Modifying the Mixed Layer Eddy Parameterization:

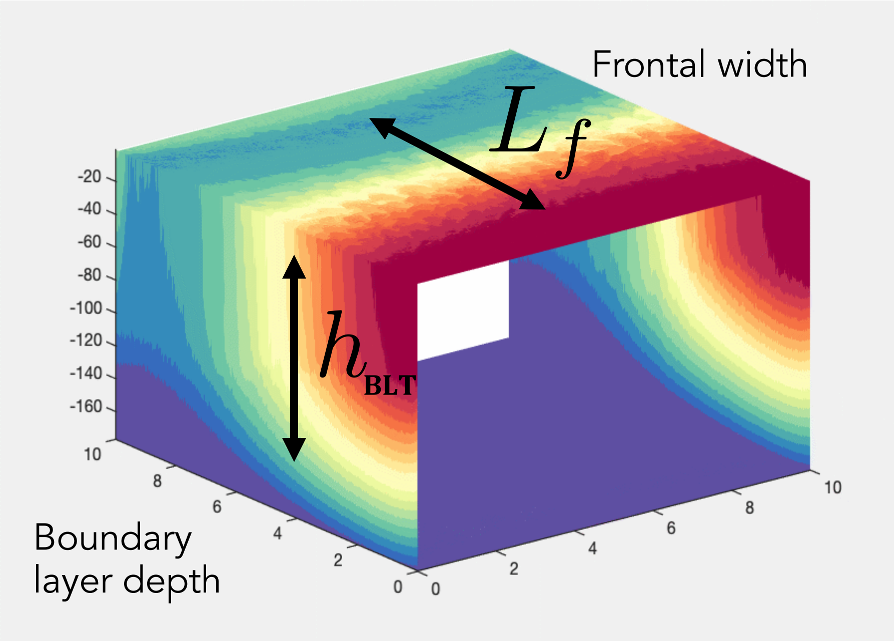
Frontogenesis Arrest by Boundary Layer Turbulence

Abigail Bodner

Baylor Fox-Kemper, Leah Johnson,
Luke Van Roekel, Jim McWilliams,
Peter Sullivan, Paul Hall & Jihai Dong

CESM Graduate Student Award

June 13, 2022



GULF OF MEXICO RESEARCH INITIATIVE

BROWN

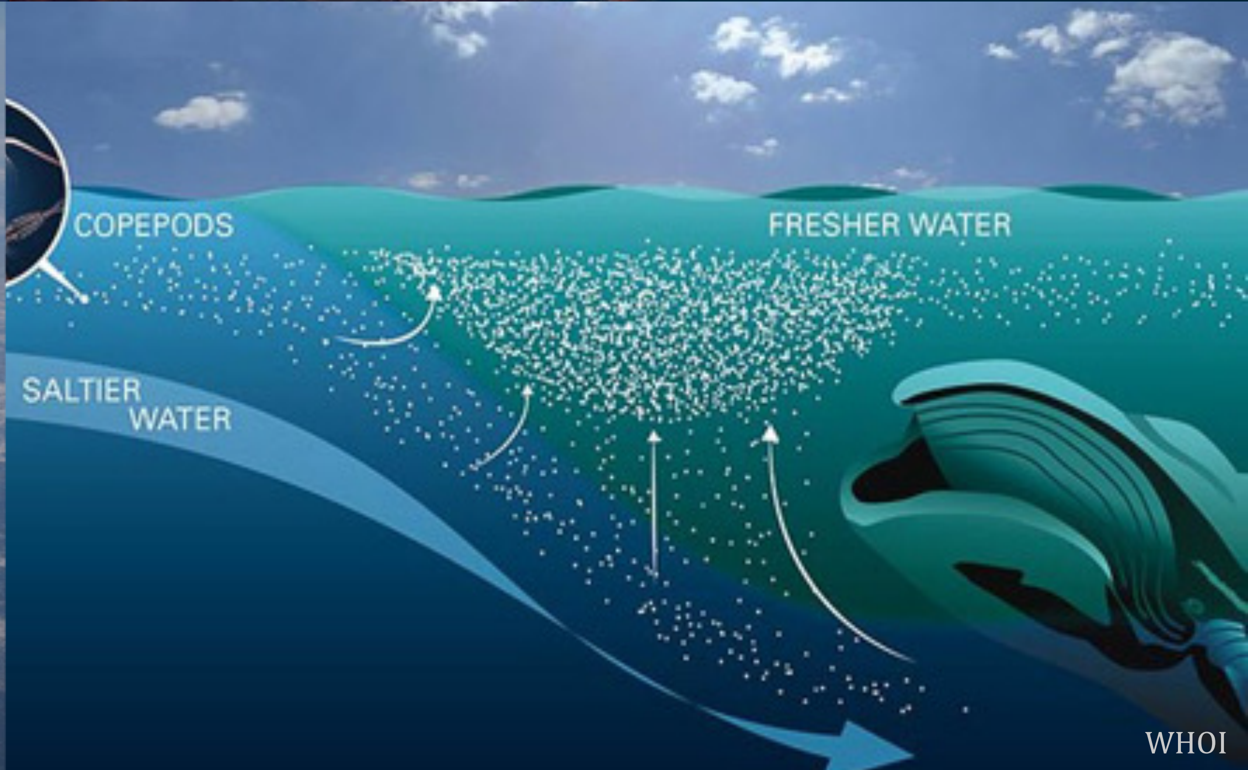
NYU

SIMONS FOUNDATION


dailymotion

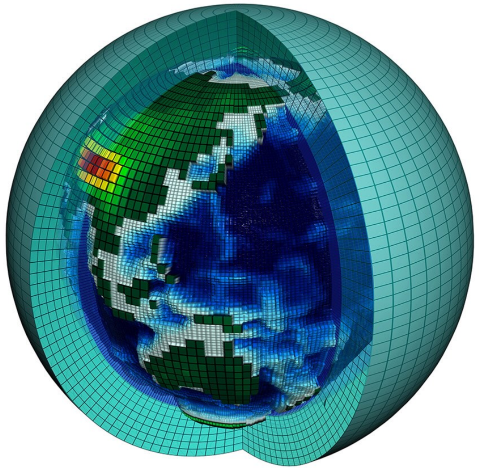

GREENPEACE

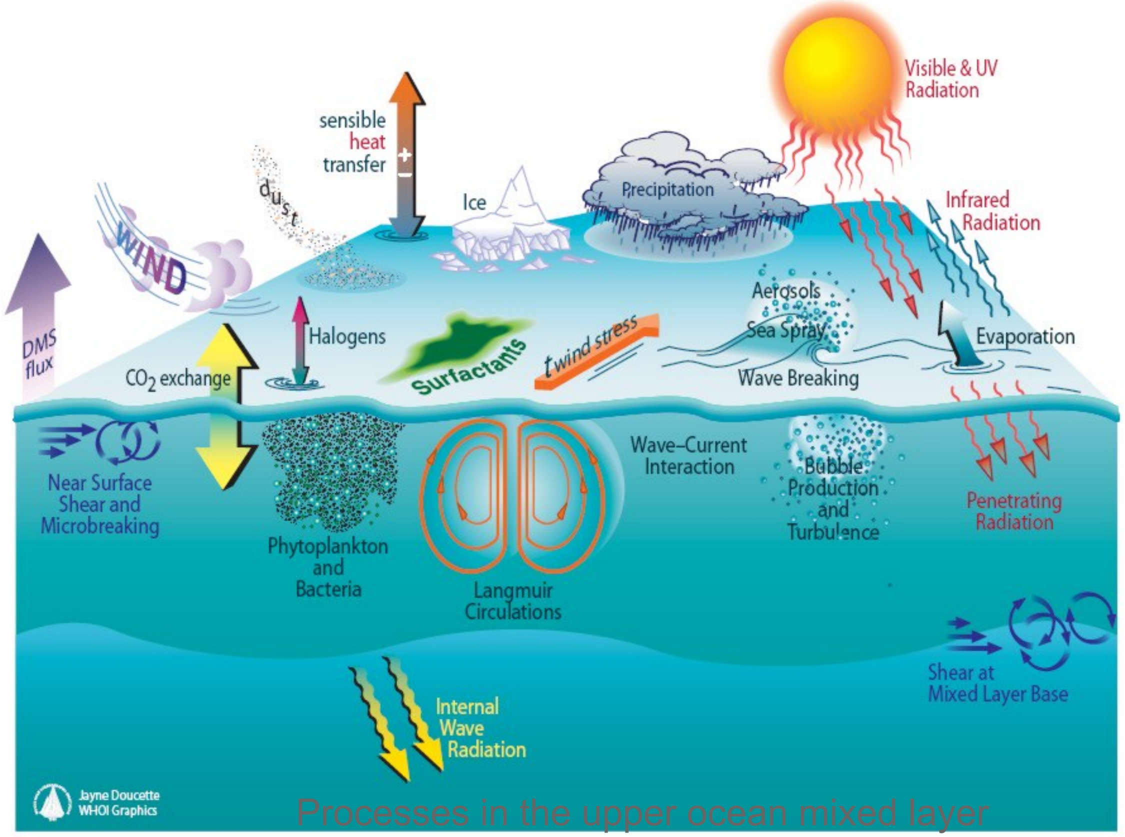

Image credit: D.
Schwen via C. Bitz


COPEPODS
FRESHER WATER
SALTIER
WATER
WHOI

Ocean Mixed Layer

- Mixing and turbulence controls atmosphere-ocean interactions
- Accurate representation is crucial for climate simulations
- Small, fast and complex processes
- Unresolved in General Circulation Models

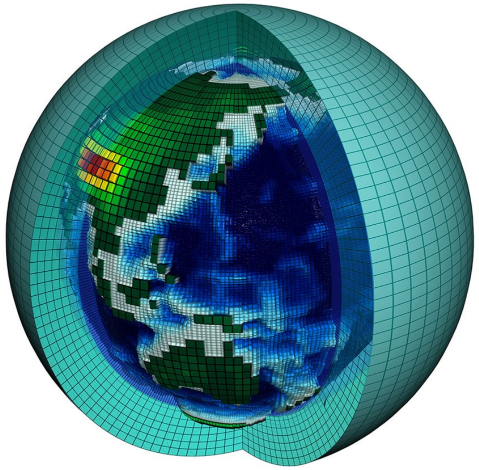


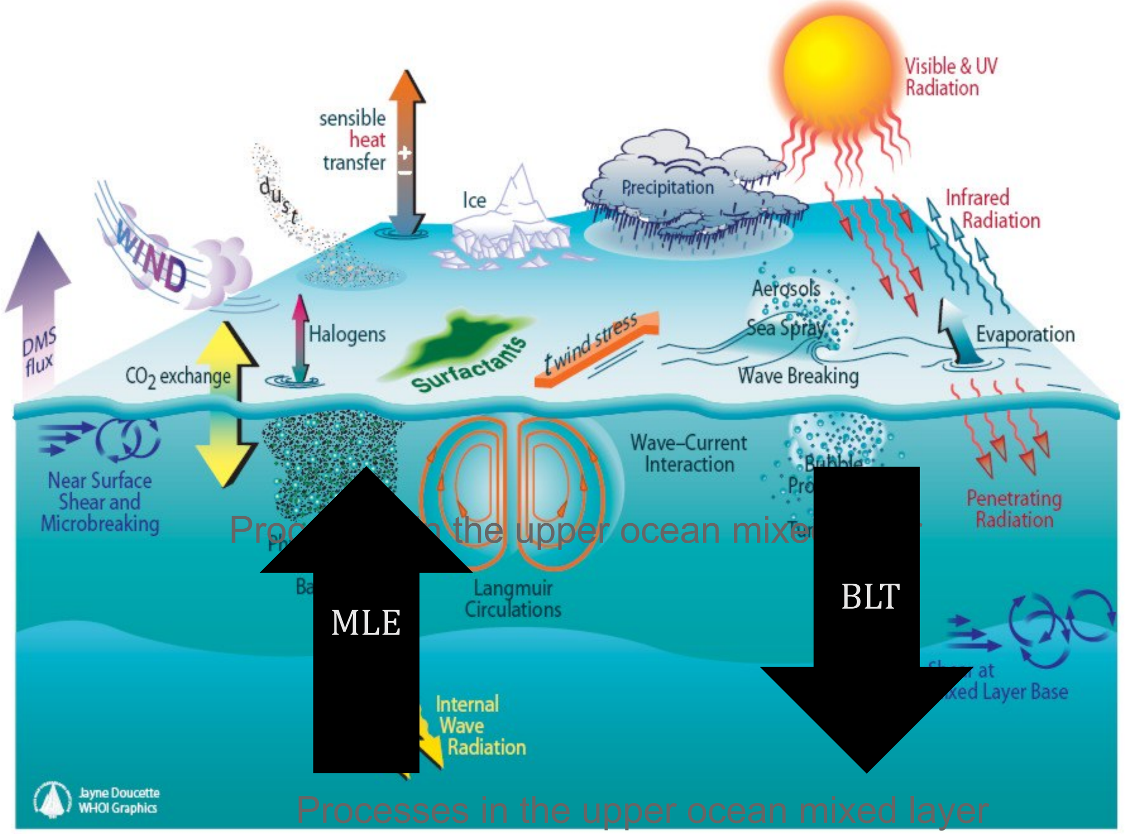


Processes in the upper ocean mixed layer

Ocean Mixed Layer parameterizations

- Vertical fluxes dominated by submesoscales and boundary layer turbulence
- Boundary layer turbulence mix and deepen the mixed layer
- Mixed layer (submesoscale) eddies restratify and shoal the mixed layer





The Mixed Layer Eddy (MLE) parameterization

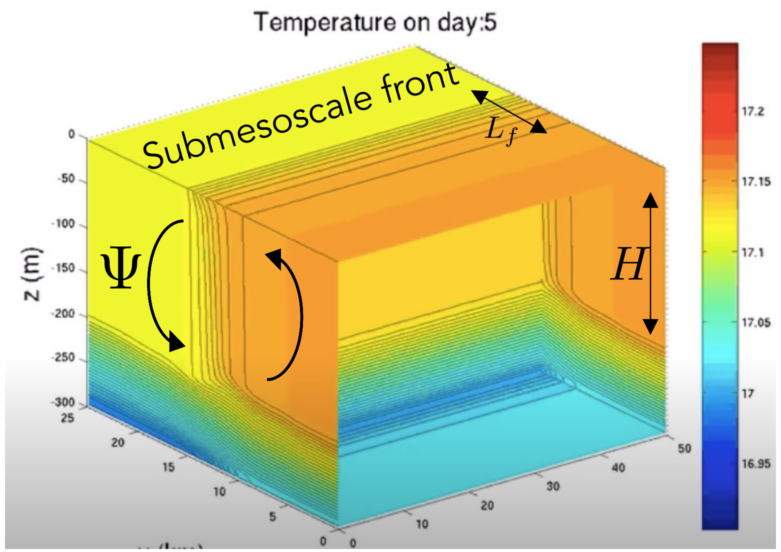
- Overturning streamfunction within the mixed layer, acting to slump isopycnals (submesoscale fronts)

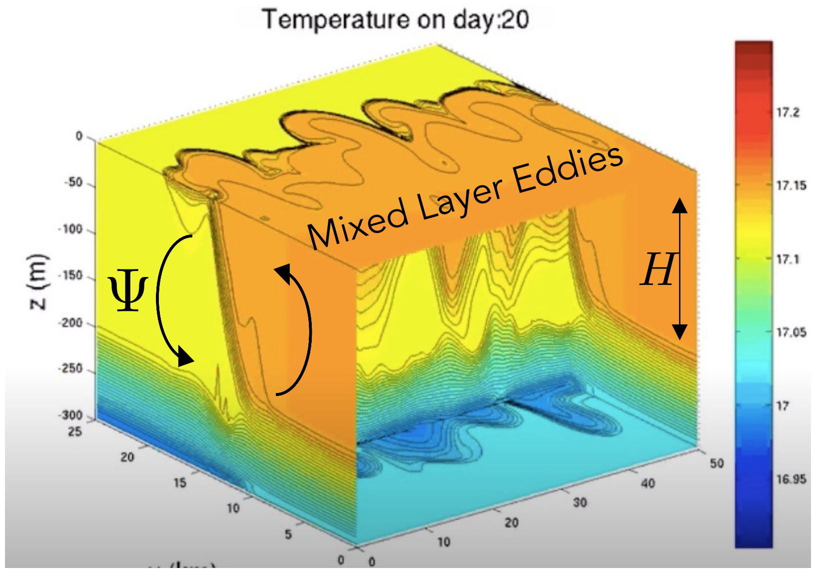
$$\Psi = C_e \frac{\Delta s}{L_f} \frac{H^2 \nabla \overline{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z)$$

- Strength depends on **frontal width** L_f

- Some models (e.g. POP) set as deformation radius In MOM set as constant 500m-2km. $L_f = \frac{NH}{f}$

- Determined by boundary layer turbulence ?





Fox-Kemper et. al. 2011

The Mixed Layer Eddy (MLE) parameterization

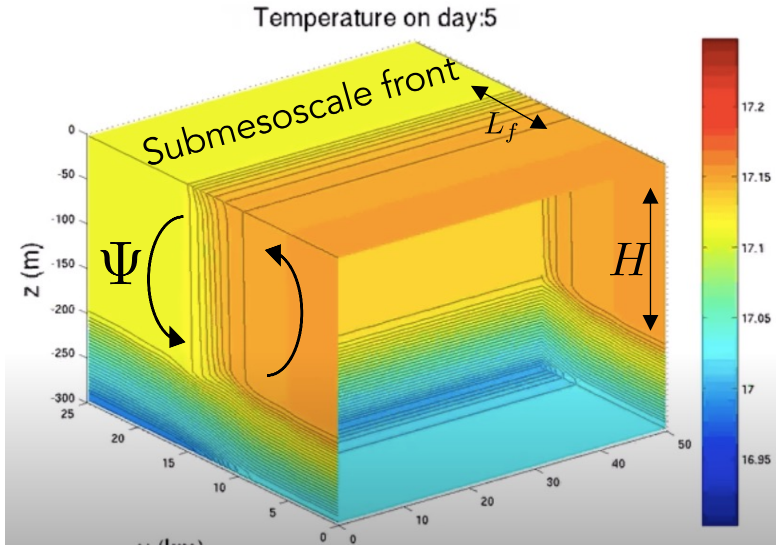
- Overturning streamfunction within the mixed layer, acting to slump isopycnals (submesoscale fronts)

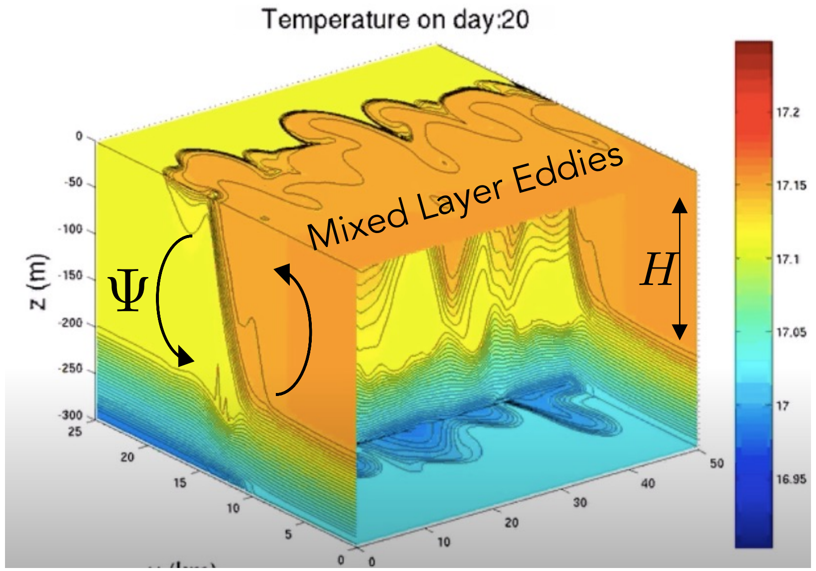
$$\Psi = C_e \frac{\Delta s}{L_f} \frac{H^2 \nabla \bar{b}^z \times \hat{\mathbf{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z)$$

- Strength depends on **frontal width** L_f

- Some models (e.g. POP) set as deformation radius
  In MOM set as constant 500m-2km. $L_f = \frac{NH}{f}$

- Determined by boundary layer turbulence ?

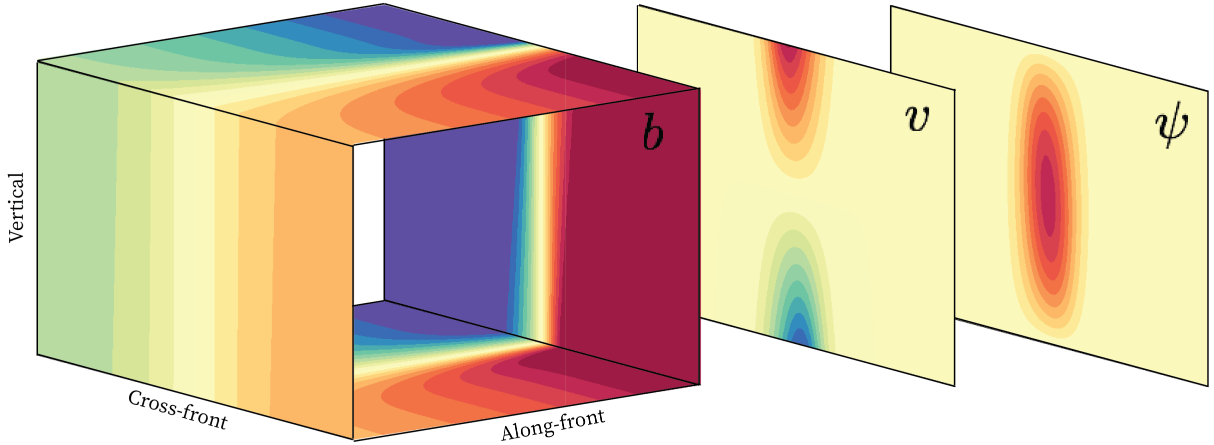


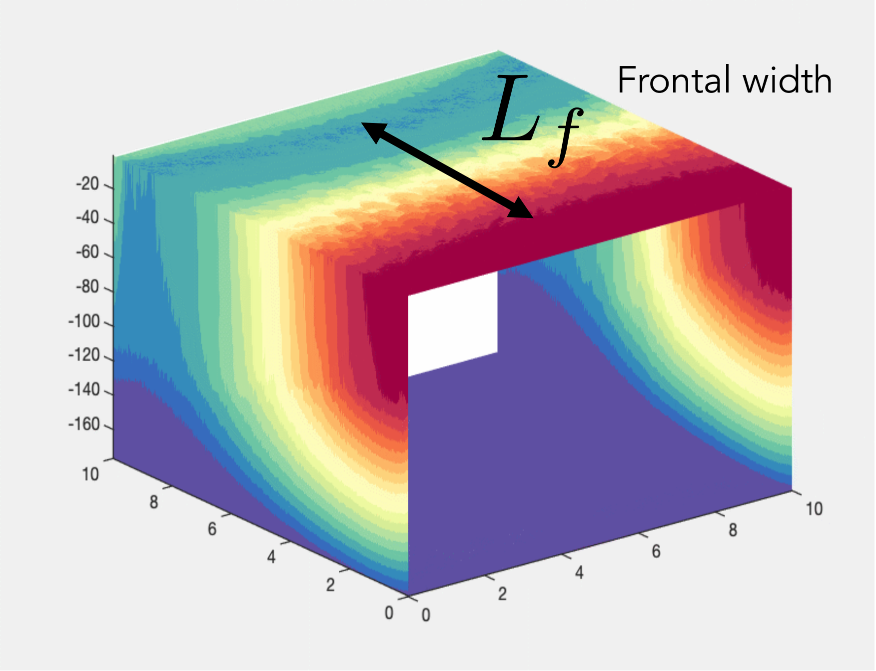


Fox-Kemper et. al. 2011

A new scaling for frontal width L_f

Frontogenesis by vertical turbulent fluxes
Frontal arrest by horizontal turbulent fluxes

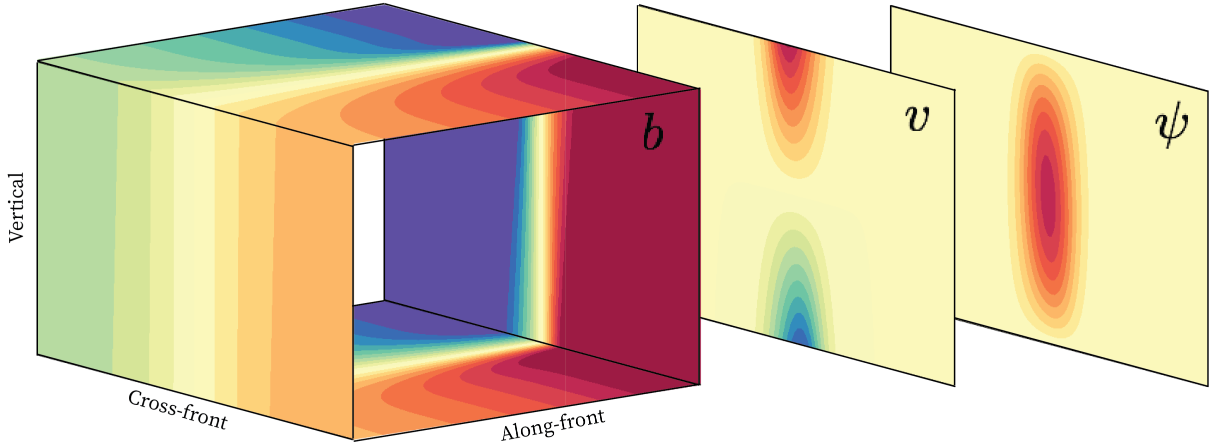




McWilliams (2015)
Sullivan, P.P. & McWilliams, J.C. (2018)
Bodner et. al. (2019)

A new scaling for frontal width L_f

Frontogenesis by vertical turbulent fluxes
Frontal arrest by horizontal turbulent fluxes



Turbulent thermal wind balance

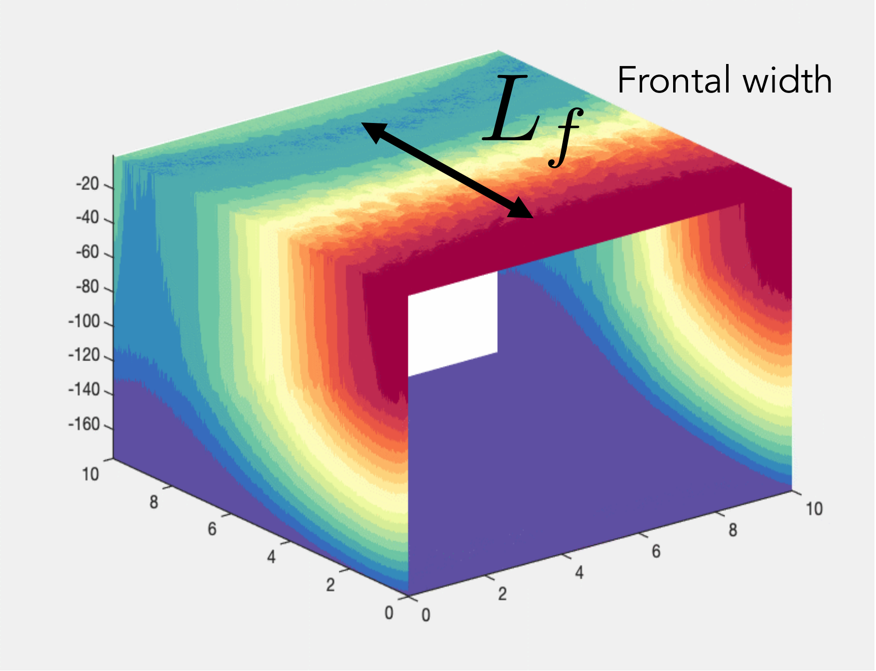
$$\nabla_H b = -f\hat{\mathbf{z}} \times \mathbf{s} + \frac{\partial^2(\nu \mathbf{s})}{\partial z^2}$$

Buoyancy gradient

Vertical shear

Vertical eddy viscosity

Vertical shear $\mathbf{s} = \frac{\partial \mathbf{u}}{\partial z}$



McWilliams (2015)
Sullivan, P.P. & McWilliams, J.C. (2018)
Bodner et. al. (2019)

A new scaling for frontal width L_f

Frontogenesis by vertical turbulent fluxes
Frontal arrest by horizontal turbulent fluxes

Turbulent friction velocity

$$u_* = \sqrt{\frac{|\tau|}{\rho_0}}$$

Turbulent convective velocity

$$w_* = (B_0 h)^{\frac{1}{3}}$$

$$L_f = C_f \cdot \frac{(m_* u_*^3 + n_* w_*^3)^{\frac{2}{3}}}{f^2} \cdot \frac{1}{h_{\mathrm{BLT}}}$$

$Ri_T \approx 0.25$
Horizontal shear instability

From boundary layer turbulence schemes (KPP, ePBL)

Turbulent thermal wind balance

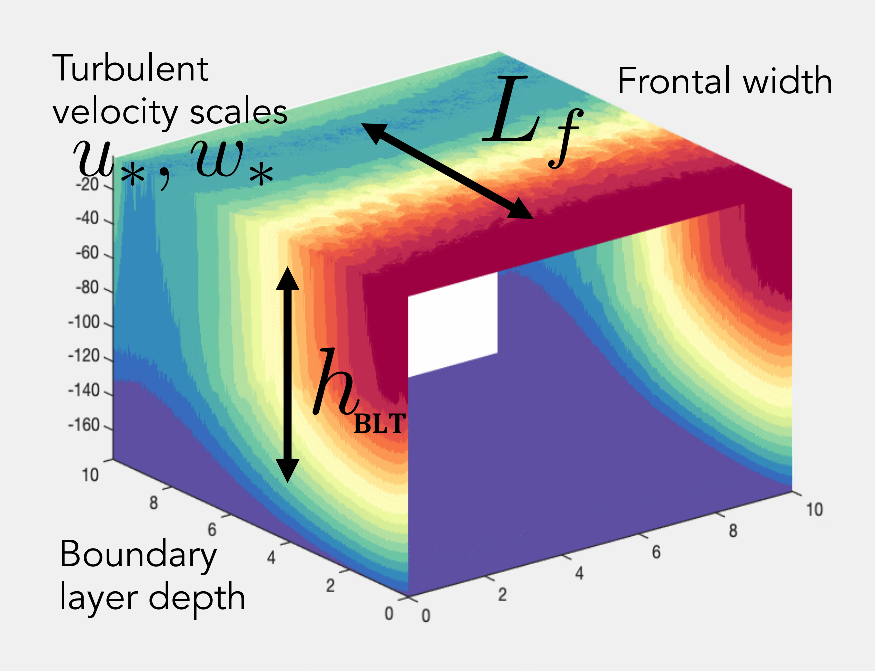
$$\nabla_H b = -f\hat{\mathbf{z}} \times \mathbf{s} + \frac{\partial^2(\nu \mathbf{s})}{\partial z^2}$$

Buoyancy gradient

Vertical shear

Vertical eddy viscosity

Vertical shear $\quad \mathbf{s} = \frac{\partial \mathbf{u}}{\partial z}$



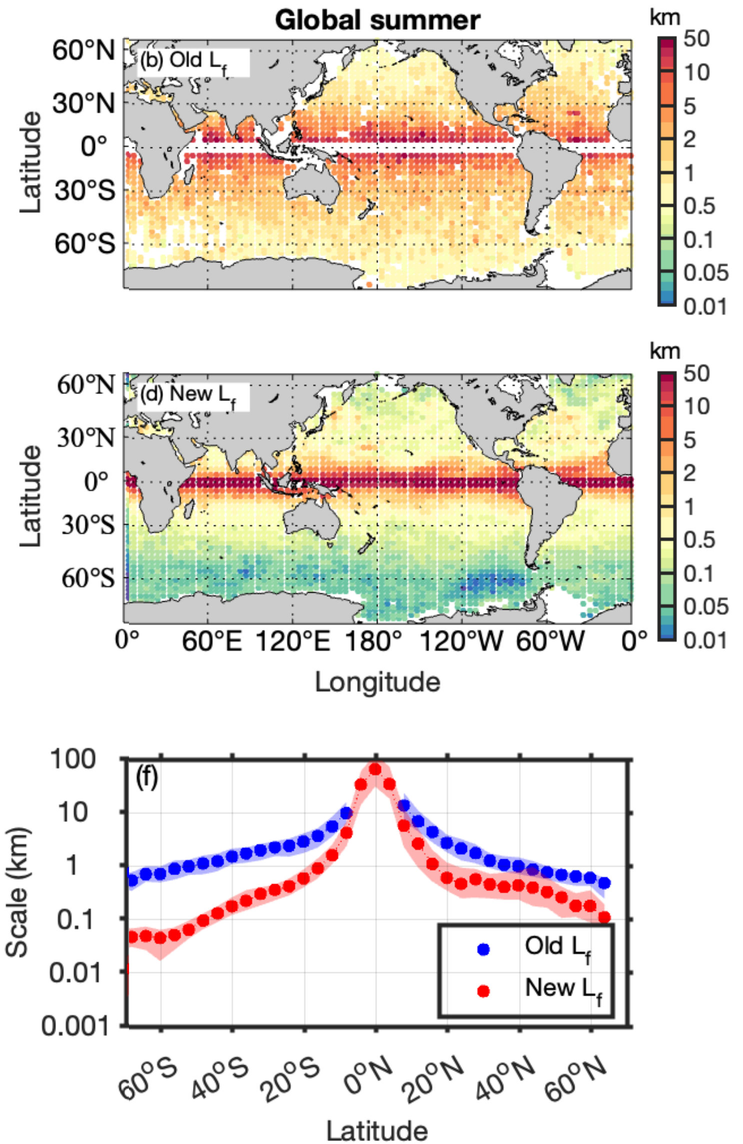
McWilliams (2015)
Sullivan, P.P. & McWilliams, J.C. (2018)
Bodner et. al. (2019)

Proofs of concept:

$$L_f = C_f \cdot \frac{(m_* u_*^3 + n_* w_*^3)^{\frac{2}{3}}}{f^2} \cdot \frac{1}{h_{\mathrm{BLT}}}$$

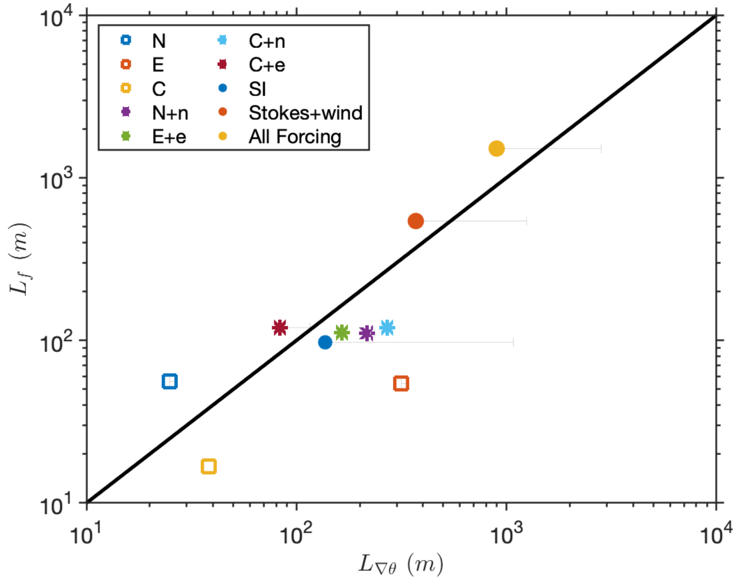
(c) Evaluations on a global scale

MITgcm-LLC4320 +GOTM



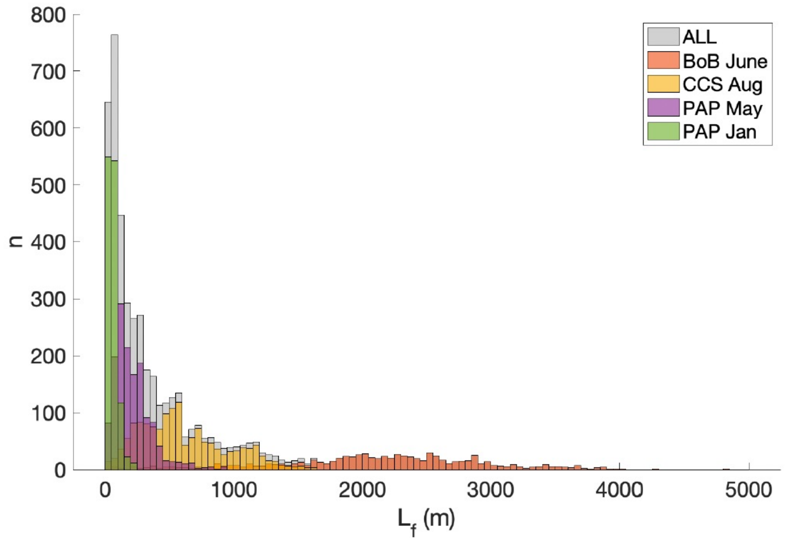
Much sharper fronts

(a) Testing in Large Eddy Simulations



predicted vs measured L_f

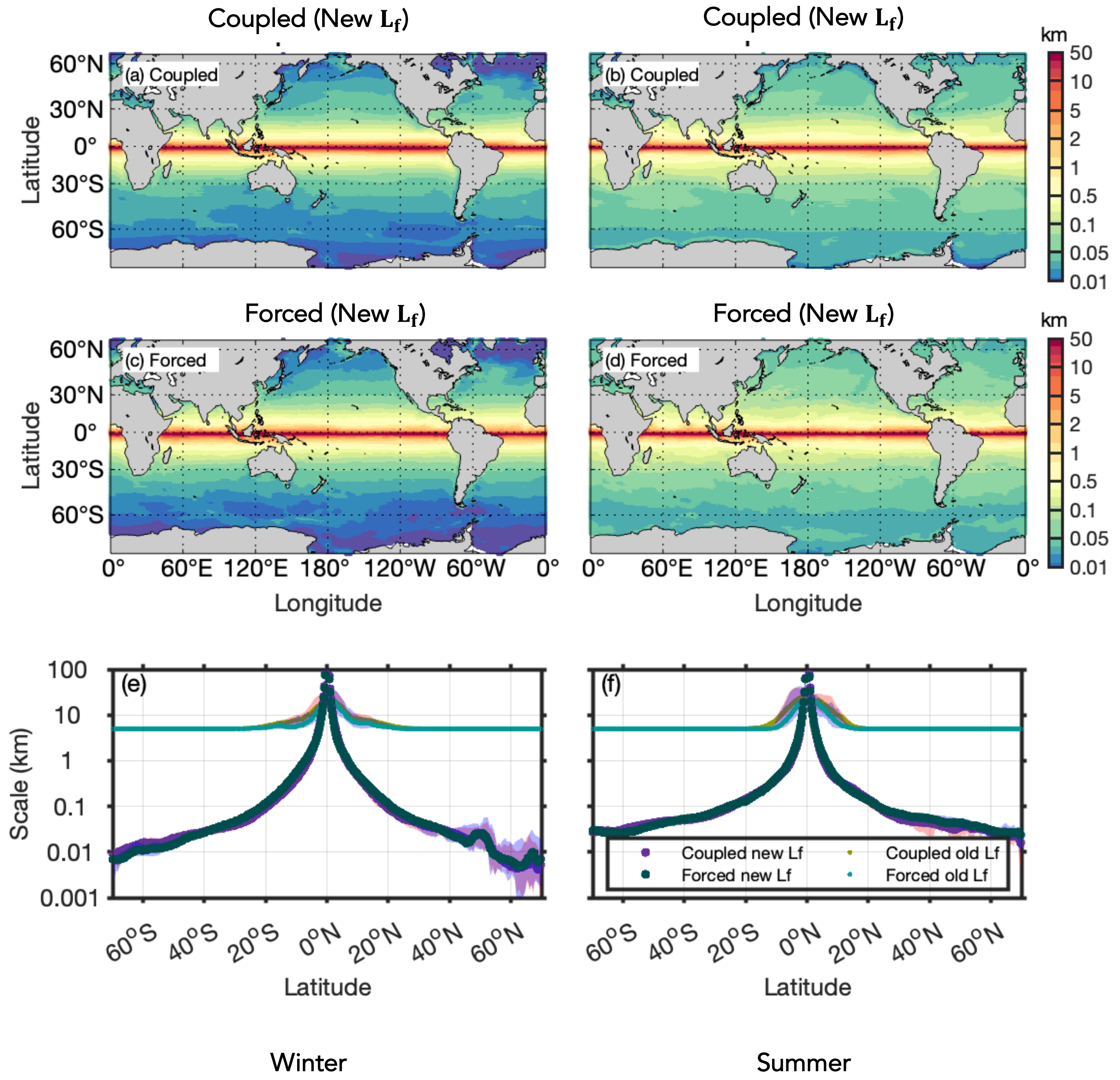
(b) Estimates from the General Ocean Turbulence Model



realistic distribution of L_f ~O(1km)

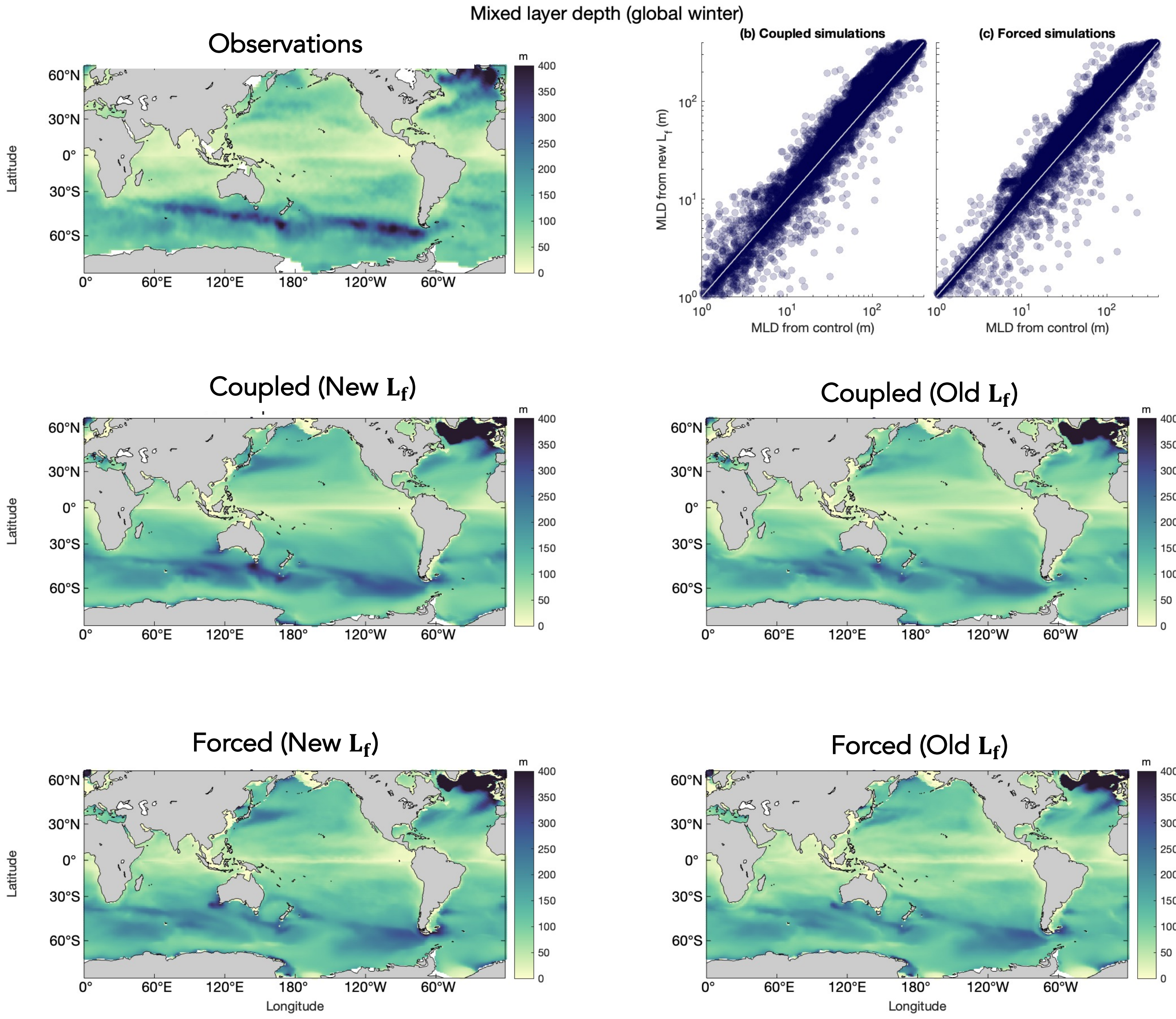
Implementing in CESM-POP: frontal width

- CESM2-POP implementation, with standard KPP for u*,w*,h.
- Coupled and forced simulations comparing new and old Lf as control.
- The standard Lf_min=5km is applied in the control simulations.



Implementing in CESM-POP: mixed layer depth

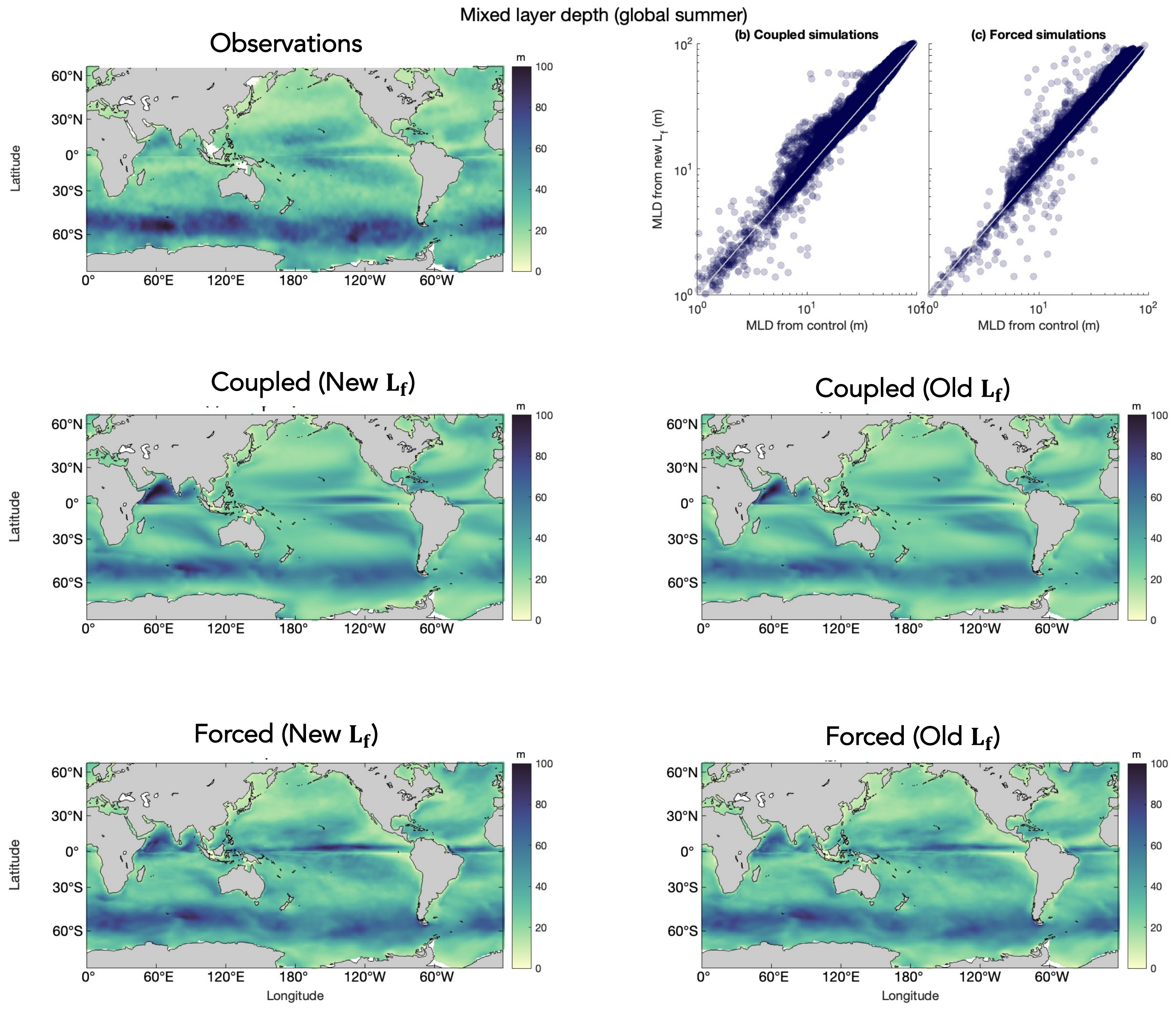
- Climate sensitivity estimated through impact on mixed layer depth
- Coupled and forced simulations are qualitatively similar to observations



CESM: Winter

Implementing in CESM-POP: mixed layer depth

- Climate sensitivity estimated through impact on mixed layer depth
- Coupled and forced simulations are qualitatively similar to observations



CESM: Summer

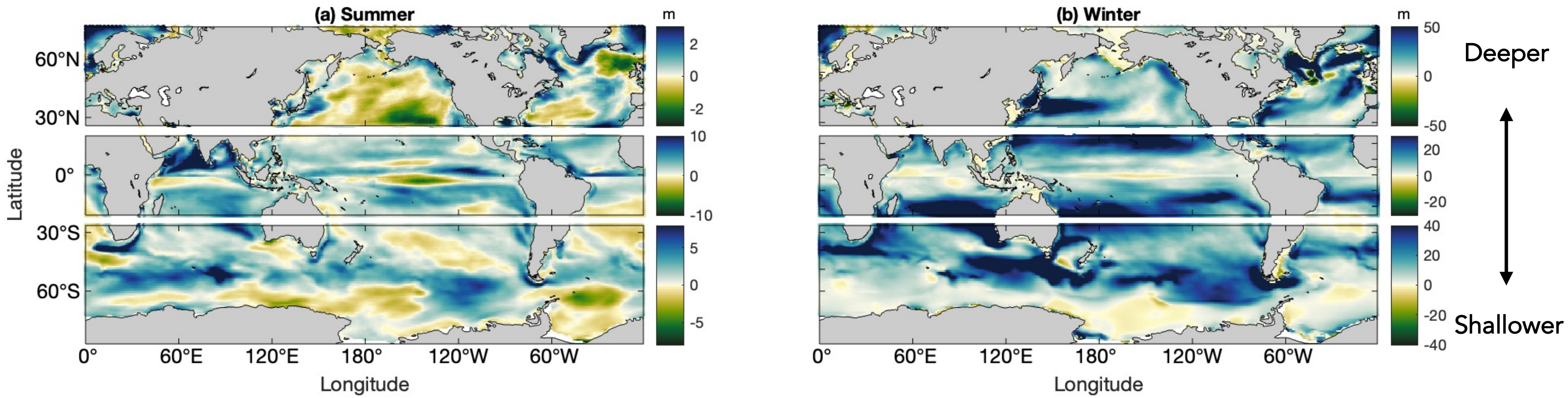
Implementing in CESM-POP: mixed layer depth

- Some climatologically important regions are modified by this scale factor

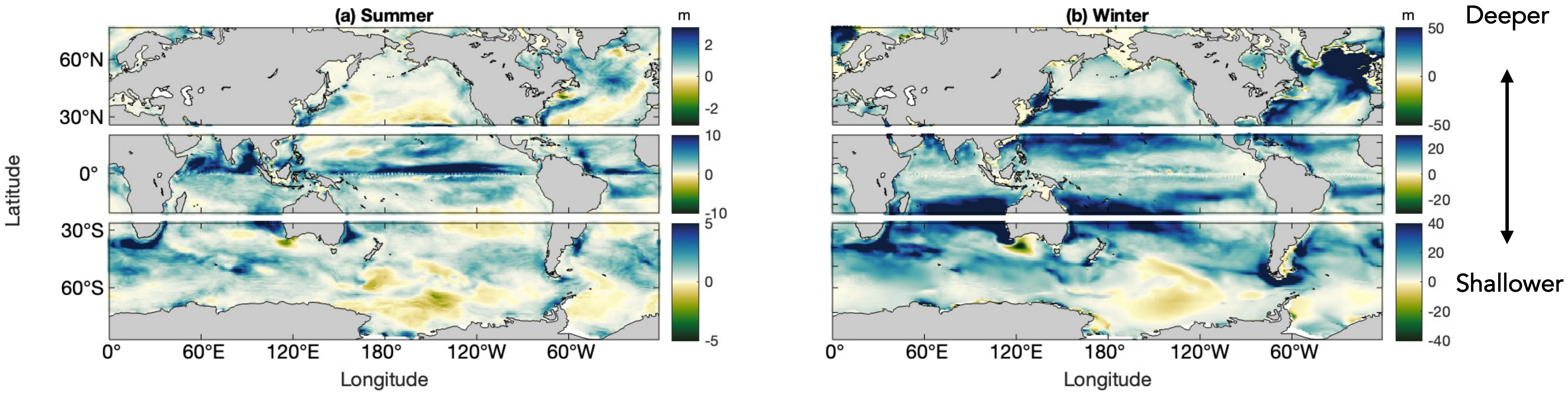
- e.g. Equatorial Pacific, Southern Ocean, Arctic

Differences: New – Old

Mixed Layer Depth Difference: New Lf minus Control (coupled simulation)



Mixed Layer Depth Difference: New Lf minus Control (forced simulation)



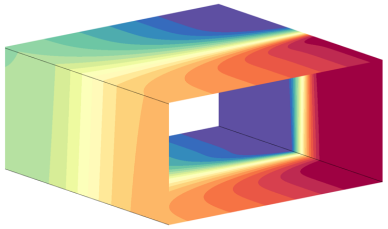
Summary and future work

- A new scaling law is developed for arrested frontal width as a function of turbulent fluxes.

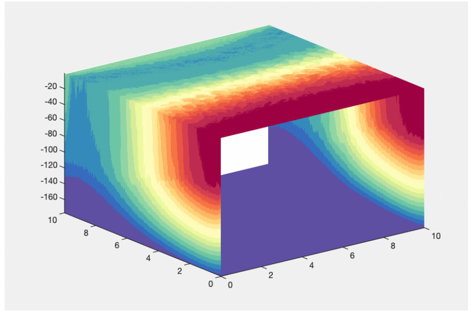
- Scaling is found to be consistent in:
    - LES with varying forcing parameters.
    - GOTM calculated boundary layer parameters drawn from observations
    - MITgcm-LLC4320 used in tandem with GOTM for global estimates

- Results from implementing the new parameterization in CESM-POP reveal changes in MLD biases

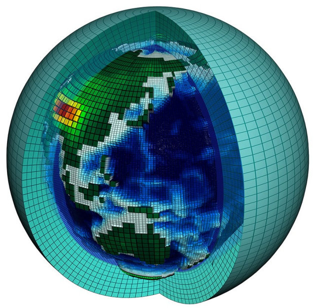
- A more comprehensive study is ongoing to compare with observations and understand full impact on climate simulations.



Theory



Simulations



Climate models