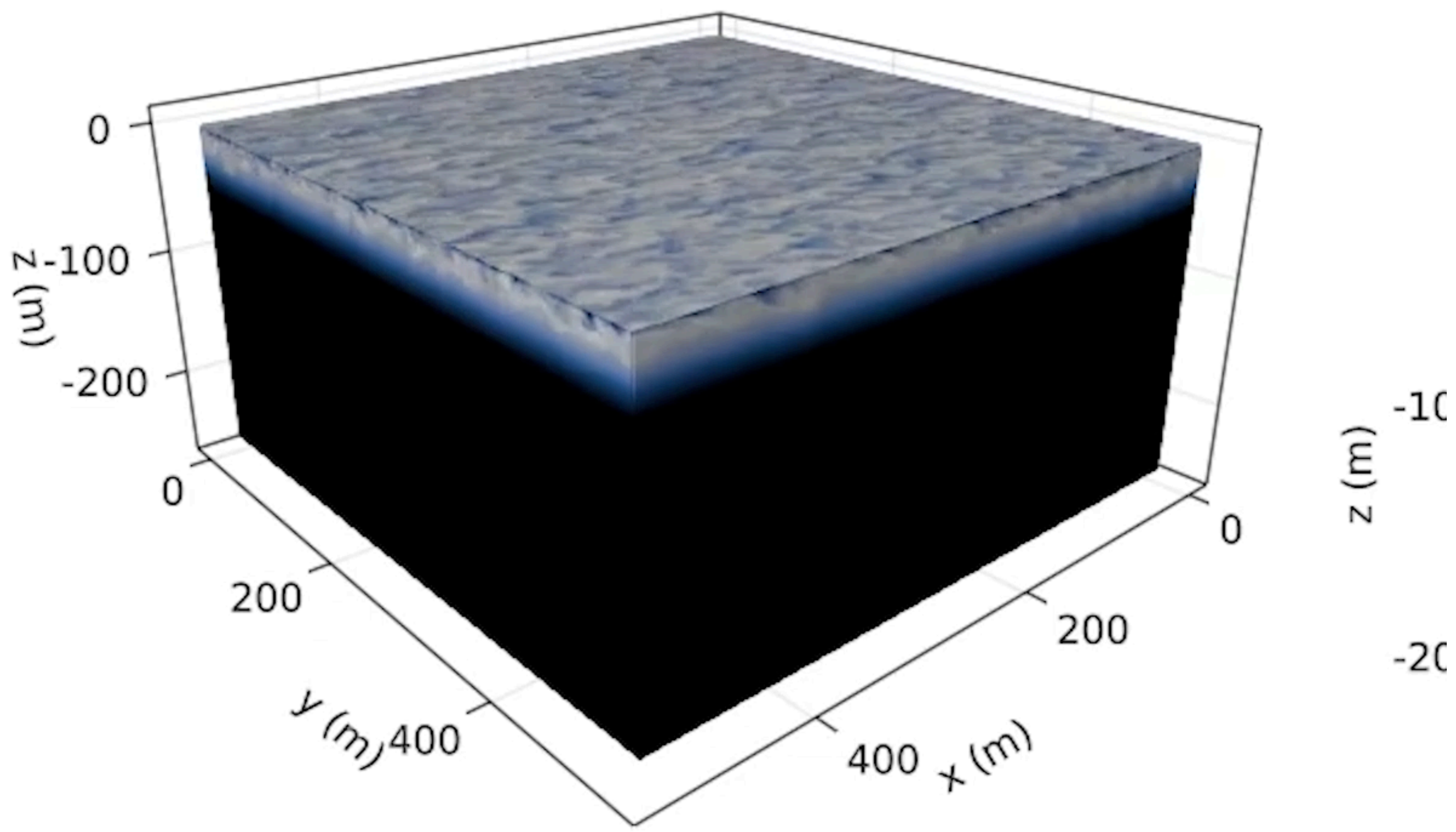
CATKE development + calibration



A microscale turbulence closure based on
Convective Adjustment and Turbulent Kinetic Energy

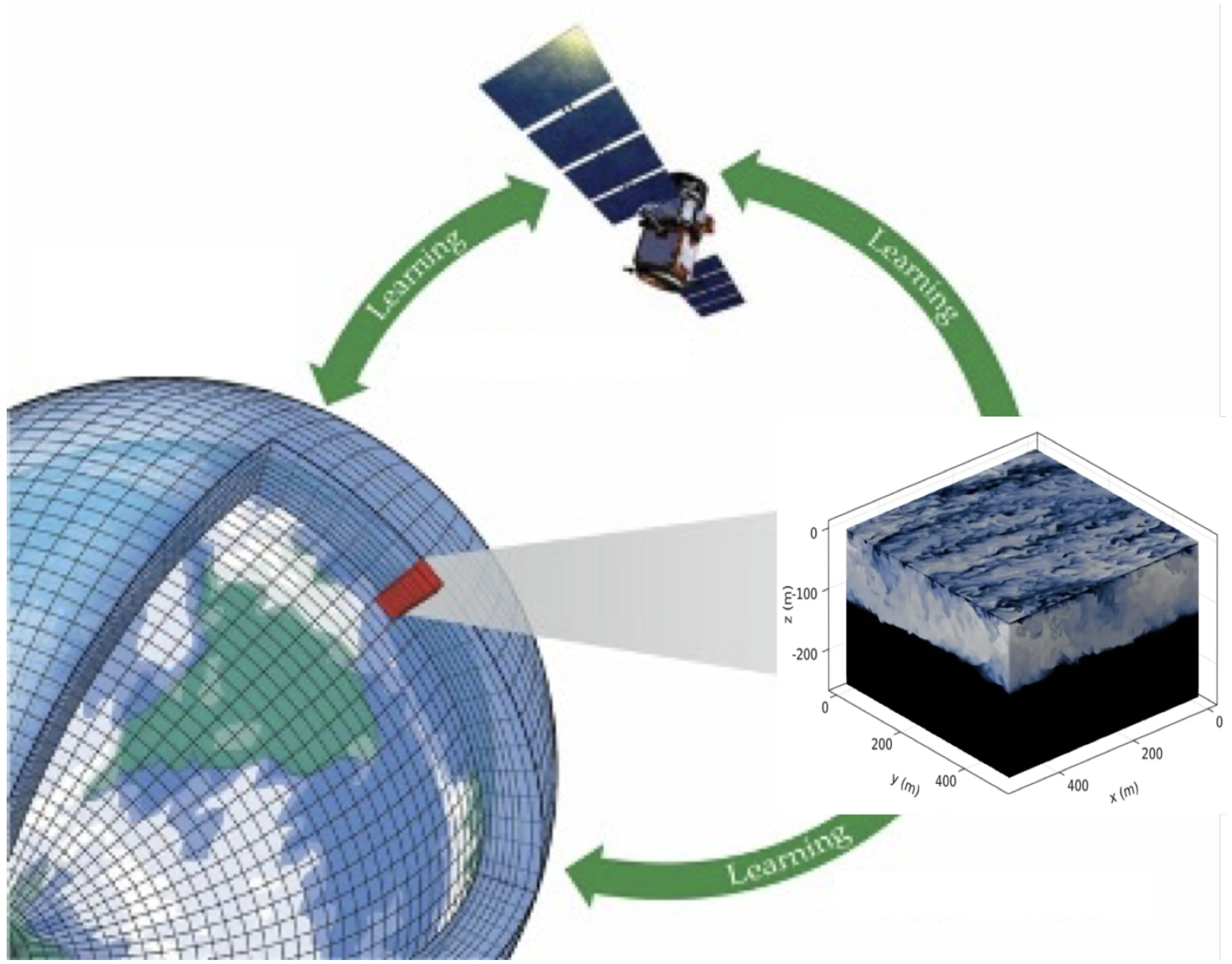
Gregory Wagner and Clima-Ocean
CESM Ocean Model Working group meeting Friday February 10 2023

CliMa objectives

1. Develop a trainable climate model

2. Calibrate and quantify model uncertainties leveraging diverse observations

3. Improve parameterization of unresolved physical processes



Some challenges

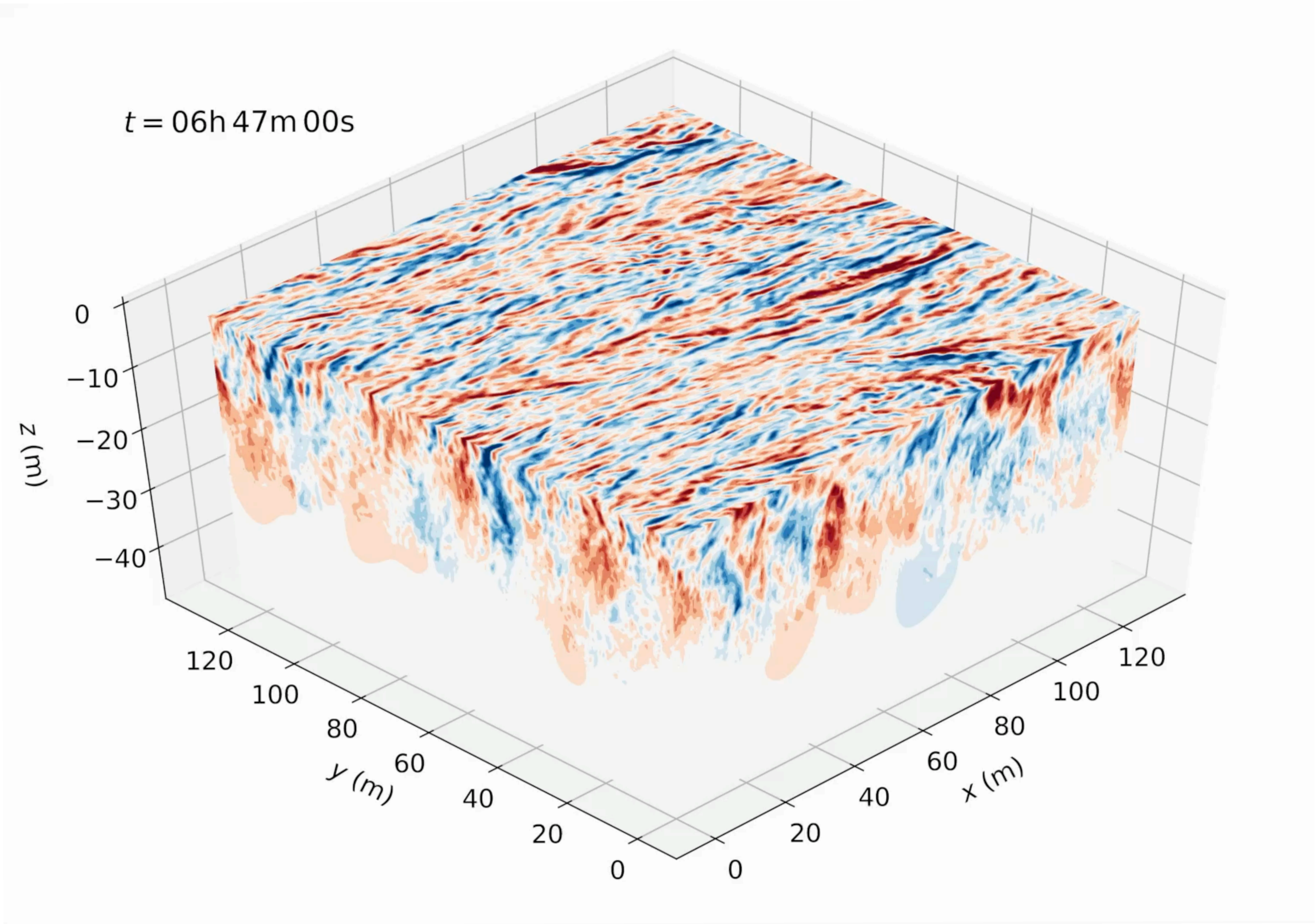
- Expensive calibrations at hierarchy of scales
  Single columns to global simulations

- Need lots of high-fidelity synthetic data
  LES, regional simulations

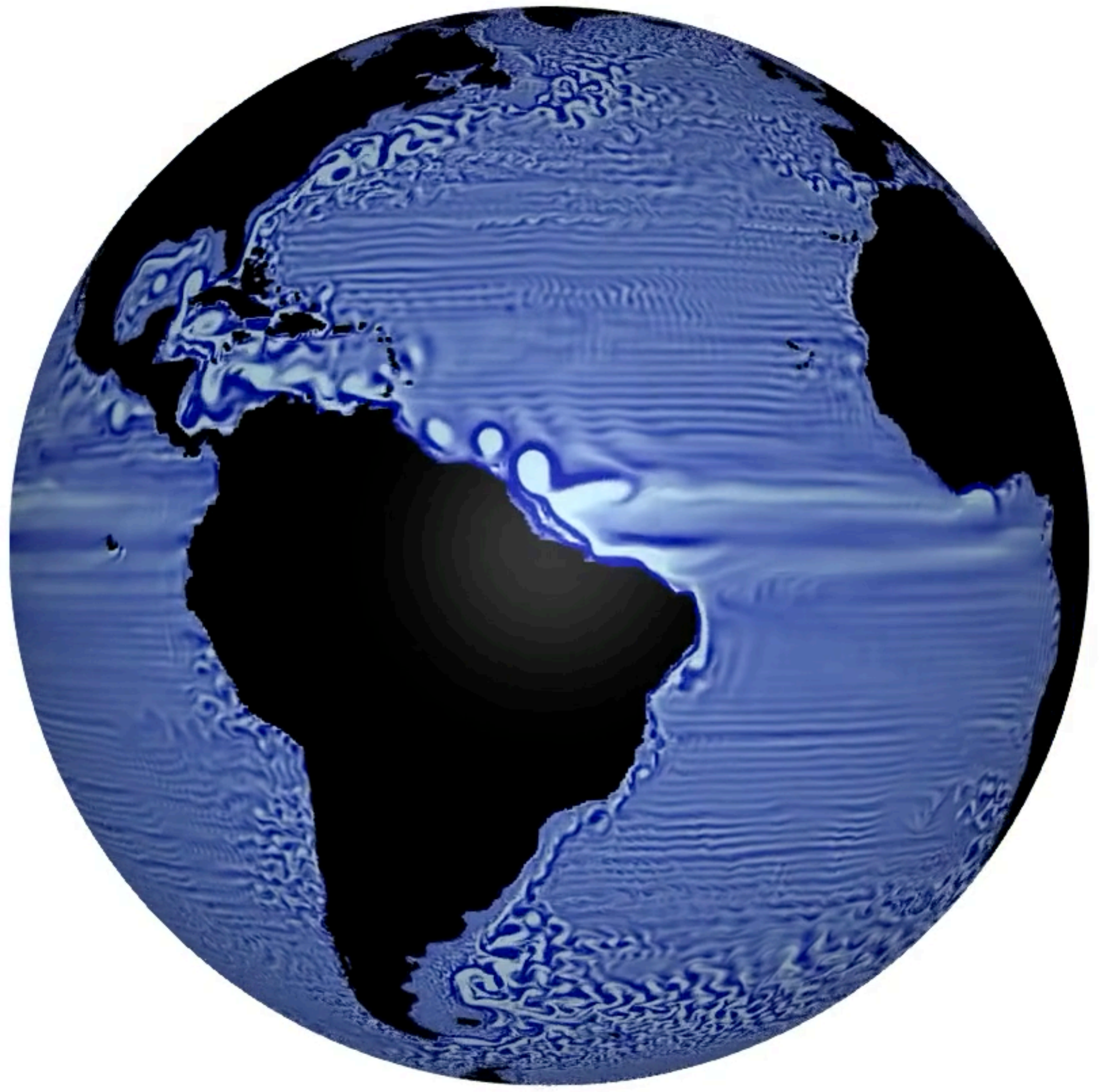
- Need fast, flexible software that's easy to develop

Oceananigans.jl

CliMa's ocean component



Langmuir turbulence LES
(w/ FFT-based pressure solver)

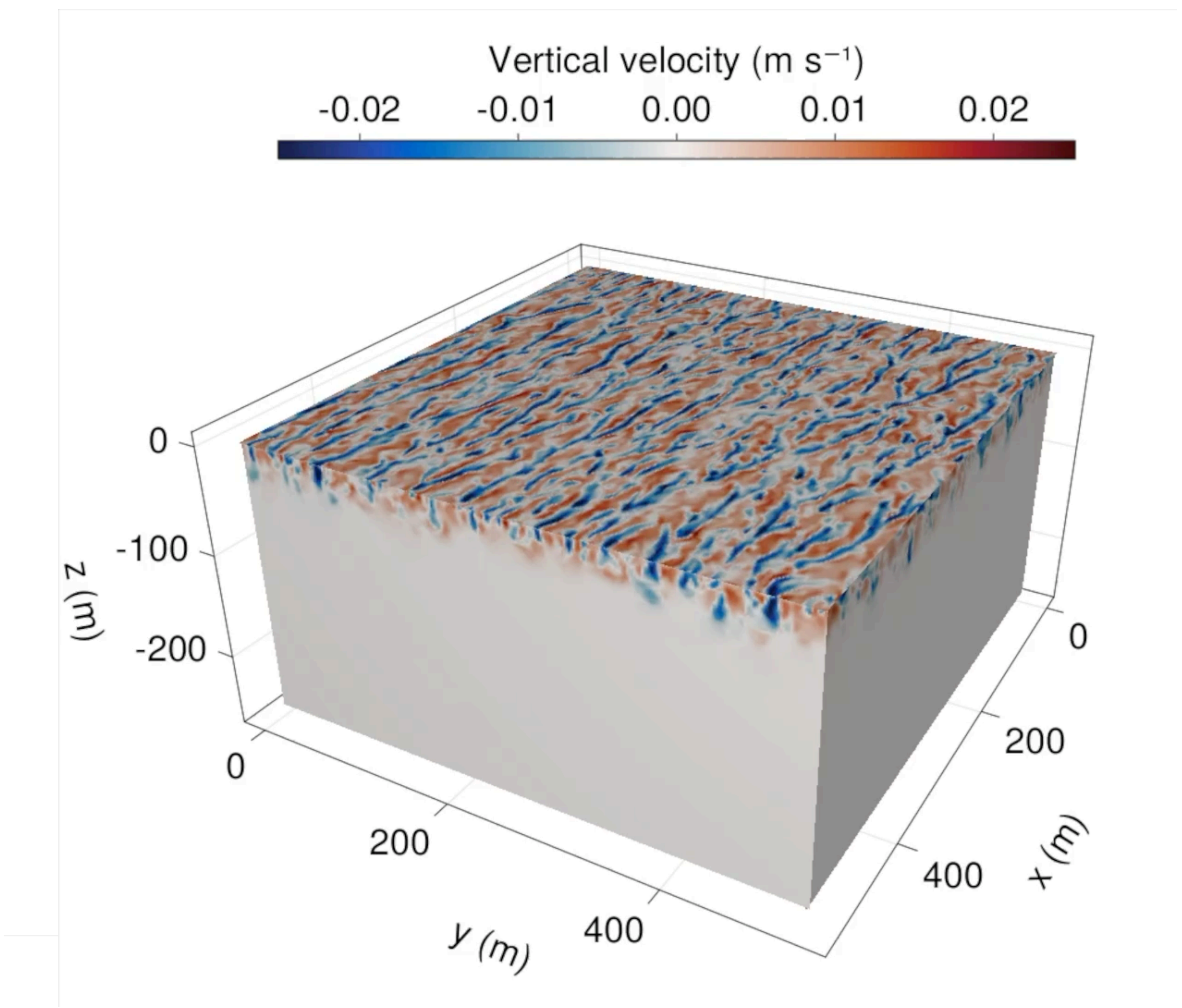


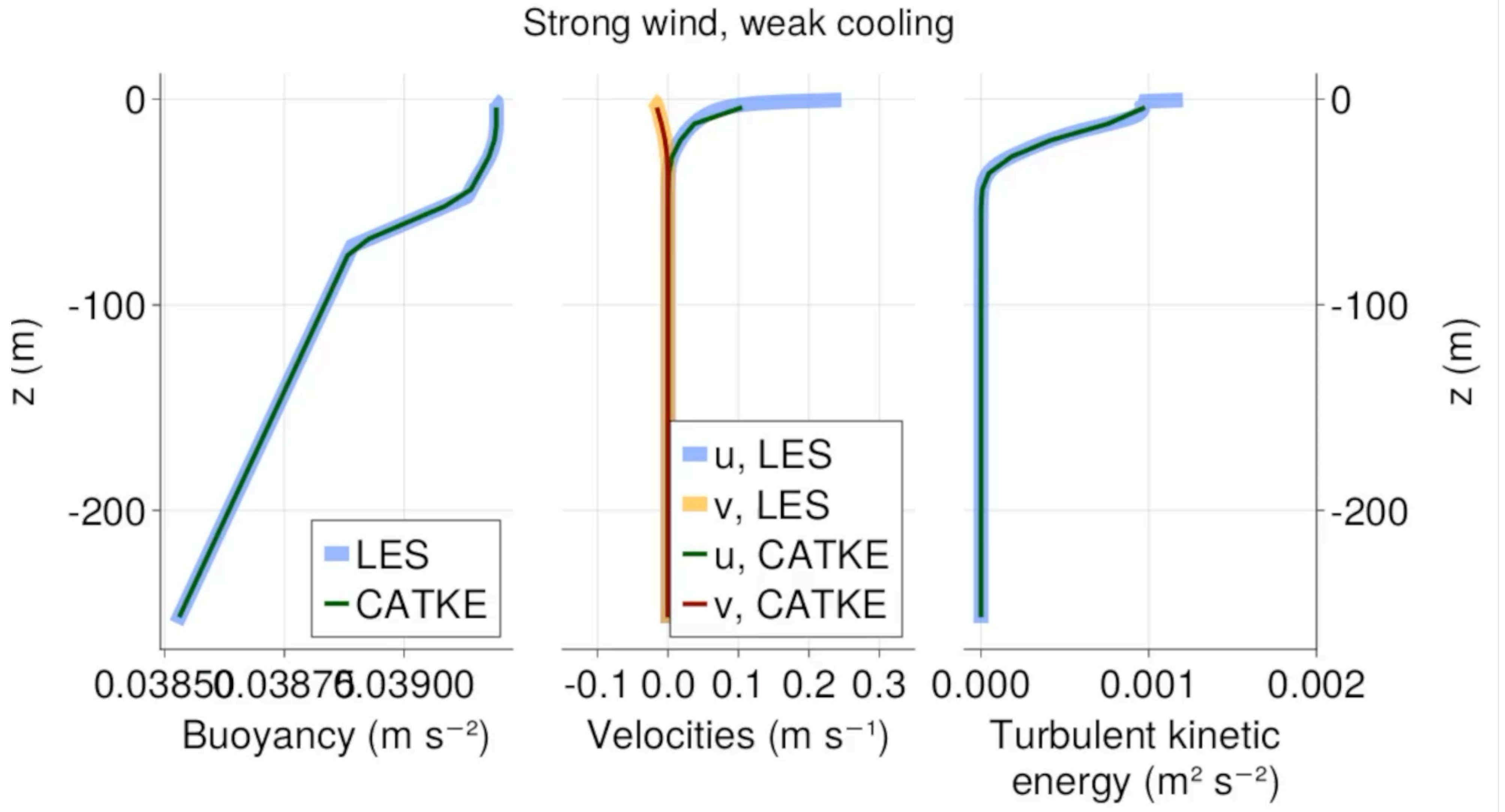
1/4 degree near global simulation
(~ 3 SYPD on 1 Nvidia V100 GPU)

```
julia> using Oceananigans

julia> grid = RectilinearGrid(size=(5,5,5),extent=(1,1,1))
5×5×5 RectilinearGrid{Float64, Periodic, Periodic, Bounded} o
n CPU with 3×3×3 halo
├── Periodic x ∈ [0.0, 1.0)  regularly spaced with Δx=0.2
├── Periodic y ∈ [0.0, 1.0)  regularly spaced with Δy=0.2
└── Bounded  z ∈ [-1.0, 0.0] regularly spaced with Δz=0.2

julia> model = HydrostaticFreeSurfaceModel(; grid);

julia> simulation=Simulation(model, Δt=1.0, stop_time=10);

julia> run!(simulation)
```

Why CATKE?

- Extends widely-used parameterization
  > Blanke and Delecluse ’93, Madec et al ’17
  - Standard, portable, efficient
  - Wide range of applications
    > Planetary to submesoscale (to near LES?)
- We advance state of the art by:
  1. **Leveraging CliMA-developed calibration methods and 42 new LES**
  2. **Measured yet crucial improvements to closure formulation**





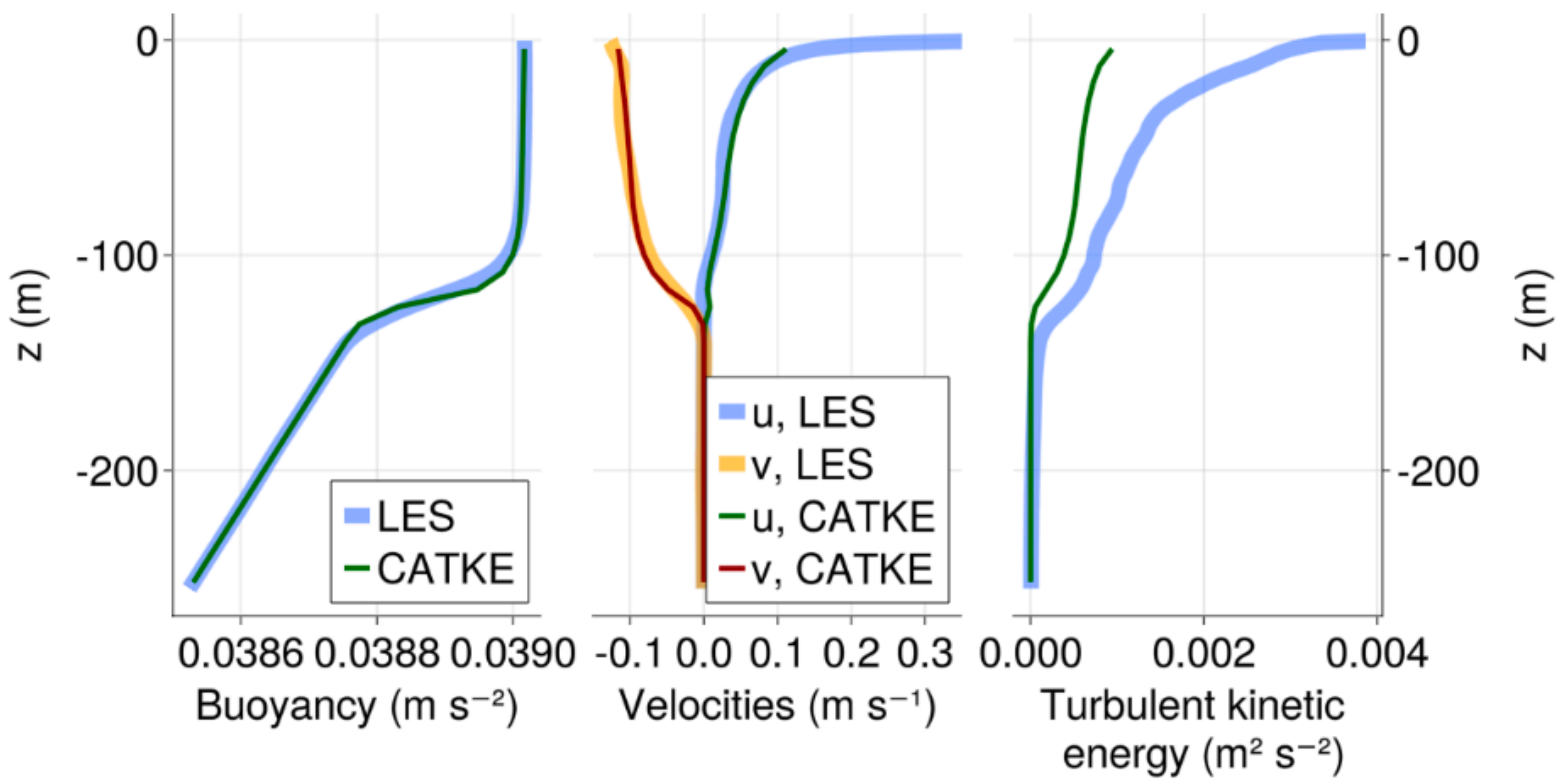
Calibration with Ensemble Kalman Inversion

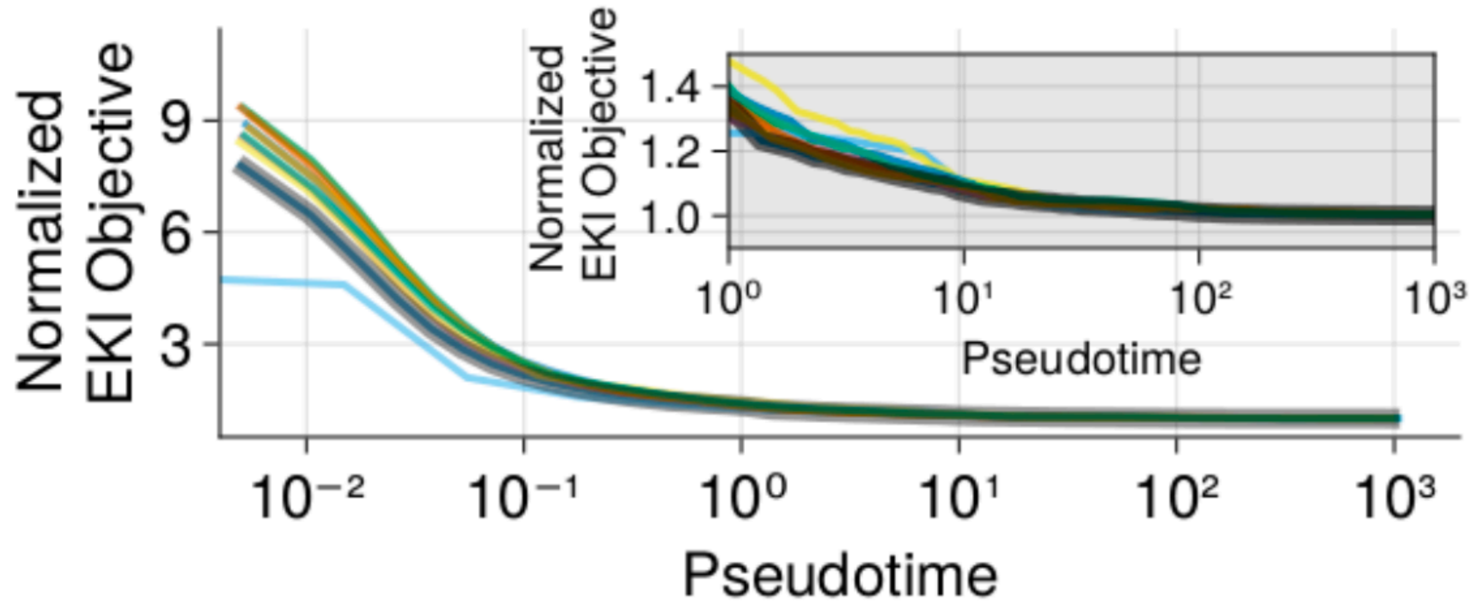
- “A posteriori” or “online"
  Incorporates numerical errors and “indirect” data

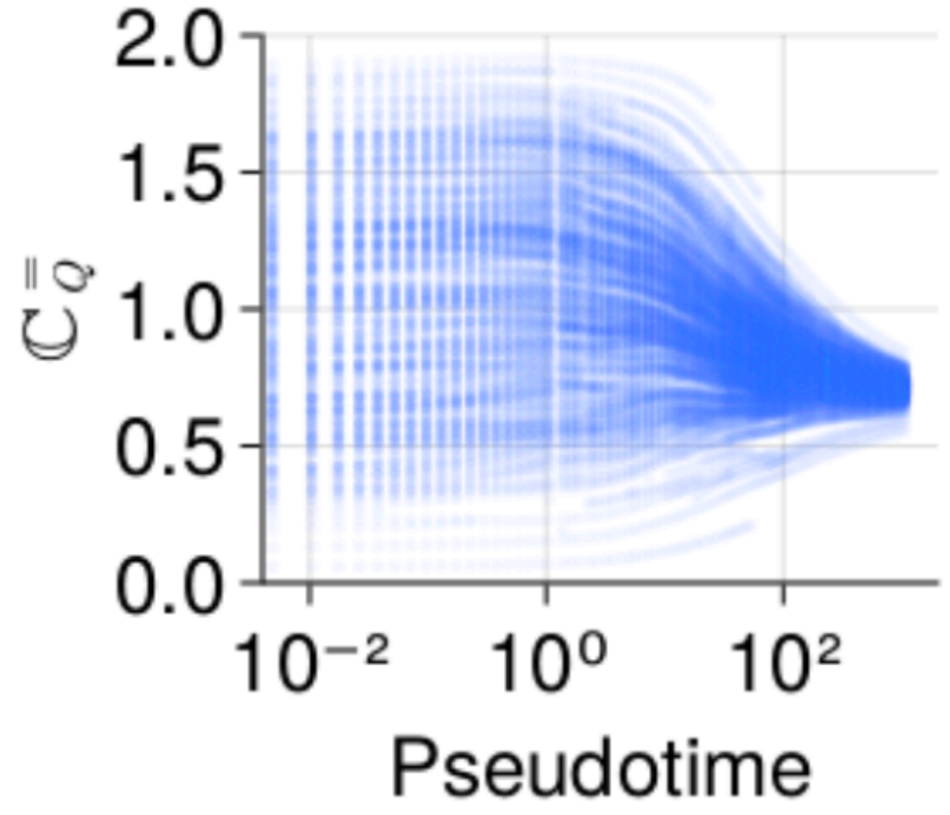
- Guides model development
  Distinguish parametric from structural biases

- Yields strong physical constraints on parameters
  Essential for trustable predictions and further calibration

$$\Phi(\mathbb{C}) \sim \omega_T \left\| \bar{T}_{\text{LES}}(z, t) - \bar{T}_{\text{CATKE}}(z, t; \mathbb{C}) \right\|^2 + \cdots$$







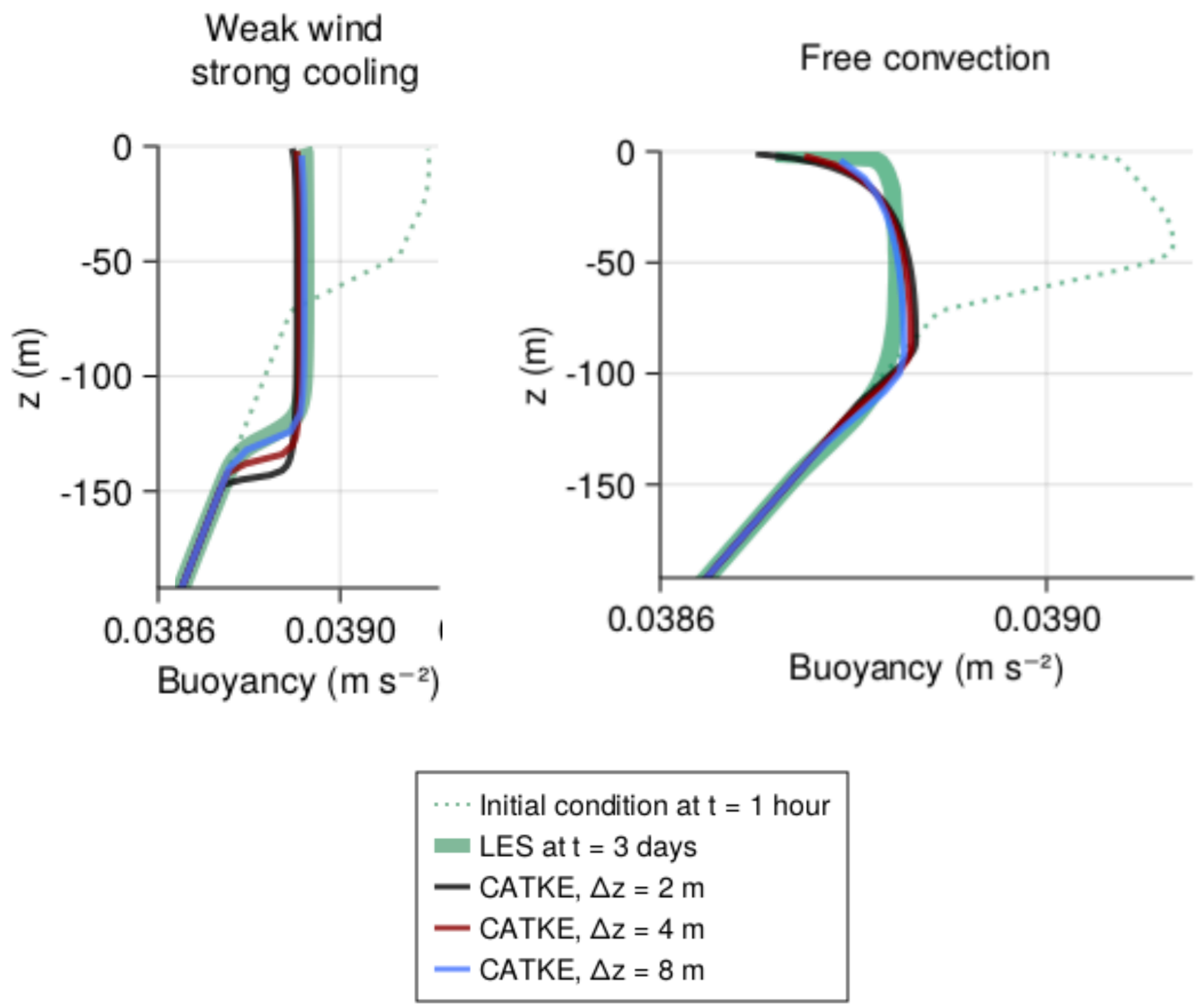
Minimalist CATKE

Simple… but sensitive to resolution (7 free parameters)

$$\overline{w'T'} \approx -\underbrace{\ell_c \sqrt{E}}_{\equiv \kappa_c} \, \partial_z \bar{T}$$

$$\ell_T = \mathbb{C}_T^K \min \left(d, \mathbb{C}^b \frac{\sqrt{E}}{N} \right)$$

$$\partial_t E = \partial_z \left(\kappa_e \partial_z E \right) + \kappa_u |\partial_z \boldsymbol{U}|^2 - \kappa_c N^2 - \frac{E^{3/2}}{\ell_D}$$



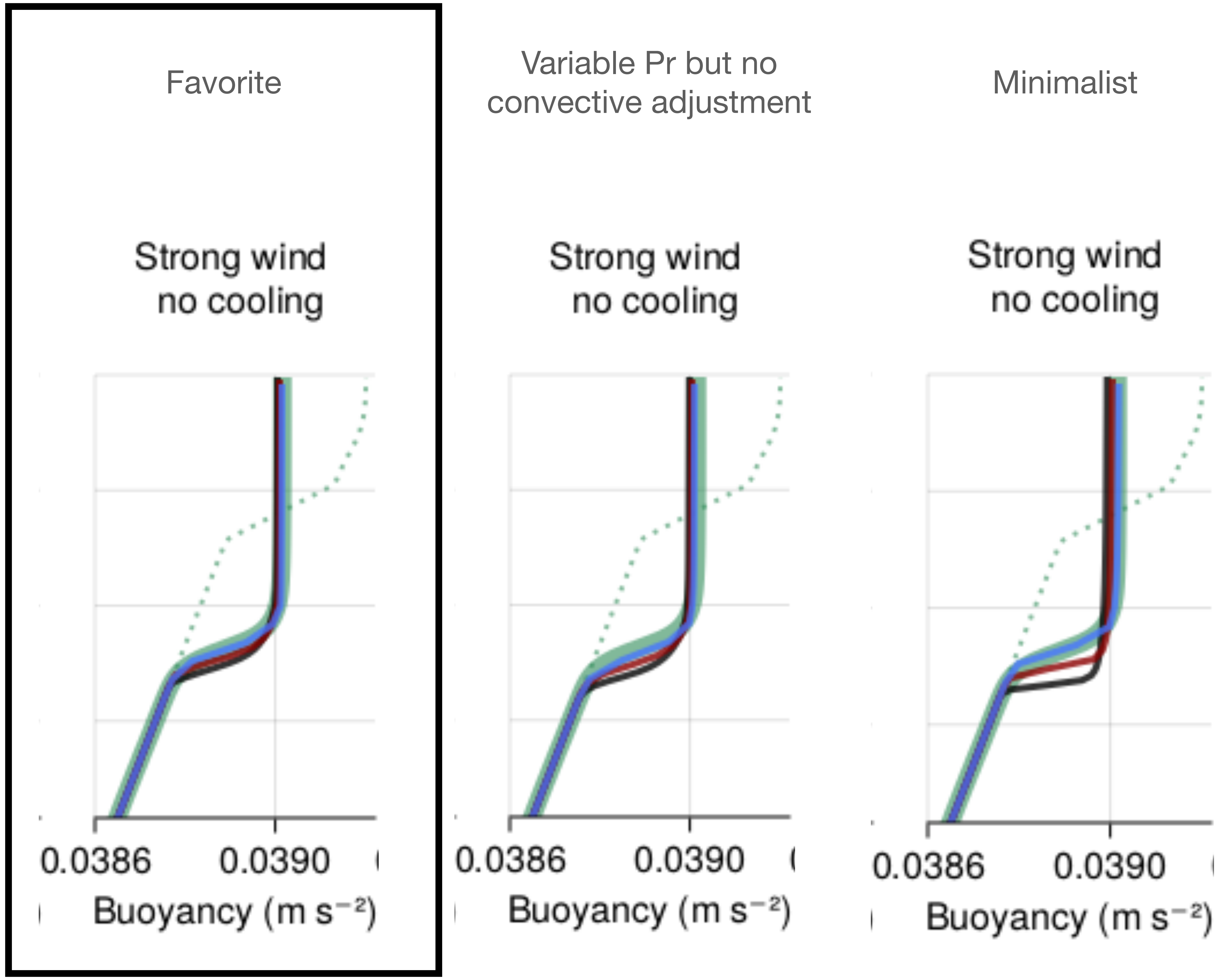
Favorite CATKE

More complicated, but more accurate (19 free parameters)

$$\overline{w'T'} \approx -\underbrace{\ell_c \sqrt{E}}_{\equiv \kappa_c} \partial_z \bar{T}$$

$$\ell_c = \ell_c^{\text{conv}} + \sigma_c\,(\text{Ri}) \min\left(d, \mathbb{C}^b \frac{\sqrt{E}}{N}\right)$$

$$\ell_c^{\text{conv}} \sim \frac{E^{3/2}}{Q_b} \qquad \text{if} \qquad N^2 > 0$$



Next steps for CATKE + Oceanangians

- Bigger, more realistic LES suite with realistic surface waves
- Explicit surface wave state dependence
- Implement in GOTM?
- Re-calibration and uncertainty quantification in global context