Subpolar North Atlantic responses to increased stratospheric aerosols in two climate model sensitivity experiments

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Background: Stratospheric Aerosol Injection and Subpolar North Atlantic (SPNA)

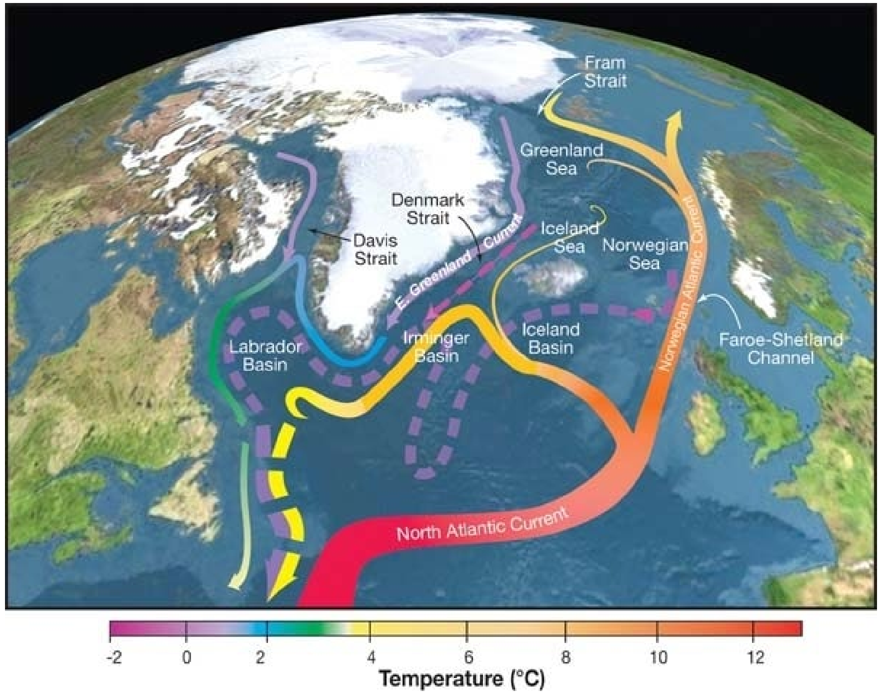
What is SAI?

- **Stratospheric aerosol injection** (SAI) has been proposed as a strategy to offset some of the negative consequences of global warming. However, **the impact of SAI on regional climate remains largely uncertain**.

Why do we care about the Subpolar North Atlantic (SPNA)?

- The SPNA (45–65°N, 0–60°W) is a critical region for the global climate system, as ocean deep convection in this region is part of the **Atlantic Meridional Overturning Circulation** (AMOC), which is crucial for regulating global heat and carbon transport.

- There may be significant processes associated with the interplay between **the hydrological responses of the SPNA, the strength of the AMOC, and the Arctic climate**. Freshening in the Arctic due to sea ice melting can greatly affect AMOC strength and the associated heat transport (*Sévellec et al. 2017; Liu et al. 2019; Liu and Fedorov 2019; Li et al., 2021*).



A schematic of the Atlantic Meridional Overturning Circulation (Curry and Mauritzen, 2005)

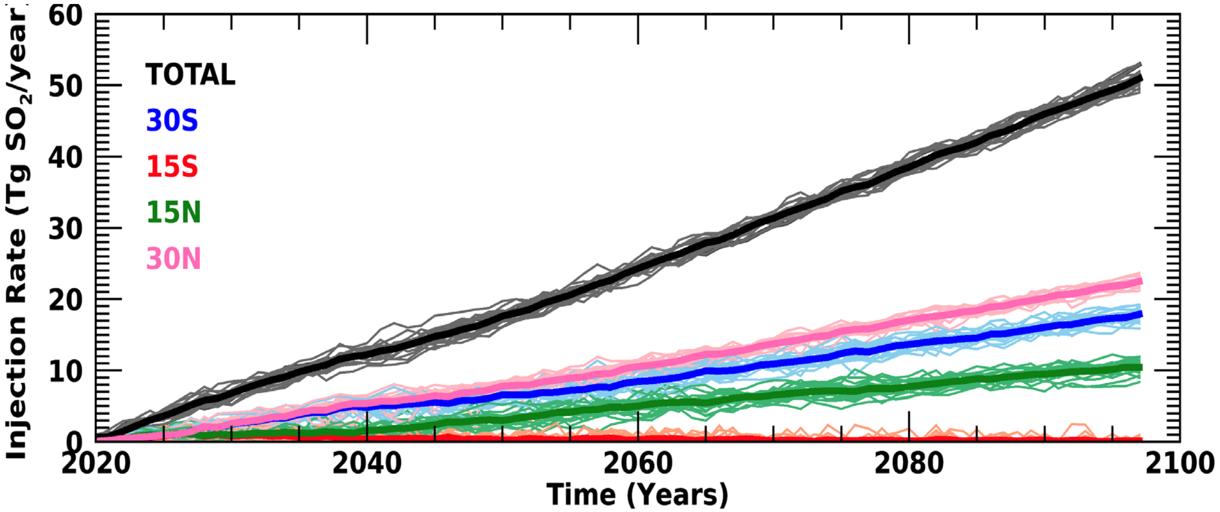
Model experiments

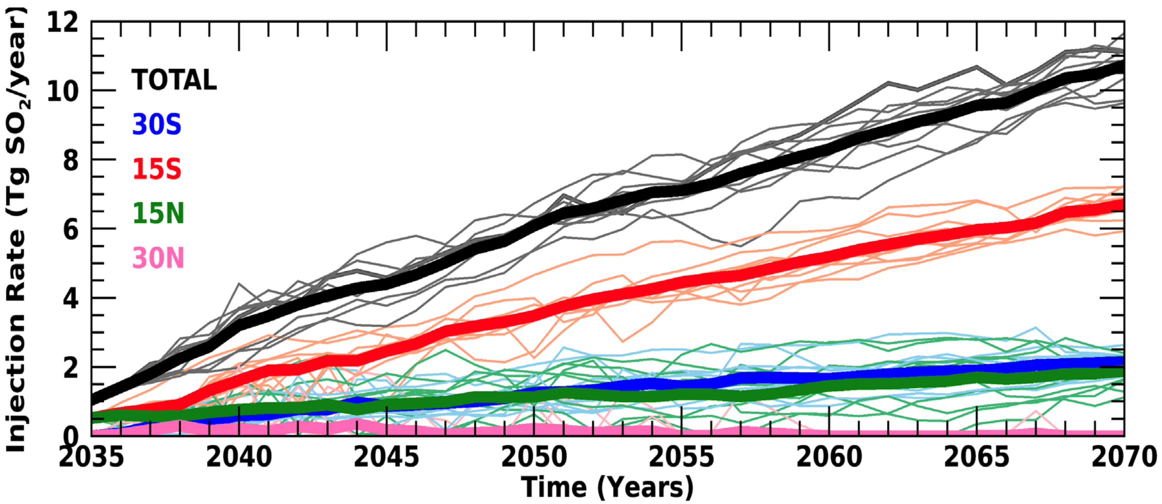
GLENS-SAI (Tilmes et al. 2018)

- CESM1-WACCM5
- **Reference simulation**: RCP8.5, run form 2005 through 2030 with 17 ensemble members, with an additional three members continuing through 2099
- **SAI simulation**: 20 members of GLENS-SAI run through ~2100
- Aims to keep the global mean surface temperature, equator-to-pole, and pole-to-pole temperature gradients near 2020 levels.

ARISE-SAI (Richter et al. 2022)

- CESM2-WACCM6
- **Reference simulation**: SSP2-4.5 with 10 ensemble members
- **SAI simulation**: 10 members of ARISE-SAI run through 2070
- Aims to keep global mean temperature at 1.5 C above PiControl.



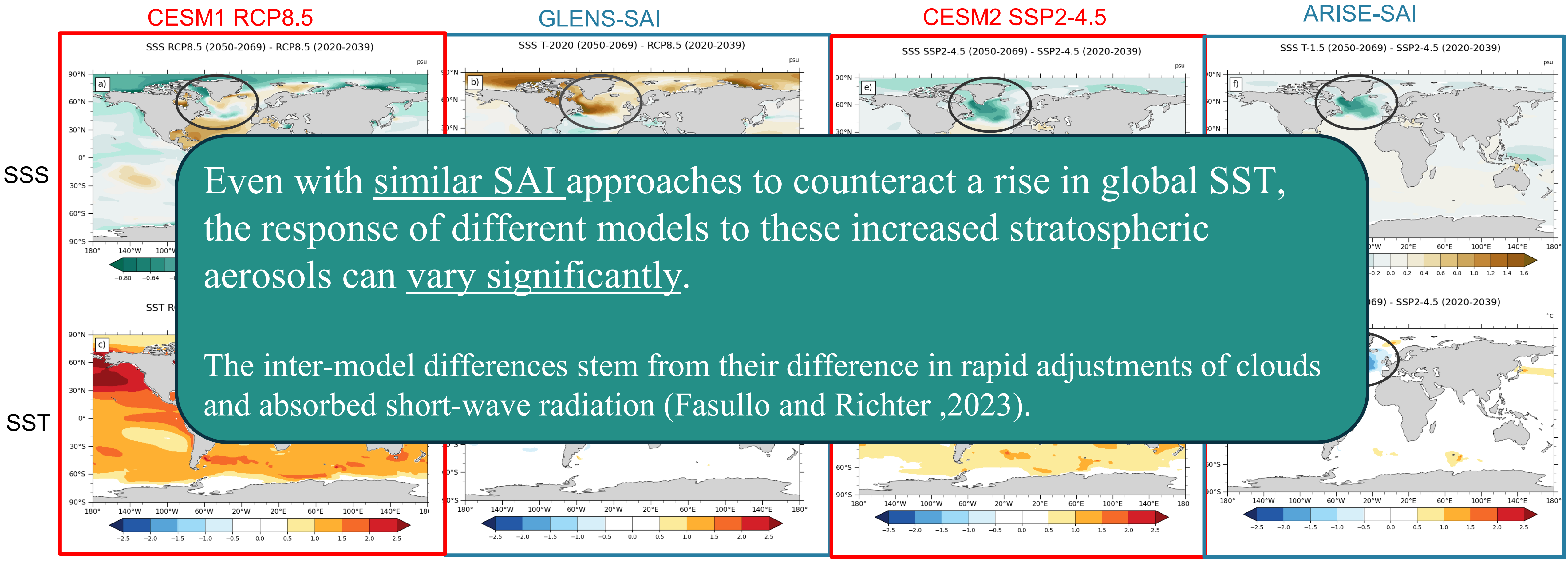


Time series of yearly sulfur dioxide injections

Li et al., 2023

SPNA temperature and salinity responses

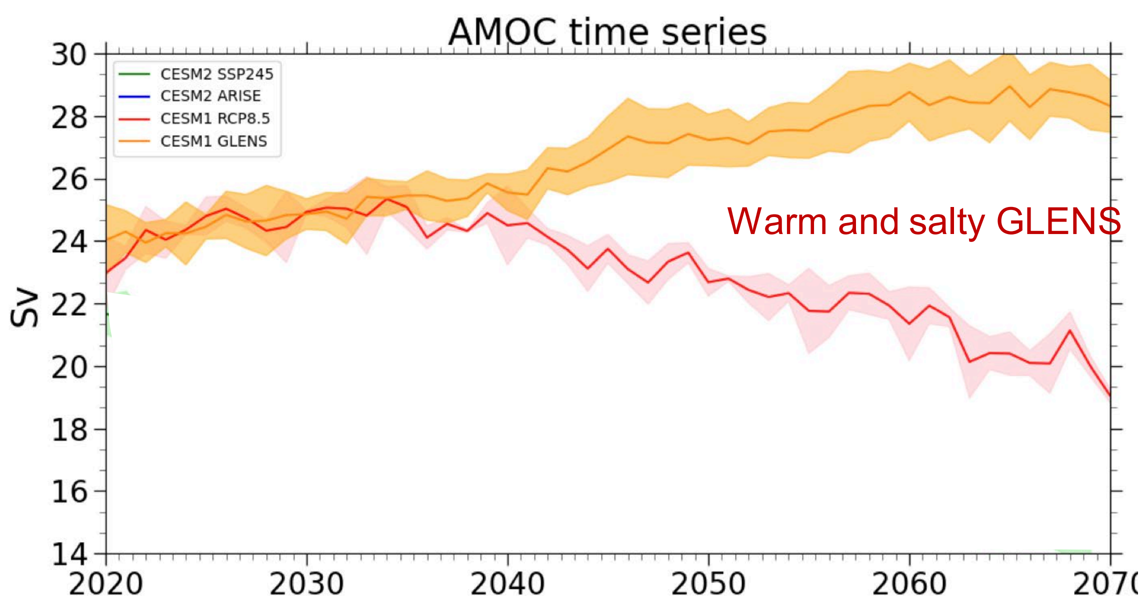
The SPNA hydrological responses are **drastically different** in the two experiments – GLENS becomes warm and salty, and ARISE cool and fresh.

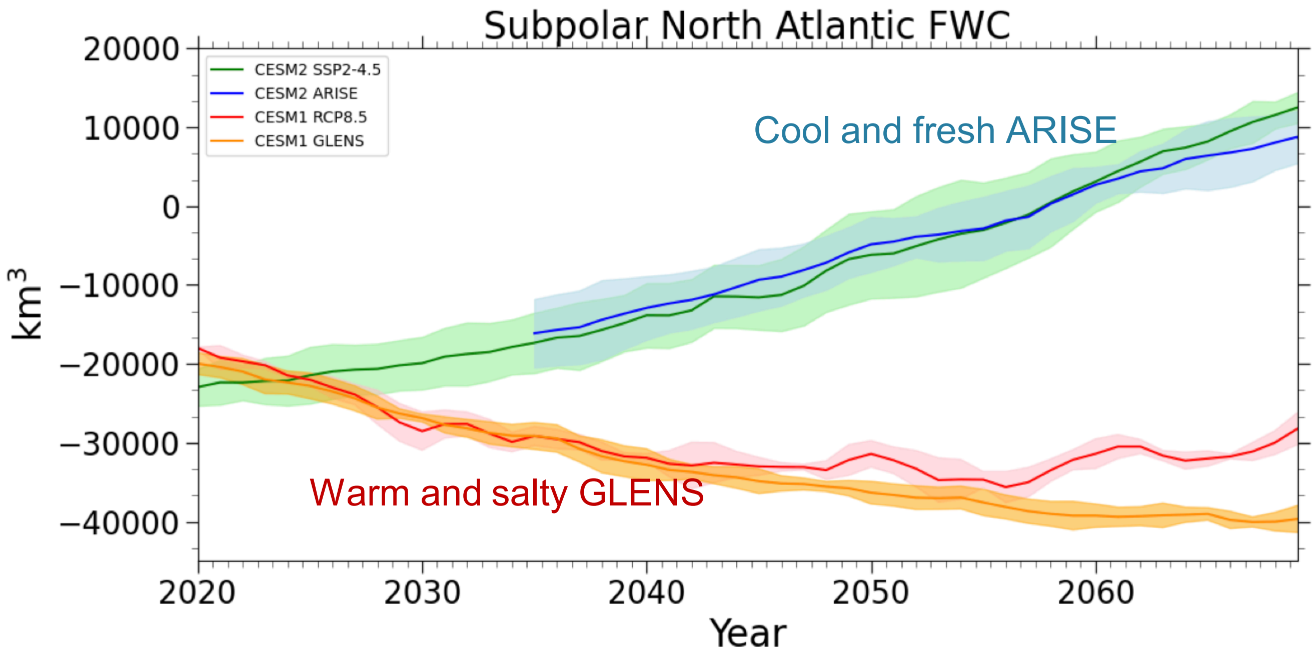


Even with similar SAI approaches to counteract a rise in global SST, the response of different models to these increased stratospheric aerosols can vary significantly.

The inter-model differences stem from their difference in rapid adjustments of clouds and absorbed short-wave radiation (Fasullo and Richter ,2023).

AMOC responses in GLENS and ARISE





- The AMOC in CESM2 is weaker and more prone to weakening under the projected greenhouse gas forcing.
- The AMOC strength in GLENS-SAI increases, opposing the weakening trend seen in the CESM1-RCP-8.5. The AMOC change is 9.5 Sv by 2070.
- ARISE-SAI has a much smaller impact on the AMOC, ~ 2 Sv increase.
- Even with SAI, the AMOC strength in CESM2 is still weaker than CESM1 without SAI.

$$\mathrm{FWC} = \iint\int_D^0 \frac{[S_{\mathrm{ref}} - S(x, y, z)]}{S_{\mathrm{ref}}} dz dy dx,$$ Sref = 34.8 g/kg

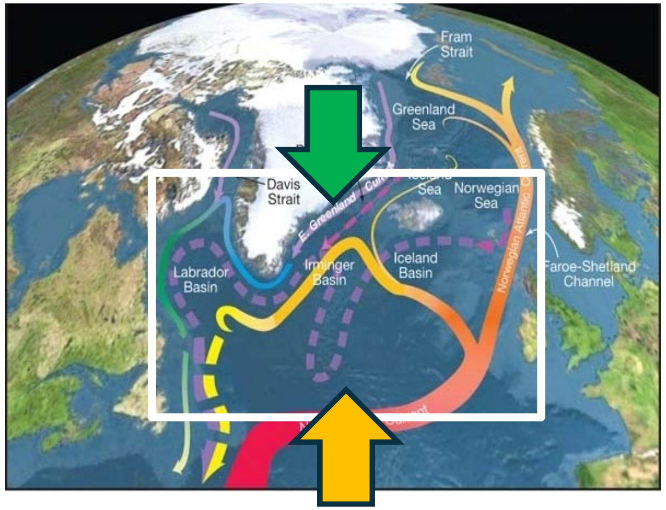
- CESM1-RCP8.5 and GLENS-SAI both show decreased freshwater content over time.
- ARISE-SAI and the CESM2-SSP2-4.5 show steady increases of freshwater content.

What are our scientific questions again?

- **What is the impact of SAI on the hydrological responses in the SPNA, is there any connection with the Arctic climate, and how do these physical processes impact the AMOC?**

- We will be focused on the anomalies induced by SAI relative to the reference simulations in the two experiments, respectively.
- We examine the physical processes **through the lens of SPNA freshwater budget**, focusing on understanding whether these changes originate from the AMOC variations or other sources.

Mechanism -- Freshwater budget in SPNA



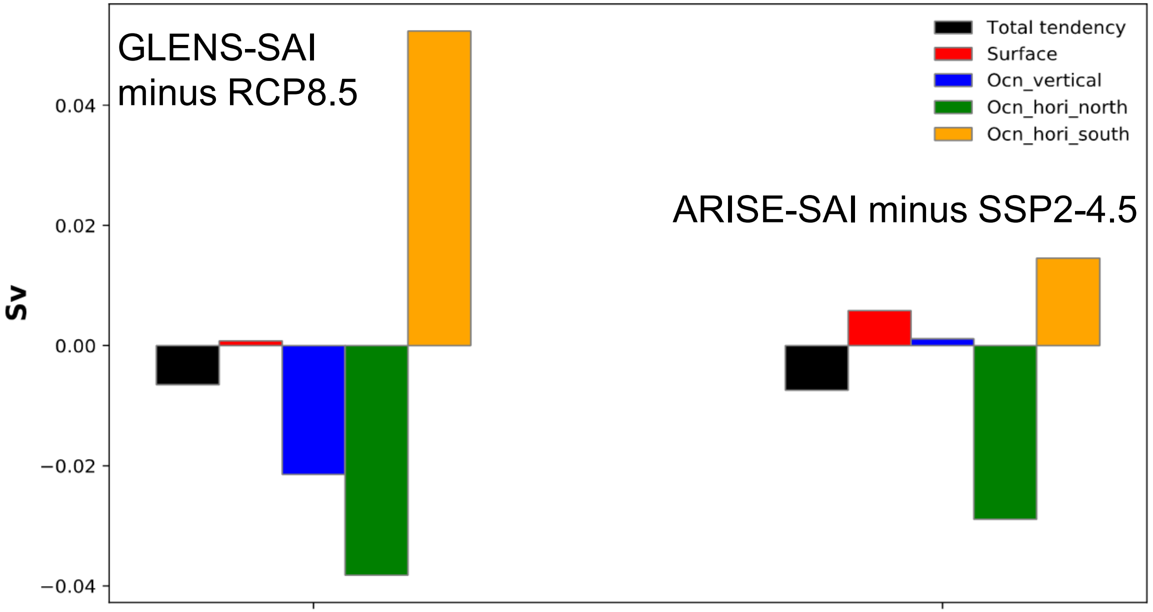
Freshwater content: $$\mathrm{FWC} = \iint\int_D^0 \frac{[S_{\mathrm{ref}} - S(x,y,z)]}{S_{\mathrm{ref}}} dzdydx,$$ Sref = 34.8 g/kg

Freshwater budget:

$$\frac{dFW}{dt} = SFWF + ADV_{horizontal} + ADV_{vertical} + DIA\_S + HDIFS$$

- $SFWF$: surface FW flux
- $ADV_{horizontal}$: northern boundary & southern boundary
- $ADV_{vertical}$: Vertical advection
- DIA_S: Vertical mixing
- $HDIFS$: Diffusion

FW tendency anomalies averaged over 2050-2069



Negative freshwater tendency in GLENS

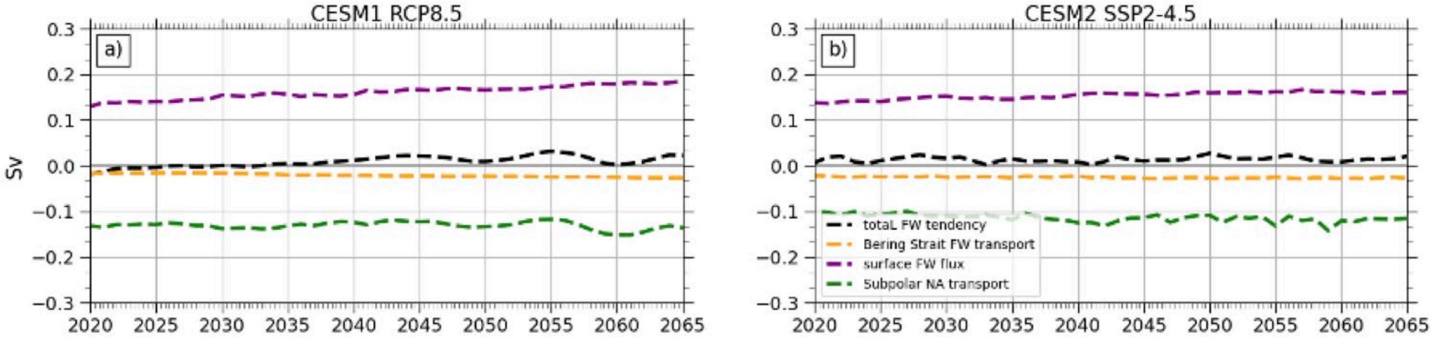
- Vertical advection and mixing
- Reduced horizontal freshwater import from the north boundary (the Arctic)

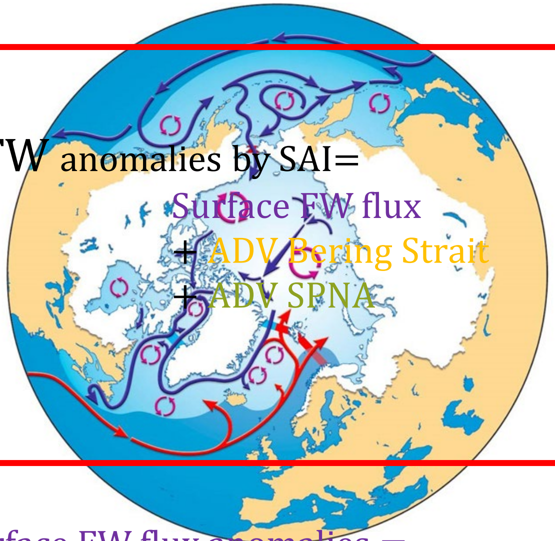
Negative freshwater tendency in ARISE

- Reduced horizontal freshwater import from the north boundary (the Arctic)

Mechanism -- Influence of the Arctic and the role of sea ice

dFW / dt = Surface FW flux
+ ADV Bering Strait
+ ADV SPNA





FW anomalies by SAI= =
Surface FW flux
+ ADV Bering Strait
+ ADV SPNA

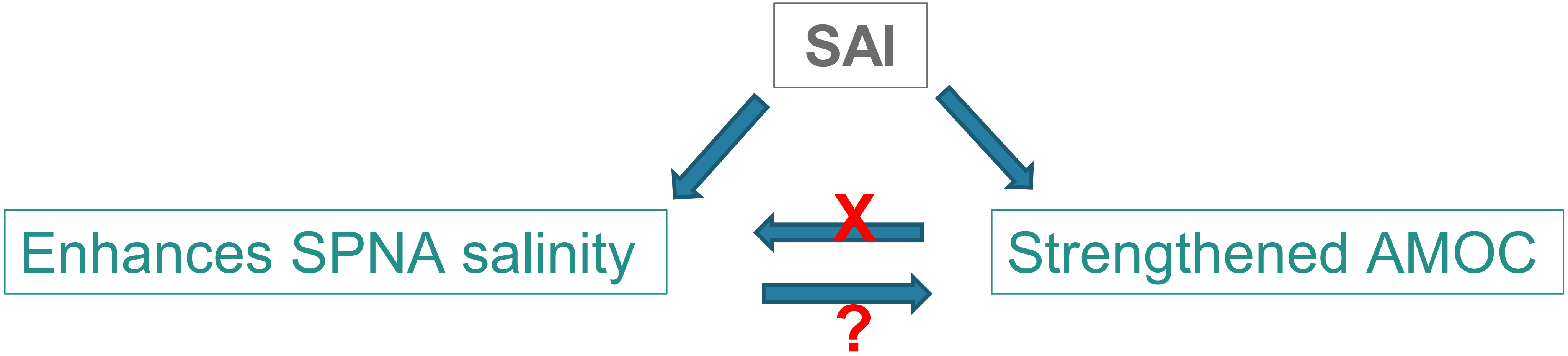
Surface FW flux anomalies =
+ sea ice melt-brine
+ river runoff
+ PE

Reduced FW export to SPNA
to compensate for the FW loss from the surface

Therefore, the story goes:

- Compared with the reference simulations, the Arctic ocean loses freshwater from the surface in both GLENS-SAI and ARISE-SAI.
- The reduced surface freshwater input is due to sea ice growth, and changes in PE and river runoff.
- To compensate for the surface freshwater loss, freshwater export from the Arctic to SPNA decreases, which leads to the decline of freshwater content in SPNA.
- **The connection with the Arctic is key to the SPNA hydrological responses.**

Freshwater impact on AMOC?

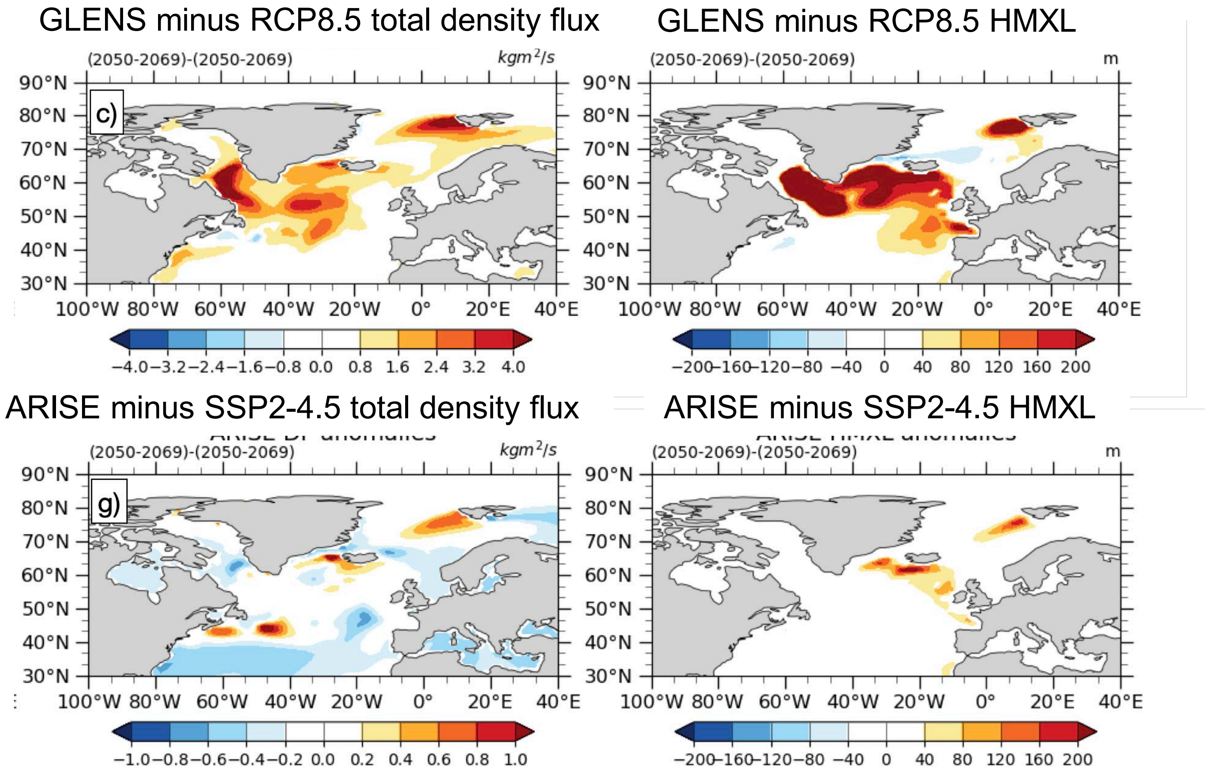


Freshwater impact on AMOC?

Surface density flux anomalies and contributions from surface heat and freshwater fluxes.

From heat flux

From freshwater flux



In both cases, the changes in surface total density fluxes are dominated by surface heat fluxes. The hydrological responses, though acting to reduce the upper ocean freshwater content and increase density, only play a small part.

Summary

- The SPNA shows contrasting responses in GLENS-SAI (warm and salty) and ARISE-SAI (cool and fresh), highlighting that despite implementing similar SAI approaches, different models exhibit significant variations in the physical processes and their responses.

- In both cases, we found that SAI reduces the SPNA freshwater content and increases the upper ocean salinity. The extent of changes is much larger in GLENS-SAI.

- In both cases, we found a close connection between the SPNA and the Arctic -- the SPNA freshwater loss is mainly driven by decreased freshwater export form the Arctic, where there is a total decrease of surface freshwater fluxes resulting from changes in PE, river runoff, and sea ice growth.

- The SAI-induced SPNA deep convection is mainly attributed to changes in surface heat fluxes, while the freshwater-induced buoyancy fluxes only play a small role.

Li, H., J. H. Richter, A. Hu, G. A. Meehl, and D. MacMartin, 2023: Responses in the Subpolar North Atlantic in Two Climate Model Sensitivity Experiments with Increased Stratospheric Aerosols. *J. Climate*, **36**, 7675–7688, https://doi.org/10.1175/JCLI-D-23-0225.1.

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