Estimating trends in freshwater fluxes using linear response theory

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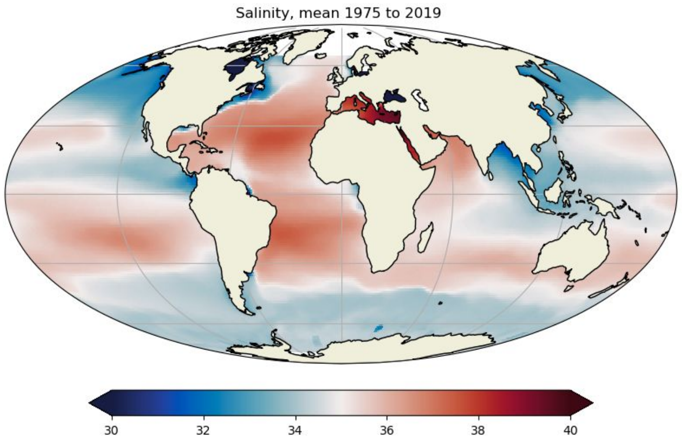
Surface salinity patterns and freshwater fluxes

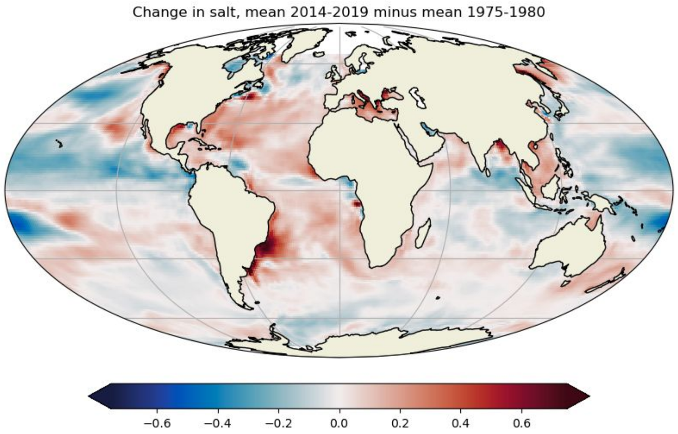
- Salinity pattern change is used to estimate amount of water cycle change as surface freshwater fluxes are difficult to directly measure

- Change in local surface salinity also affected by change in ocean transport:

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \nabla \cdot (D \nabla c) + S$$

Material derivative of tracer — Mixing of tracer — sources -sinks





Hosoda et al. 2009, Durack et al. 2012, Zika et al. 2018, Vinogradova and Ponte 2017, IPCC AR5 & AR6

Salinity data from Cheng et al. 2020

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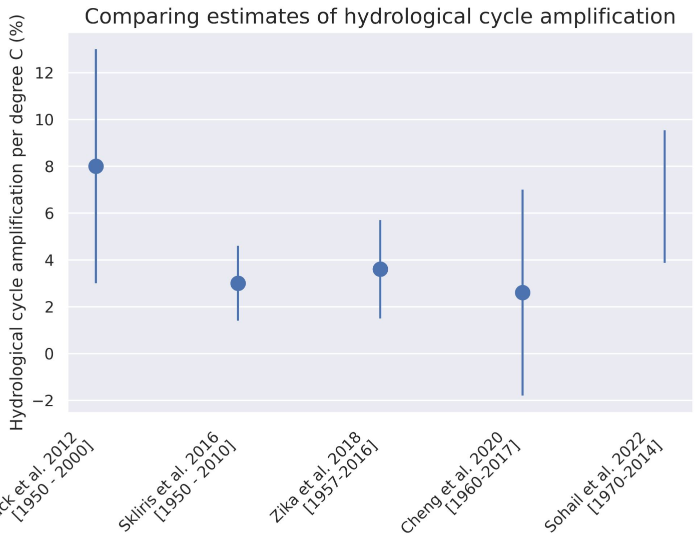

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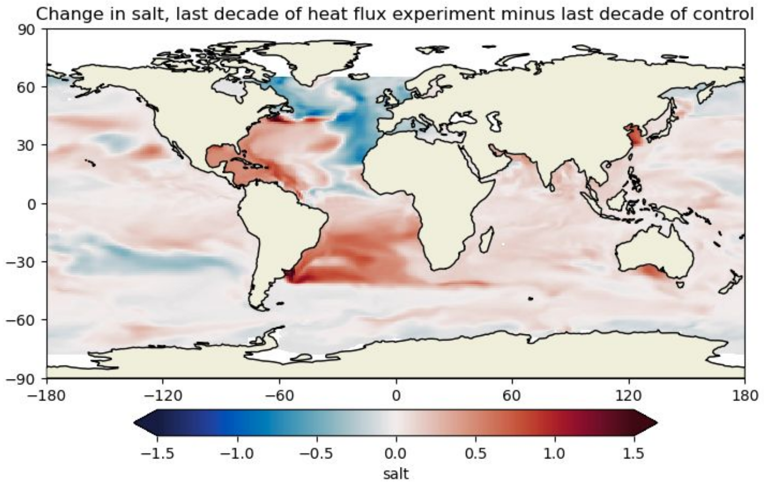
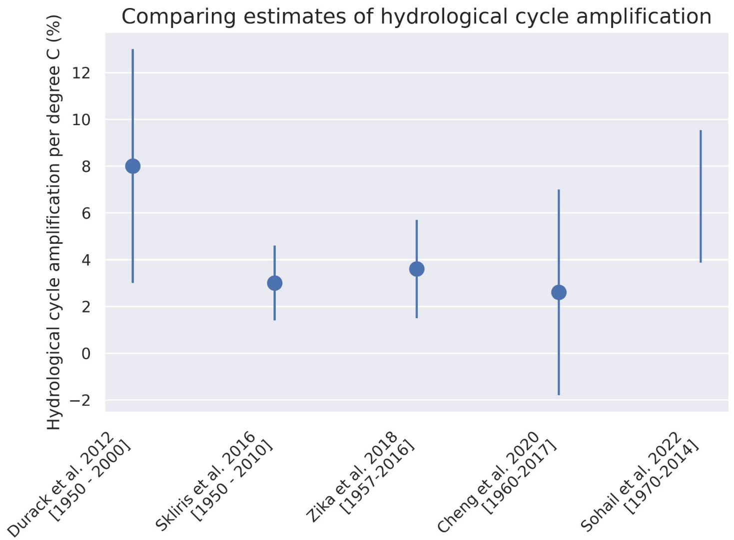
Goal of work

- **Additional physics to capture:** change in salinity from ocean circulation change is local/regional





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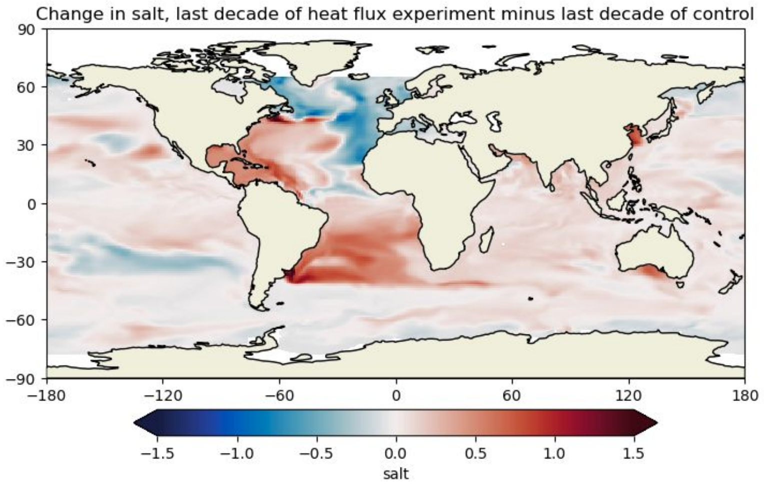
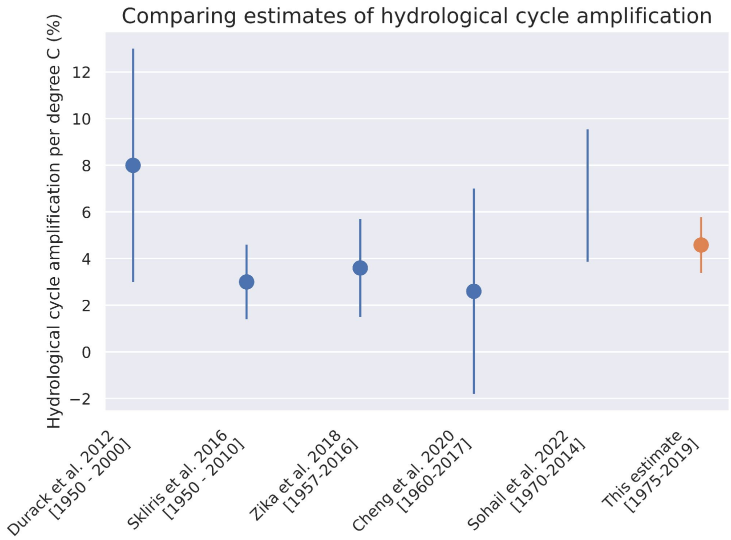
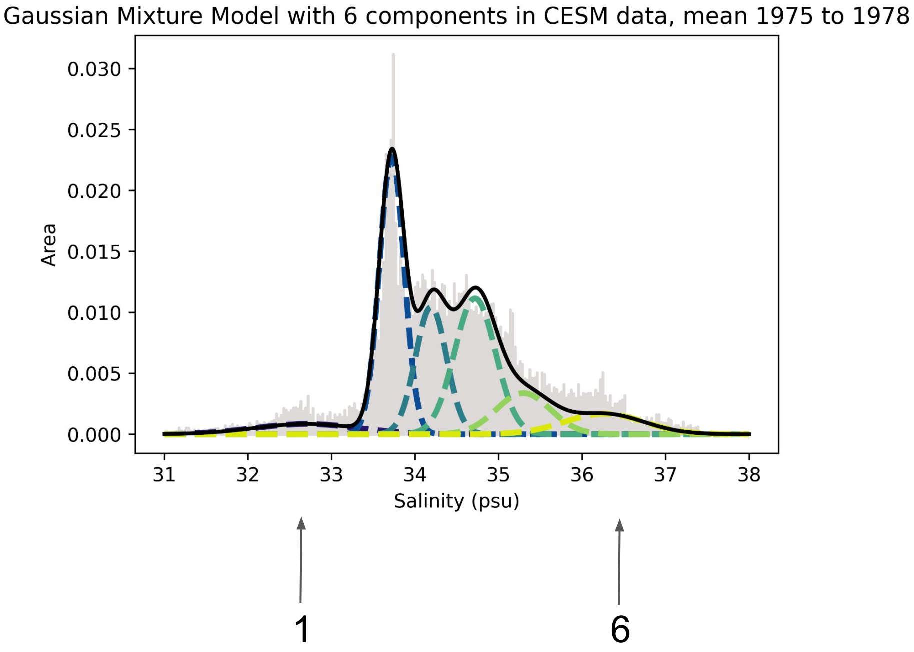
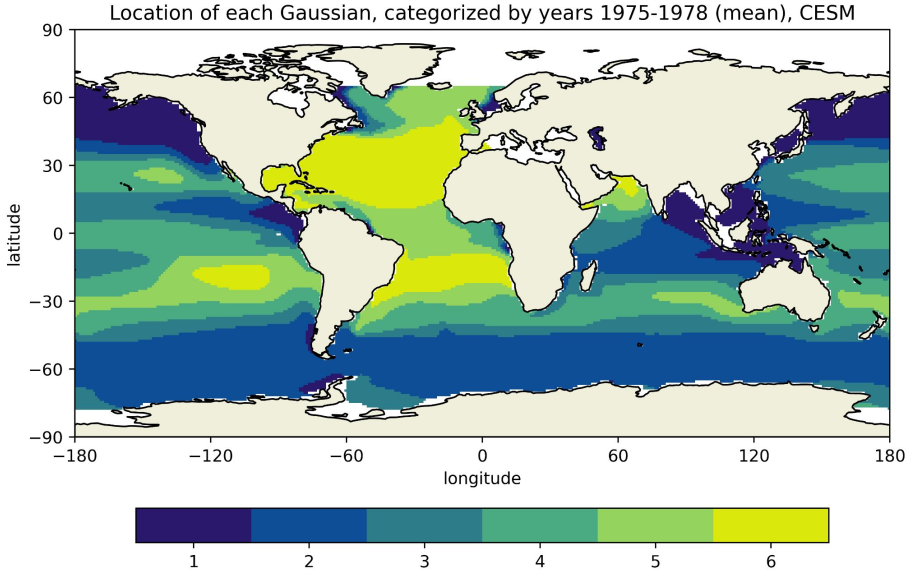




Characterizing regions of the salinity pattern

- Find regions making up salinity pattern by fitting surface salinity distribution with a Gaussian mixture model (GMM)



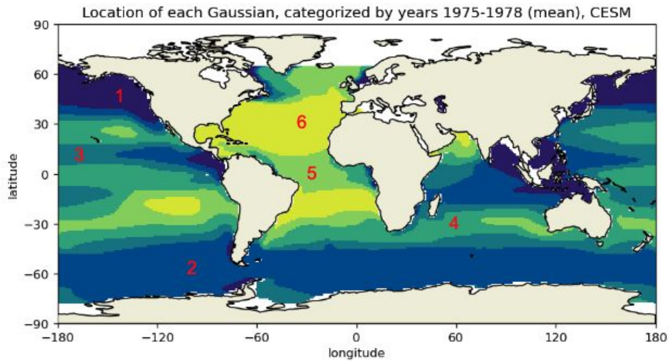


Linear response theory

- Response theory finds the change in statistical properties of a dynamical system due to a forcing

Change in **ensemble average of salinity and temperature** in each GMM region	=	Convolution of **response to step function** with time derivative of **forcing time-series**

- Using normalized surface salinity/temperature in each region identified by the GMM



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$\langle \Delta \mathbf{Y}(t) \rangle$		$\int_0^t \mathbf{R}(t-t') \frac{dF}{dt'}(t')dt' + O(f^2)$

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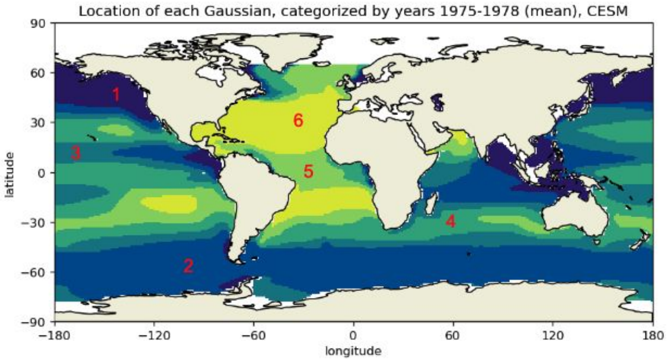

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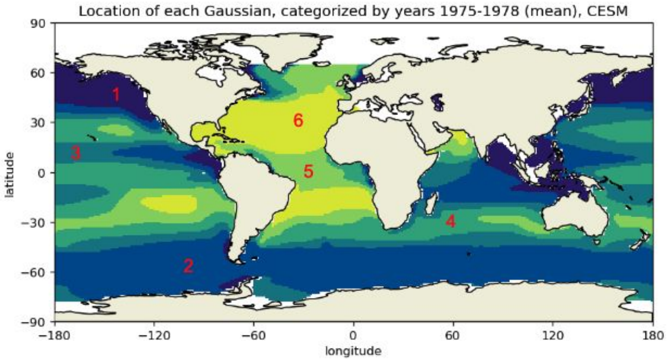
- Response to step functions taken from ocean only FAFMIP → ocean models forced separately with flux perturbations (freshwater, heat, wind stress) associated with CO2 doubling



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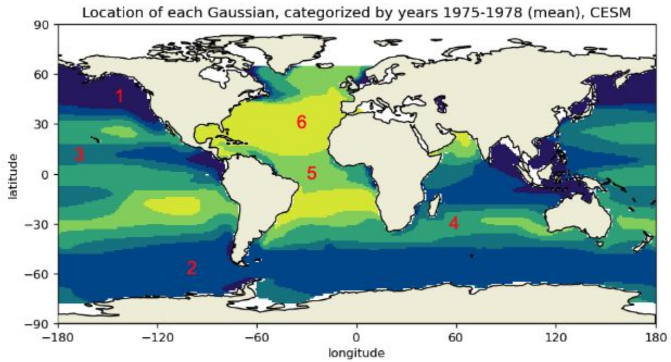
Set-up of problem

- Assume total response of regional salinity and temperature is a **linear combination** of the response to a heat flux perturbation, freshwater flux perturbation, and wind stress change

Change in **ensemble average of salinity and temperature** in each GMM region	=	Contribution due to changes in **heat fluxes**	+	Contribution due to changes in **freshwater fluxes**	+	Contribution due to changes in **wind stress**



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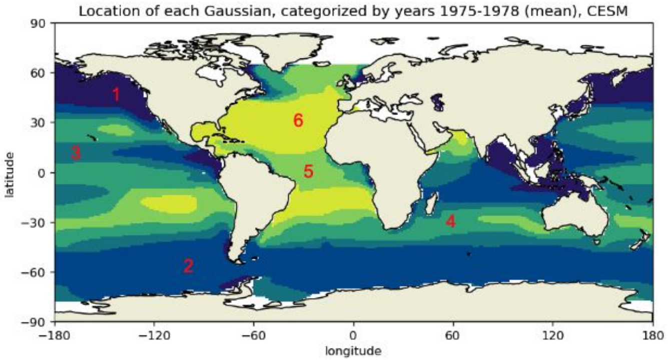
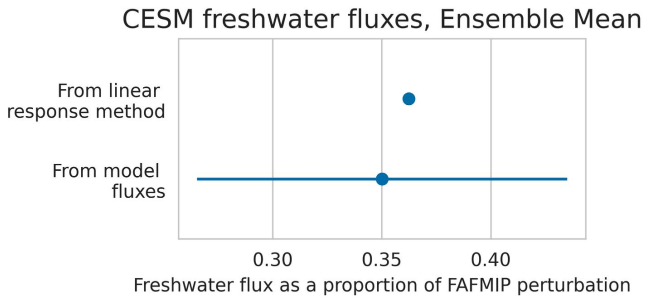
$\langle \Delta \mathbf{Y}(t) \rangle$		$\int_0^t \mathbf{R}^h(t-t')\frac{dF^h}{dt'}dt'$		$\int_0^t \mathbf{R}^w(t-t')\frac{dF^w}{dt'}dt'$		$\int_0^t \mathbf{R}^s(t-t')\frac{dF^s}{dt'}dt'$

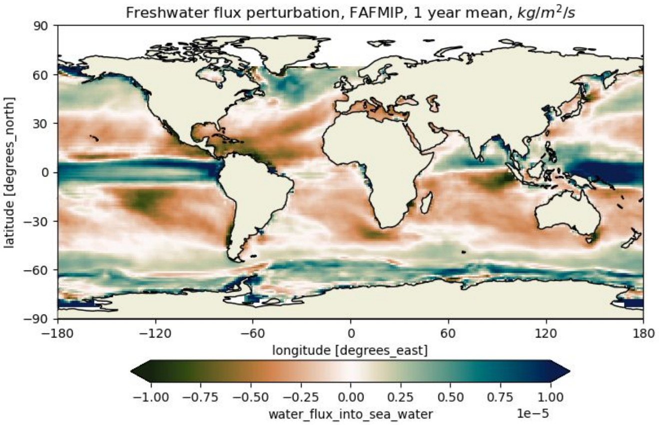
- Discretize and solve for time series of heat flux, freshwater flux, and wind stress forcing

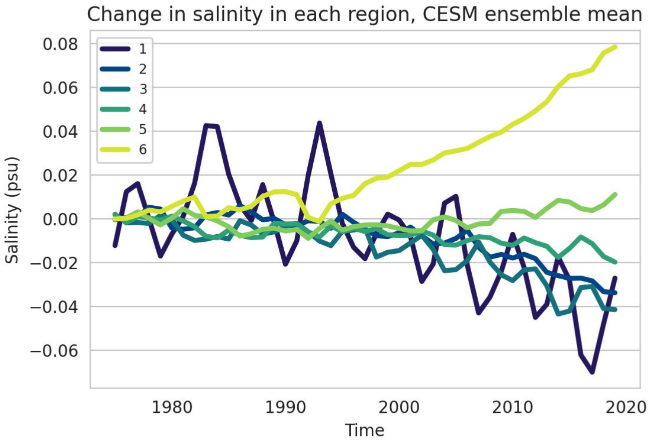


Validation of method – CESM data

- **Tested method** on salinity and temperature from Community Earth System Model (CESM) large ensemble data over the period 1975 to 2019
    - Ensemble mean: **Find true response** from model fluxes







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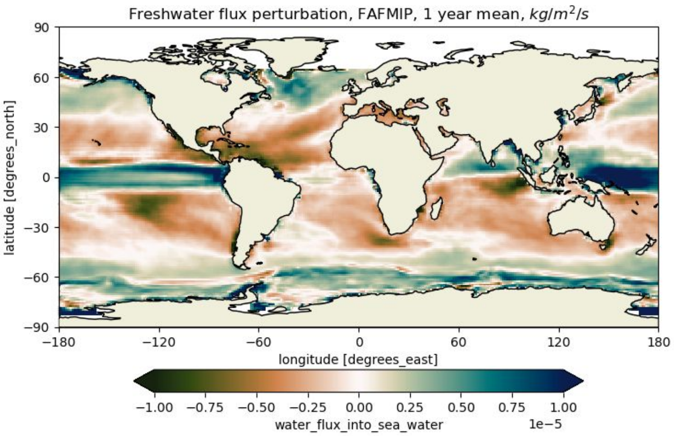
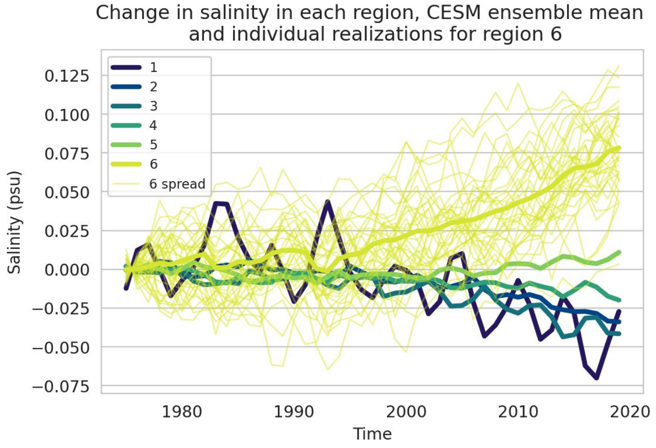
  - Individual members: **Find true response** provided significance criteria on salinity trends



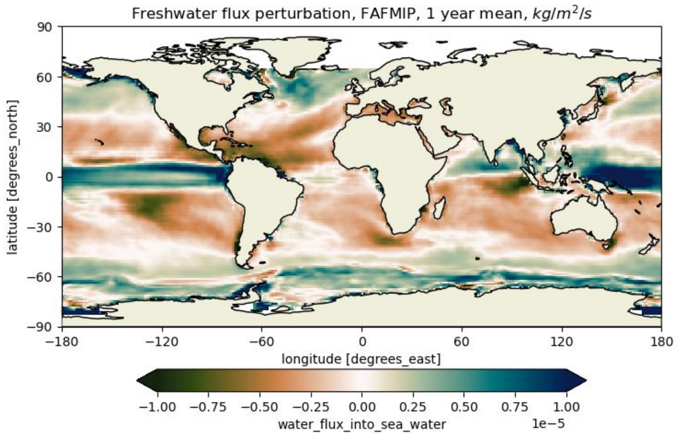


Application to observations

- Apply method to temperature and salinity surface data from Cheng et al. 2020, find: **0.303 ± 0.079** times FAFMIP perturbation

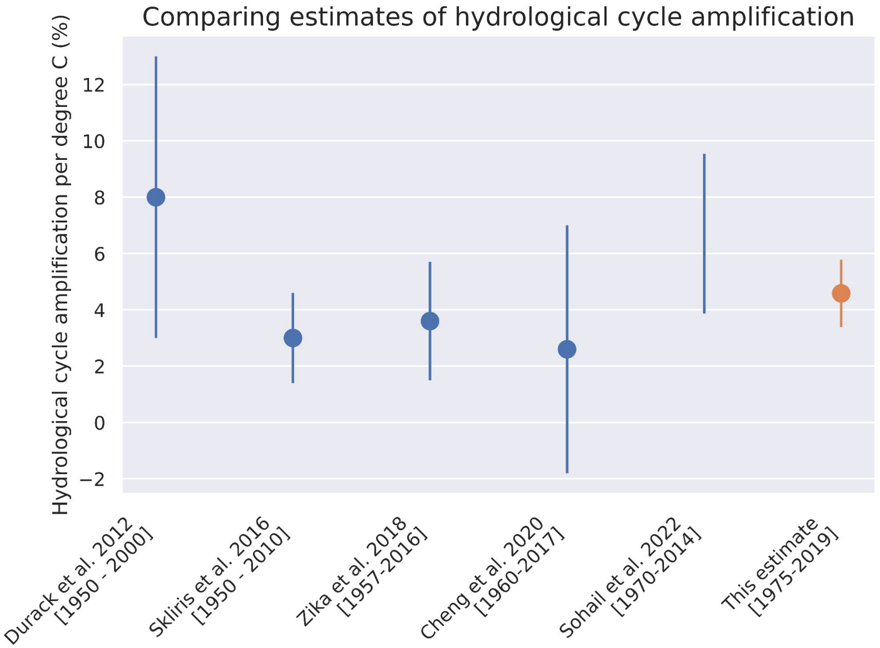
↓

4.58 ± 1.19 % per °C



Conclusions

- Ocean transport change primarily affects surface salinity regionally
- Our method, taking this effect into account, finds the true CESM flux amplification
- Applied to observations, **agrees with previous estimates** of hydrological cycle amplification and adds confidence that the **rate has been less than Clausius-Clapeyron**



- Caveat: error bars not capturing all uncertainty

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