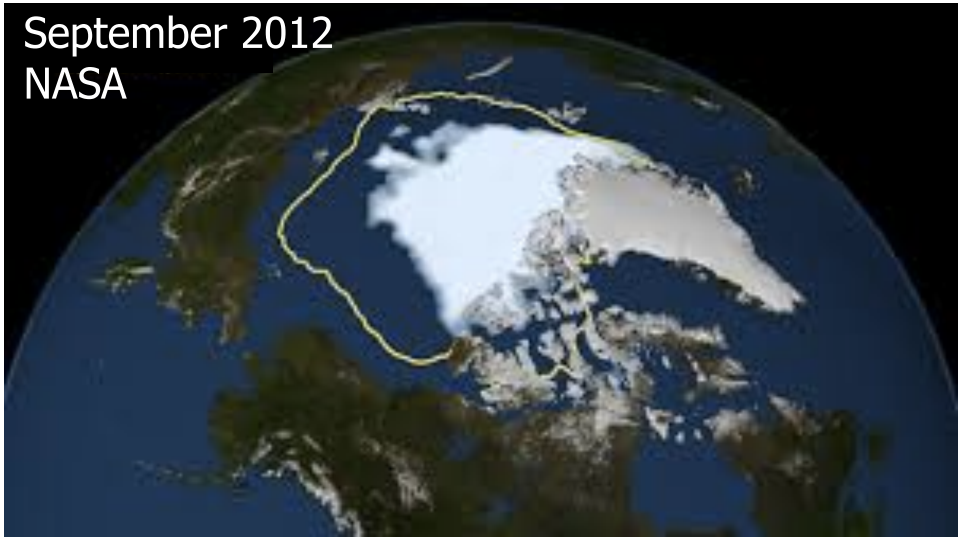
Can Arctic sea ice decline drive a slow-down of the Atlantic Meridional Overturning Circulation (AMOC)?

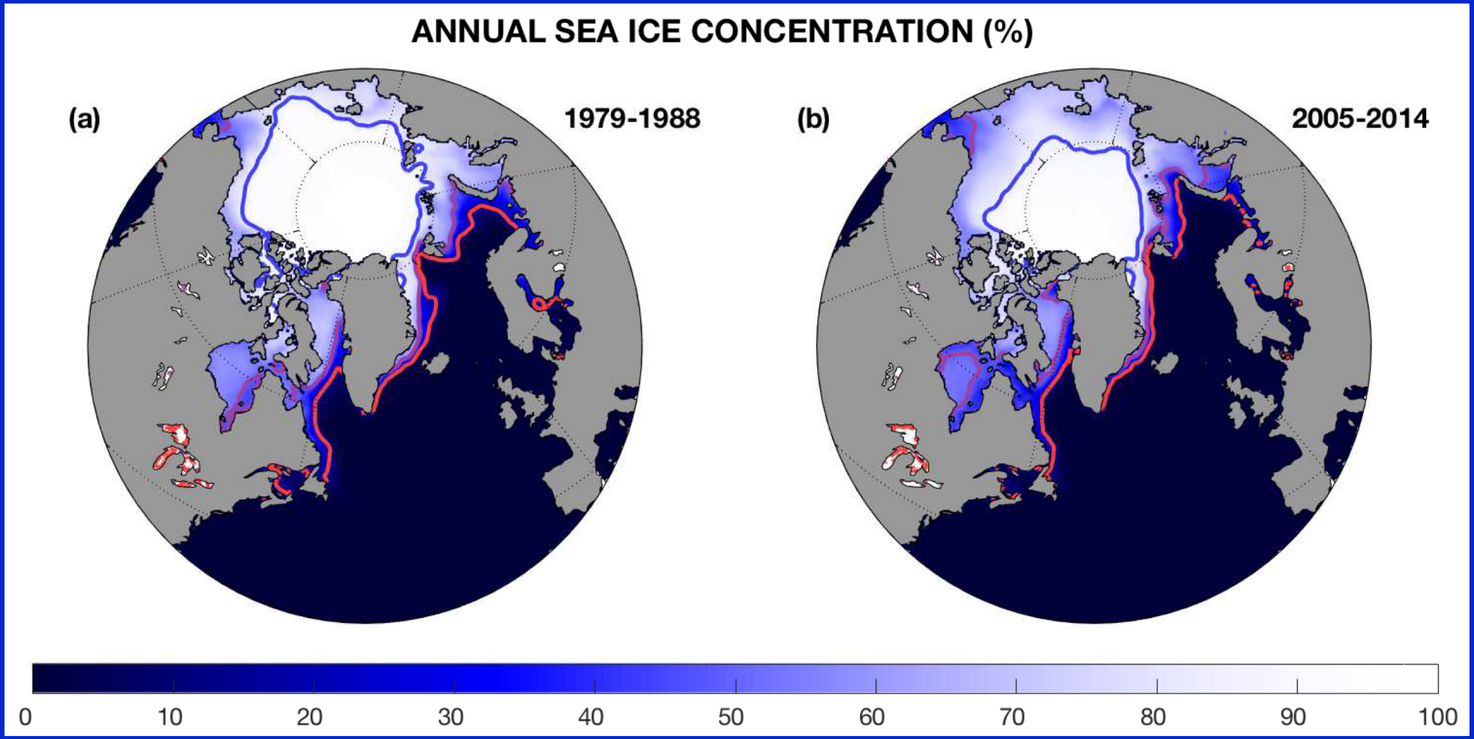
Alexey Fedorov

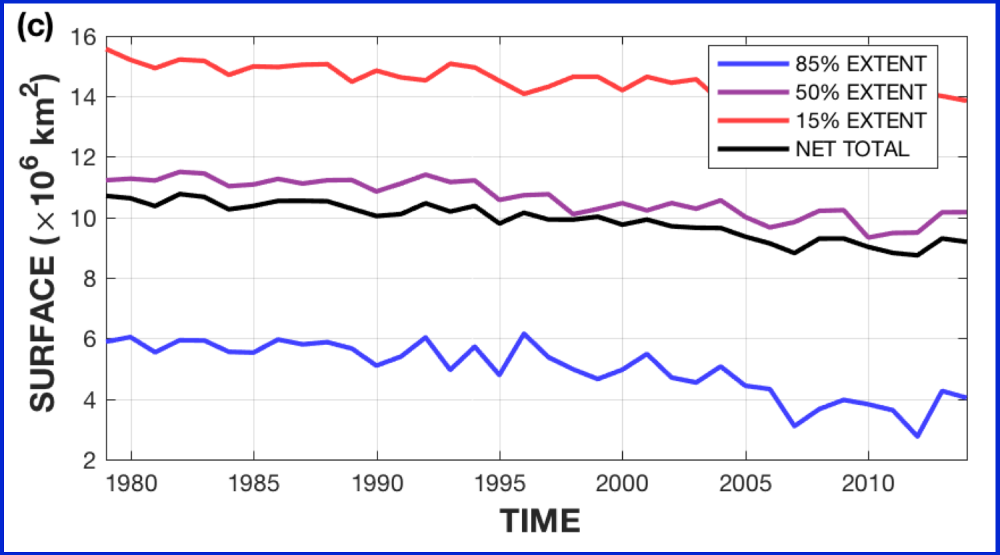
Yale University



with Florian Sevellec (NOC, Southampton) and Wei Liu (Yale)

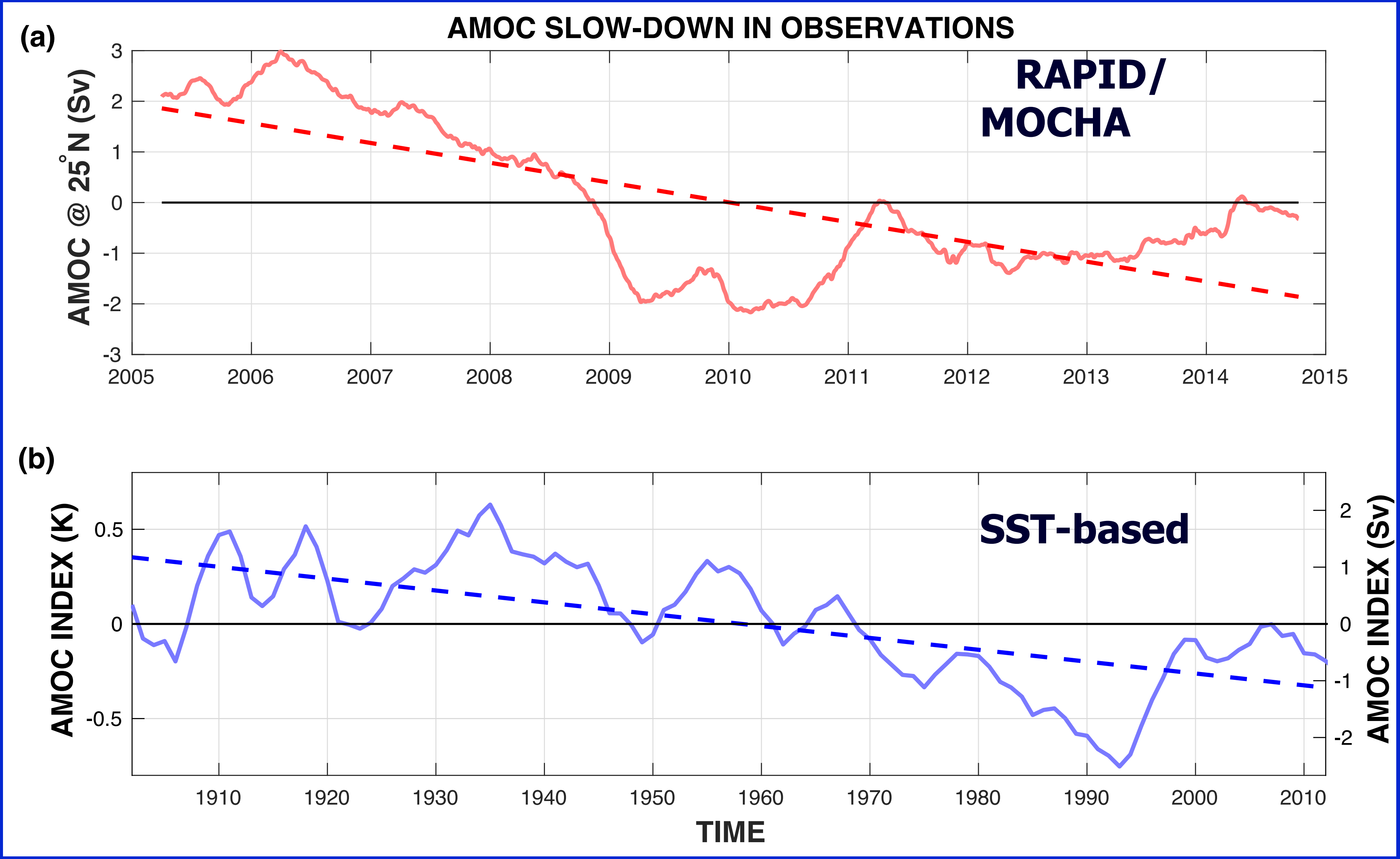
Arctic sea ice decline since 1979





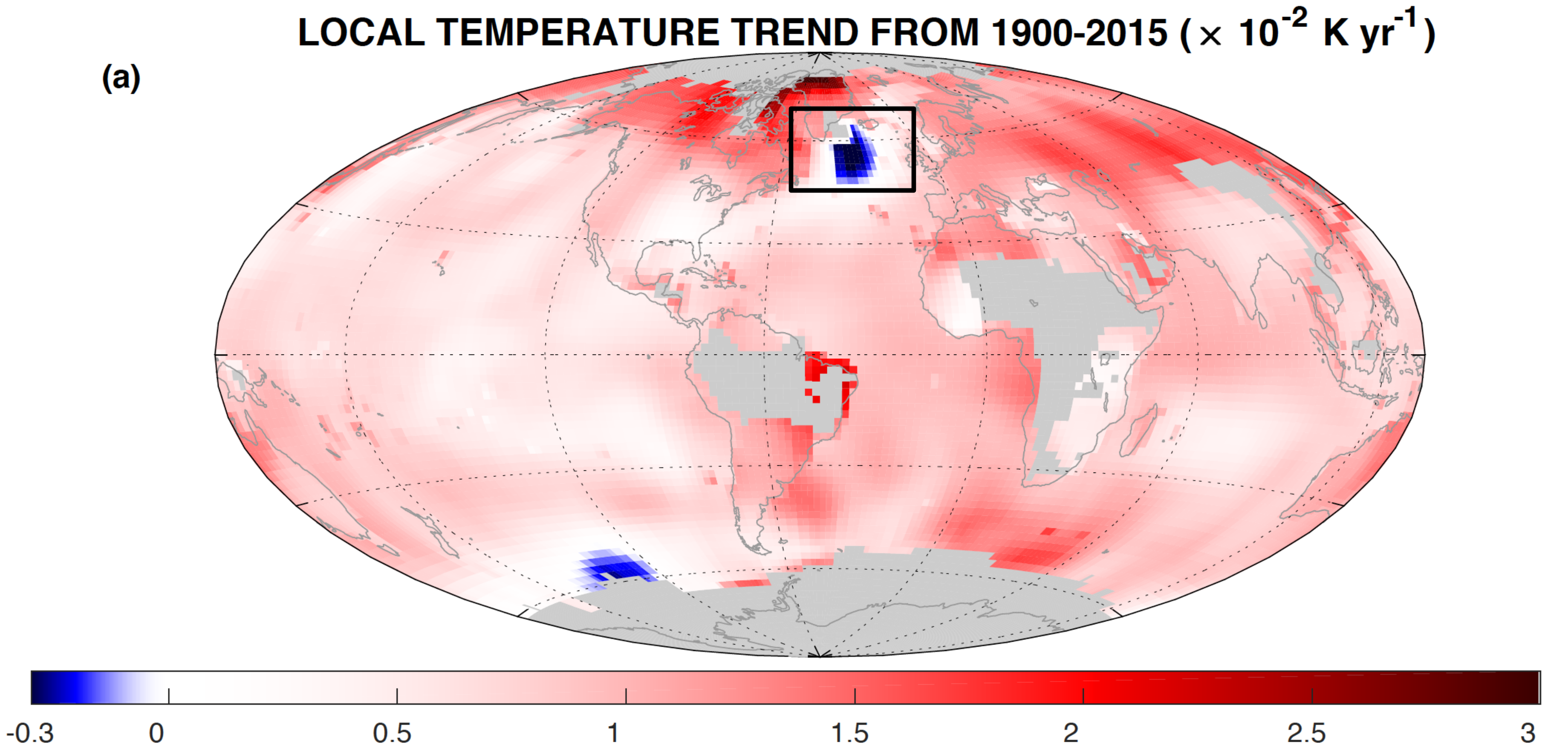
NSIDC data

Is the AMOC slowing-down?



Sevellec et al. 2017, also Rahmstorf et al. 2015

The "Warming Hole" in the subpolar North Atlantic



Sevellec et al. 2017, also Rahmstorf et al. 2015

i. Adjoint analysis: AMOC sensitivity to global surface heat and freshwater fluxes

- Ocean model: NEMO and its tangent linear and adjoint versions

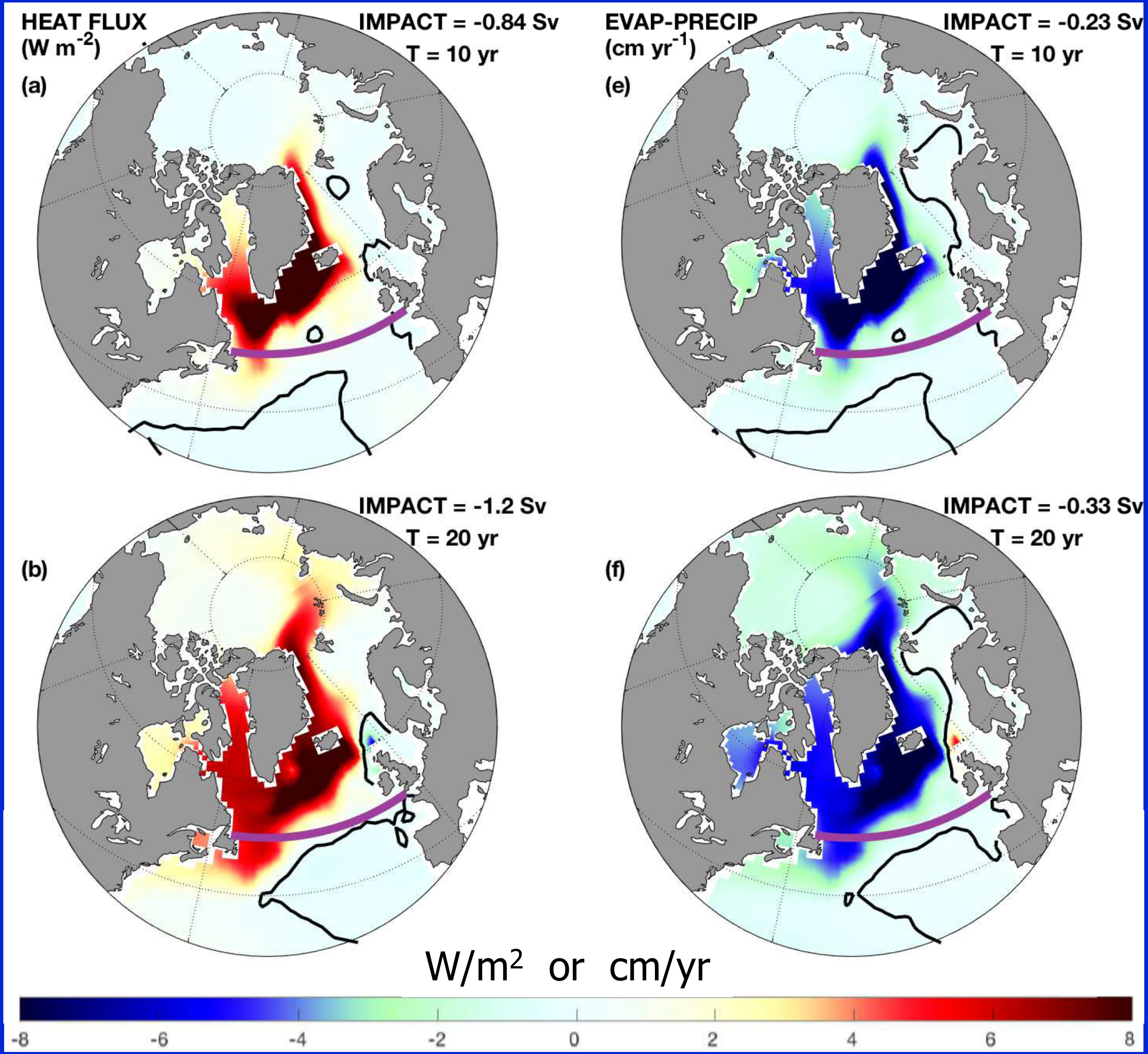
- Method:
  computing optimal flux perturbations (maximizing AMOC volume transport) via an optimization procedure with Lagrange multipliers

- Flux durations are varied in the range 1-200 years

Optimal heat and freshwater fluxes for the AMOC

Flux duration: 10 years

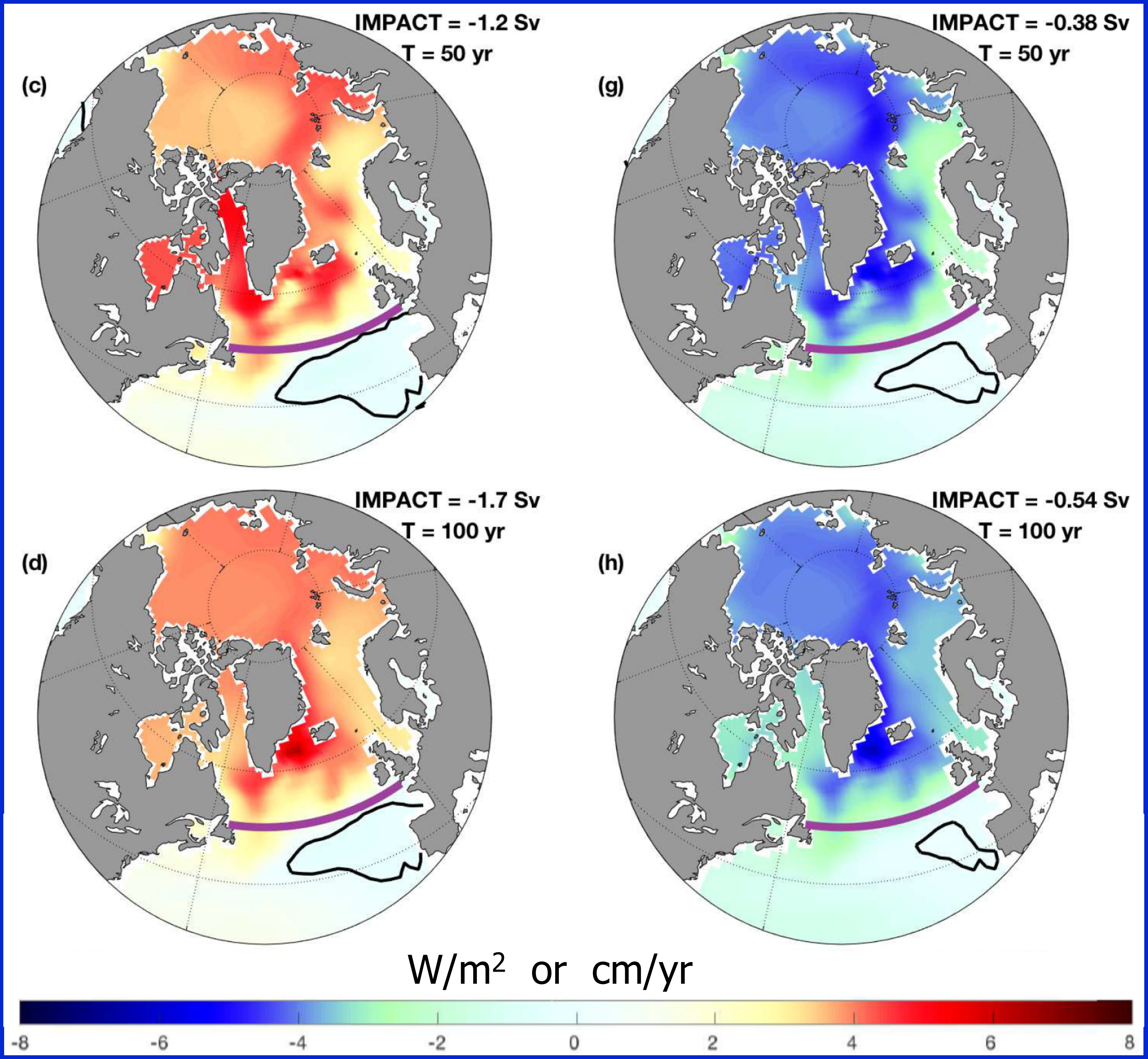
Flux duration: 20 years



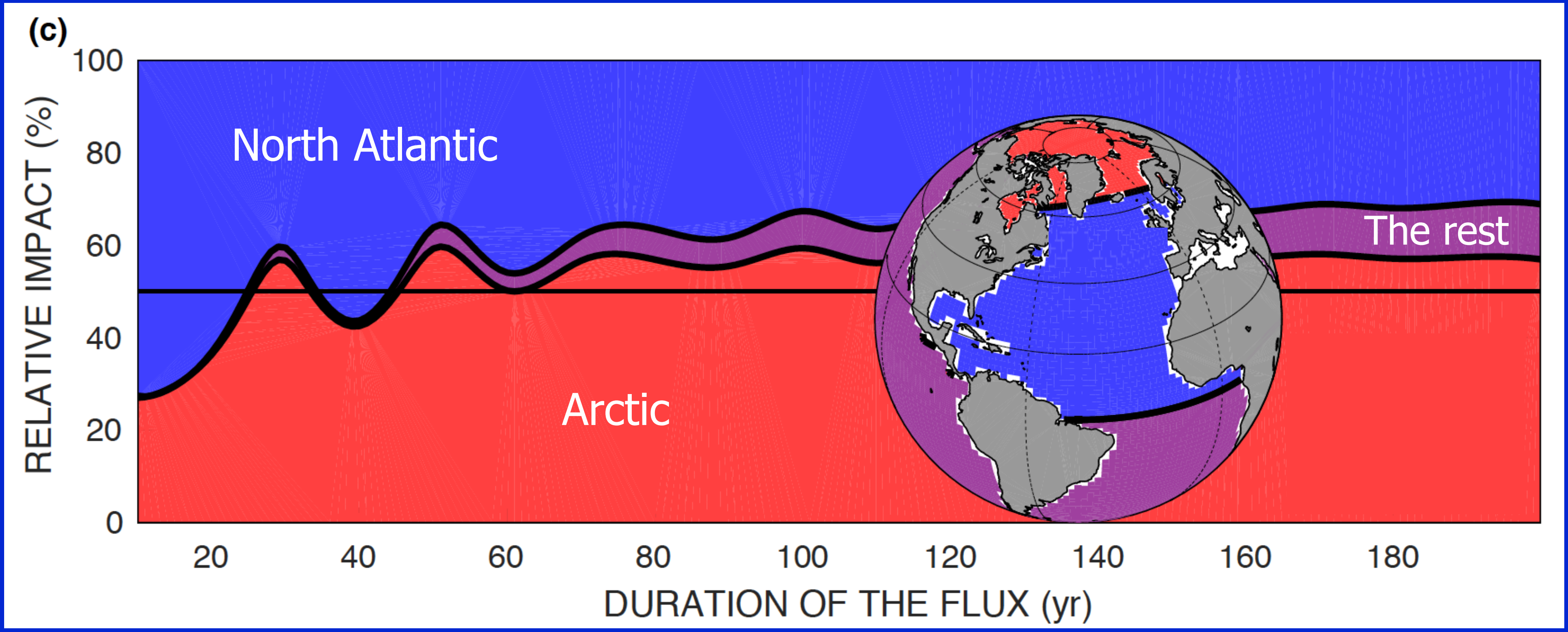
Optimal heat and freshwater fluxes for the AMOC

Flux duration: 50 years

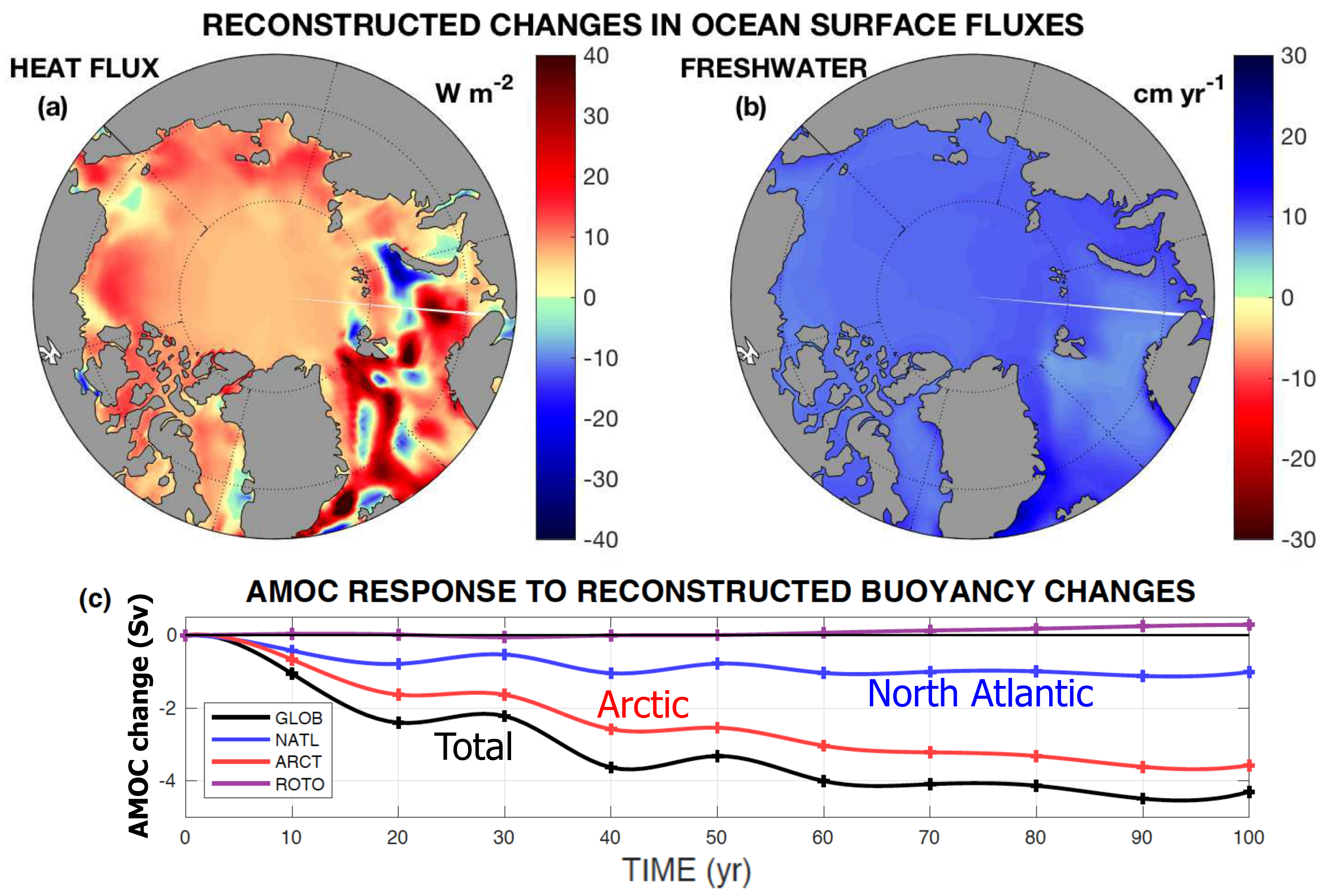
Flux duration: 100 years



Relative impacts of different regions on the AMOC weakening for different flux durations



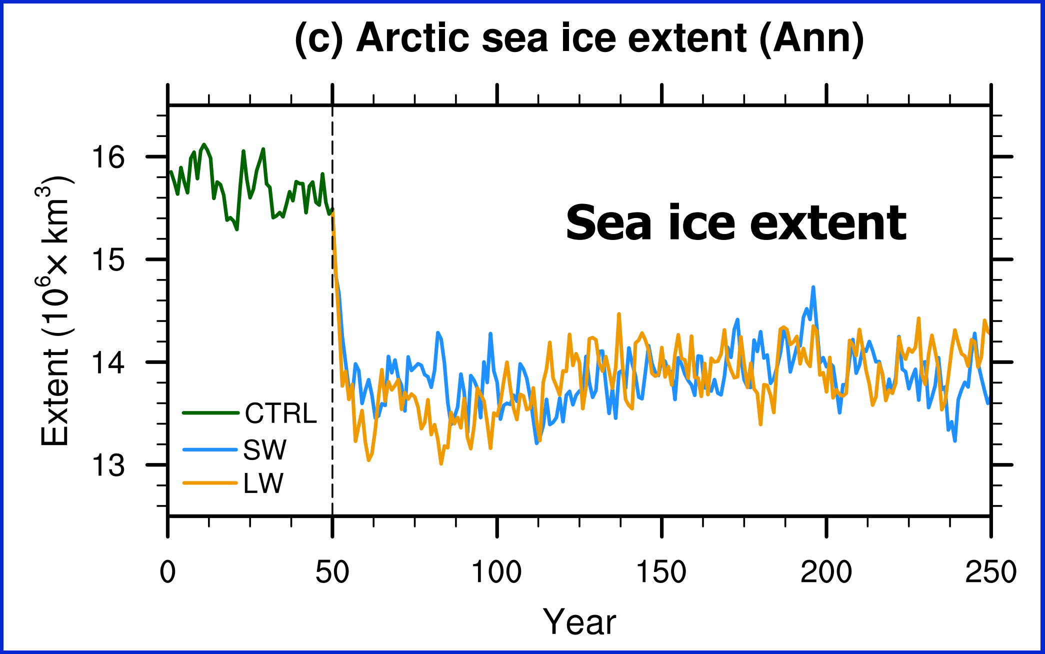
"Observed" surface flux anomalies and AMOC response



ii. Idealized numerical experiments forcing sea ice contraction

- Climate model: CESM-T31
- Methods:
  (1) reducing albedo of sea ice (SW experiments)
  (2) reducing effective emissivity of sea ice (LW experiments)
- 200-year perturbation experiments

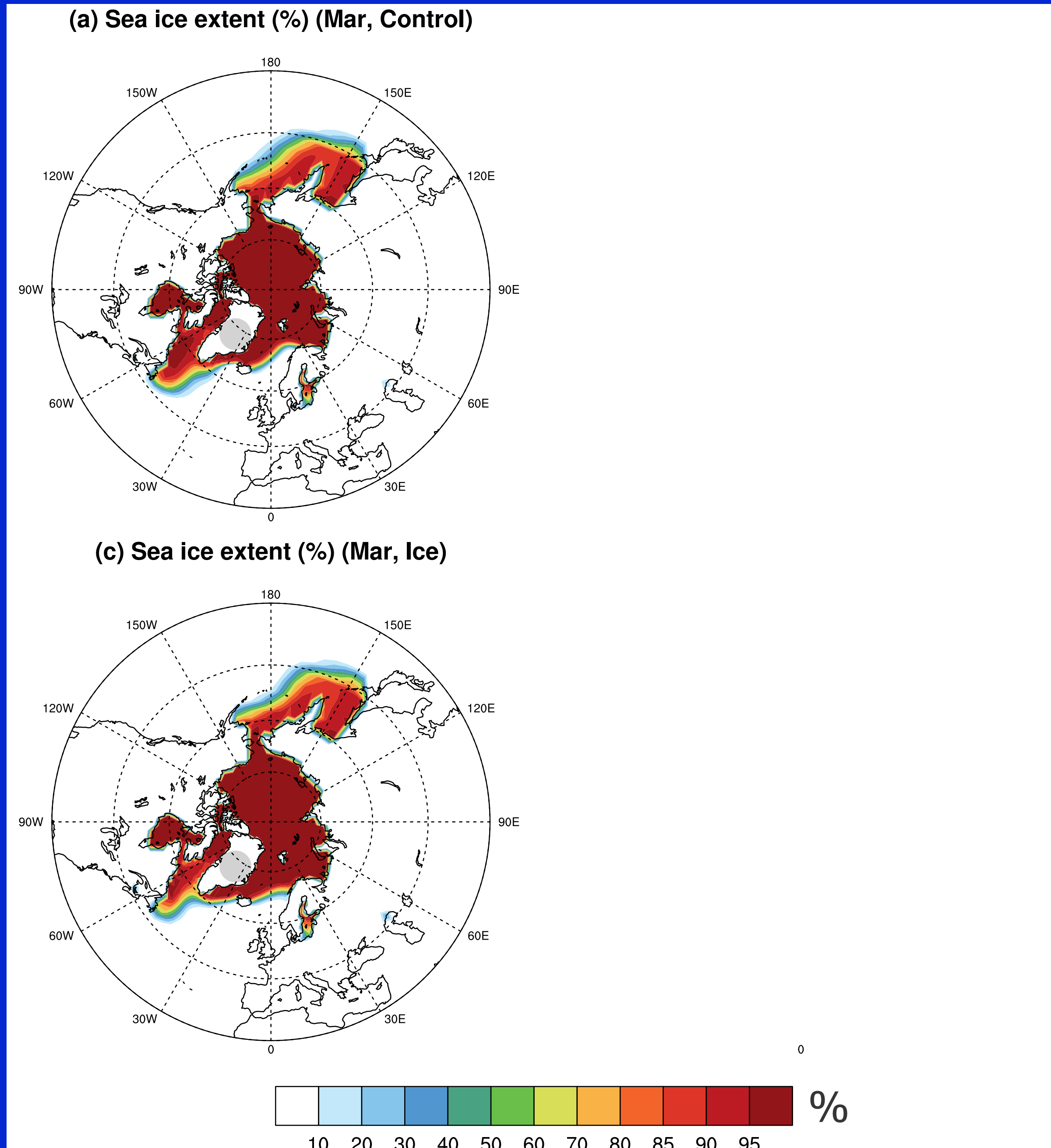
Changes in sea ice and the AMOC response



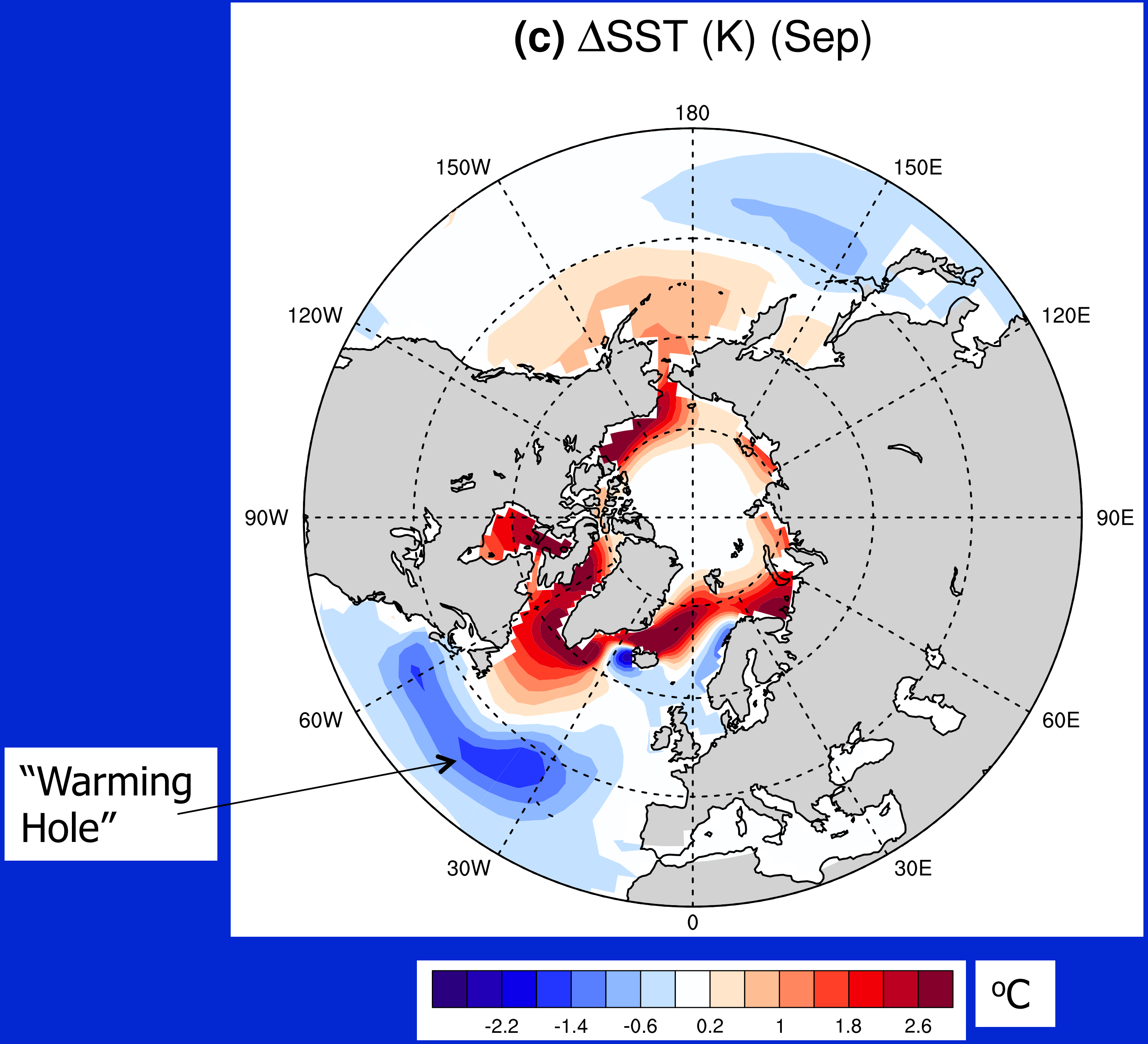
Simulated sea ice retreat (SW experiment)

Winter, CTRL

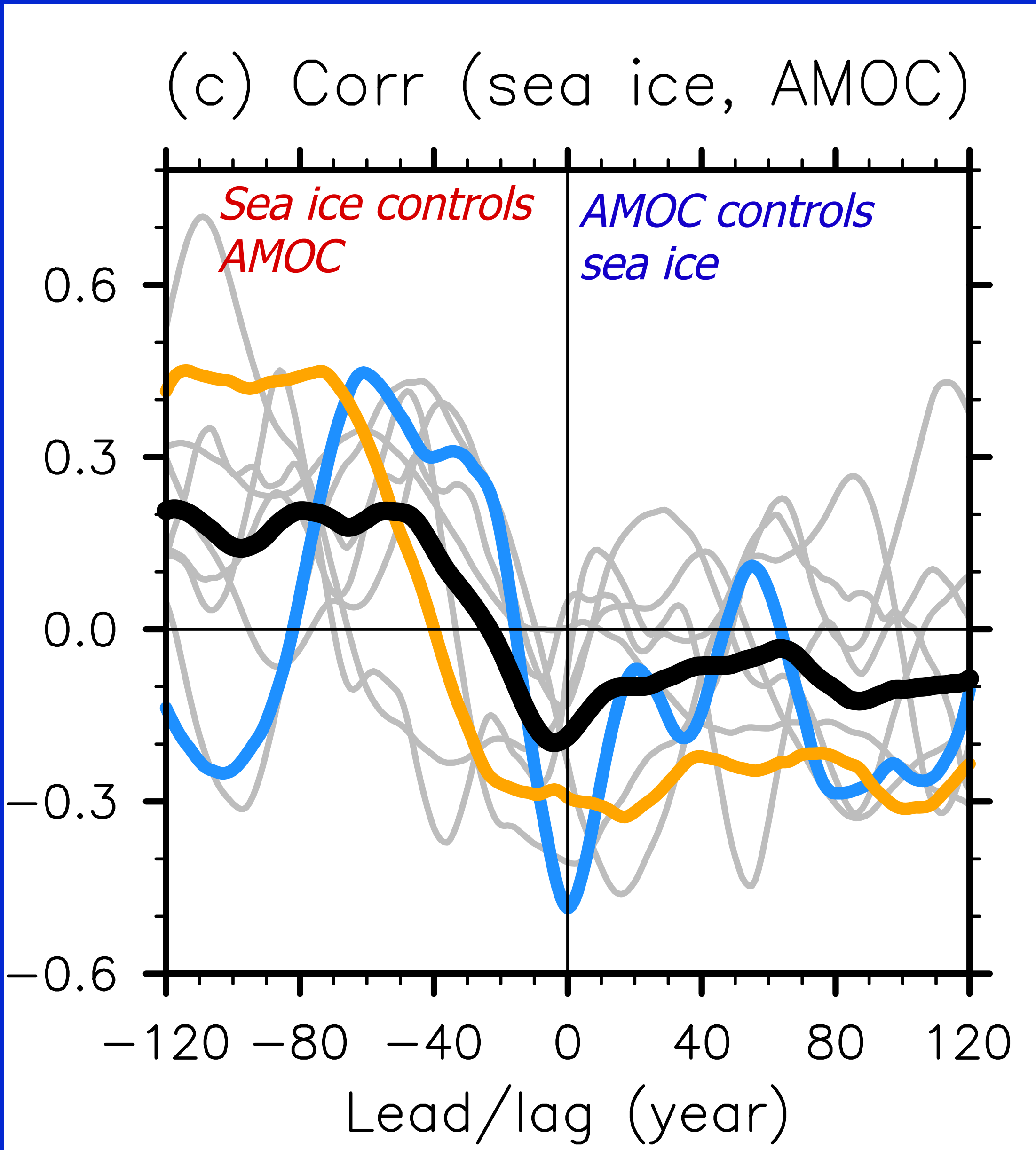
Winter, Perturbed Experiment



SST anomaly induced by sea ice retreat (SW)



iii. Model intercomparison: CMIP5, CESM1-LE, CESM-T31



Lag-correlations between Arctic sea ice and AMOC variations

Negative lag with positive correlations = sea ice leads AMOC variations

CMIP5 models (gray), CESM-Large Ensemble (blue), CESM-T31 (orange), and ensemble mean (black)

Preindustrial control runs (500 years+)

Summary

- On decadal timescales, buoyancy anomalies in the subpolar North Atlantic (the Irminger and Labrador Seas) drive AMOC weakening
- On multi-decadal timescales (longer than 20 years), buoyancy anomalies originating in the Arctic ocean become important
- Sea ice decline exposes the Arctic ocean to additional sunlight and freshwater, generating such buoyancy anomalies that weaken the AMOC and potentially contributing to the "Warming Hole"
- These conclusions are supported by (1) adjoint sensitivity analysis, (2) idealized experiments forcing sea ice decline, (3) control simulations of CMIP5 models, and (4) historical/future simulations within the CESM large ensemble
- The recent AMOC slow-down appears to be consistent with this mechanism (sea ice decline weakens the AMOC)

References

Sevellec, F., Fedorov, A.V., and Liu, W. 2017: Arctic sea ice decline weakens the Atlantic meridional overturning circulation. In revision for Nature Climate Change

Sevellec, F., and Fedorov, A.V., 2016: AMOC sensitivity to surface buoyancy fluxes: Stronger ocean meridional heat transport with a weaker volume transport? Climate Dynamics, doi 10.1007/s00382-015-2915-4.

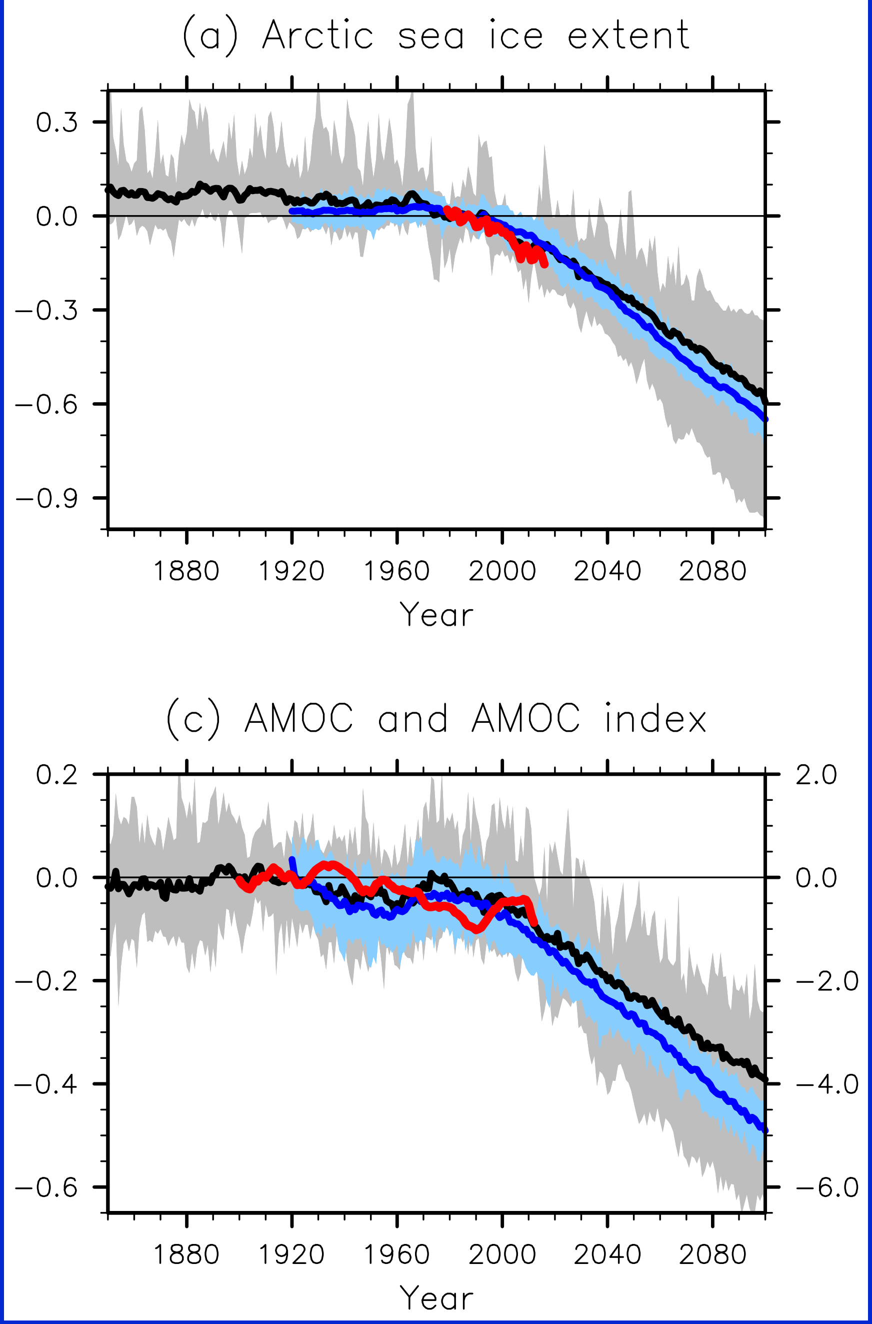
CMIP5, CESM-LE & Observations

Gray: CMIP5 models
Black: ensemble mean
Light blue: CESM-LE: ensemble mean
(scenario: RCP 8.5)

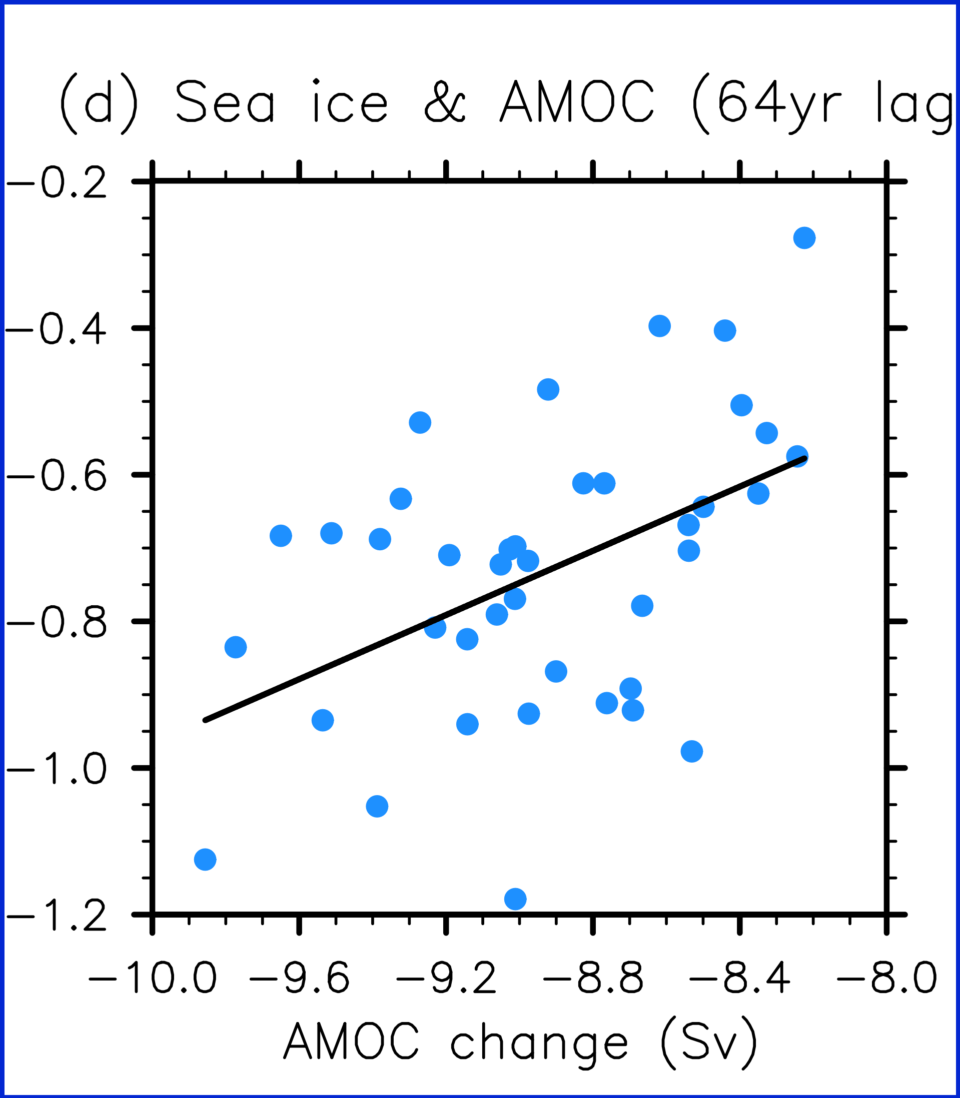
Red: observations

Ice extent is normalized by 1979-1989 average

AMOC index is normalized by the 1900-1919 mean



CMIP5, CESM-LE & Obs

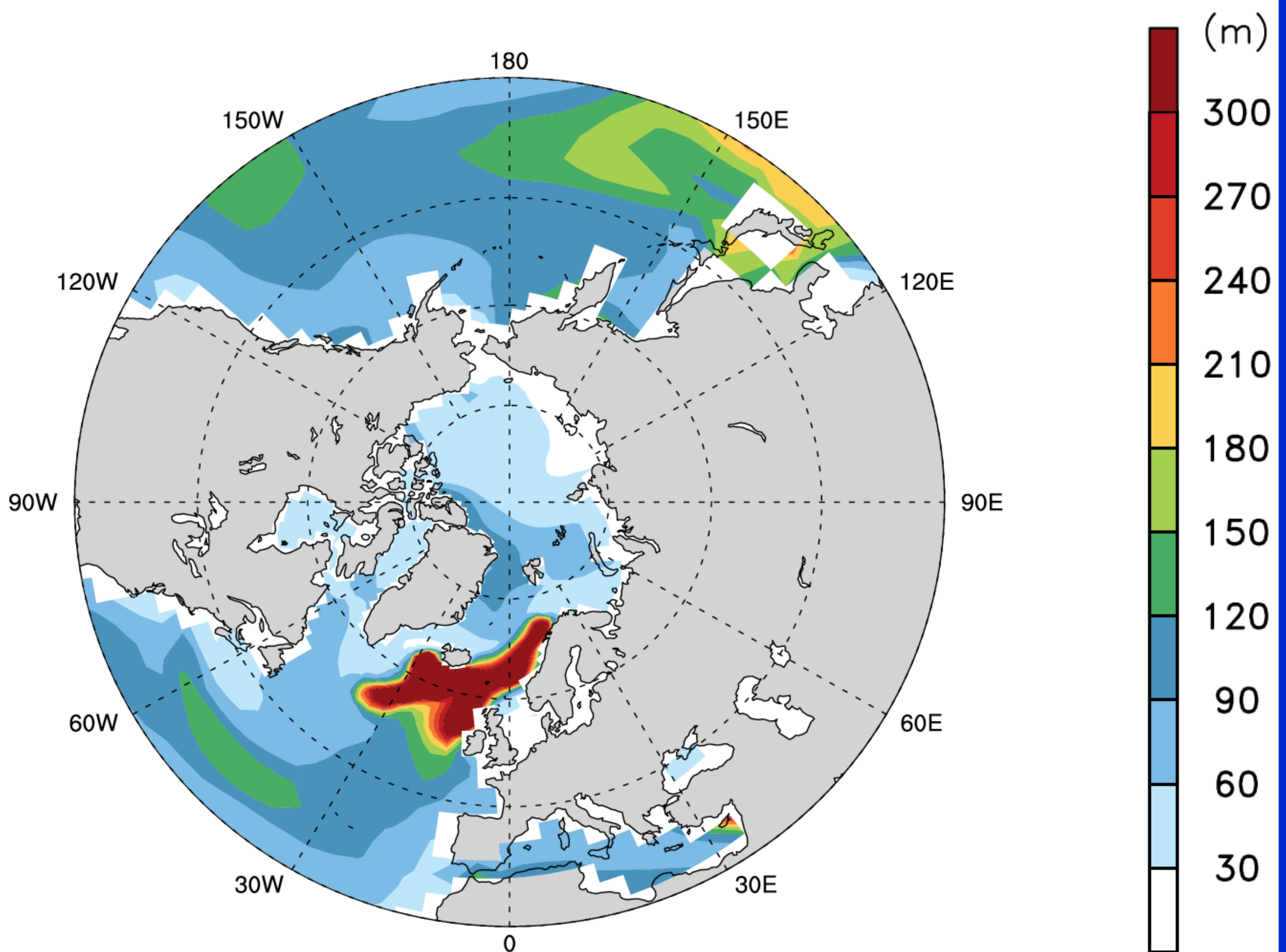


CESM-LE historical +RCP85 runs:

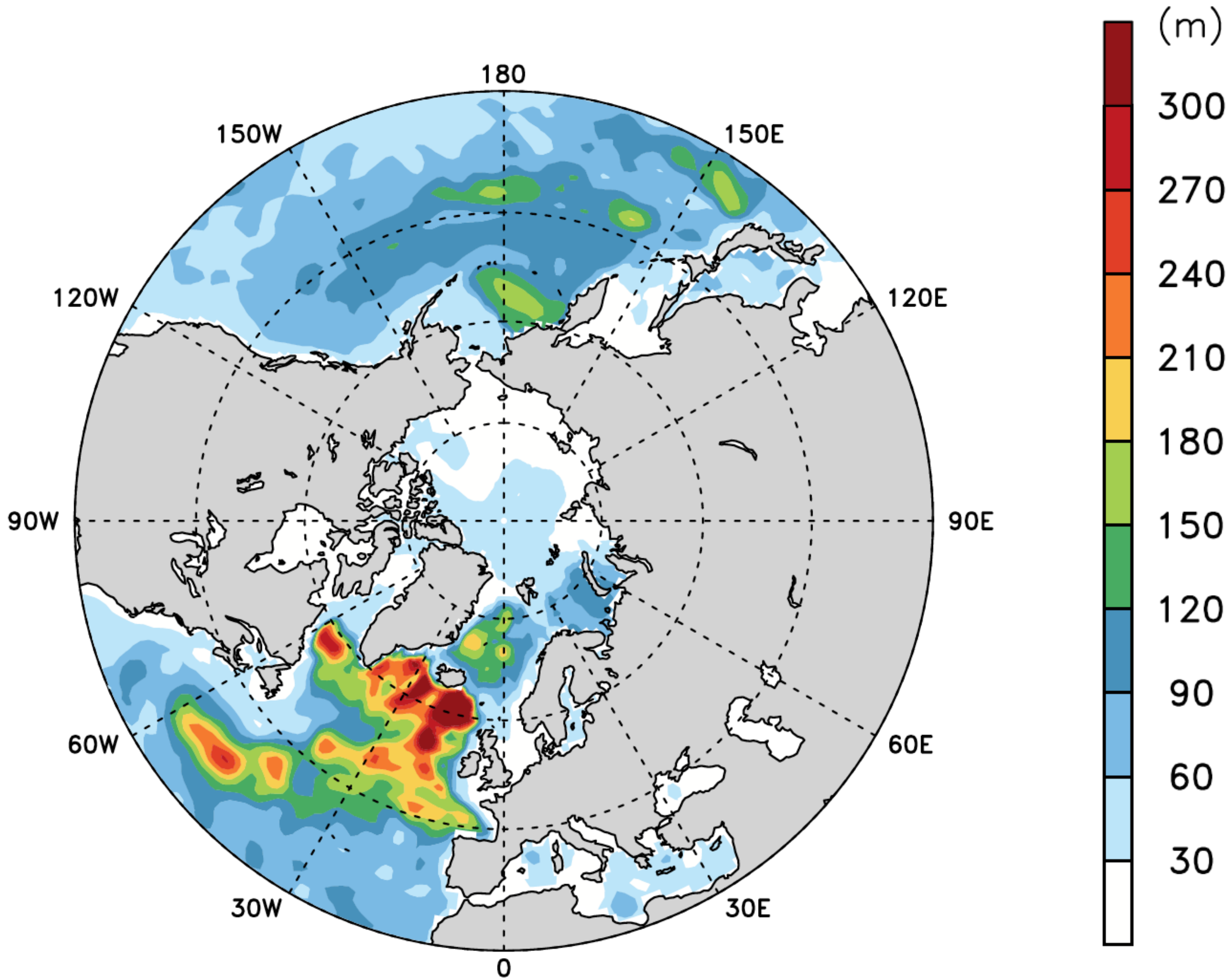
Arctic sea ice change
(1997-2016) – (1920-1939)
and AMOC change with 64yr lag
(2061-2080) – (1984-2003)

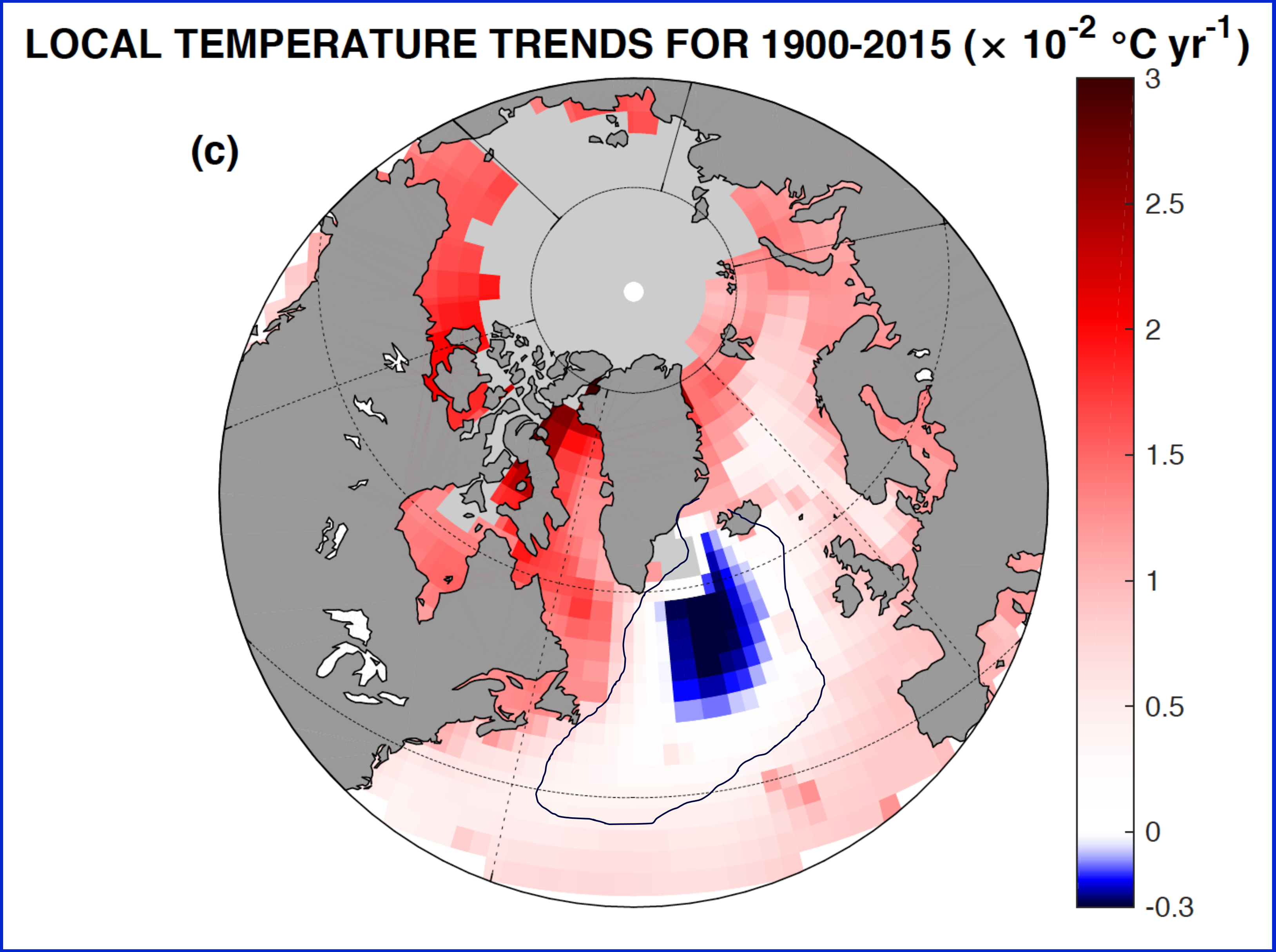
Correlation between the two =0.5

March mixed layer depth (CESM_T31)

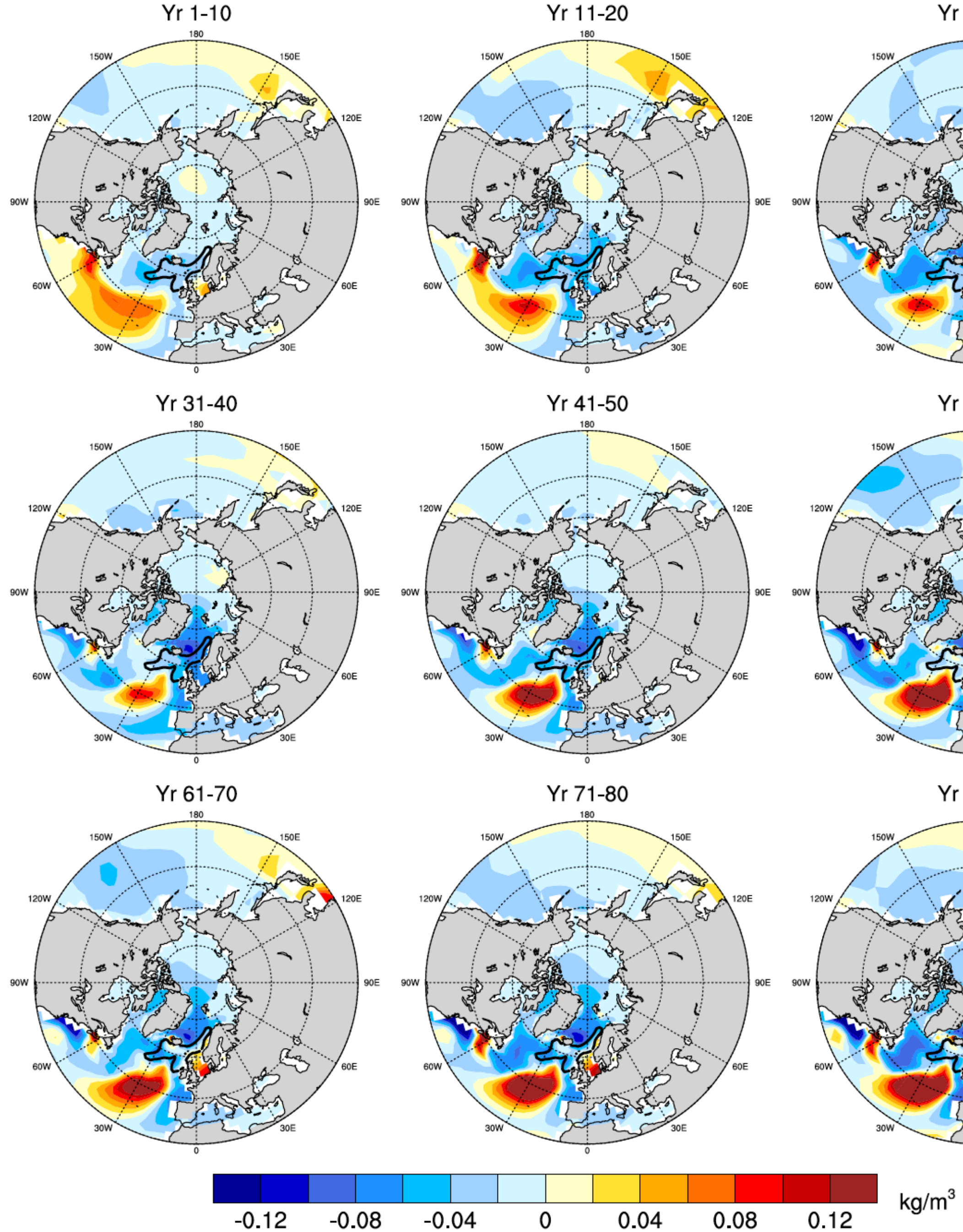


March MLD (Observations: MIMOC)

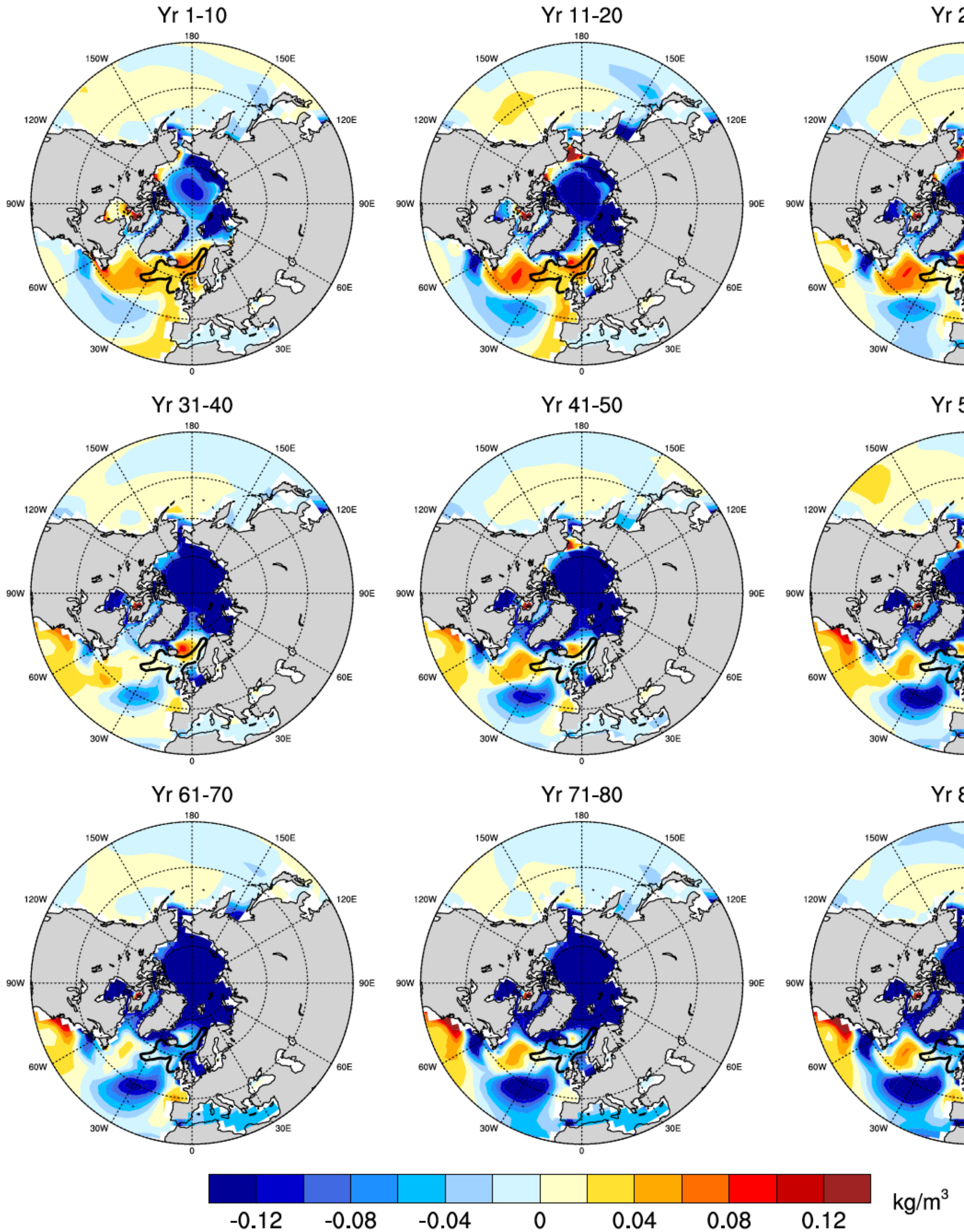



LOCAL TEMPERATURE TRENDS FOR 1900-2015 (× 10^-2 °C yr^-1)
(c)
3
2.5
2
1.5
1
0.5
0
-0.3

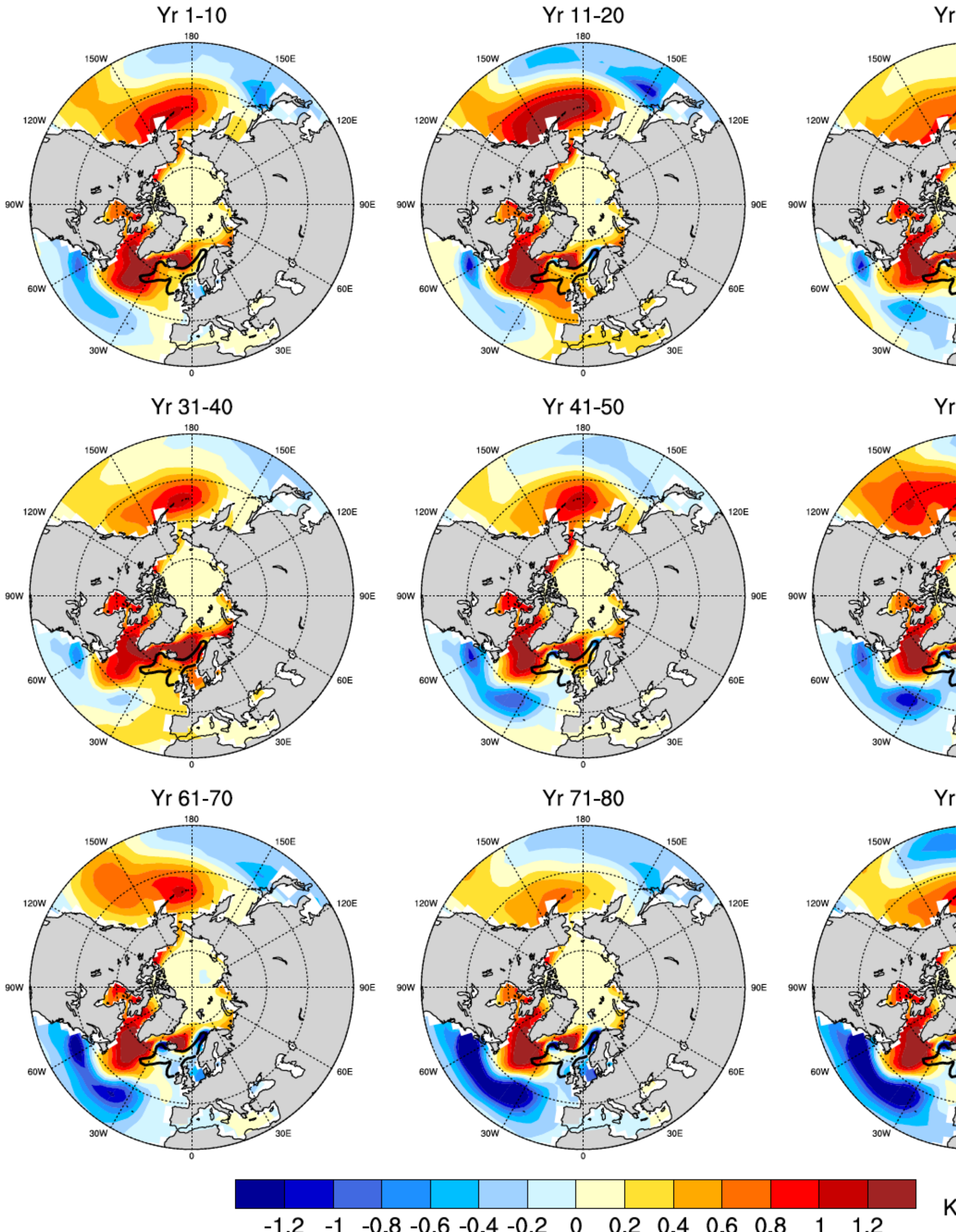
LW experiment, $\Delta\rho_T$ (upper 1000m)



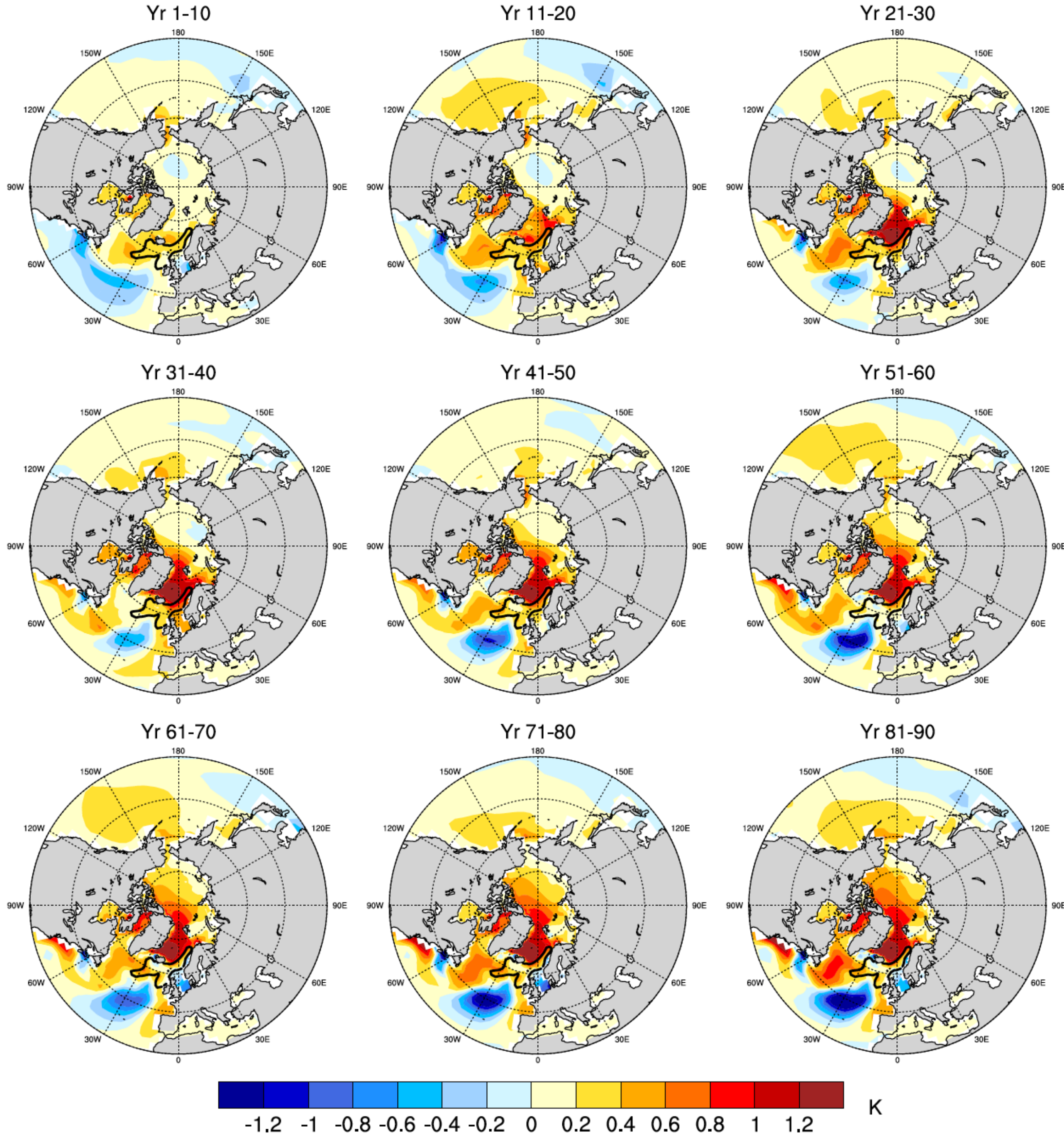
LW experiment, $\Delta\rho_S$ (upper 1000m)



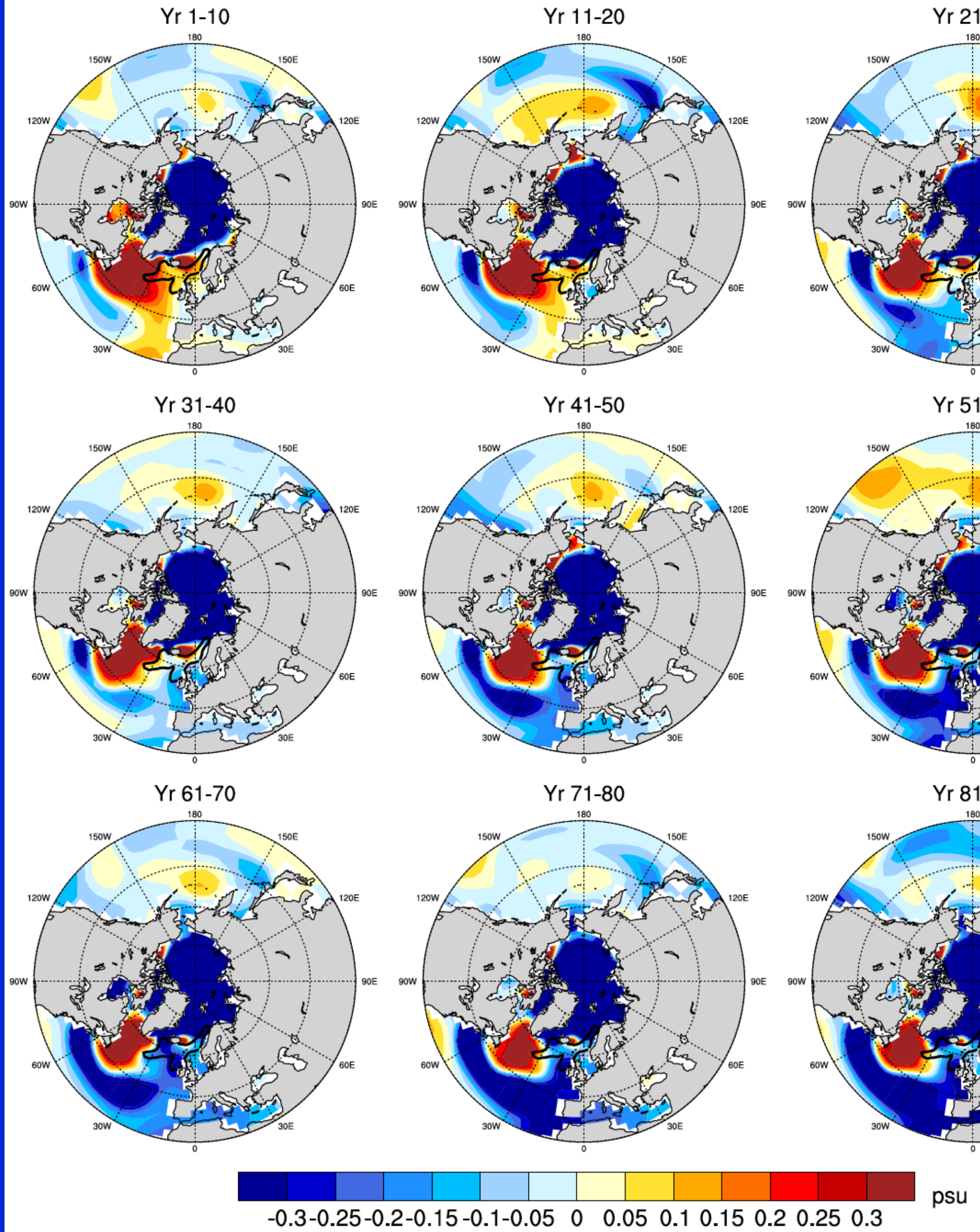
LW experiment, ΔSST



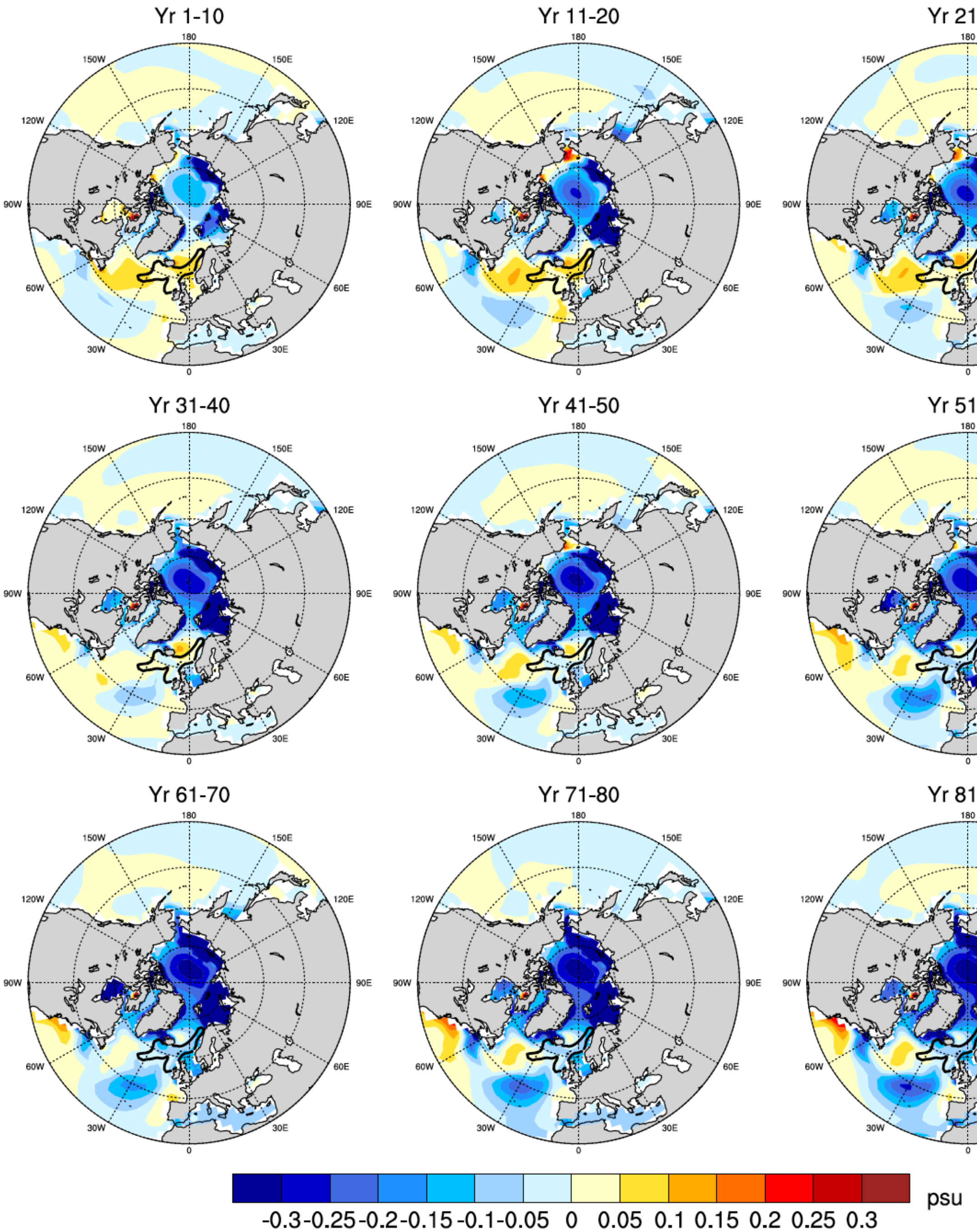
LW experiment, ΔT (upper 1000m)

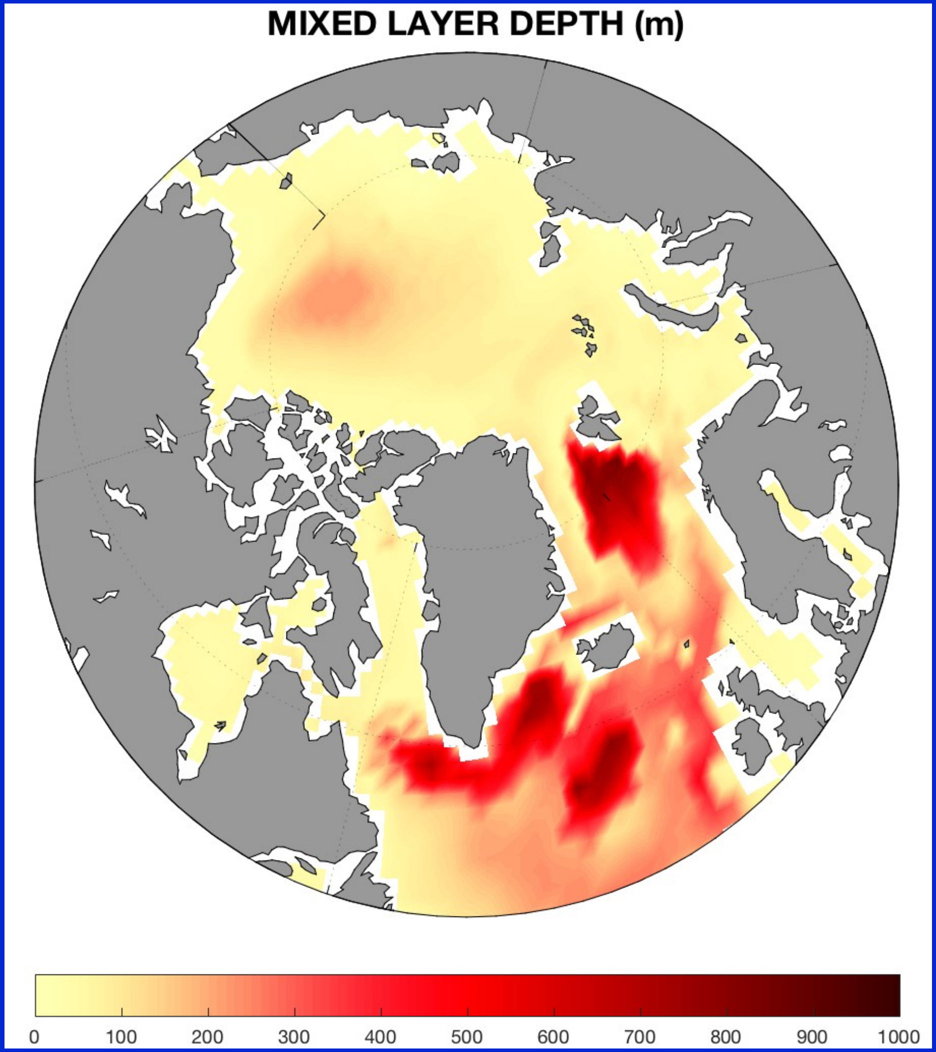


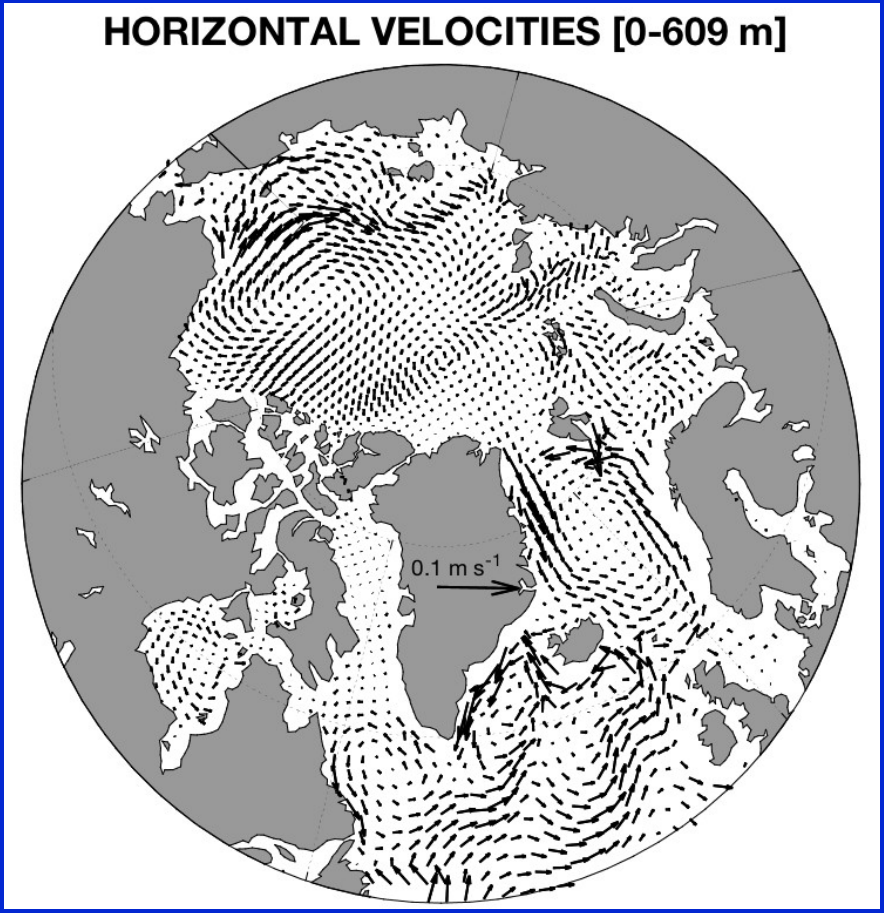
LW experiment, ΔSSS



LW experiment, ΔS (upper 1000m)




MIXED LAYER DEPTH (m)
0
100
200
300
400
500
600
700
800
900
1000


HORIZONTAL VELOCITIES [0-609 m]
0.1 m s-1

a normalization constraint on the flux amplitude, we introduce a Lagrangian function:

$$\mathcal{L}\left(|\boldsymbol{f}_{\mathrm{hf/fw}}\rangle, \gamma\right) = \langle \boldsymbol{F}|\boldsymbol{u}(\tau)\rangle - \gamma\left(\langle \boldsymbol{f}_{\mathrm{hf/fw}}|\mathbf{S}|\boldsymbol{f}_{\mathrm{hf/fw}}\rangle - \epsilon^2\right), \tag{2}$$

where γ is a Lagrange multiplier, $\mathbf{S}$ is a normalization operator, and ϵ is a parameter associated with the normalization constraint:

$$\langle \boldsymbol{f}_{\mathrm{hf/fw}}|\mathbf{S}|\boldsymbol{f}_{\mathrm{hf/fw}}\rangle = \frac{\iint d\sigma\, f^2_{\mathrm{hf/fw}}}{\iint d\sigma} = \epsilon^2, \tag{3}$$

where $d\sigma$ is a unit surface and $f_{\mathrm{hf/fw}}$ is surface heat and freshwater fluxes, respectively. We set ϵ=1 W m^{-2} or 1 cm yr^{-1}, which gives the root mean square amplitude of the fluxes. Our goal is to maximize the cost function subject to this normalization constraint.

From expression (2) and the general optimization condition $d\mathcal{L}$=0, optimal flux perturbations for the duration τ are computed as

$$|\boldsymbol{f}^{\tau}_{\mathrm{hf/fw}}\rangle = \pm\frac{1}{\gamma}\int_0^{\tau} ds\, \mathbf{S}^{-1}\mathbf{B}^{\dagger}_{\mathrm{hf/fw}}\mathbf{M}^{\dagger}(s)\,|\boldsymbol{F}\rangle, \tag{4}$$

where $\dagger$ represents an adjoint (defined through an Euclidean scalar product) and

$$\gamma^2 = \iint_0^{\tau} ds ds'\, \langle \boldsymbol{F}|\mathbf{M}(s)\mathbf{B}_{\mathrm{hf/fw}}\mathbf{S}^{-1}\mathbf{B}^{\dagger}_{\mathrm{hf/fw}}\mathbf{M}^{\dagger}(s')|\boldsymbol{F}\rangle. \tag{5}$$

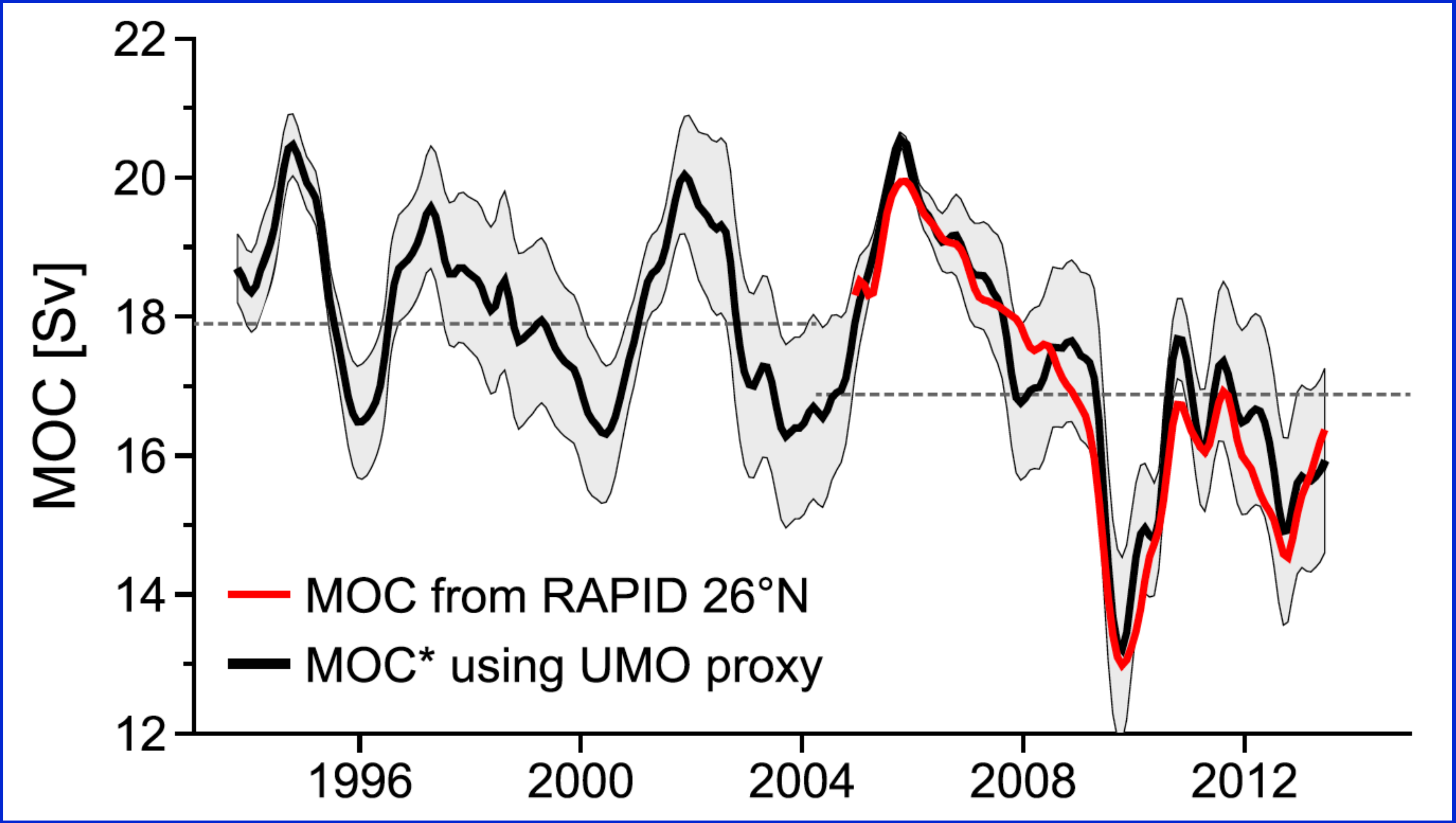
Consequently, γ gives the optimal impact of the normalized flux anomalies.

Sevellec and Fedorov 2016


Freshwater surface current from Arctic
Denmark Strait Overflow
Greenland
Greenland-Scotland Ridge
Faroe Bank Channel Overflow
Scotland
500 meters
500 meters
500 meters
North Atlantic Current

Figure: WHOI

AMOC slow-down



Frajka-Williams-2015

AMOC weakening for different flux durations and regions