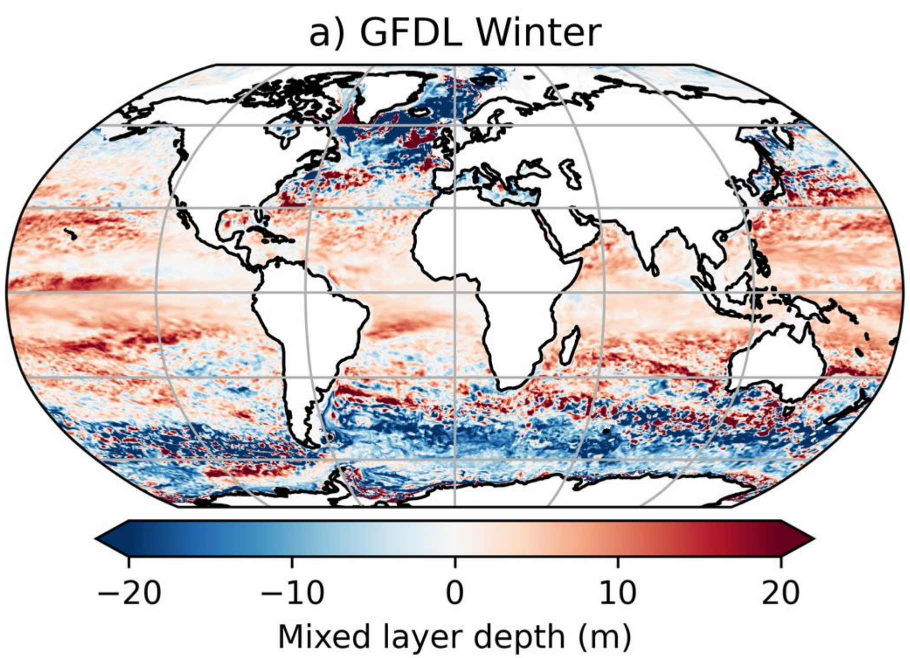
Representation of surface mixed-layer eddies affects the large-scale ventilation of the global ocean

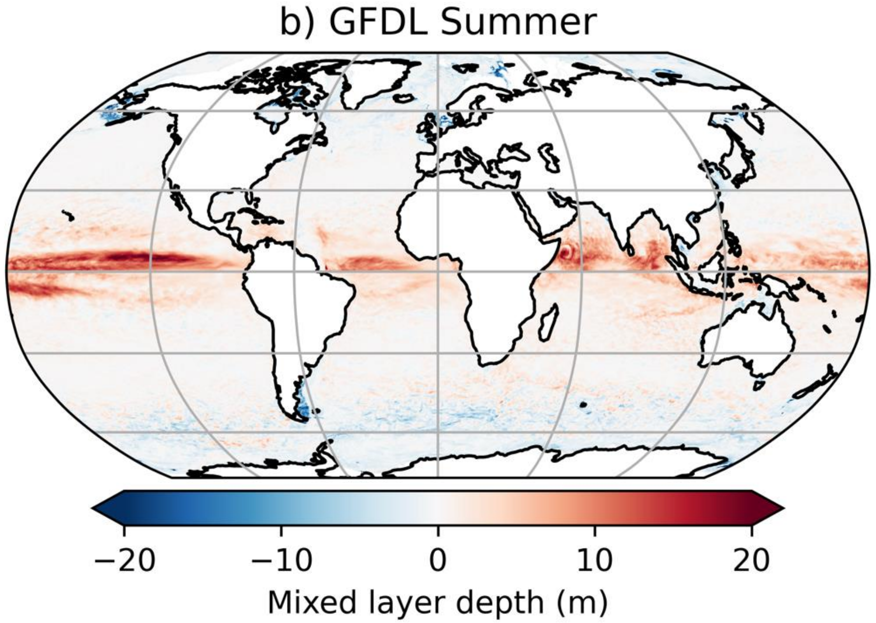
Abigail Bodner

Takaya Uchida, Baylor Fox-Kemper, Brandon Reichl, Alistair Adcroft, Gustavo Marques, William Large, Mehmet Ilicak, Mats Bentsen

OMWG workshop

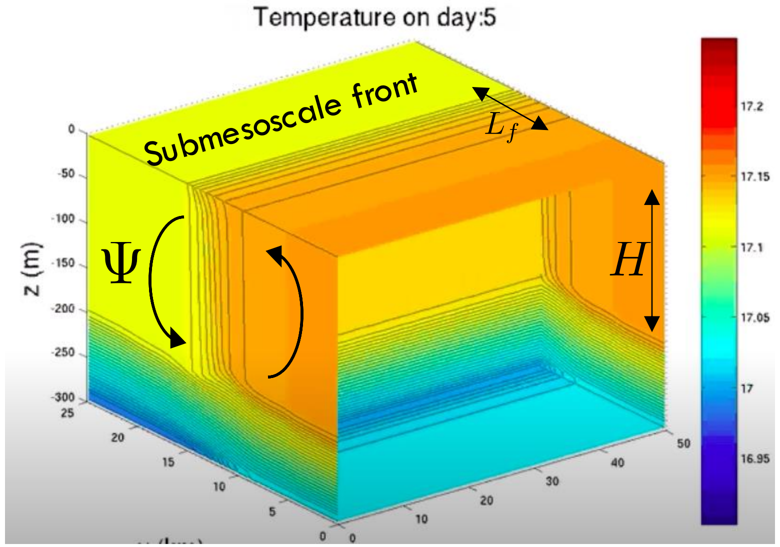
February 28, 2025

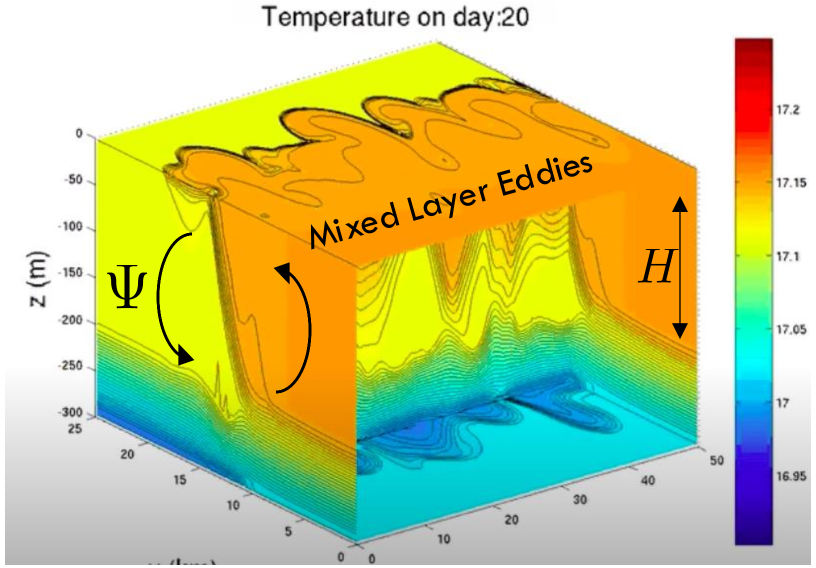




The Mixed Layer (Submesoscale) Eddy parameterization

- Represents the **restratification** effect of mixed layer eddies acting to slump submesoscale fronts





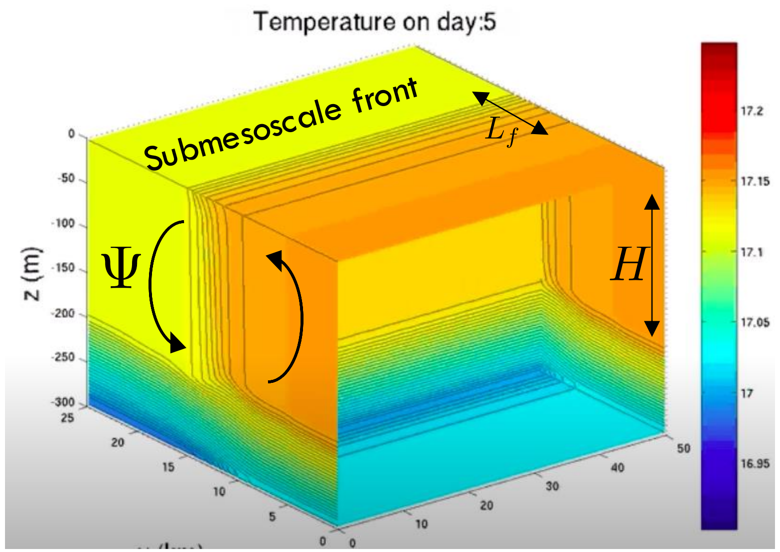
Fox-Kemper et. al. 2011

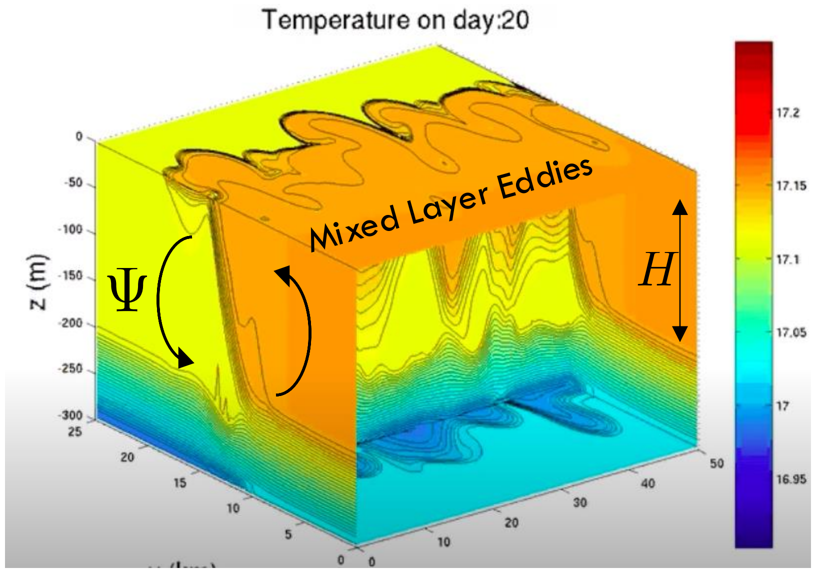
The Mixed Layer (Submesoscale) Eddy parameterization

- Represents the **restratification** effect of mixed layer eddies acting to slump submesoscale fronts

$$\Psi = C_e \frac{\Delta s}{L_f} \frac{H^2 \nabla \bar{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z)$$

- Strength depends on **frontal width** L_f
- Previously set as deformation radius $L_f = \frac{NH}{f}$





Fox-Kemper et. al. 2011

A new scaling for frontal width L_f

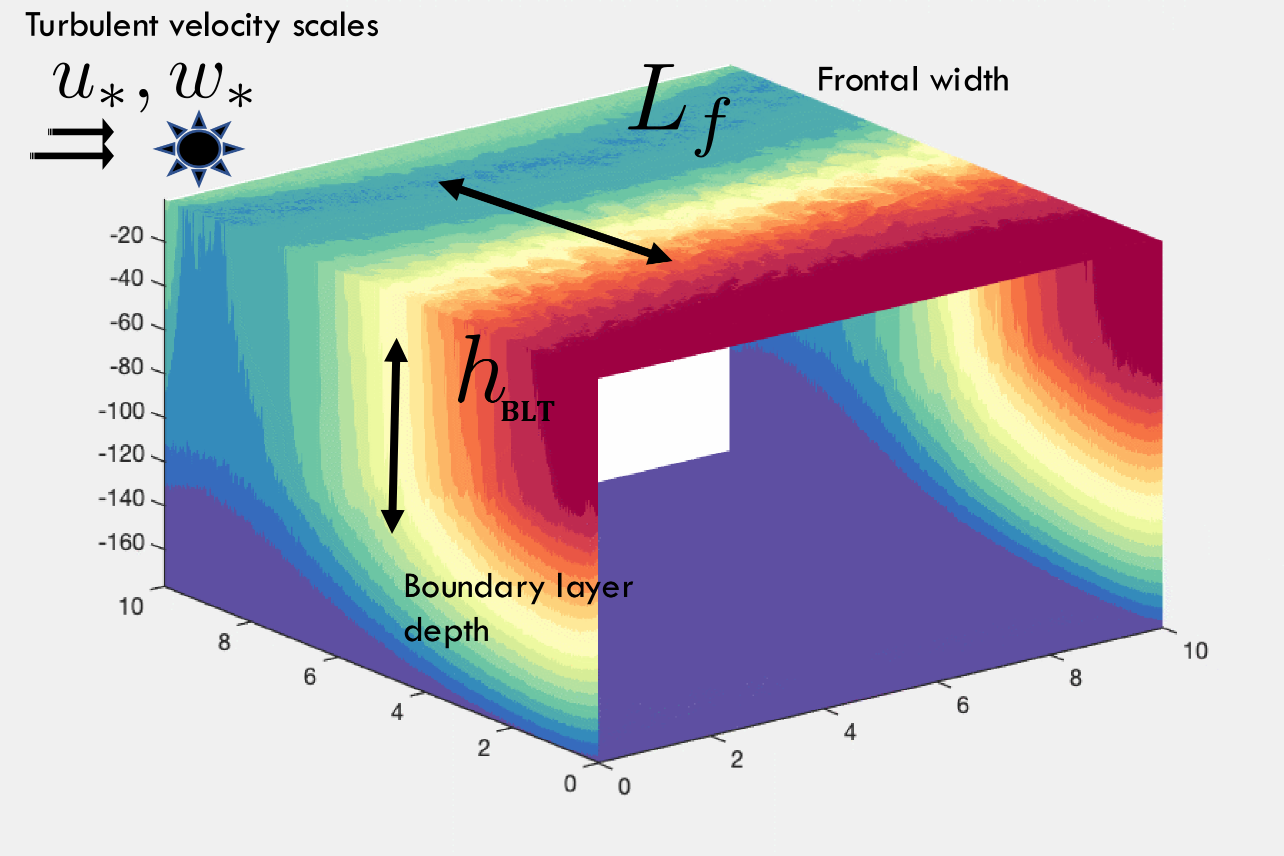
Turbulent thermal wind balance

$$\nabla_H b = -f\hat{\mathbf{z}} \times \mathbf{s} + \frac{\partial^2(\nu \mathbf{s})}{\partial z^2}$$

Buoyancy gradient — Vertical shear — Vertical eddy viscosity

Bodner, et al. (2023)

$$L_f = C_L \cdot \frac{(m_* {u_*}^3 + n_* {w_*}^3)^{2/3}}{f^2} \cdot \frac{1}{h}$$



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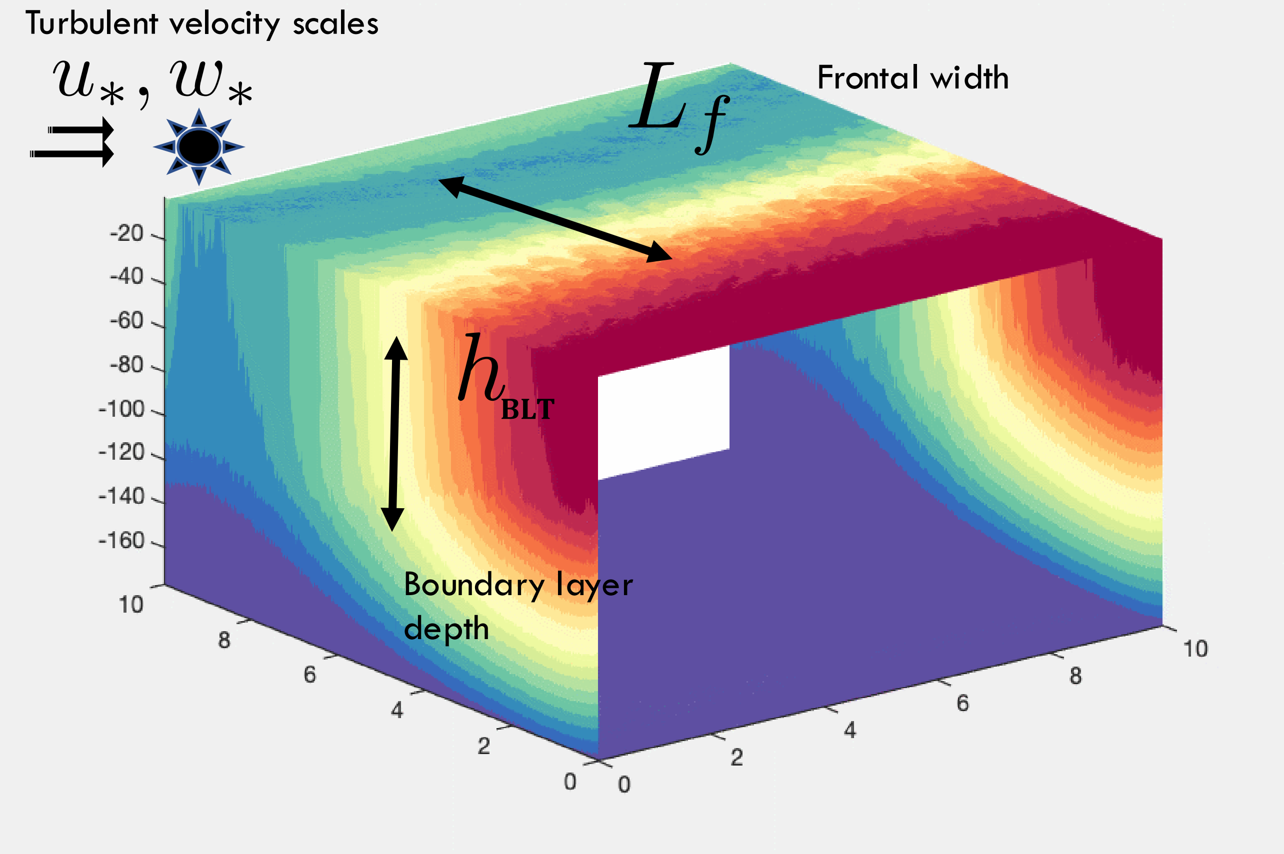
$Ri_T \approx 0.25$

Horizontal shear instability

From boundary layer turbulence schemes (KPP, ePBL)



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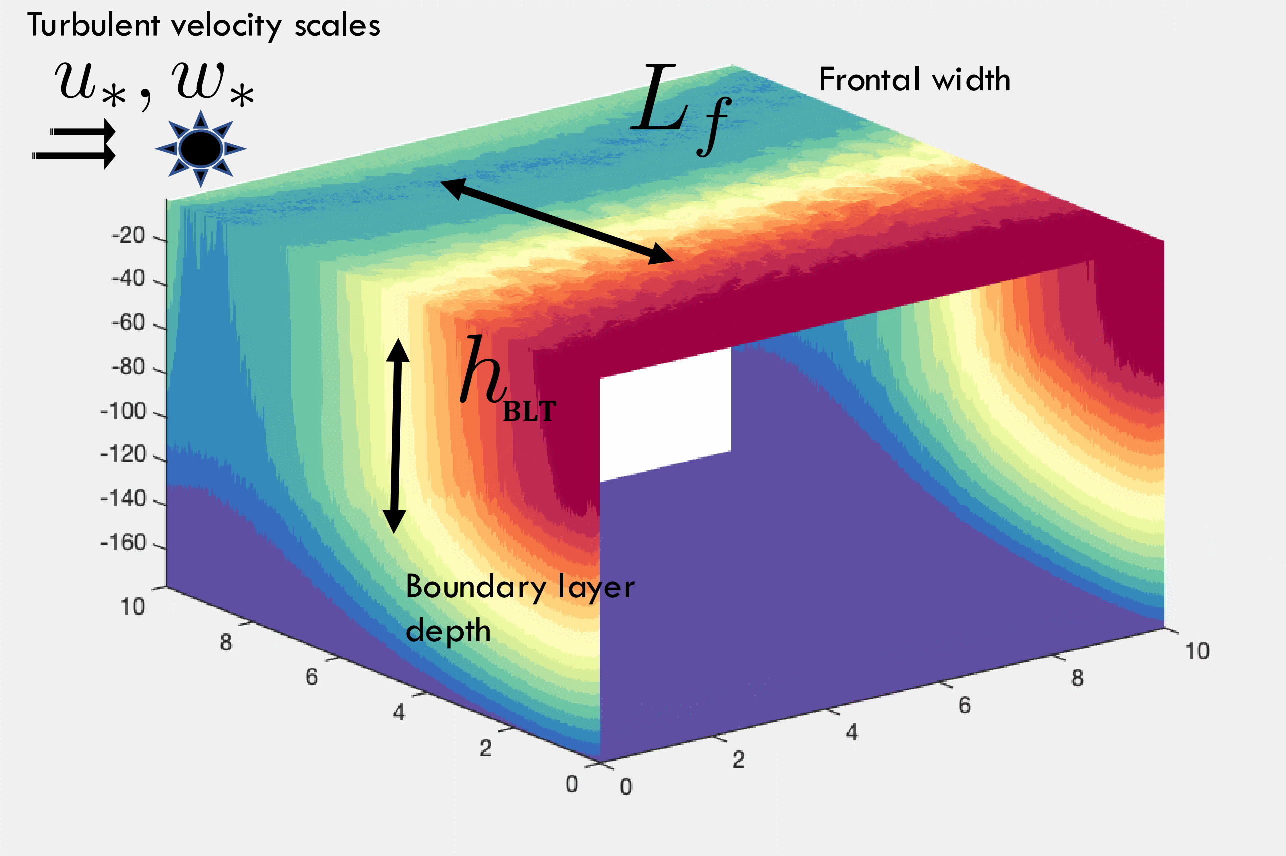


$$\Psi = C_e \frac{\Delta s}{L_f} \frac{H^2 \nabla \overline{b}^z \times \mathbf{z}}{\sqrt{f^2 + \tau^{-2}}} \mu(z) \quad \Rightarrow \quad C_r \frac{\Delta s |f| h H^2 \nabla \overline{b}^z \times \mathbf{z}}{(m_* {u_*}^3 + n_* {w_*}^3)^{2/3}} \mu(z)$$

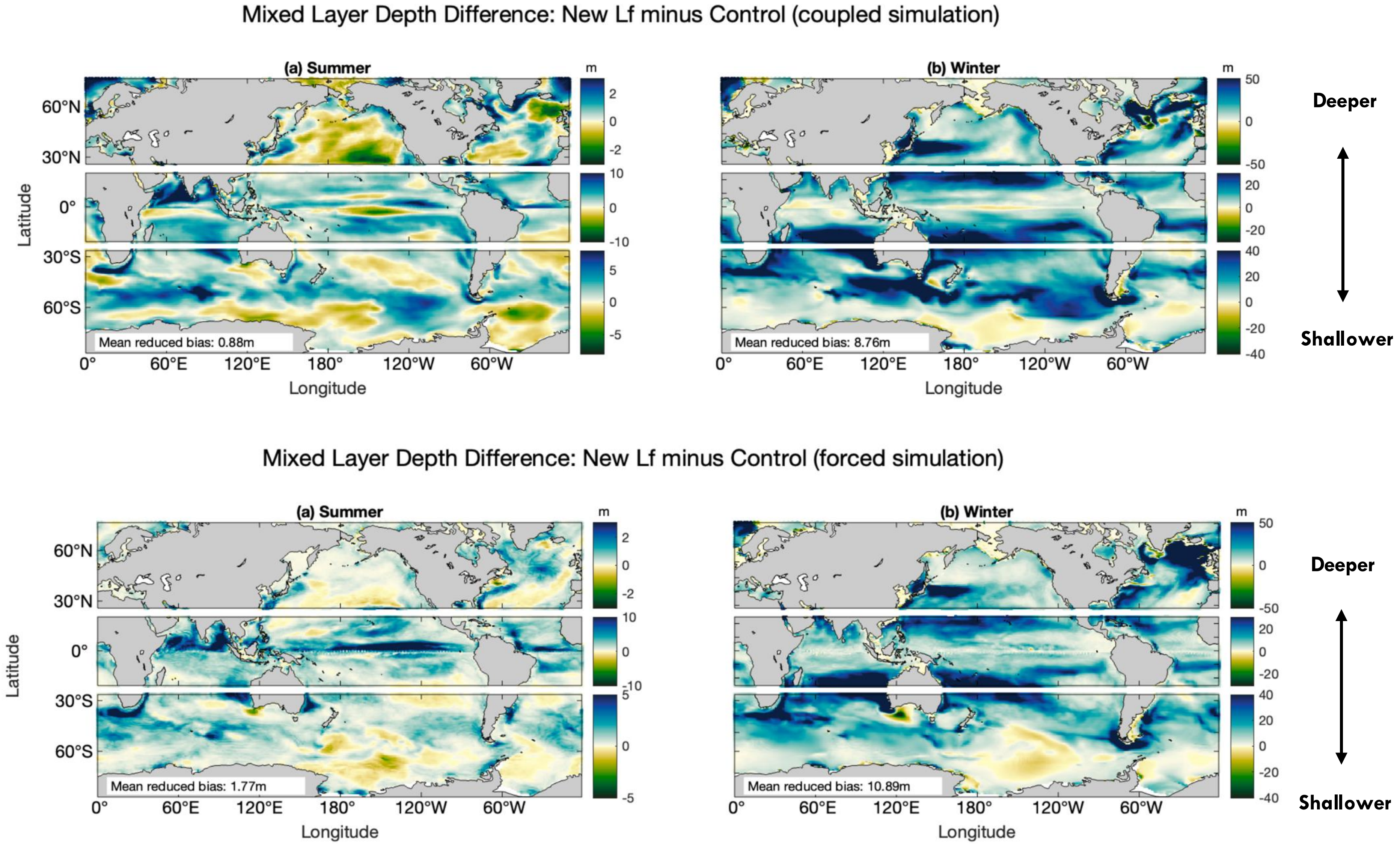
$$C_r \approx \frac{0.07}{0.25} \approx 0.28$$

Implementation in CESM-POP:
mixed layer depth

- Some climatologically important regions are modified by this scale factor

- What are the impacts of an updated parameterization?

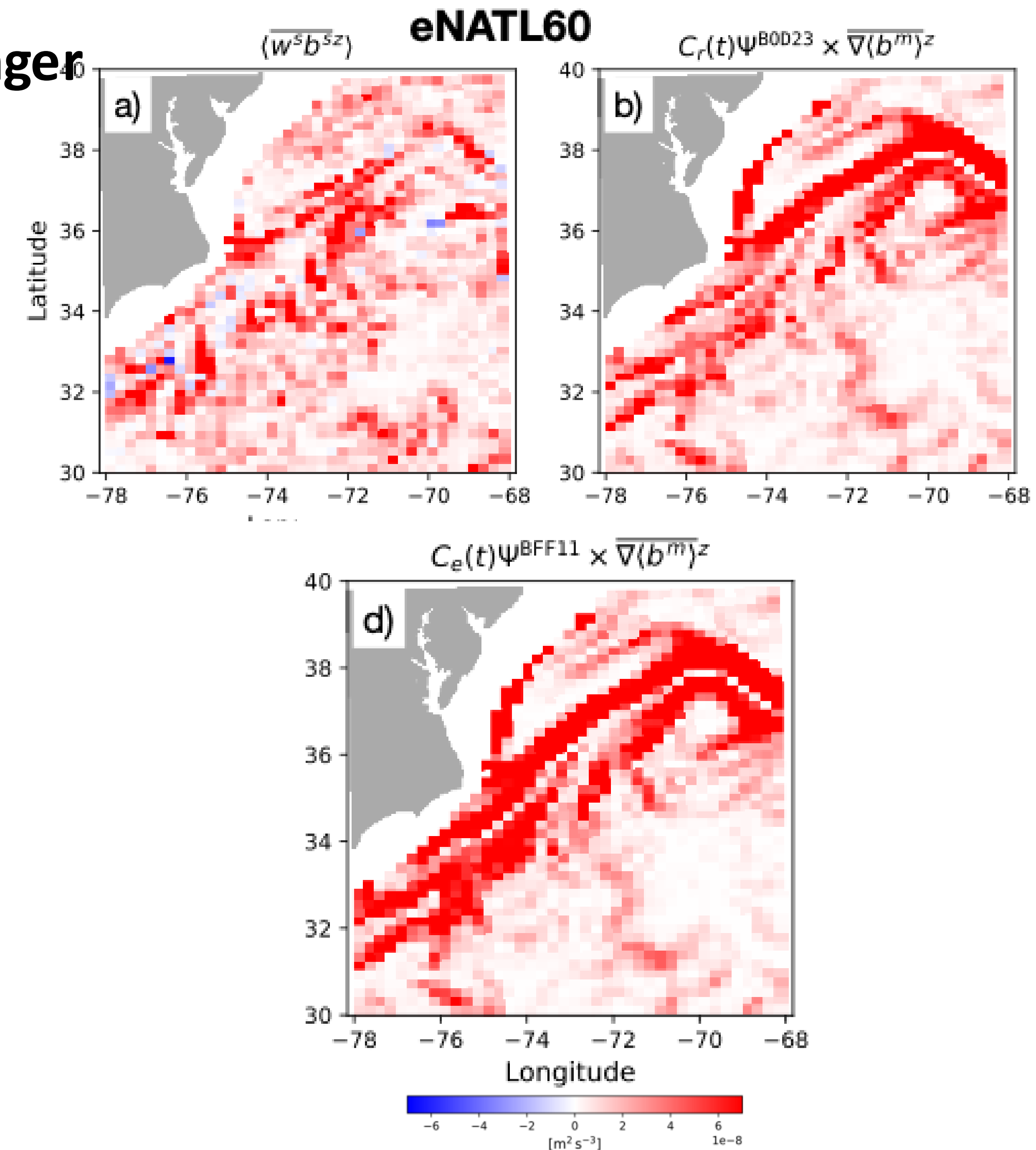
Differences: New – Old

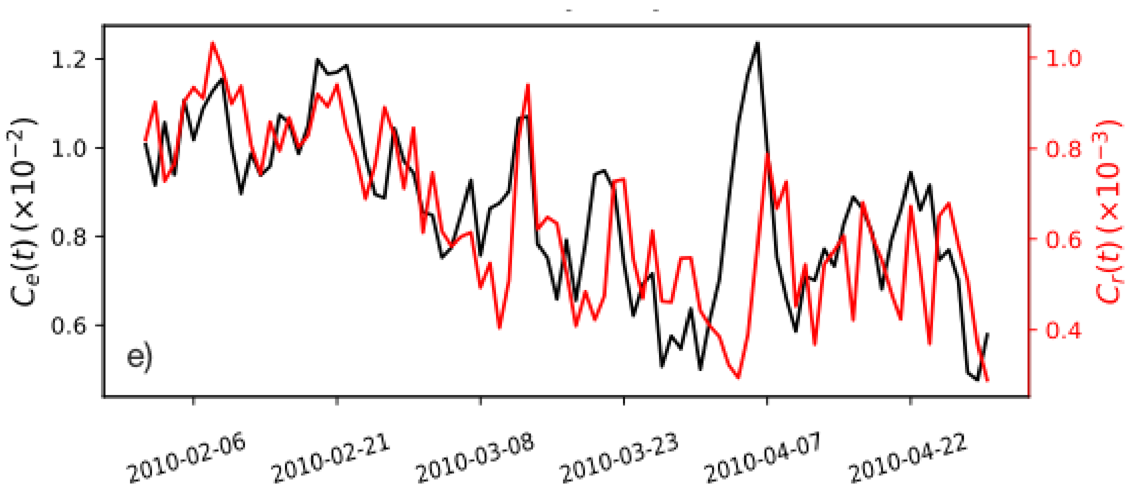


New parameterization estimates stronger submesoscale fluxes

Uchida et al (in prep)

Cr estimated from resolved fluxes is several orders of magnitude smaller than originally suggested





Multi Model Comparison:
GFDL-MOM6 CESM-MOM6 BLOM

$$\mathbf{\Psi} = C_r \frac{\Delta s |f| h H^2 \nabla \overline{b}^z \times \mathbf{z}}{(m_* u_*{}^3 + n_* w_*{}^3)^{2/3}} \mu(z)$$

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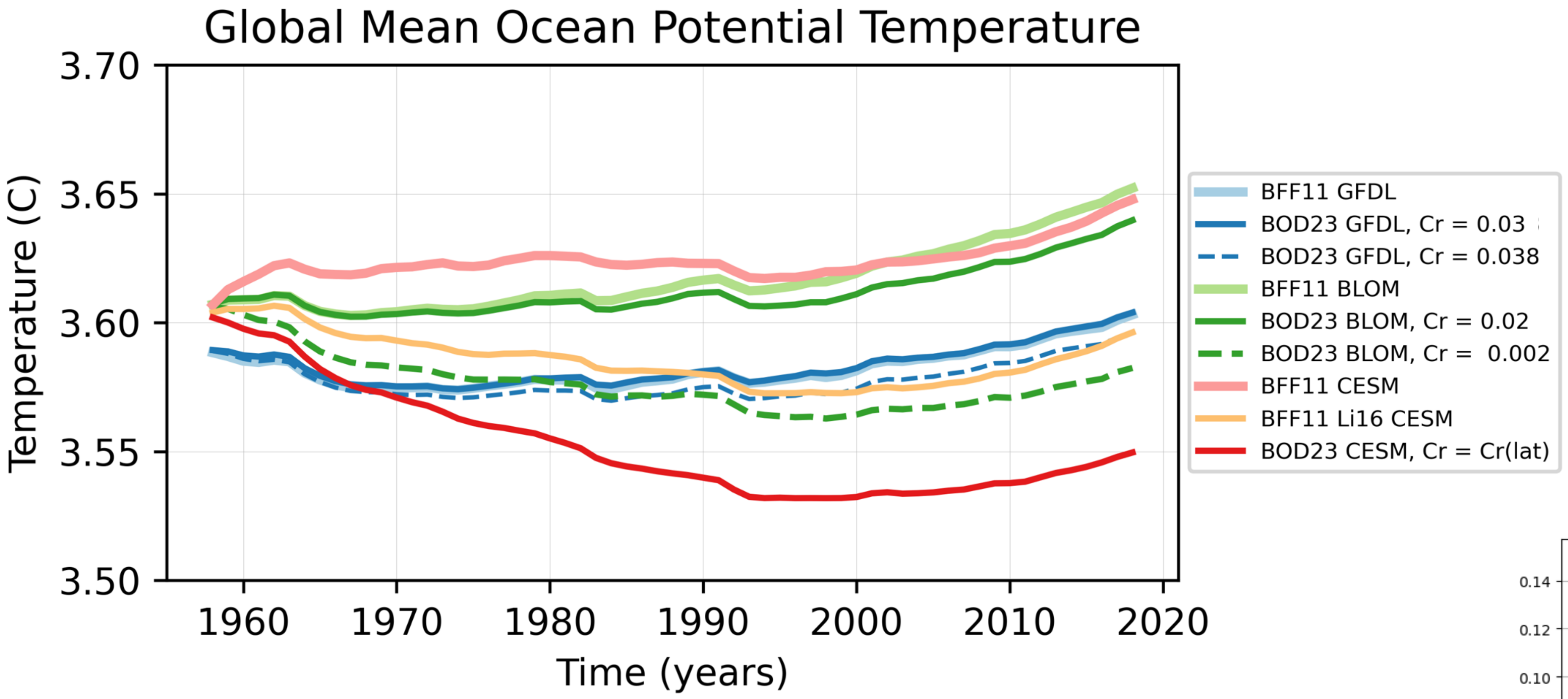
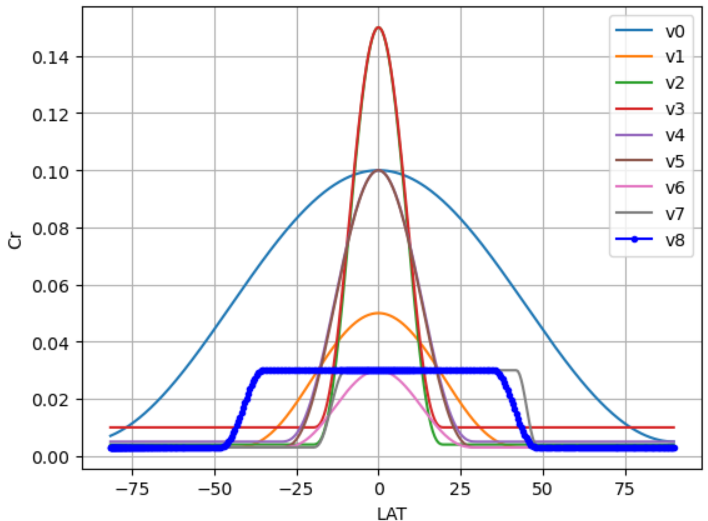


Cr=Cr(lat)



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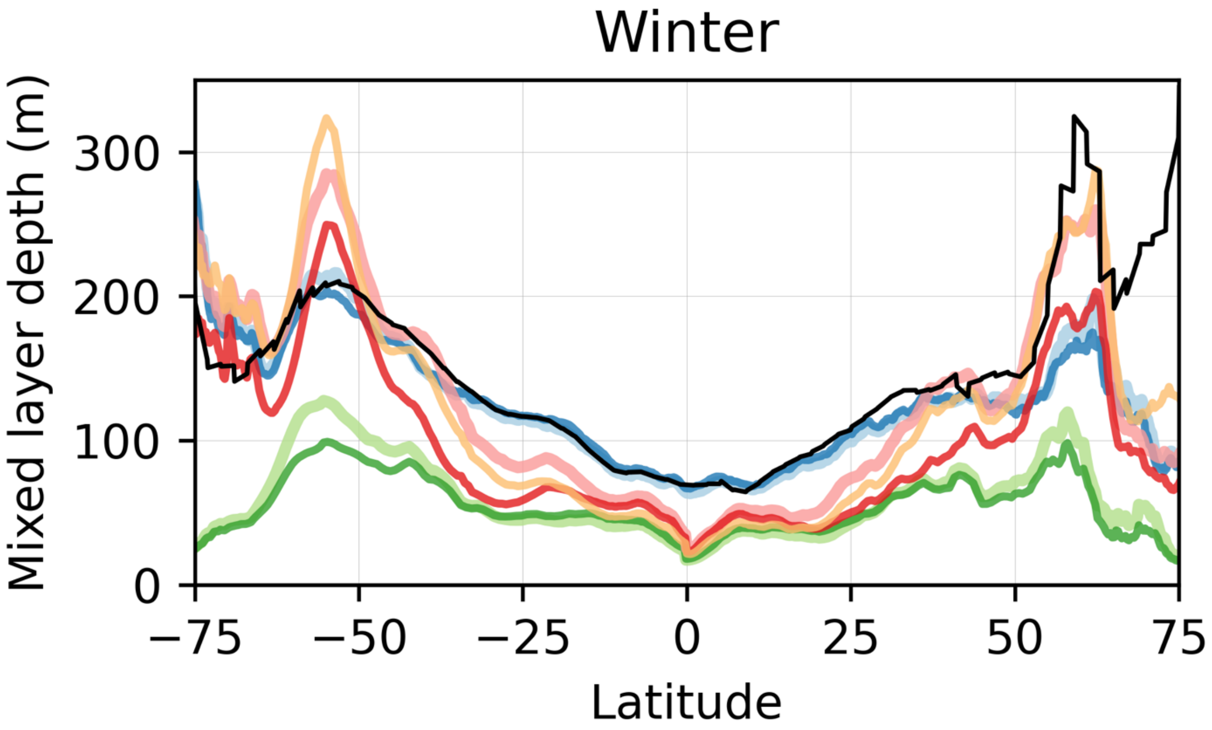

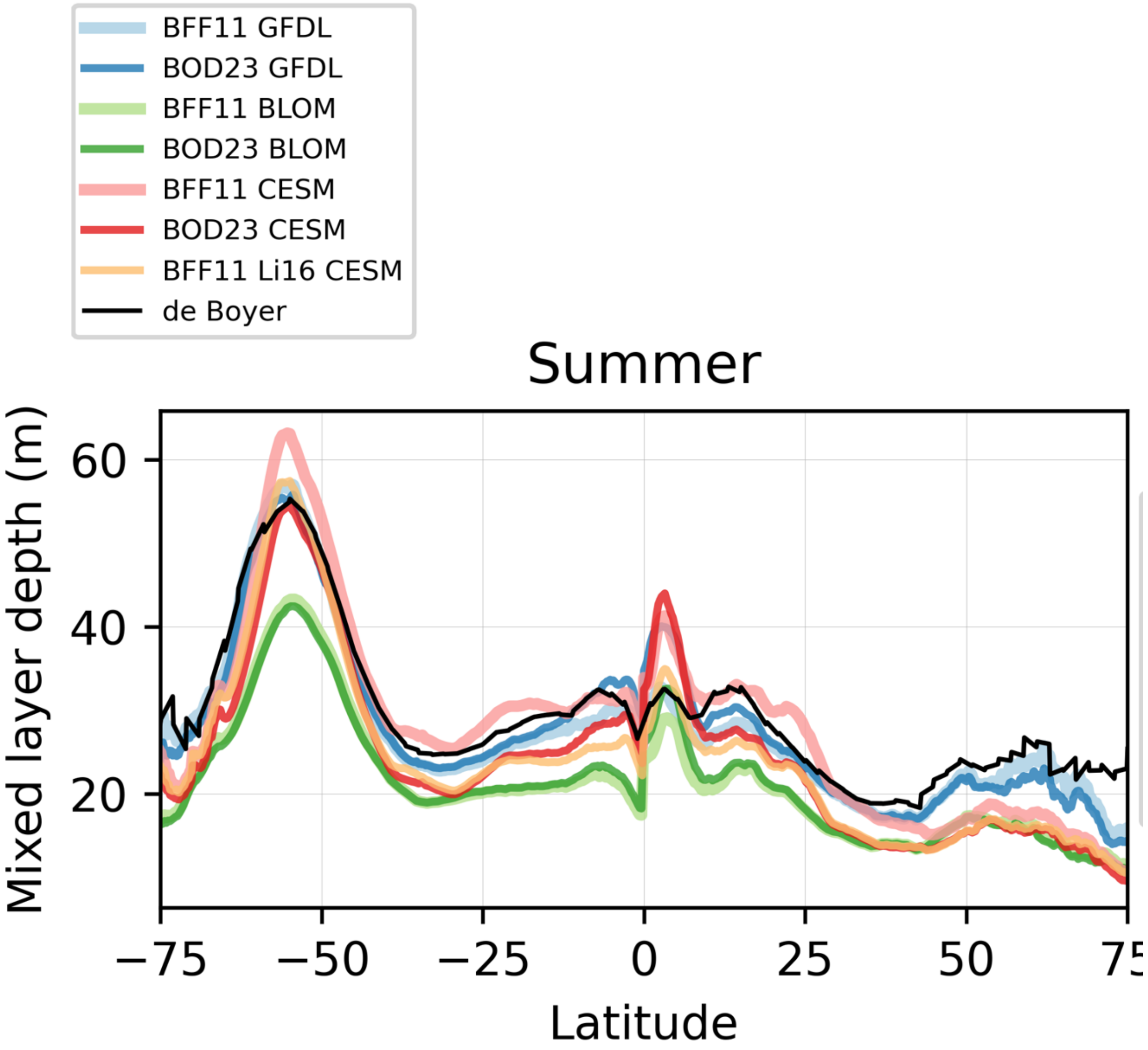

Mixed layer depth

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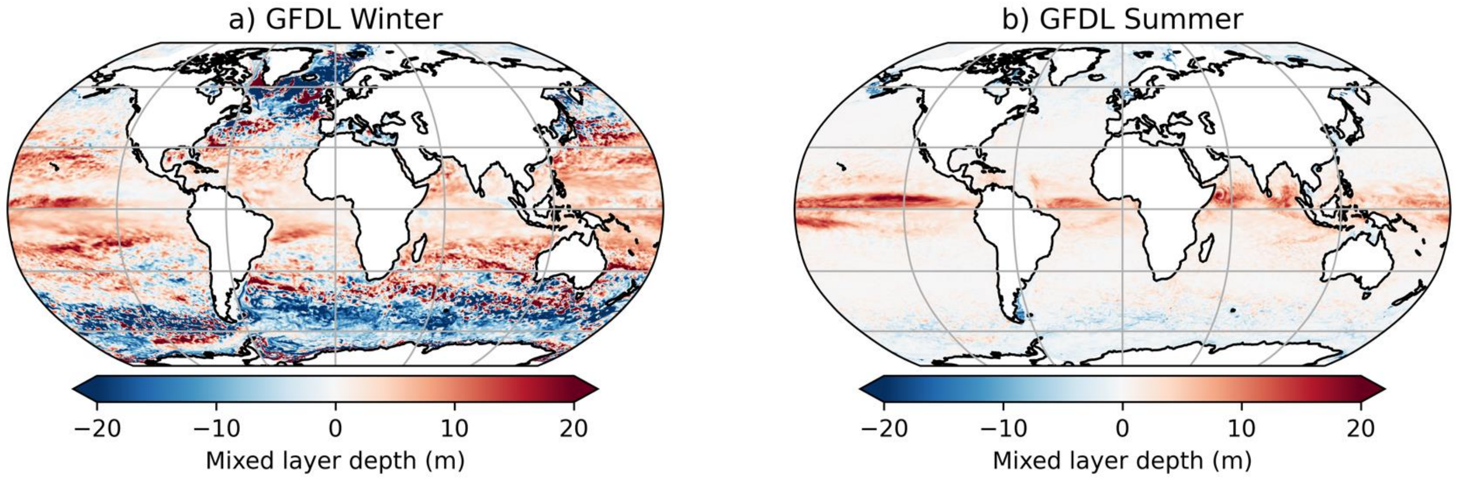
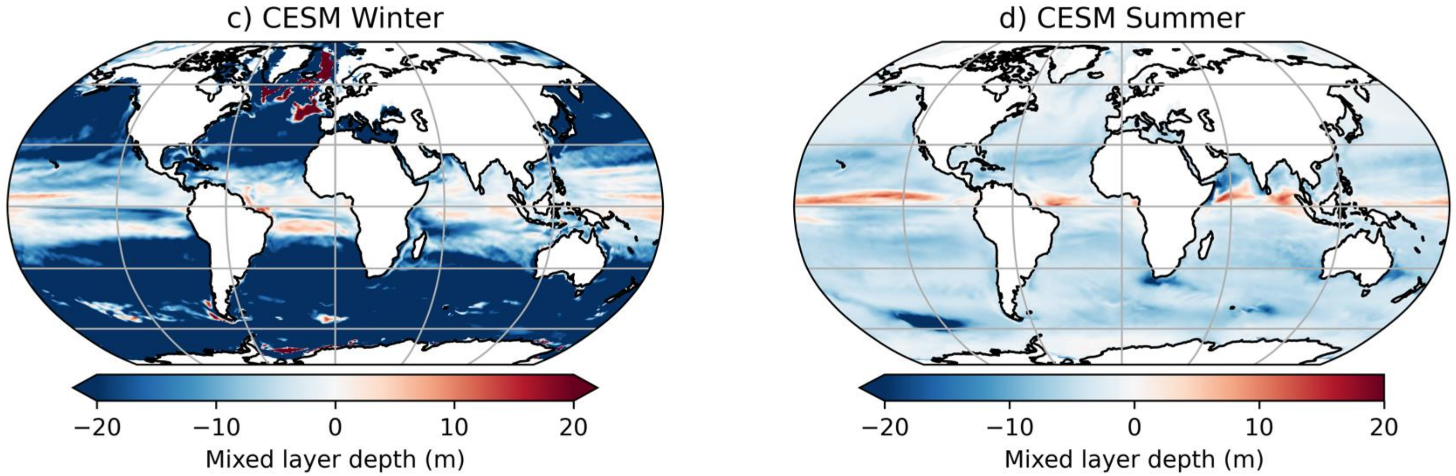
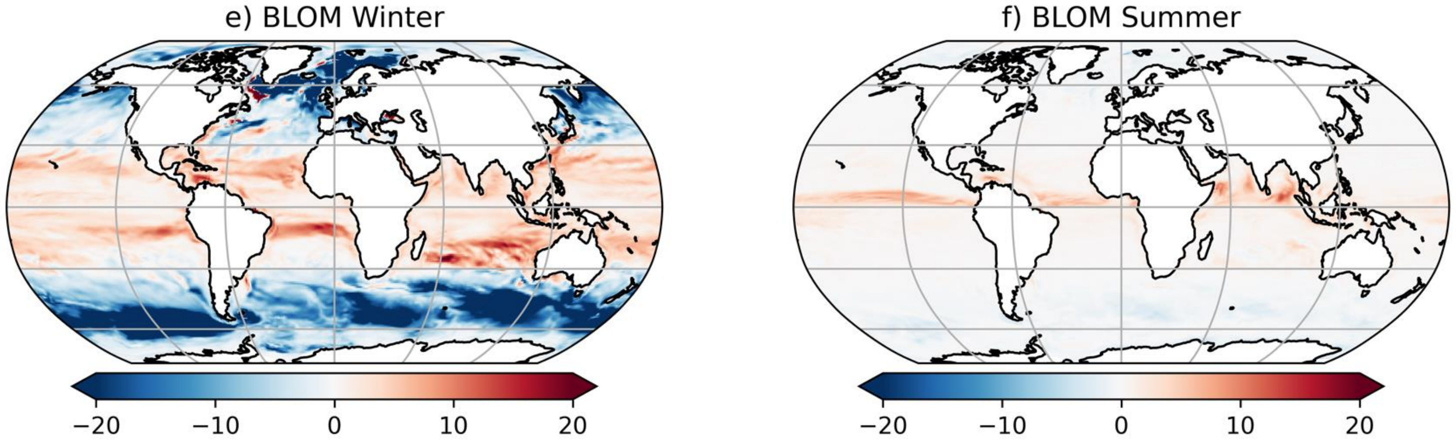
Results from Bodner23 minus results from Fox-Kemper 2011







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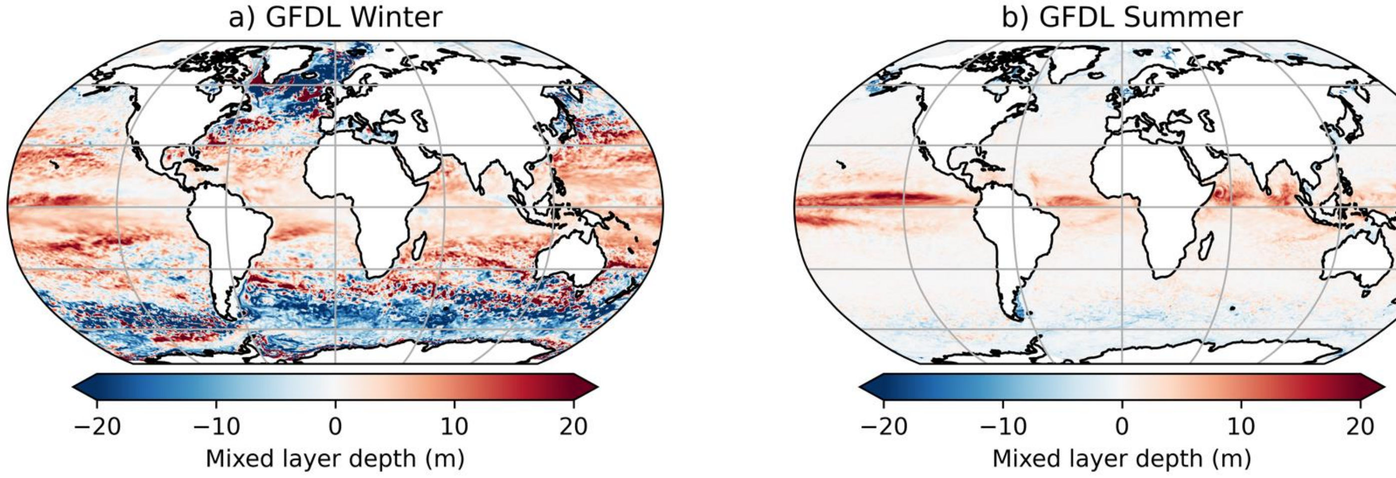
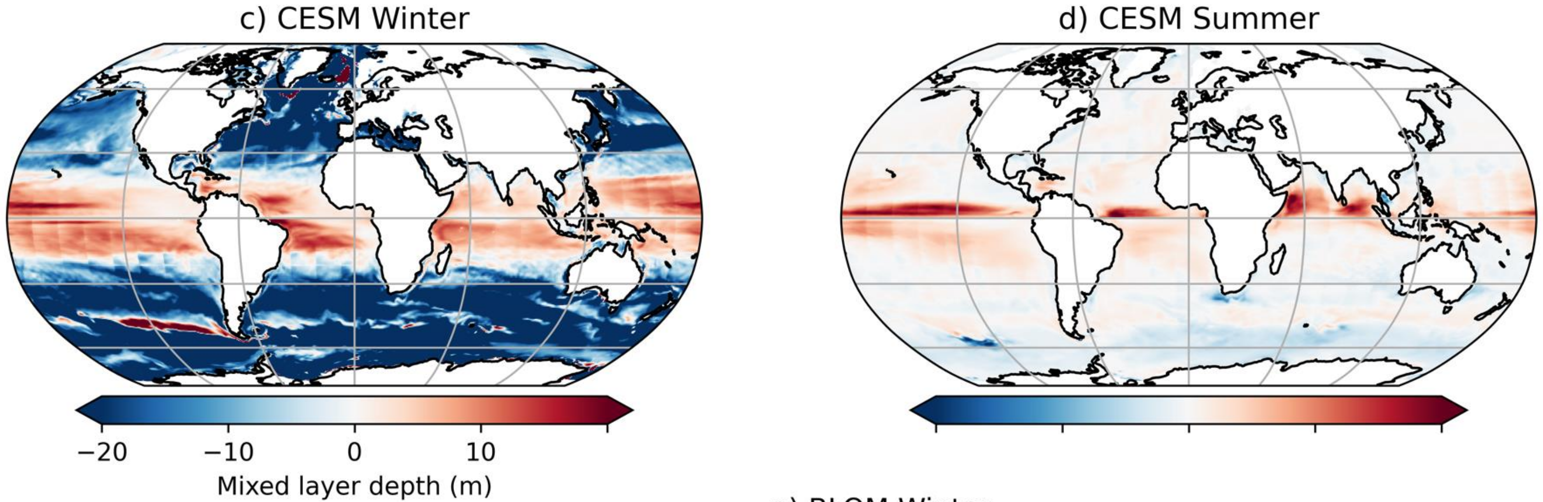
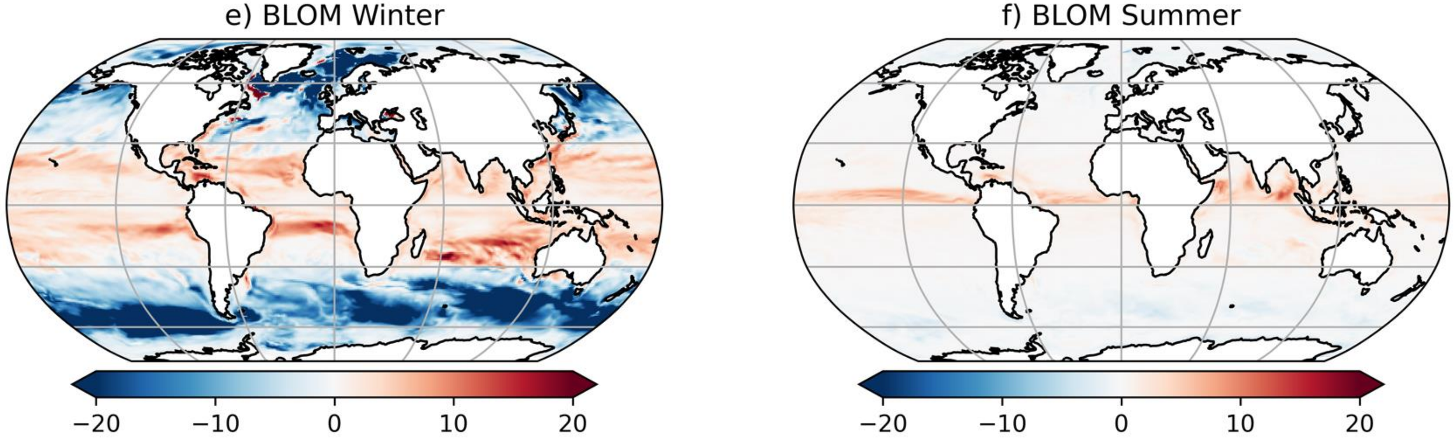


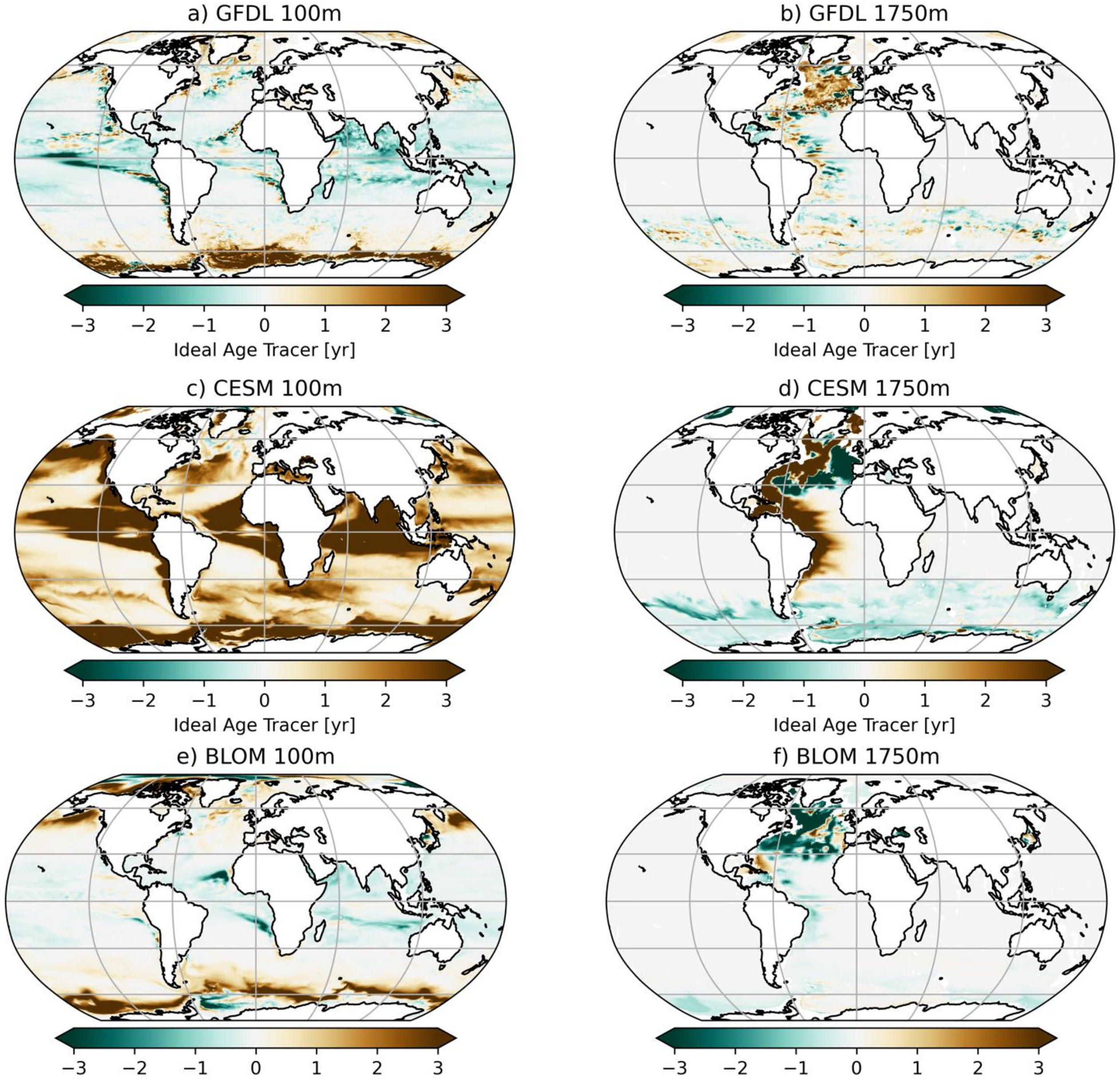
Li et al 2016
Mixing scheme





Ideal Age

Results from Bodner23 minus results from Fox-Kemper 2011



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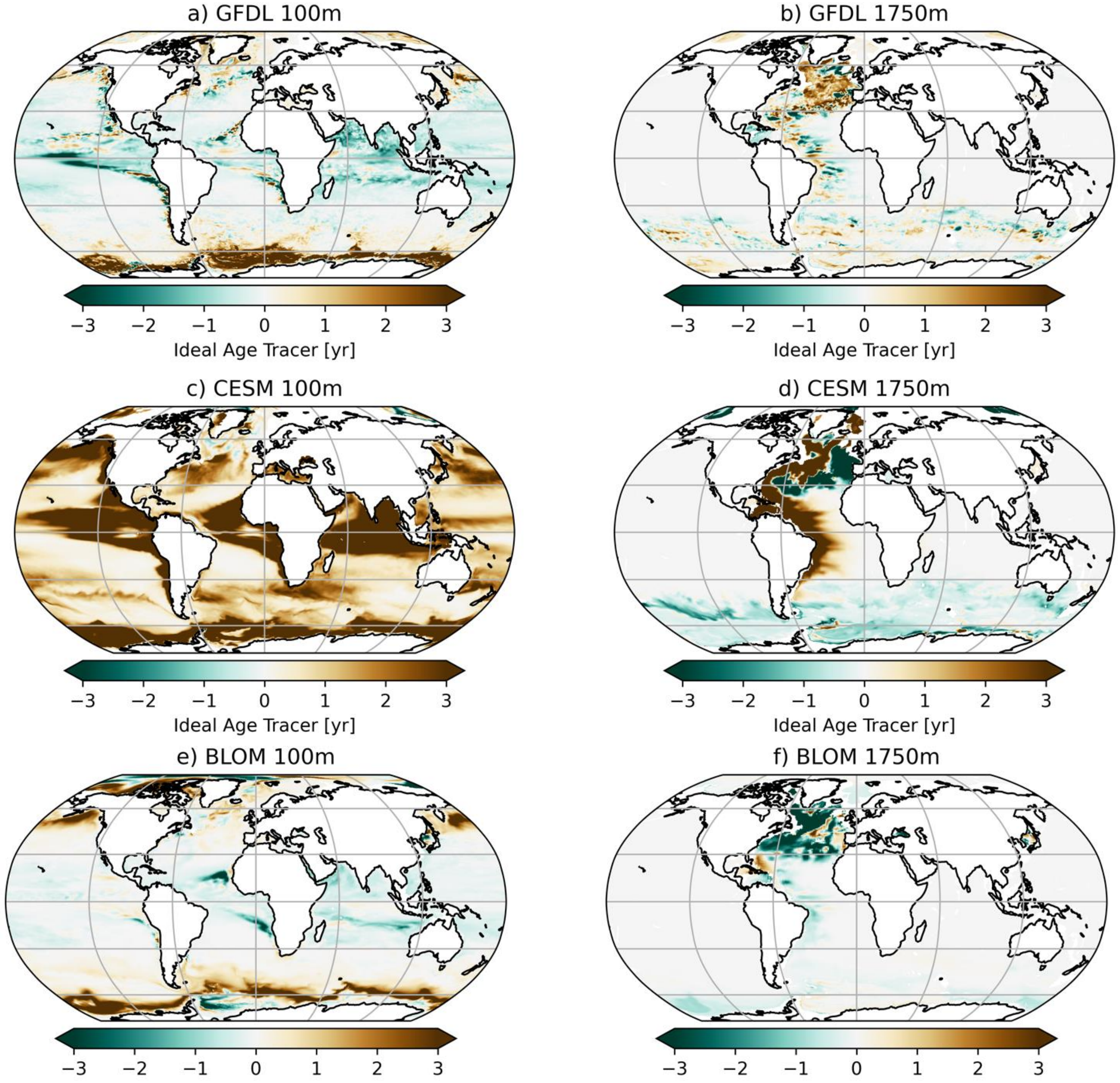

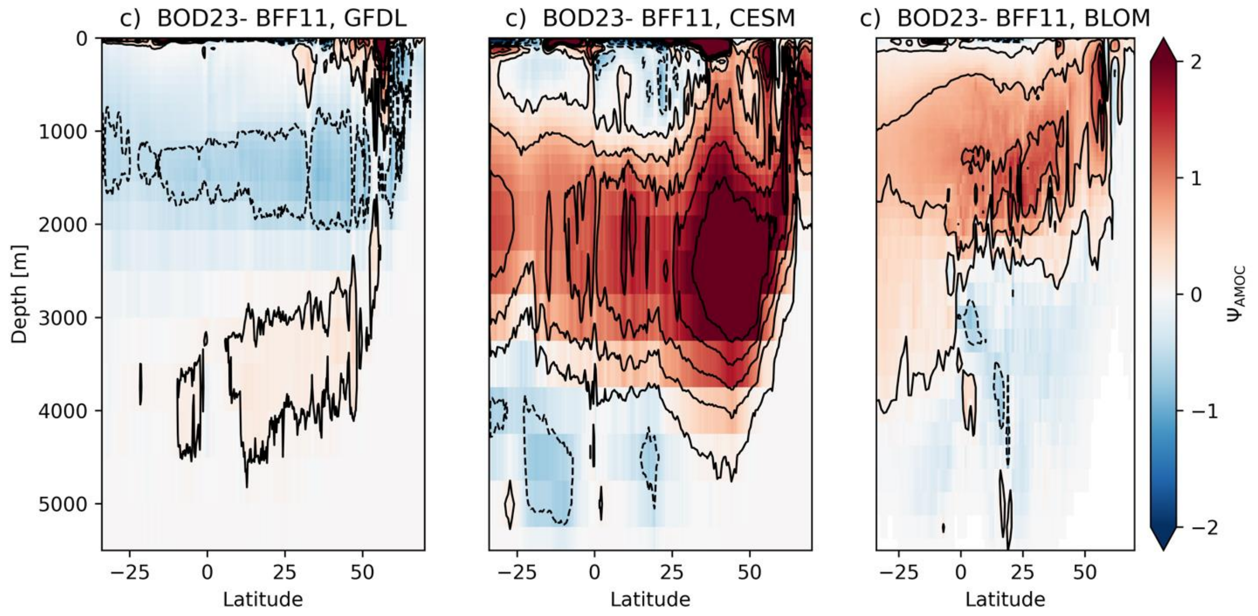

AMOC

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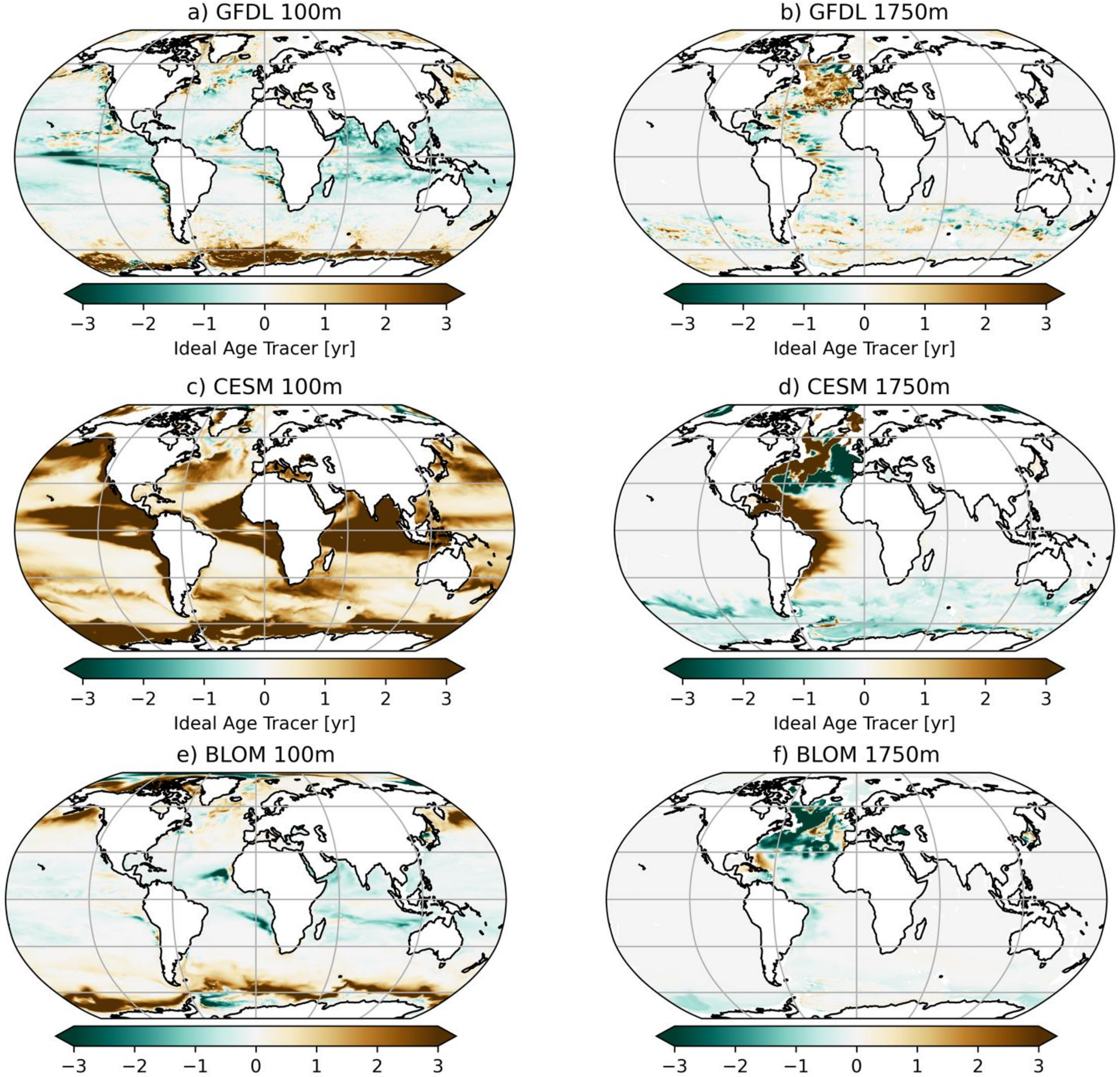

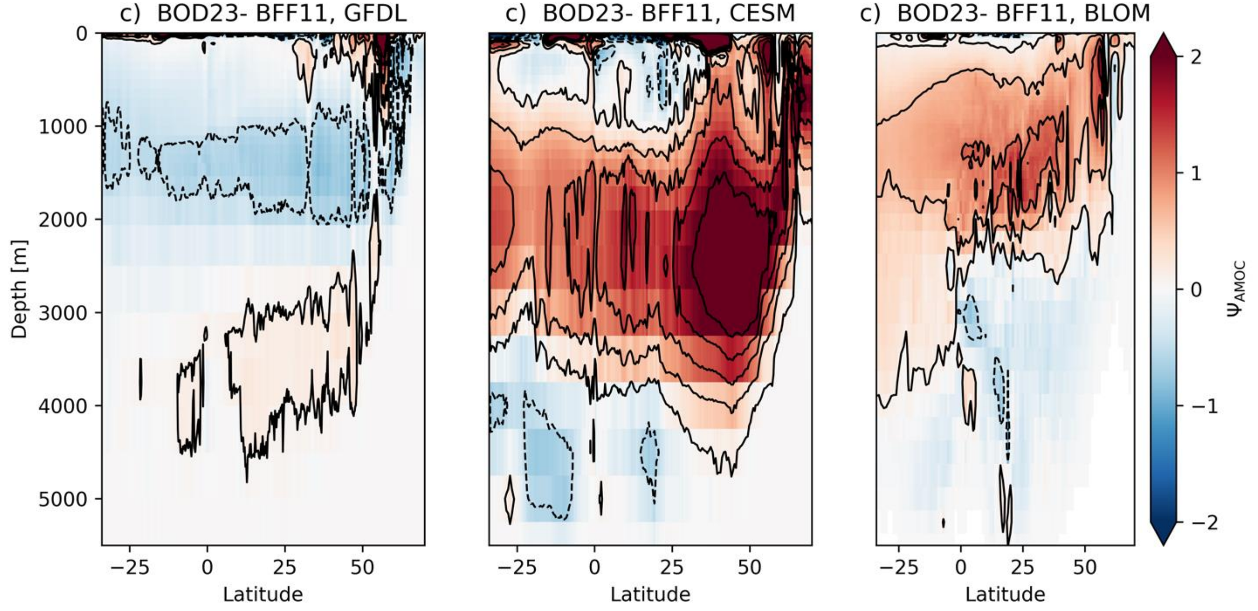

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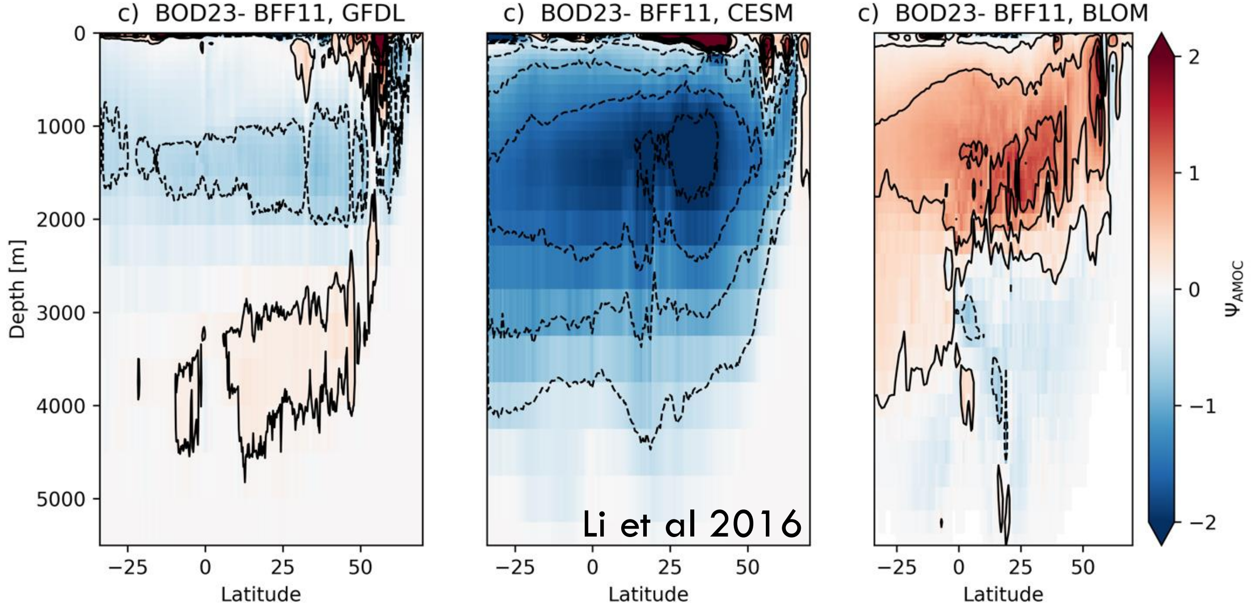


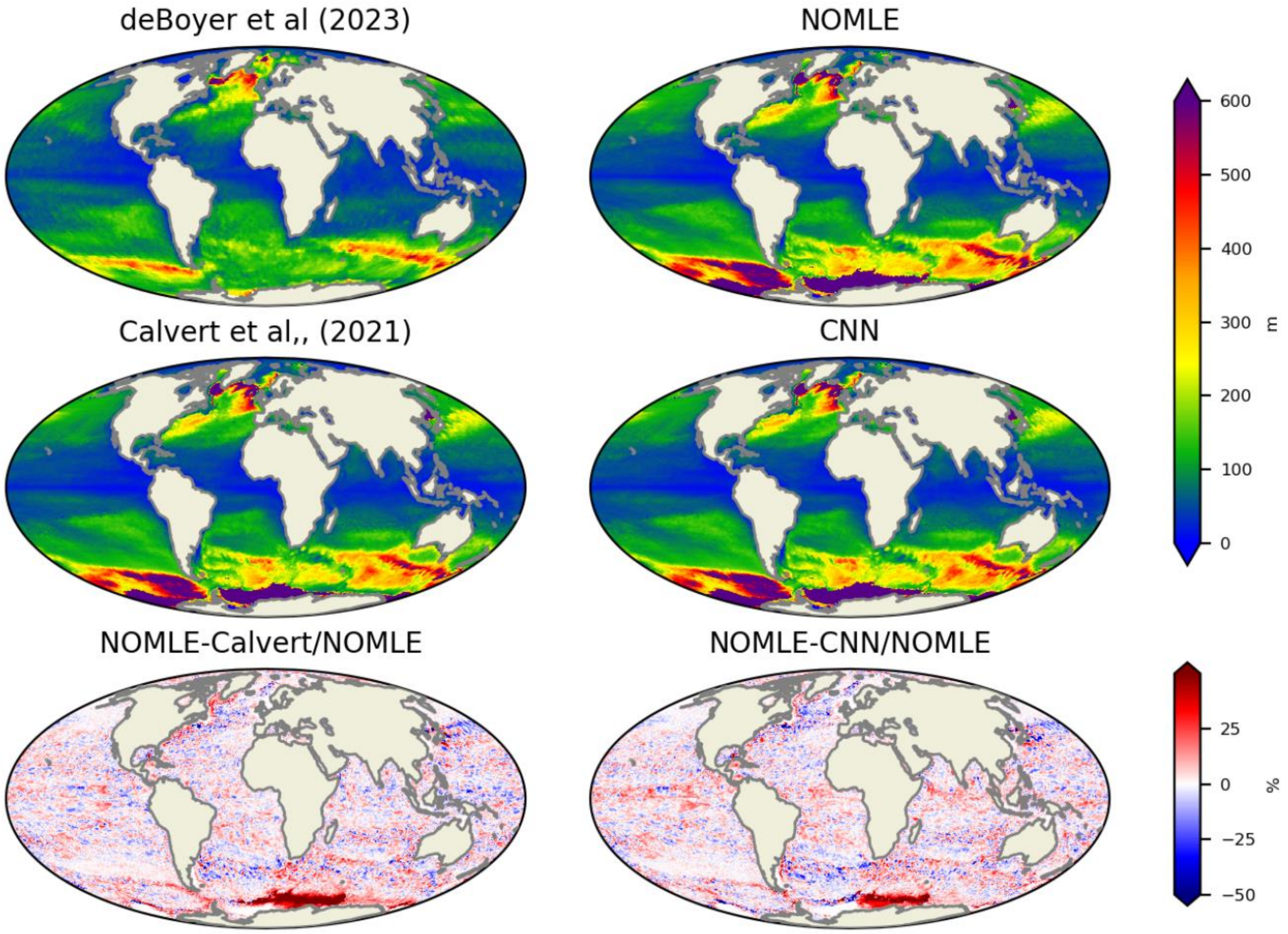
CNN submesoscale parameterization

Bodner, Balwada, Zanna (under review)
Contreras et al. (in prep.)

- CNN implemented in NEMO
- Streamfunction inverted from predicted fluxes

$$\Psi = \frac{\overline{w'b'}^z}{\overline{|\nabla b|}^z}$$

- Online performance compared with Calvert MLE parameterization



Conclusions

$$\mathbf{\Psi} = C_r \frac{\Delta s |f| h H^2 \nabla \overline{b}^z \times \mathbf{z}}{(m_* {u_*}^3 + n_* {w_*}^3)^{2/3}} \mu(z)$$

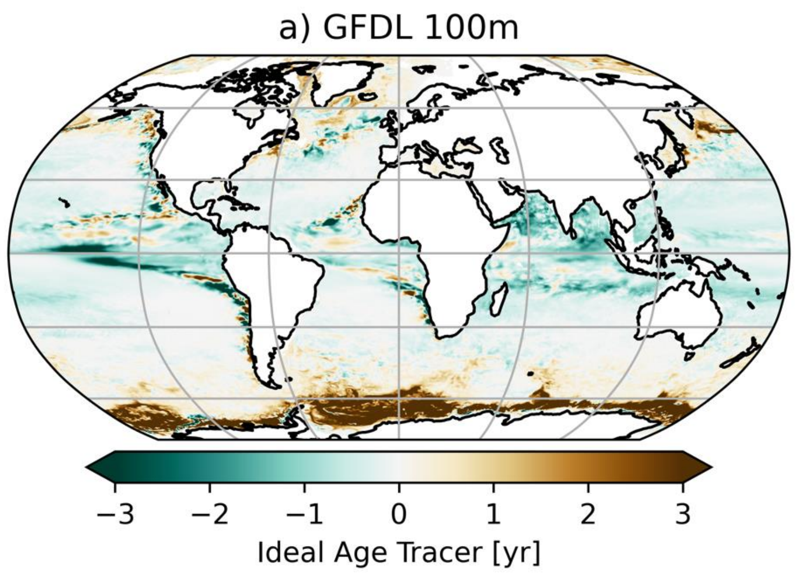
- MLE is still an important tuning nob

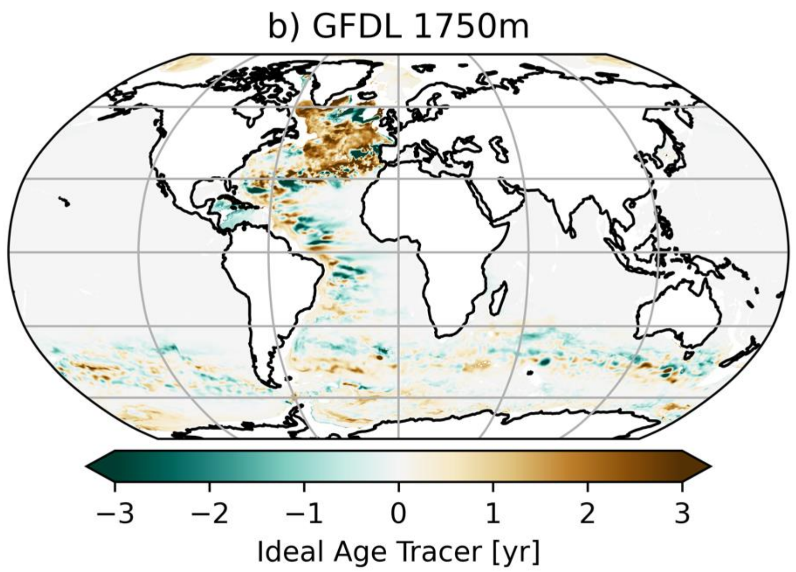
- New parameterization infers stronger fluxes

- Impact on global circulation patterns, but different in every model (GFDL, CESM, BLOM)

- The new relationship with boundary layer turbulence parameters makes it more sensitive to choices of the parameterization (KPP, ePBL, waves)

- More work is needed to determine the optimal Cr





Extra slides

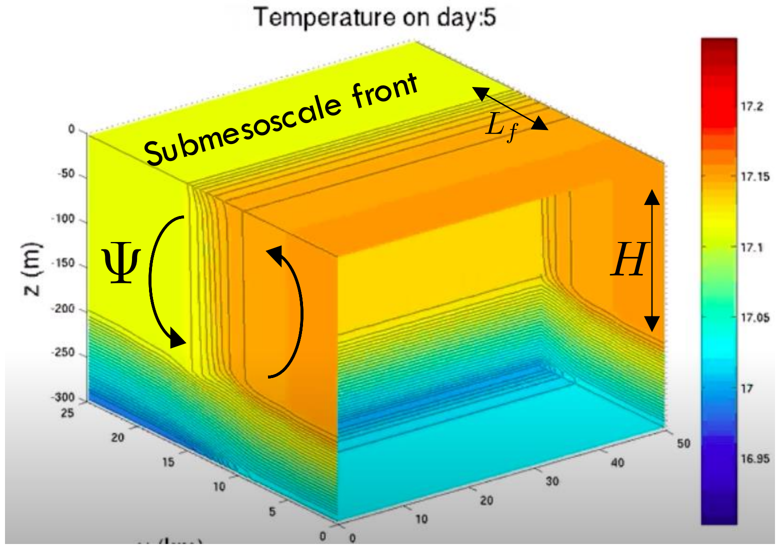
The Mixed Layer (Submesoscale) Eddy parameterization

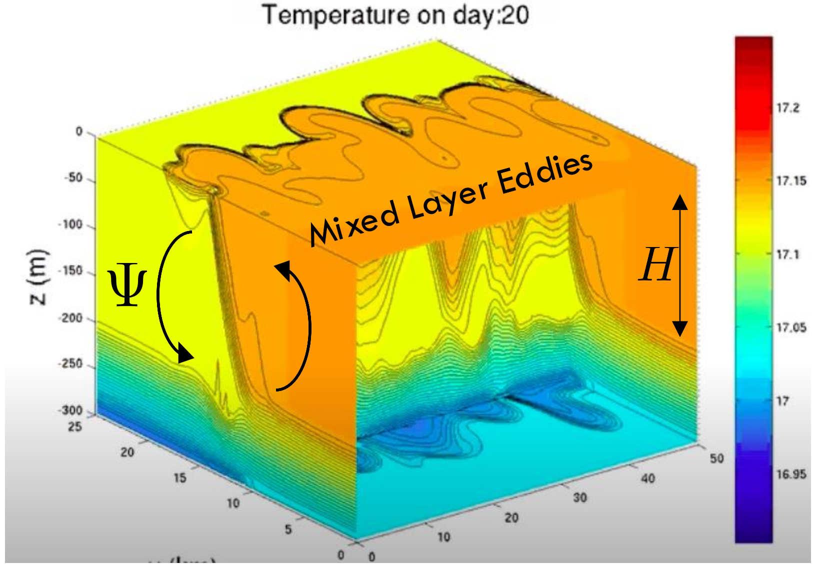
- Overturning streamfunction within the mixed layer, acting to slump isopycnals (submesoscale front)
- For a single front

$$\Psi_{MLE} = C_e \frac{H^2 \nabla_H \overline{b}^z \times \mathbf{z}}{|f|} \mu(z)$$

- Coriolis parameter f, mixed layer depth H
- Depth averaged horizontal buoyancy gradient $\nabla_H \overline{b}^z$
- Efficiency factor $0.06 \le C_e \le 0.08$
- Vertical structure function

$$\mu(z) = \max\left(0, \left[1 - \left(\frac{2z}{H}+1\right)^2\right]\left[1 + \frac{5}{21}\left(\frac{2z}{H}+1\right)^2\right]\right)$$





Fox-Kemper et. al. 2008

The Mixed Layer (Submesoscale) Eddy parameterization

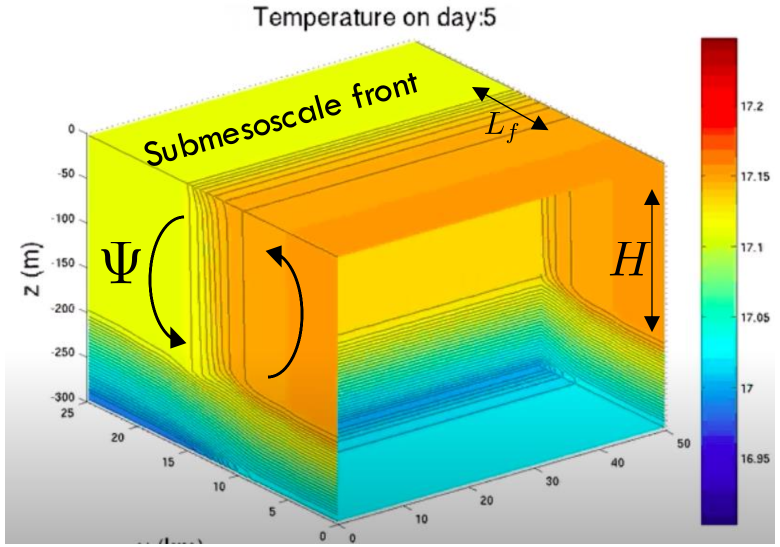
- Assuming a submesoscale buoyancy spectral slope of k^{-2} estimates the intensity of unresolved fronts in a single grid cell

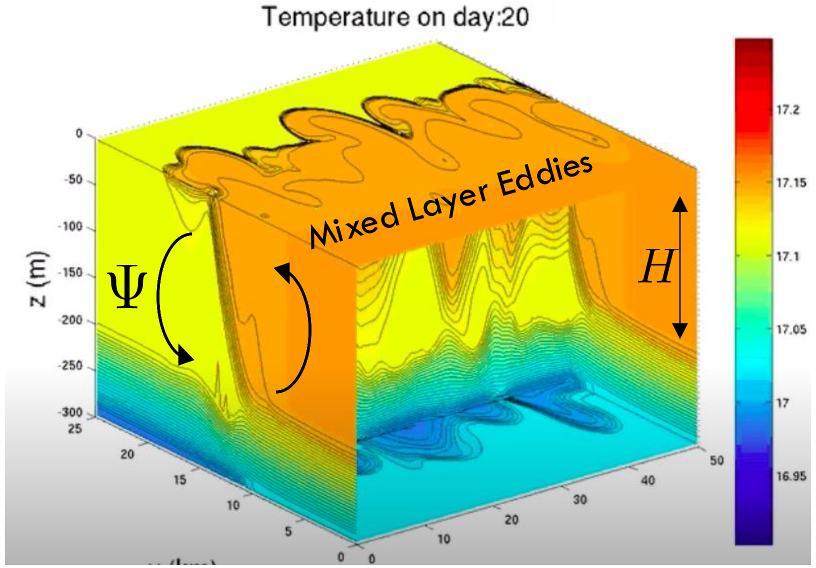
- Introduces a factor ${}^{\Delta s}/_{L_f}$: L_f Is the width of the front, Δs is the GCM grid scale

- Implementing in coarse resolution climate models

$$\Psi = C_e \frac{\Delta s}{L_f} \frac{H^2 \nabla \bar{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z)$$

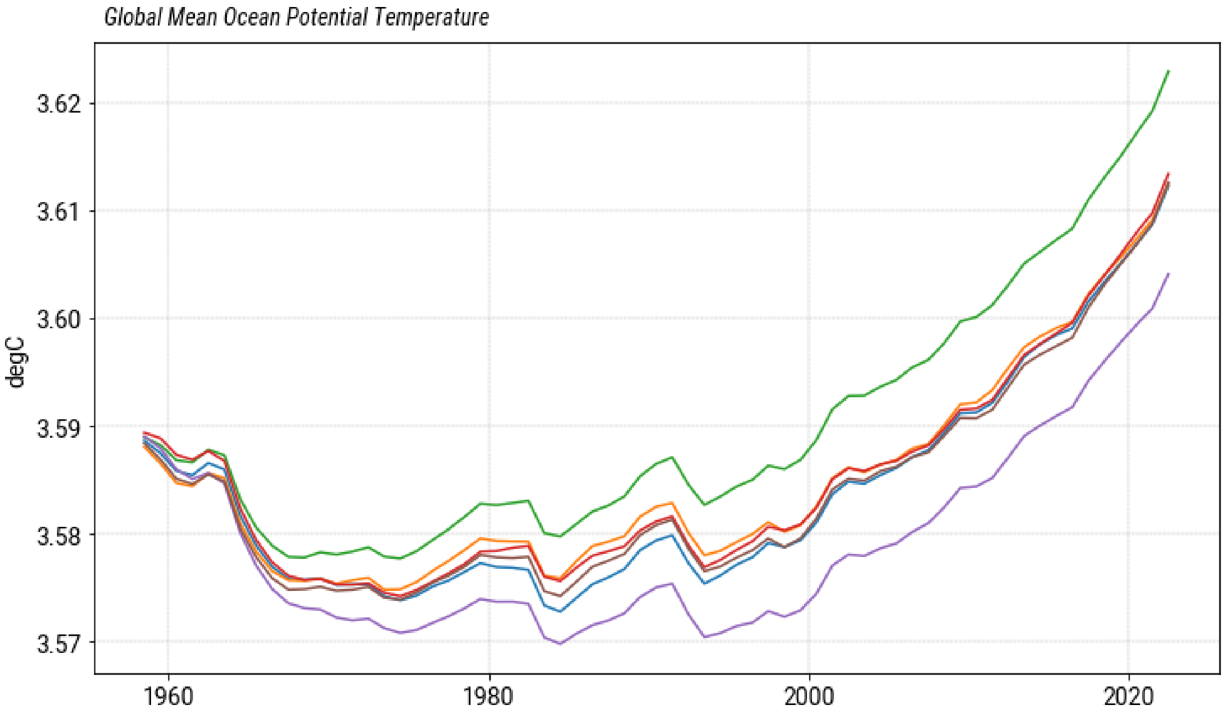
- The substitution of $f \rightarrow \sqrt{f^2 + \tau^{-2}}$ is used to renormalize across the equator

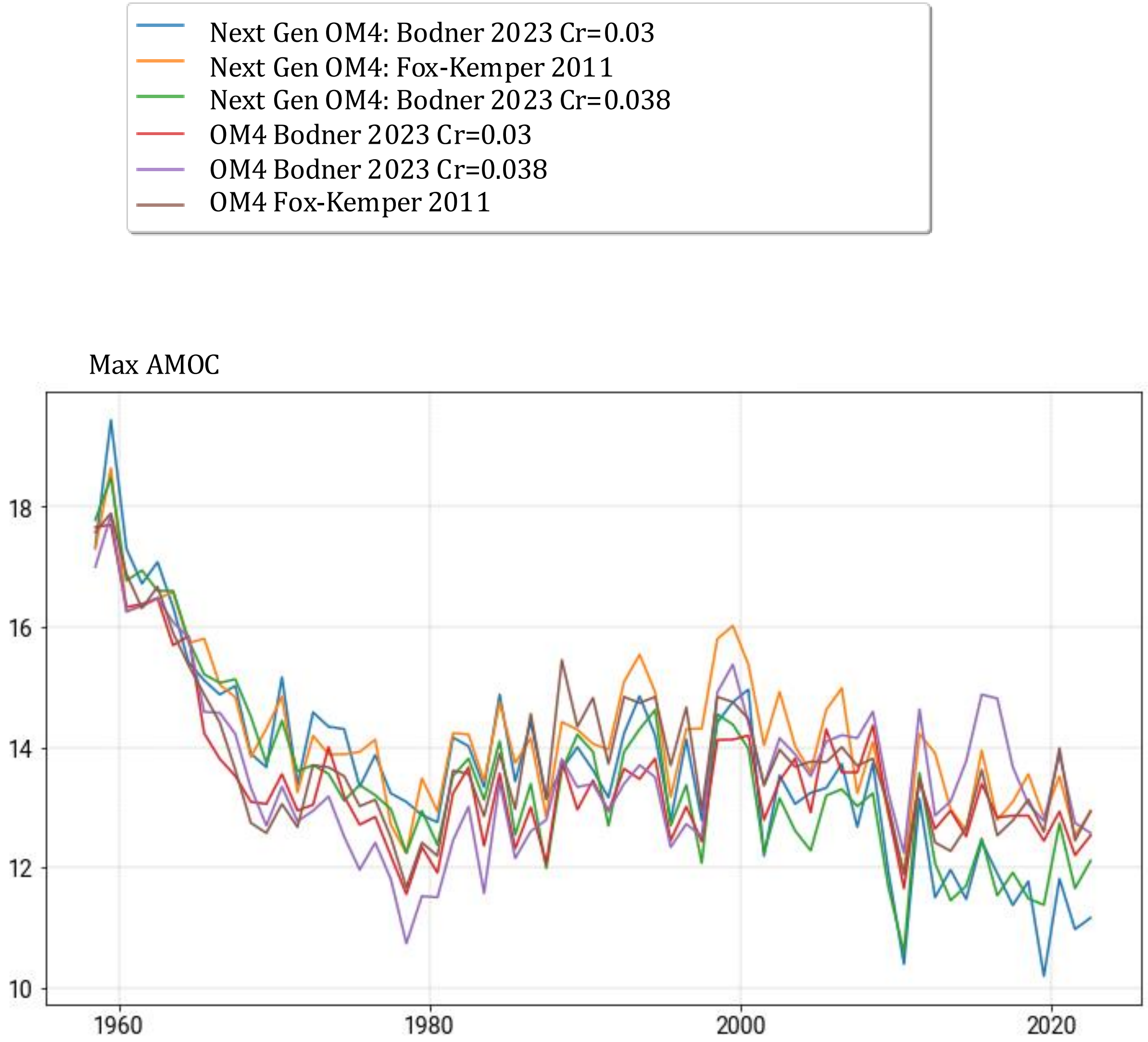




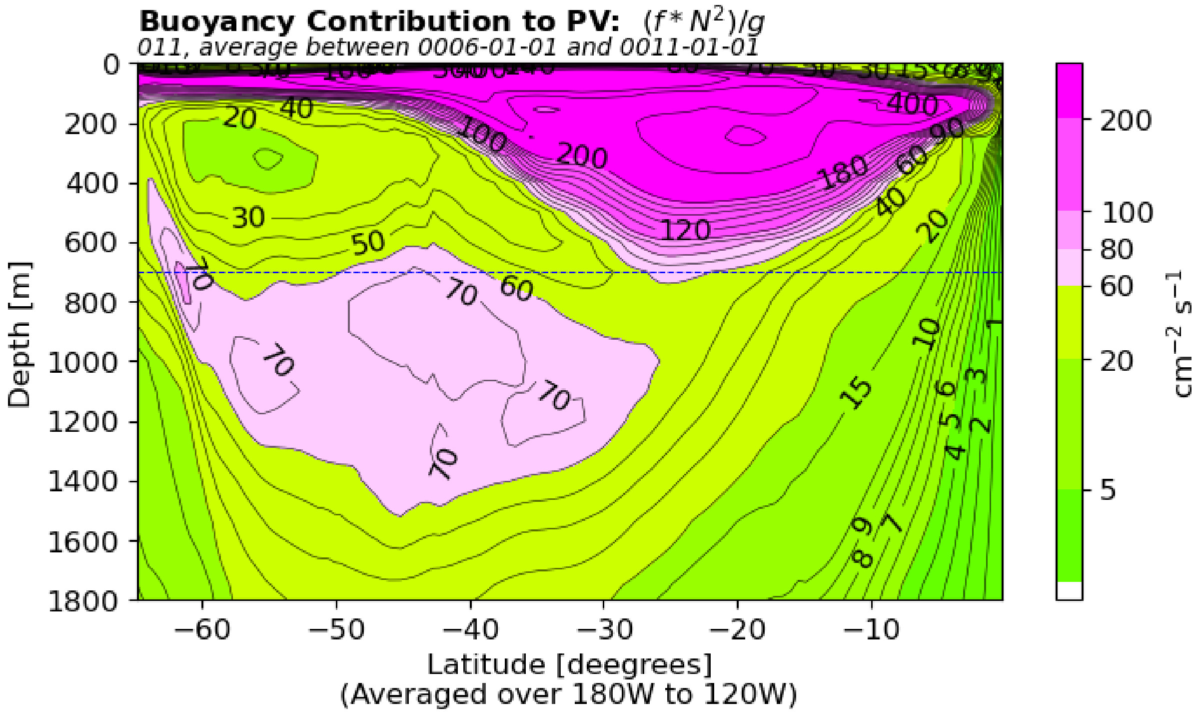
Fox-Kemper et. al. 2011

Timeseries from GFDL

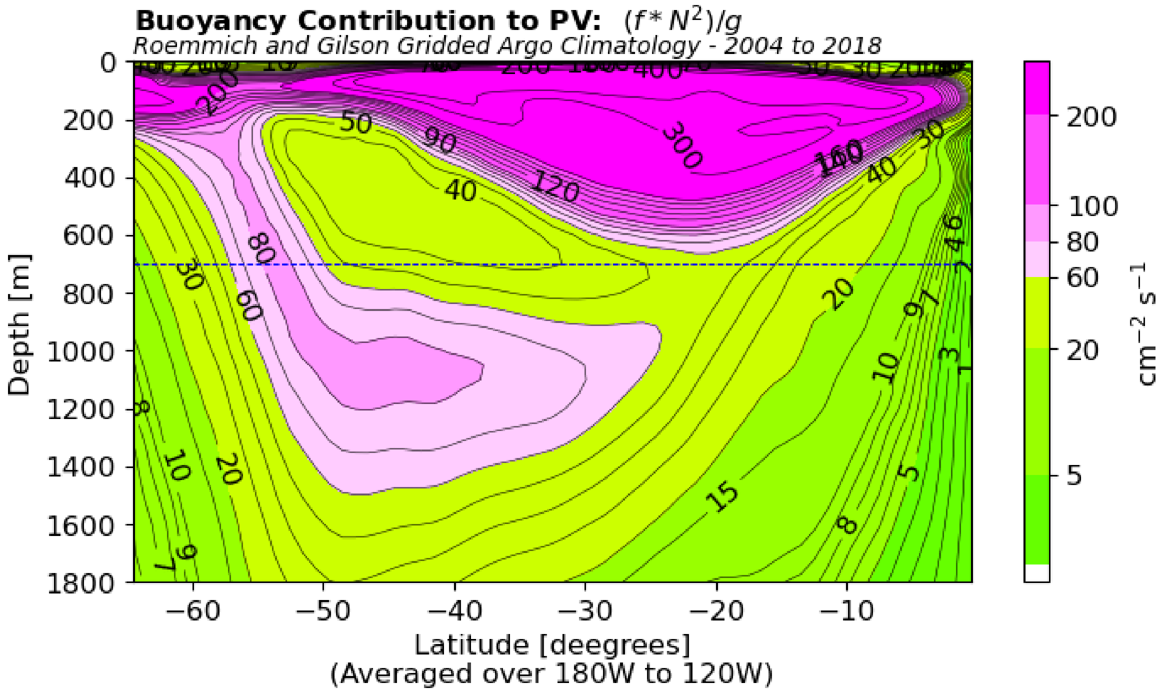




PV from CESM

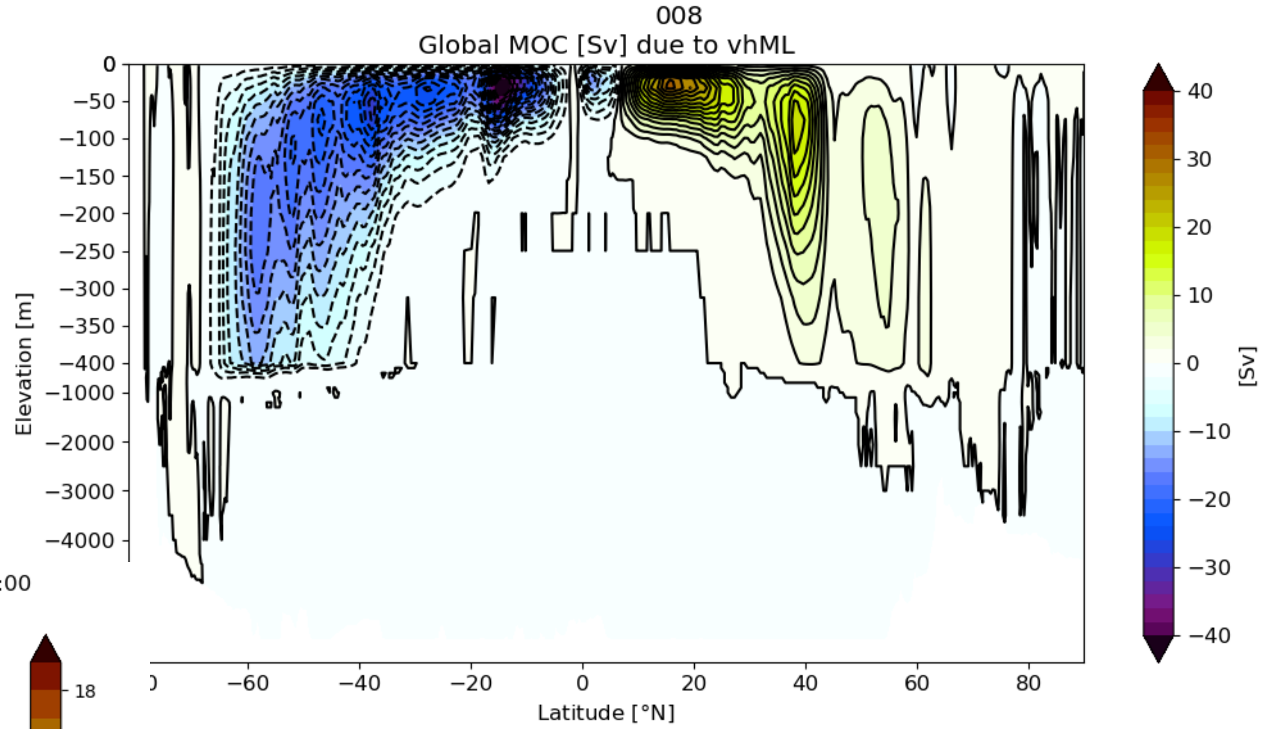


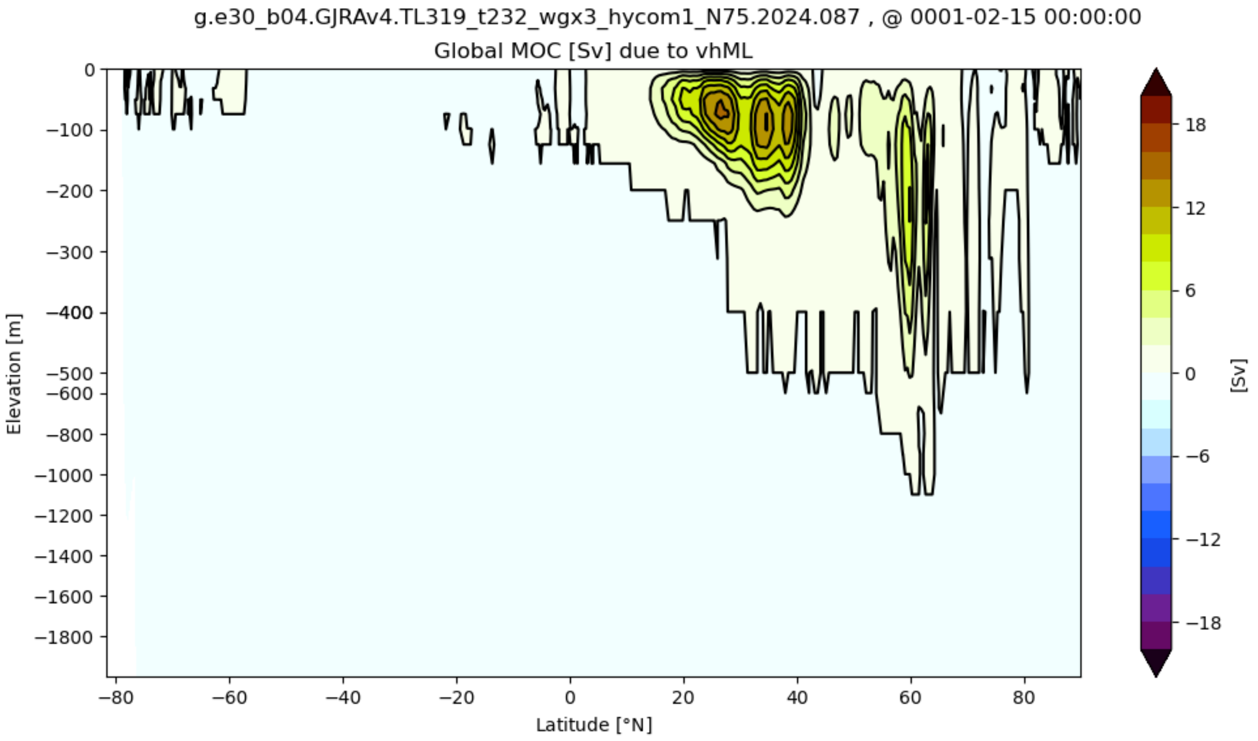
Buoyancy Contribution to PV: $(f * N^2)/g$
011, average between 0006-01-01 and 0011-01-01
Depth [m]
Latitude [deegrees]
(Averaged over 180W to 120W)
$cm^{-2}\ s^{-1}$



Buoyancy Contribution to PV: $(f * N^2)/g$
Roemmich and Gilson Gridded Argo Climatology - 2004 to 2018
Depth [m]
Latitude [deegrees]
(Averaged over 180W to 120W)
$cm^{-2}\ s^{-1}$

Tropics from CESM





Streamfunction from BLOM