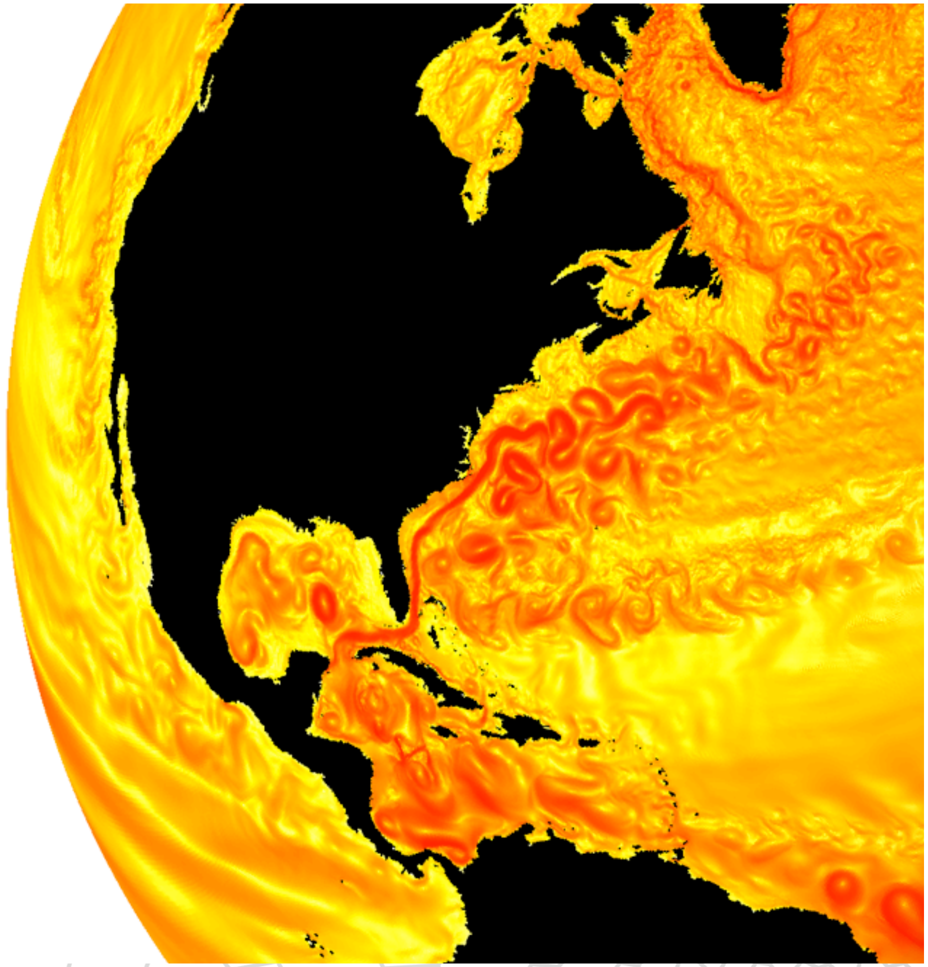
The MPAS-Ocean
Vertical Coordinate



Mark Petersen

and the MPAS-Ocean development team

Los Alamos National Laboratory

MPAS
Model for Prediction Across Scales

The MPAS-Ocean Vertical Coordinate

- **Z-Level:** Fixed coordinate. *POP, MOM, MIT-GCM, NEMO*
- **Z-star:** Layers expand with SSH. *MOM, recently POP, others*
- **sigma:** terrain-following. *ROMS, NEMO*
- **isopycnal**: *MyCOM, GOLD*
- **hybrid isopycnal:** *HyCOM*
- **partial bottom cells** (in addition to others)
- **z-tilde:** frequency-filtered coordinate (in addition to others)

What is the best vertical coordinate for MPAS-Ocean?

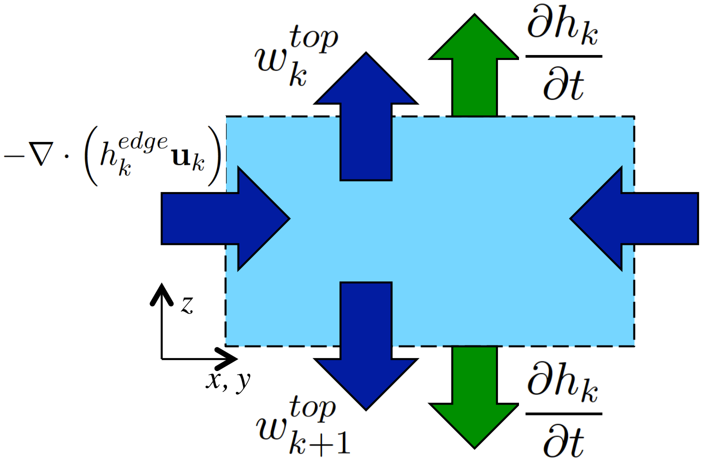
The MPAS-Ocean Vertical Coordinate

- ☑ **Z-Level**
- ☑ **Z-star**
- ☑ **sigma:** only tested in idealized cases so far
- ☑ **isopycnal:** idealized only, no zero thickness layers
- ☐ **hybrid isopycnal:** under development
- ☑ **partial bottom cells**
- ☑ **z-tilde:** frequency-filtered coordinate

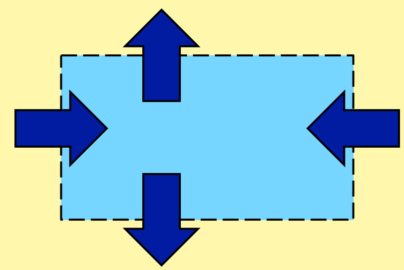
Arbitrary Lagrangian-Eulerian (ALE) Vertical Coordinate

Thickness equation: $$\frac{\partial h_k}{\partial t} = -\nabla \cdot \left(h_k^{edge} \mathbf{u}_k \right) + w_{k+1}^{top} - w_k^{top}$$

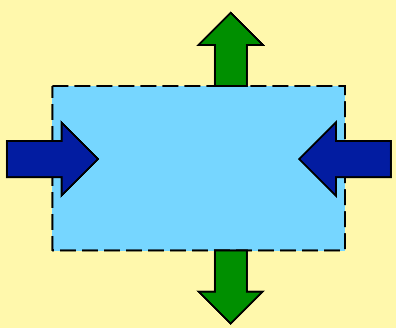
w^{top} is transport *through* interface



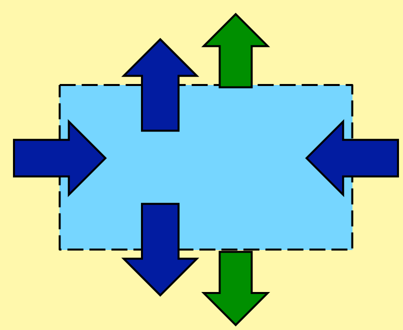
z-level $\frac{\partial h_k}{\partial t} = 0$, except layer 1



isopycnal (for adiabatic, idealized studies) w=0



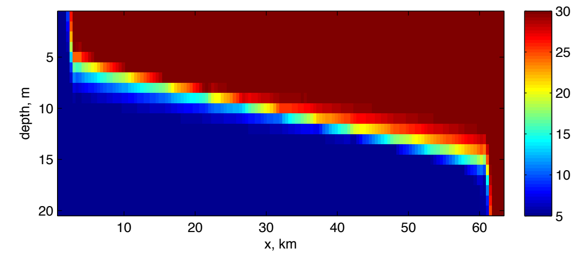
z-star Layer thickness changes in proportion to SSH



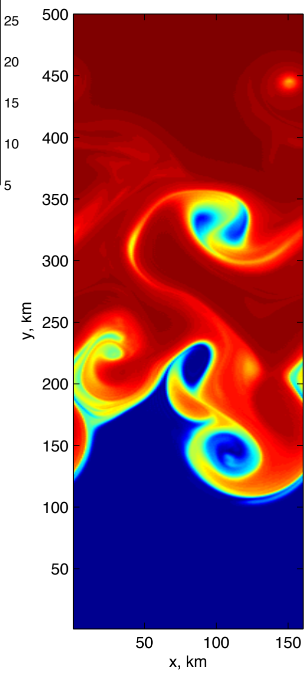
$$\frac{\partial h_k}{\partial t} = \frac{c_k}{\sum_k c_k} \frac{\partial \eta}{\partial t}$$

Test Problems (Ilicak et al. 2012)

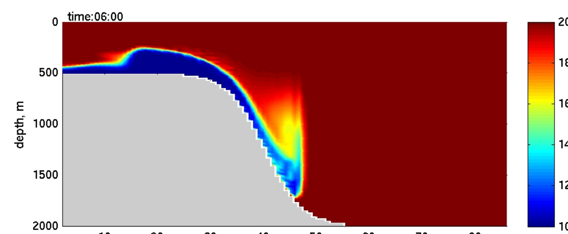
- Lock exchange



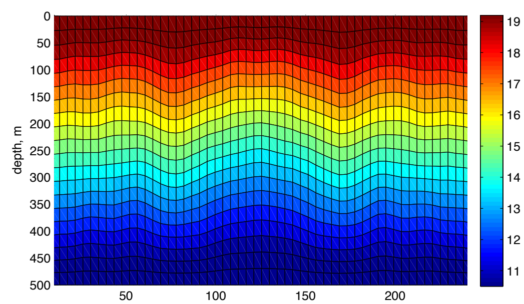
- Baroclinic eddies



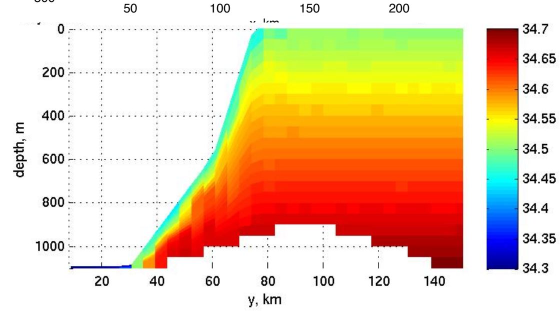
- Overflow



- Internal gravity wave

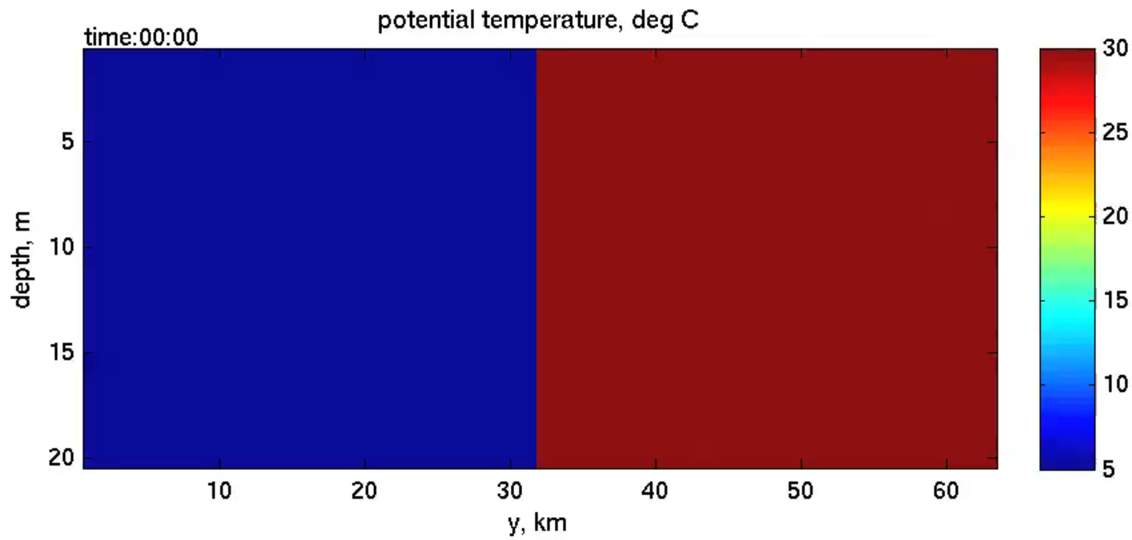


- Sub Ice-Shelf

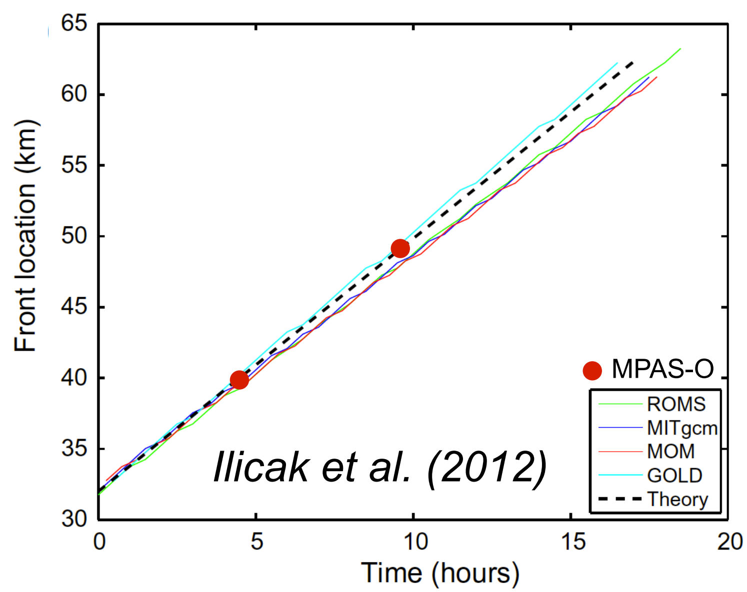


Lock Exchange Test Case

- Zero tracer diffusion
- Vary horizontal viscosity
- Linear equation of state
- Simplest test of mixing

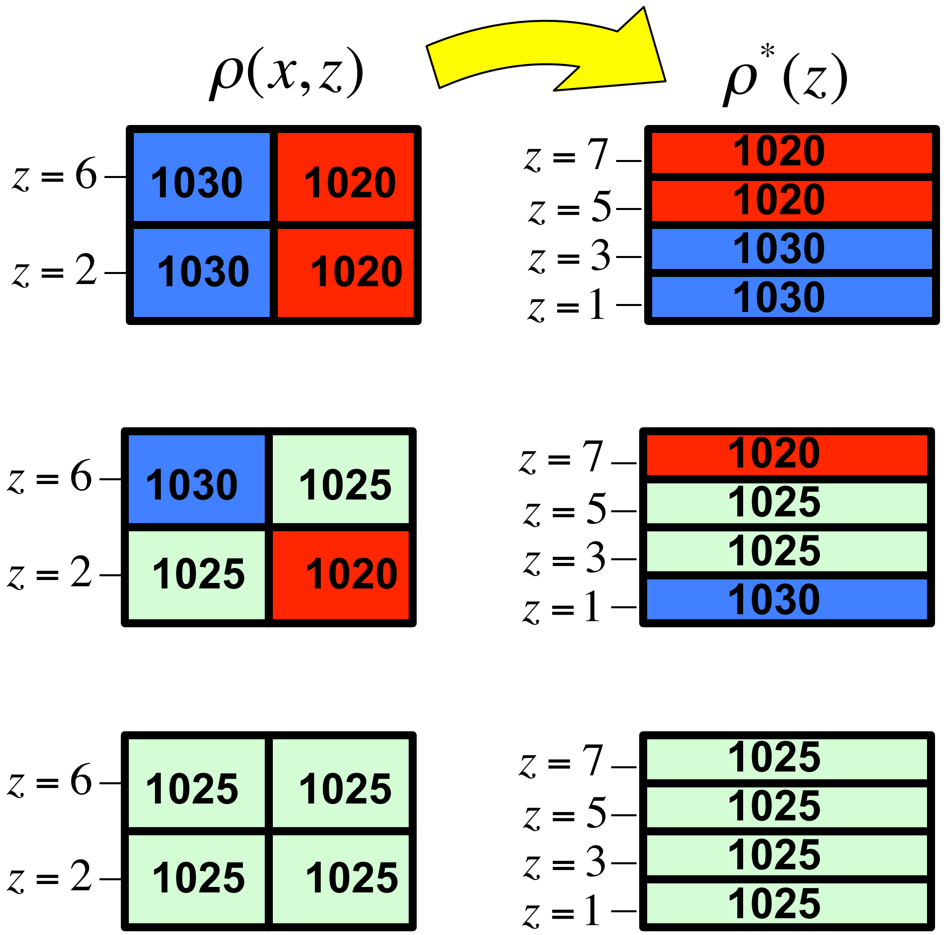


- Ilicak et al. (2012) compares ROMS, MITgcm, MOM, GOLD
- Theoretical wave propagation speed is $$u_f = 1/2\sqrt{gH\left(\delta\rho/\rho_0\right)}$$



Resting Potential Energy (RPE): a measure of mixing

- Definition (Ilicak et al. 2012): $RPE = g\iiint \rho^{*} z\, dV$
- ρ^{*} is the sorted density state, with heaviest on the bottom.



$$RPE = g\sum_i \rho_i^{*} z_i V_i$$

Example 1: No mixing

$$RPE = 16360\, g V_{cell}$$

Example 2: some mixing

$$RPE = 16370\, g V_{cell}$$

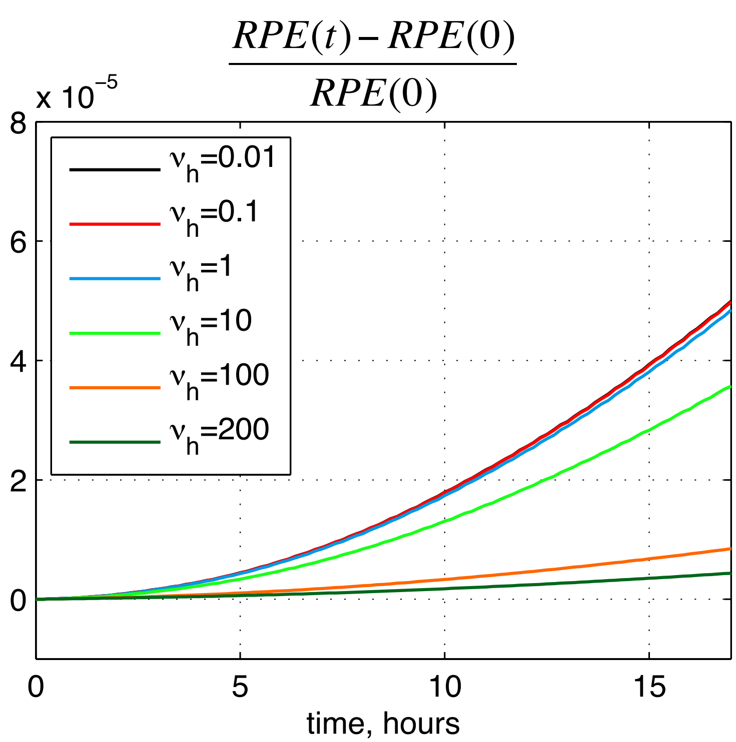
Example 3: fully mixed

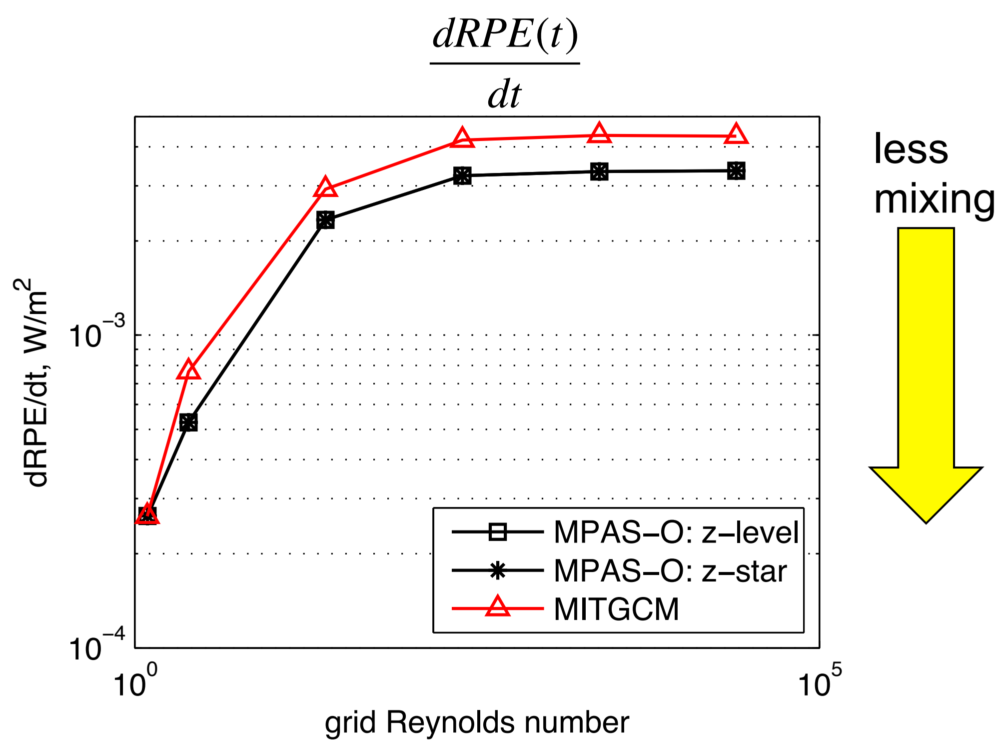
$$RPE = 16400\, g V_{cell}$$

Resting Potential Energy (RPE): Lock Exchange

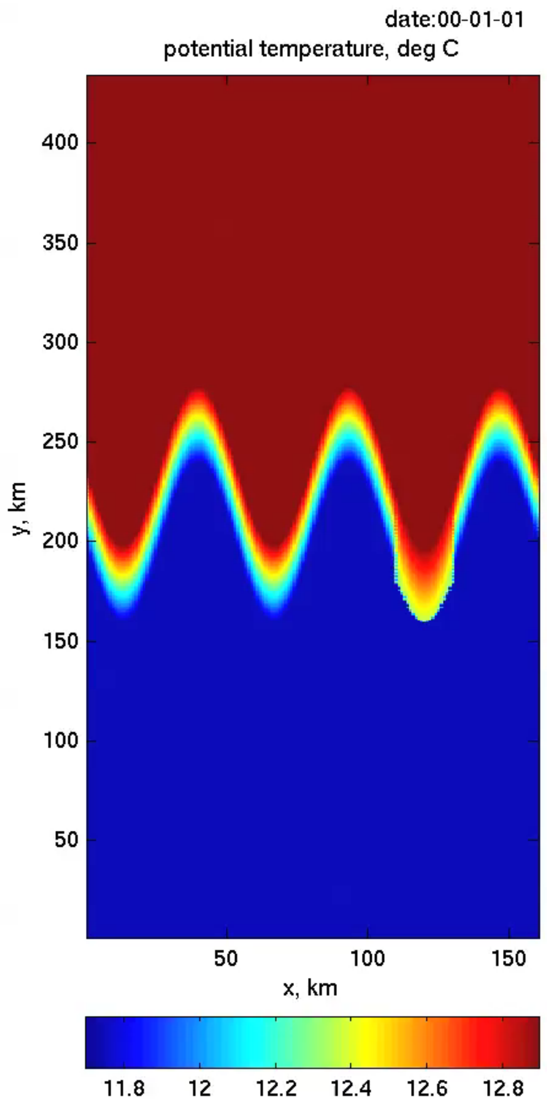
- RPE increases with time as fluid is mixed
- RPE depends on horizontal viscosity as follows:

high horizontal viscosity low Reyolds number low RPE, less mixing	⟷	low horizontal viscosity high Reyolds number high RPE, more mixing



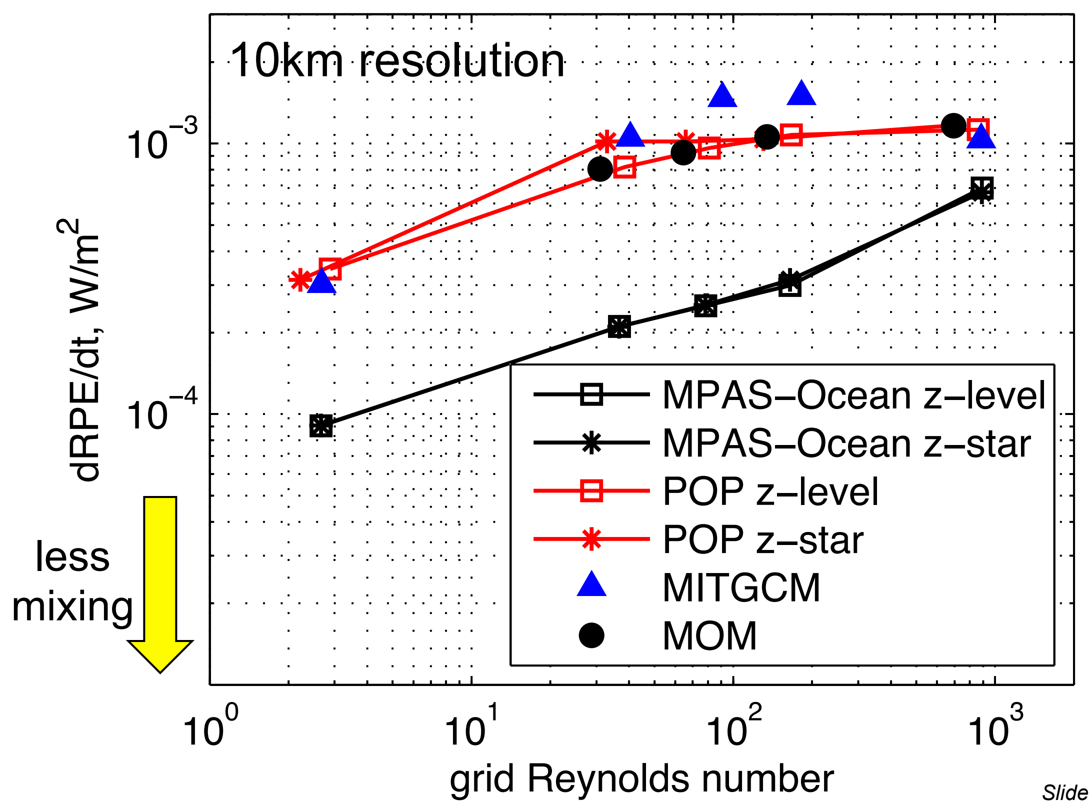


Baroclinic Eddies Test Case



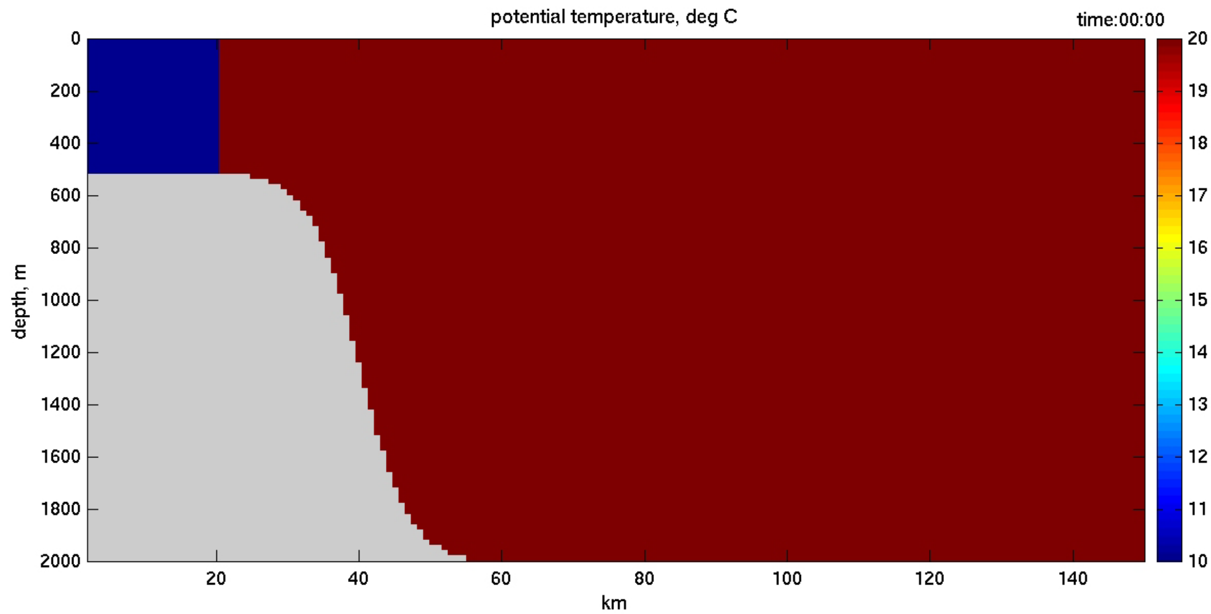
- Idealized ACC: periodic channel, f-plane
- Compare to POP z-level and POP z-star

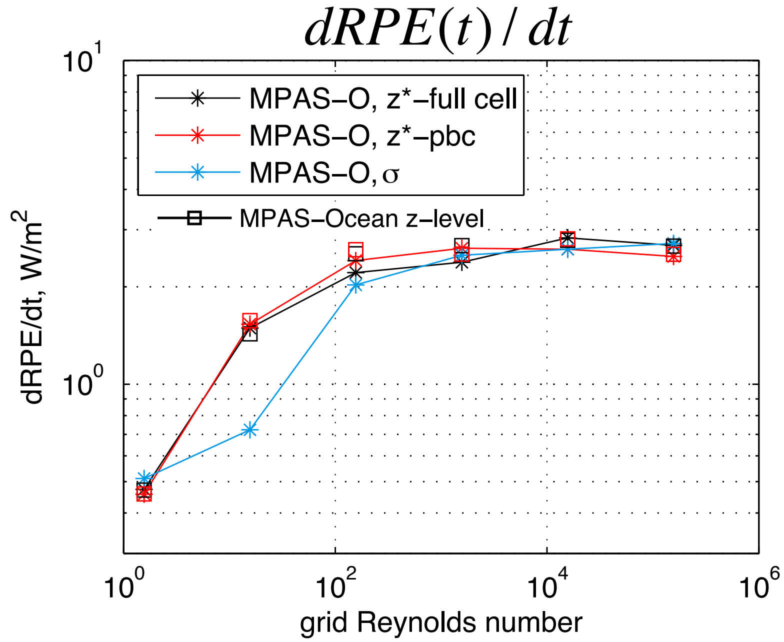
$$\frac{dRPE(t)}{dt}$$



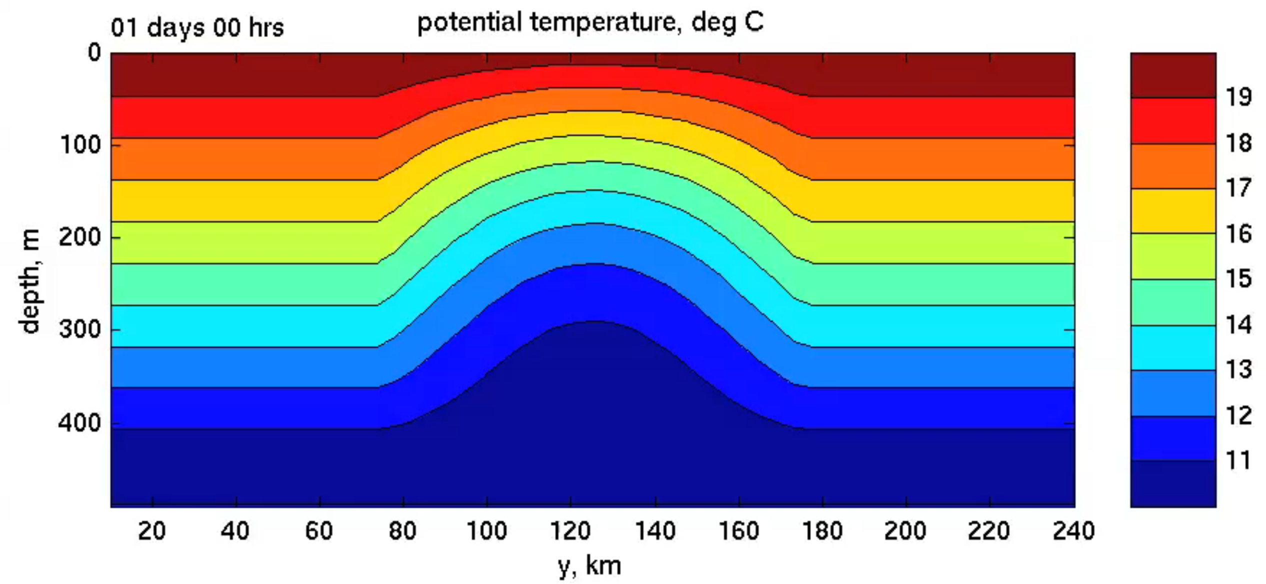
Overflow Test Case

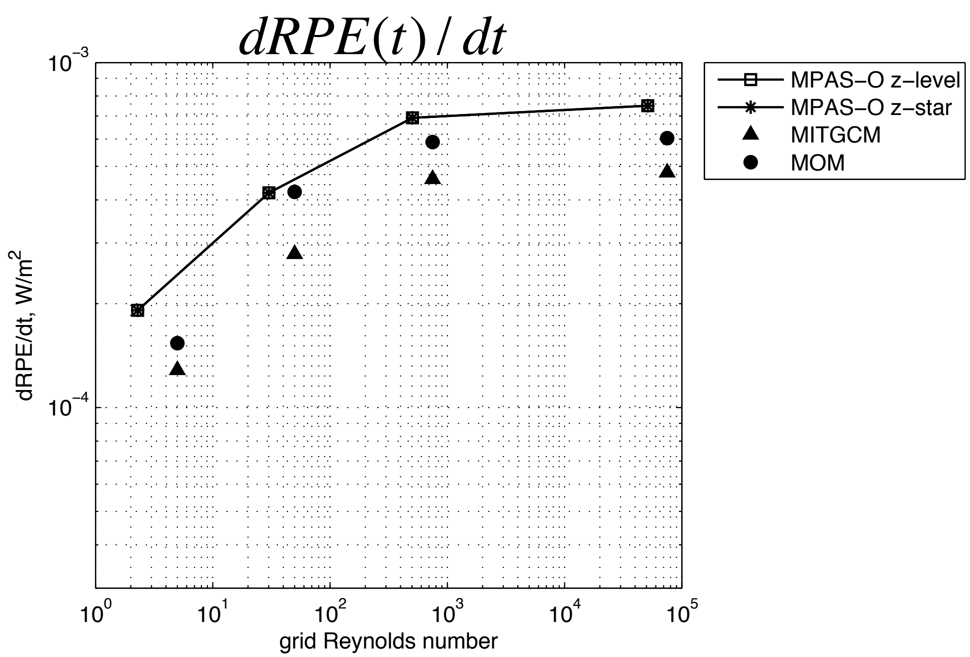
- Zero tracer diffusion
- vary hor. viscosity
- Test z-level, z-star, partial bottom cells, and sigma coordinate





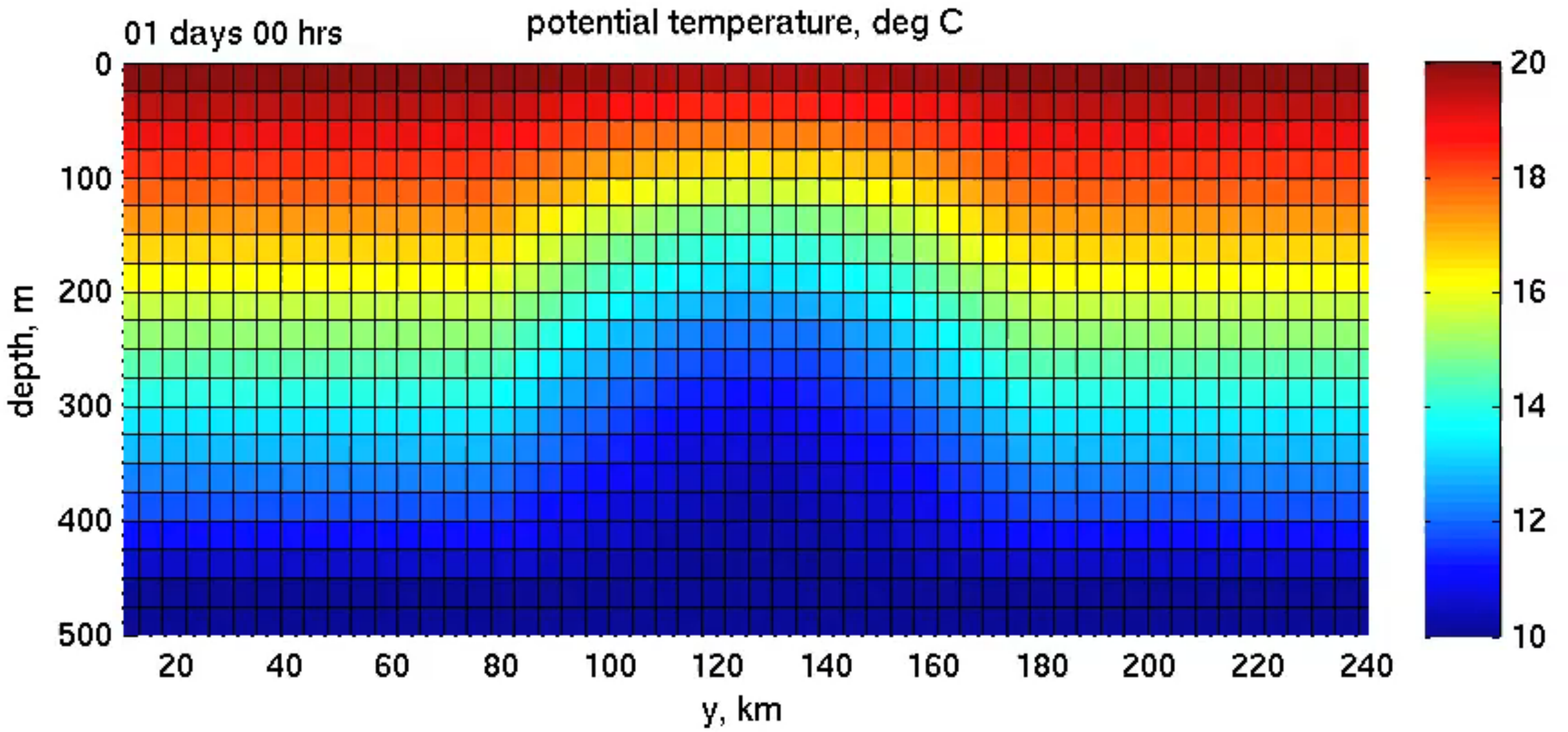
Internal Wave Test Case





Frequency-filtered thickness: z-tilde (Leclair & Madec 2011)

- Motivation: We would like internal gravity waves to not cause mixing.
- Here lines show grid cells, for z-star vertical grid:



- What if we allow layer thickness to oscillate with internal waves?
- This can be done with a low-pass filter on the divergence

Frequency-filtered thickness: z-tilde (Leclair & Madec 2011)

- A low-pass filter on the baroclinic divergence:

Divergence:

$$D_k = \bar{D} + D'_k = \bar{D} + D_k^{lf} + D_k^{hf} \qquad D_k = \nabla \cdot (h_k u_k)$$

hor. divergence (D_k)

barotropic ($\bar{D}$)

baroclinic (D'_k)

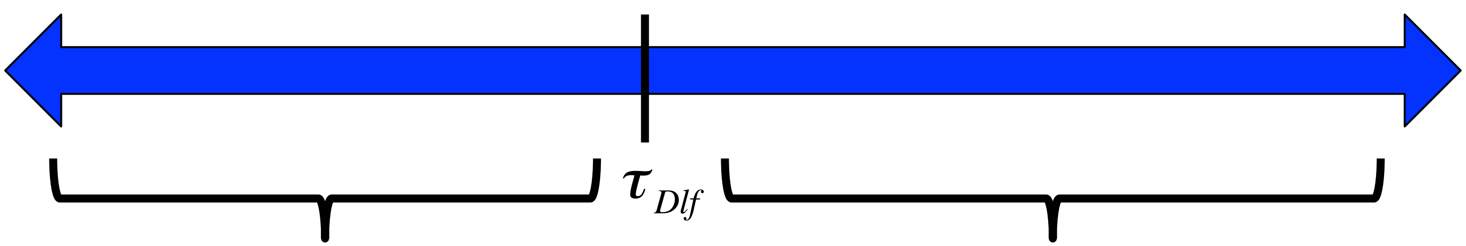
low frequency baroclinic div. (D_k^{lf})

high frequency baroclinic div. (D_k^{hf})

Low-pass filter:

$$\frac{\partial D_k^{lf}}{\partial t} = -\frac{2\pi}{\tau_{Dlf}}\left[D_k^{lf} - D'_k\right]$$

- τ_{Dlf} is the filter time scale, typically five days.
- It controls the time scales included in the low frequency divergence.



short time, high frequency oscillations change layer thickness

long time, low frequency oscillations do not change layer thickness

Frequency-filtered thickness: z-tilde (Leclair & Madec 2011)

- A low-pass filter on the baroclinic divergence:

Divergence:

$$D_k = \bar{D} + D'_k = \bar{D} + D_k^{lf} + D_k^{hf}$$

hor. divergence (D_k), barotropic ($\bar{D}$), baroclinic (D'_k), low frequency baroclinic div. (D_k^{lf}), high frequency baroclinic div. (D_k^{hf})

Low-pass filter:

$$\frac{\partial D_k^{lf}}{\partial t} = -\frac{2\pi}{\tau_{Dlf}}\left[D_k^{lf} - D'_k\right]$$

High-frequency thickness equation:

$$\frac{\partial h_k^{hf}}{\partial t} = -D_k^{hf} - \frac{2\pi}{\tau_{hhf}} h_k^{hf} + \nabla\cdot\left(\kappa_{hhf}\nabla h_k^{hf}\right)$$

forcing ($-D_k^{hf}$), restoring ($-\frac{2\pi}{\tau_{hhf}} h_k^{hf}$), diffusion ($\nabla\cdot\left(\kappa_{hhf}\nabla h_k^{hf}\right)$)

Two new prognostic equations (low-pass filter and high-frequency thickness equation)

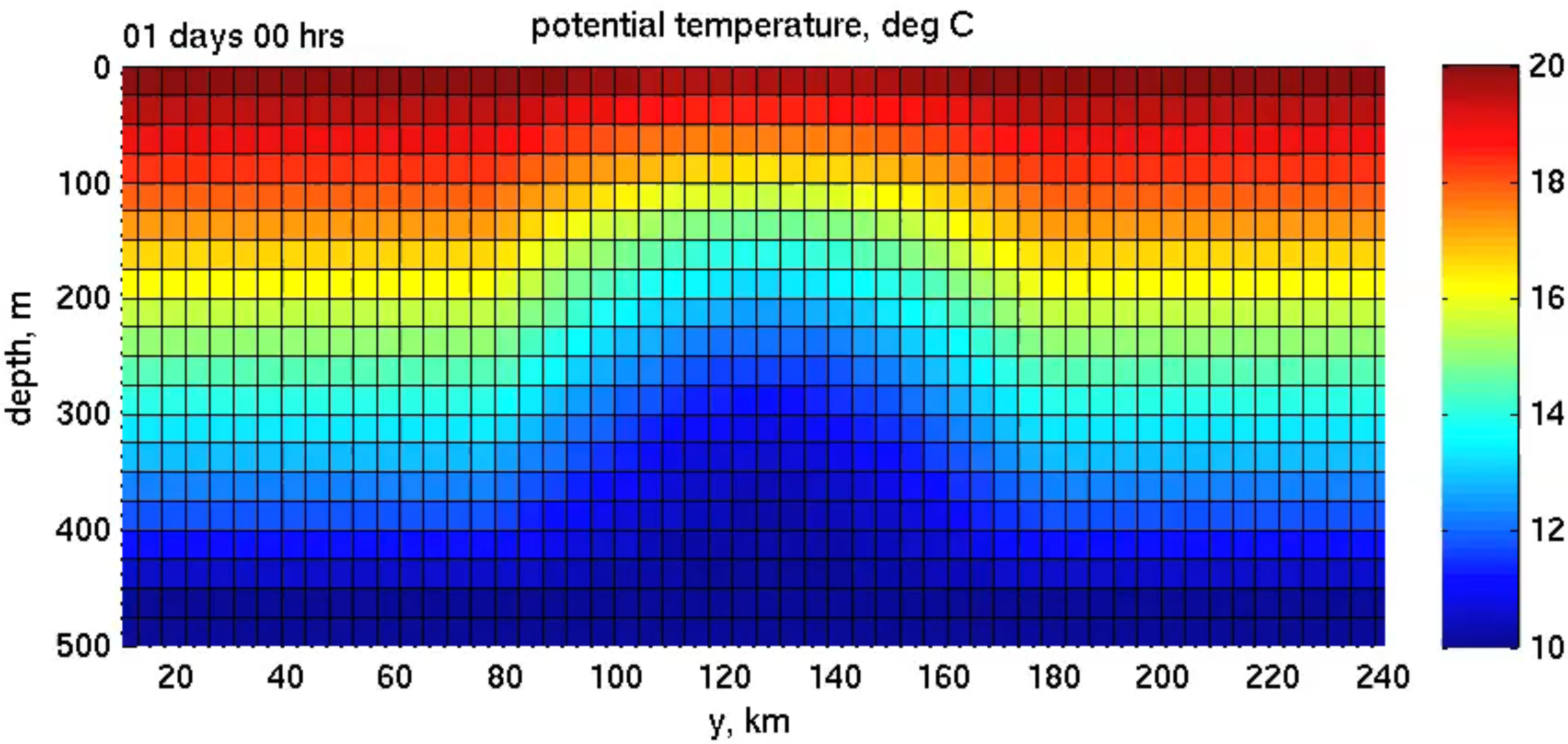
Revised thickness equation:

$$\frac{\partial h_k}{\partial t} = \frac{\partial h_k^{ext}}{\partial t} + \frac{\partial h_k^{hf}}{\partial t}$$

z-star part ($\frac{\partial h_k^{ext}}{\partial t}$), z-tilde part ($\frac{\partial h_k^{hf}}{\partial t}$)

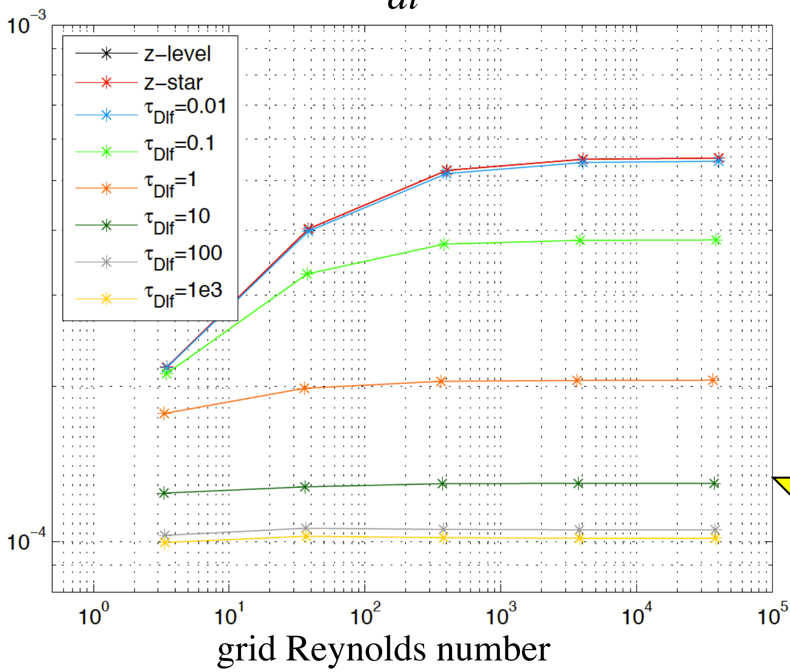
Frequency-filtered thickness: Internal Wave Test Case

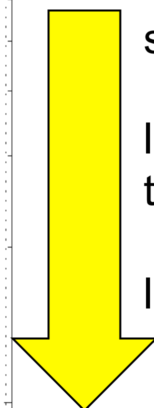
- It works!
- Here lines show grid cells, for z-tilde vertical grid:



Frequency-filtered thickness: Internal Wave Test Case

$$\frac{dRPE(t)}{dt}$$



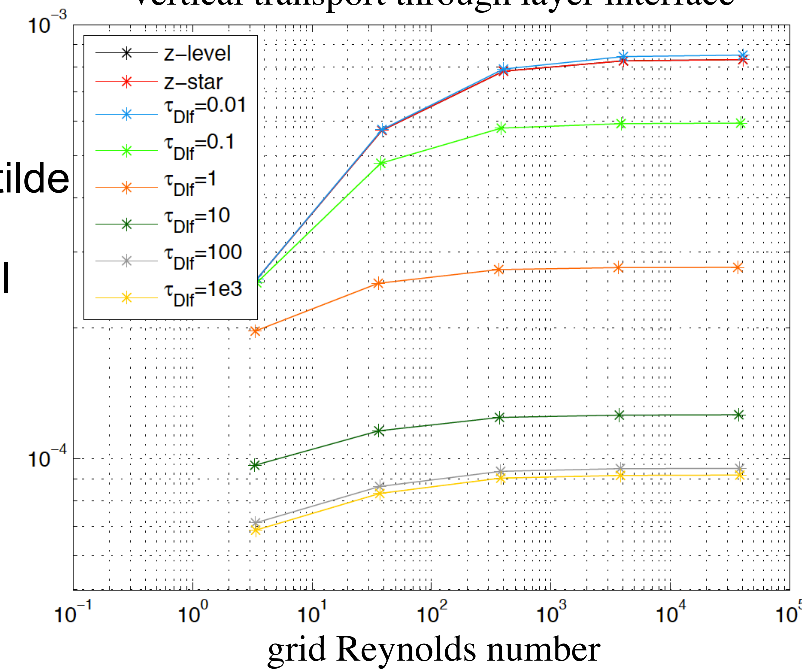


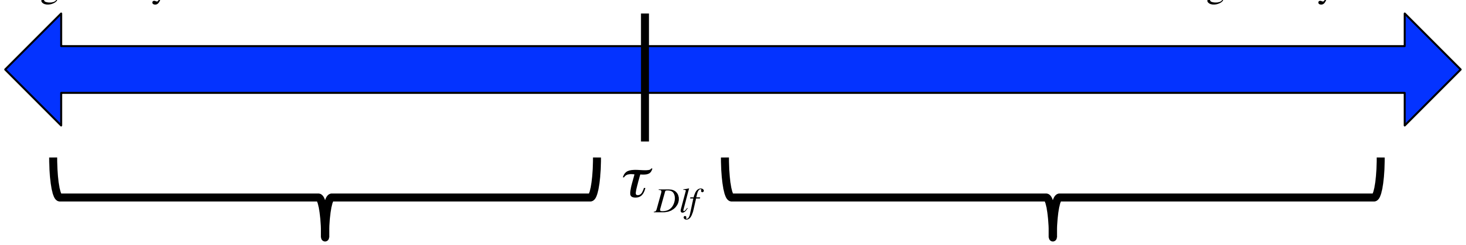
stronger z-tilde

less vertical transport

less mixing

vertical transport through layer interface





short time, high frequency oscillations change layer thickness

long time, low frequency oscillations do not change layer thickness

- Similar results for global simulations

MPAS-Ocean: Ice Shelf Above Ocean Surface

- For coupled ocean-ice shelf modeling, we need to depress the ocean surface with the weight of the ice shelf.

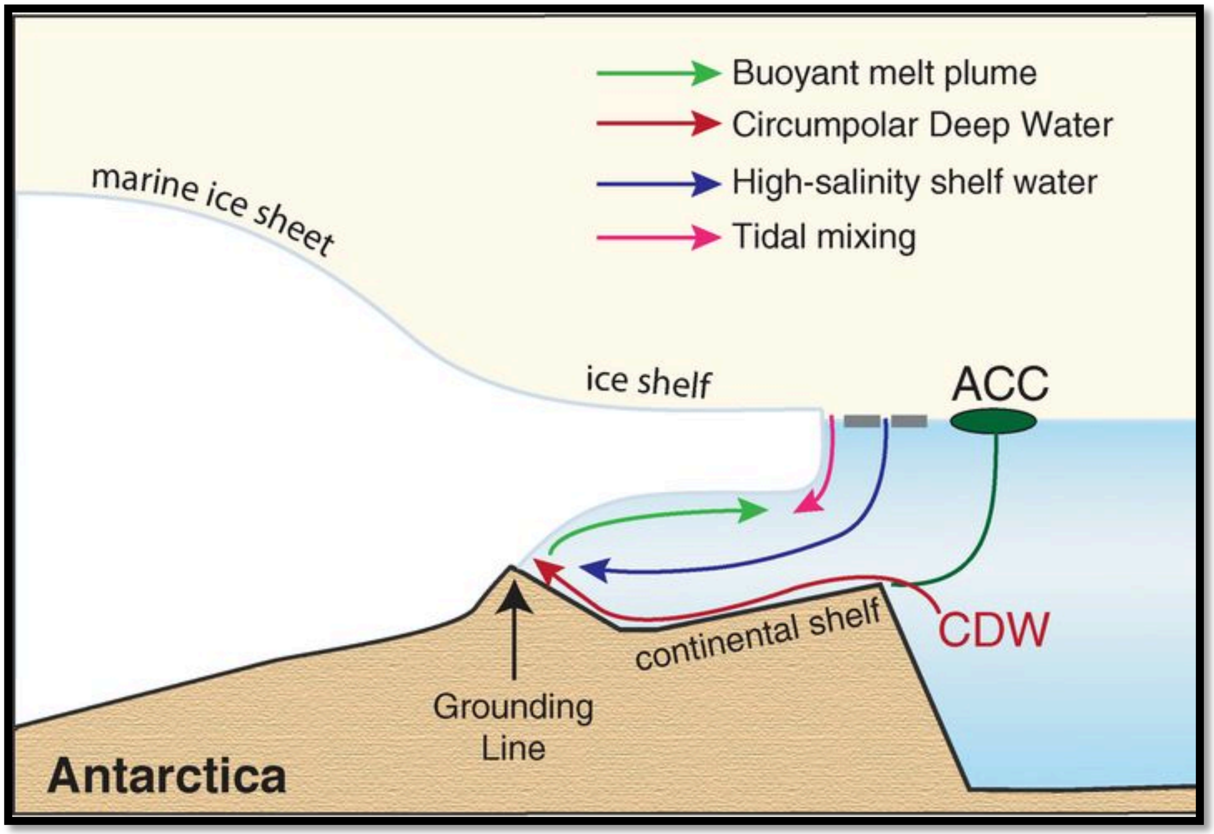


image from Joughin ea. Science, 2012

Observations:

Pine Island Glacier

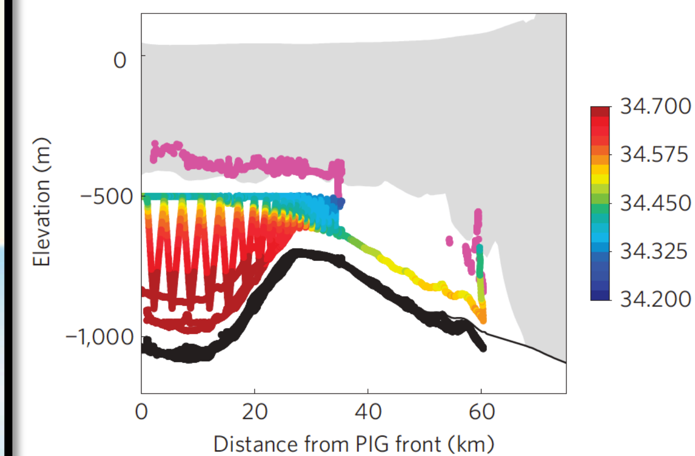
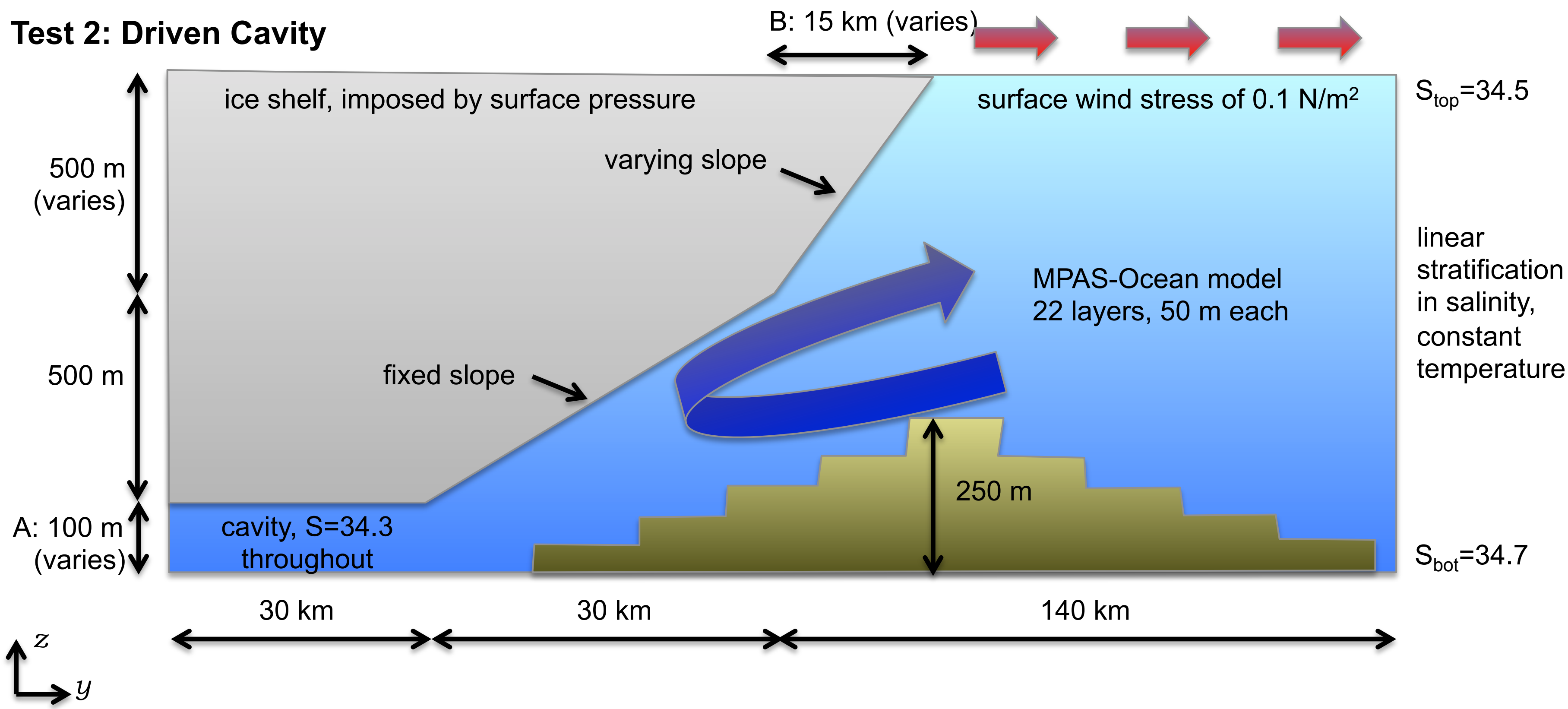


image from Jenkins ea. Science, 2010

MPAS-Ocean: Ice Shelf Above Ocean Surface

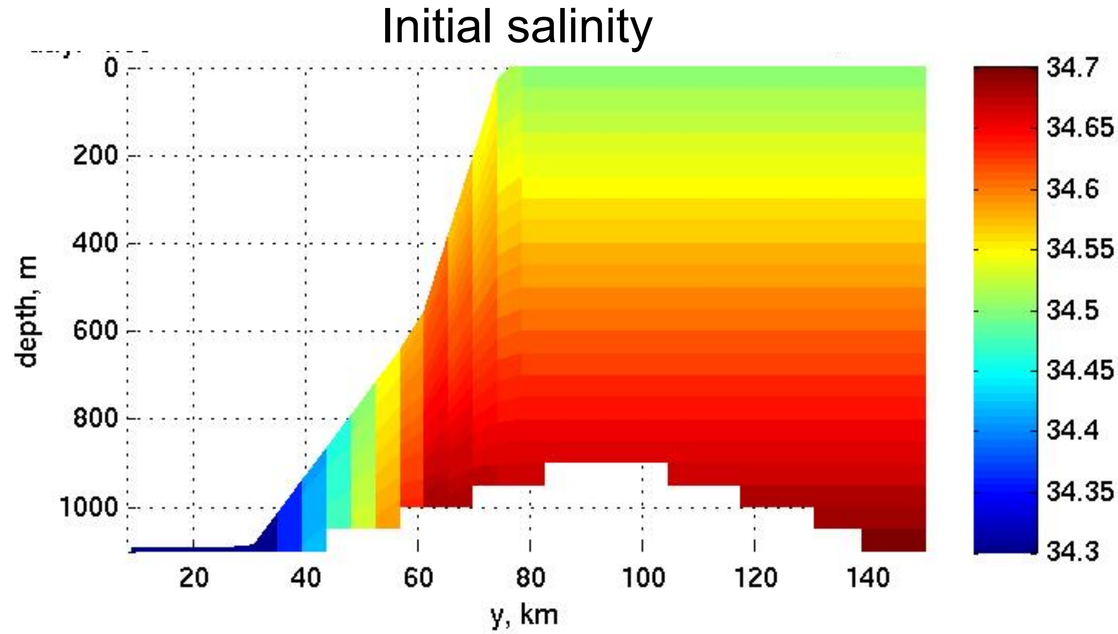
- For coupled ocean-ice shelf modeling, we need to depress the ocean surface with the weight of the ice shelf.

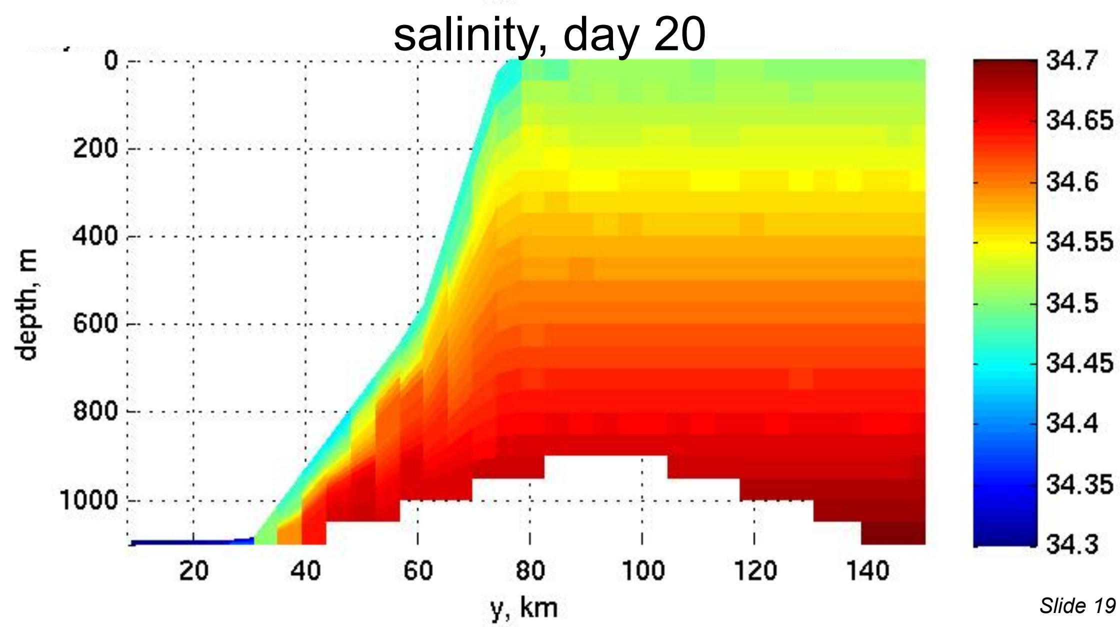
Test 2: Driven Cavity



MPAS-Ocean: Ice Shelf Above Ocean Surface

- For coupled ocean-ice shelf modeling, we need to depress the ocean surface with the weight of the ice shelf.
- Ocean layers were compressed to 5 cm thickness with no negative effects.
- Sheer cliff face may be used at ice shelf edge.
- Tests used linear EOS. For nonlinear EOS, must account for sigma-coordinate correction.





The MPAS-Ocean Vertical Coordinate

- ✔ **Z-Level**
- ✔ **Z-star**
- ✔ **sigma:** only tested in idealized cases so far
- ✔ **isopycnal:** idealized only, no zero thickness layers
- ☐ **hybrid isopycnal:** under development
- ✔ **partial bottom cells**
- ✔ **z-tilde:** frequency-filtered coordinate