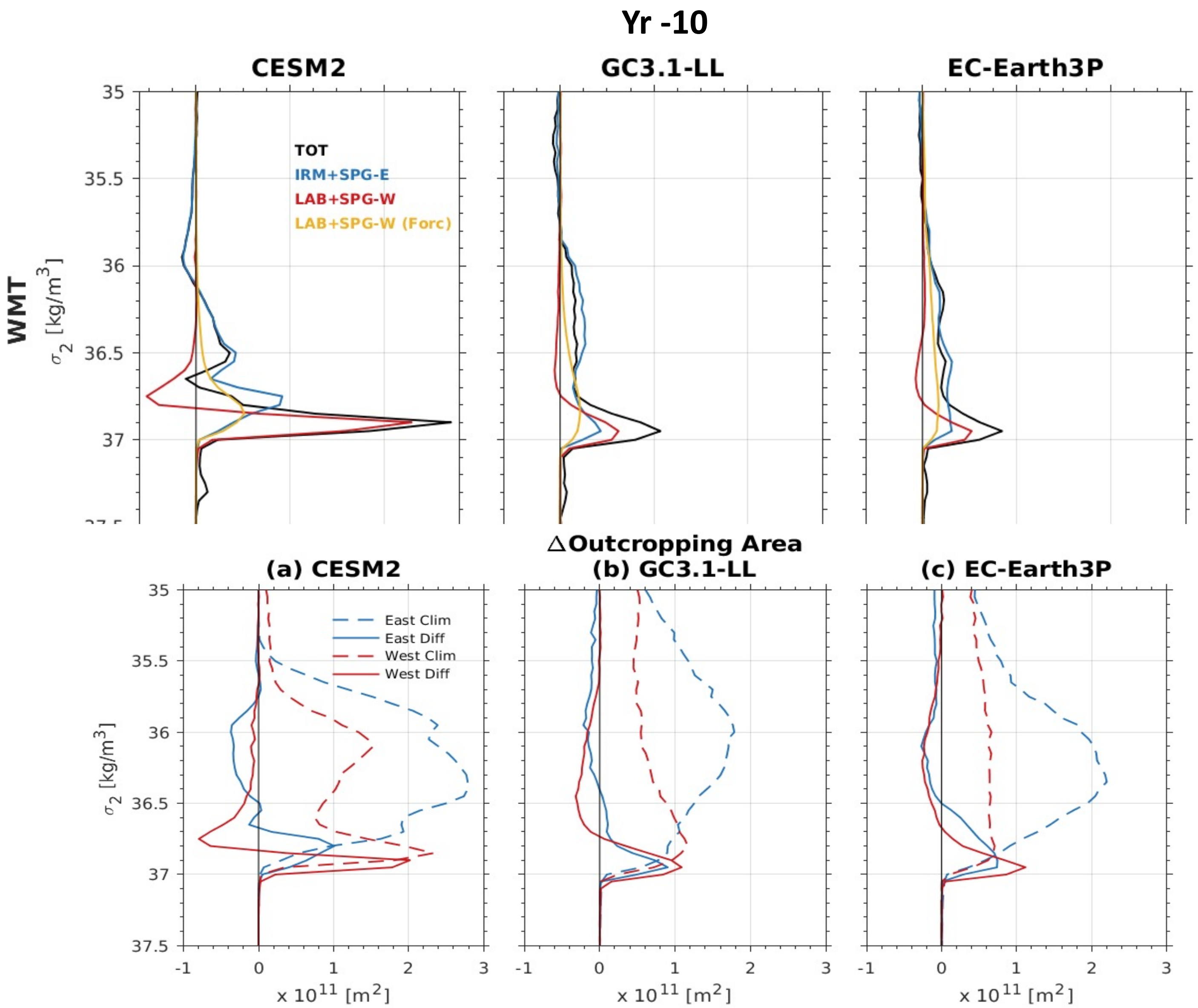
$$\mathbf{WMT}(\boldsymbol{\rho}) =$$

$$\frac{1}{\Delta\rho}\iint -\frac{\alpha}{C_p}(Q_o+Q_{NAO}) - \beta\frac{S}{1-S}F_o\, dA_\rho$$

isopycnal out-cropping area

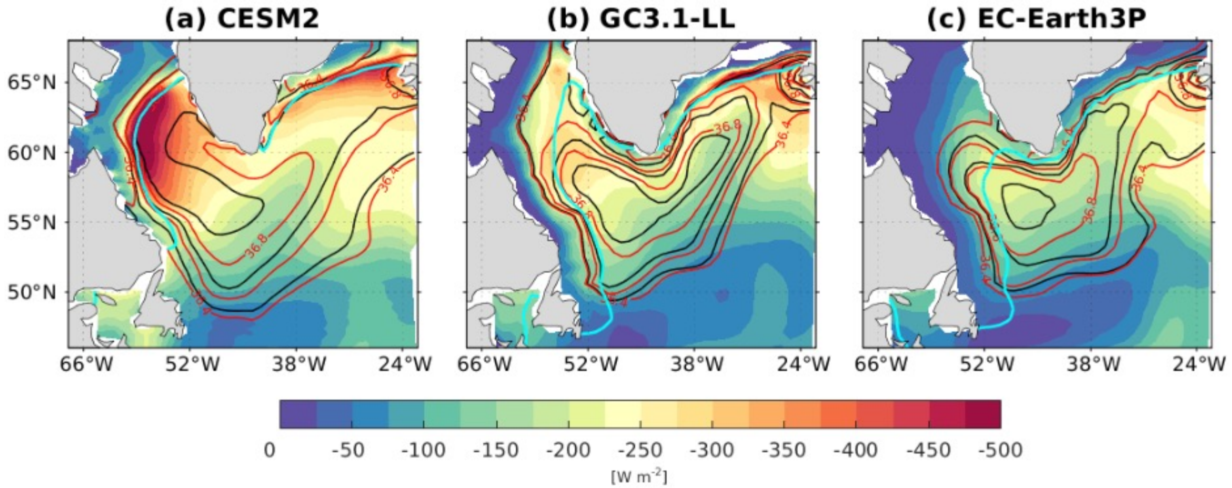




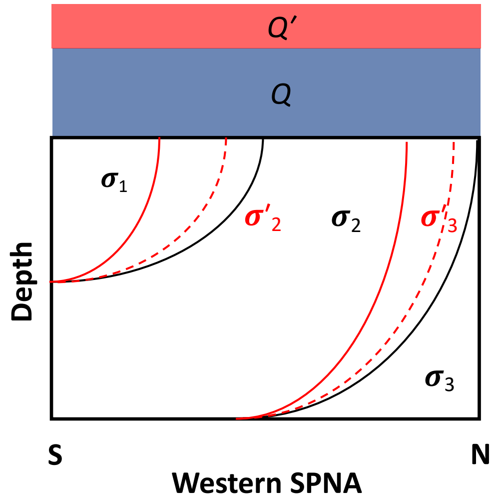


B-SPNA Experiments – WMT Response

Surface density and heat flux



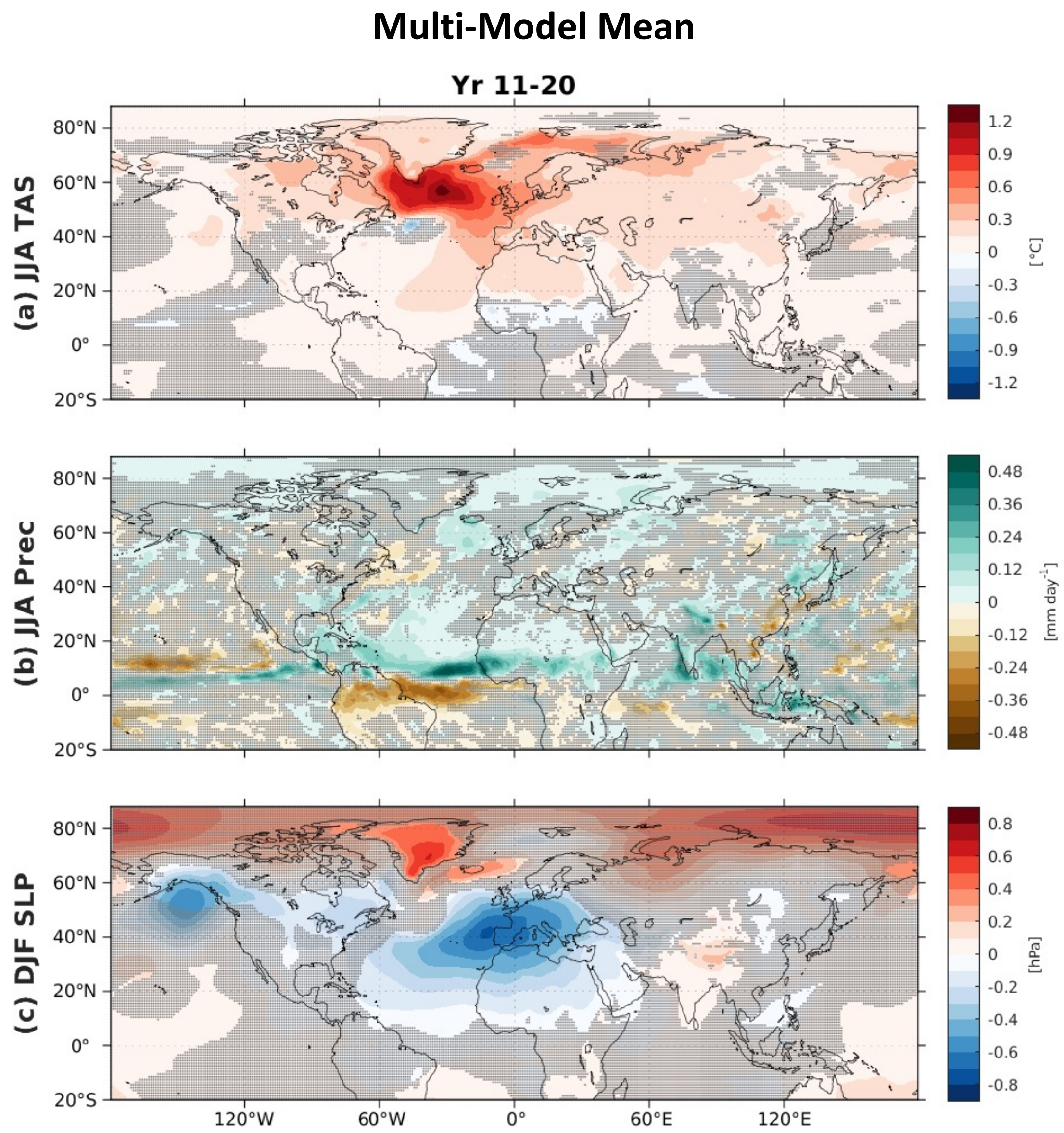
Shading: climatological surface heat flux
Black con: climatological surface density
Red con: first decade surface density from the +NAO exp.



- Q' initially cools and makes the surface dense
- $A(\boldsymbol{\sigma}'_2) > A(\boldsymbol{\sigma}_2)$
  → $\boldsymbol{\sigma}_2$ exposed to more Q + Q′ (Q > Q′)
- $\boldsymbol{\sigma}_3$ exposed to $Q + Q'$ (WMT=0 before Q')
- Exposure to Q further expands $A(\boldsymbol{\sigma}'_{2,3})$
- Because Q is larger in CESM2, ΔWMT is also larger

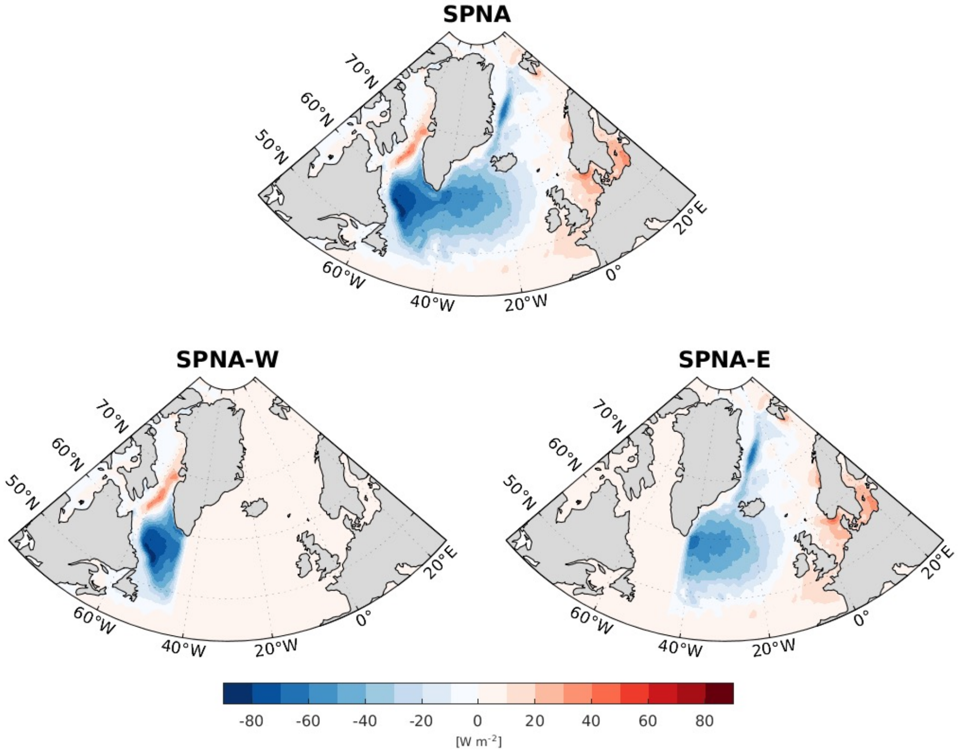
feedback

B-SPNA Experiment – Atmospheric Response



More detailed analysis will follow!

High-Resolution Ocean-Only B-SPNA Experiment



10-yr +NAO →

0.1° POP
(10 + 10 yr x 3 mem)

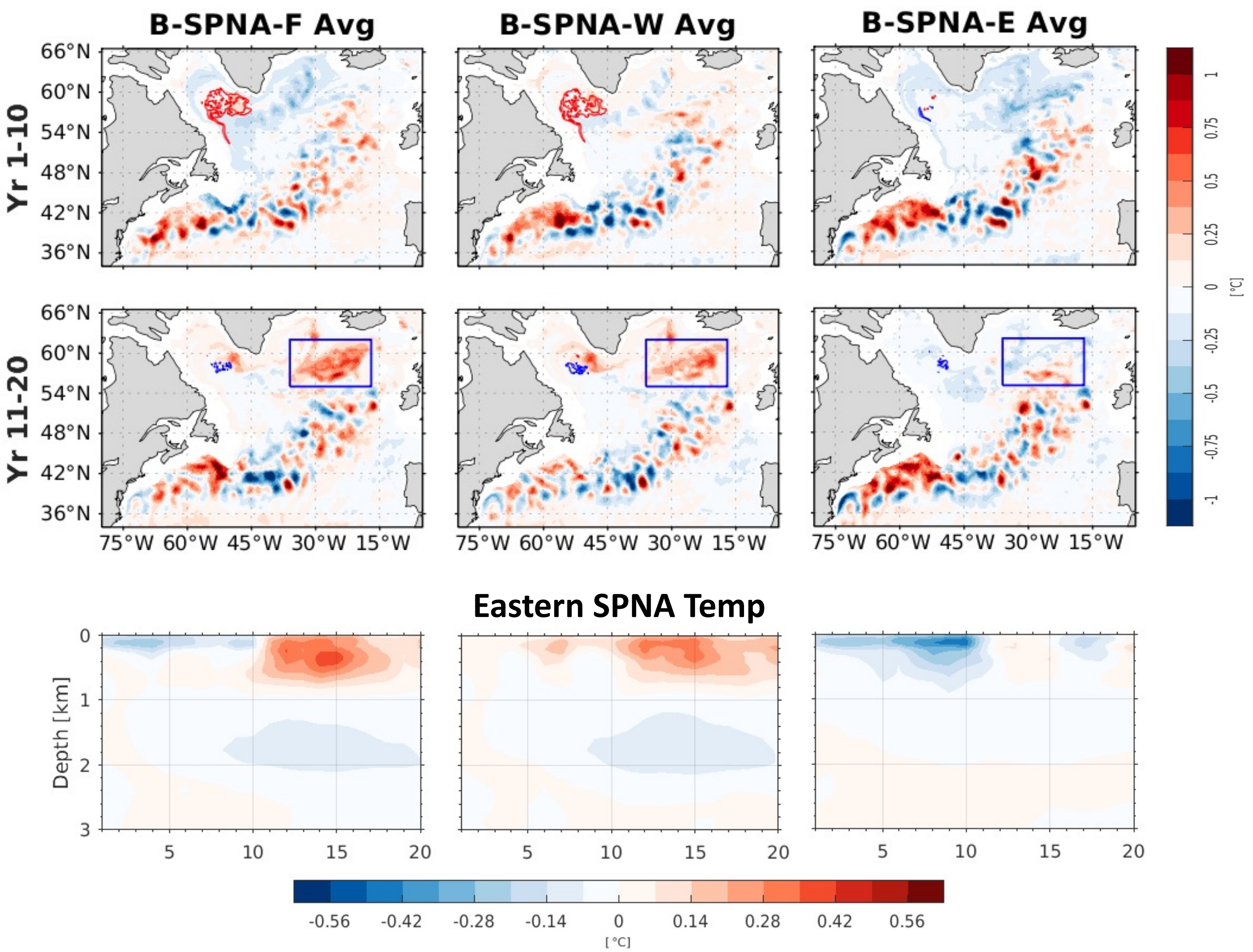
Qeustions:

1) Does the same mechanism exist in high-res models?
2) Which basin (west vs. east) is more important?

* Coordinated experiments (Participating groups: FSU, NCAR, NOC, Oxford; led by Margarita Markina, Oxford)

High-Resolution Ocean-Only B-SPNA Experiment

Upper 500 m Temp & Mar. MLD Anomalies (wrt the cntrl)



Summary

In response to observational NAO surface heat flux forcing imposed in multiple climate models from coarse- to high-resolution, we found

- **Consistent mechanism and pattern** of the North Atlantic Ocean response (dense-water formation → AMOC → heat content in the SPNA)
- **High-resolution** ocean-only experiments suggest the same mechanism is in action and western SPNA dominates
- **Changes in isopycnal outcropping area and associated exposure to the background surface heat fluxes** are the key for the initiation of the ocean response
- The different background states can explain the **inter-model amplitude difference**
- **Atmospheric response** consistent with observational estimates of the AMV impact
- **No evidence** of the AMV-IPO link likely because the tropical North Atlantic does not drive the overlying atmosphere