A data-driven approach for developing and calibrating a parametrization for mesoscale eddy fluxes

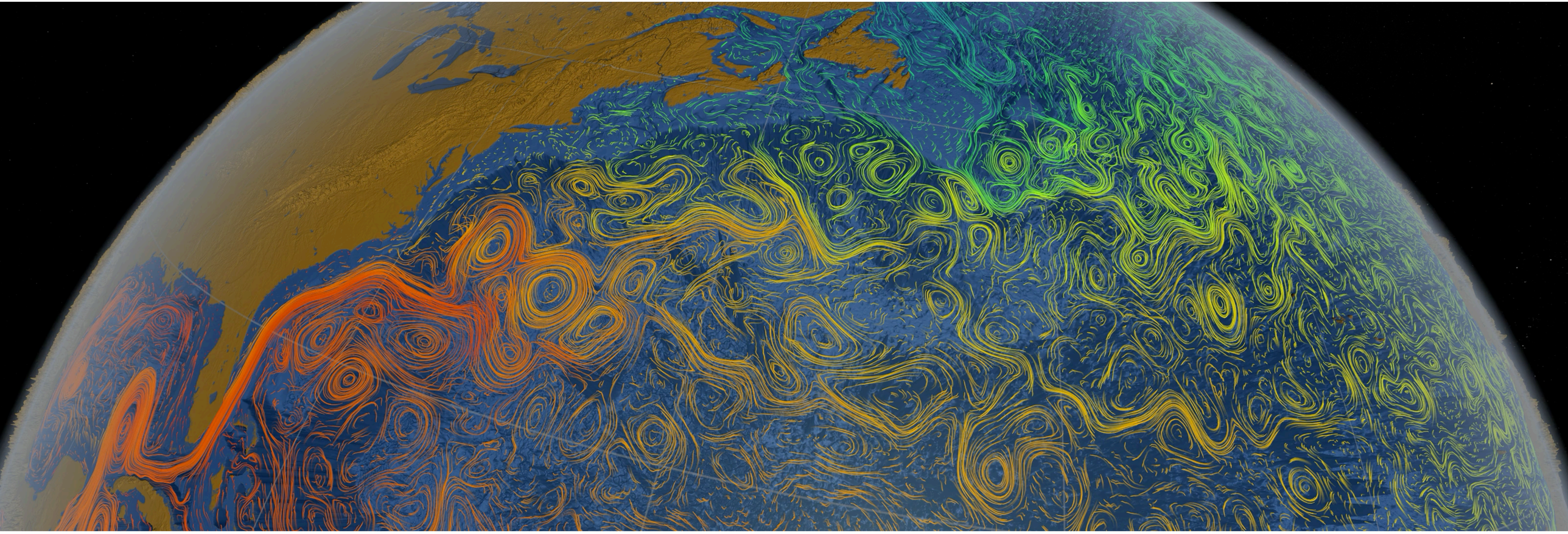
Navid Constantinou

Gregory Wagner, Adeline Hillier, Andre Souza, Xiaozhou Ruan, & Raffaele Ferrari

Australian National University

Australian Government
Australian Research Council

Massachusetts Institute of Technology



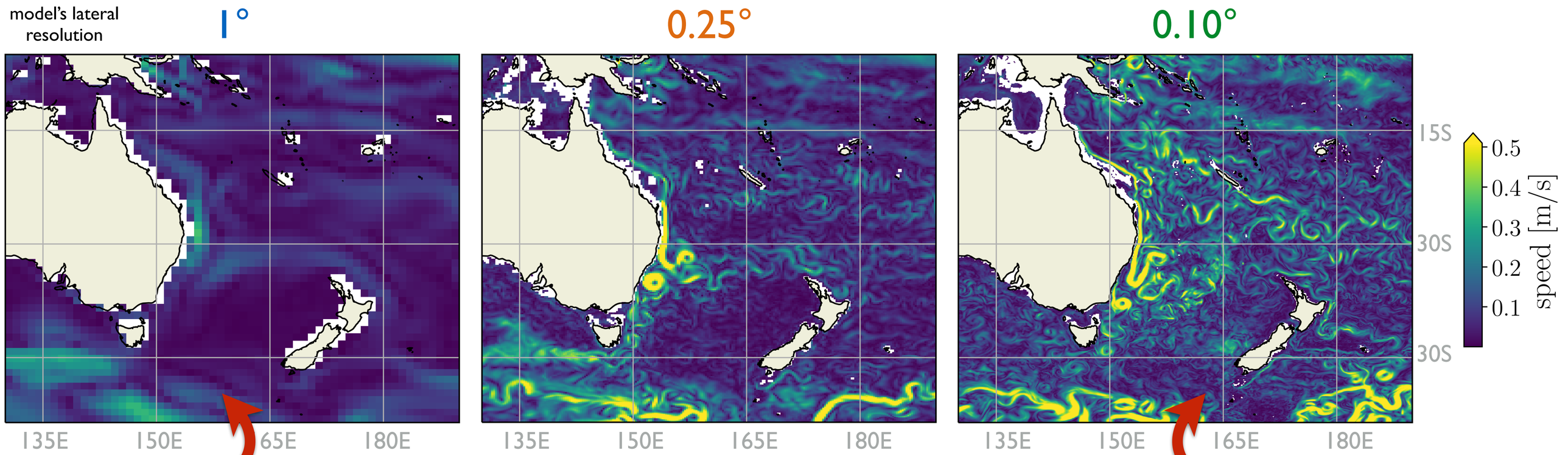
Visualization using output from the MIT/JPO project Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2)

Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

Ocean Sciences Meeting 2022

can we make the coarse model feel the effect of the flow details that it does not resolve?

[in technical terms: '*eddy parameterisation*']



typically used
In IPCC, etc…

we don't need to know what each eddy is doing!
only the low-order, long-time statistics of the system
(climate *Vs* weather)

state-of-the-art
ocean—sea-ice model

[ACCESS-OM2 ocean—sea-ice models, Kiss et al., Geosci. Model Dev. 2020]

how eddies affect tracers?

tracer dynamics (e.g. heat, salt, …)

$$\frac{\partial c}{\partial t} + \boldsymbol{u} \cdot \nabla c = \kappa \nabla^2 c$$

Reynolds decomposition

$$c = \overline{c} + c'$$

resolved

unresolved eddies

$$\boldsymbol{u} = \overline{\boldsymbol{u}} + \boldsymbol{u}'$$

$$\underbrace{\frac{\partial \overline{c}}{\partial t} + \overline{\boldsymbol{u}} \cdot \nabla \overline{c} = \kappa \nabla^2 \overline{c}}_{\text{dynamics the model solves for}} \quad \underbrace{-\nabla \cdot \left(\overline{\boldsymbol{u}' c'} \right)}_{\text{subgrid eddy fluxes}}$$

$\overline{\boldsymbol{u}' c'}$ eddy tracer flux

parametrization

express **eddy tracer flux** in terms of the **resolved fields**

$$\overline{u'c'} = \mathcal{F}(\overline{u}, \overline{c}, \ldots; \theta)$$

eddy tracer flux

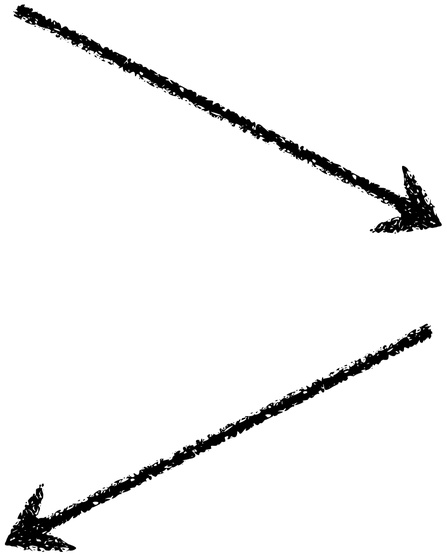
eddy tracer flux parametrization

free parameters (κ_{GM}, κ_{Redi}, ...)

how do we come up with $\mathcal{F}$?

how do we come up with parametrizations?

get inspired by data
(model output,
observations,…)

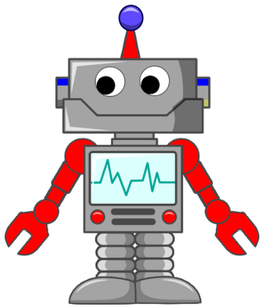


derive a model
from physical intuition
(usually involves some
free parameters)

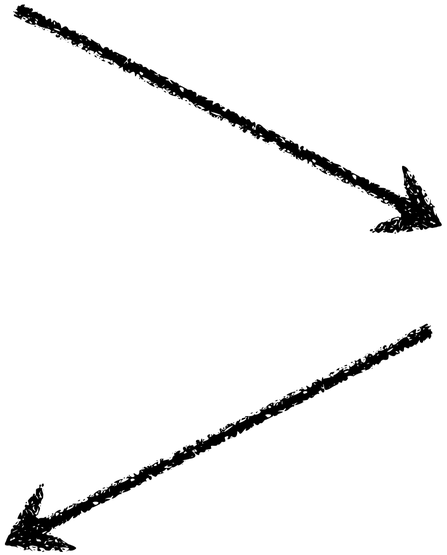
calibrate free parameters
to match data

implement in climate model
and produce IPCC reports, etc

how do we come up with parametrizations?
and how machines can help?



get inspired by data
(model output,
observations,…)



derive a model
from physical intuition
(usually involves some
free parameters)

calibrate free parameters
to match data

implement in climate model
and produce IPCC reports, etc

a proof of concept

take the standard isoneutral diffusion parametrisation (“Gent-McWilliams”)

👉 model derivation

👉 free parameters

👉 calibration of free parameters

isoneutral diffusion

Eddies mix tracers.
But it costs (potential energy) to mix across isopycnals.

downgradient flux
locally aligned with neutral direction

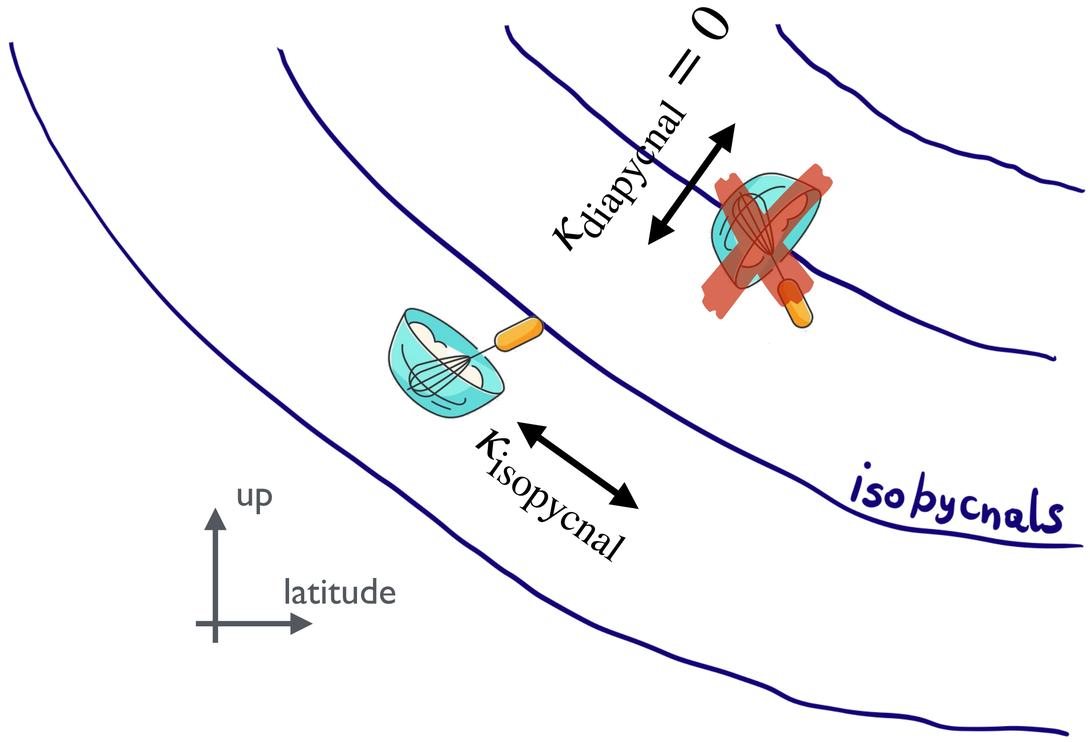
$$\overline{\boldsymbol{u}'c'} \approx -\,\mathbb{K}_{\text{eddy}} \cdot \nabla \overline{c}$$

3x3 tensor that rotates to neutral-cross neutral directions

$$\overline{\boldsymbol{u}'c'} \approx -\left(\mathbb{K}_{\text{GM}} + \mathbb{K}_{\text{Redi}}\right) \cdot \nabla \overline{c}$$

skew flux modeling stirring along isopycnals

tracer diffusion along isopycnals



[Gent & McWilliams (1990), Griffies, (1998)]

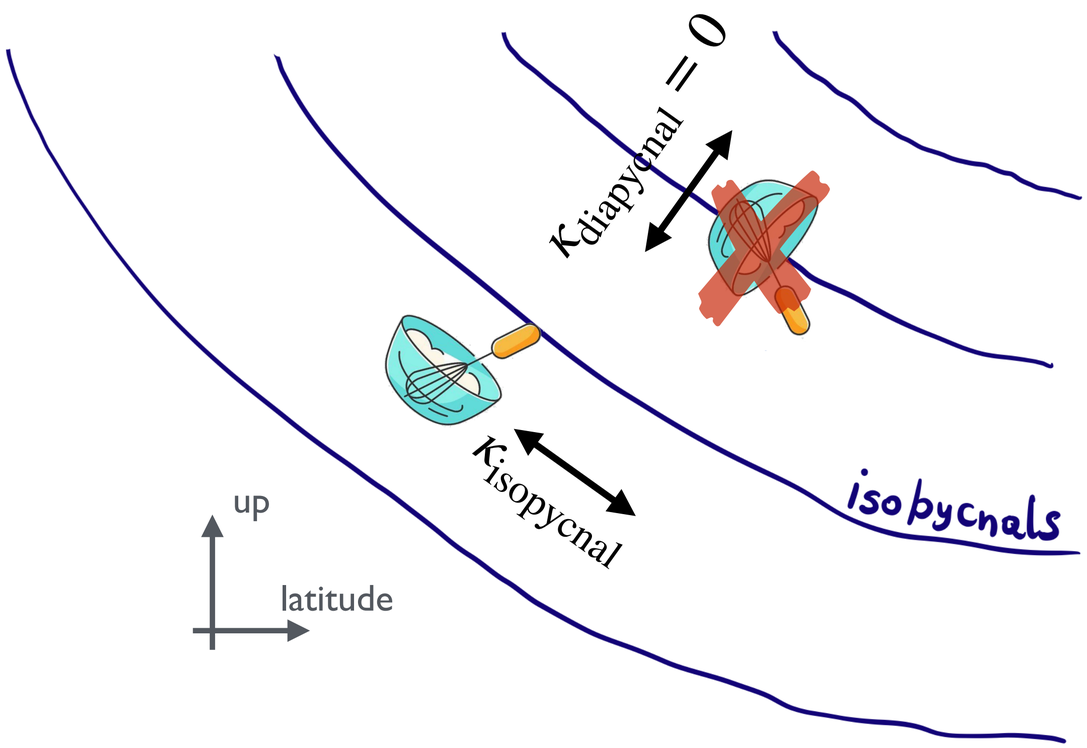
isoneutral diffusion

Eddies mix tracers.
But it costs (potential energy) to mix across isopycnals.

$$\overline{\boldsymbol{u}'c'} \approx -\left(\mathbb{K}_{\mathrm{GM}} + \mathbb{K}_{\mathrm{Redi}}\right) \cdot \nabla \overline{c}$$

skew flux modeling stirring along isopycnals

tracer diffusion along isopycnals



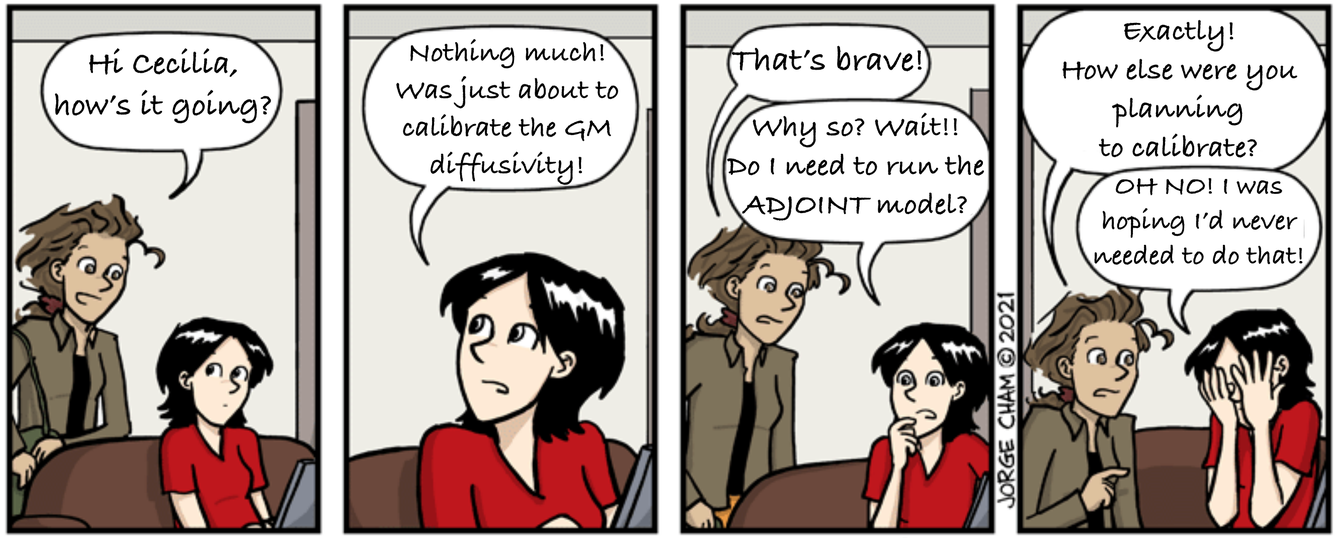
Two free parameters → κ_{GM} and κ_{Redi} diffusivities

[Gent & McWilliams (1990), Griffies, (1998)]

calibration

"All agree that calibration is great!
But most don't do it in a systematic manner
because it is so cumbersome!"

— *adage*



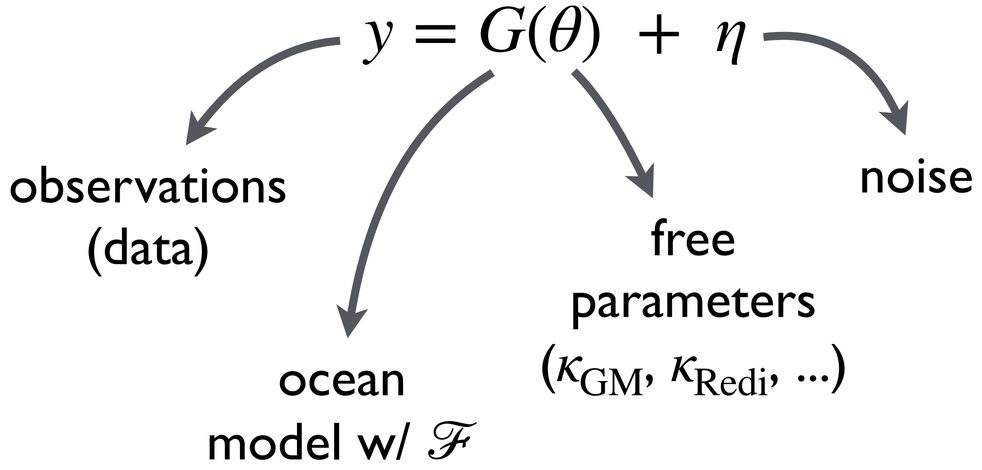
adopted from and slightly modified

derivative-free Bayesian optimization
using ensemble Kalman filters

[Iglesias et al., *Inverse Problems*, 2013]

Ensemble Kalman Inverse process

Derivative-free ensemble optimization method
that seeks to find the optimal parameters θ for inverse problem



find free parameters θ that minimize $\|y - G(\theta)\|$

Calibration is done *online* by running ***ensembles*** of ***forward*** model runs

[Iglesias et al., *Inverse Problems*, 2013]

open-source software development

Oceananigans.jl Public

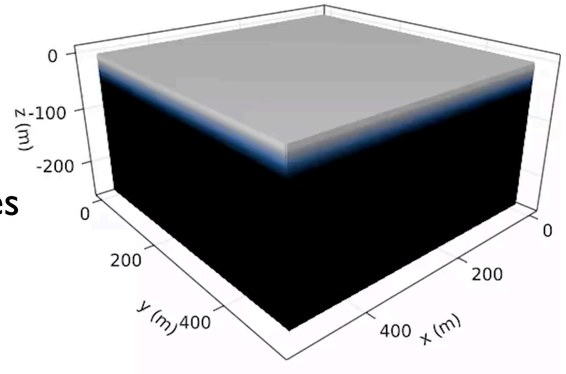
🌊 Julia software for fast, friendly, flexible, data-driven, ocean-flavored fluid dynamics on CPUs and GPUs

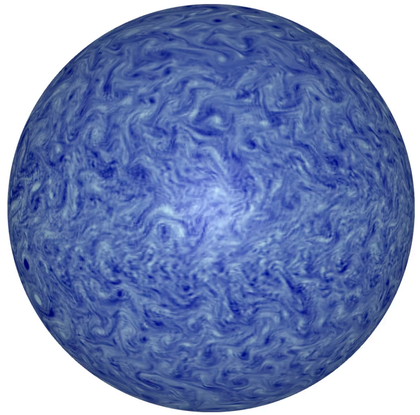
Julia ☆ 581 MIT 105 ⊙ 221 (3 issues need help) 21 Updated 4 hours ago

```
julia> N² = α * ∂z(T) - β * ∂z(S)
```

GPU-friendly finite-volume calculations on staggered grids

- Nonhydrostatic + closures for large eddy simulation
- Hydrostatic w/ free surface + boundary layer, mesoscale closures
- **Model ensembles: 1D columns, 2D slices**



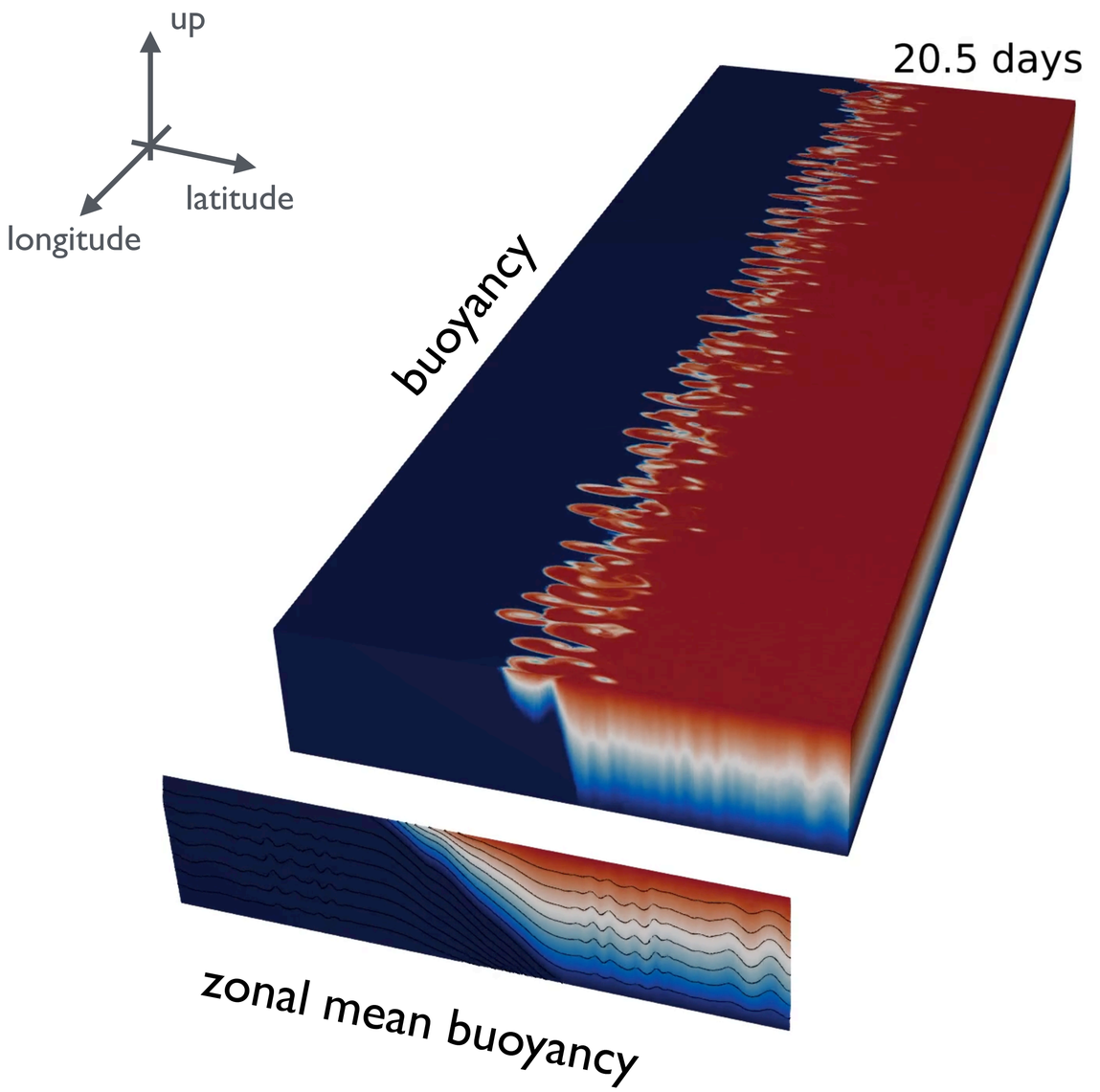


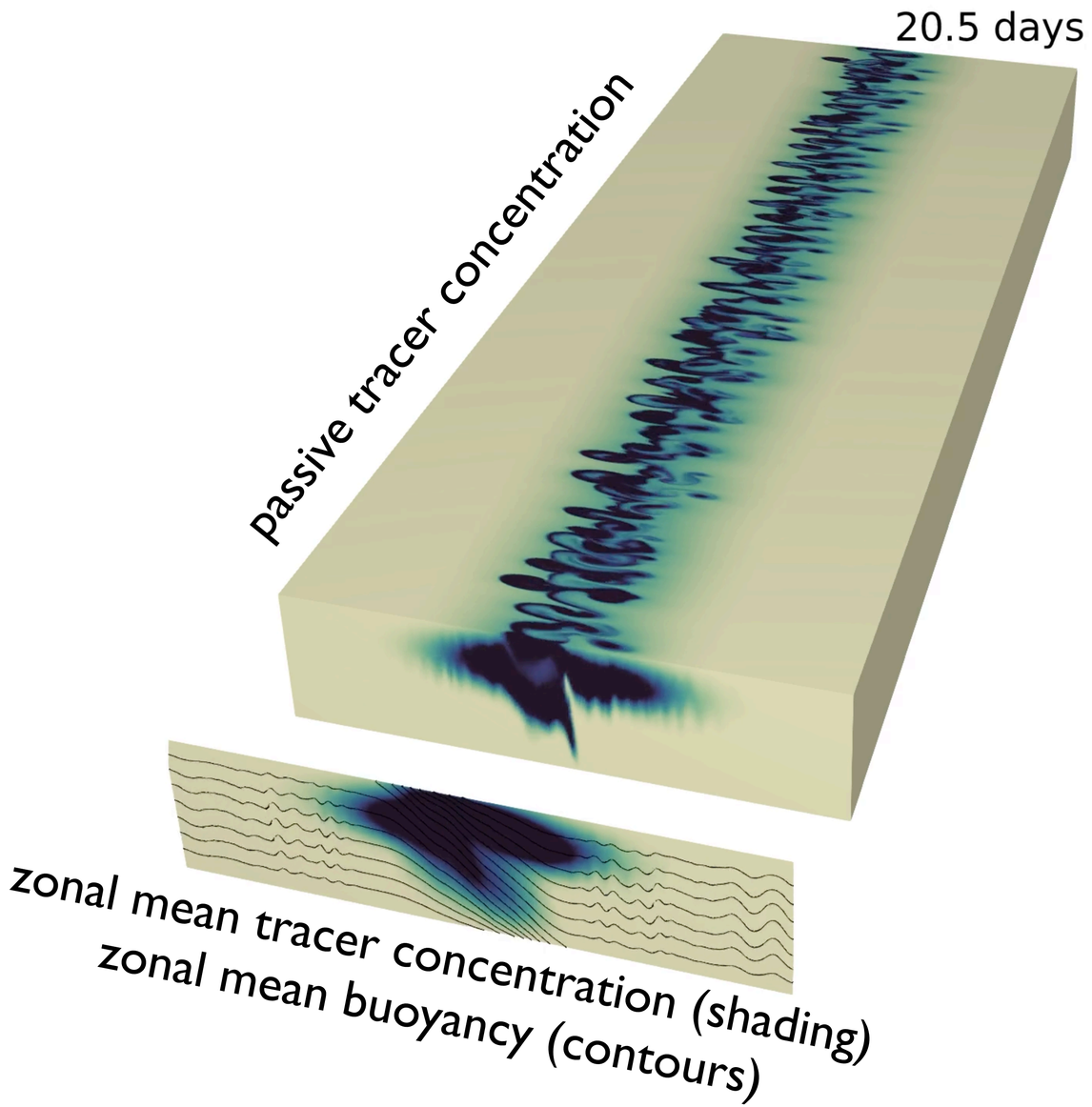
OceanTurbulenceParameterEstimation.jl Public

Estimation of turbulence closure parameters for ocean models using Ensemble Kalman Inversion.

Julia ☆ 5 MIT 2 ⊙ 19 4 Updated 9 minutes ago

baroclinic adjustment of a front





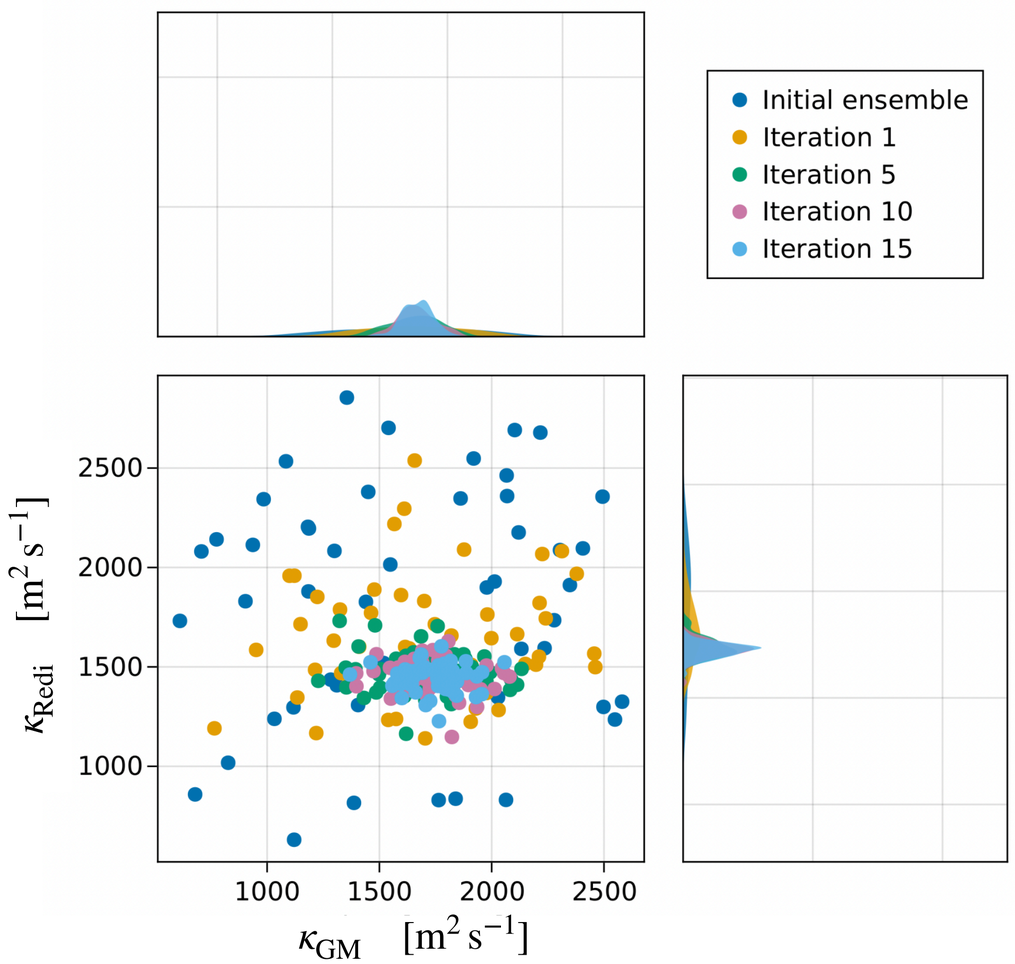
model diffusivities calibration using Ensemble Kalman Inverse process

ensemble (50) of 2D (lat-depth) simulations w/ GM parametetrization

initialize with zonal-mean state from equilibrated 3D simulation

run forward for 1 day

Update diffusivities via EKI to minimize $\|y - G(\theta)\|$



OK, so what?

we can easily calibrate free parameters of a turbulence closure

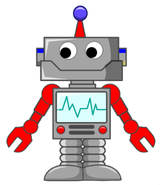
we can even calibrate *simultaneously* across various scenarios
and find optimal parameters that are robust

add depth/time/anything dependence in free parameters is trivial

any parametrization obtained this ways
is, *by construction*, numerically stable
when added back to the model

but that's only the beginning

Oceananigans.jl



produce data
(high-resolution models,
LES, DNS)
or gather observations
and use as "ground truth"

use physical intuition
enhance parametrizations
(add physics, not `if`-statements)

possibly this adds few
more free parameters

when cycle
"converges"

implement in
climate model

calibrate free parameters
to *robustly* match data
across various scenarios

Ensemble Kalman
Processes

the music in this talk was from the song

“From little things big things grow”

by

Paul Kelly