Surface factors controlling the volume of accumulated Labrador Sea Water

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Part of our contribution to the UK OSNAP community

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Distinct sources of interannual subtropical and subpolar Atlantic overturning variability

Yavor Kostov[1], Helen L. Johnson[2], David P. Marshall[3], Patrick Heimbach[4,5,6], Gael Forget[7], N. Penny Holliday[8], M. Susan Lozier[9], Feili Li[9], Helen R. Pillar[4] and Timothy Smith[4]

Aug. 2022

Climate Dynamics
https://doi.org/10.1007/s00382-022-06459-y

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Fast mechanisms linking the Labrador Sea with subtropical Atlantic overturning

Yavor Kostov[1] · Marie-José Messias[1] · Herlé Mercier[2] · Helen L. Johnson[3] · David P. Marshall[4]

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Surface factors controlling the volume of accumulated Labrador Sea Water

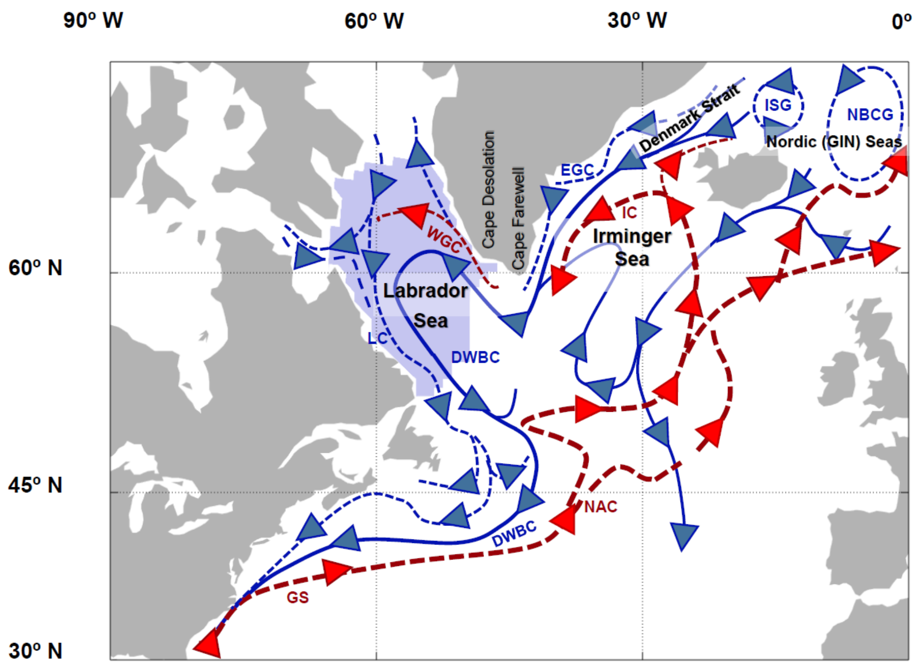
Yavor Kostov[1,2], Marie-José Messias[1], Herlé Mercier[3], David P. Marshall[4], Helen L. Johnson[5]

Formation, transport, accumulation of LSW

- LSW is important for long-term Atlantic variability and the storage of heat and other tracers
- Production in the Labrador (and Irminger) Sea
- A fraction exported to the subtropical gyre
- Spreading to the Irminger and Iceland Basins
- Recirculation within the subpolar gyre and import of deep water formed in the Irminger Sea
- Destruction via isopycnal mixing / restratification

Zou and Lozier (JPO 2016), Yashayaev et al. (GRL 2007a,b), Pickart et al. (Nature 2003)

Defining the LSW volume in the ECCO state estimate



Low-stratified NADW component in the Labrador Sea bound by the OSNAP-West line

$$27.7\text{kg m}^{-3} < \sigma_\theta < 27.84 \text{ kg m}^{-3},$$

$$\text{PV} < 4 \times 10^{-12} m^{-1} s^{-1}, \quad PV \approx f\,\frac{N^2}{g}.$$ PV is the more important constraint!

Following Zou and Lozier (2016)

Convolution of boundary conditions $\mathcal{P}$ with lagged LSW sensitivity maps $\mathcal{G}_{\mathcal{P}}$

Surface boundary condition at location **x** and time *t*

$$C_{\mathcal{P}}(t) = \int_{t-\tau}^{t} \int \mathcal{P}(\mathbf{x}, t') \mathcal{G}_{\mathcal{P}}(t; \mathbf{x}, t - t') \, \mathrm{d}\mathbf{x} \mathrm{d}t'$$

Contribution of a given surface boundary condition (e.g., surface heat fluxes) to the LSW volume anomaly at time *t*

Sensitivity of the LSW volume to the surface boundary condition at location **x** at a given lead time. (seasonally dependent)

We integrate in space over the ocean surface and in time up to a lead time τ

Reconstruction/attribution of LSW variability using *only* surface boundary conditions

The adjoint of a model outputs lagged linear sensitivity (first derivatives) of an objective function to past boundary conditions and parameters.

Pillar et al. (2016), Jones et al. (2018), Smith and Heimbach (2019), Boland et al. (2019), Kostov et al. (2021), Boland et al. (2021) use the adjoint of the MITgcm.

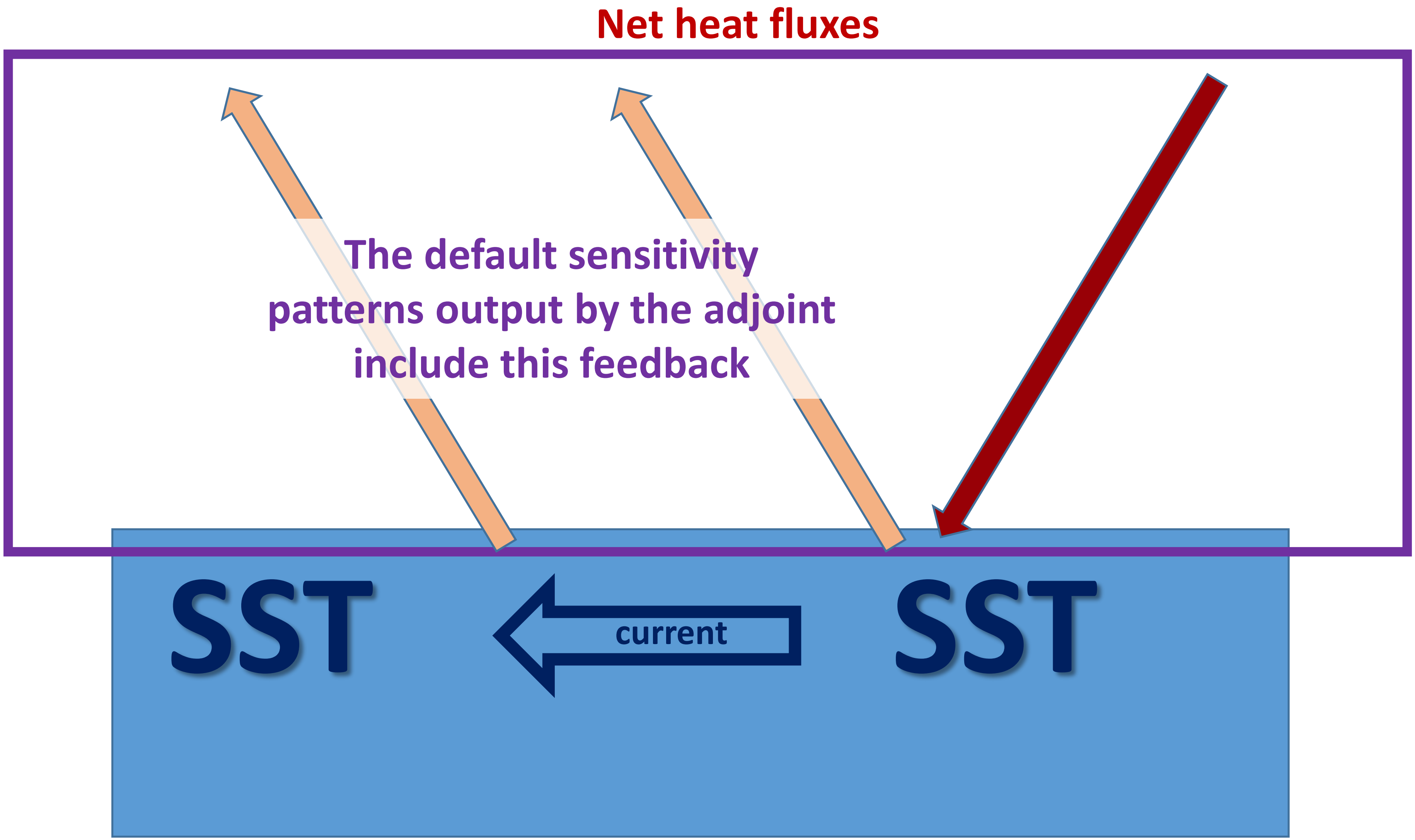
Here we use the adjoint of the MITgcm in the ECCOv4r2 state estimate (Forget et al., 2015) configuration.

Jones et al. (2018) explore total heat content in the Labrador Sea basin.

Aspects specific to this study:

1) using time-evolving potential vorticity to define LSW volume as an objective function. Not relying on a fixed volume mask in depth space.
2) customizing the adjoint, so as not to differentiate the air-sea feedback code

ECCO state estimate boundary conditions



Double-counting air-sea feedback

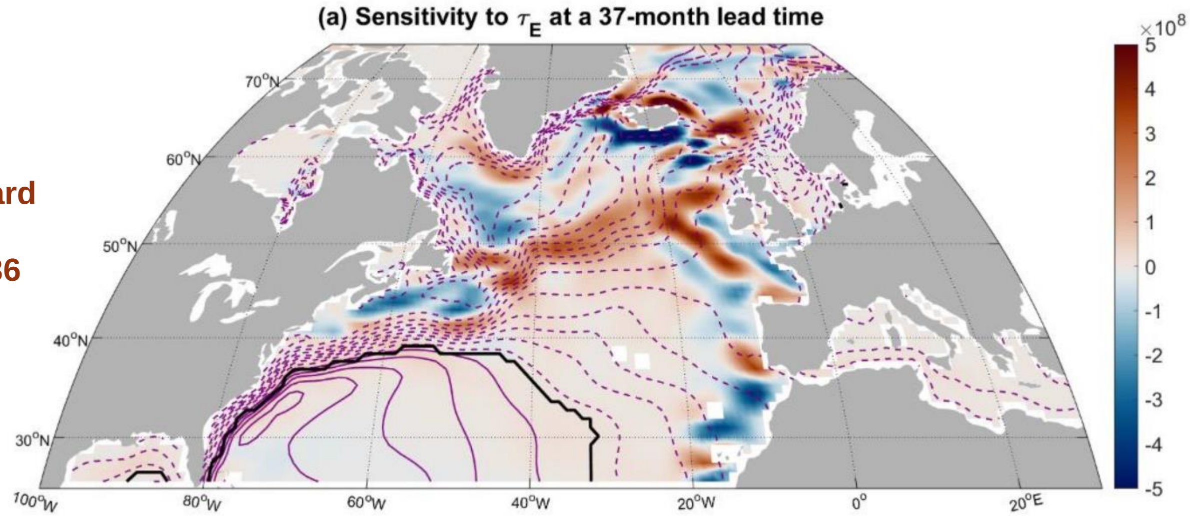
Air-sea feedback included here

$$C_{\mathcal{P}}(t) \neq \int_{t-\tau}^{t} \int \mathcal{P}(\mathbf{x}, t') \mathcal{G}_{\mathcal{P}}(t; \mathbf{x}, t - t') \, \mathrm{d}\mathbf{x} \mathrm{d}t'$$

Air-sea feedback also included here

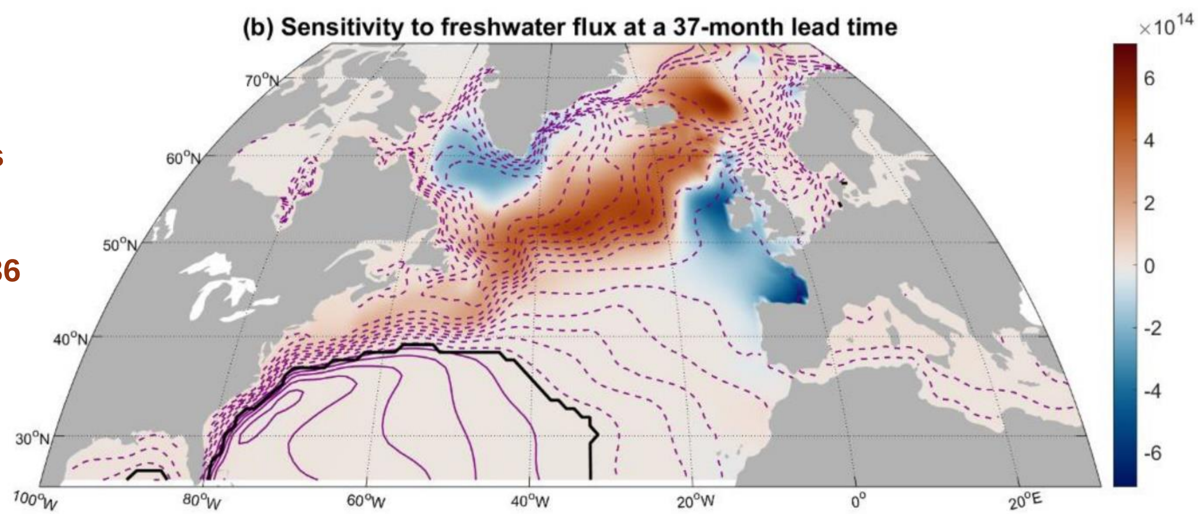
We have to tell the automatic differentiation software not to take derivatives of the air-sea feedback code.

Red: An eastward anomaly would increase LSW 36 months later.



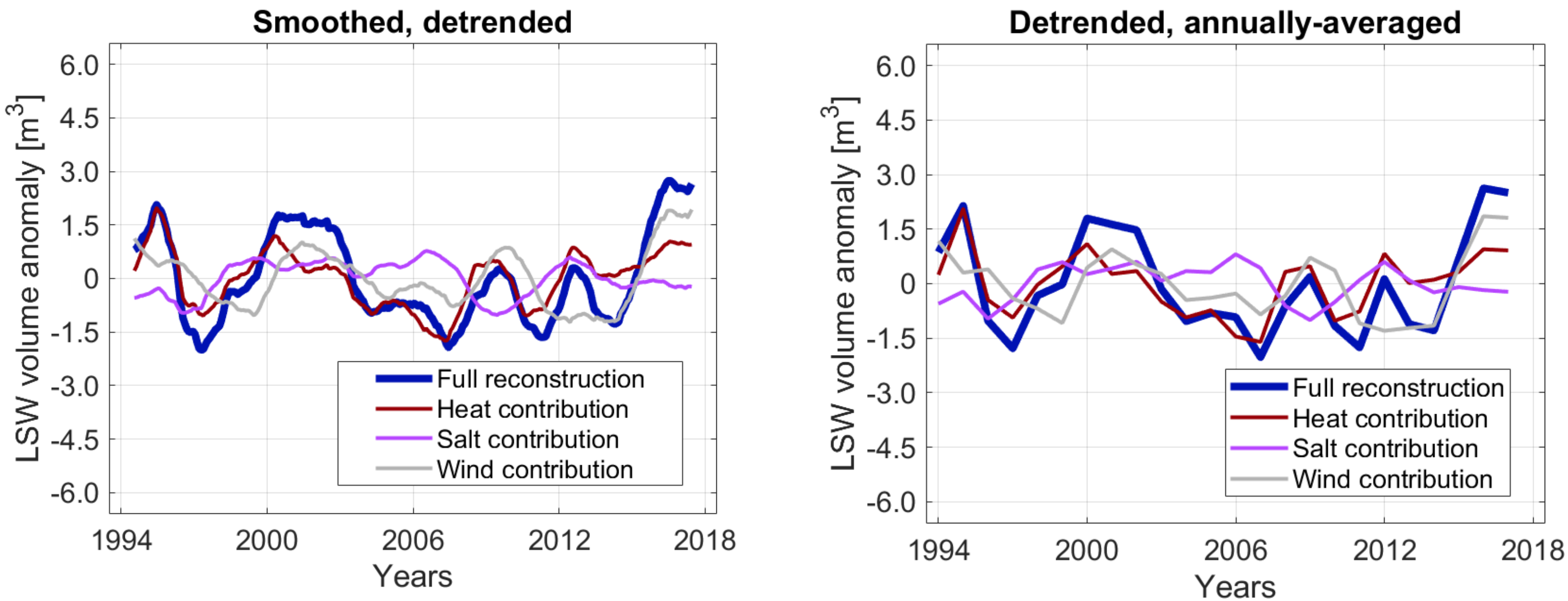
$[m^3 N^{-1} m^2$ **over 1 hour**$]$

Red: An excess evaporation anomaly would increase LSW 36 months later.



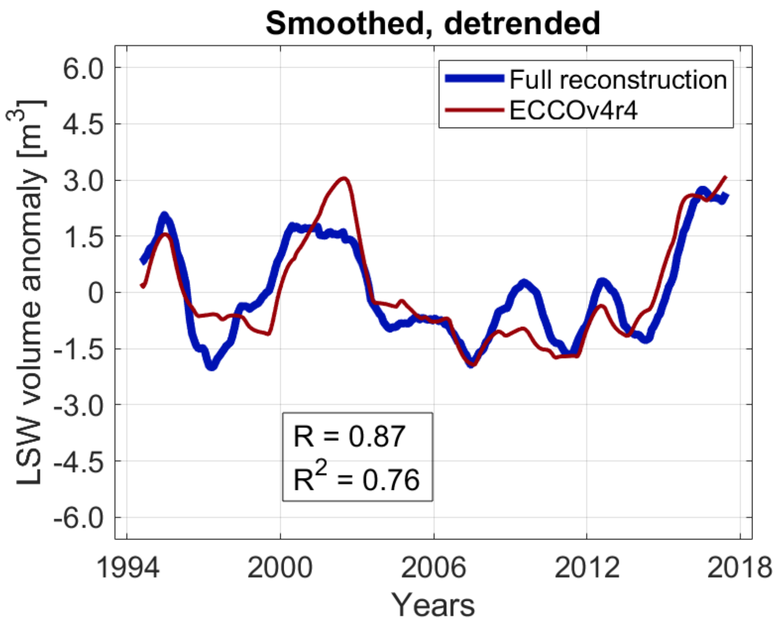
$[m^3 m^{-1} s$ **over 1 hour**$]$

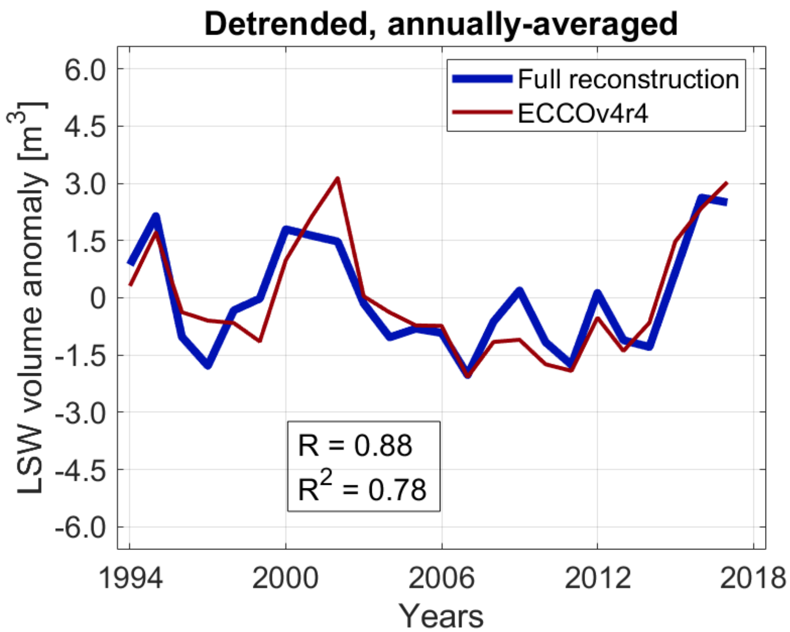
Attribution



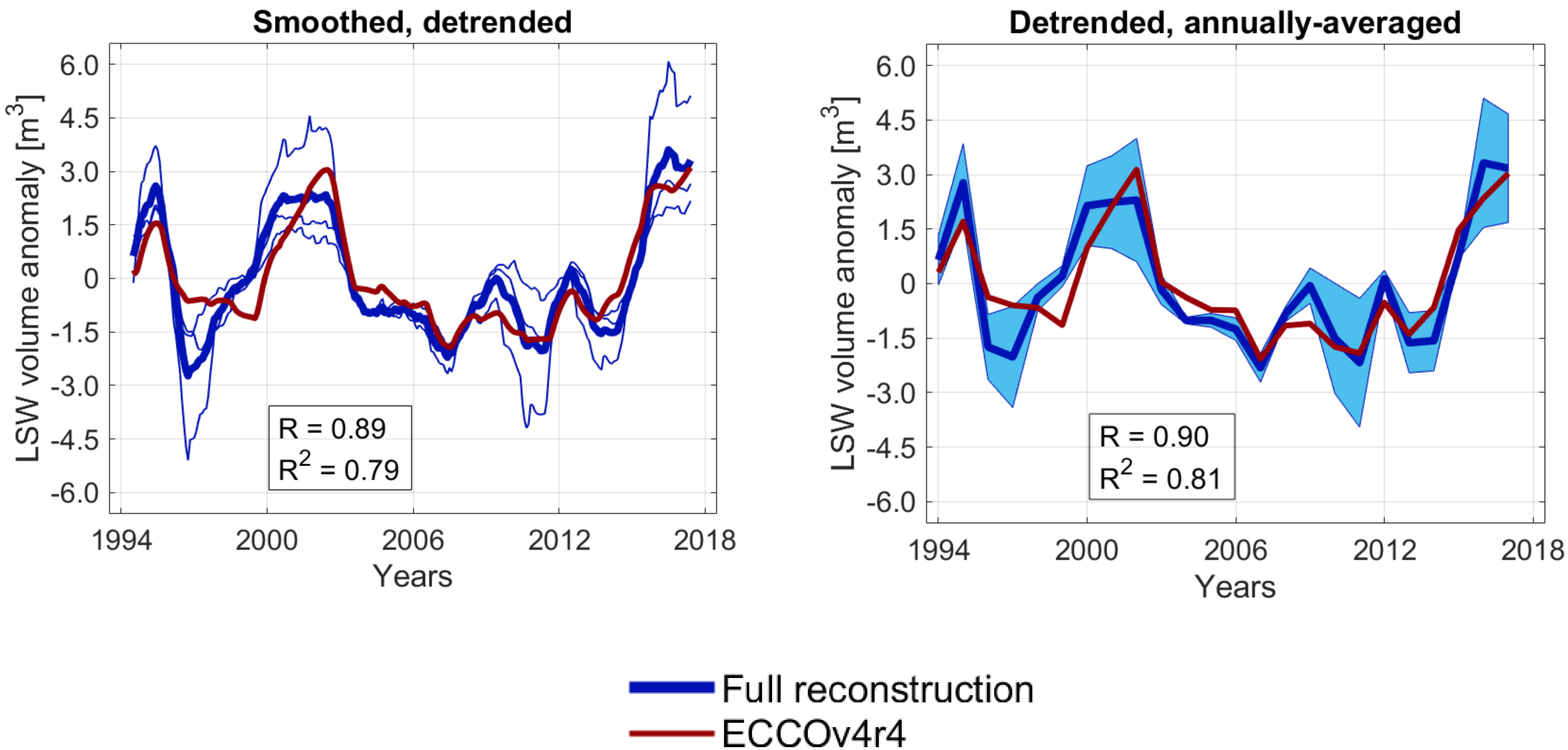
Comparable contributions of the surface boundary condition anomalies in winds, surface heat fluxes, and surface freshwater fluxes.

Single reconstruction

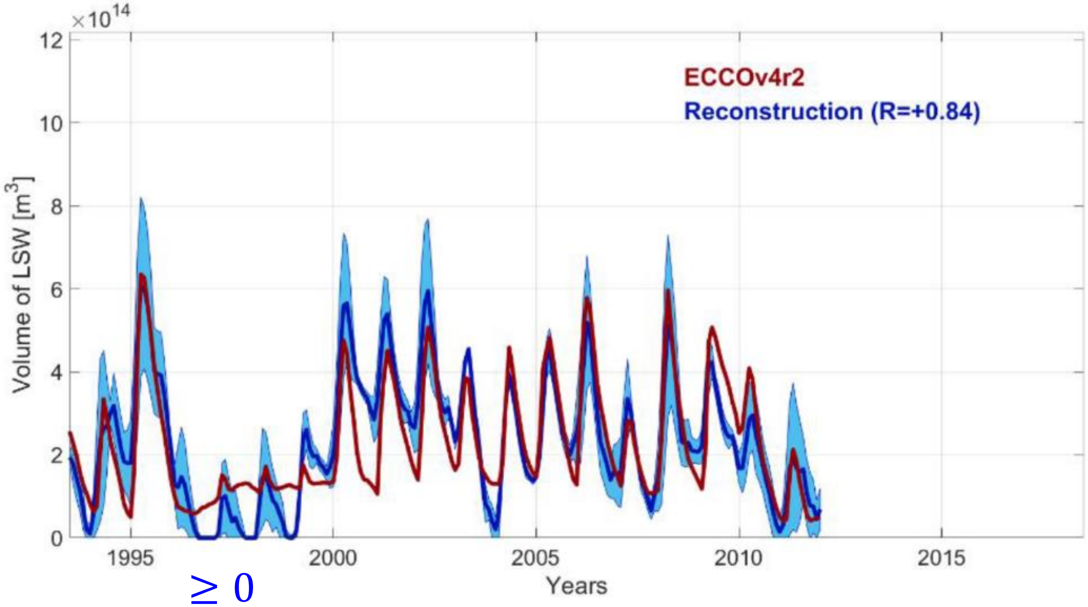




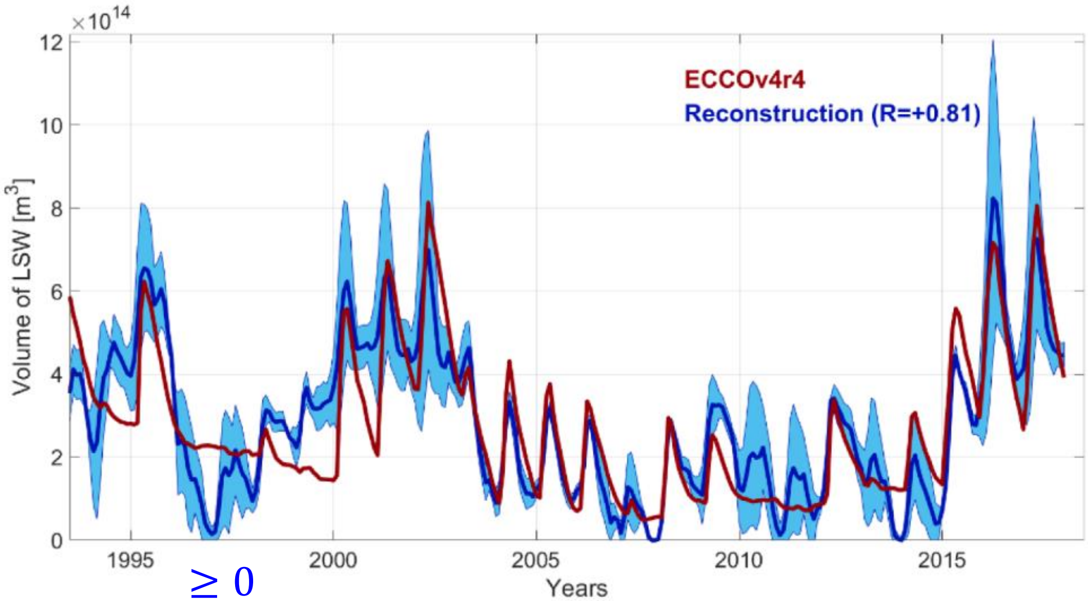
Ensemble of reconstructions



Including the climatological seasonal cycle



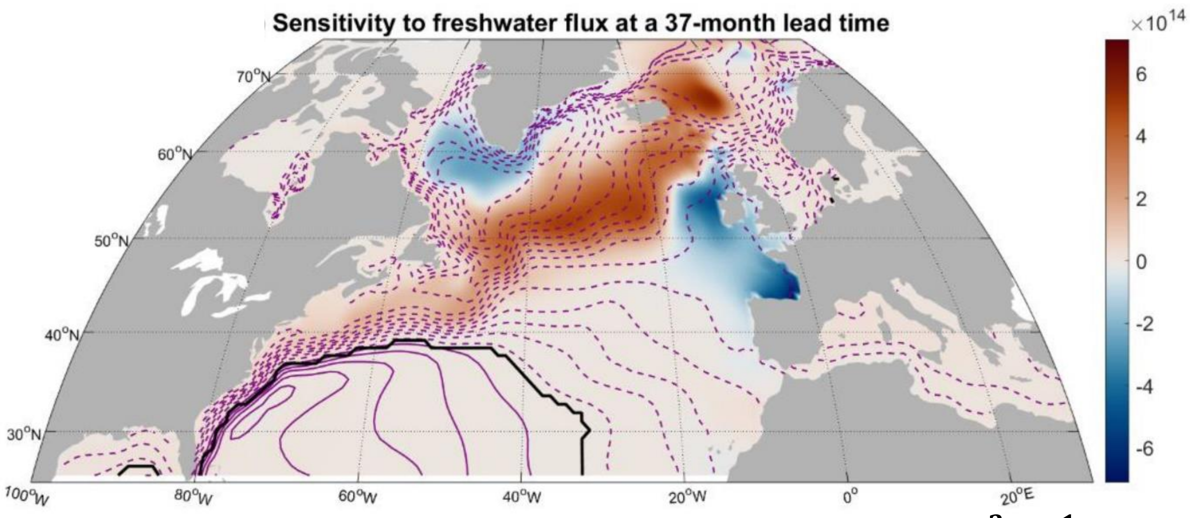
≥ 0



≥ 0

Physical understanding of the sensitivity patterns from the perturbation experiment

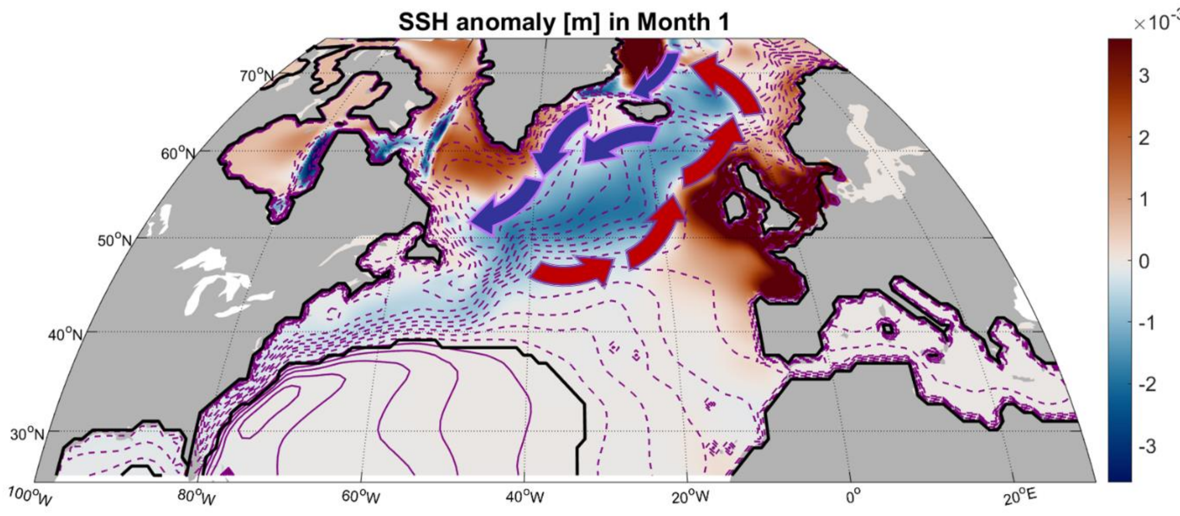
Rescale to match the order of magnitude of the standard deviation in surface freshwater fluxes. Apply this pattern as a forward perturbation to rainfall.



$[m^3 m^{-1} s \text{ over 1 hour}]$

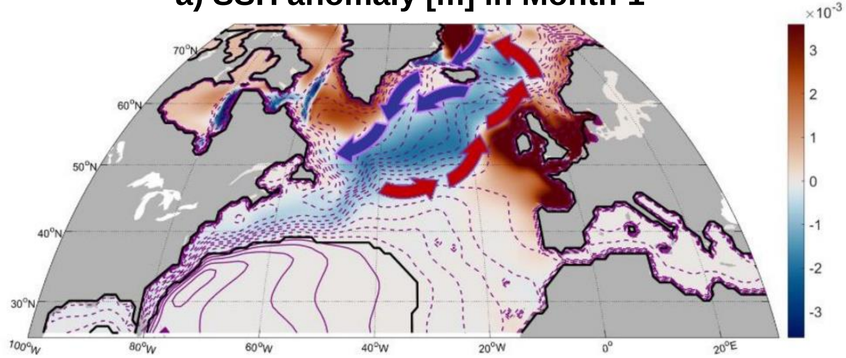
Physical understanding of the sensitivity patterns from the perturbation experiment

- **The freshwater flux anomaly has an immediate impact on SSS, surface density, and consequently on SSH.**
- **Anomalous SSH gradients sustain anomalies in the ocean surface currents and the NAC pathways.**



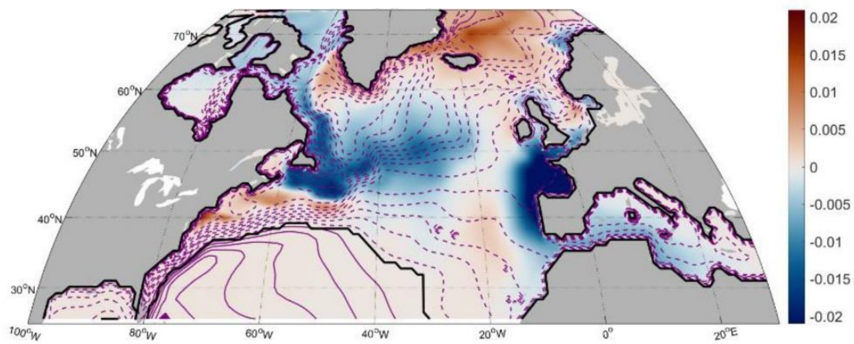
NAC "Traffic Controller" pattern

a) SSH anomaly [m] in Month 1

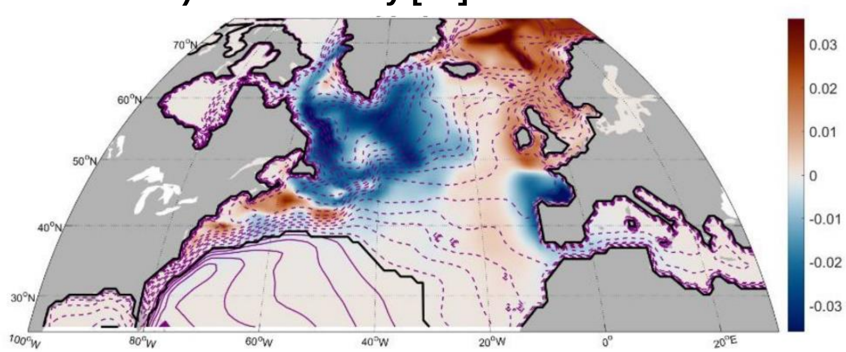


NAC "Traffic Controller" pattern

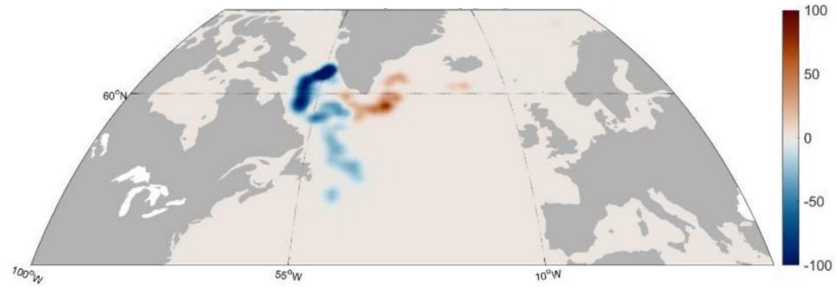
b) SSS anomaly [psu] in Month 37



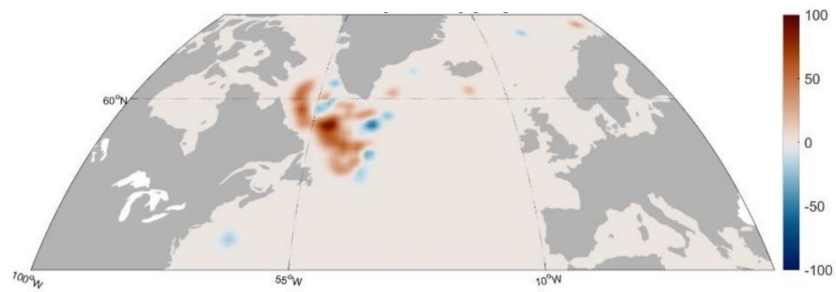
c) SST anomaly [°C] in Month 37



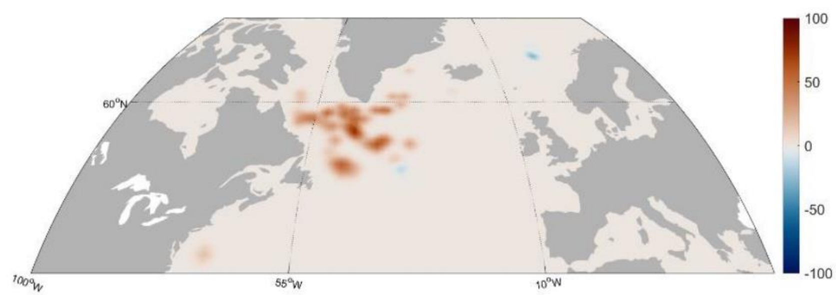
a) LSW thickness anomaly [m] in Month 16

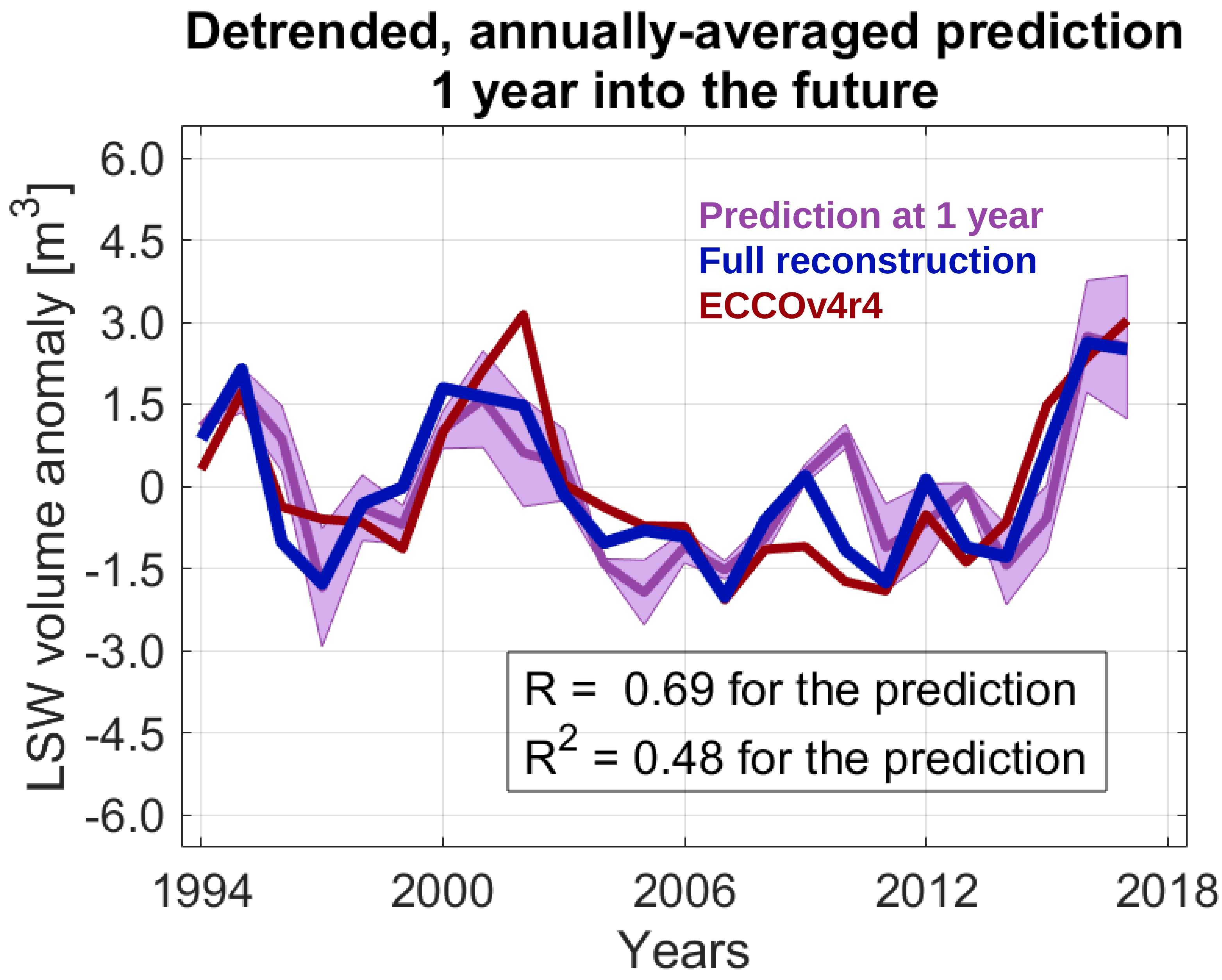


b) LSW thickness anomaly [m] in Month 37



c) LSW thickness anomaly [m] in Month 61





Surface conditions along the NAC pathways contribute to this predictability.

Summary

1) *Linear* reconstructions of accumulated LSW volume in the Labrador Sea using *only* surface boundary conditions: surface fluxes and wind-stress.
2) Wind, surface freshwater fluxes, and heat fluxes make comparable contributions to LSW variability.
3) LSW is particularly sensitive to remote forcing along the pathway of the NAC but also parallel to the NAC pathway. (NAC “Traffic Controller” pattern).
4) The predictive skill at a 1-year horizon suggests an important role for preconditioning.

Thank you!

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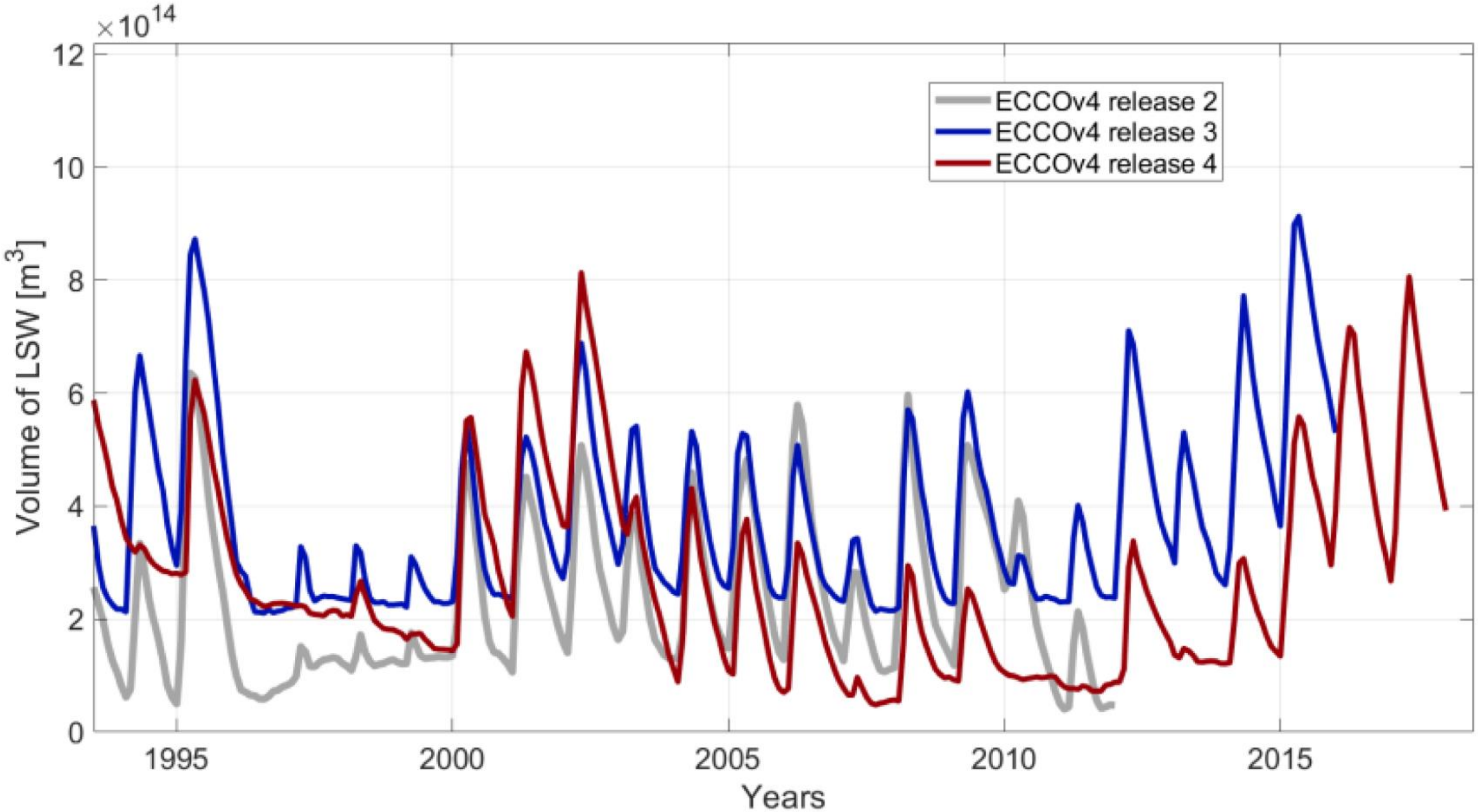
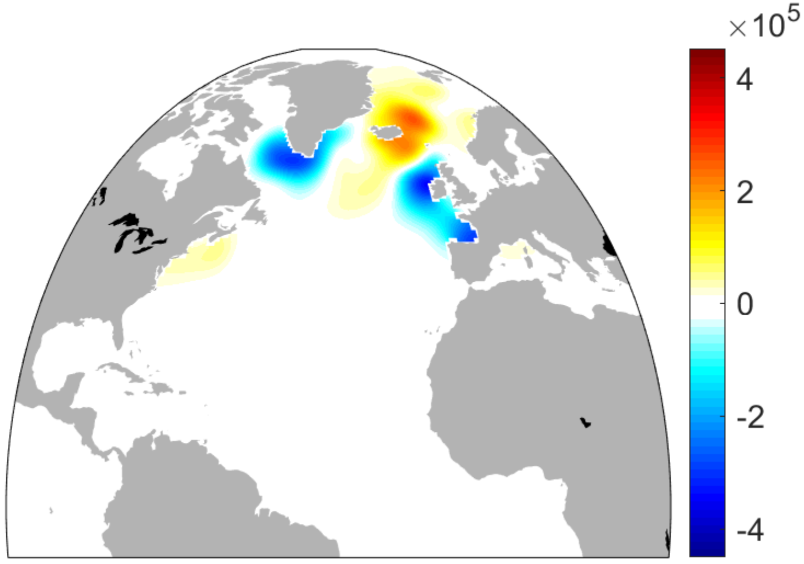
Historical variability



Sensitivity of the volume of winter LSW to surface heat fluxes at a lead time of 37 months

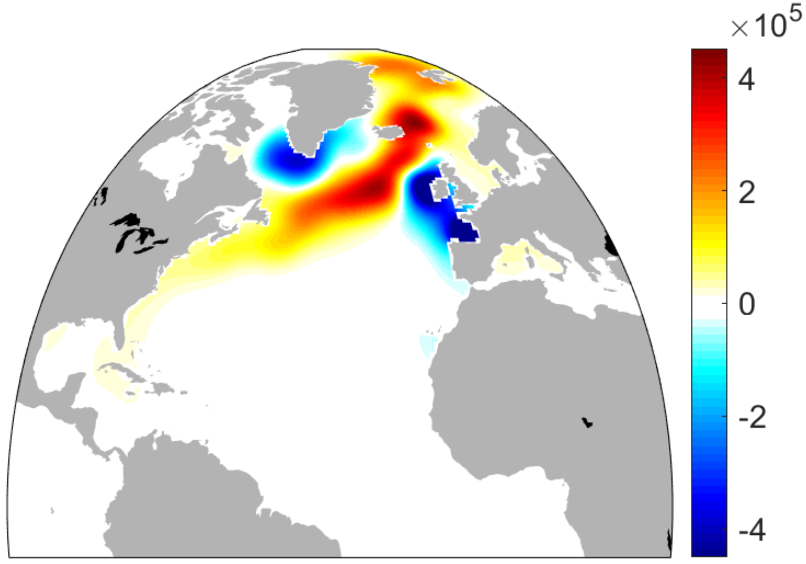
spatially smoothed

Bulk formulae differentiated



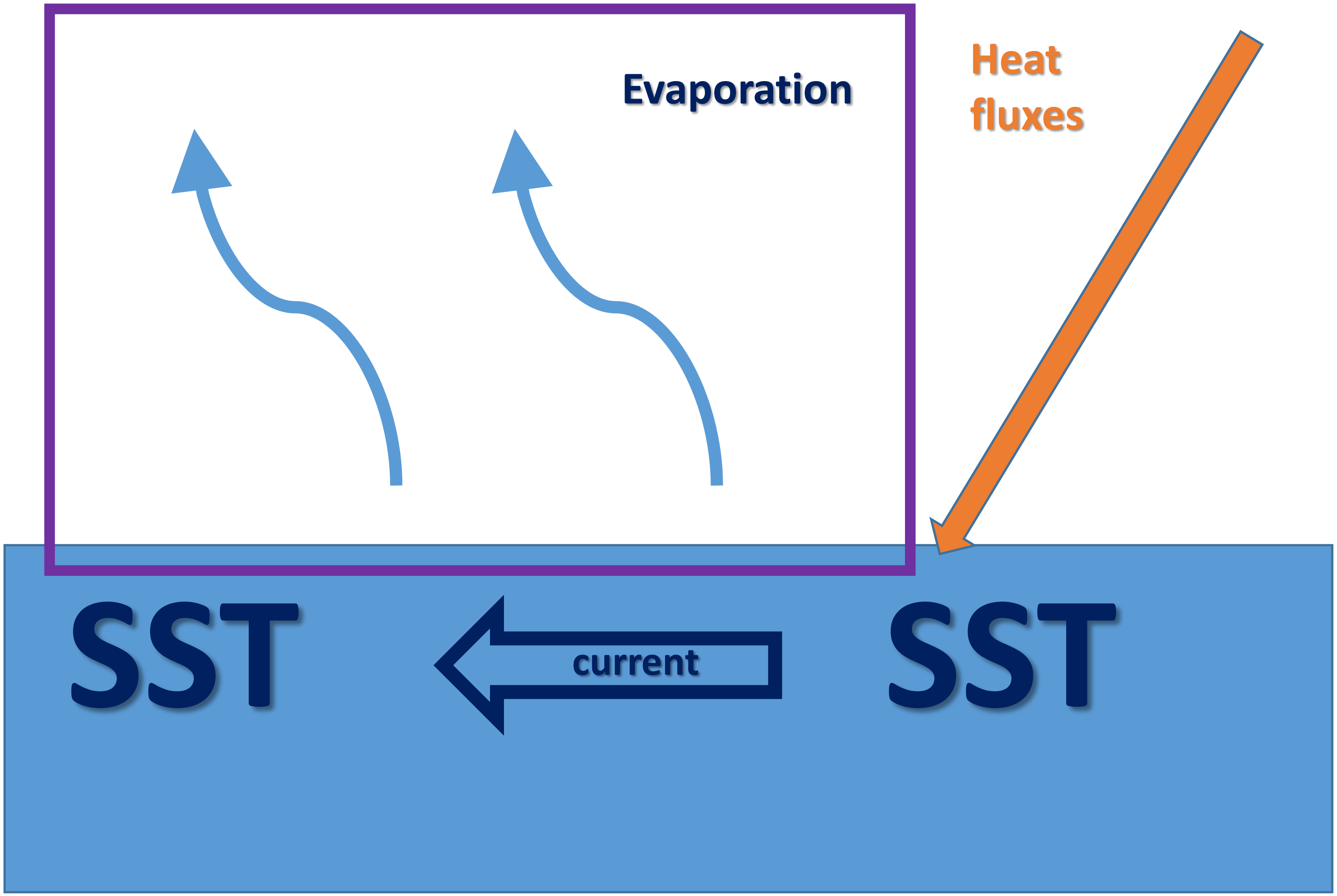
Takes into account the built-in atmospheric damping of ocean heat content anomalies and air-sea feedback.

Bulk formulae *NOT* differentiated



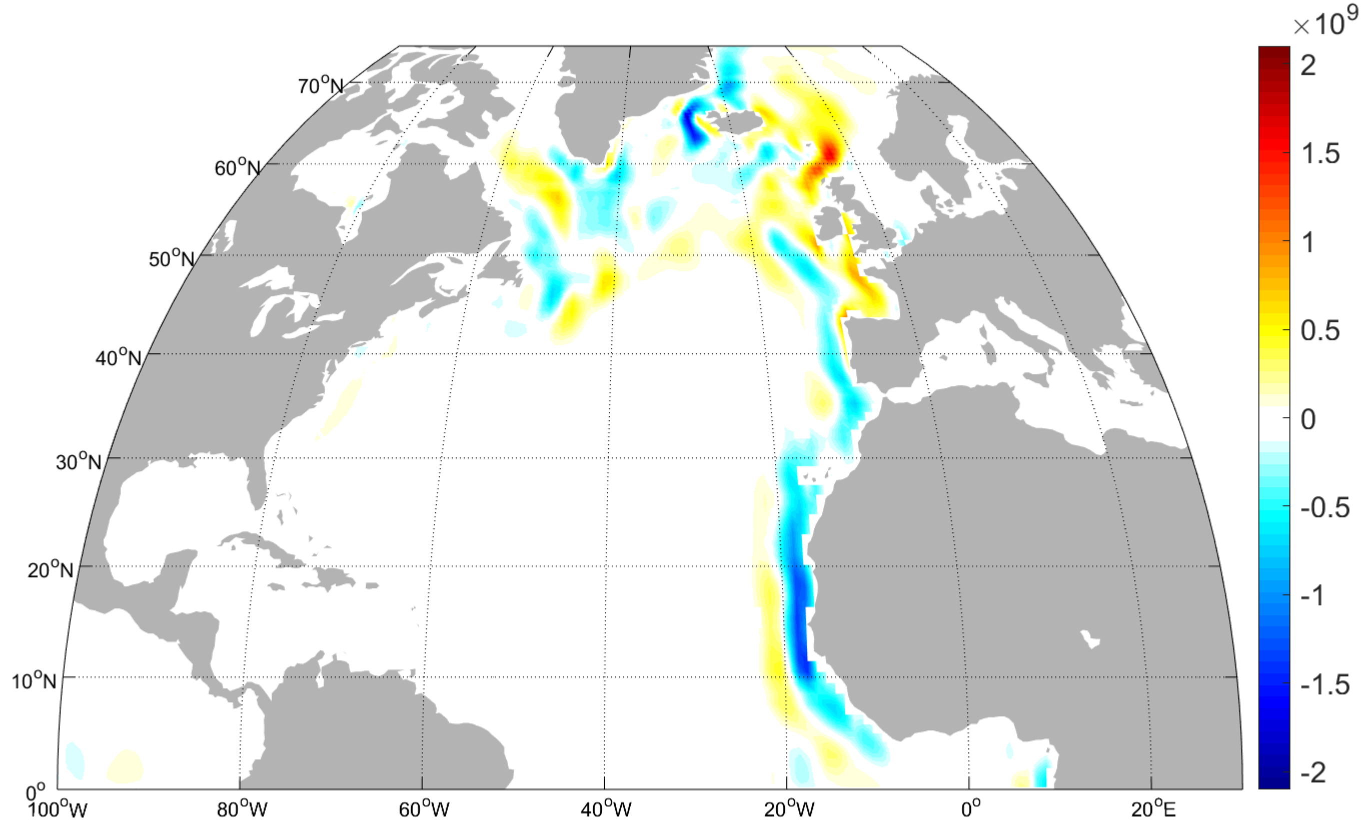
Can be convolved with a timeseries of net surface heat fluxes like a Green's function convolution.

ECCO state estimate boundary conditions



And similarly for the freshwater budget forced with surface humidity, rainfall, etc.

Sensitivity of LSW volume to northward meridional wind stress at a lead time of 31 months

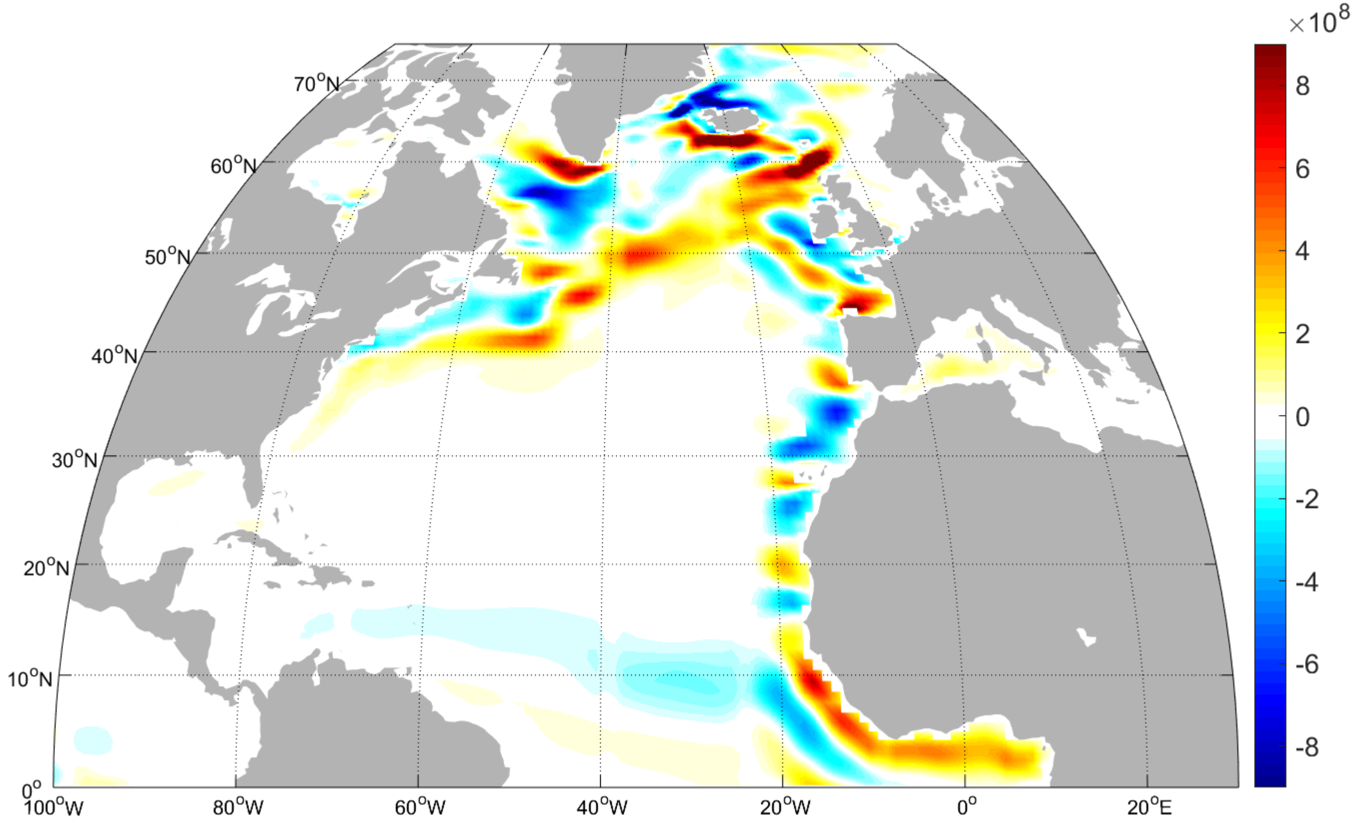


$[m^3/(N/m^2$ sustained over 1 hour$)]$

Coastal waveguide from the low-latitudes.

Waves change the SSH and density gradients in the subpolar gyre → geostrophic transport anomaly

Sensitivity of LSW volume to eastward zonal wind stress at a lead time of 31 months



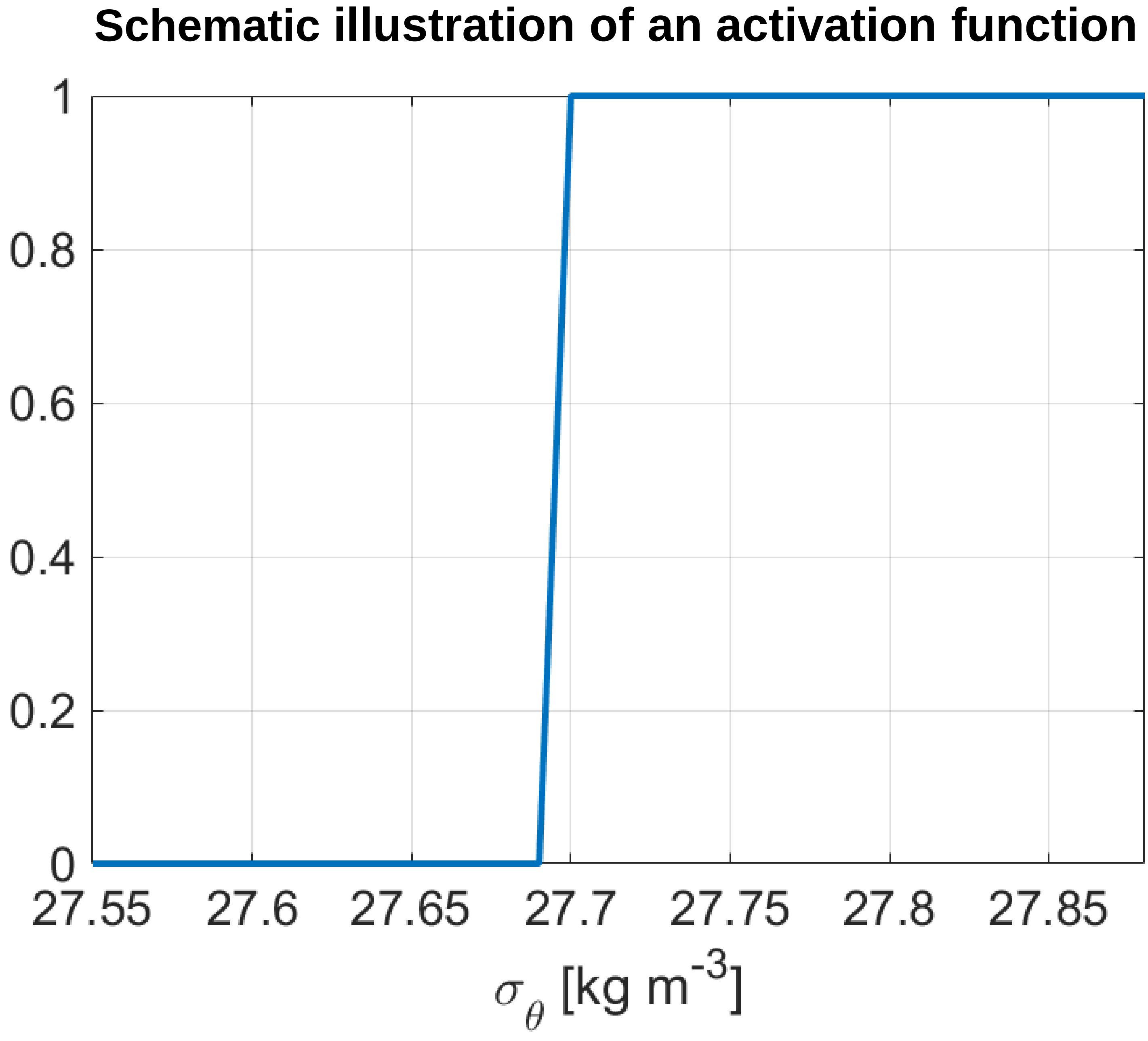
[m³/(N/m² sustained over 1 hour)]

Along the Gulf Stream – NAC pathways

Continuous activation function

&   *((1+tanh((SigmaLoc-SigmaLowBnd)*100000))/2)
&   *(1-((1+tanh((SigmaLoc-SigmaUpBnd)*100000))/2))
&   *((1+tanh((PVloc-PVlowBnd)*100000))/2)
&   *(1-((1+tanh((PVloc-PVupBnd)*100000))/2))

Each factor has values between 0 and 1.


Schematic illustration of an activation function
1
0.8
0.6
0.4
0.2
0
27.55
27.6
27.65
27.7
27.75
27.8
27.85
σ_θ [kg m^{-3}]

Formation, transport, accumulation of LSW

"waters produced from any one particular convection event are not collectively and contemporaneously exported to the subtropical gyre" (Zou and Lozier, JPO 2016)

Spreading of the Labrador Sea Water to the Irminger and Iceland basins (Yashayaev et al., GRL 2007a)

"substantial recirculation of newly formed LSW in the subpolar gyre" (Zou and Lozier, JPO 2016)

"The deep water formed in the Irminger Sea has the characteristic temperature and salinity of the water mass that fills the mid-depth North Atlantic Ocean, which had been believed to be formed entirely in the Labrador basin." (Pickart et al., Nature 2003)

"Once convection weakens, the LSW class becomes isolated from the upper layer and starts to decay, rapidly losing its volume while retaining the same density due to isopycnal mixing with the neighbouring warm saline intermediate waters. " (Yashayaev et al., GRL 2007b)