Mean state AMOC affects AMOC weakening through subsurface warming in the Labrador Sea

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1. Introduction

- Climate models commonly show that the AMOC weakens in response to increasing CO_2 (IPCC, 2013, 2021). While the models qualitatively agree on the sign of AMOC weakening, **they disagree on the projected magnitudes.**
- Studies show that the models with stronger mean state AMOC correspond to stronger AMOC weakening to CO_2 increase (Fig 1; Gregory et al., 2005; Jackson et al., 2020). However, explanations for the diverse magnitudes of AMOC weakening among models and their dependence on the mean state climate are not fully understood.
- In this work, we propose mechanisms to explain the spread of model projections of AMOC weakening and its dependence on mean state climate.

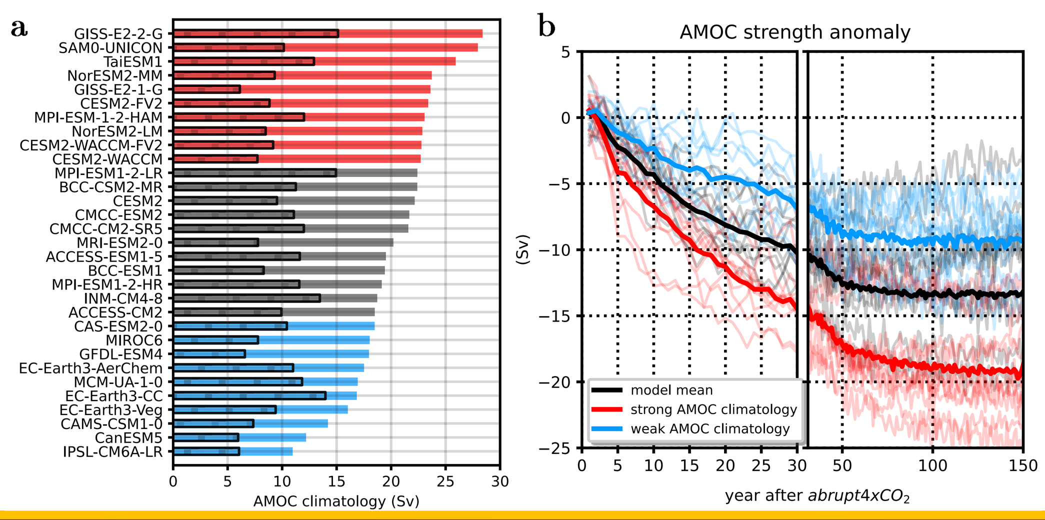


Fig. 1. (a) Climatological AMOC strength in 31 CMIP6 models. The strongest 10 models are colored in red (S10) and the weakest 10 models are in blue (W10). The remaining 11 models are in gray. Hatches indicate the year 30 AMOC strength in each model. (b) AMOC weakening in abrupt-4xCO2 simulations, sorted by the climatological AMOC strength. The black line denotes the 31-models mean. Red and blue lines denote the ensemble mean from S10 and W10 models, respectively.

2. What causes the model spread of AMOC weakening?

a) Mean state climate in the N. Atlantic

- The models with stronger AMOC climatology bring warmer and saltier water from the subtropics, along the cyclonic subpolar gyre in the upper ocean, and creates warmer and saltier western subpolar gyre, especially over the Labrador Sea (Figs 2a-c).
- Models with stronger mean state AMOC strength significantly correspond to weaker stratification in the upper (<500m) Labrador Sea in the mean state climate (Figs 2d-i).

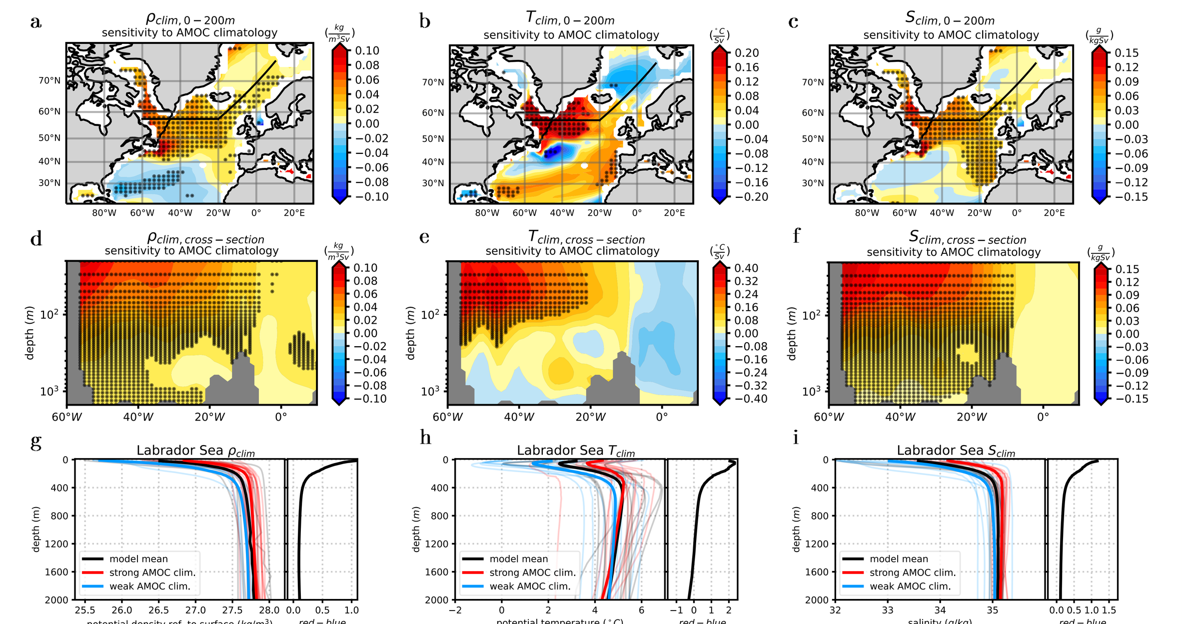


Fig. 2. Dependence of climatological potential density relative to the surface (ρ_{clim}), potential temperature (T_{clim}), and salinity (S_{clim}) on AMOC climatology. Regression slopes of 0–200m averaged (a) ρ_{clim} (b) T_{clim} (c) S_{clim} against the AMOC climatology. Stippling denotes the significance at 95% confidence level. (d)–(f) Same as (a)–(c), but for the cross-section from the Labrador Sea to GIN sea. Area-weighted average of Labrador Sea (g) ρ_{clim} (h) T_{clim} (i) S_{clim}.

b) Subsurface warming in the Labrador Sea

Stronger mean state stratification during late winter to early spring → Enhanced subsurface (500-1000m) warming during late winter to early spring to CO_2 forcing

- For the models with stronger mean state AMOC, since the upper (<500m) Labrador Sea is less stratified in the mean state, the surface warming is mixed to the subsurface Labrador Sea (500-1000m) under CO_2 forcing, especially during late winter to early spring (Fig 3a).
- For the models with weaker mean state AMOC, the warming is contained in the upper ocean (<500m) due to the more stratified upper Labrador Sea in the mean state climate (Fig 3b).

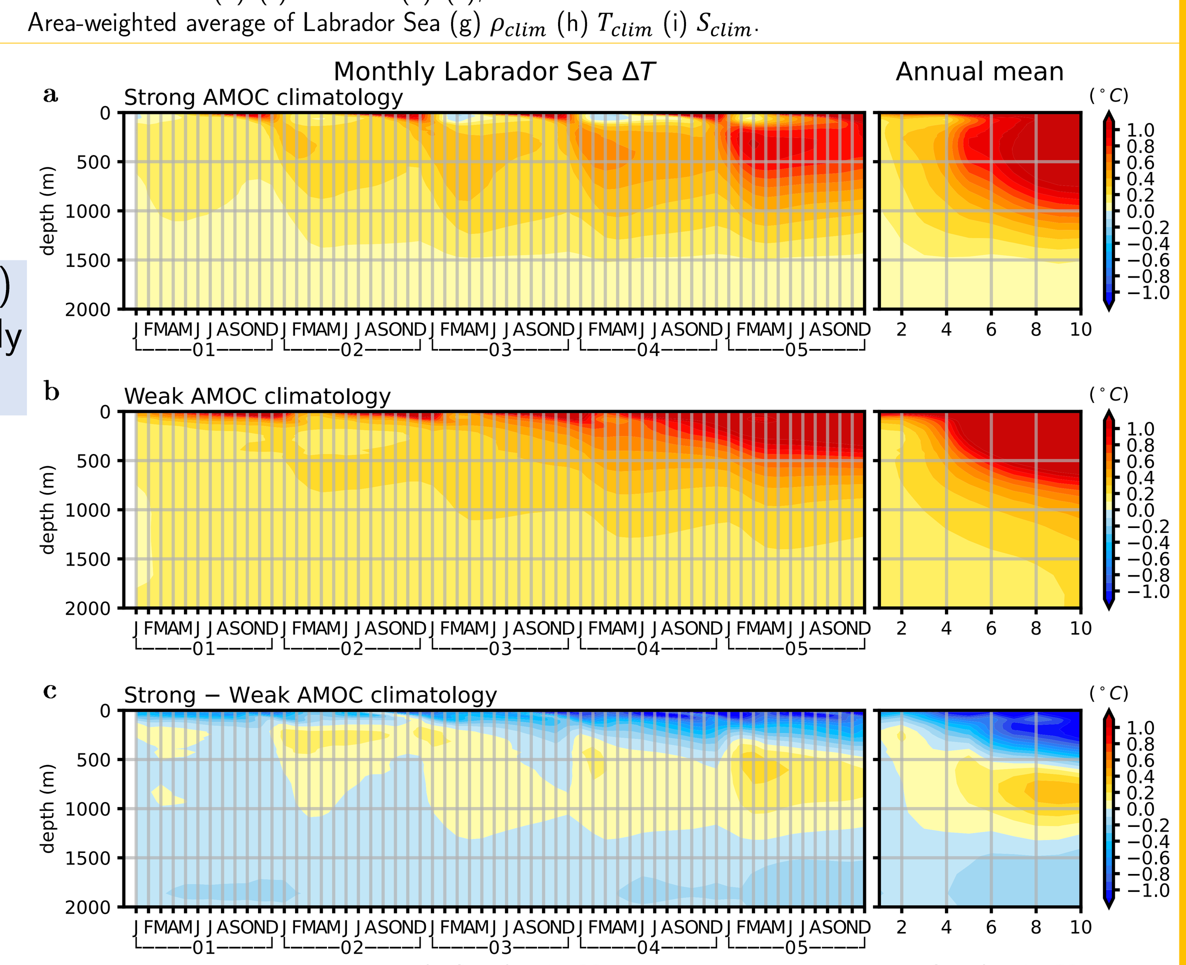


Fig. 3. Time evolution of the Labrador Sea averaged temperature responses in the models with (a) strong AMOC climatology (S10 models) (b) weak AMOC climatology (W10 models), and (c) their difference (S10−W10) in abrupt-4xCO2 simulations.

c) Time series analysis

- Most CMIP6 models agree that the significant decrease in subsurface density leads the significant AMOC weakening by 1-5 years, consistent with the advective timescale of the **Deep Western Boundary Current** (DWBC; Zhang, 2010)

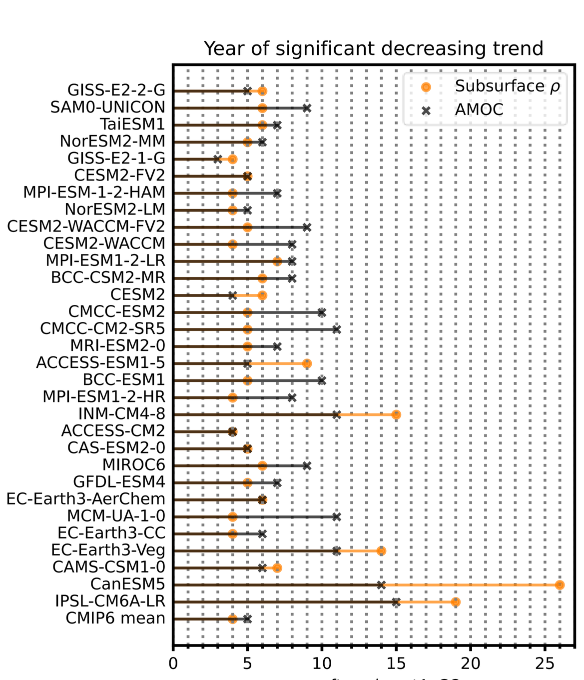


Fig. 4. The comparison between the year when the 500-1500m averaged ρ in the Labrador Sea first has a significant decreasing trend at 99% confidence level (orange circles) and the AMOC strength first has a significant weakening trend at 99% confidence level (black crosses) in abrupt-4×CO2 simulations. The model on the y-axis is sorted by its AMOC climatology.

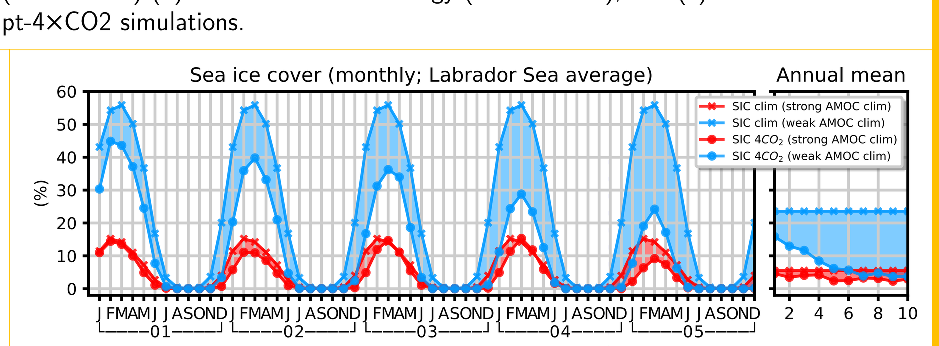


Fig. 5. Labrador Sea averaged sea ice cover climatology and that in abrupt-4×CO2 simulations. Red (blue) lines indicate models with strong (weak) AMOC climatology.

d) Sea ice and surface energy budget

- Consistent with cooler and fresher mean state, the models with weaker AMOC climatology, corresponding to larger sea ice extent (contrasting climatology of >40% and <15% in JFMA), tend to project stronger sea ice decline in winter and spring (Fig 5).
- Models with weaker mean state AMOC (also weaker AMOC weakening) correspond to less net surface heat flux input (Fig 6a). This is due to stronger sea ice loss that creates open ocean area for upwelling turbulent fluxes, offsetting the downwelling fluxes due to CO_2 forcing in winter and spring (Fig 6b). Meanwhile, sea ice loss leads to stronger net SW radiation in spring (surface ice-albedo feedback) with weaker amplitudes (Fig 6c).

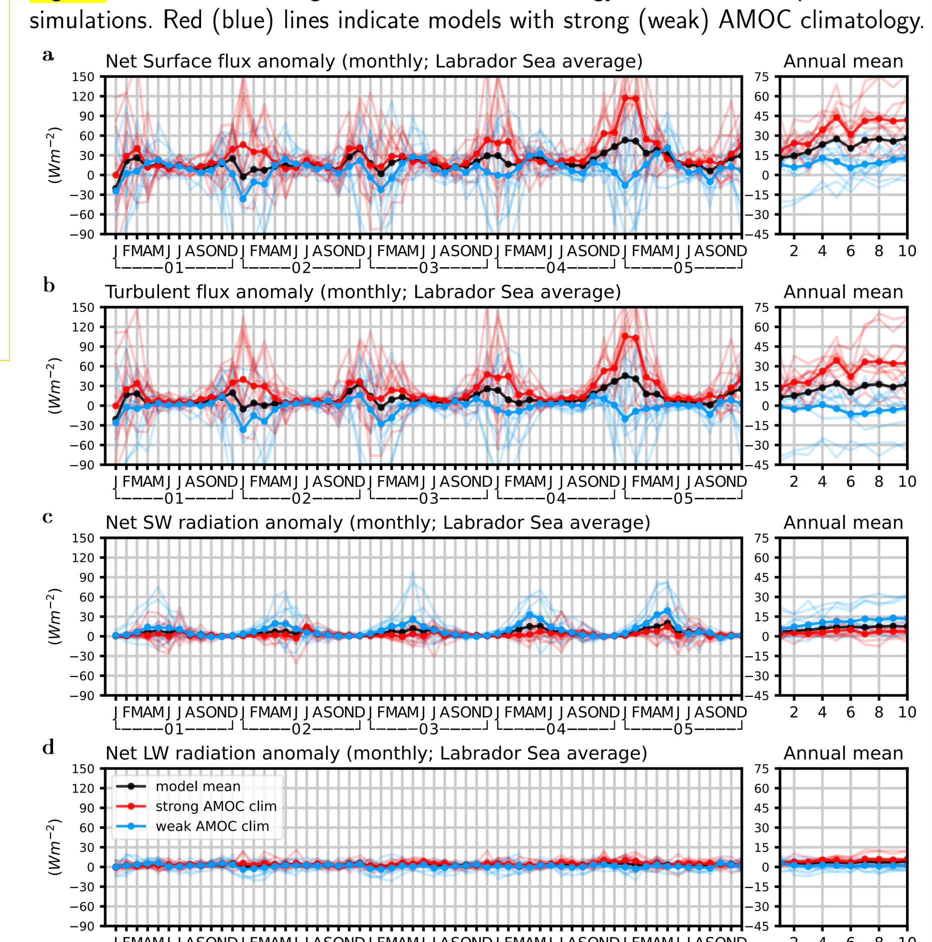


Fig. 6. Changes in (a) net surface flux (b) turbulent flux (c) net SW radiation (d) net LW radiation in the Labrador Sea. Red (blue) lines indicate the models with strong (weak) AMOC climatology.

3. Idealized experiments

a) Model & Experiment design

Model	CESM1.2.1 (only the ocean component – POP2 is active)
Compset	C_NORMAL_YEAR
Control	Run for 300 years. The last 30 years were used.
Experiments	6 experiments were run, with each being forced by the potential temperature anomaly ($T_{forcing}$) *only* in the Labrador Sea and run for 10 years (the first 5 years are shown). 5 ensembles were run for each experiment.
Forcing	$T_{forcing} = A\cos(\frac{z-z_c}{d}\pi),\ z_c-\frac{d}{2}<z<z_c+\frac{d}{2}$. z_c=250,500,750,1000,1250m; A=1°C; d=500m.

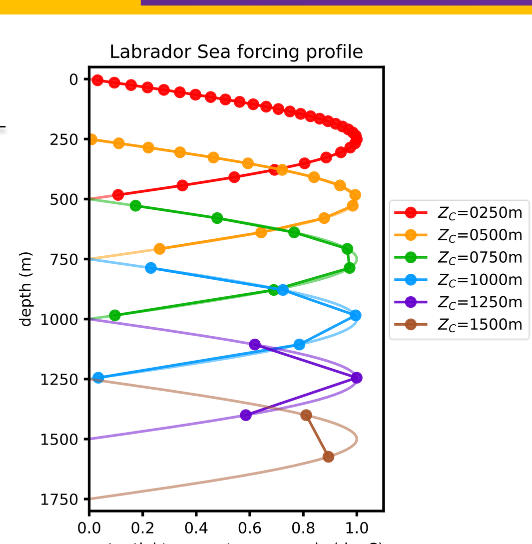


Fig. 7. Potential temperature forcing ($T_{forcing}$) in the Labrador Sea in six experiments.

b) Result I: AMOC weakening

- For the warming imposed in the subsurface Labrador Sea (z_c=500,750,1000m), the model projects stronger AMOC weakening (>1 Sv) in a timescale of 1-5 years (Fig 8).
- In contrast, for the warming imposed in the upper (z_c=250m) or the deep Labrador Sea (z_c=1500m), the AMOC weakening is less significant (<0.5 Sv; Fig 8).
- The result is consistent with the CMIP6 inter-model spread of Labrador Sea ΔT (Fig 3).

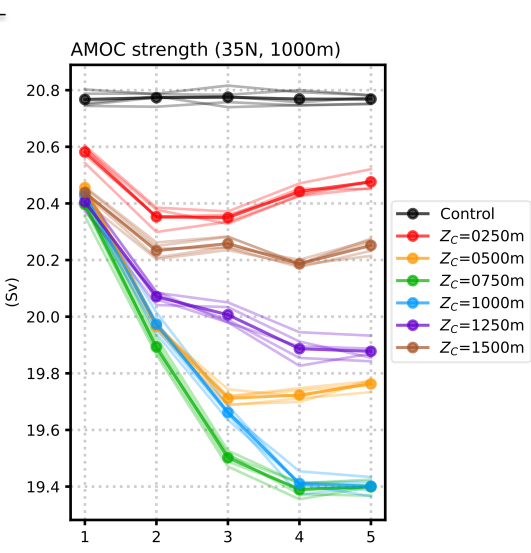


Fig. 8. AMOC strength at 35°N and 1,000m depth. For each experiment, ensembles are shown as the thin lines and the ensemble mean as the thick line.

c) Result II: Subsurface warming along the west Atlantic

When the forcing is applied to the subsurface, the warming can be carried by the DWBC, accounting for the density decrease along the West Atlantic (Fig. 9a-b). The reduced zonal density gradient would further drive the AMOC weakening, following the thermal wind balance.

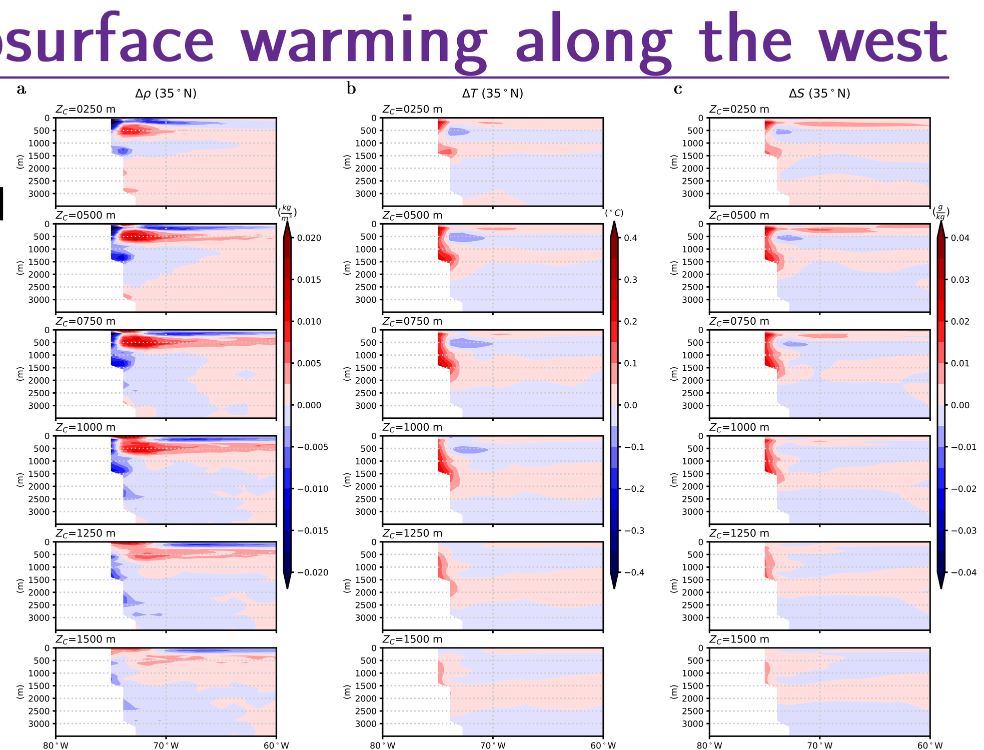
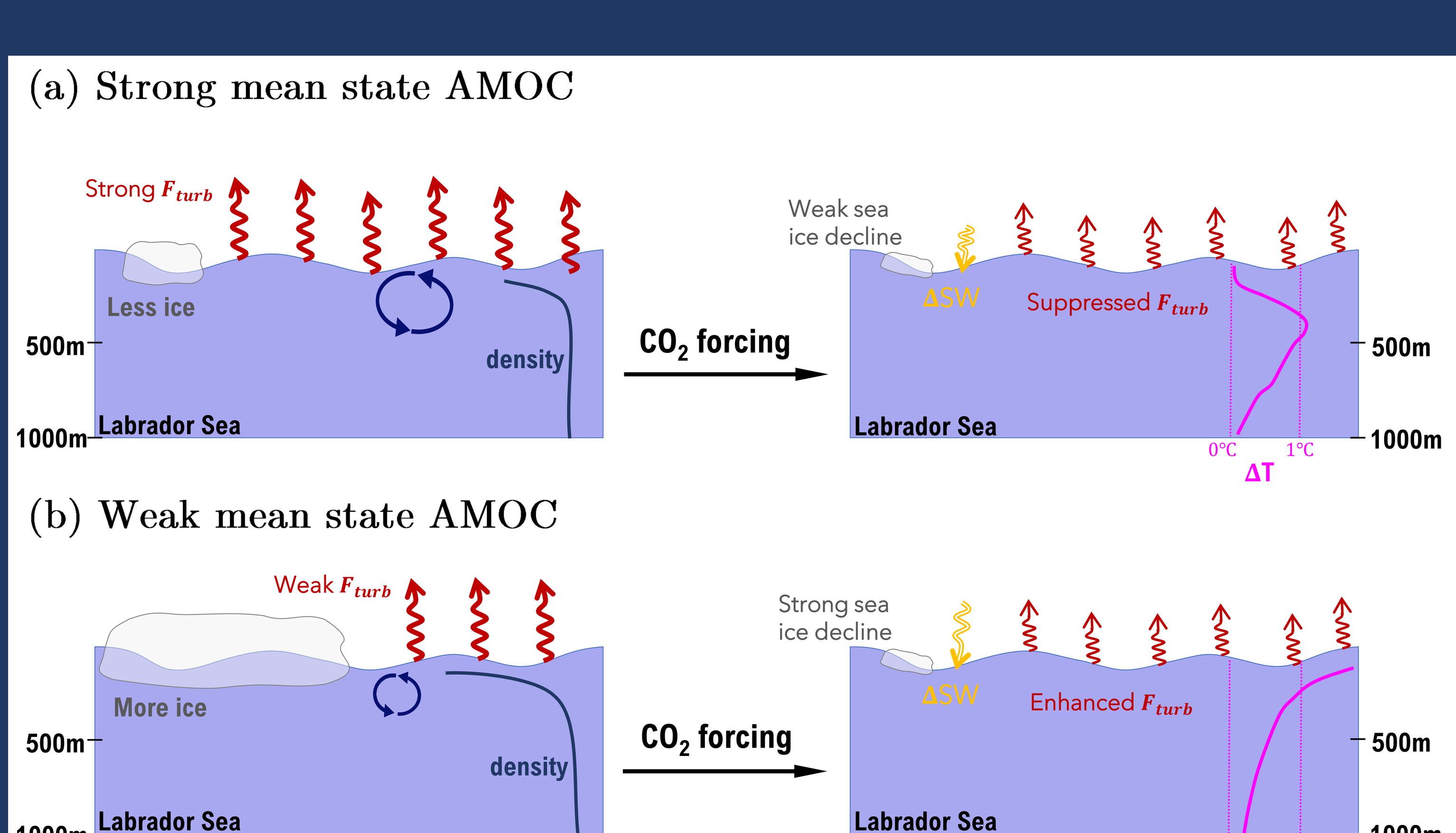


Fig. 9. Ensemble-mean responses of (a) ρ (b) T, and (c) S along 35°N at the year 5 in each experiment.

Schematic



4. Summary & Conclusion

- For the models with strong mean state AMOC strength, the upper Labrador Sea is warmer, saltier, with less sea ice and stronger upward turbulent fluxes. The stratification over the upper ocean (<500m) is weaker, thus the mixing is stronger. Opposite is also true for the models with weak mean state AMOC (Fig 2).
- In response to CO_2 forcing, a stronger mixing of the surface warming to the subsurface (500-1000m) occur in the models with less stratified mean-state Labrador Sea, especially during late winter to early spring (Fig 3).
- The subsurface warming and the corresponding density decrease drive the AMOC weakening at a leading timescale of 1-5 years, consistent with the advective timescale of the DWBC (Fig 4).
- Idealized experiments support the driving role of subsurface warming in AMOC weakening. The subsurface warming occurring at 500-1000m drives the most pronounced AMOC weakening in a timescale of 1-5 years (Fig 8). The Western Atlantic at 1000-2000 m is warmer and the density is weaker, again highlighting the southward transport by the DWBC (Fig 9).

References

* Gregory, J. M., et al. "A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration." Geophysical Research Letters 32.12 (2005).
* Jackson, Laura C., et al. "Impact of ocean resolution and mean state on the rate of AMOC weakening." Climate Dynamics 55.7 (2020): 1711-1732.
* Zhang, Rong. "Latitudinal dependence of Atlantic meridional overturning circulation (AMOC) variations." Geophysical Research Letters 37.16 (2010).