Parameterizing vertical mixing in global ocean models: progress and challenges

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REVIEWS

The polar ocean and glacial cycles in atmospheric CO_2 concentration

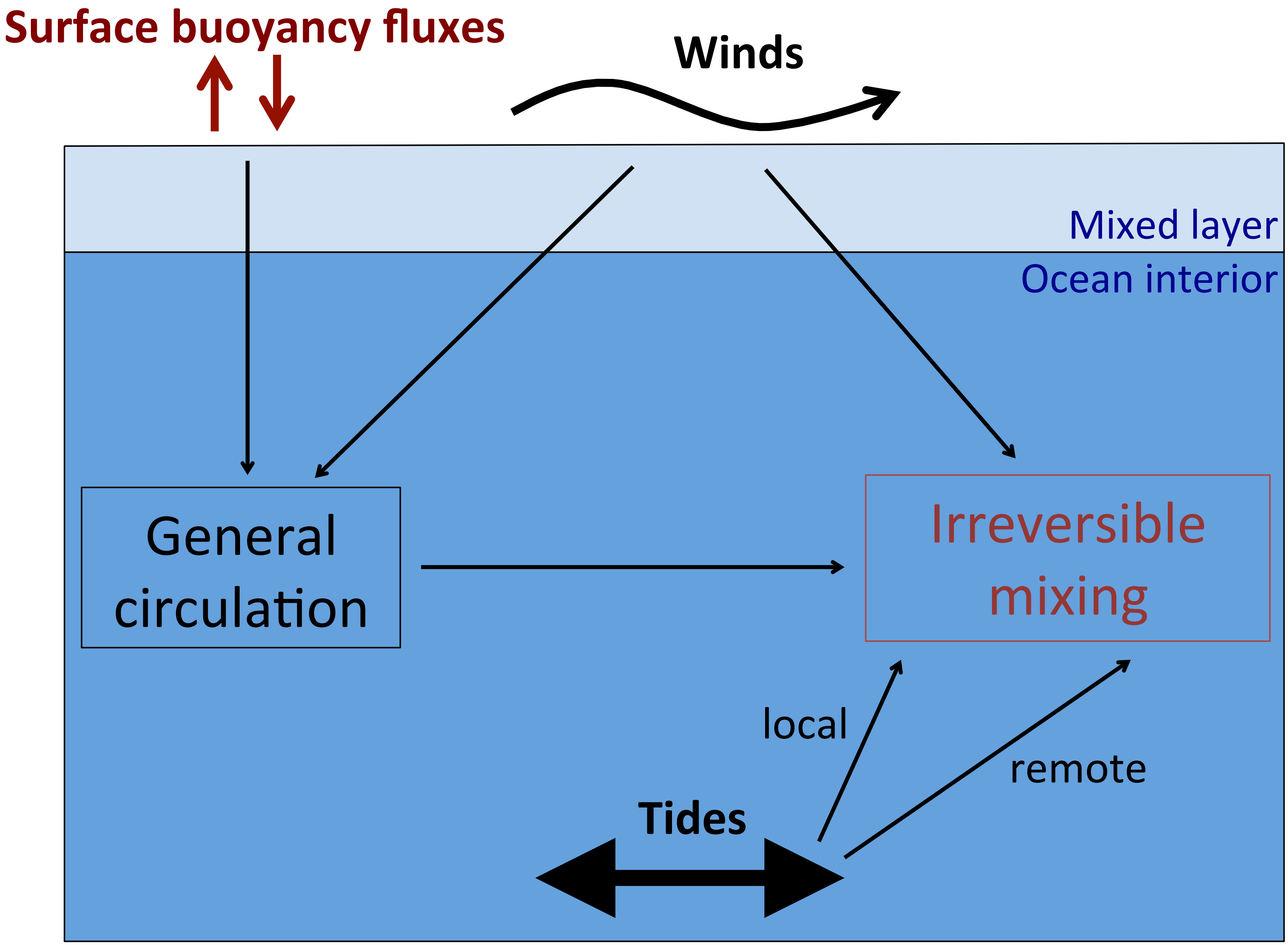
Daniel M. Sigman[1], Mathis P. Hain[1,2] & Gerald H. Haug[2,3]

"In defence of the stratification hypothesis, **the models' calculation of mixing between different density waters in the ocean interior is highly suspect**, and yet this mixing is central to the models' tendency for inverse behaviour between North Atlantic and Antarctic overturning.

The models can have too much deep mixing, and they **generally do not take into account the fact that more energy is required to mix across a greater density difference.**

Deep mixing may be the Achilles' heel of the models that has prevented them from capturing a climate change that greatly decreases the global demand for new deep water."

Energy flows from forcing to dissipation



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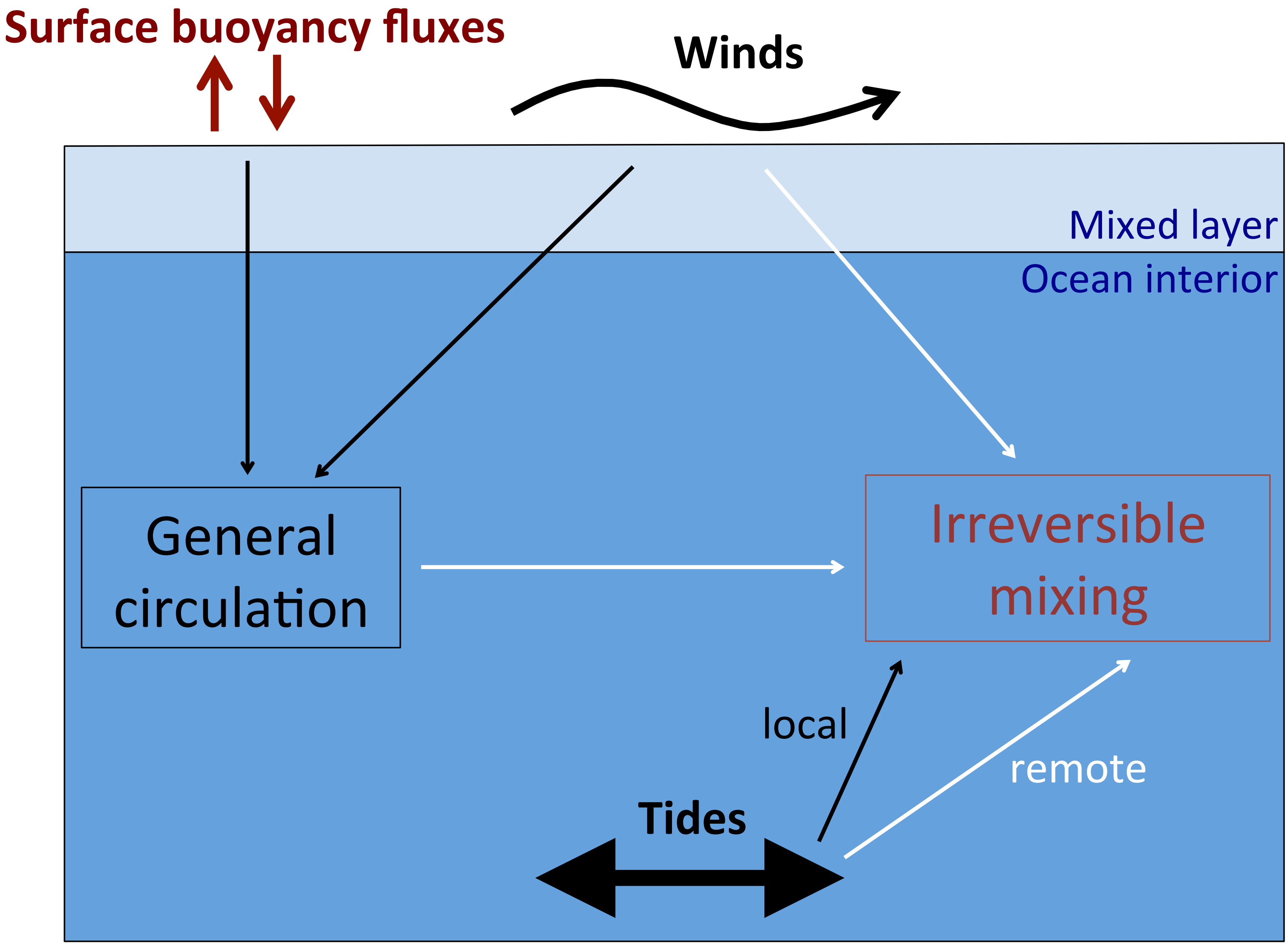
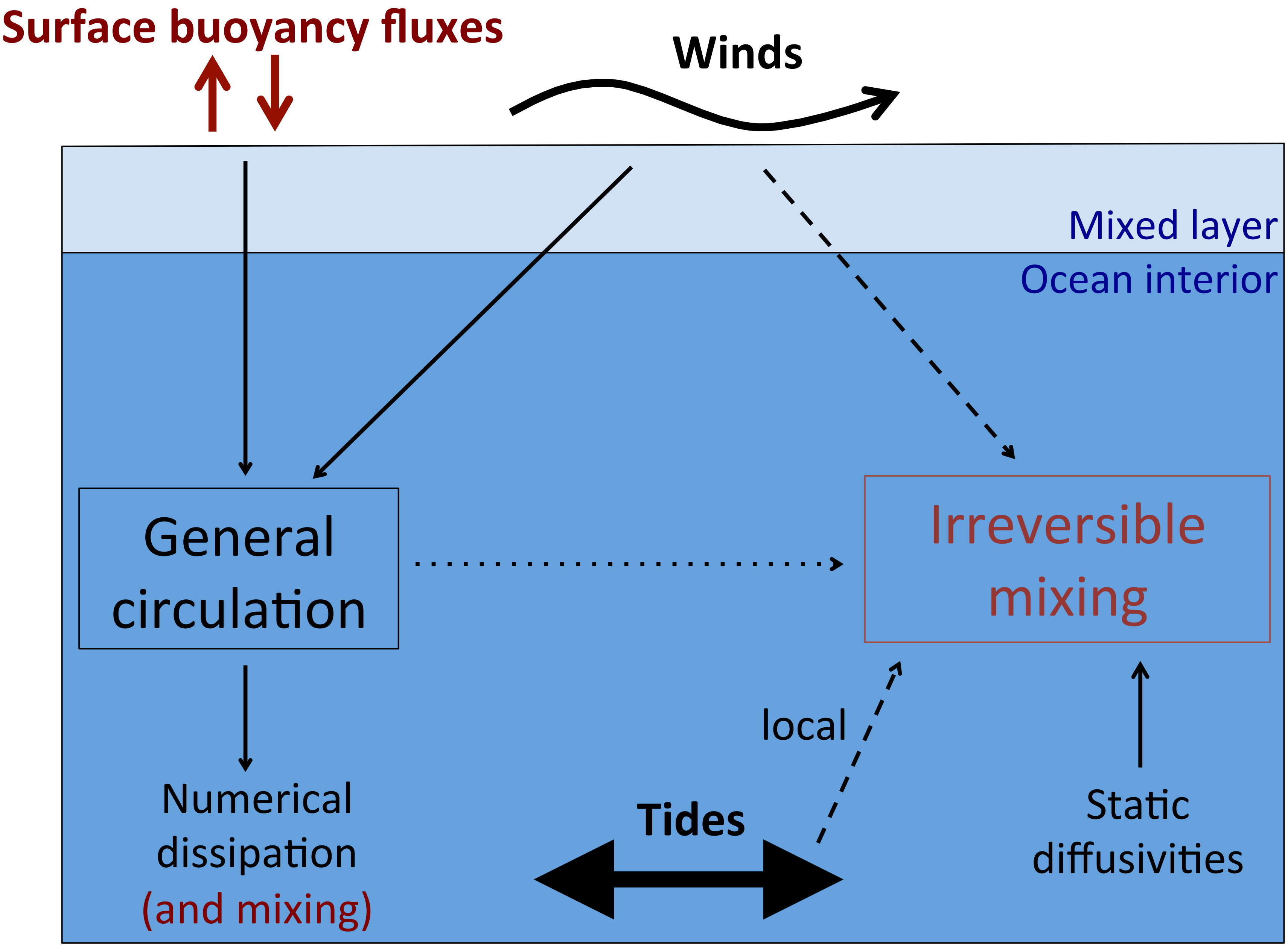


Energy flows **in ocean models**



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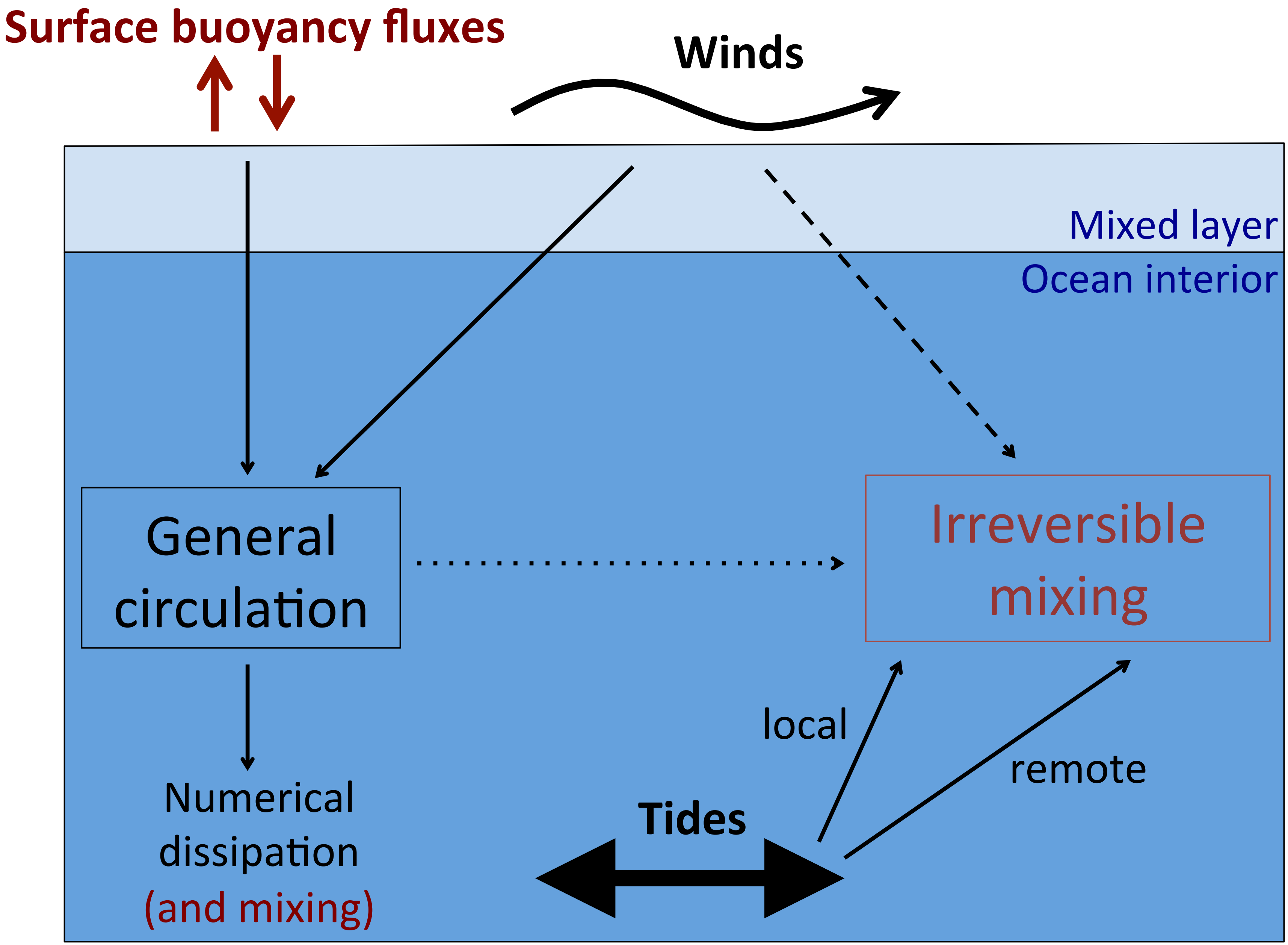

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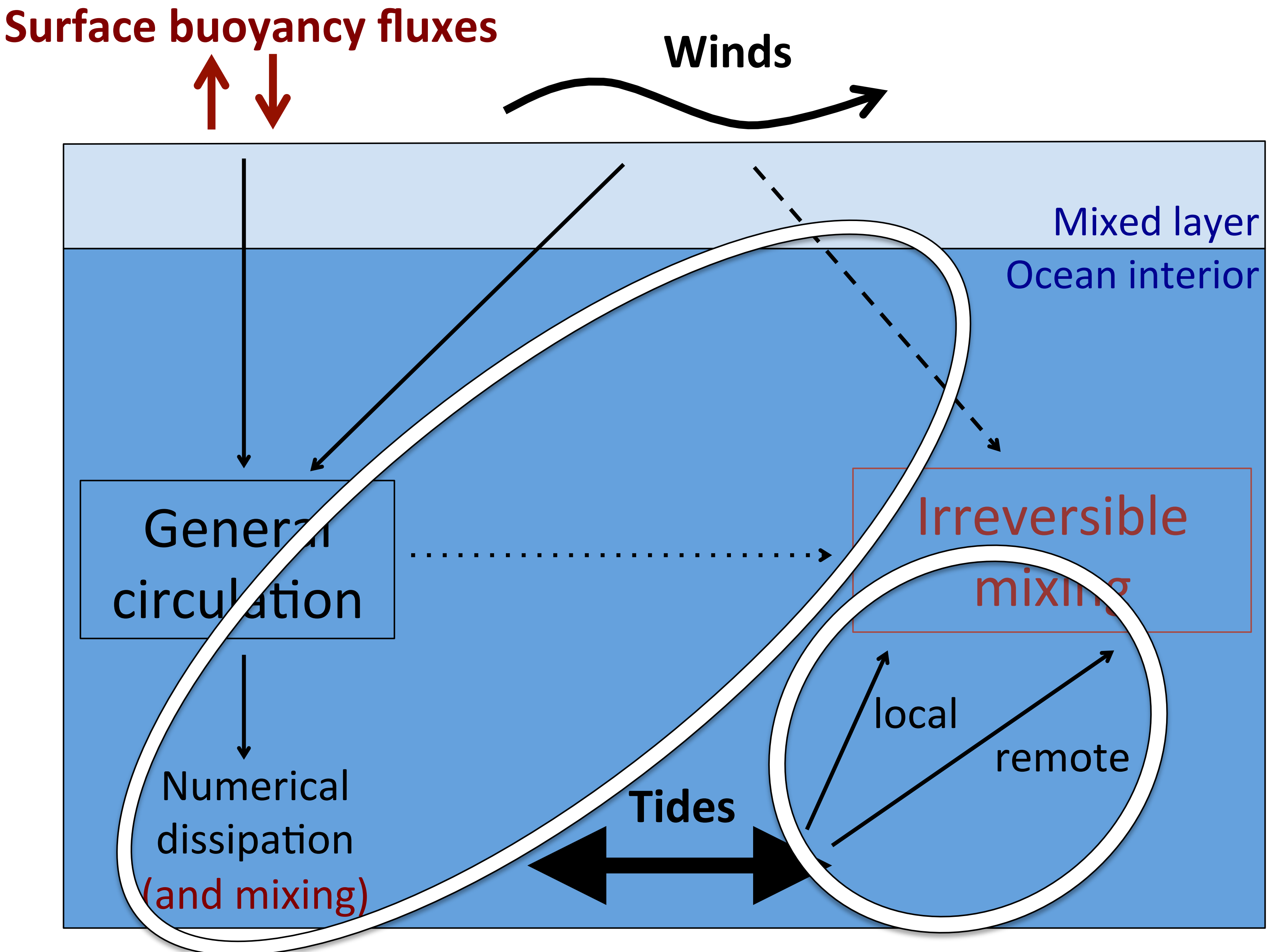

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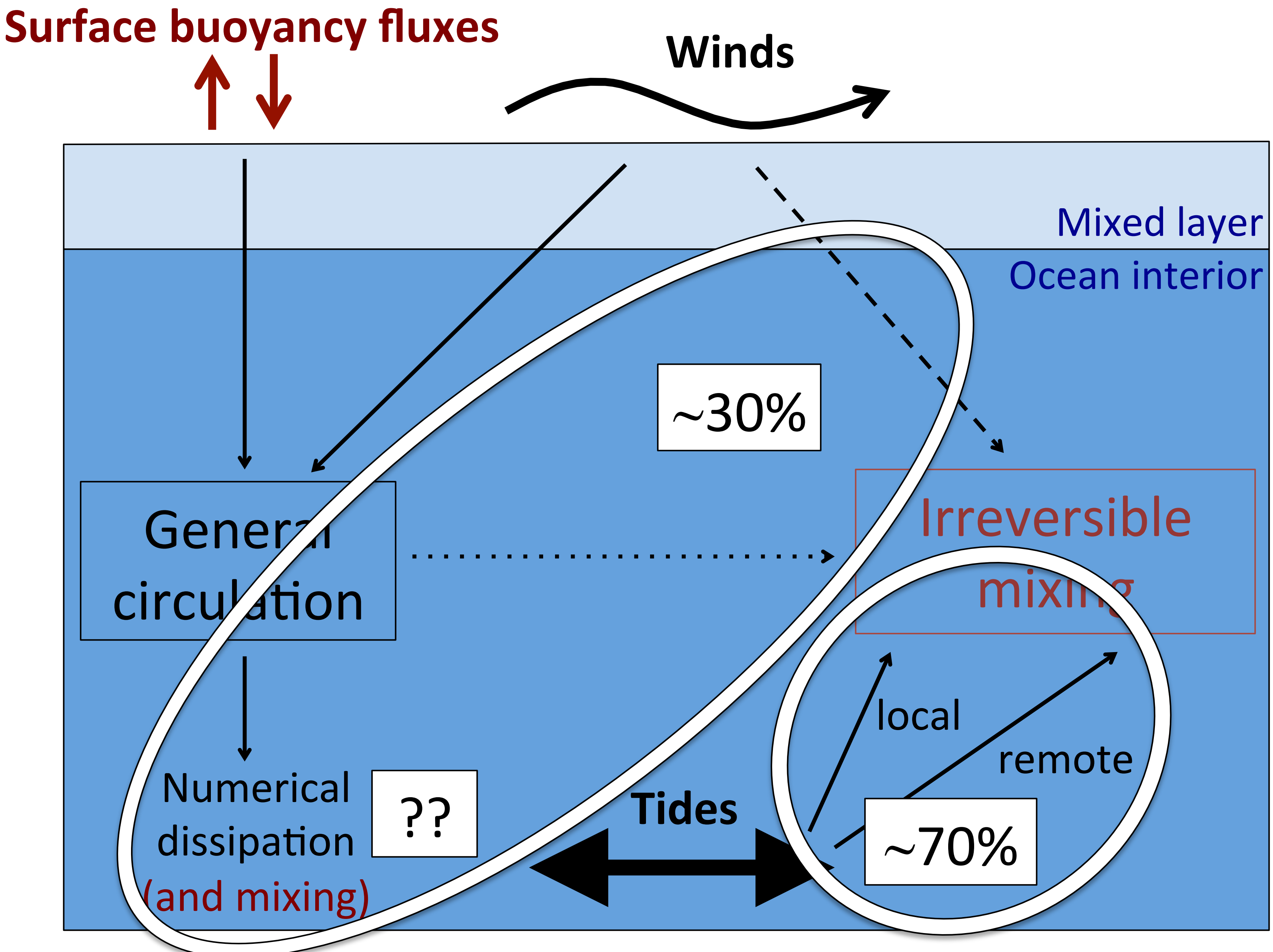

Outline

1. Progress: new tidal mixing schemes

- Rationale
- Impact in global ocean simulation
- Comparison to mixing observations

2. Challenges:

- Wind-induced inertial oscillations
- Submesoscale instabilities
- Numerical mixing

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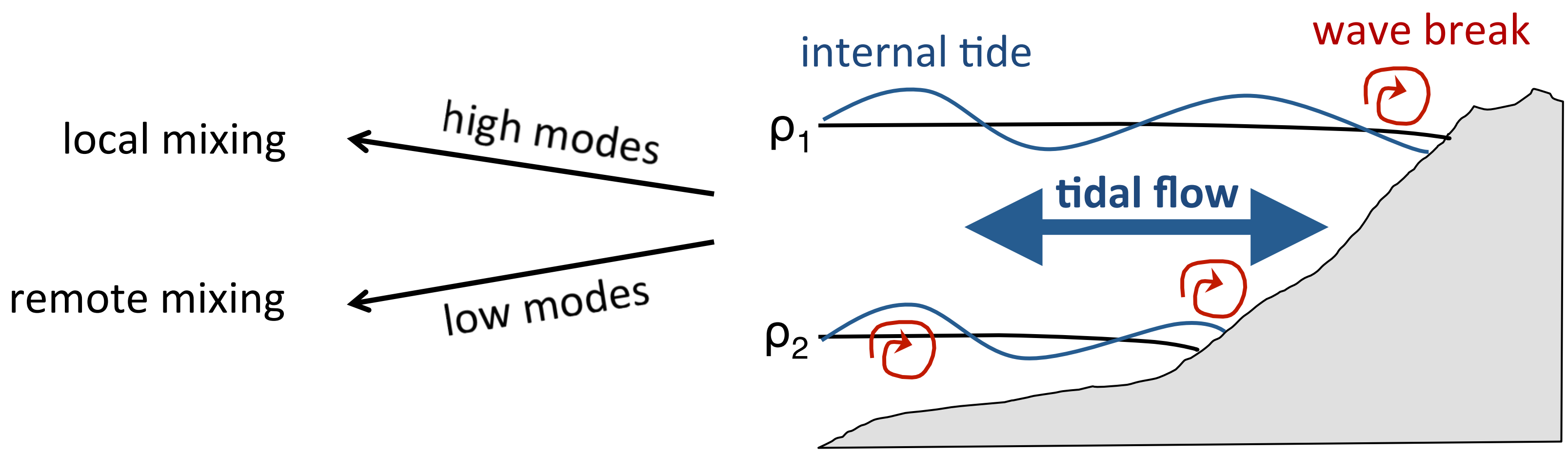
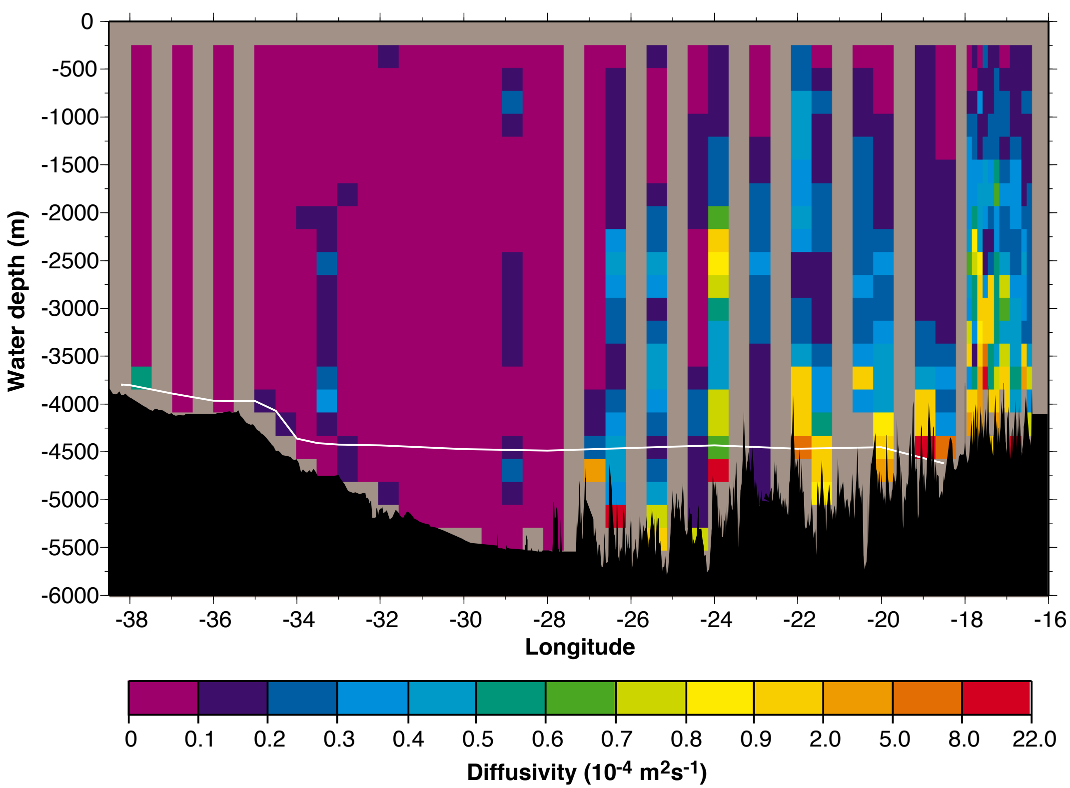
Local and remote tidal mixing





Depth-longitude transect of turbulent diffusivity across the Brazil Basin.

From Polzin et al. (1997).

Old practice in global ocean models

- Remote: tuneable background K_z ($\approx 10^{-5}\ m^2s^{-1}$).
  - Independent of ocean state.
  - No control on (evolving) energy required to maintain such background mixing.
- Local: bottom-intensified mixing energy.
  - 2D map of locally-dissipating internal tide energy (qE).
  - Fixed (exponential) vertical energy structure (F).

$$K_z = 0.2\, qE\, F / \rho N^2$$

New schemes

- No background diffusivity.
- All mixing comes from known energy sources.
  - Read static 2D maps of power input to internal tides.
  - Redistribute this power within simulated stratification.
  - Deduce Kz from local dissipation ε via a standard turbulent closure (e.g. zero order, $Kz = R_f\, \varepsilon / N^2$).

Eden and Olbers 2014, de Lavergne et al. 2020

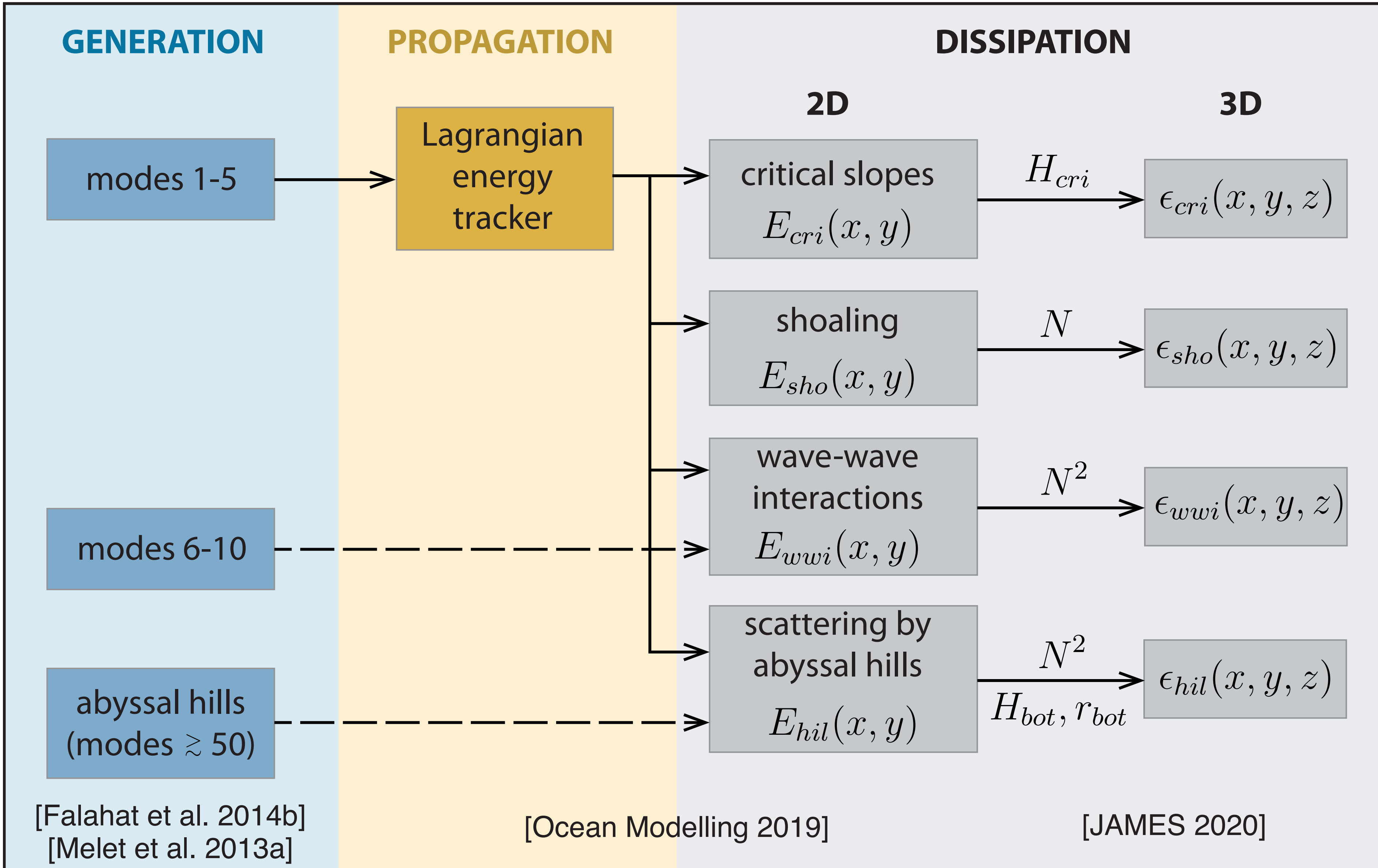
Online vs offline strategy

Internal tide lifecycle stage	Eden and Olbers 2014	de Lavergne et al. 2020
GENERATION	offline	offline
PROPAGATION	online	offline
2D DISSIPATION	online	offline
3D DISSIPATION	online	online

interactivity **vs** **accuracy**

Methodology (de Lavergne et al. 2020)

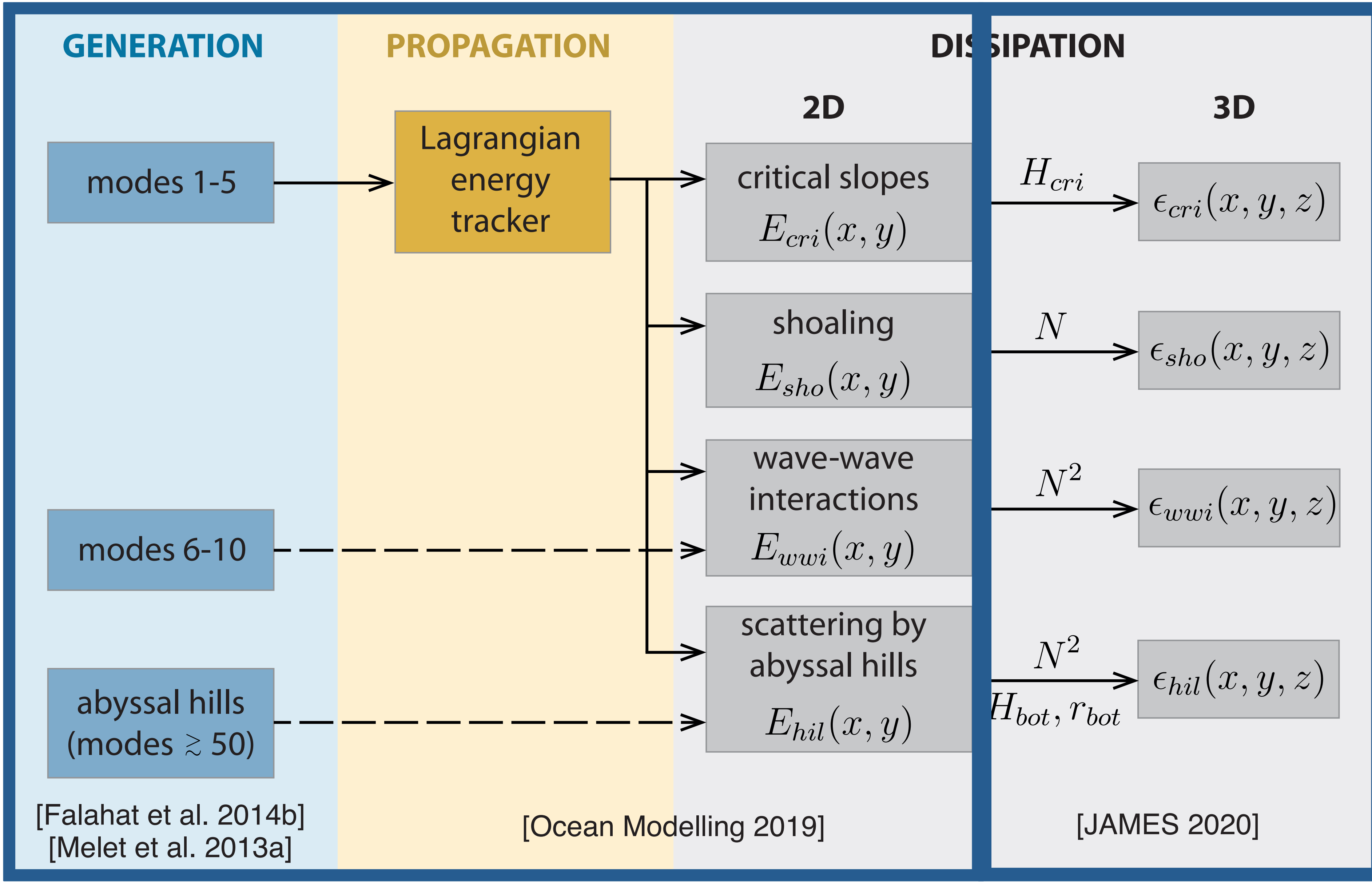
Mode-by-mode tracking of energy from sources to sinks



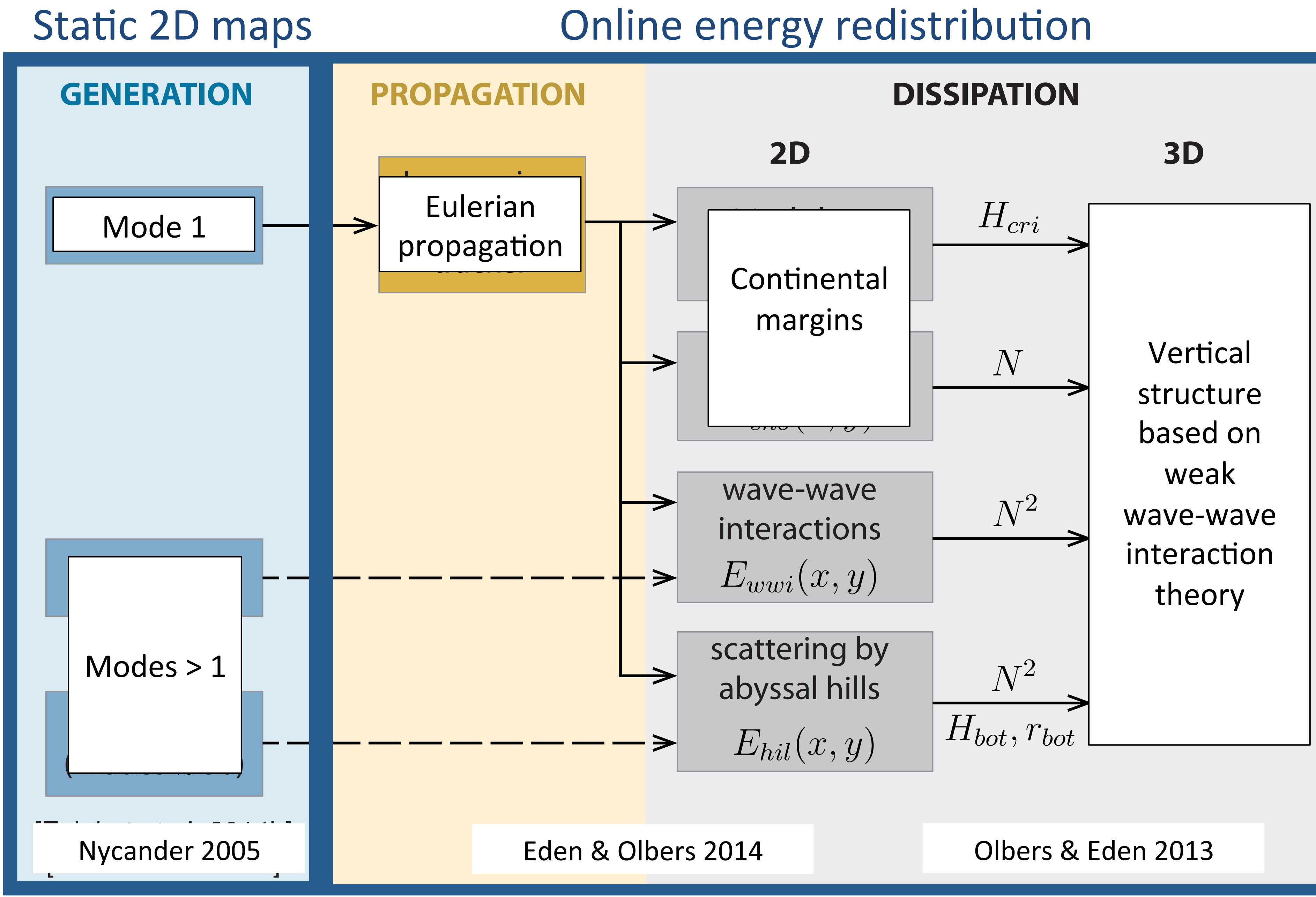
Methodology (de Lavergne et al. 2020)

Static 2D maps of depth-integrated dissipation

Vertical structures



Methodology (Eden and Olbers 2014)



Tracking low modes from sources to sinks

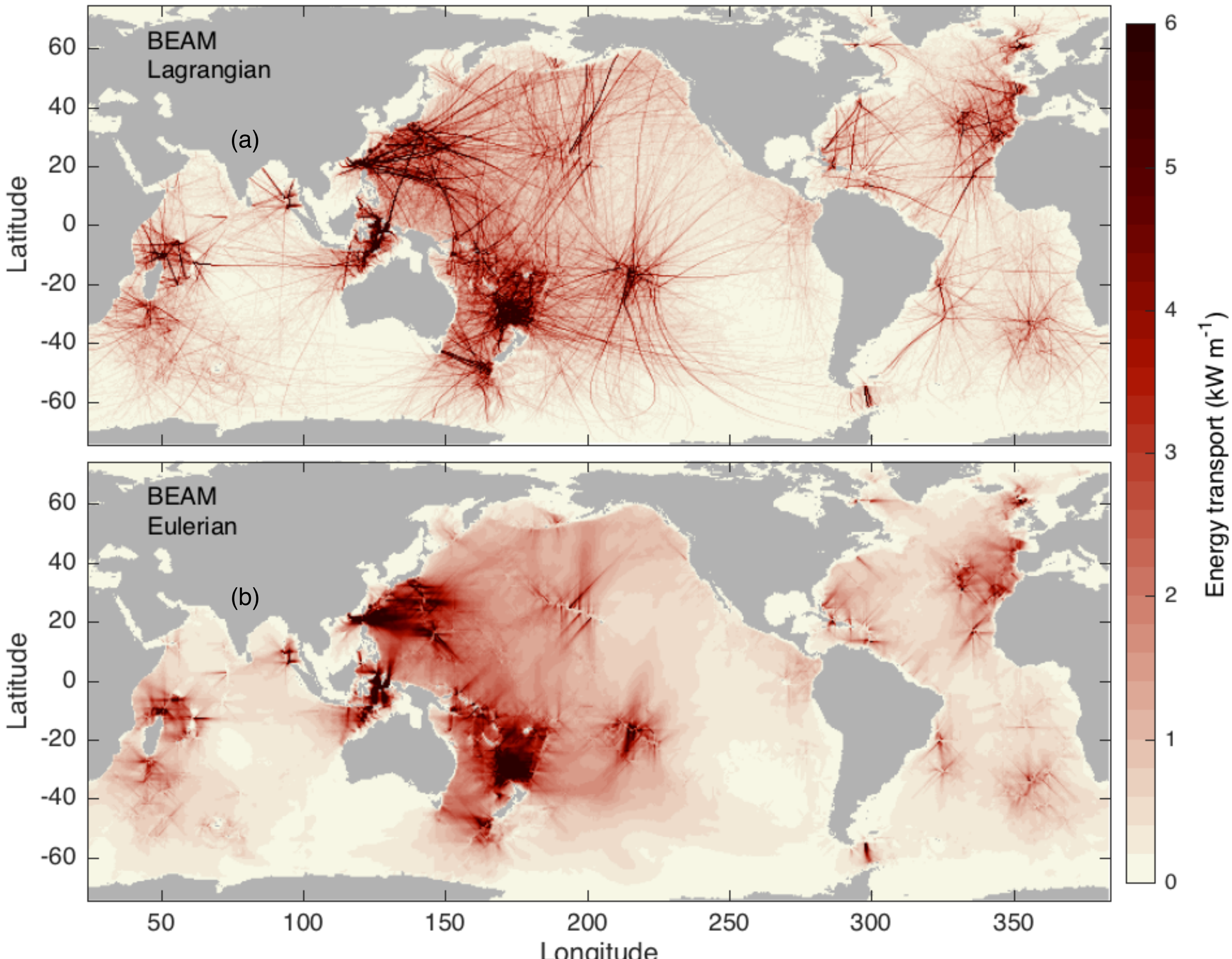
Evolution equation for a given mode's column-integrated energy $E(t,x,y,\phi)$:

$$\partial_t E + \mathrm{div}_{\vec{r},\phi}\,\vec{F} = G - D$$

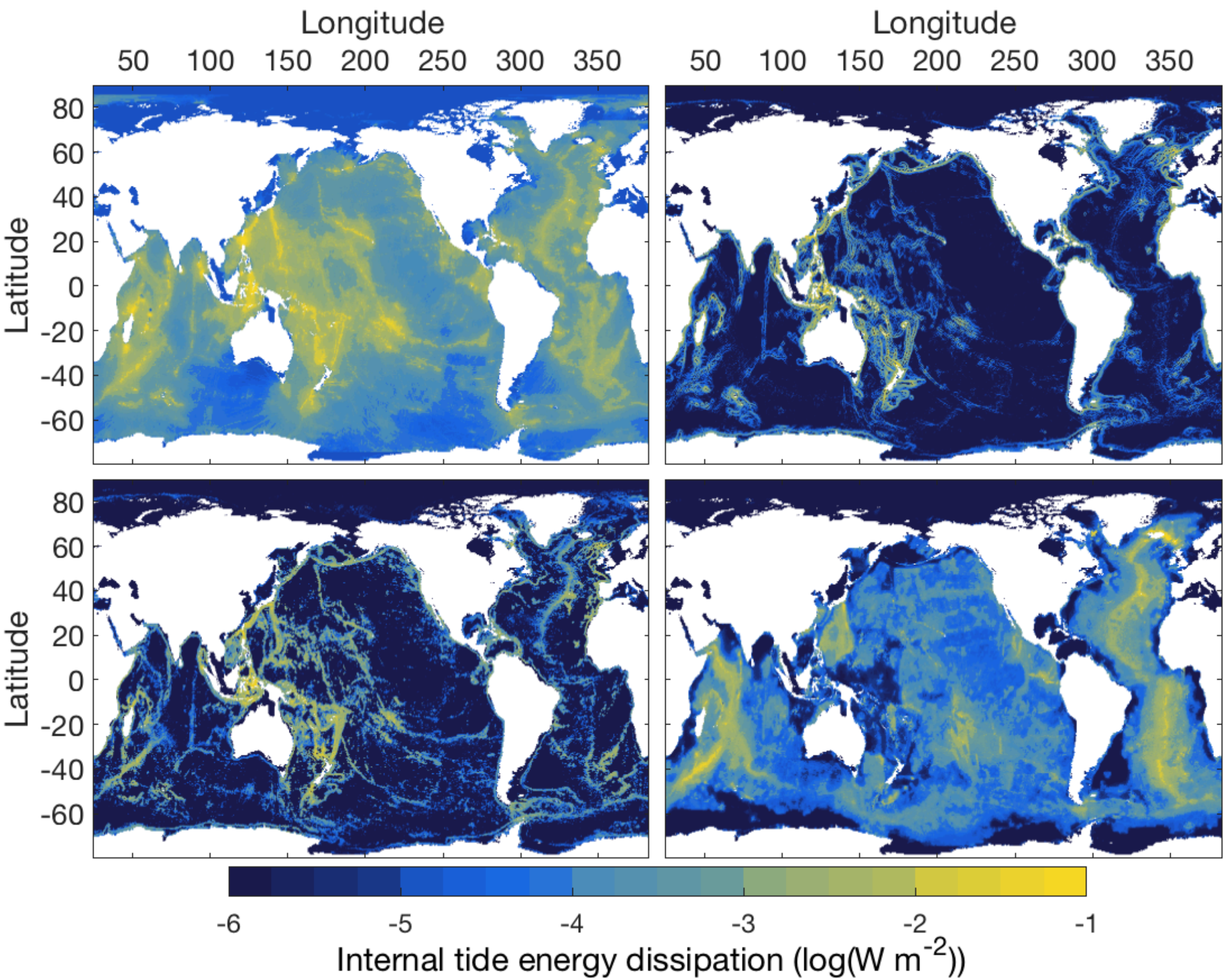
D: energy sinks.
G: angle- and position-dependent generation rate of considered mode.
F: horizontal energy transport by modal group velocity: $\vec{F} = \vec{c_g} E$

- 60 maps: 5 vertical modes (1 to 5)
  x 3 tidal constituents (M_2, S_2 and K_1)
  x 4 dissipative processes.

Lagrangian versus Eulerian scheme



4 static maps...



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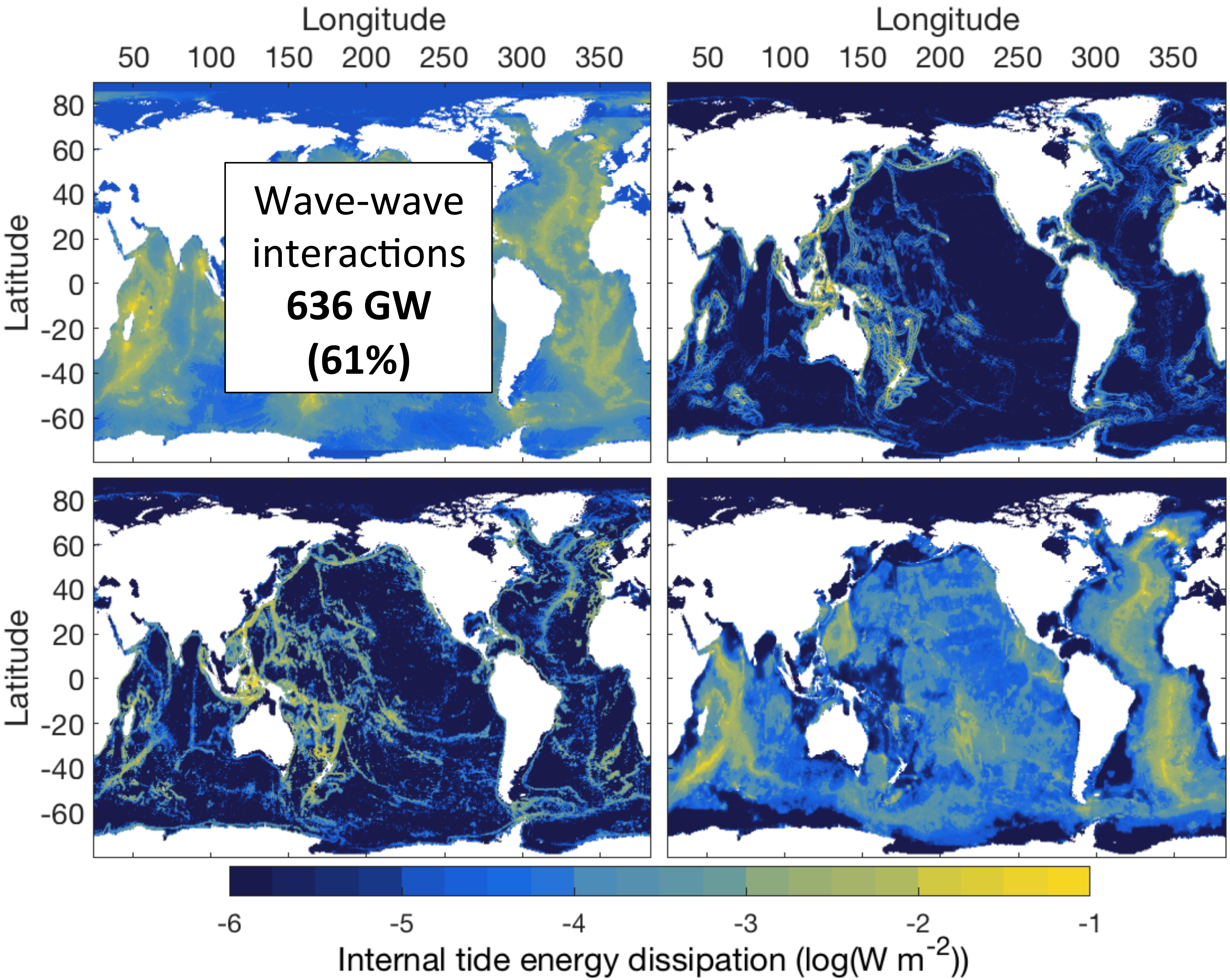

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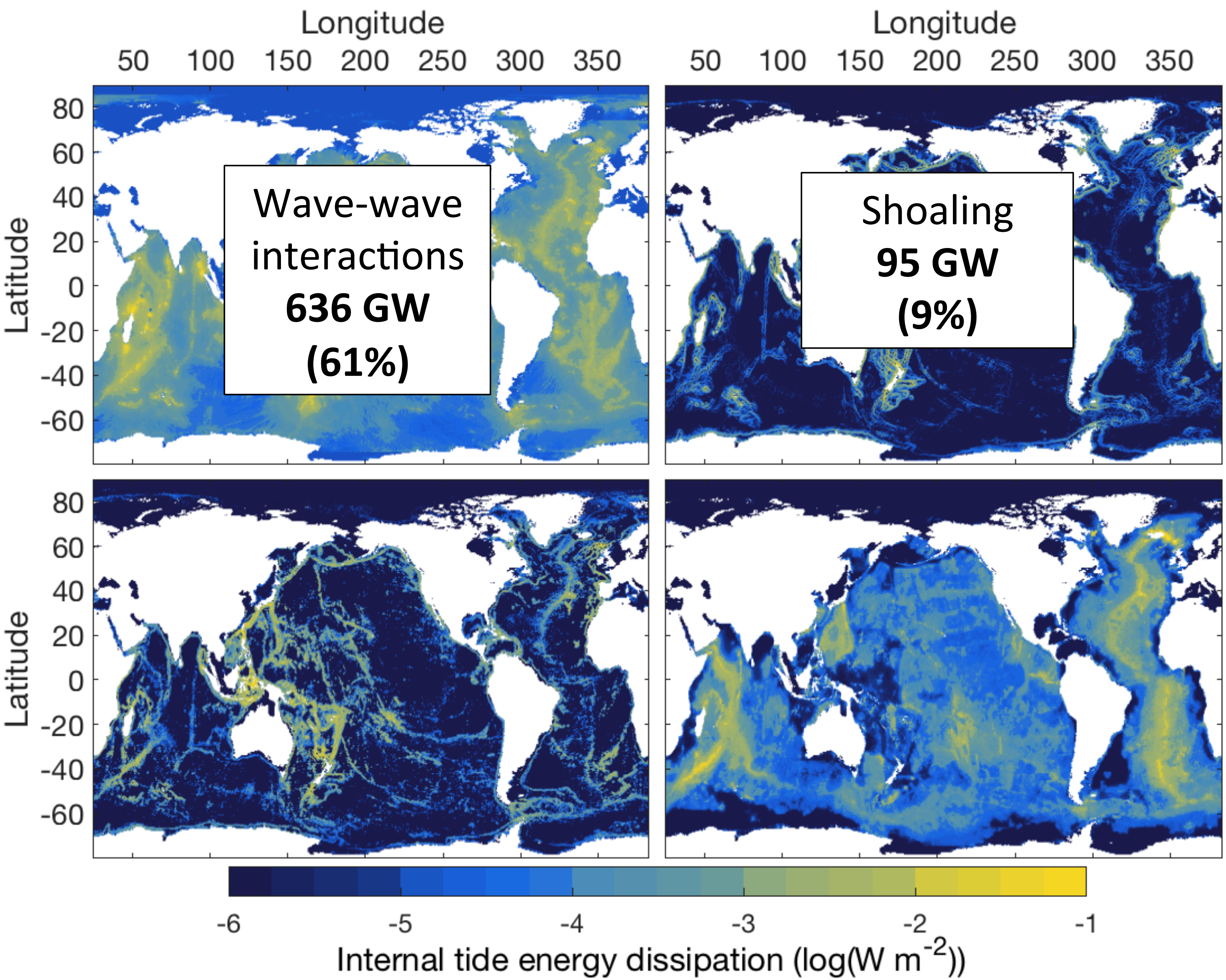

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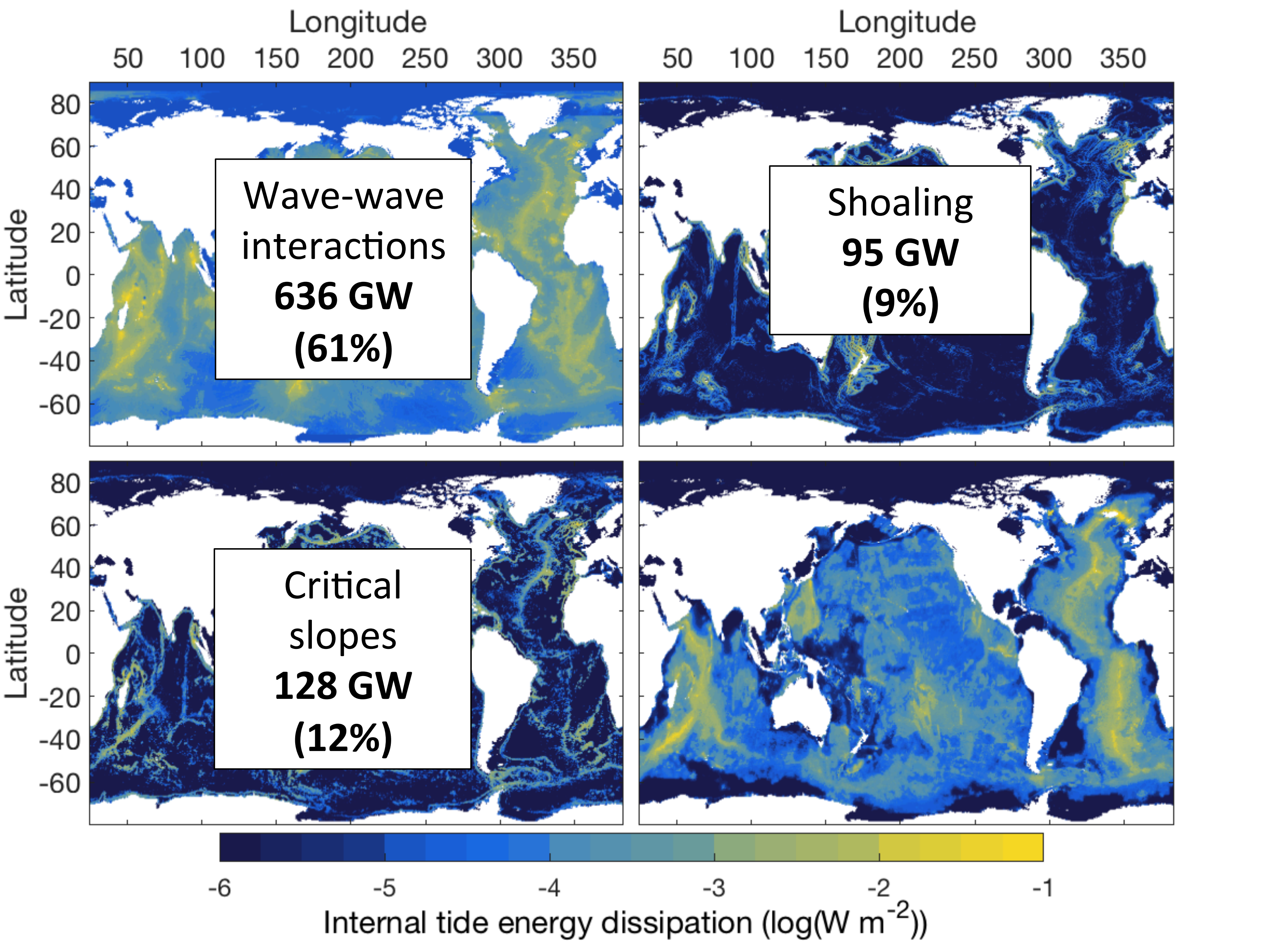

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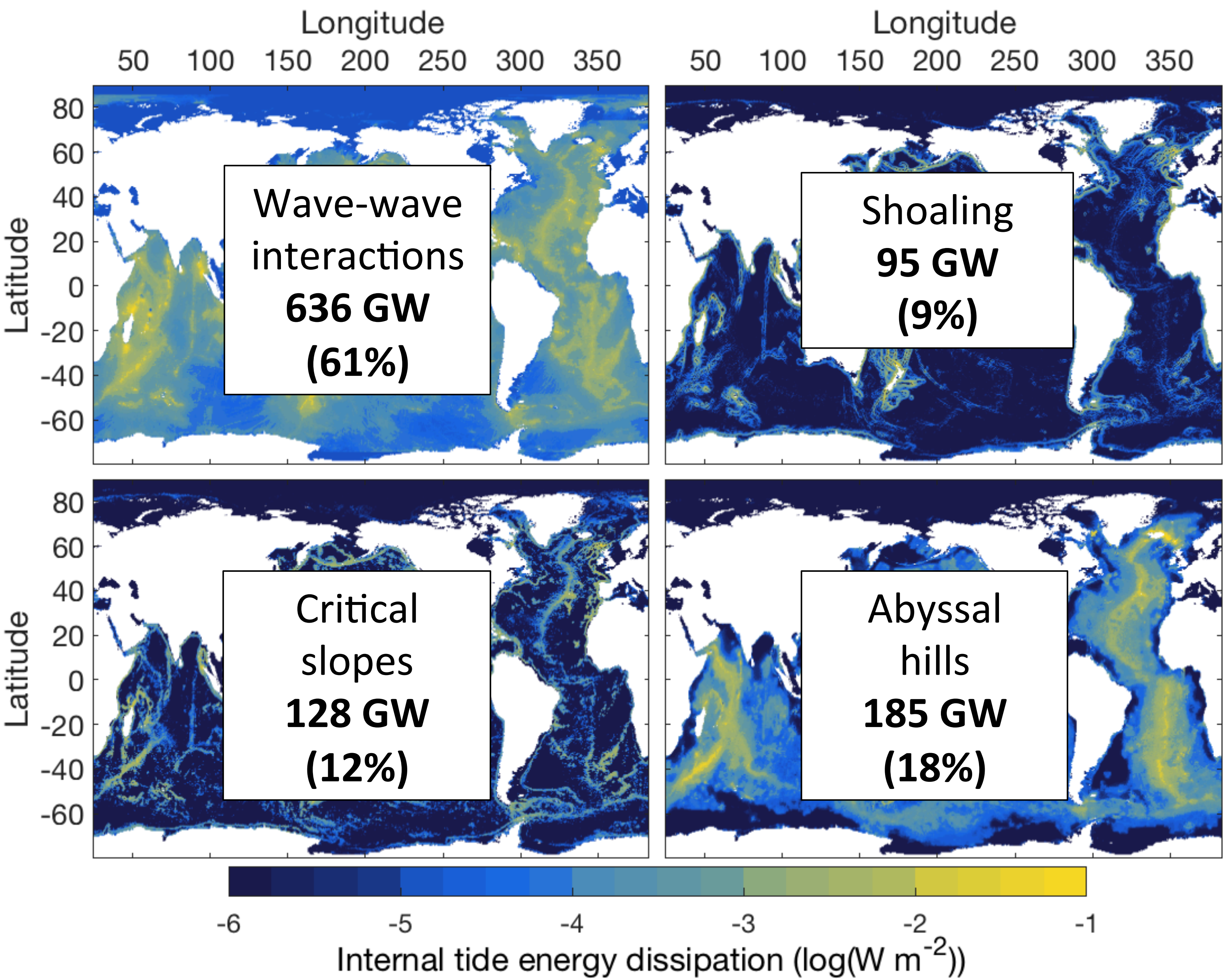
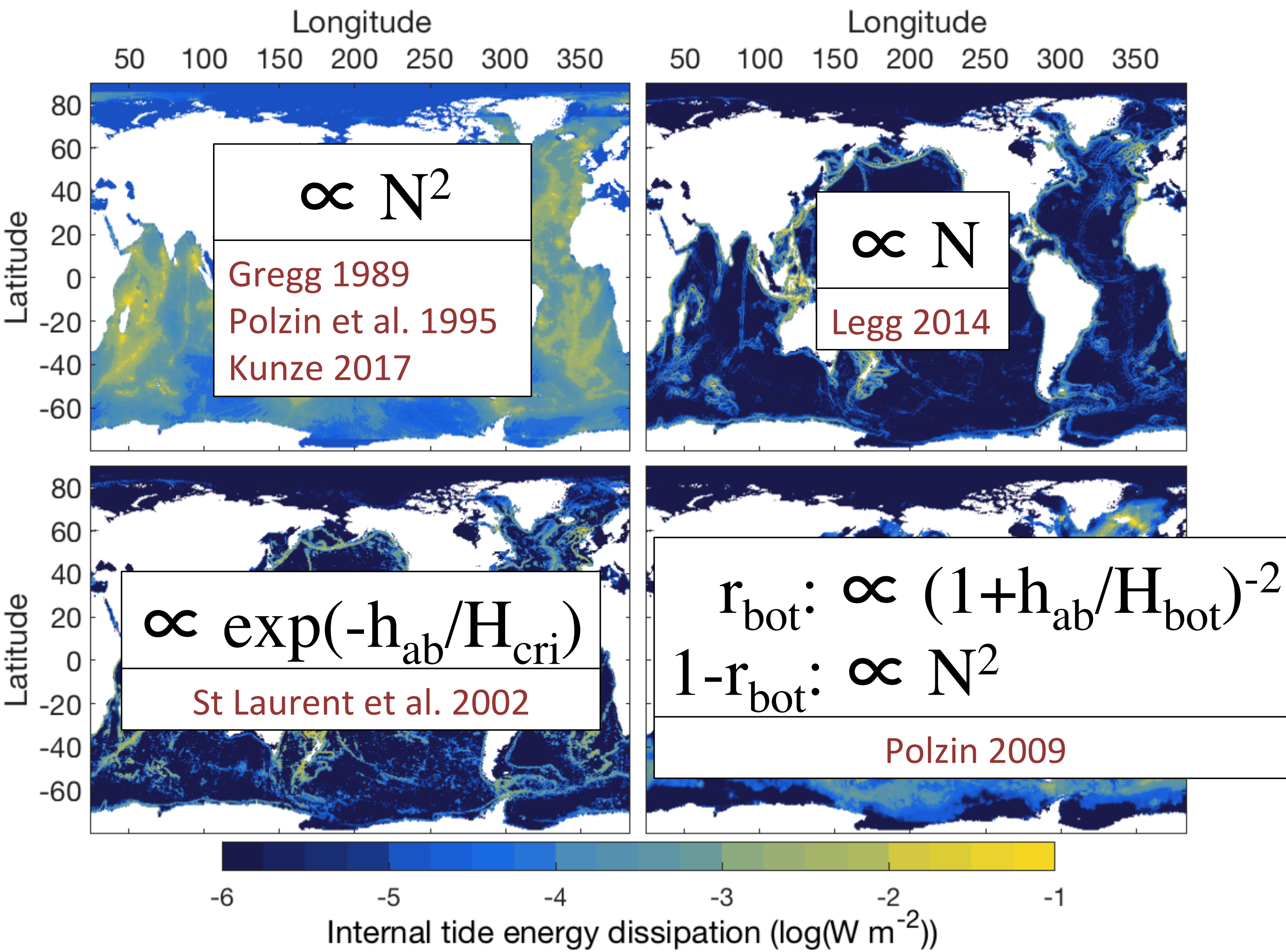


…and 4 vertical structures



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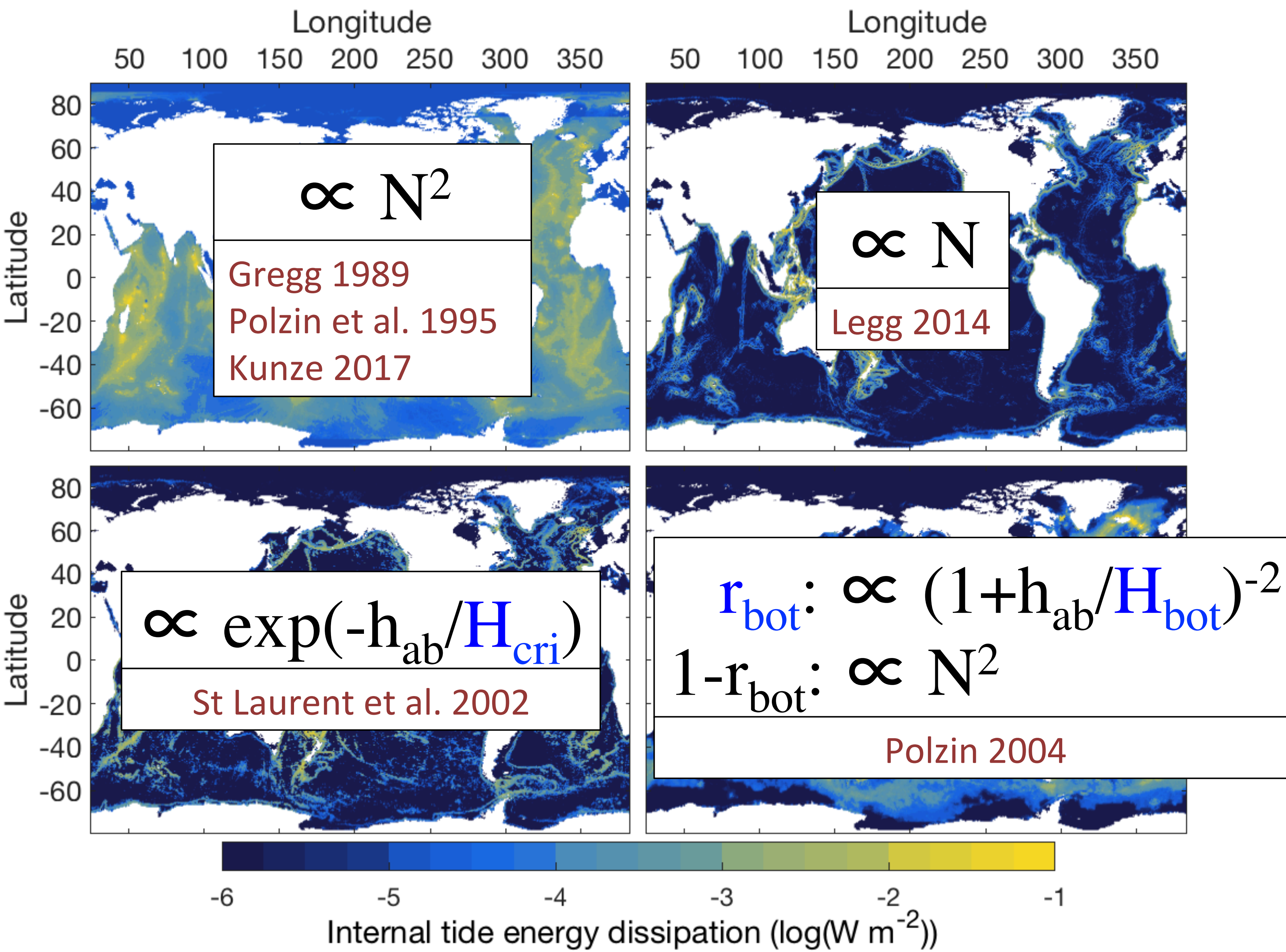
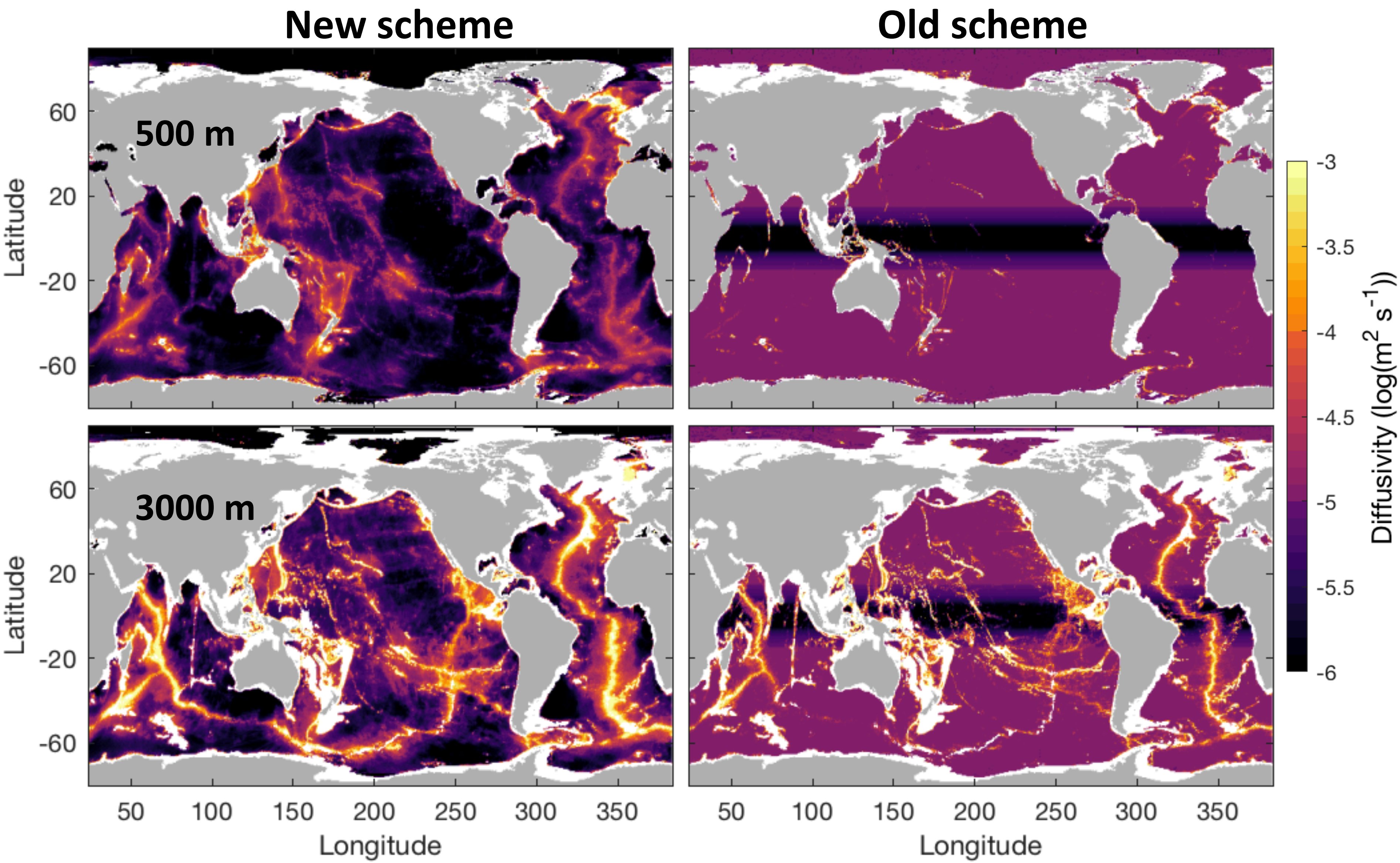
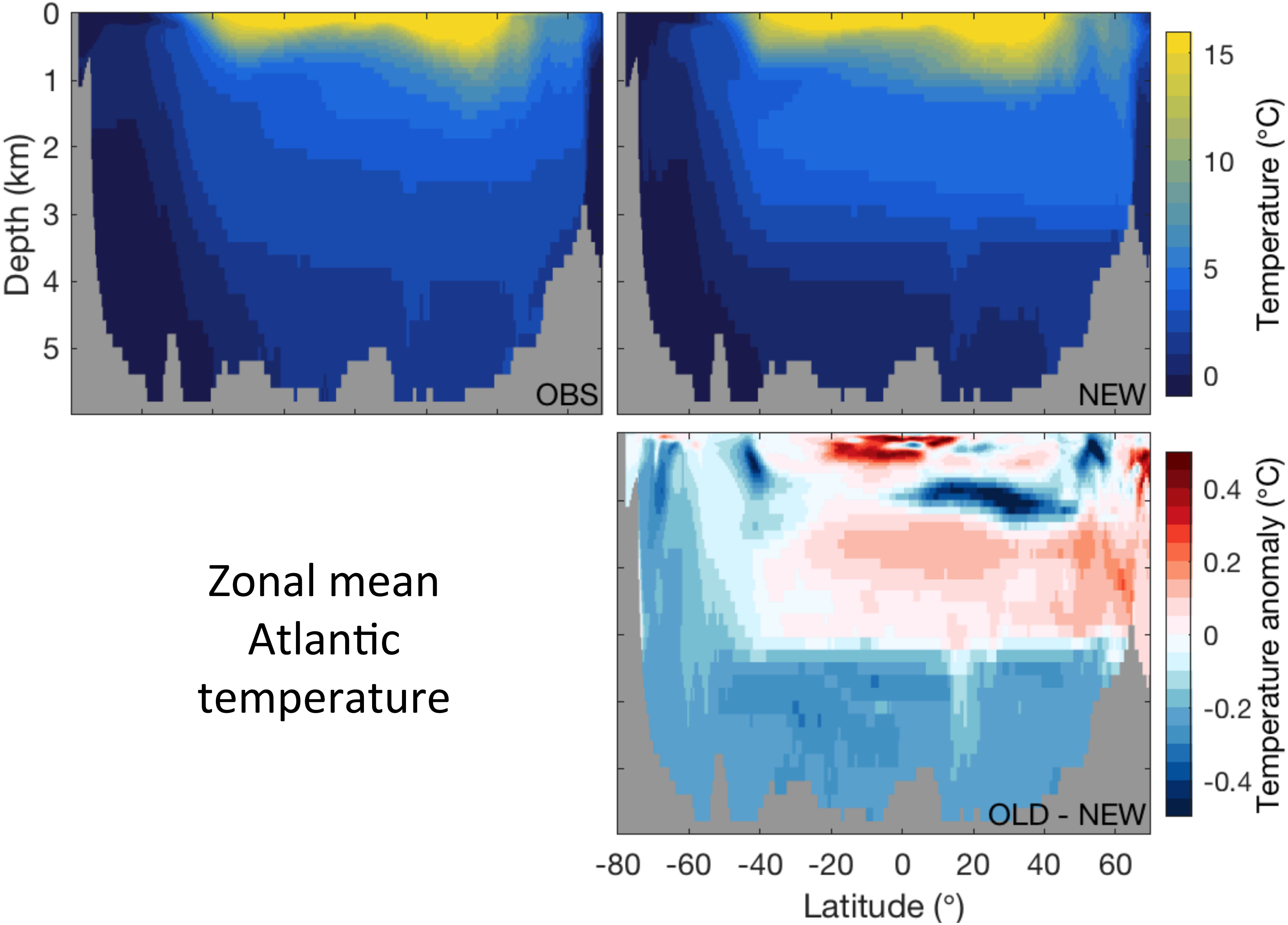


Diffusivity distribution



Impact in NEMO 1° global ocean model



Zonal mean
Atlantic
temperature

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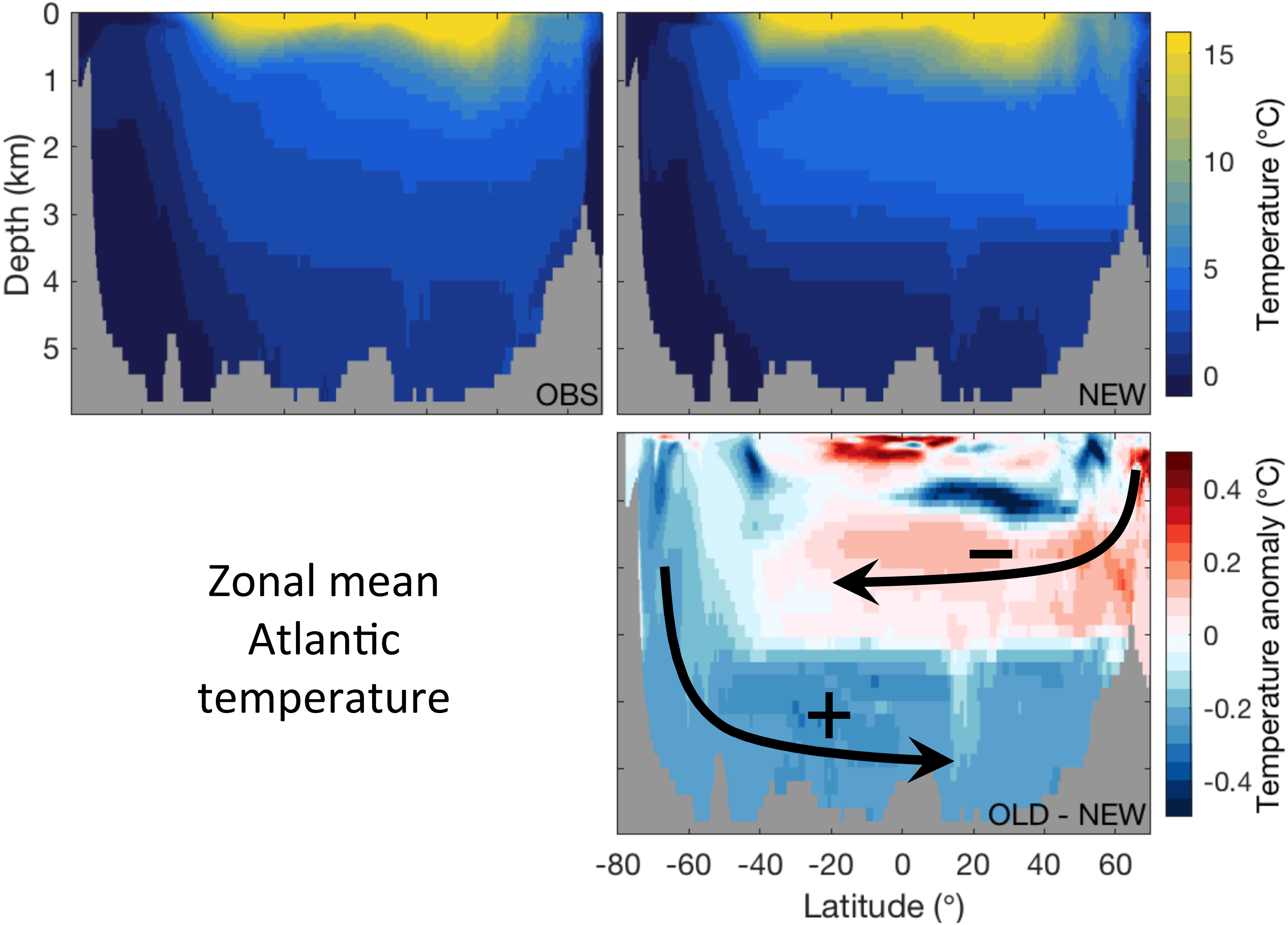

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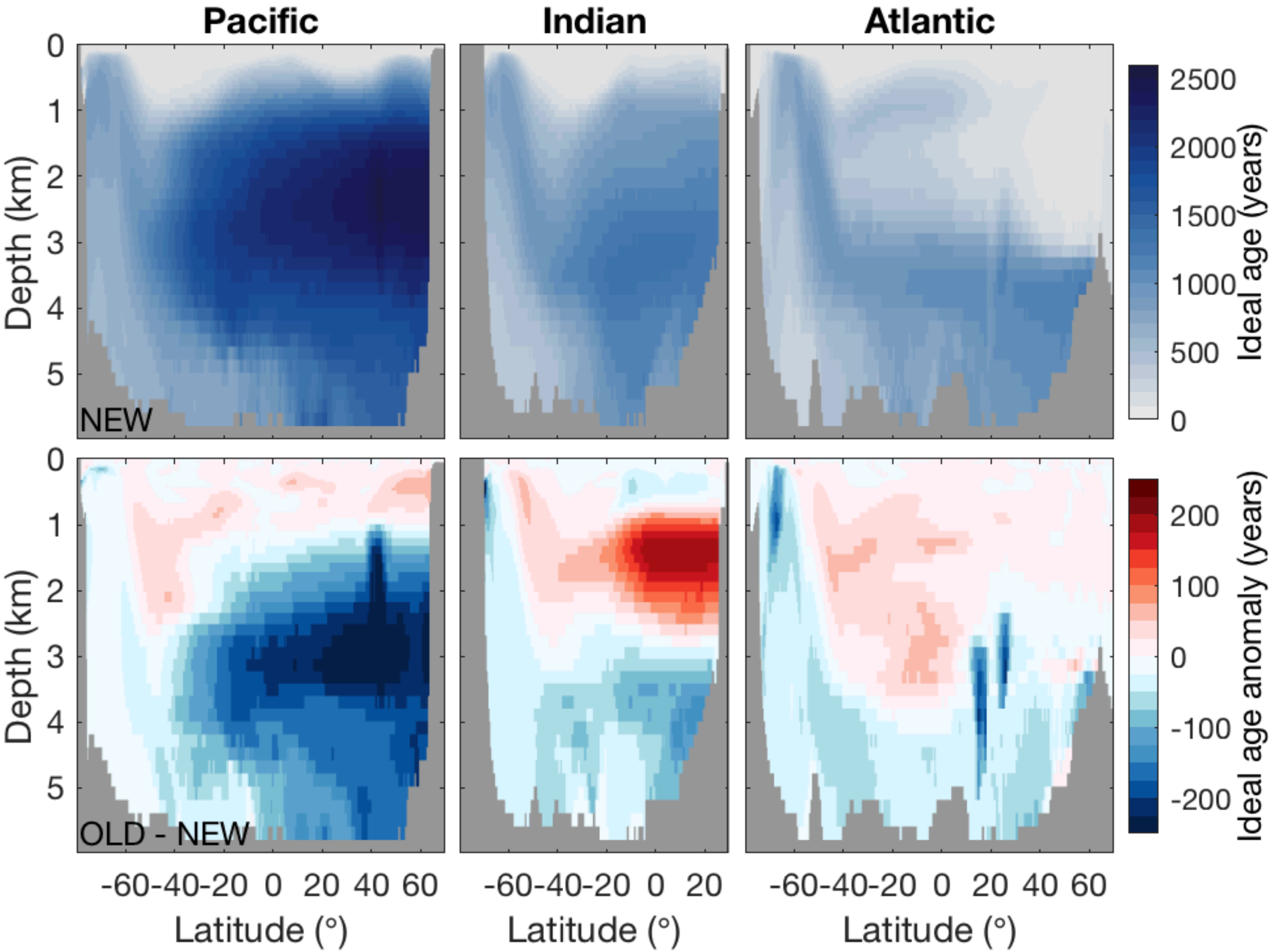

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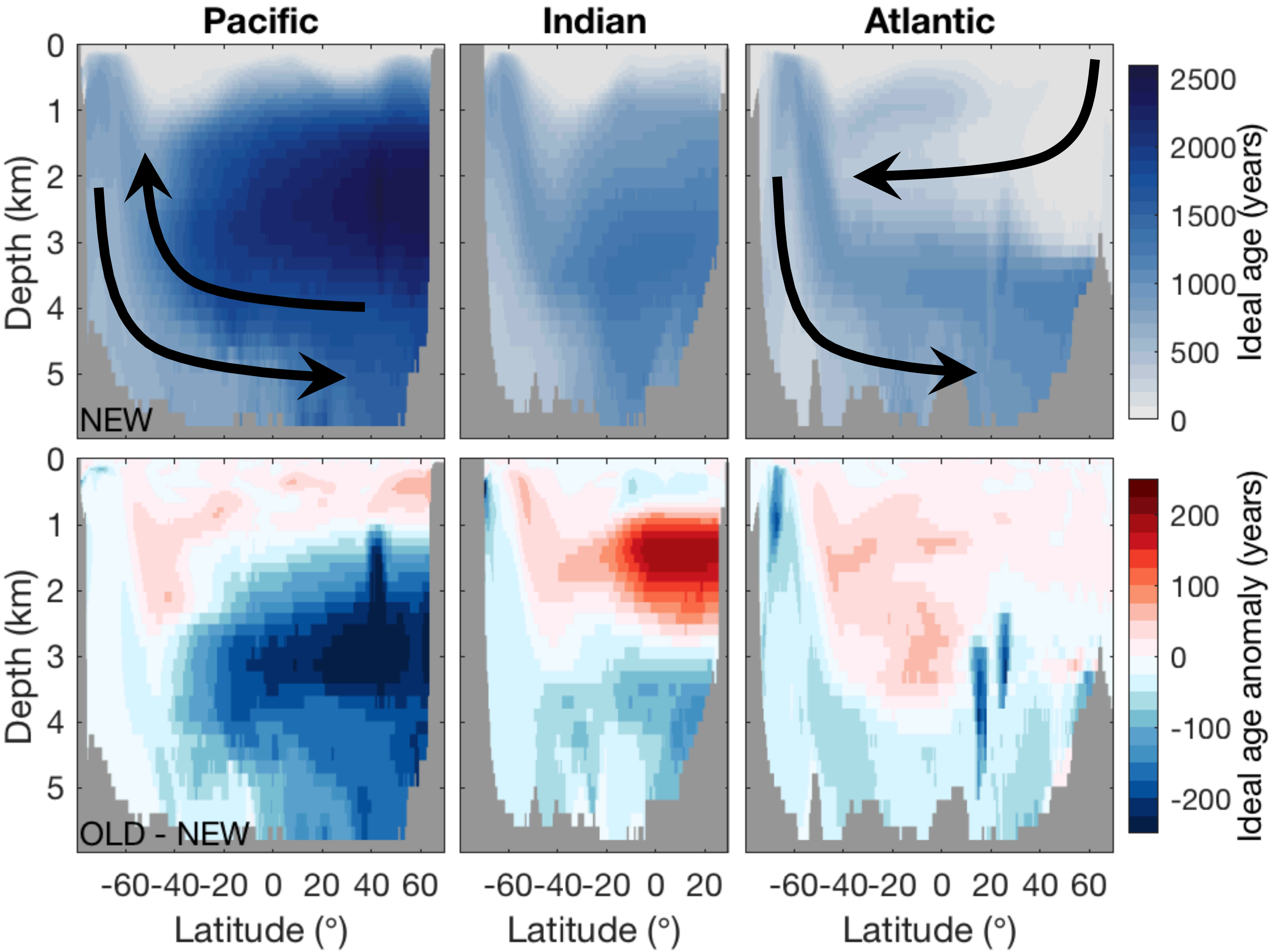
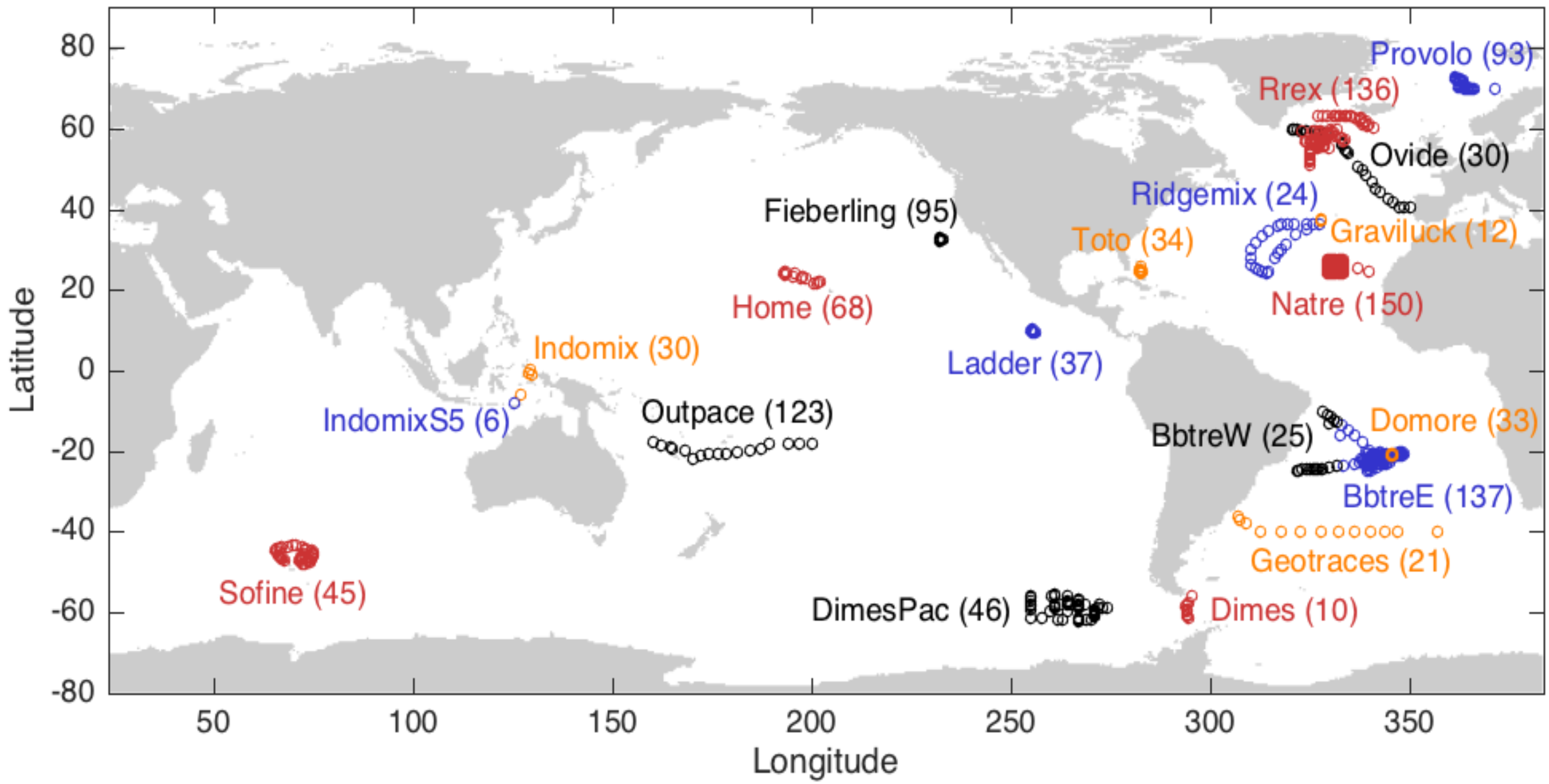
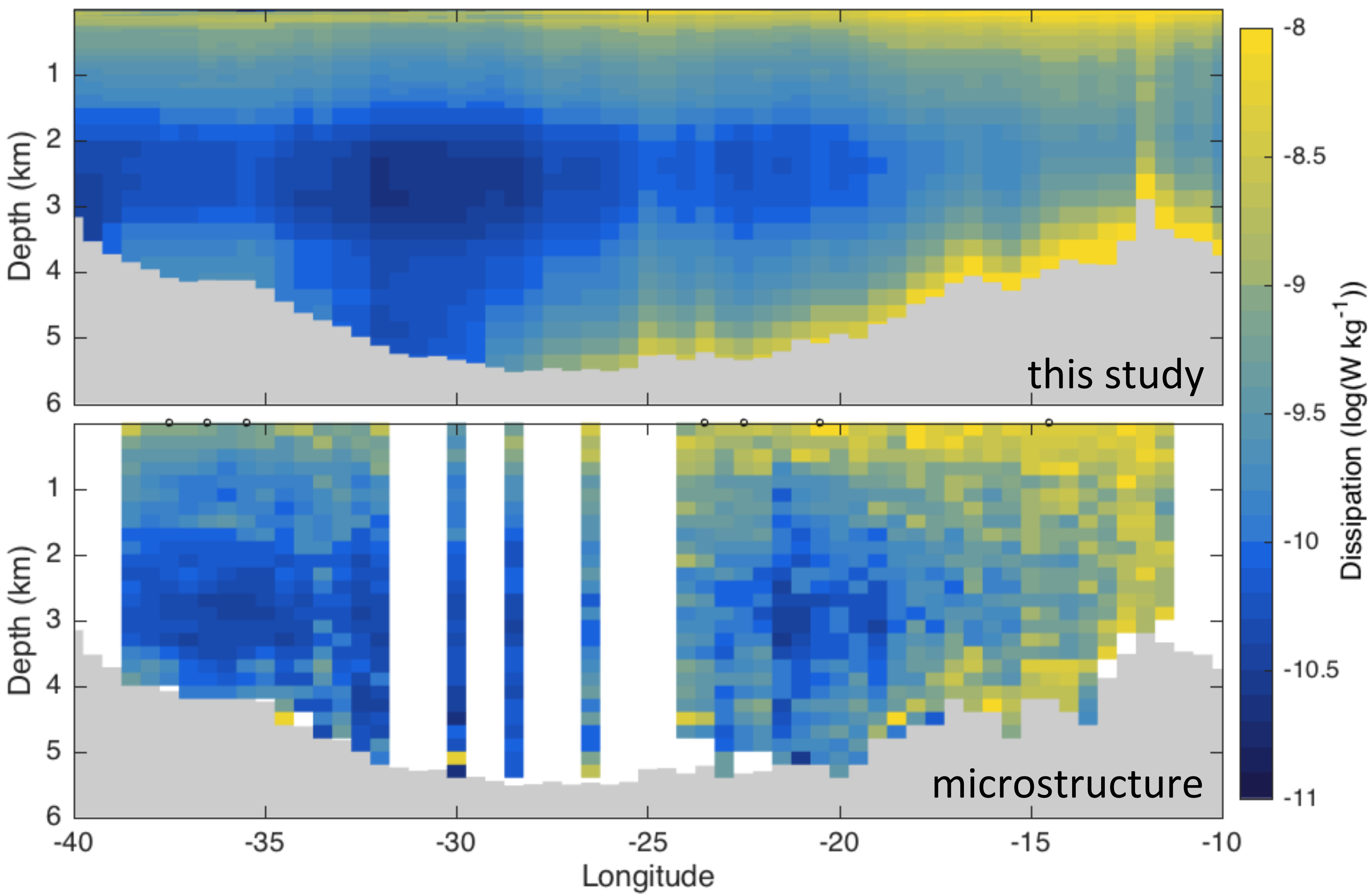


Comparison with microstructure data

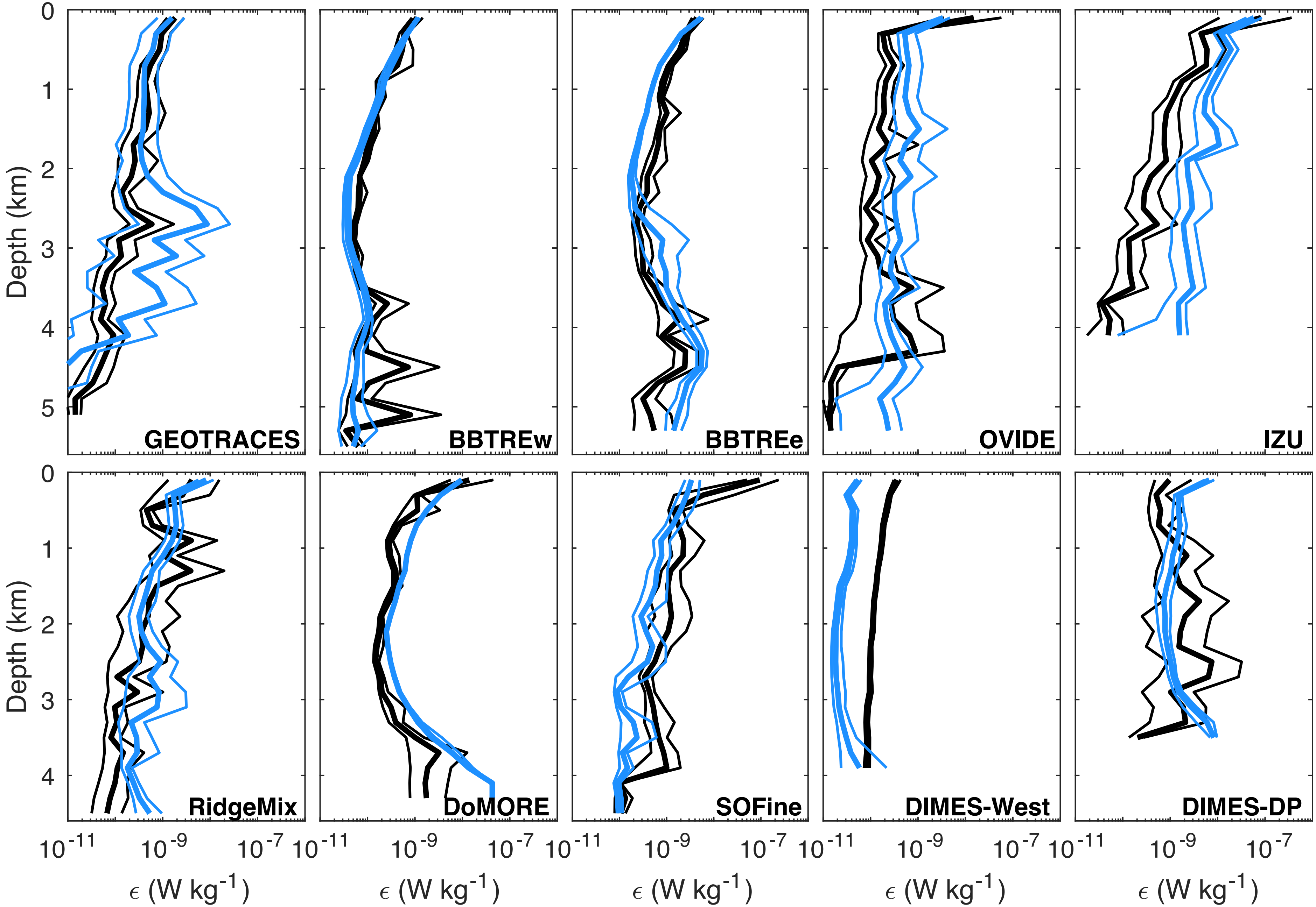
18 projects, 1155 profiles



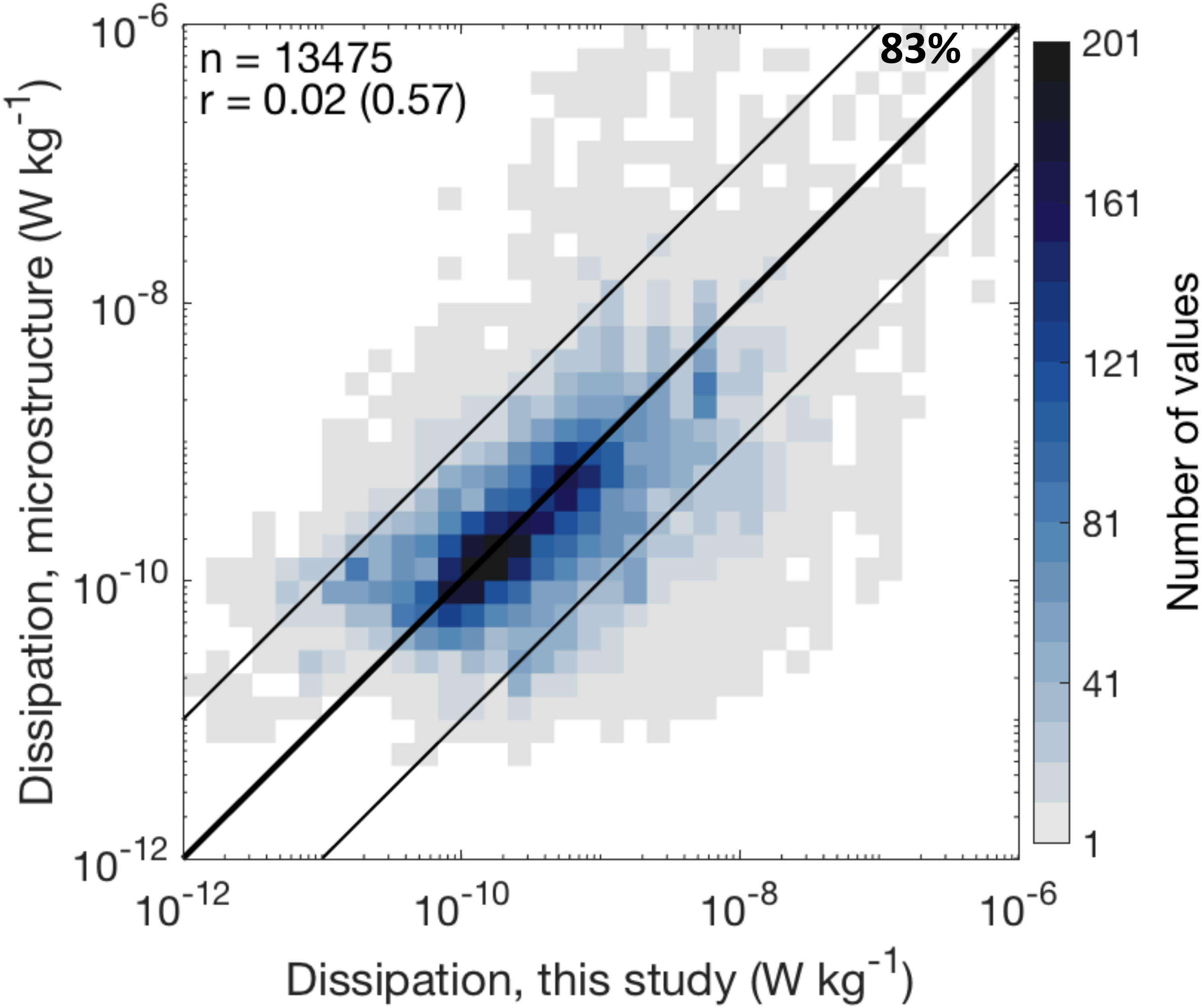
Comparison with microstructure: Brazil Basin



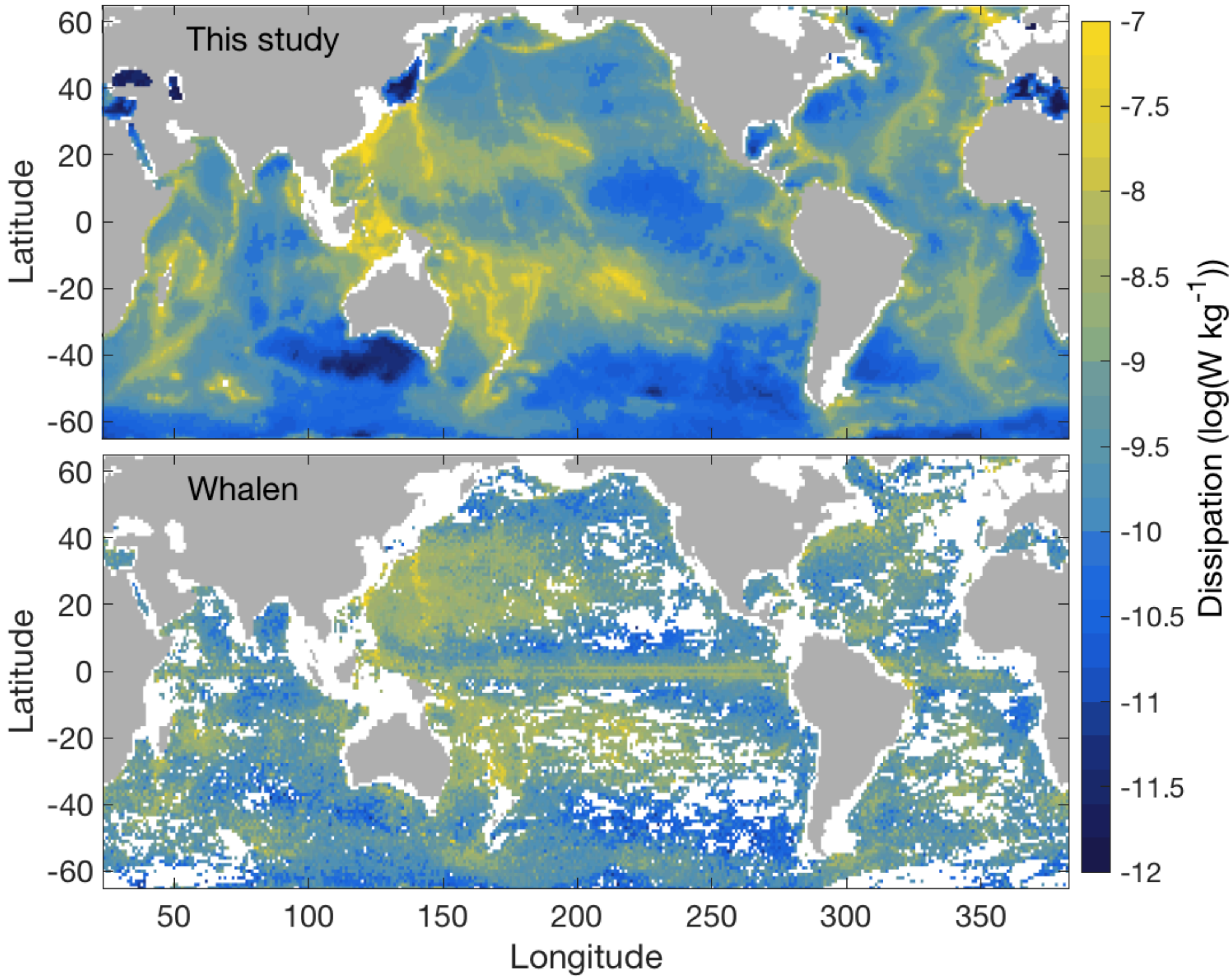
Comparison with microstructure: profiles



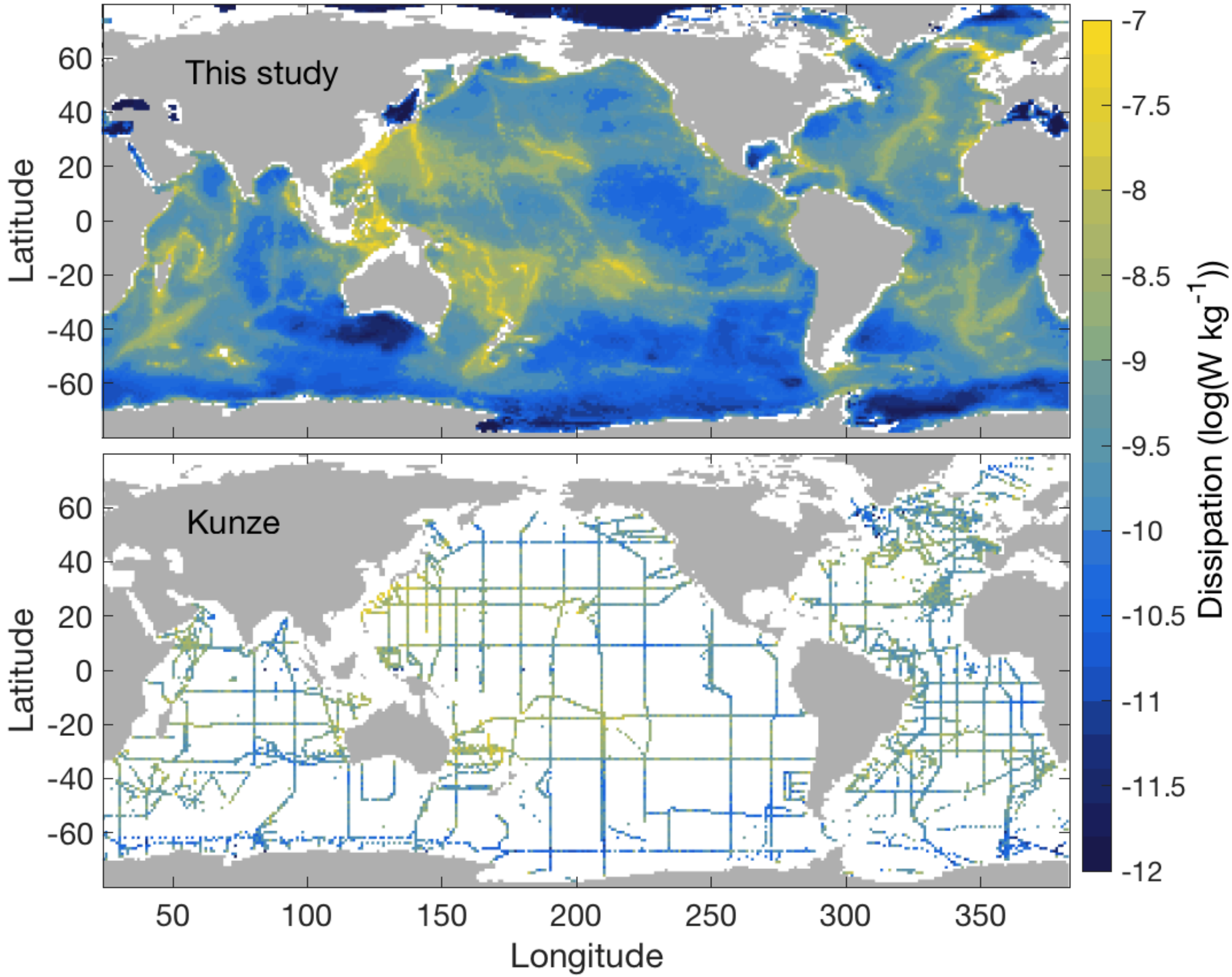
Comparison with microstructure: scatter



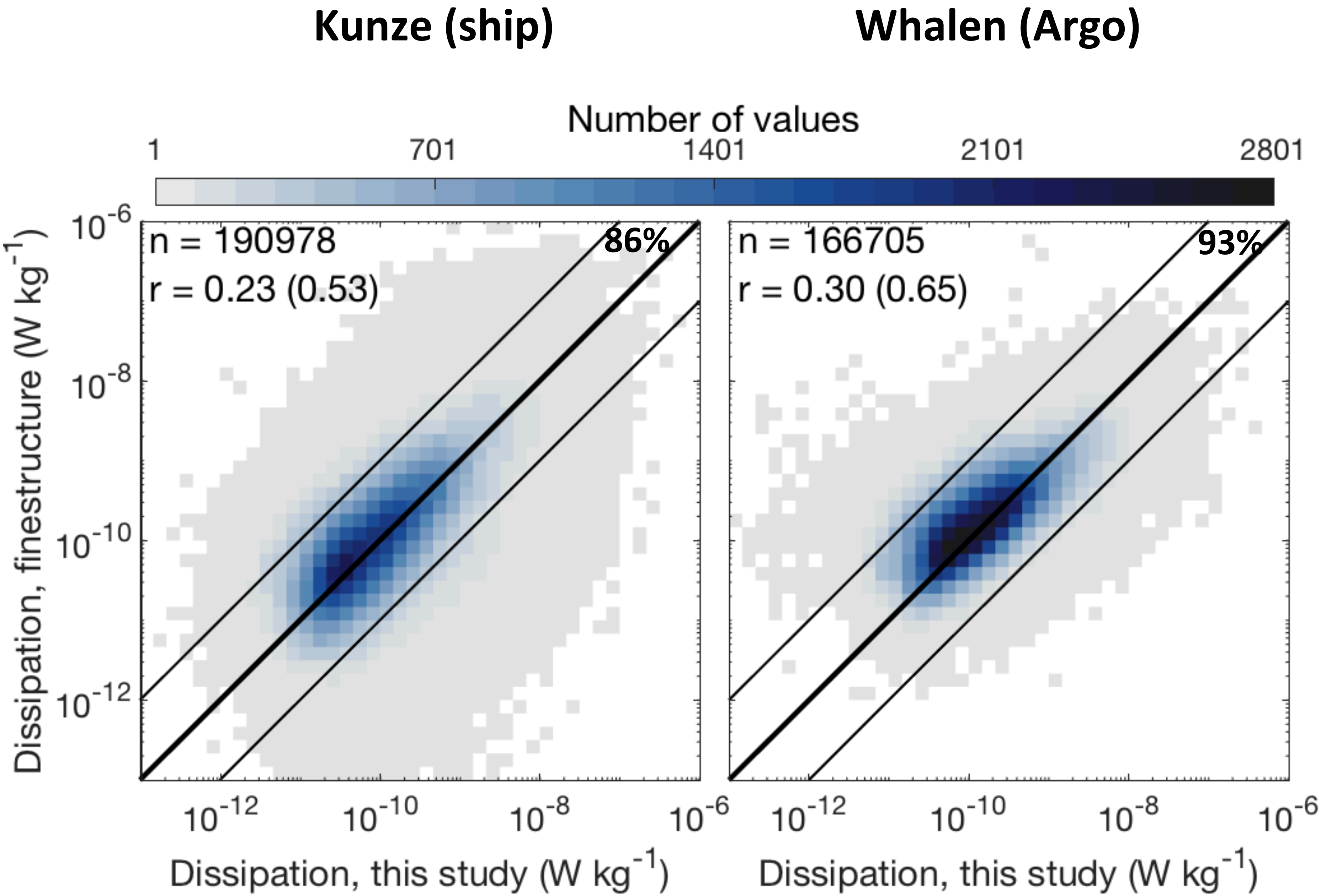
Comparison with finestructure (Argo)



Comparison with finestructure (ship)



Comparison with finestructure



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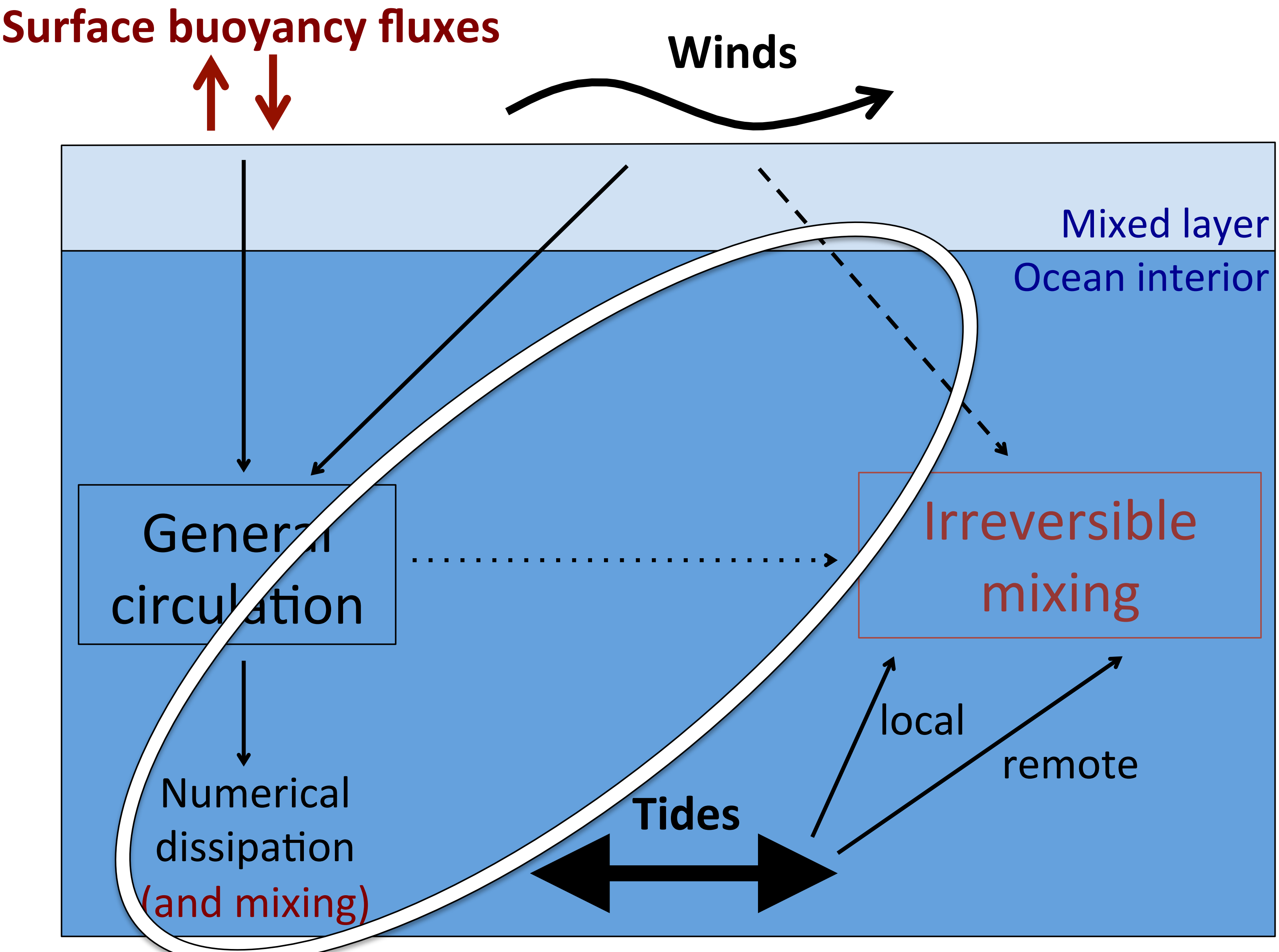

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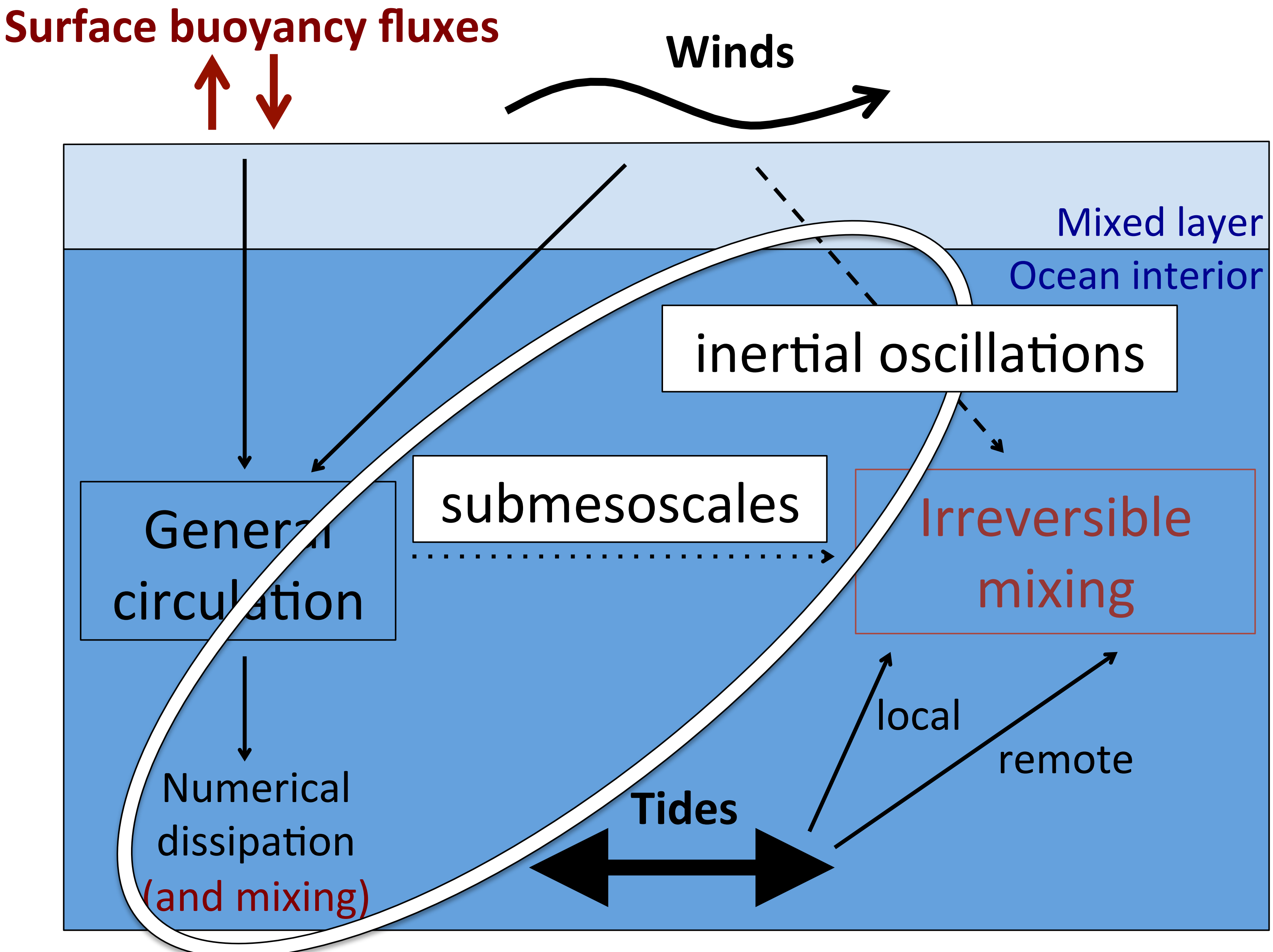


Wind-induced inertial oscillations

- Large source of mixing at base of mixed layer, weak source below.
  - Alford 2020: power into deep mixing ~ 0.1 TW

- Ad hoc parameterizations exist for mixing near the base of the mixed layer:
  - Jochum et al. 2013: amplification of resolved shear in surface boundary layer module (resolution dependent)
  - NEMO: imposed vertical profile of TKE, function of surface TKE (not energy constrained)

- Challenge: parameterizations must be interactive with atmosphere (online).

Submesoscale currents

- Submesoscale (< 20 km) flows are abundant in the ocean interior.
    - Siegelman et al. 2020: energetic submesoscales in Southern Ocean interior down to 900 m
    - Naveira Garabato et al. 2019: submesoscale instabilities in bottom boundary currents

- Several effects (restratification, vertical mixing, isopycnal mixing) that might require separate parameterizations.

- No parameterization available for OGCMs yet, except for restratification by mixed-layer eddies (Fox-Kemper et al. 2008).

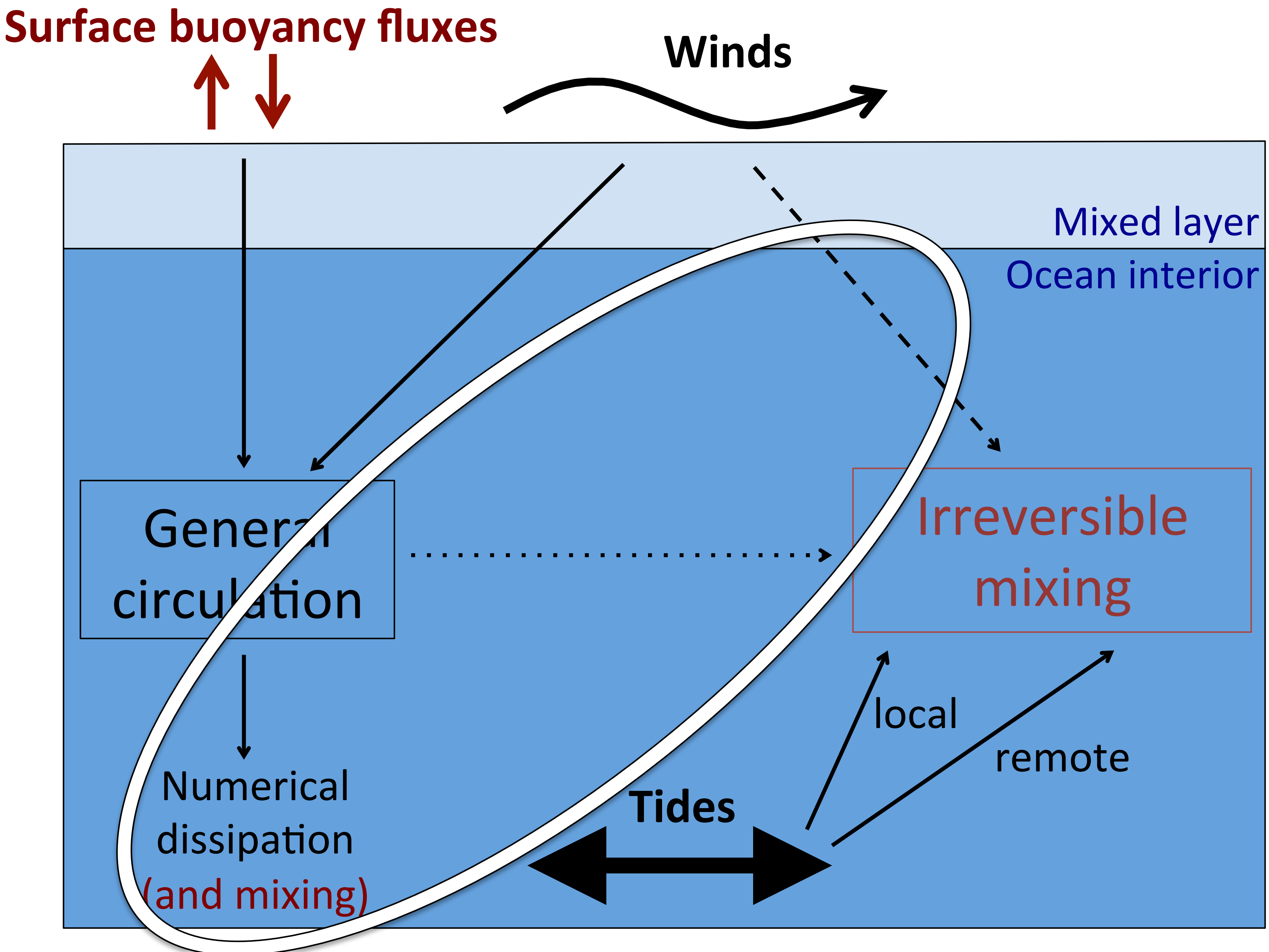
Numerical mixing

- Progress in mapping and understanding spurious mixing due to discretization of advection.
  - Holmes et al. 2021: spurious mixing depends on resolution, viscosity, explicit mixing

- Adaptive vertical coordinates and improved advection schemes are promising pathways to reduce spurious mixing.
  - Griffies et al. 2020: Lagrangian-remap coordinate

- Many models still have large amounts of numerical mixing that can exceed the explicit mixing in the ocean interior.

Conclusion



Surface buoyancy fluxes
Winds
Mixed layer
Ocean interior
General circulation
Irreversible mixing
local
remote
Numerical dissipation
(and mixing)
Tides