CESM CVCWG Winter Meeting
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CESM Pencil Ocean Model

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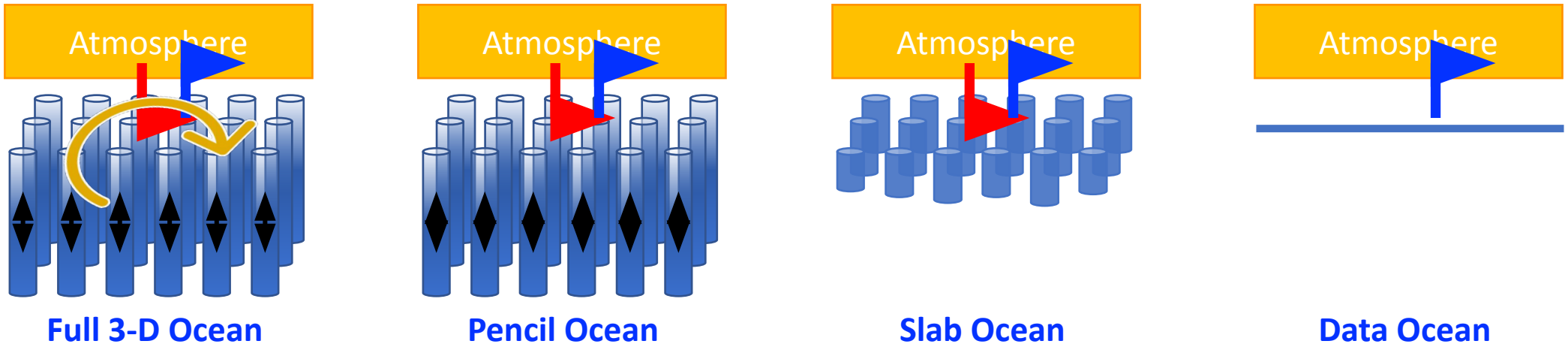
(1: WHOI, 2: NCAR. 3: LANL, 4: RSMAS, 5: NTU)

Pencil Ocean Model (aka 1dPOP / column ocean model / mixed layer ocean model)

Choices for the ocean model component in CESM



Previous studies using similar 1-D ocean models

- Bhatt et al. (1998), Alexander et al. (2000), Cassou et al. (2007), Kwon et al. (2011)
  ⇦ prognostic mixed layer scheme, but not consistent with the corresponding full ocean model.

- Hsu et al. (2022)
  ⇦ prescribed spatial and temporal variability of MLD.

- Klingaman and Woolnough (2014), Hirons et al. (2015)
  ⇦ prognostic mixed layer scheme (K Profile Parmeterization, KPP), but did not have a corresponding full ocean model.

CESM2 Pencil Ocean Model

- Uses CESM2 ocean model component (POP2) by disabling lateral processes.
- 3-D mean flux corrections for the temperature and salinity are applied to ensure the climatologies are consistent with the fully coupled CESM2.
- 3-D mean flux corrections are also applied to the horizontal velocity to ensure the realistic vertical shear for the KPP mixing scheme.

Governing Equations for the pencil ocean model

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_\theta \left(\frac{\partial \theta}{\partial z} - \gamma_\theta\right)\right] + SfcHFlx_{non-SWFlx} + SWFlx(z) + Q_{ice} + G_\theta$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_s \left(\frac{\partial S}{\partial z} - \gamma_s\right)\right] + SfcFWFlx + (FWFlx + Salt)_{ice} + G_S$$

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_m \frac{\partial U}{\partial z}\right] + fV + SfcMFlx_U + G_U$$

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_m \frac{\partial V}{\partial z}\right] - fU + SfcMFlx_V + G_V$$

The momentum equations are needed to provide velocity vertical shear for the KPP parameterization, κ_θ, κ_s, γ_θ, γ_s.

Step 1: Calculate *G*-terms by restoring to a target climatological annual cycle.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_\theta \left(\frac{\partial \theta}{\partial z} - \gamma_\theta\right)\right] + SfcHFlx_{non-SWFlx} + SWFlx(z) + Q_{ice} + G_\theta$$

$$G_\theta(x, y, z, t) = \lambda\left[\overline{\theta}_{ref}(x, y, z, \bar{t}) - \theta(x, y, z, t)\right]$$

$\overline{\theta}_{ref}$ can be a climatological monthly mean calculated from a long full 3-D control simulation or observation.
θ is the temperature prognostically calculated by the pencil ocean model coupled CESM2 at each time step.

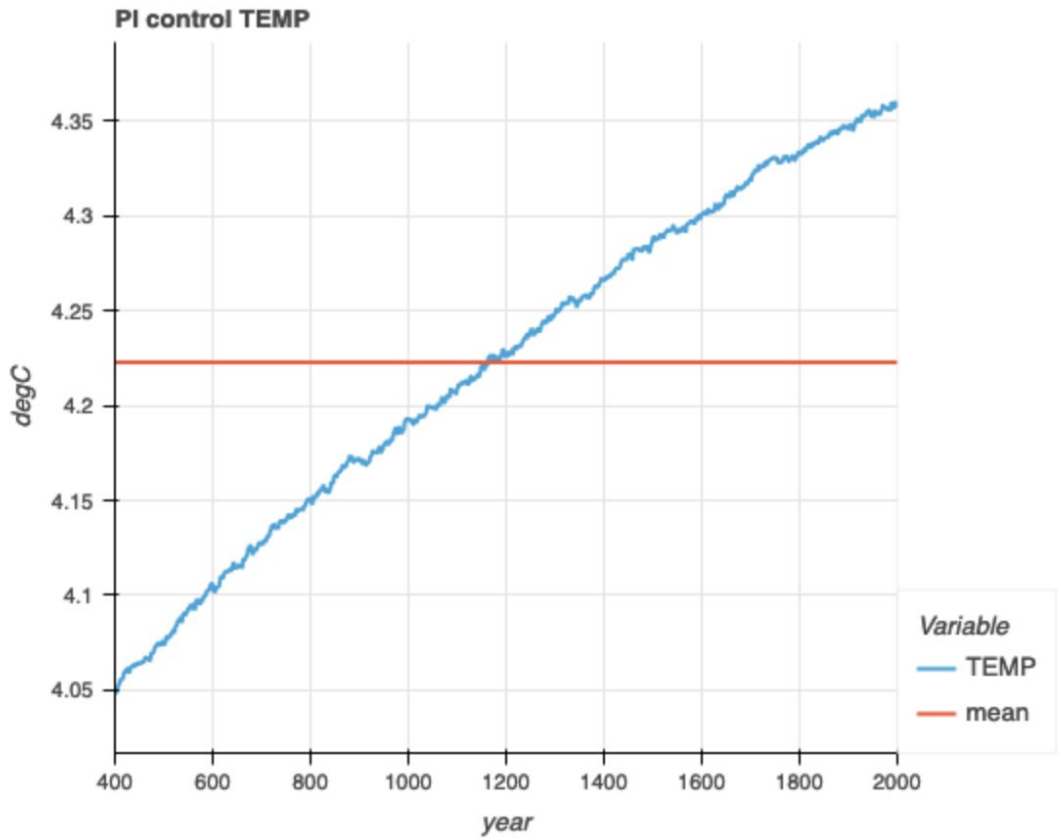
$\overline{\theta}_{ref}$ ⇦ Monthly climatology from Yrs 400-2000 of CESM2 PI control (b.e21.B1850.f09_g17.CMIP6-piControl.001)

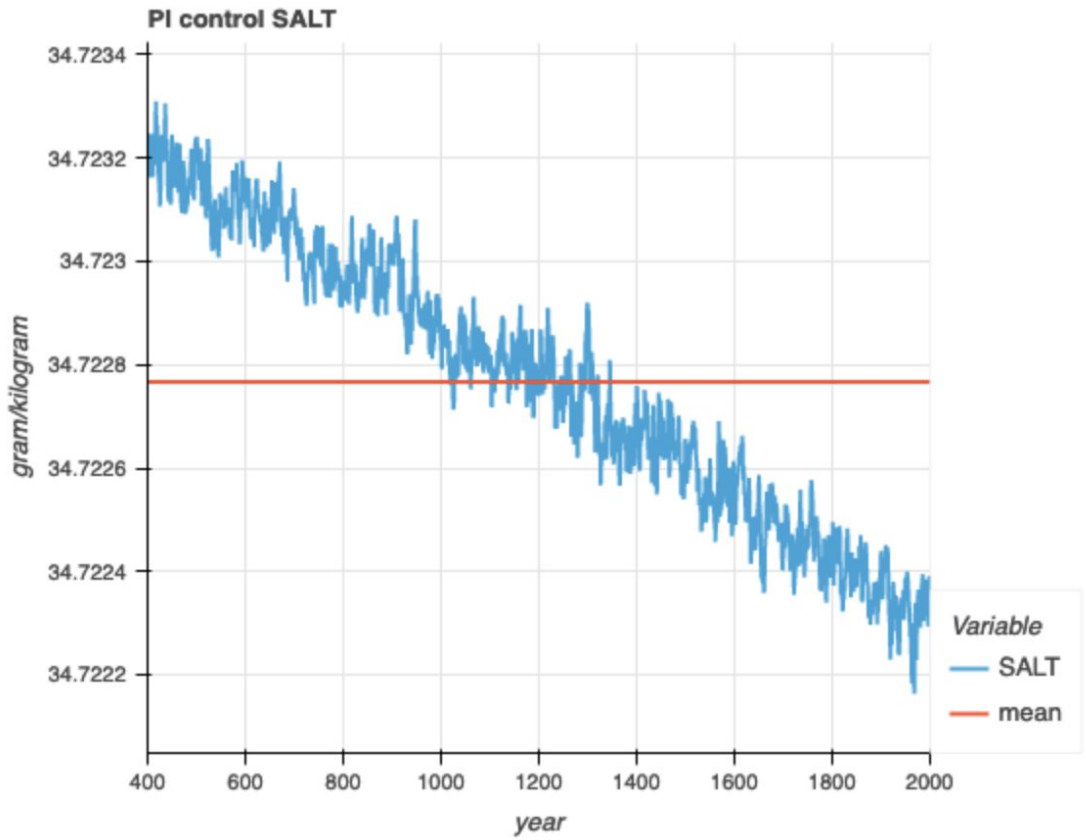
"***Restoring run***": 20-yr simulation of the PI control configuration using CESM2.1.4+1dPOP
with the restoring strength of $\tau_{\theta,S}$=15 days and $\tau_{U,V}$=3 hours (I.C. = Yr 1161 of CESM2 PI control).

➡ $\overline{G}_\theta(x, y, z, mon)$, $\overline{G}_S(x, y, z, mon)$, $\overline{G}_U(x, y, z, mon)$, $\overline{G}_V(x, y, z, mon)$ **for the step 2 "G-term runs".**

Global 3-D mean temperature and salinity from CESM2 PI Control

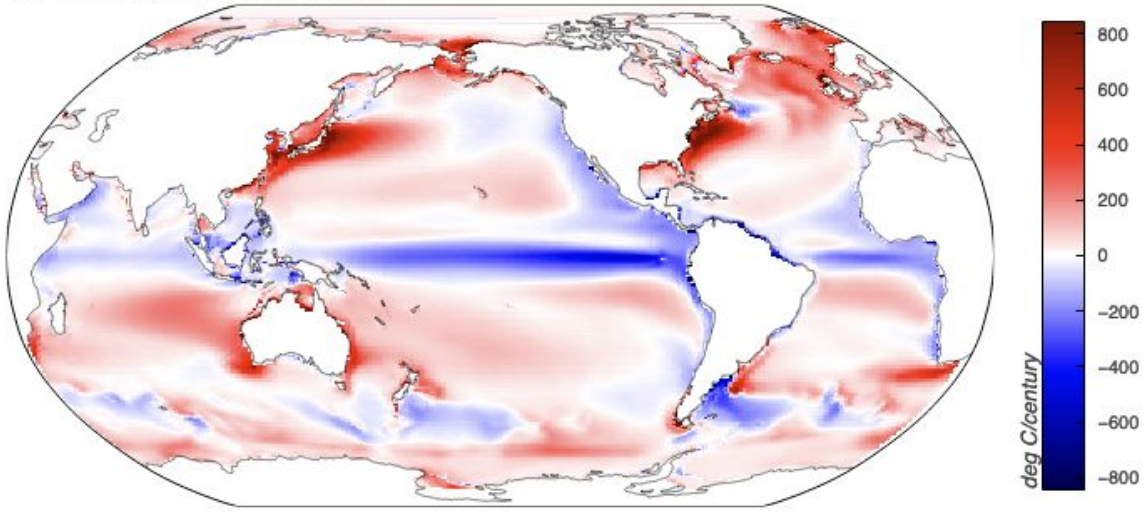
I.C. = Yr 1161 of CESM2 PI control (b.e21.B1850.f09_g17.CMIP6-piControl.001)



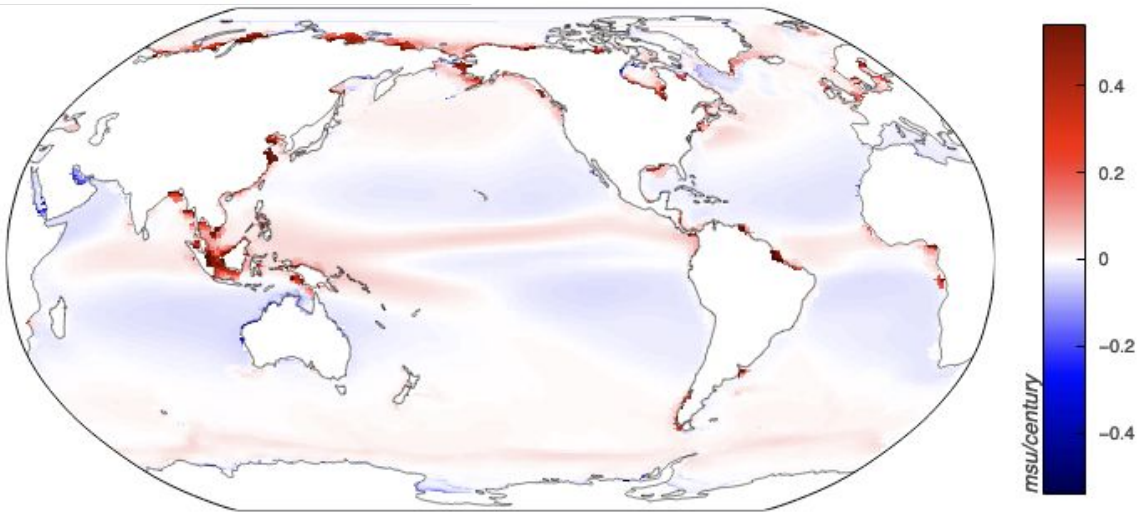


Spatial patterns of the annual & upper 200 m mean G-terms

$\overline{G}_\theta$



$\overline{G}_S$



Step 2: Prescribe $\overline{G}$-terms in the pencil ocean model coupled CESM2.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_\theta \left(\frac{\partial \theta}{\partial z} - \gamma_\theta\right)\right] + SfcHFlx_{non-SWFlx} + SWFlx(z) + Q_{ice} + \bar{G}_\theta$$

"***G-term run***": Use the fixed climatological monthly mean $\bar{G}$-terms saved from the step 1 **+ additional SSS restoring**

Two 100-yr simulations of the PI control configuration CESM2.1.4+1dPOP
using the climatological *monthly* mean $\overline{G}$- terms from the restoring run
+ SSS restoring
(I.C. = Yr 1161 of CESM2 PI control)

CESM2 pencil ocean coupled simulations

- **1dpop.010**: restoring run
- Target monthly climatology: Yrs 400-2000 of CESM2 PI control
- I.C.: Yr 1161 restart file of CESM2 PI control
- Run length: 20 years

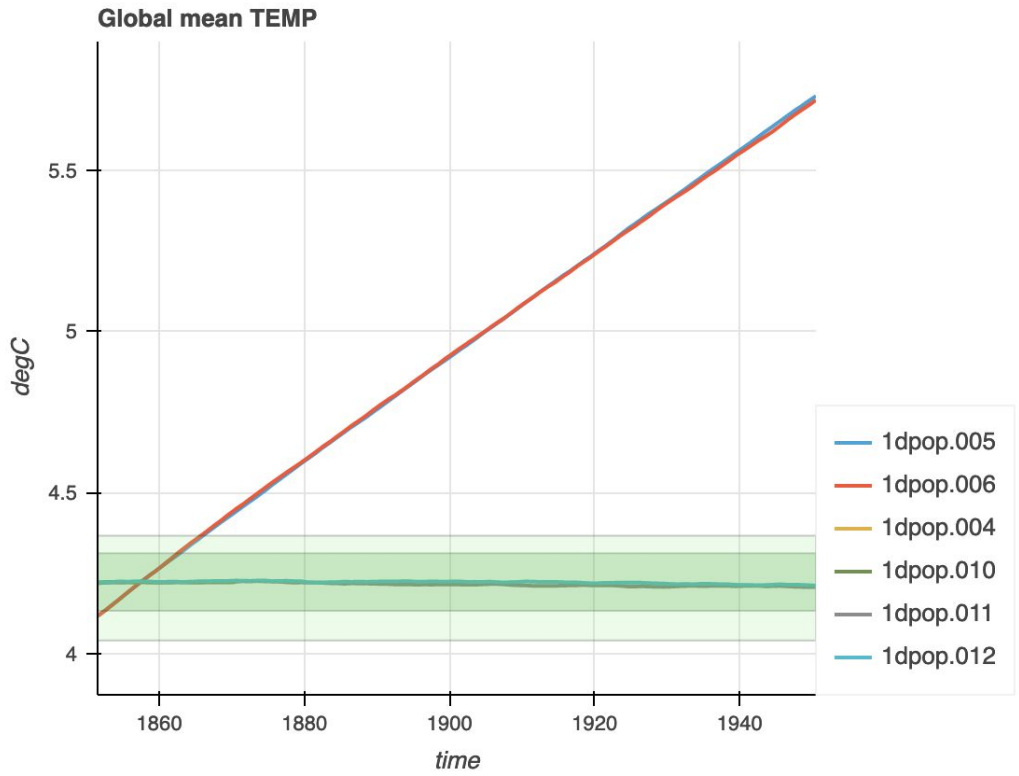
➜ *Climatological monthly mean G-terms.*

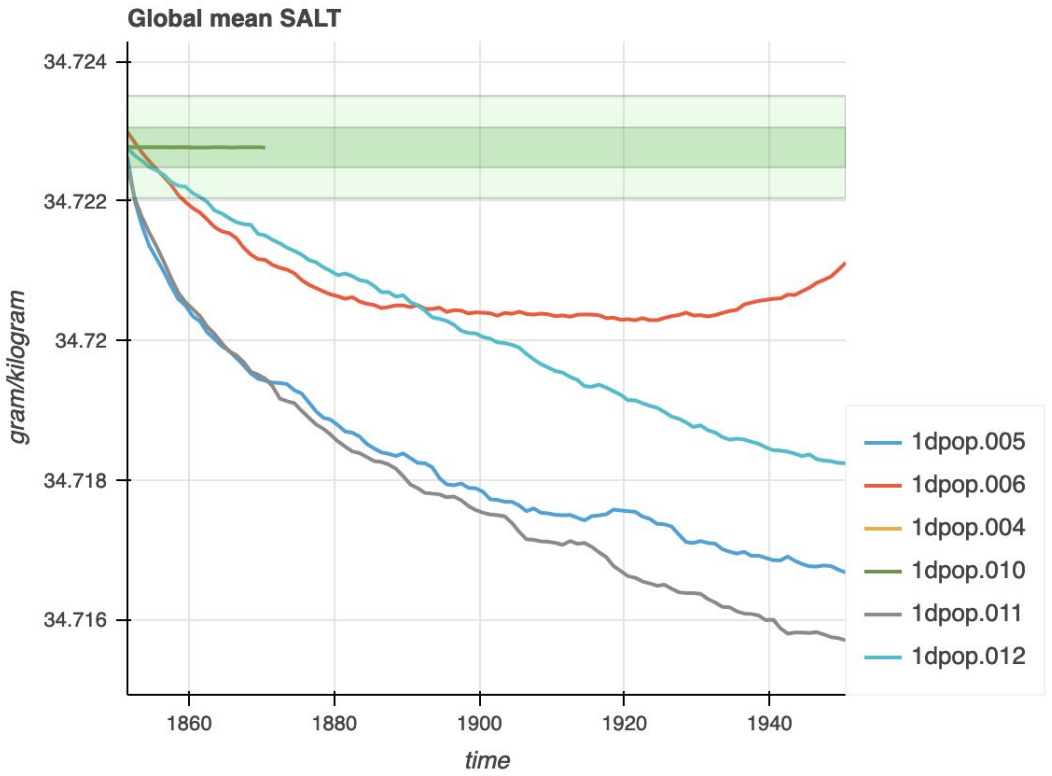
- **1dpop.011**: G-term run
- I.C.: Yr 1161 restart file of CESM2 PI control
- Run length: 100 years
- SSS restoring strength = 1 month

- **1dpop.012**: G-term run
- Same as the 1dpop.011, but the SSS restoring strength = 1 year

Stable temperature for 100-yrs, while salinity drifts slightly.

Global 3-D mean time series

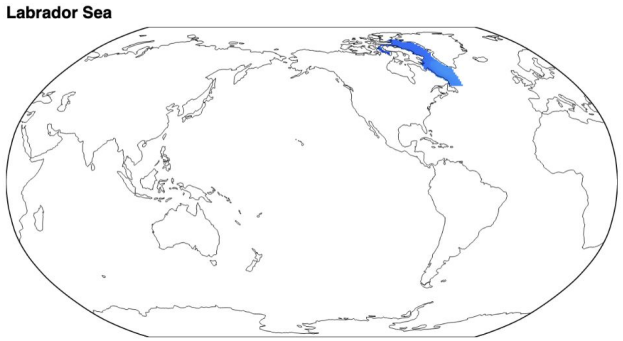




- Darker shading: PI control yrs 400-2000 annual mean (mean±std)
- Lighter shading: PI control yrs 400-2000 monthly mean (min/max)

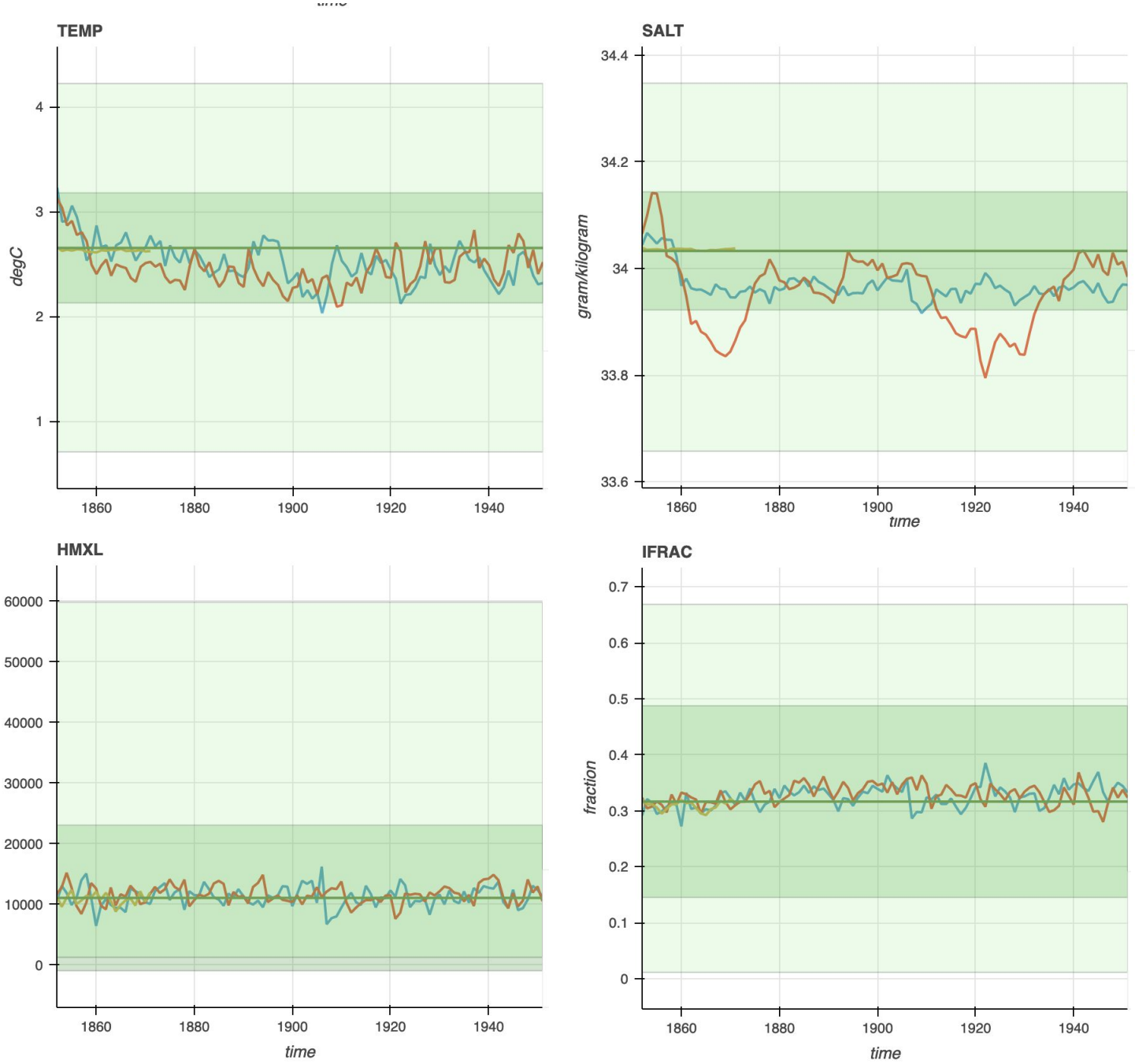
- 1 mo SSS restoring: 1dpop.005, 1dpop.011
- 1 yr SSS restoring: 1dpop.006, 1dpop.012

Labrador Sea (upper 200 m average)

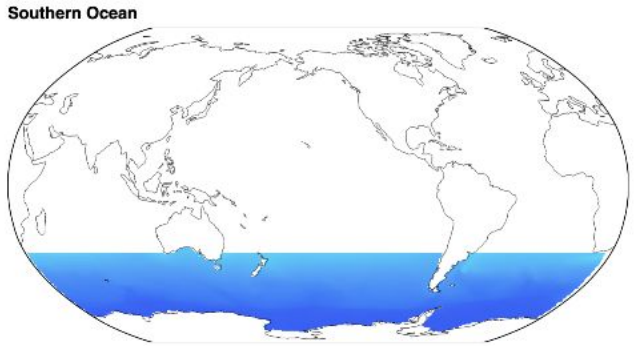


1 mo SSS restoring ➔

1 yr SSS restoring ➔

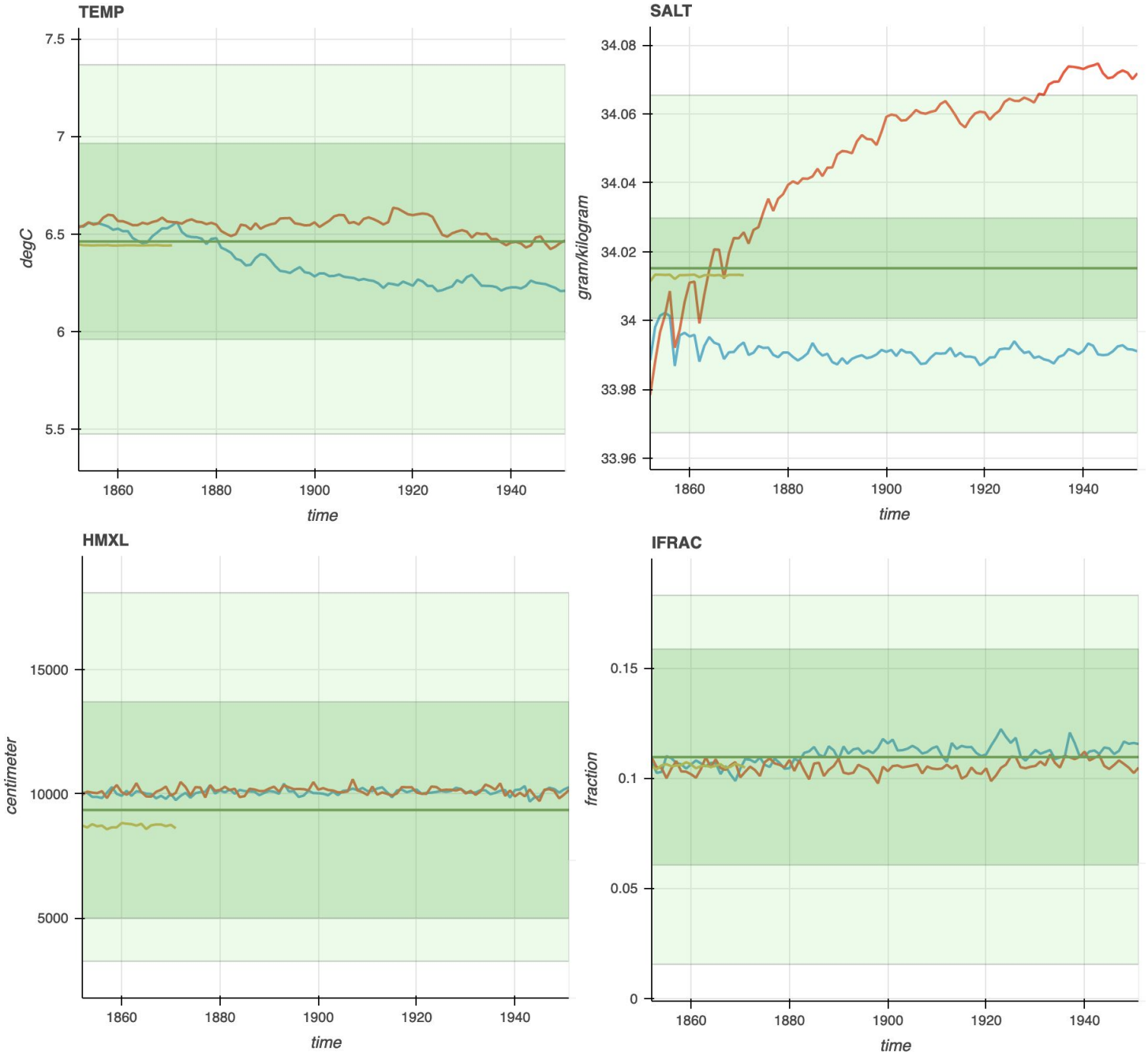


Southern Ocean (upper 200 m average)



1 mo SSS restoring ➔

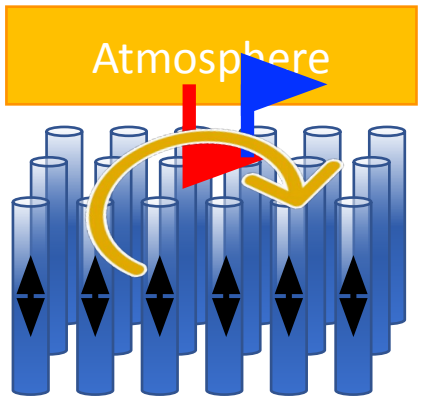
1 yr SSS restoring ➔



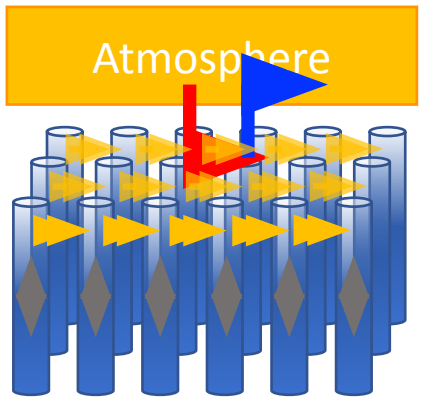
Summary

- Implementation of the pencil ocean model within the CESM2 is ongoing.
- There are still some outstanding issues, e.g., salinity drift, potentially too small MLD variability.
- The goal is to have a multi-century (up to 1000 years) PI control simulation using CESM2 coupled with pencil ocean model, which will be made available through CVCWG.
- Additional pencil model configuration with Ekman transport will be followed.

CESM Ocean Model Hierarchy

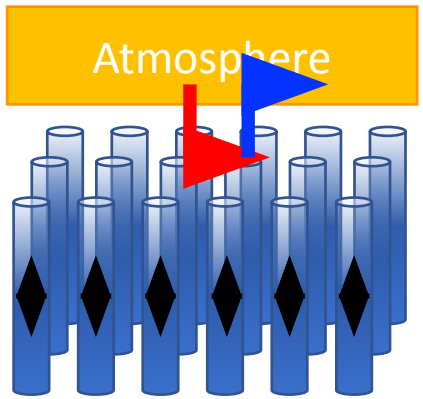


Full 3-D Ocean

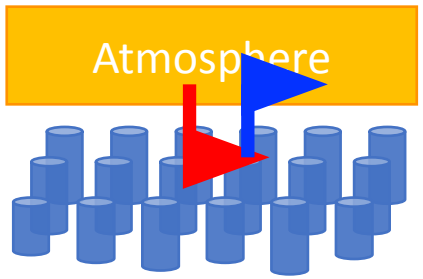


Pencil Ocean

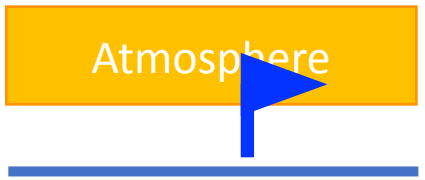
+ Ekman Transport



Pencil Ocean



Slab Ocean



Data Ocean