Frontogenesis and frontal arrest in the submesoscale mixed layer

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Background

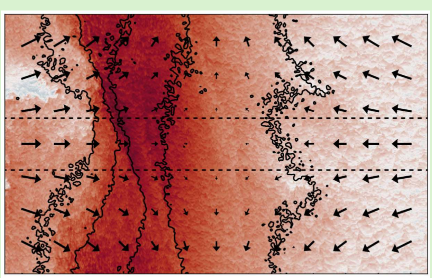
- The submesoscale (Ro ≈ 1) ocean is peppered with fronts – highly anisotropic step changes in density [1] .
- An ageostrophic secondary circulation is generated at a front when it is subject to mixing or the influence of mesoscale background flow.
- In a background flow with non-zero strain, the growth rate of frontal gradients increases super-exponentially as Ro $\rightarrow 1$ leading, in idealized analytic models, to an infinitely sharp front in finite time [2].
- We aim to tackle a few questions:
  - How do we implement a “minimum working example” of strain-driven frontogenesis with 3D convection?
  - What does a front look like as it *reaches* submesoscales, rather than starts there?
  - Does vertical momentum mixing help or hinder frontal growth?
  - How are infinite gradients avoided in the real ocean?

Setup

- 3D frontal zone simulation in Oceananigans
- Aiming for LES resolutions $(\Delta x, \Delta y, \Delta z) \approx (2\text{m}, 2\text{m}, 0.7\text{m})$
- Generate a mixed front by cooling until $t = 0$, then a background strain turns on
- Periodic in along-front direction, scaling argument suggests we can ignore the aperiodic term in

$$\frac{\mathrm{D}\phi}{\mathrm{D}t} = \frac{\partial \phi}{\partial t} + \boldsymbol{u} \cdot \nabla \phi - \alpha x \frac{\partial \phi}{\partial x} + \alpha y \frac{\partial \phi}{\partial y}$$

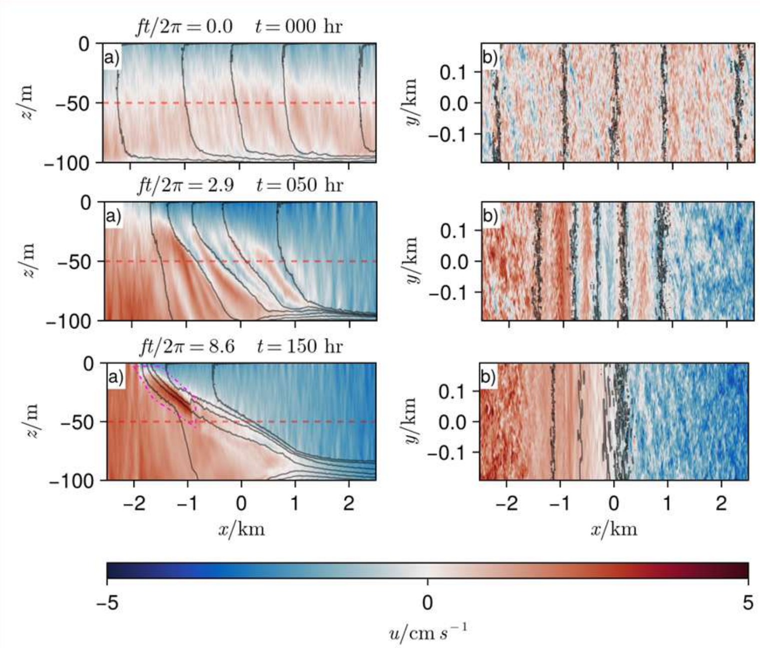
if the simulation domain is a thin slice in the y direction (right).



Evolution

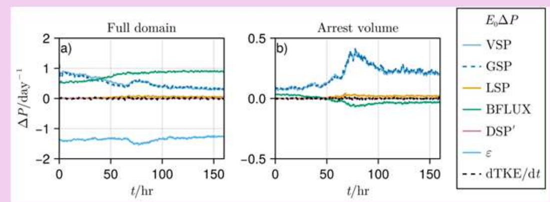
As the front evolves:

- Vertical convection transitions to along-isopycnal, symmetric cells within the front
- Cooling-driven mixing and restratification due to the secondary circulation compete
- The symmetric cells eventually coalesce and a highly turbulent region forms near the surface.
- The across-front density gradient is finite near the surface and doesn’t depend on resolution.



Energy transfer

- Vertical shear production dominates in the arrest region and peaks during the transition phase.
- Together with the low potential vorticity (not shown here) indicates marginally stable symmetric instability / internal gravity wave activity as the front reaches smaller scales.



Frontal width

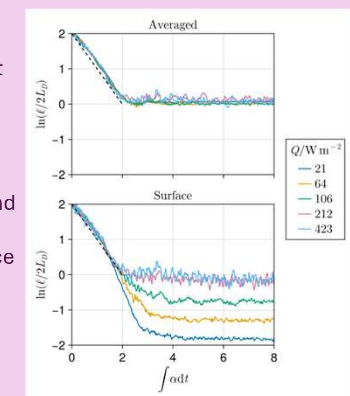
Low mixing

Sharp surface front

High mixing

The surface front looks more like a vertical average, and the width is constrained to twice the deformation radius.

$$L_D = \frac{\sqrt{\Delta b H}}{f}$$



[1] McWilliams, James C. 2021. “Oceanic Frontogenesis.” *Annual Review of Marine Science*

[2] Hoskins, B. J., and F. P. Bretherton. 1972. “Atmospheric Frontogenesis Models: Mathematical Formulation and Solution.” *Journal of the Atmospheric Sciences*

Want to check out Oceananigans? Get CREATE credit for it with my module! https://github.com/erin-atkinson/FrontalInstabilities