North Atlantic Ocean Response to NAO Surface Heat Flux in Three Climate Models

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NCAR

NSF

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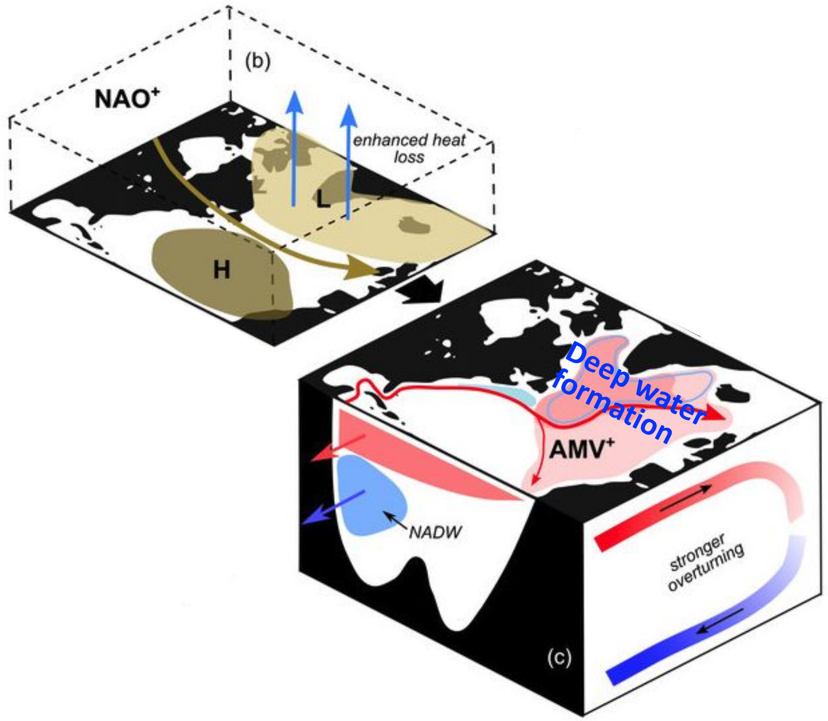
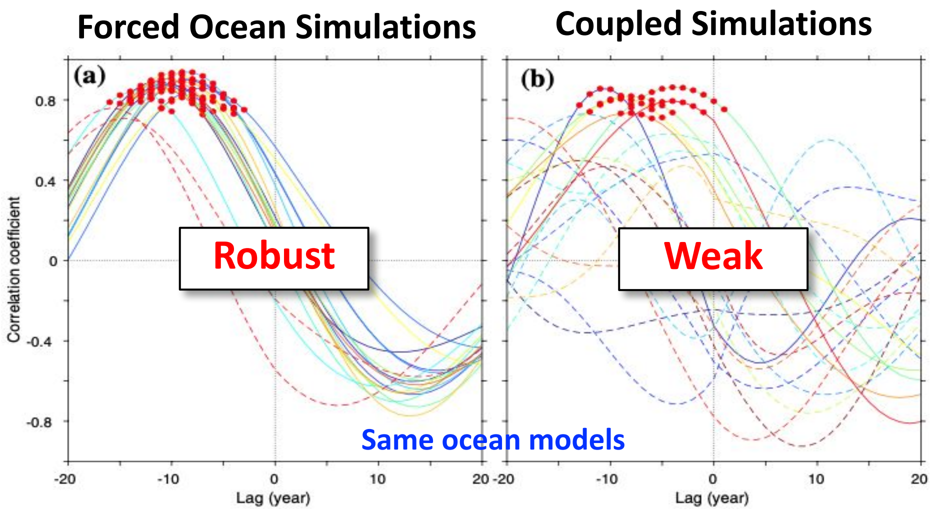
Mechanisms of decadal SPNA Variability



Sutton et al. (2018)

North Atlantic Oscillation (NAO)
↓
Deep water formation
↓
AMOC & Subpolar gyre
↓
SPNA heat and salt content

correlation



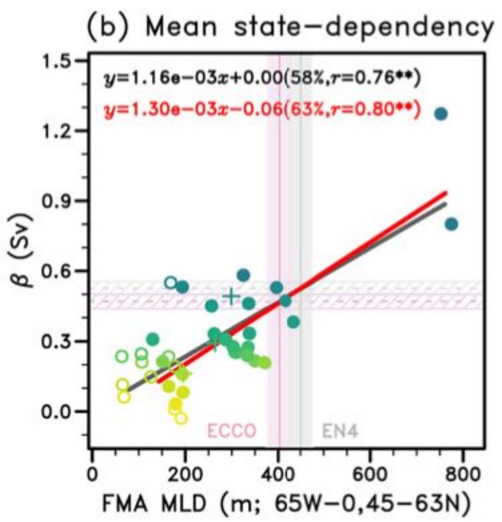
Xu et al. (2019)

Weak NAO-AMOC Relationship in Coupled Models

- Different representation of surface buoyancy (heat) fluxes associated with NAO
- Different efficacy of NAO buoyancy forcing for driving ocean response due to different mean states

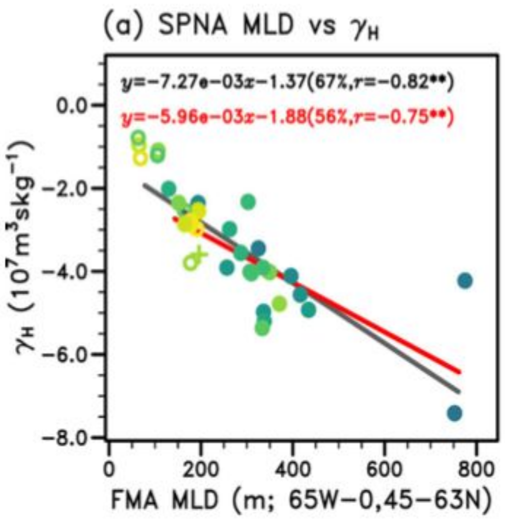
CMIP6 piControl

Strength of NAO-AMOC Link



Mean Stratification

Mean Surface Heat Flux



Mean Stratification

H. Kim et al. (2023)

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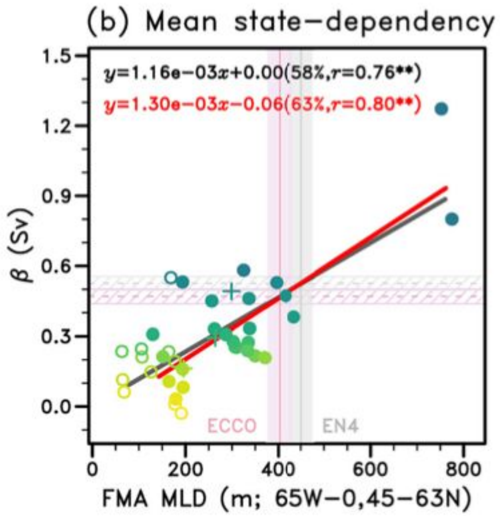

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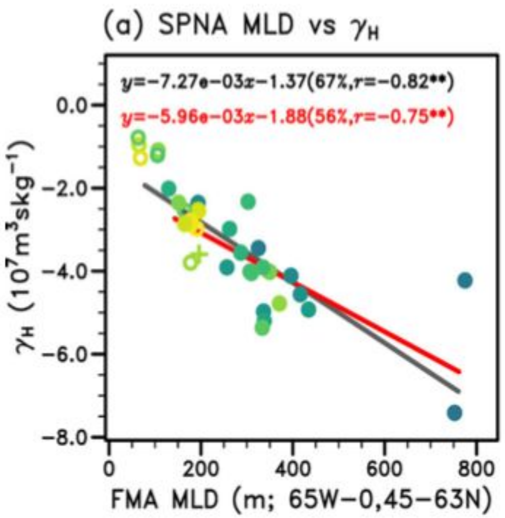
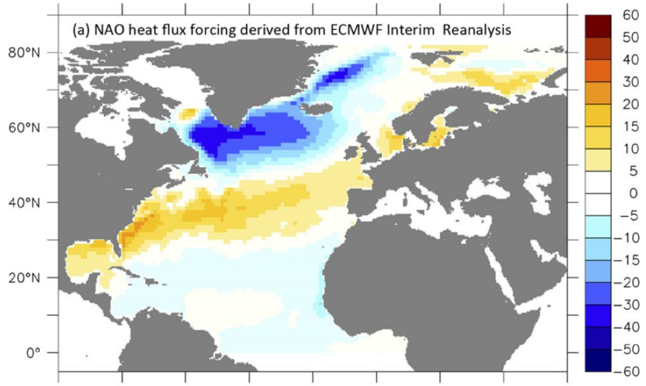
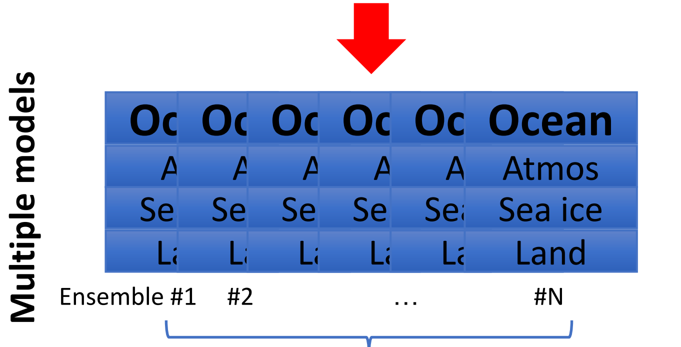


Mean Stratification

H. Kim et al. (2023)

Delworth & Zeng (2016); W. Kim et al. (2020)

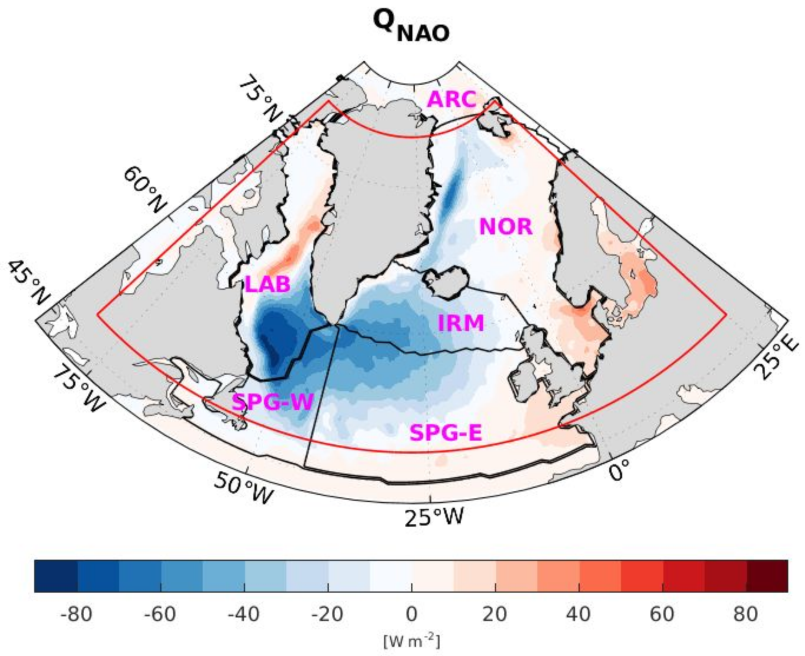




Ensemble mean: response to the forcing

Allowing for assessing the robust responses and the differences arising from different background states

Experimen ts



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)

- Obtained by regressing ERA5 surface heat flux onto an observed DJFM NAO index
- $\pm 2\sigma$ applied over the SPNA for 10 years (winter only); run for additional 10-20 years without the forcing

Focus: link between **surface water-mass transformation (WMT)**, AMOC and SPNA upper ocean temperature responses (ensemble mean differences)

WMT
Response

$$\mathrm{WMT}(\rho) = \frac{1}{\Delta\rho}\iint -\frac{\alpha}{C_p}Q_o - \beta\frac{S}{1-S}F_o\,dA_\rho$$

heat flux

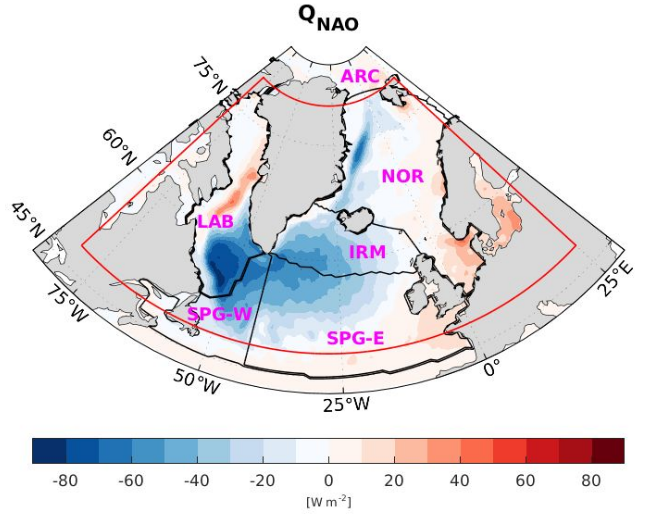
freshwater flux

isopycnal outcropping area

$$Q_o = Q_c + Q_{NAO}^{eff}, \quad Q_{NAO}^{eff} = Q_{NAO}\times(1 - a_i)$$

heat flux from coupler

heat flux forcing



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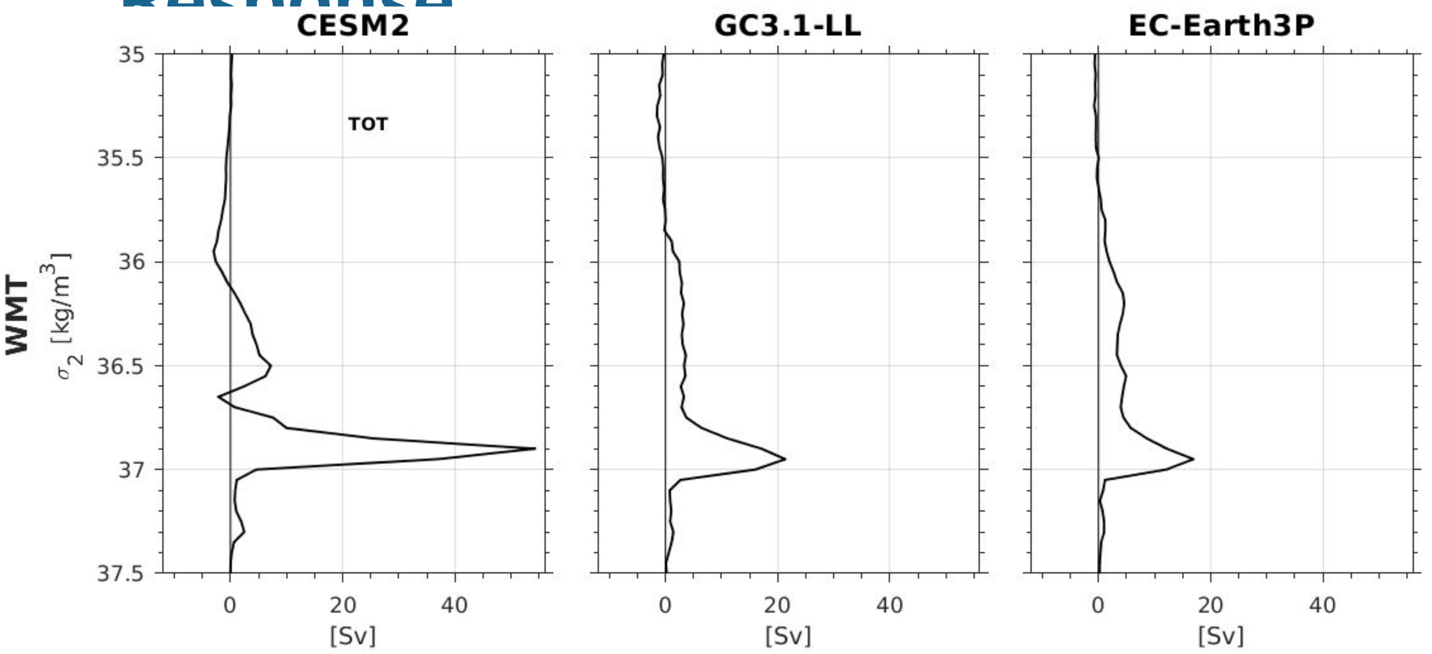

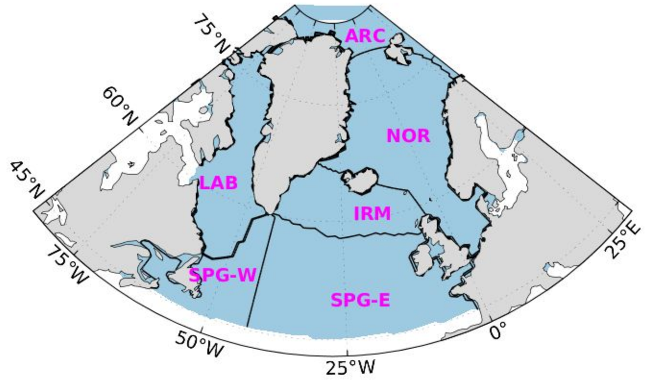

- ΔWMT over a similar density range, but larger (>2x) in CESM2

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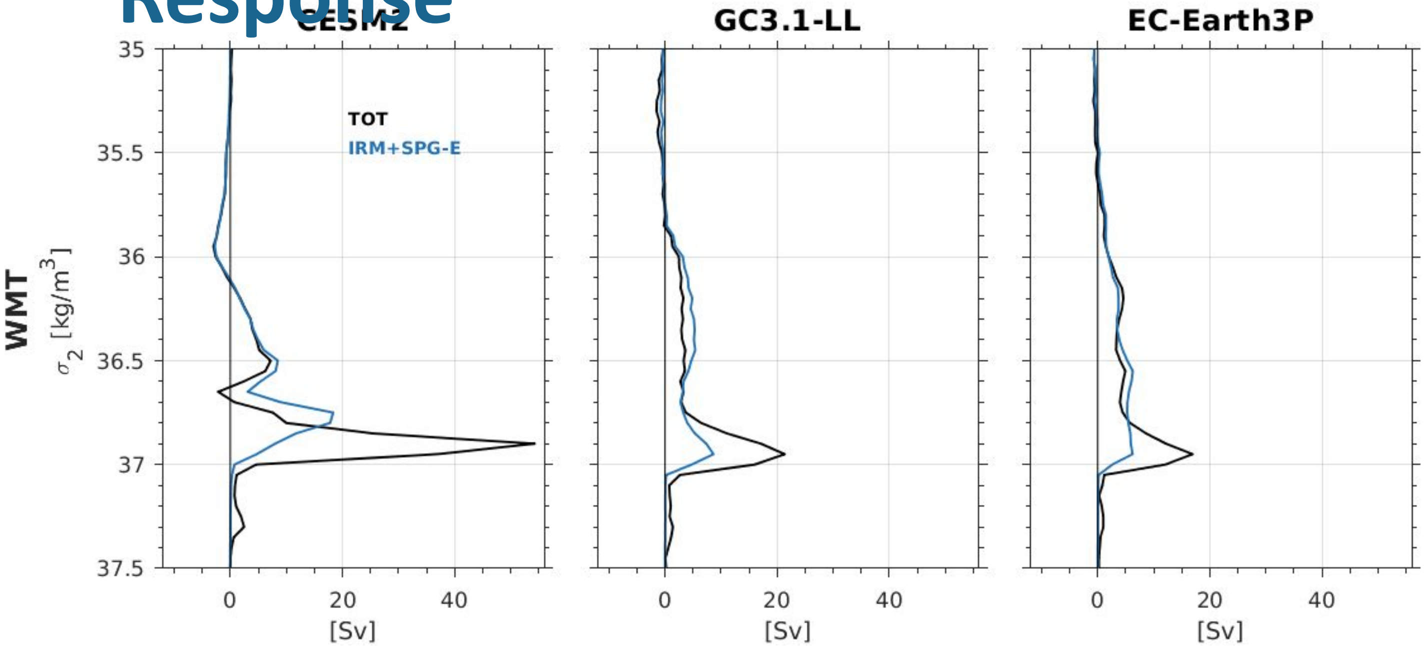

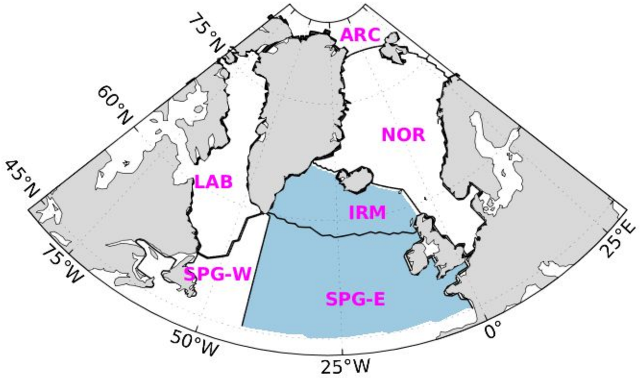

- ΔWMT over a similar density range, but larger (>2x) in CESM2
- Weak and lighter ΔWMT in the eastern SPNA

WMT Response

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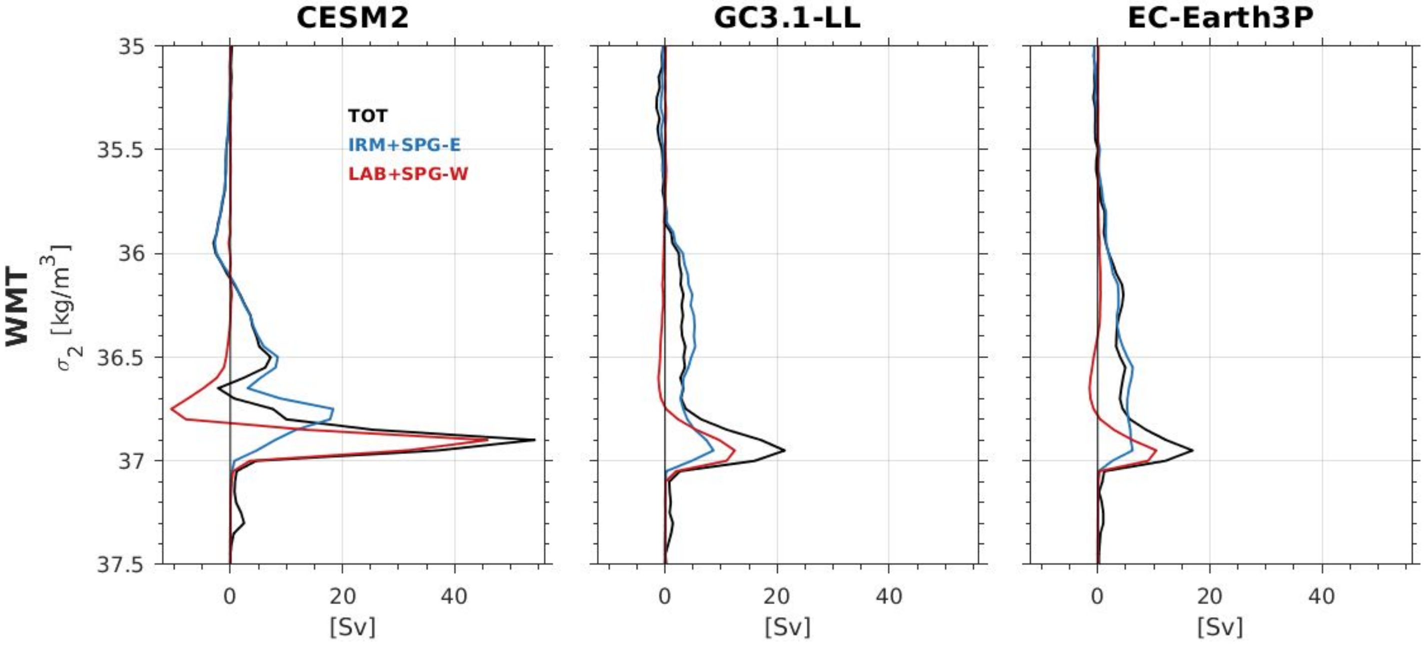

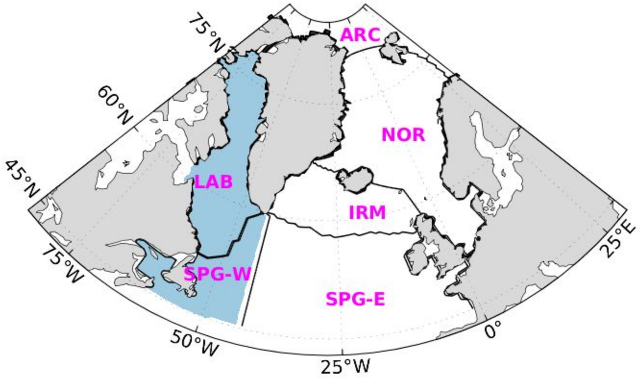

- ΔWMT over a similar density range, but larger (>2x) in CESM2
- Weak and lighter ΔWMT in the eastern SPNA
- Large ΔWMT contribution from the western SPNA (dominating in CESM2) – climatological WMT contributed by different locations
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WMT Response

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heat flux; freshwater flux; isopycnal outcropping area

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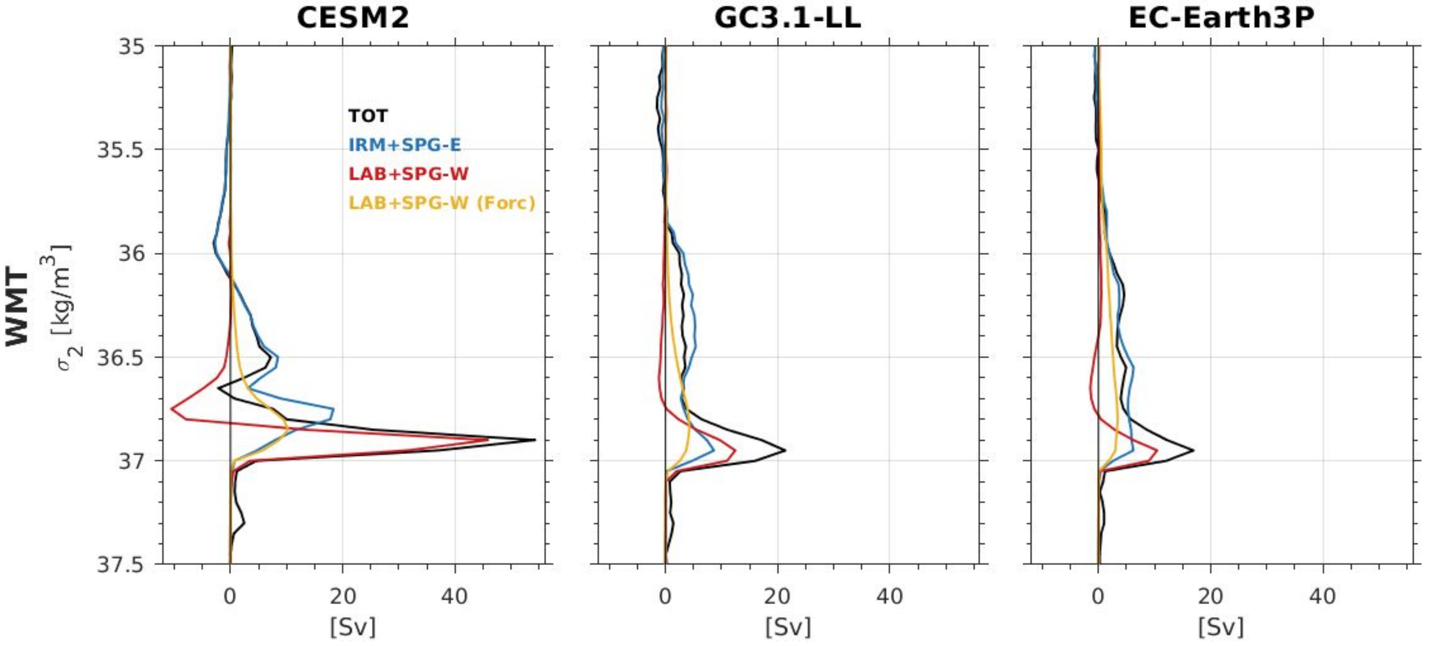
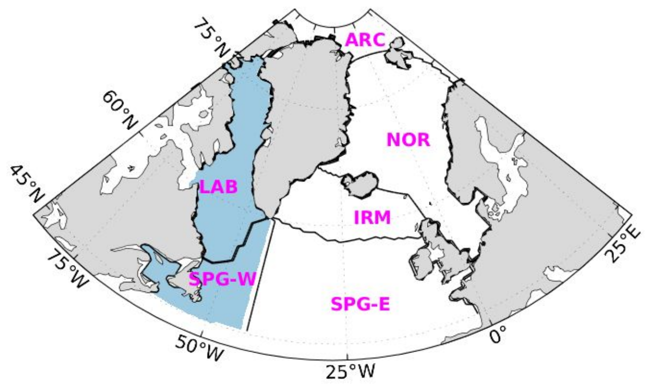
heat flux from coupler; heat flux forcing





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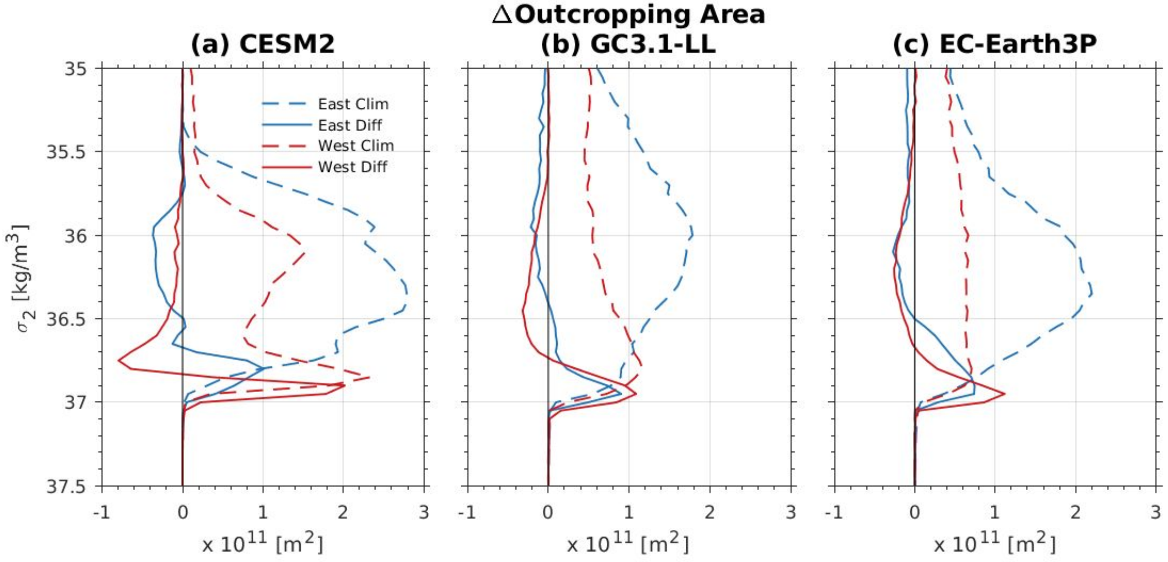
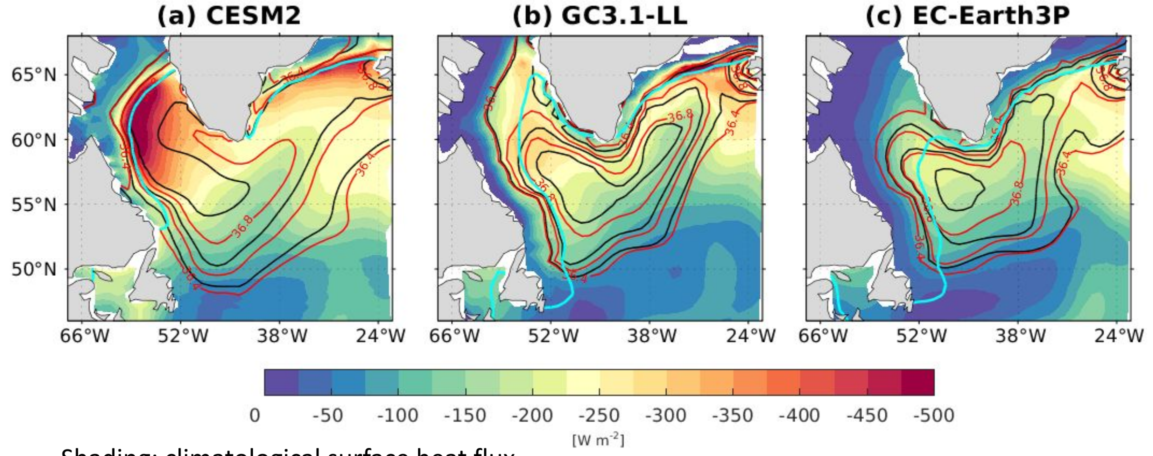
- ΔWMT directly induced by the forcing is relatively small
- ΔQ_c itself is small ➞ ΔWMT is largely induced by ΔA_ρ

Outcropping Area Response and Heat Flux Feedback



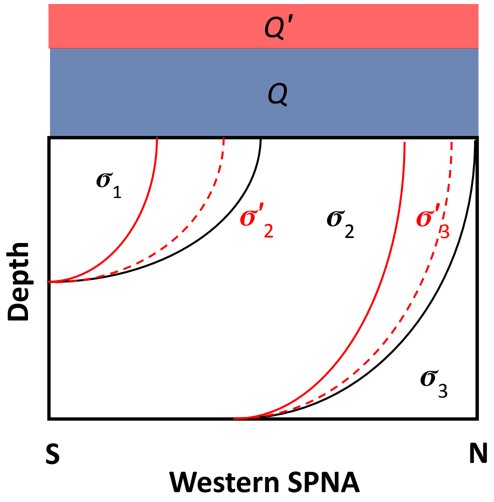
Surface density and heat flux



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

- ΔA_ϱ mirrors the ΔWMT pattern
- ΔA_ϱ is exposed to the background surface heat flux, which is stronger in CESM2 than in the other two models

Outcropping Area Response and Heat Flux Feedback



- Q' initially cools and makes the surface dense
- $A(\sigma'_2) > A(\sigma_2)$
  $\rightarrow \sigma_2$ exposed to more $Q + Q'$
- σ_3 exposed to $Q + Q'$ (WMT=0 before Q')
- More exposure to Q further expands $A(\sigma'_{2,3})$
- Because Q is larger in CESM2, ΔWMT is also larger

feedback

WMT Response

Climatology

$$\mathrm{WMT}(\rho) = \frac{1}{\Delta\rho} \iint \left(-\frac{\alpha}{C_p} Q_o - \beta \frac{S}{1-S} F_o \right) dA_\rho$$

heat flux — freshwater flux — isopycnal outcropping area

$$Q_o = Q_c + Q_{NAO}^{eff}, \quad Q_{NAO}^{eff} = Q_{NAO} \times (1 - a_i)$$

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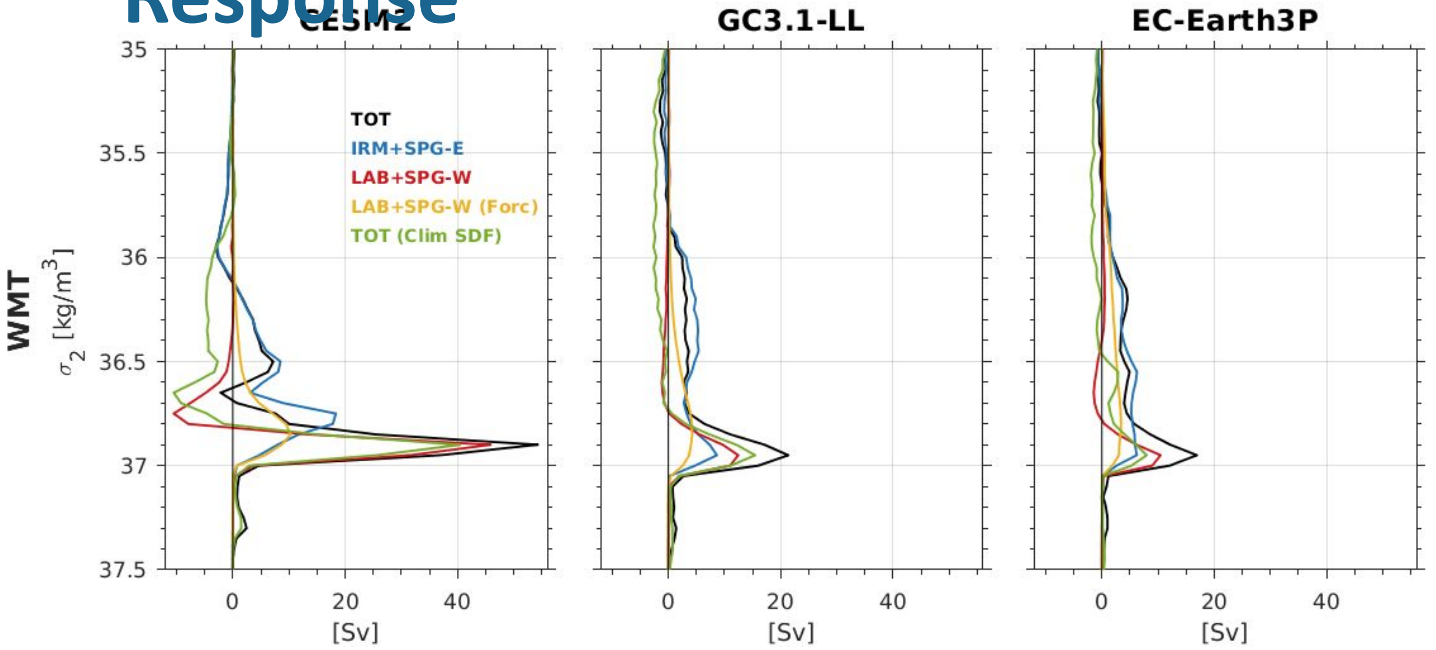

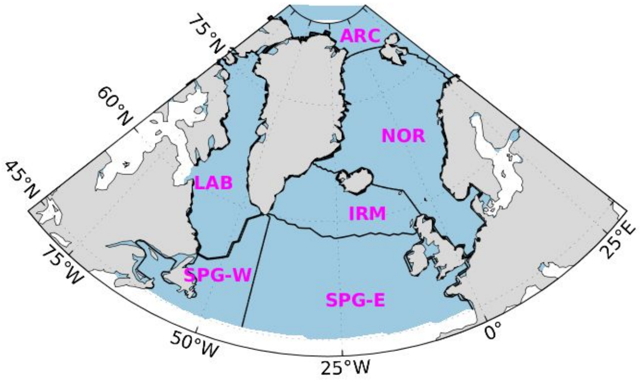

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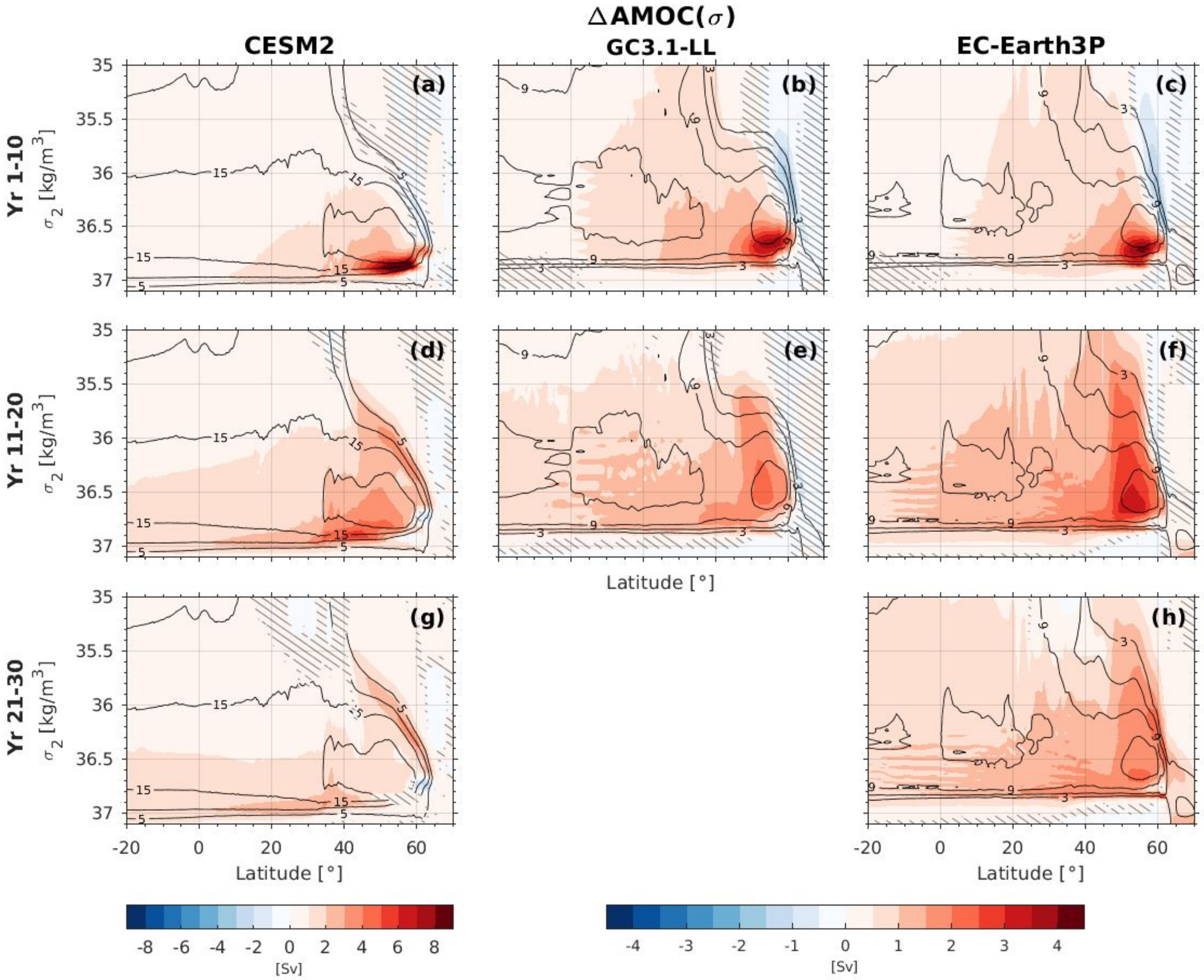
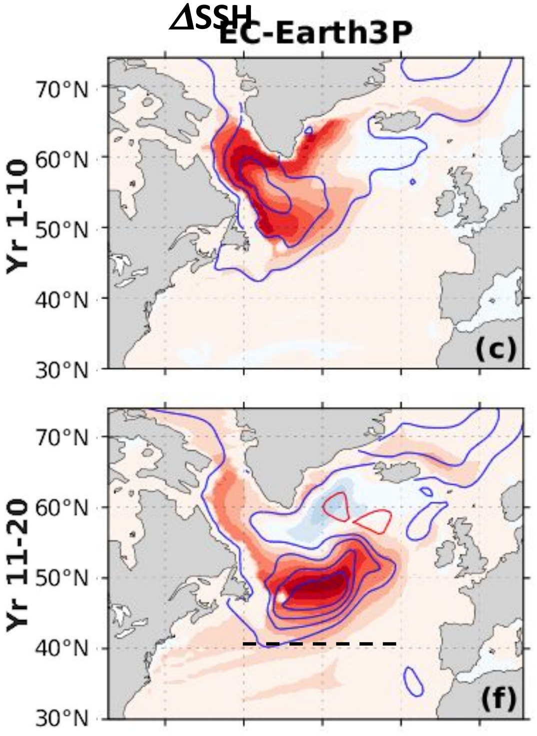
AMOC (σ) Response

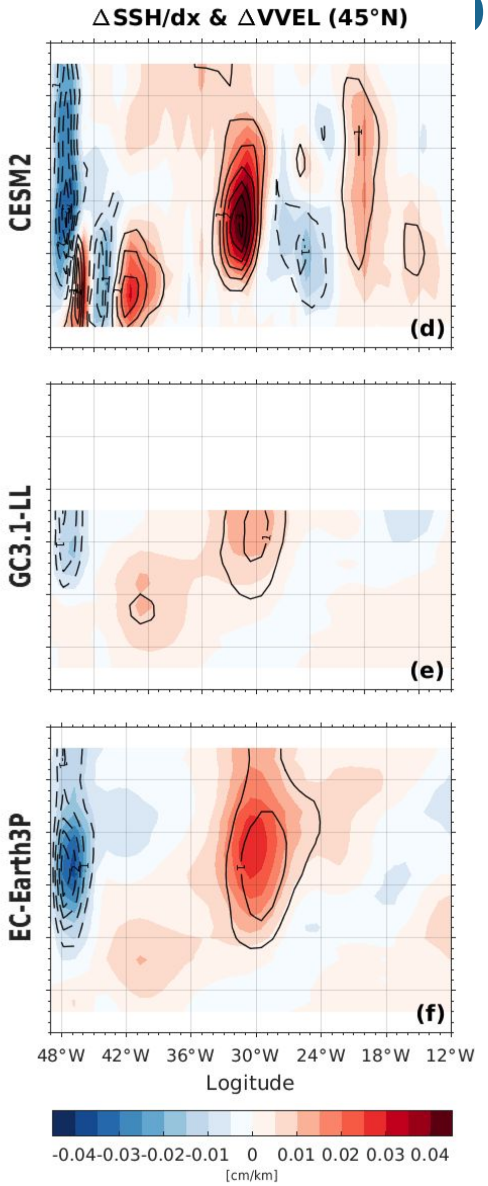


- Spin-up of the lower (denser) AMOC(σ) limb in the subpolar latitudes (first decade)
- Lower limb anomalies ∼2x larger in CESM2, consistent with the WMT anomalies
- No significant anomalies in the upper (lighter) limb
- Southward propagation of the lower limb anomalies (second and third decades)
- Development of the upper limb anomalies

AMOC (σ) Response

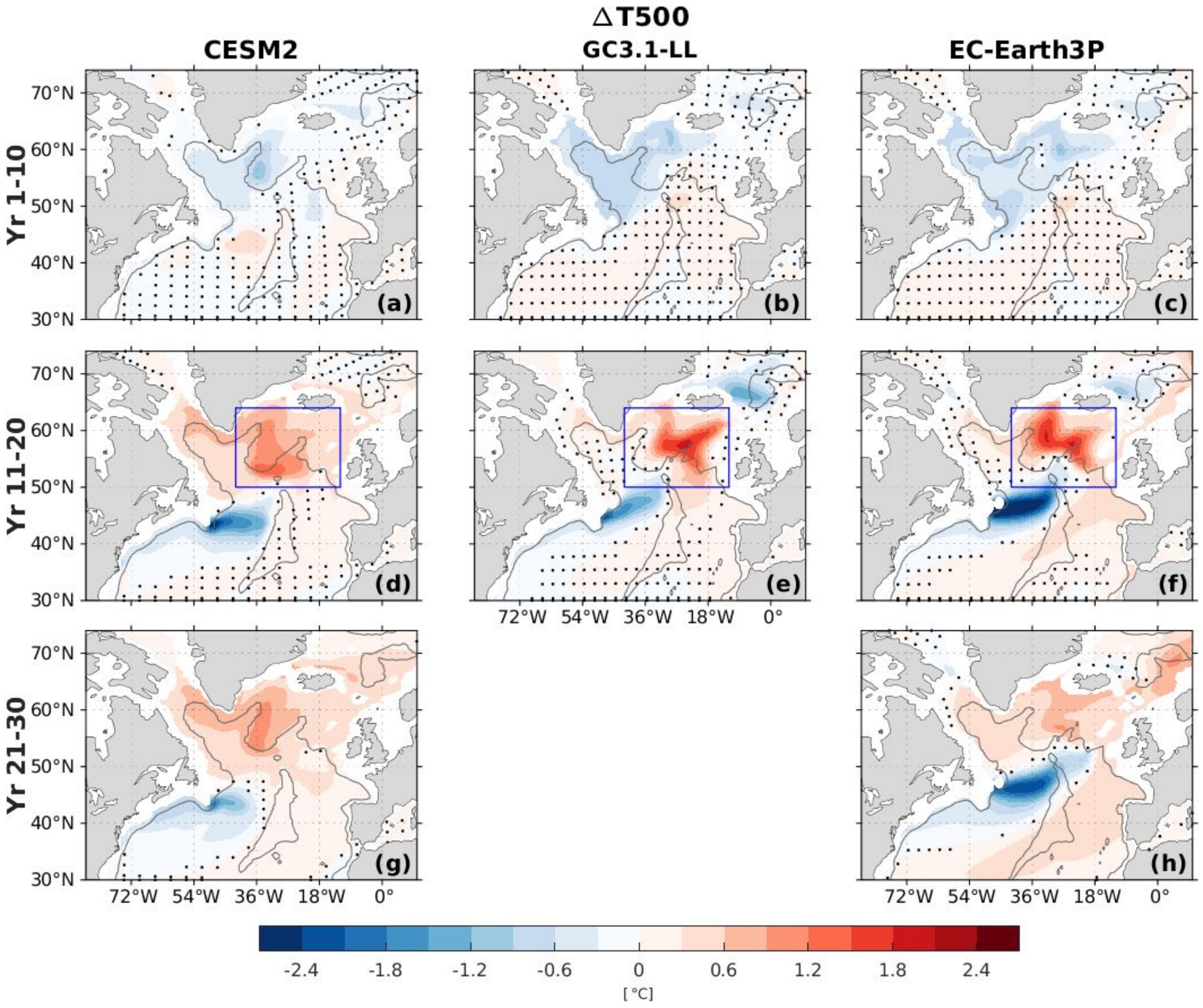
Δh_{σ} (>36.8) & ΔSSH





- Anomalous dense water advects southward and is accumulate near the gyre boundary west of the Mid-Atlantic Ridge (MAR)
- Generating zonal SSH gradient
- Driving anomalous meridional flow (anomalous NAC)
- Bringing warm and salty subtropical waters into the SPNA (for +NAO)
- This mechanism working for all three models and consistent with that found by Yeager (2020) and Yeager et al. (2021) from both low- and hi-res CESM1

Upper Ocean Temperature Response



- Initial cooling due to direct forcing effect
- Delayed warming in the SPNA
- Dipole pattern with a anomaly of opposite sign off the Grand Banks (AMOC fingerprint)
- Warming penetrating into the Nordic Seas (third decade) ➞ sea-ice response
- Patterns strikingly similar across the models
- Very similar patterns for the upper ocean salinity

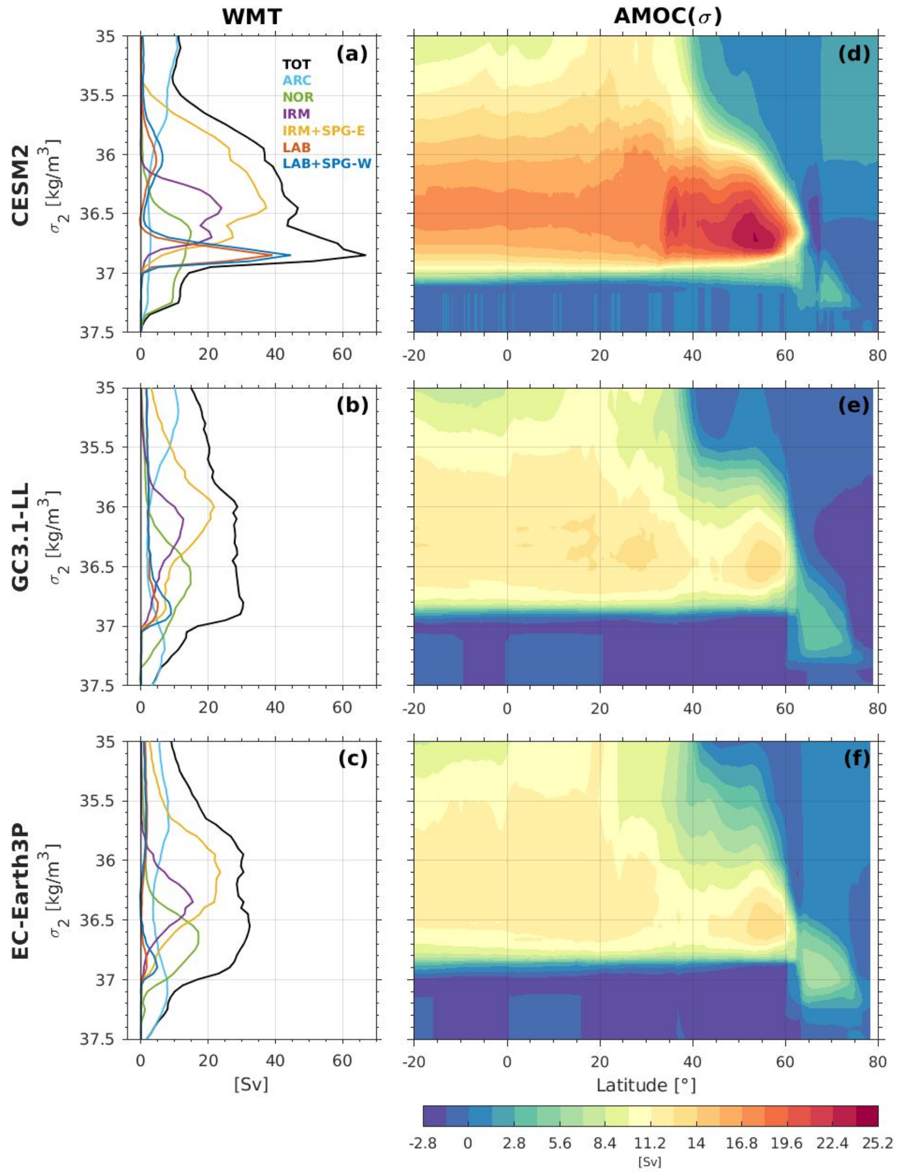
Summary

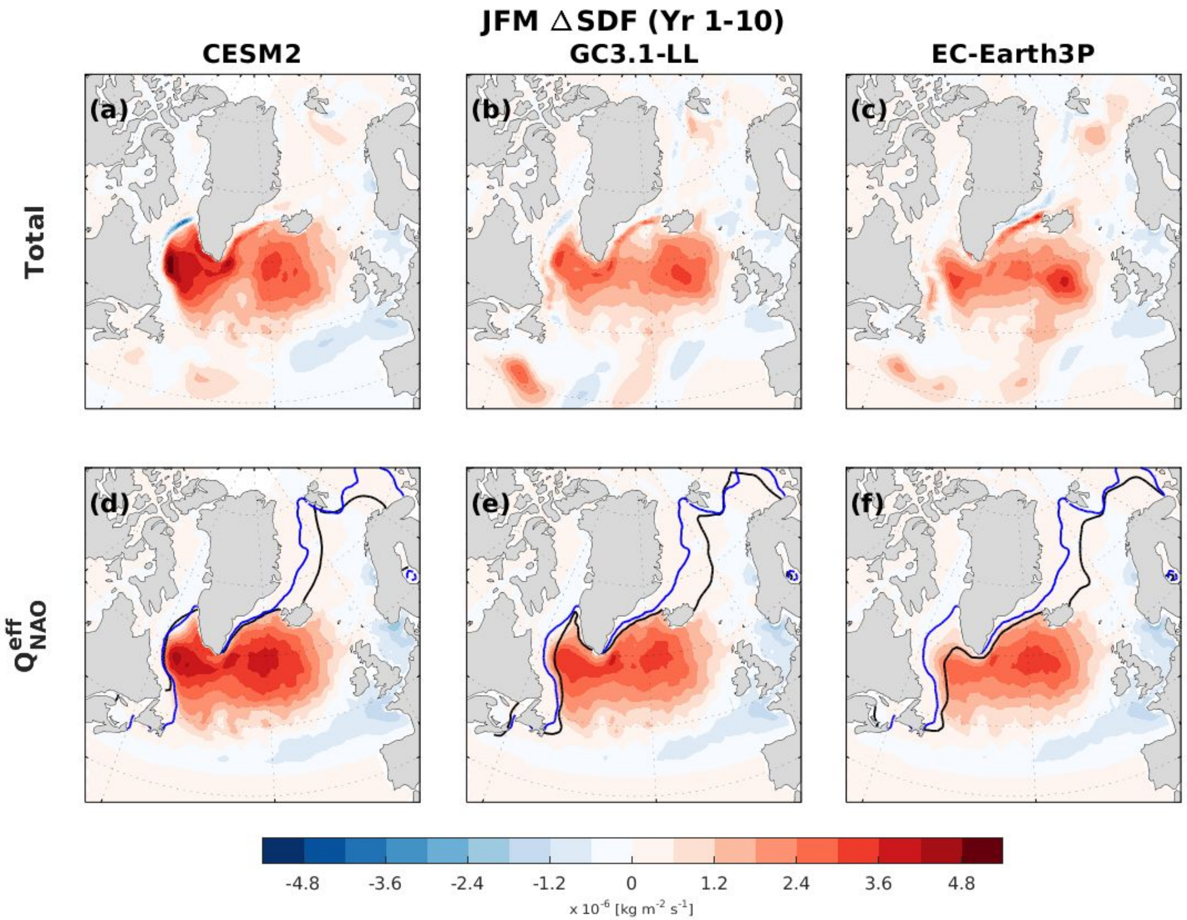
In response to the NAO surface heat flux forcing identically imposed in three CMIP6-class models, we found:

- **Consistent mechanisms and patterns** of the North Atlantic Ocean response (dense-water formation ➞ AMOC ➞ heat content in the SPNA)
- **Different amplitude** of the response
- Anomalous dense-water formation mainly occurs in the western SPNA
- **Changes in isopycnal outcropping area and associated exposure to the background surface heat fluxes** are the key for the ocean response
- Weak response directly driven by the imposed forcing
- The different background state can explain the inter-model amplitude difference
- Delayed SPNA warming due to a slow advection of anomalous dense waters and associated adjustment of the upper AMOC(σ)

Extra #1

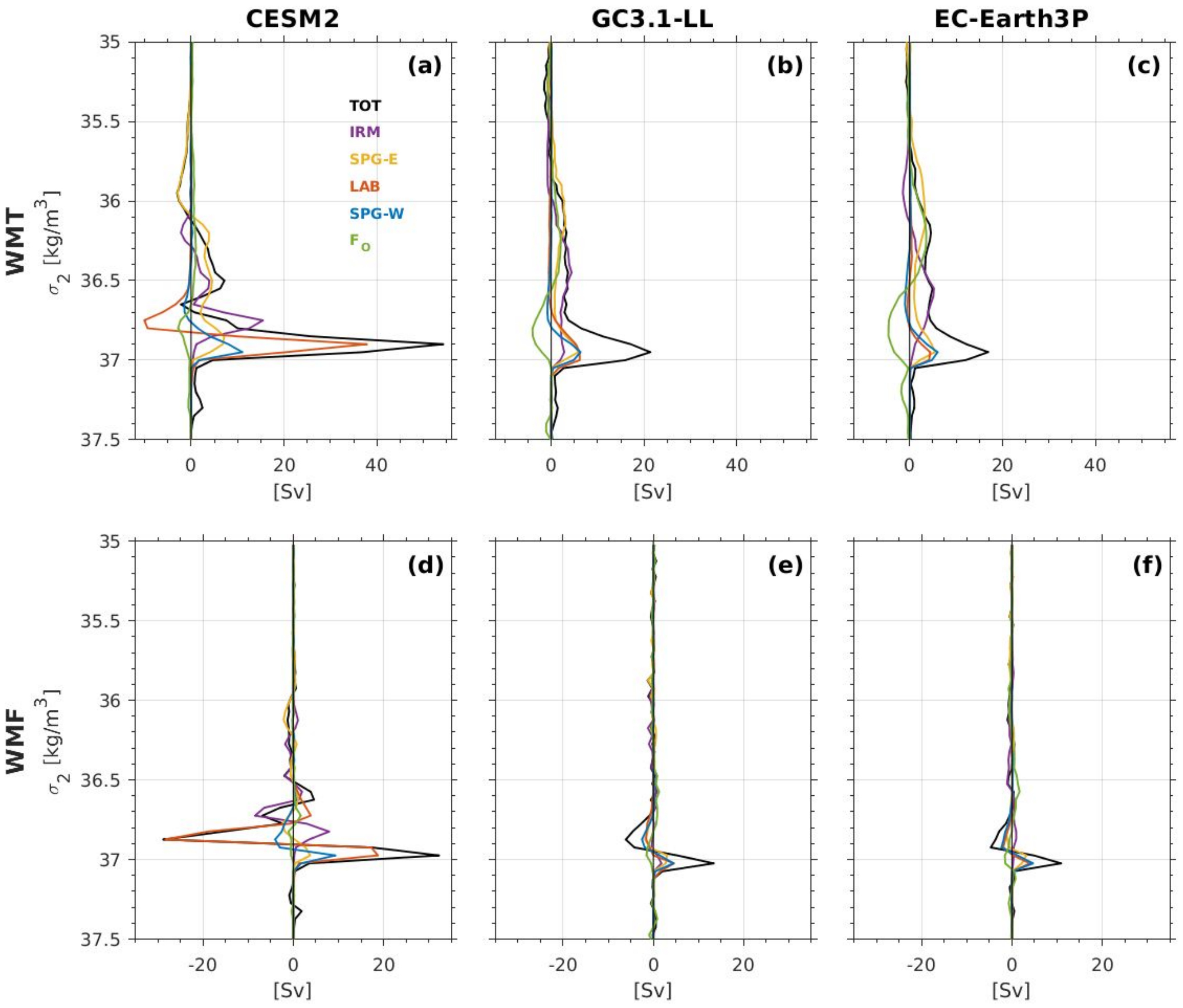
Background WMT & AMOC



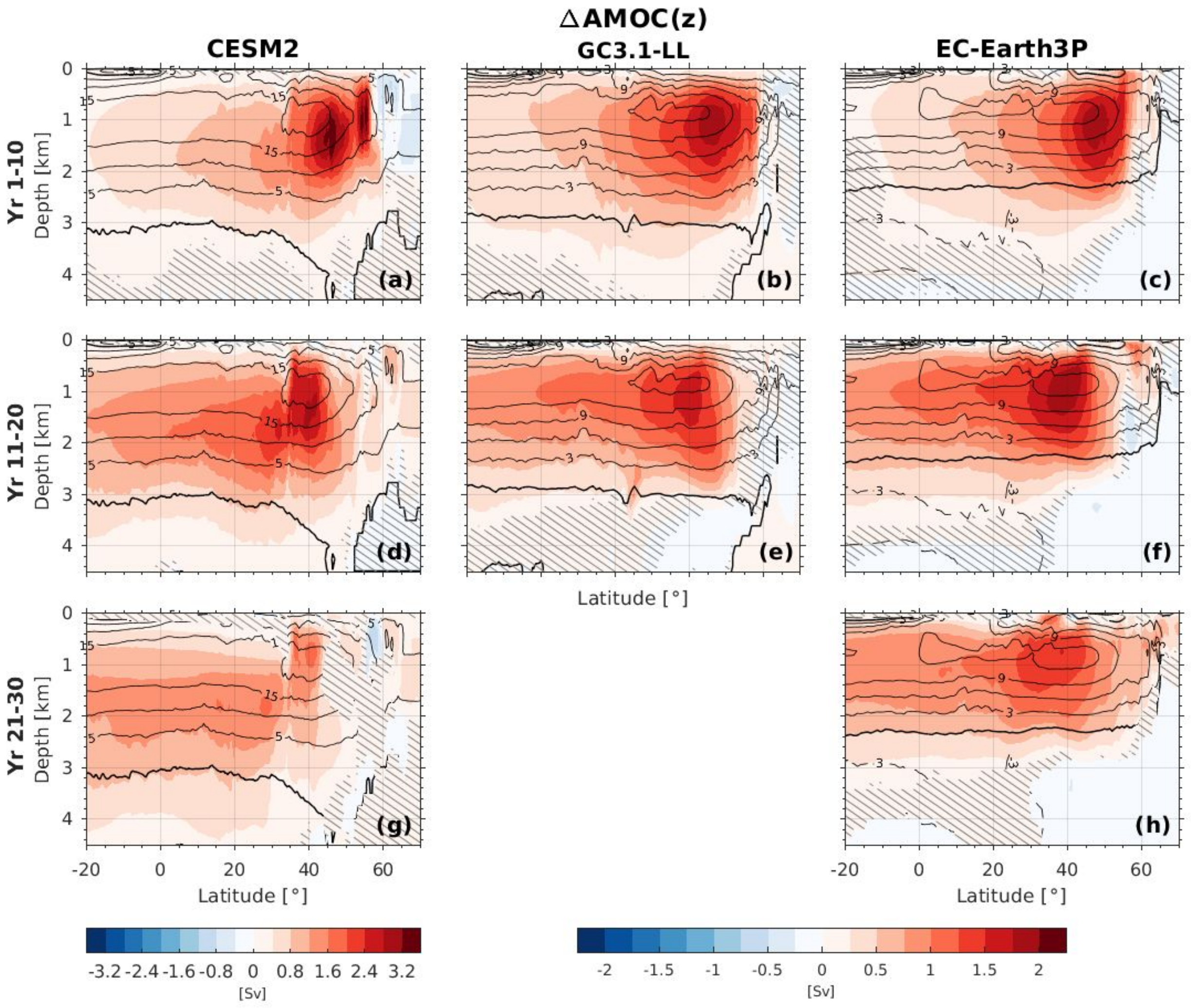


Extra #2

ΔWMT & ΔWMF for the First Decade



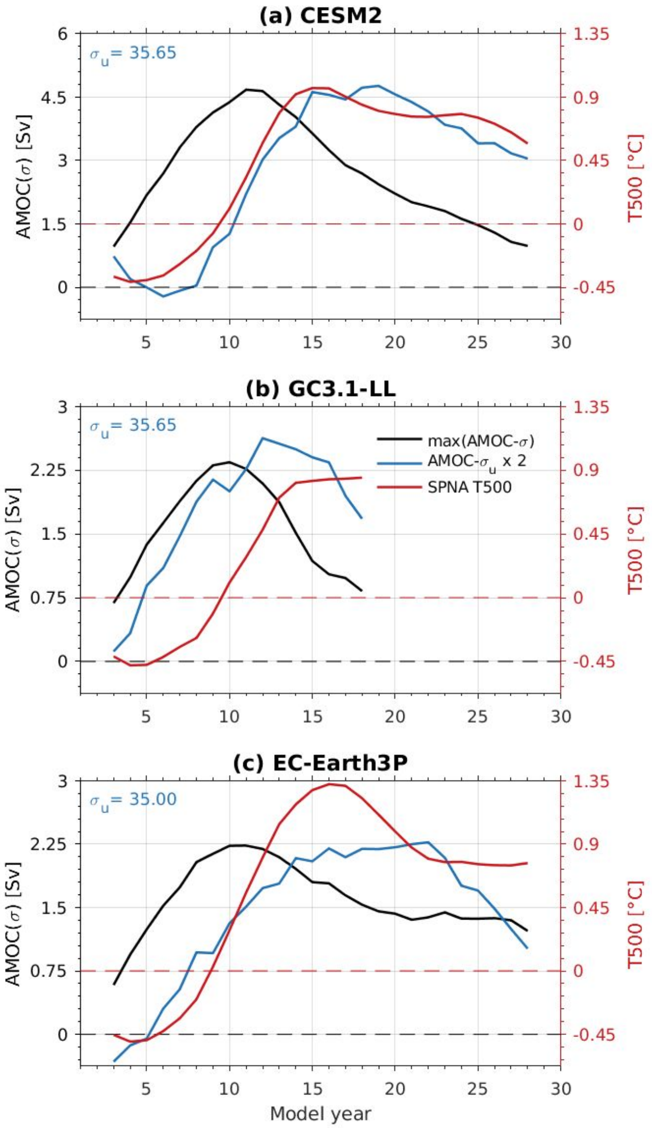
Extra #3

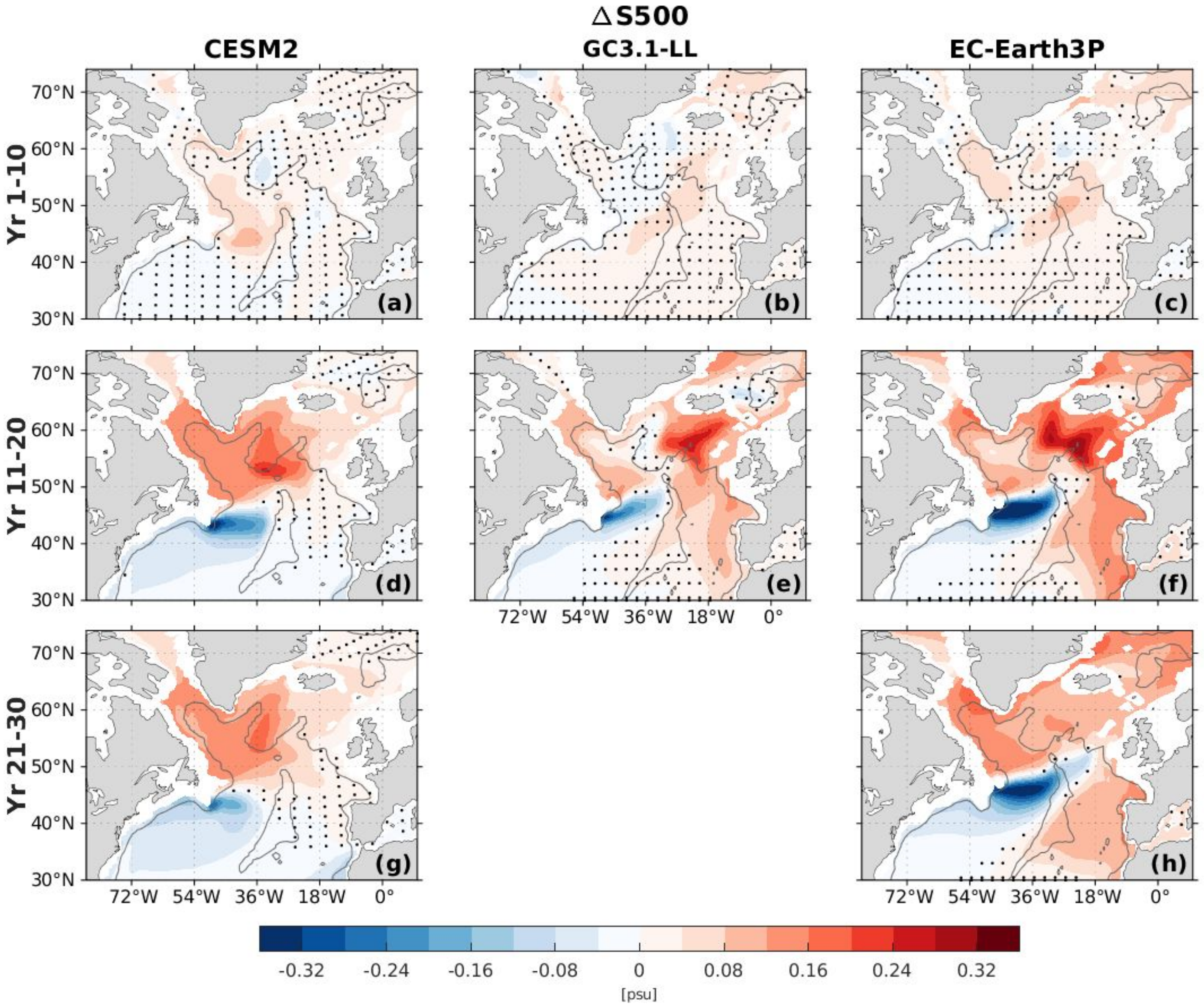


ΔAMOC(z)
CESM2
GC3.1-LL
EC-Earth3P
Yr 1-10
Yr 11-20
Yr 21-30
Depth [km]
Latitude [°]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
-3.2 -2.4 -1.6 -0.8 0 0.8 1.6 2.4 3.2
[Sv]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
[Sv]

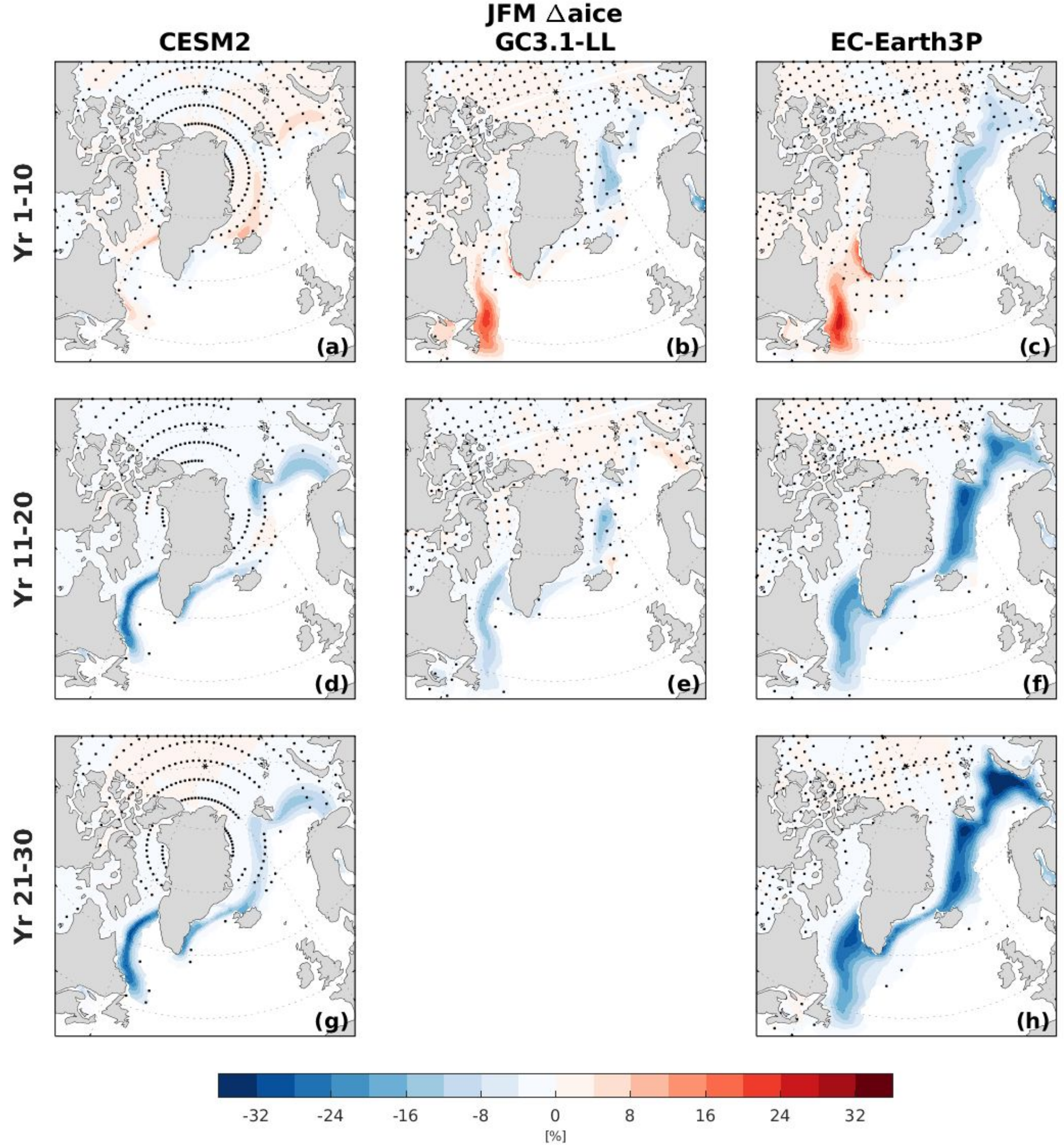
Extra #4

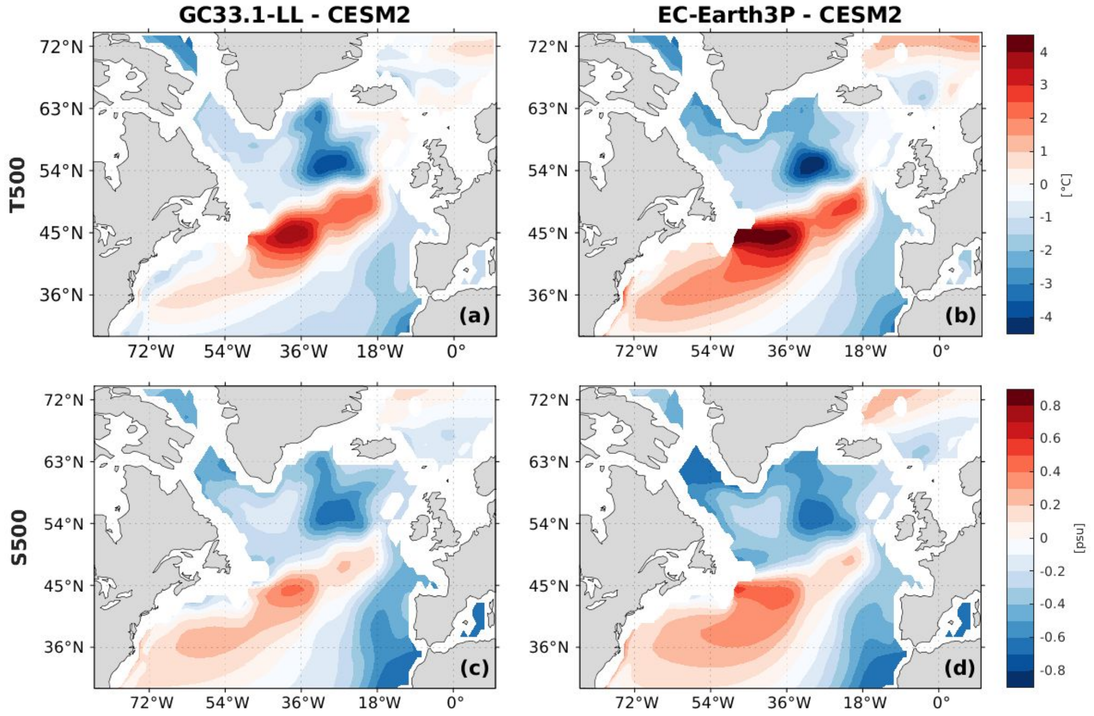
ΔAMOC and SPNA UOT Time Series



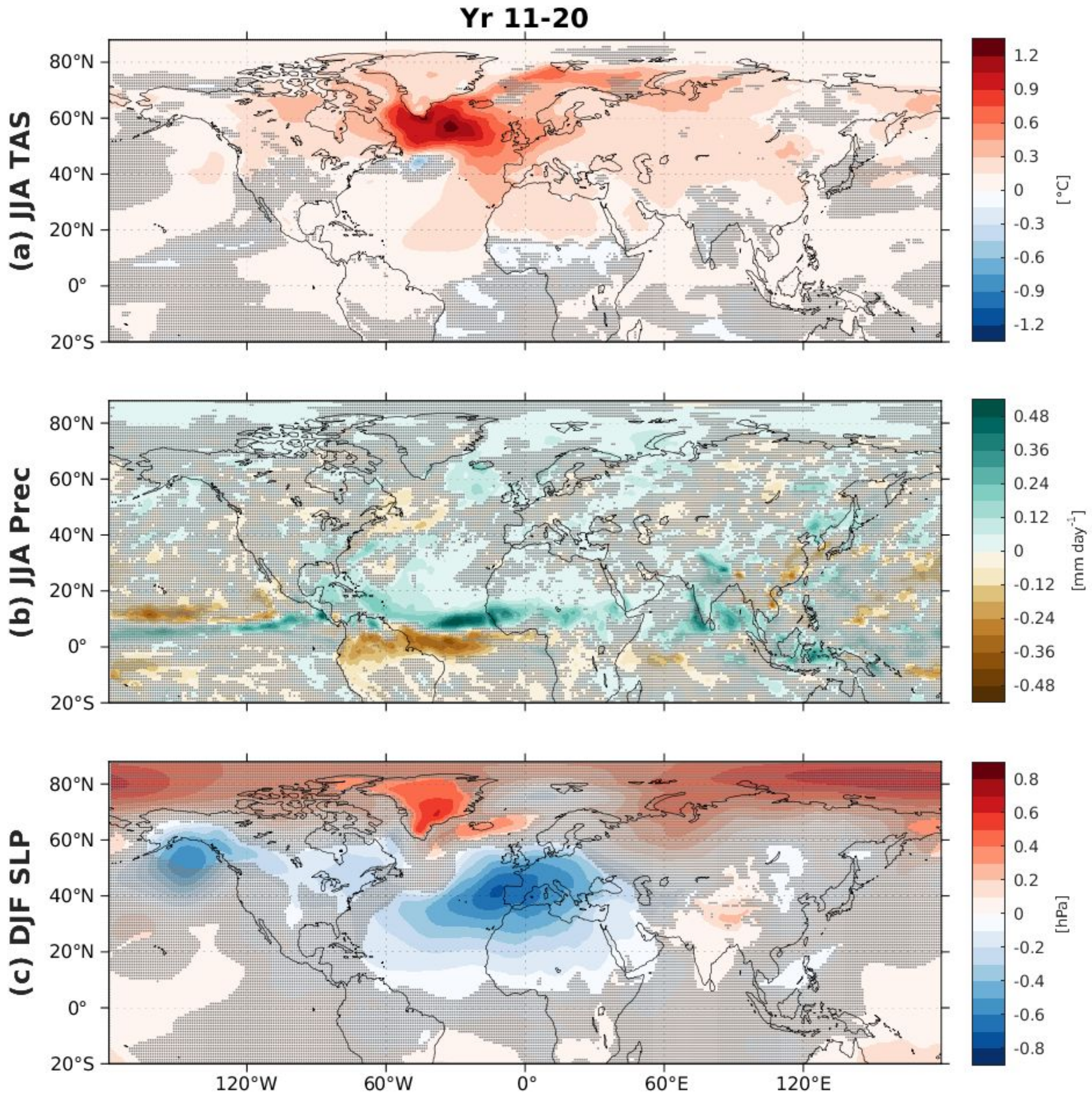


Extra #5


JFM △aice
CESM2
GC3.1-LL
EC-Earth3P
Yr 1-10
Yr 11-20
Yr 21-30
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
-32
-24
-16
-8
0
8
16
24
32
[%]


GC33.1-LL - CESM2
EC-Earth3P - CESM2
T500
S500
72°N
63°N
54°N
45°N
36°N
72°W
54°W
36°W
18°W
0°
(a)
(b)
(c)
(d)
4
3
2
1
0
-1
-2
-3
-4
[°C]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
[psu]

Extra #6



Yr 11-20
(a) JJA TAS
(b) JJA Prec
(c) DJF SLP
80°N
60°N
40°N
20°N
0°
20°S
120°W
60°W
0°
60°E
120°E
[°C]
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
[mm day-1]
0.48
0.36
0.24
0.12
0
-0.12
-0.24
-0.36
-0.48
[hPa]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8