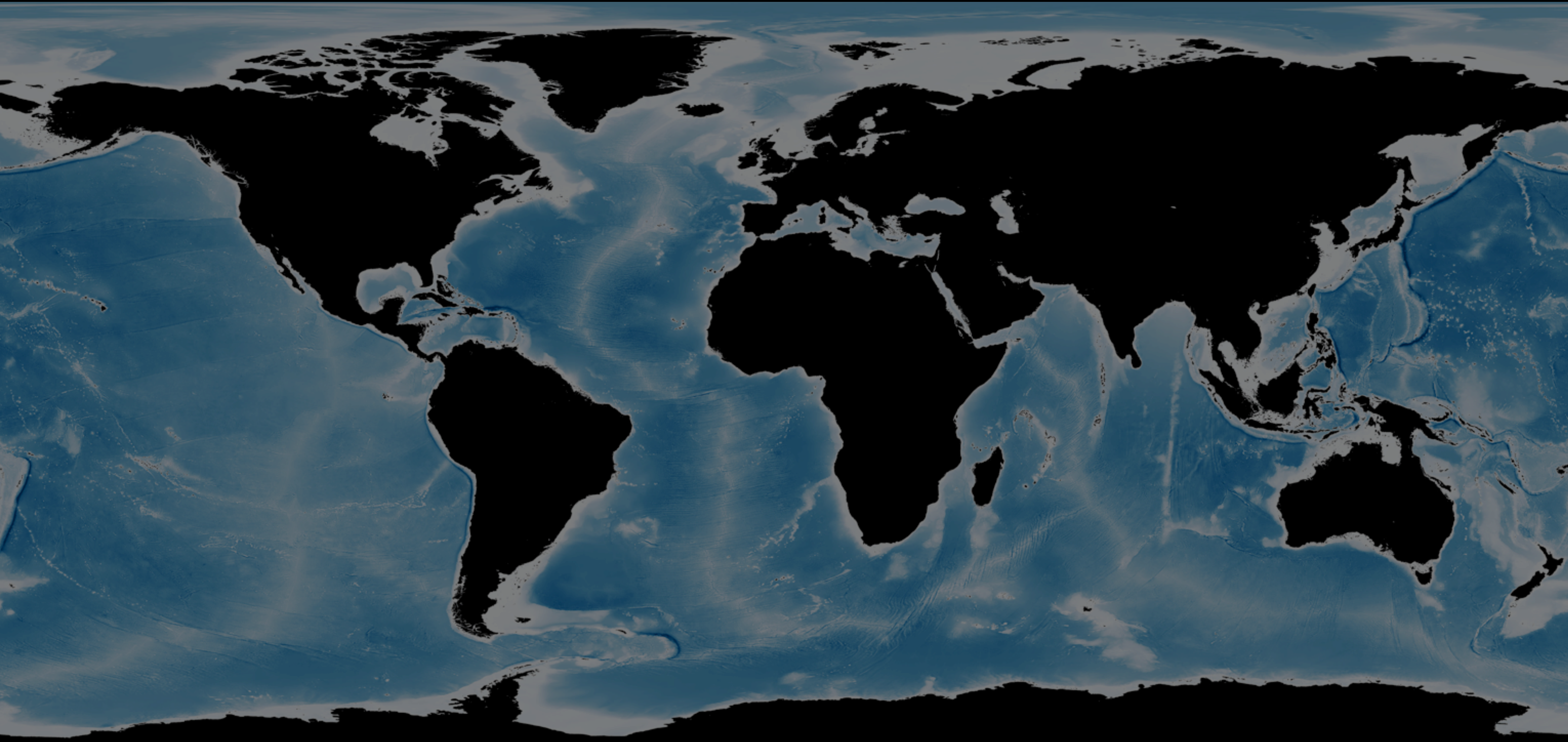
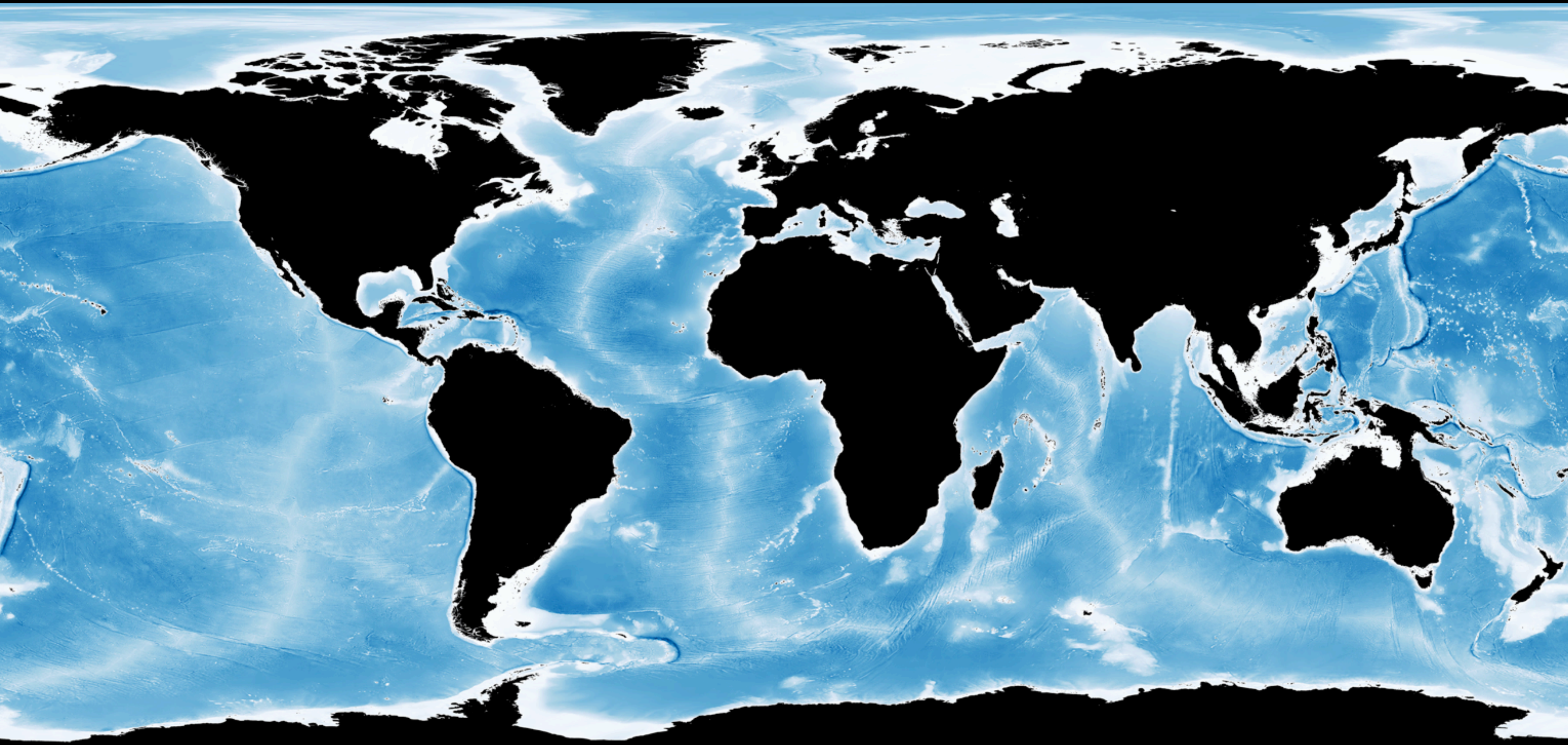
The evolution and arrest of a turbulent stratified bottom boundary layer over a slope



Xiaozhou Ruan[1], Andrew Thompson[1] & John Taylor[2]
[1] California Institute of Technology and [2] University of Cambridge

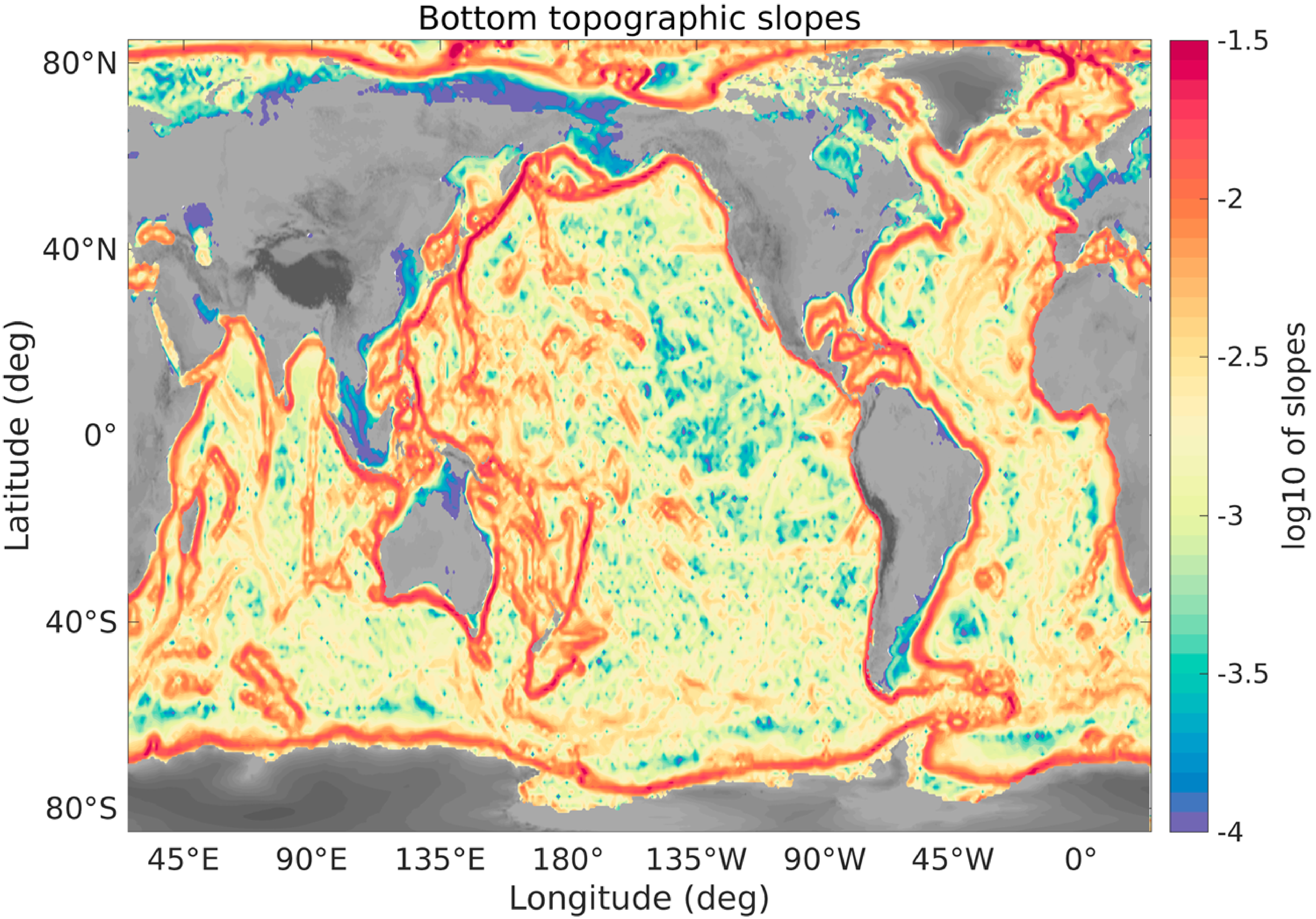
Planetary Boundary Layers in Atmospheres, Oceans, and Ice on Earth and Moons
Kavli Institute for Theoretical Physics, University of California, Santa Barbara
May 26, 2018

Ocean bathymetry



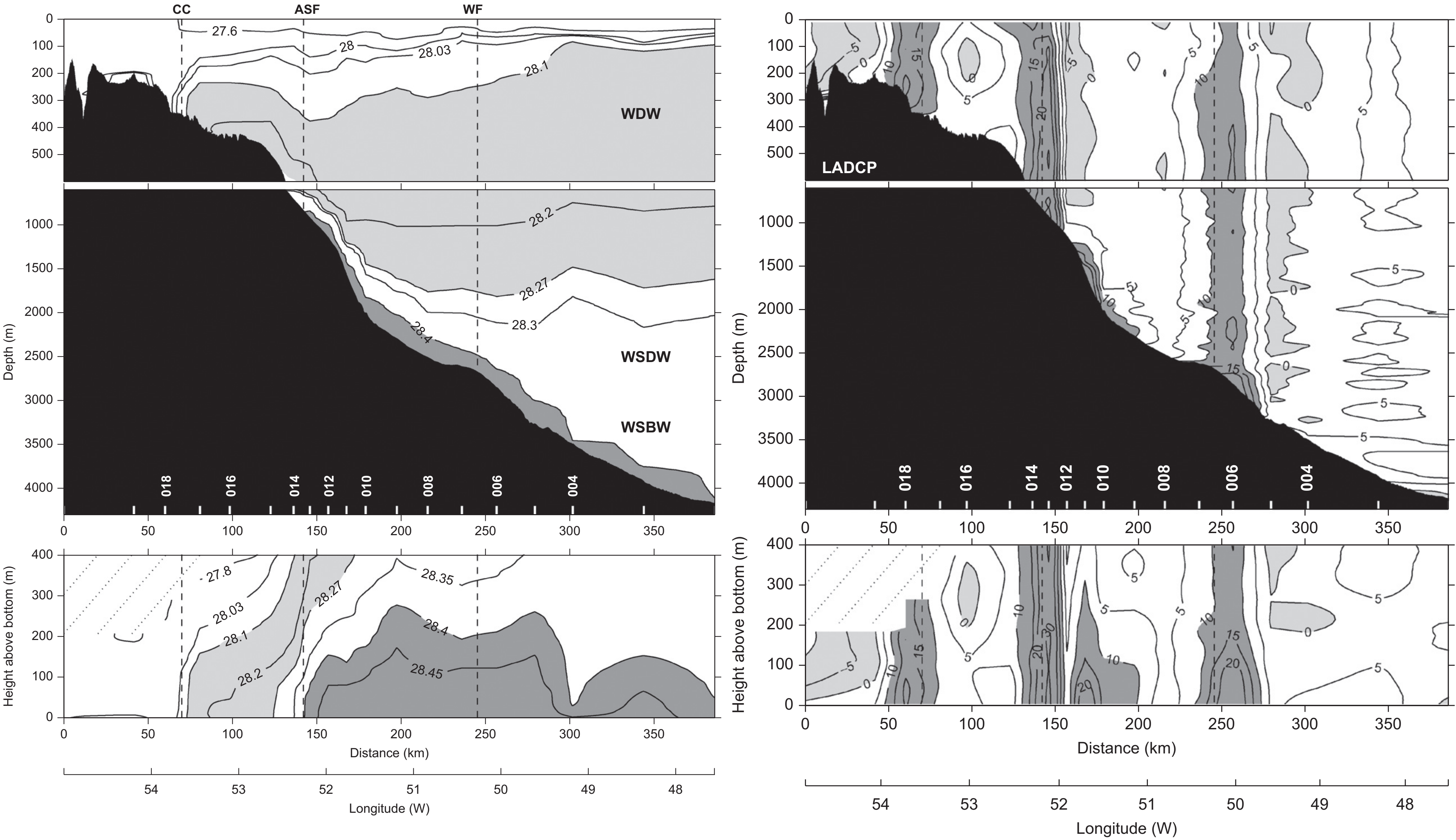
Dissipation by bottom drag is a non-negligible, but poorly constrained, component of the ocean’s energy budget.

Estimates of dissipation occurring in the bottom boundary layer range between 0.2 - 0.83 TW.



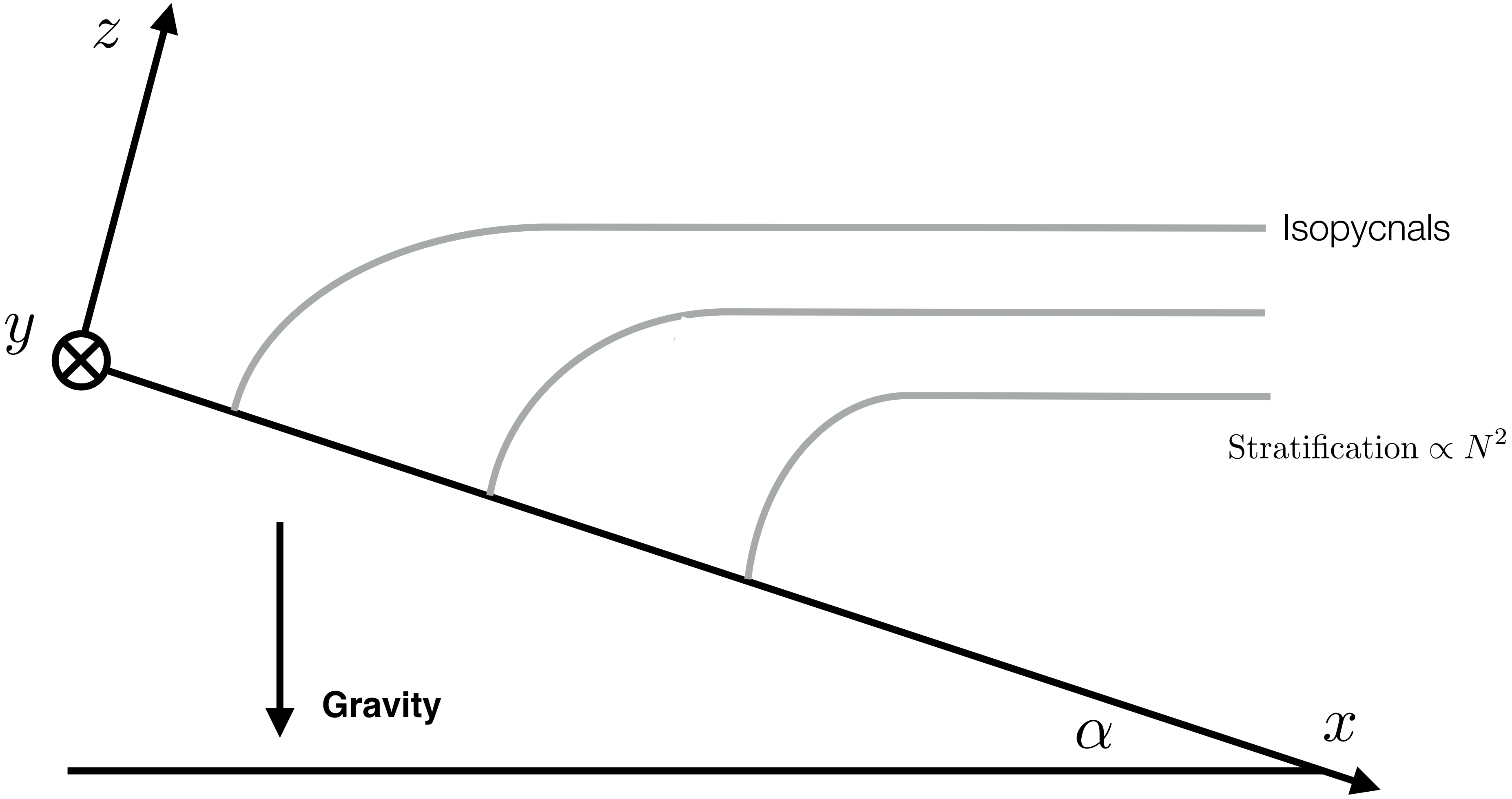
LaCasce (2017)

Boundary currents in the northwestern Weddell Sea



Thompson and Heywood (2008)

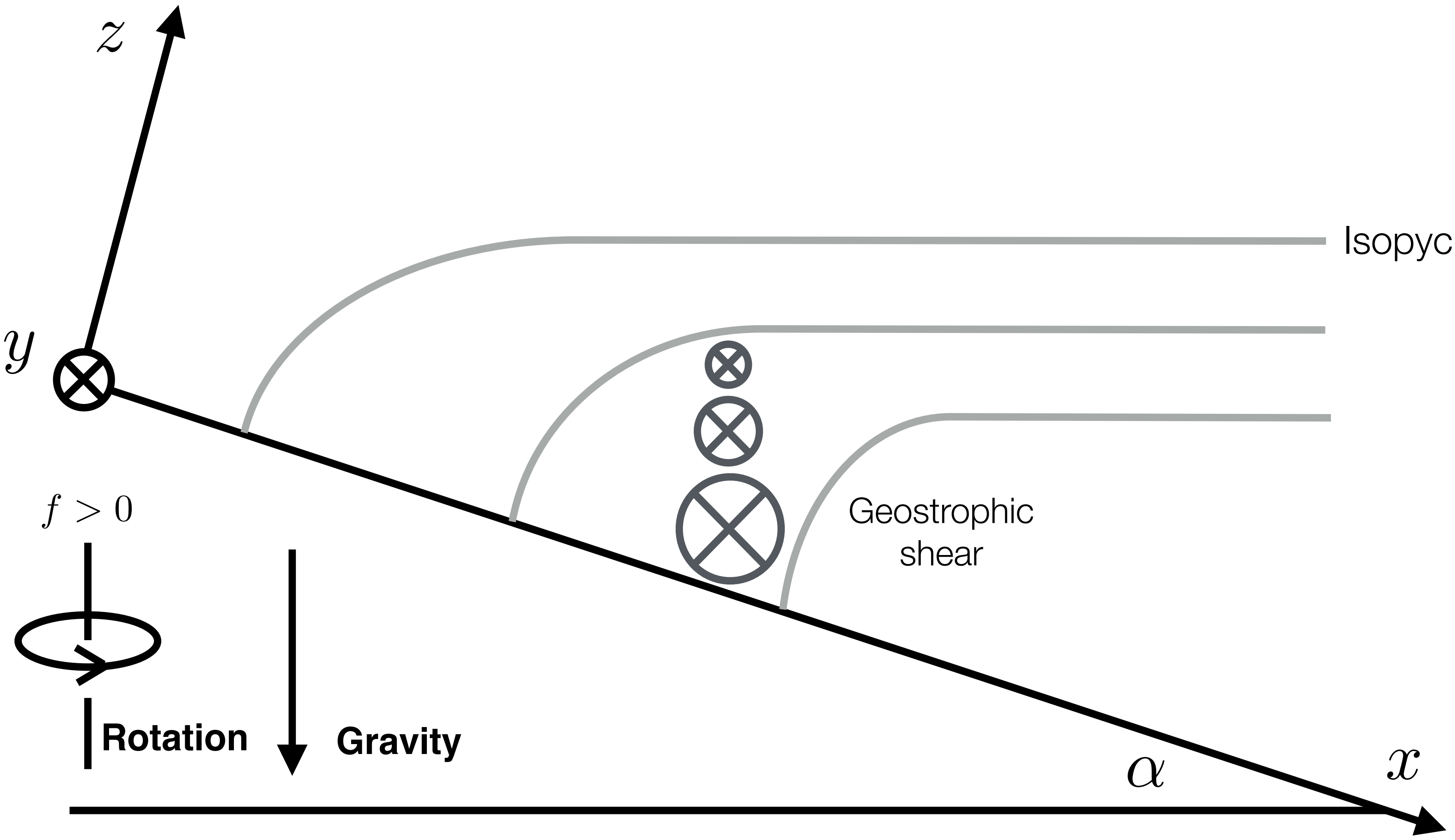
Stratification over a sloping bottom



Insulating bottom boundary conditions imply a tilting of density surfaces over a sloping seafloor.

Phillips (1970); Wunsch (1970)

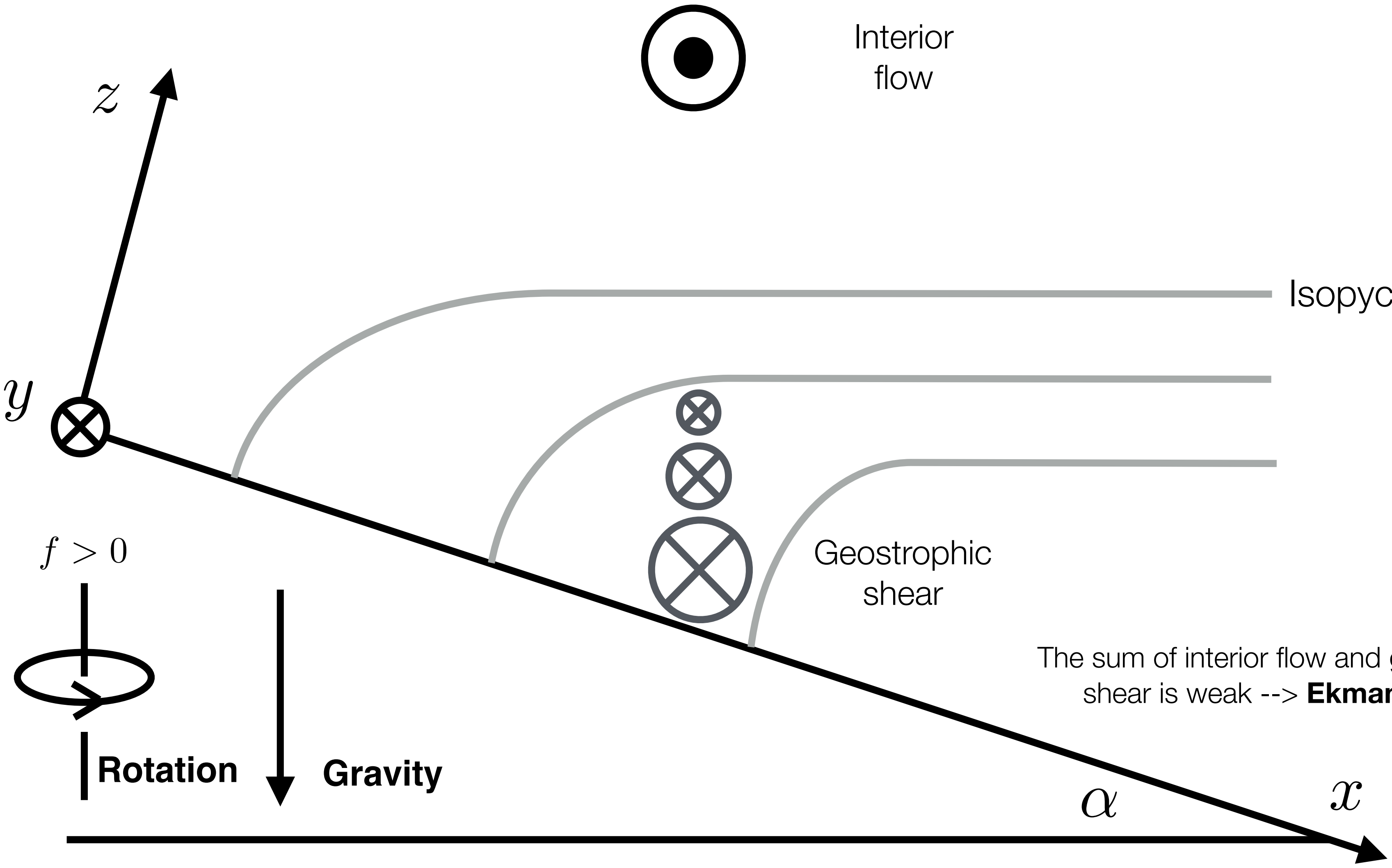
Stratification over a sloping bottom



Insulating bottom boundary conditions imply a tilting of density surfaces over a sloping seafloor.

Thorpe (1987)

Stratification over a sloping bottom



The sum of interior flow and geostrophic shear is weak --> **Ekman arrest**

Insulating bottom boundary conditions imply a tilting of density surfaces over a sloping seafloor.

Thorpe (1987); MacCready & Rhines (1991)

Ekman arrest

"On application of the insulating boundary condition Thorpe (1989) finds that the interior flow far from the boundary is specified as a part of the solution. Thus, while steady solutions exist for any interior flow if density is specified at the boundary . . . there is only one interior flow that has a steady boundary layer in the insulating case."

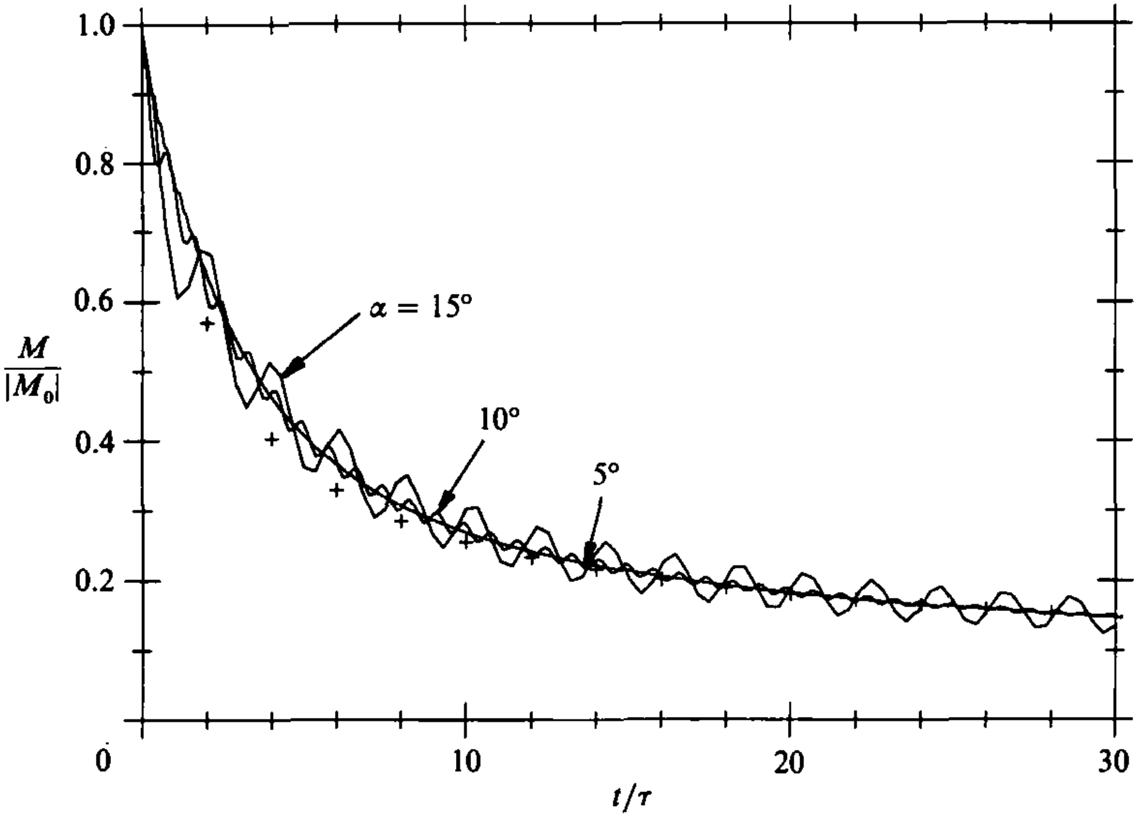
$$S = \text{Slope Burger number} = \left(\frac{N \sin\alpha}{f \cos\alpha}\right)^2$$

Time scale towards Ekman arrest

$$\tau = \frac{1}{S^2 f \cos\alpha}\left(\frac{1/\sigma + S}{1+S}\right)$$

The cross-slope transport decays as:

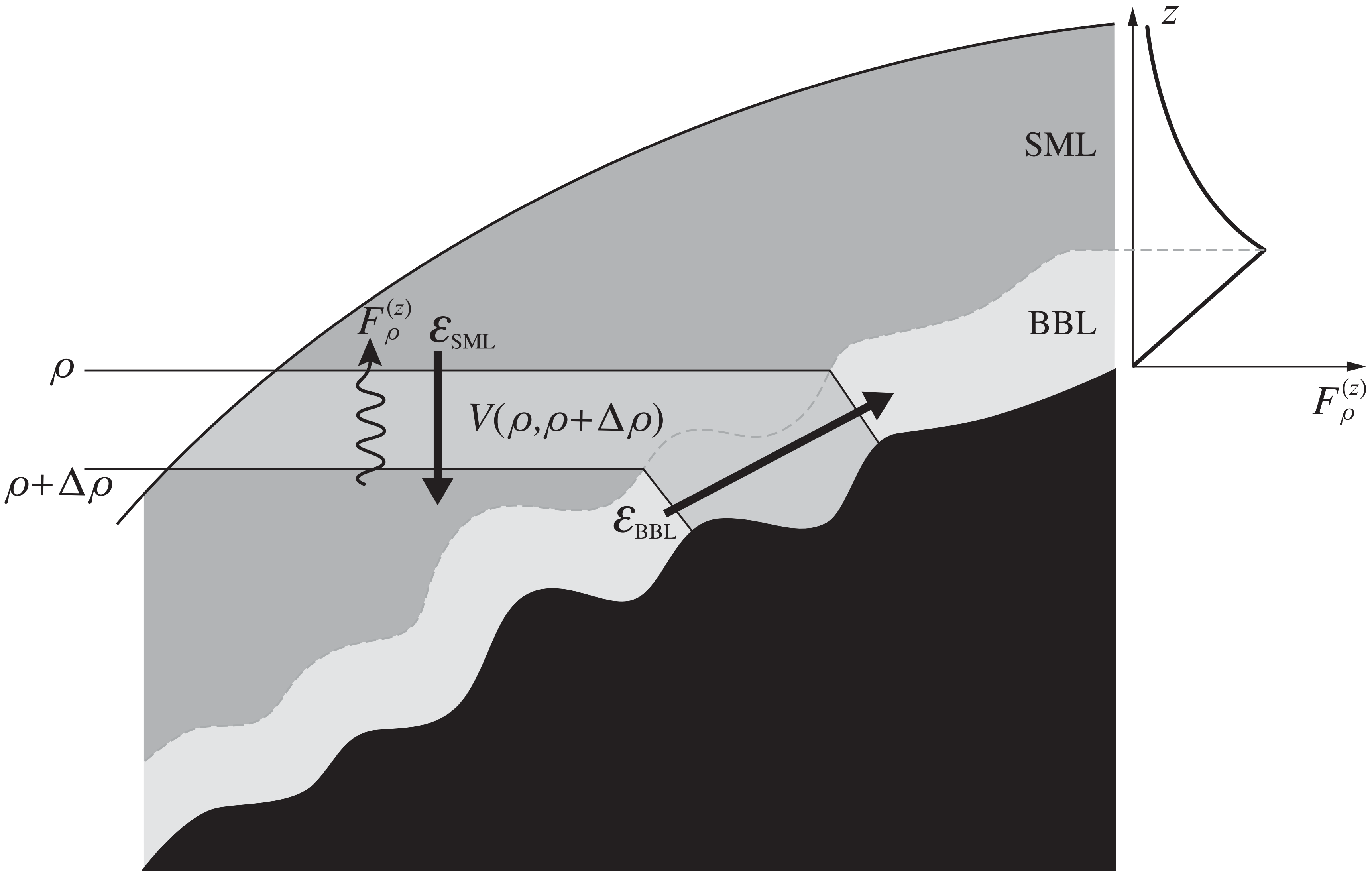
$$\left(\frac{t}{\tau}\right)^{-1/2}$$



The boundary layer diffuses into the interior, unlike an Ekman layer (although at a slower rate than non-rotating diffusion).

MacCready & Rhines (1991); Brink and Lentz (2010)

Bottom boundary layers and water mass modification

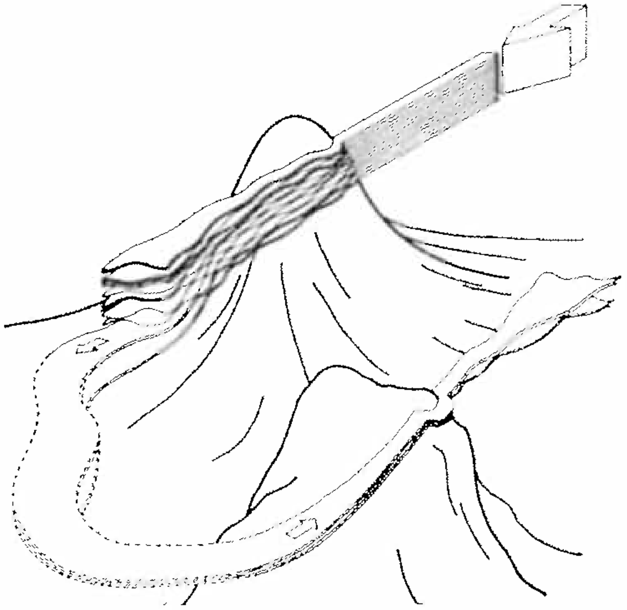


Ferrari *et al.* (2016)
deLavergne *et al.* (2017)

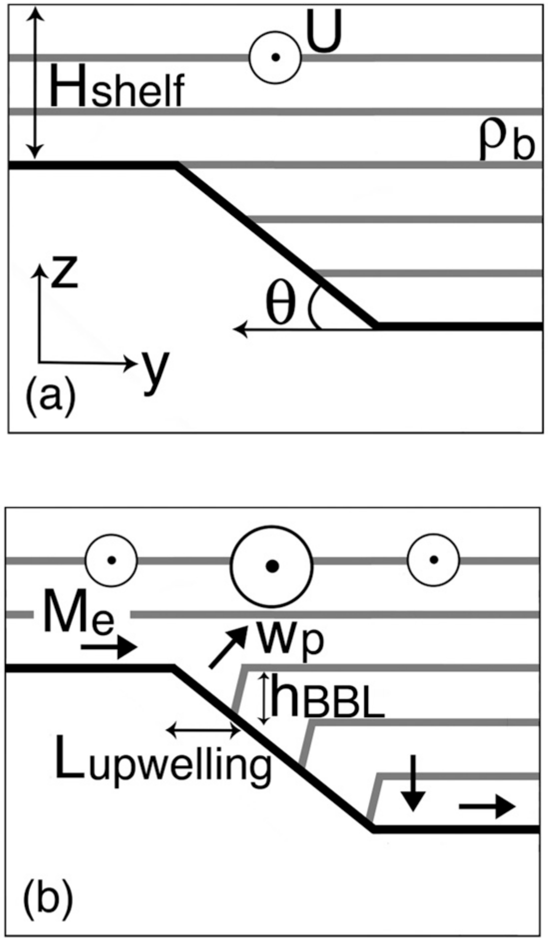
$$\kappa\frac{\partial\overline{\rho}}{\partial z} = -F_\rho^z$$

To maintain an overturning you need to sustain the stratification --> need to exchange with the interior!

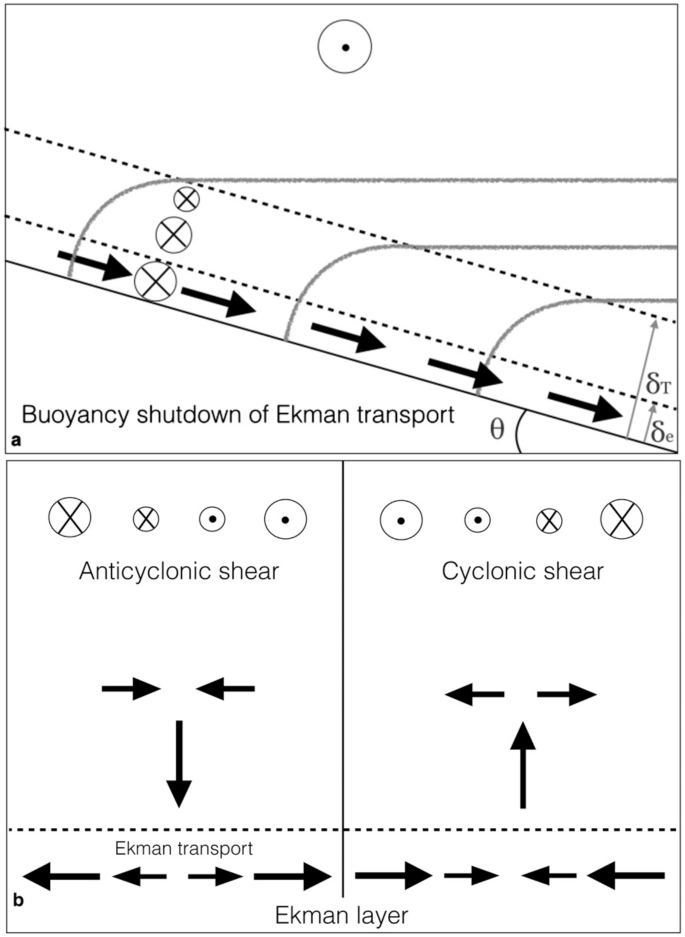
Boundary layer and interior exchange



Armi (1979)



Benthuysen and Thomas (2015)



Ruan and Thompson (2016)

A range of processes will enable (enhance?) exchange between the bottom boundary and the interior.

Governing equations

- Scalings for the arrested BBL thickness
- Characterize different BBL regimes over a slope.

Cross-slope momentum equation:

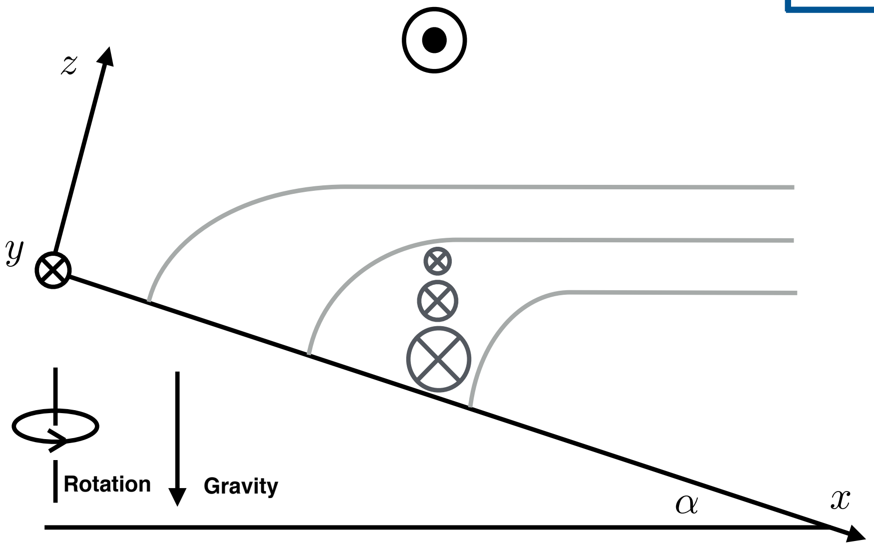
$$\frac{Du}{Dt} - fv\cos\alpha = -\frac{1}{\rho_0}\frac{\partial p'}{\partial x} - b\sin\alpha - \partial_j \tau_{1j}$$

Ekman arrest

Ekman balance

Buoyancy equation:

$$\frac{Db}{Dt} - (u\sin\alpha - w\cos\alpha)\,N^2 = \kappa\nabla^2 b$$



Small-angle approximation: $\sin\alpha \approx \alpha, \quad \cos\alpha \approx 1$

Ekman arrest scaling analysis (momentum balance)

Cross-slope
momentum scalings:

Coriolis: $F_c \sim fV$

Buoyancy: $B \sim \alpha \left(\alpha \Delta x N_\infty^2\right) \sim \alpha N_\infty^2 H$

The arrested
Ekman height:

$$H_a \sim \frac{fV}{\alpha N_\infty^2}$$

Non-dimensional number
(degree of “arrest”)

$$E_{\mathrm{arr.}} \equiv \frac{B}{F_c} \sim \frac{\alpha N_\infty}{f} \frac{N_\infty H}{V_\infty} = \frac{\mathrm{Bu}}{\mathrm{Fr}}$$

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The appropriate velocity scale will be the along-slope velocity near the bottom:

$$V_b = V_\infty - \alpha N^2 H/f.$$

$$\boxed{H_a \approx \frac{fV_\infty}{2\alpha N_\infty^2}}$$

Ekman arrest scaling analysis (turbulence suppression)

Obukhov length scale: $L \equiv \frac{-u_*^3}{kF_b}$

Slope Obukhov length scale: $L_s \equiv \frac{u_*^3}{k\alpha U N_\infty^2} = \left(1 + S^2\right) \frac{f u_*}{k\alpha N_\infty^2}$

Viscous Obukhov length scale (non-dimensional): $L^+ \equiv \frac{L u_*}{\nu}$

We will associate Ekman arrest with a suppression of turbulence.

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We will associate Ekman arrest with a suppression of turbulence.

Riley and Flores (2011) have shown that in atmospheric boundary layers turbulence collapses and the BL re-laminarizes for $L^+ < 100$.

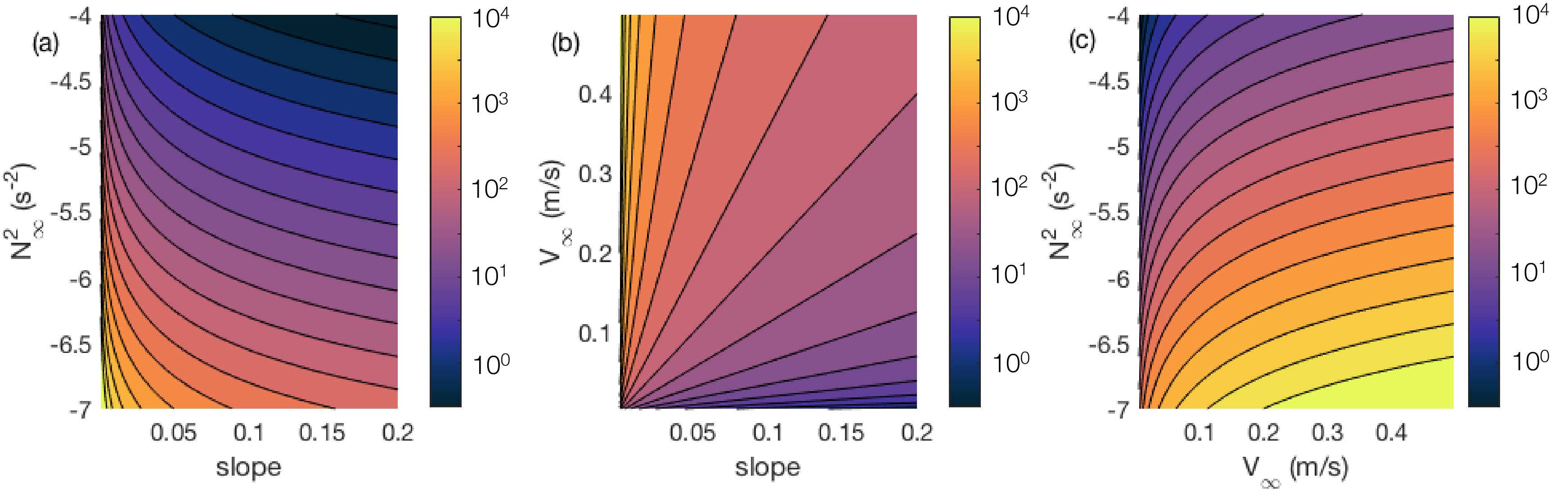
$$u_*^2 = C \frac{\nu k \alpha N_\infty^2}{f\left(1 + S^2\right)} = C_d \left(V_\infty - \frac{\alpha N_\infty^2 H_a}{f}\right)$$

$$\boxed{H_a = \frac{f V_\alpha}{\alpha N_\infty^2} - \left(\frac{C k \nu f}{\alpha N_\infty^2 C_d \left(1 + S^2\right)}\right)^{1/2}}$$

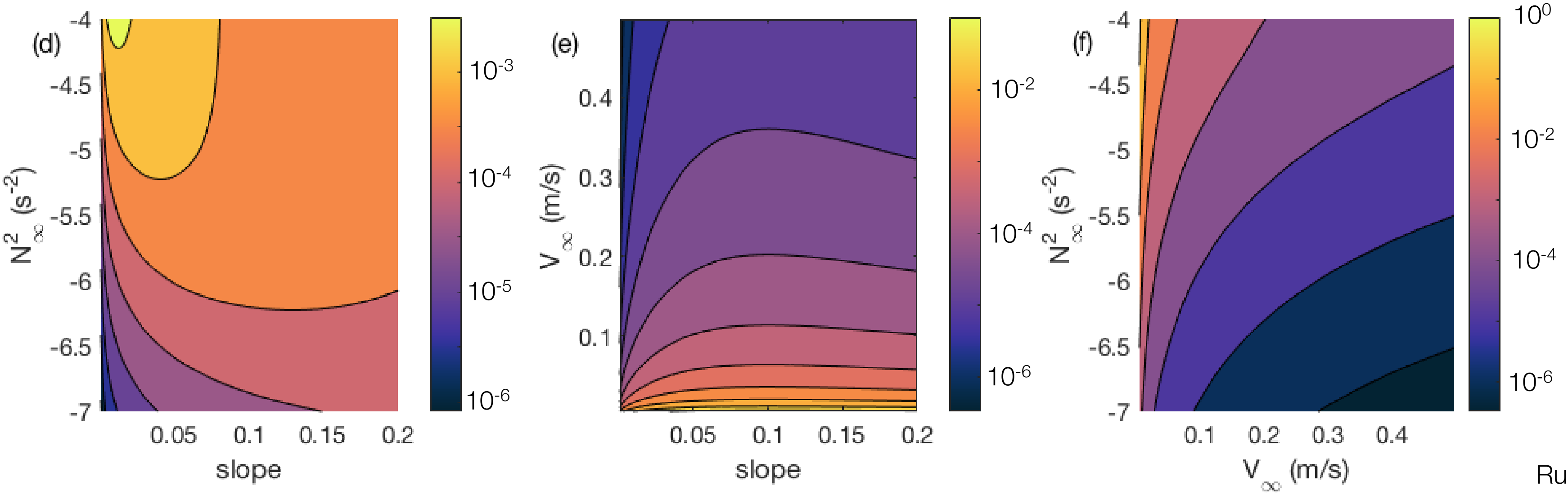
Scaling analysis summary

- Two independent predictions for the arrested Ekman depth (*H_a*)
- The latter scaling also provides a prediction of the critical friction velocity (that will lead to arrest).

$$H_a \approx \frac{fV_\infty}{2\alpha N_\infty^2} \qquad H_a = \frac{fV_\alpha}{\alpha N_\infty^2} - \left(\frac{Ck\nu f}{\alpha N_\infty^2 C_d \left(1 + S^2\right)} \right)^{1/2}$$



$$H_a(\mathrm{m})$$

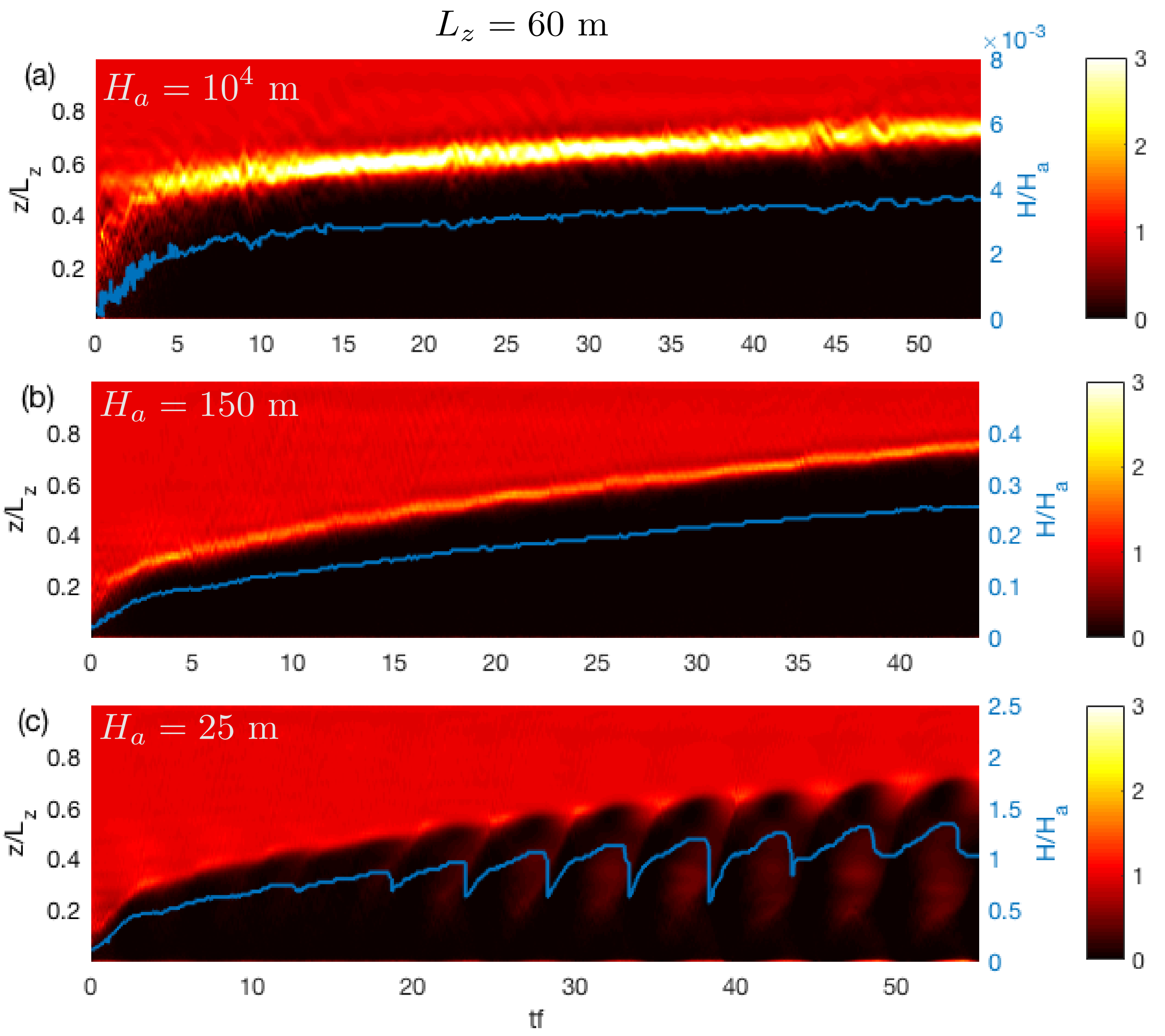


$$C_d = \frac{u_*^2}{V_b^2}$$

Ruan *et al.* (2018, submitted)

LES simulations

- LES experiments with near-wall resolution; resolves ~80% of the energy.
- First two grid points are in the viscous layer; minimum resolution in slope-normal direction is $2\nu/u_*$.
- Domain size is 30 m x 30 m x 60 m; a sponge layer is placed at the surface.
- Three-stage spin-up to focus on turbulent state (rather than transition to turbulence).
- Constant Smagorinsky model for sub-grid scale turbulence with constant sub-grid scale Prandtl number.



Ruan *et al.* (2018, submitted)

LES simulations

- $H/H_a \ll 1$

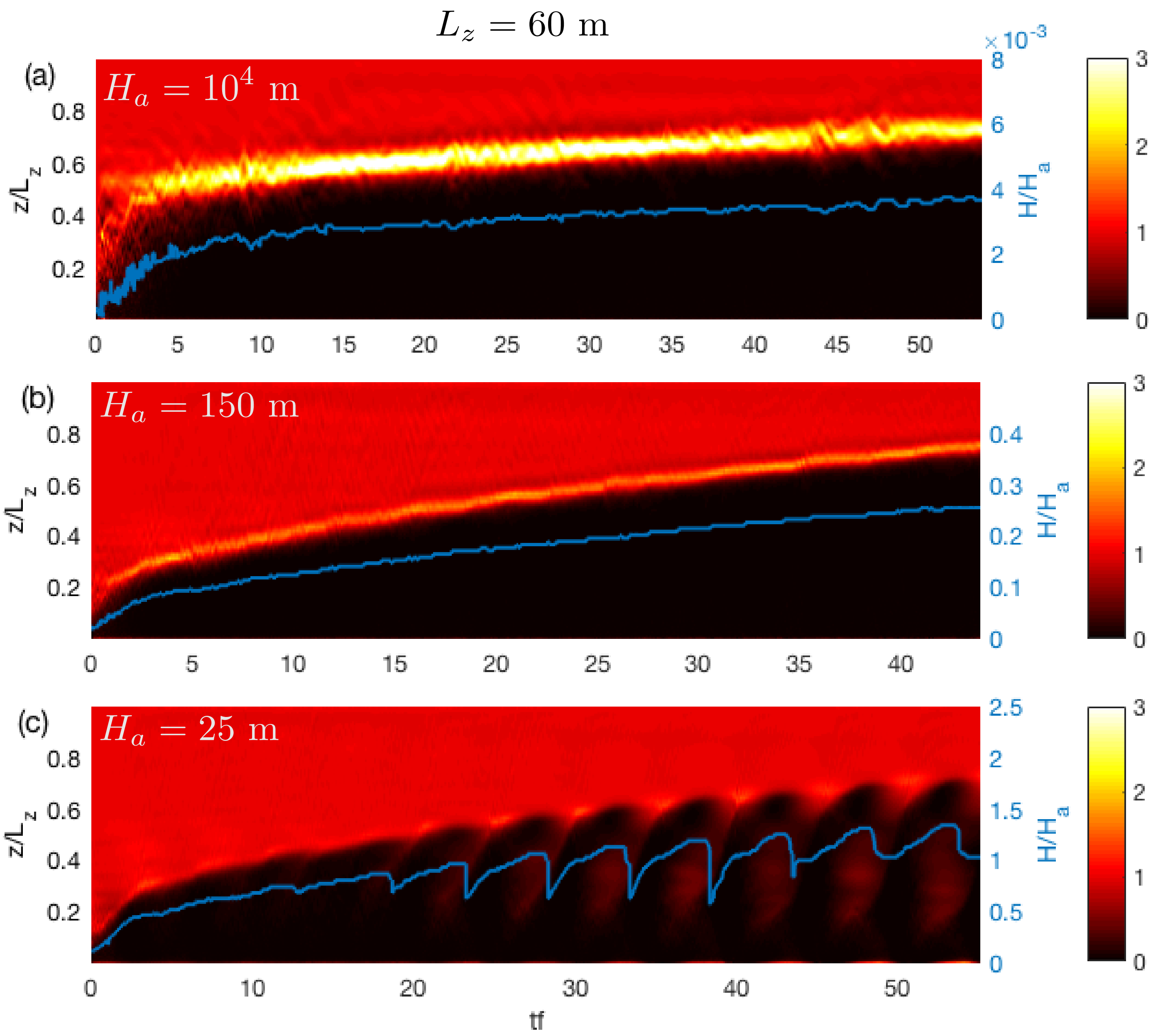
  - Formation of a strong pycnocline
  - Cross-slope transport is steady

- $H/H_a \sim O(0.1)$

  - Pycnocline is weaker
  - Vertical buoyancy convergence is transferred to being in the lateral direction.

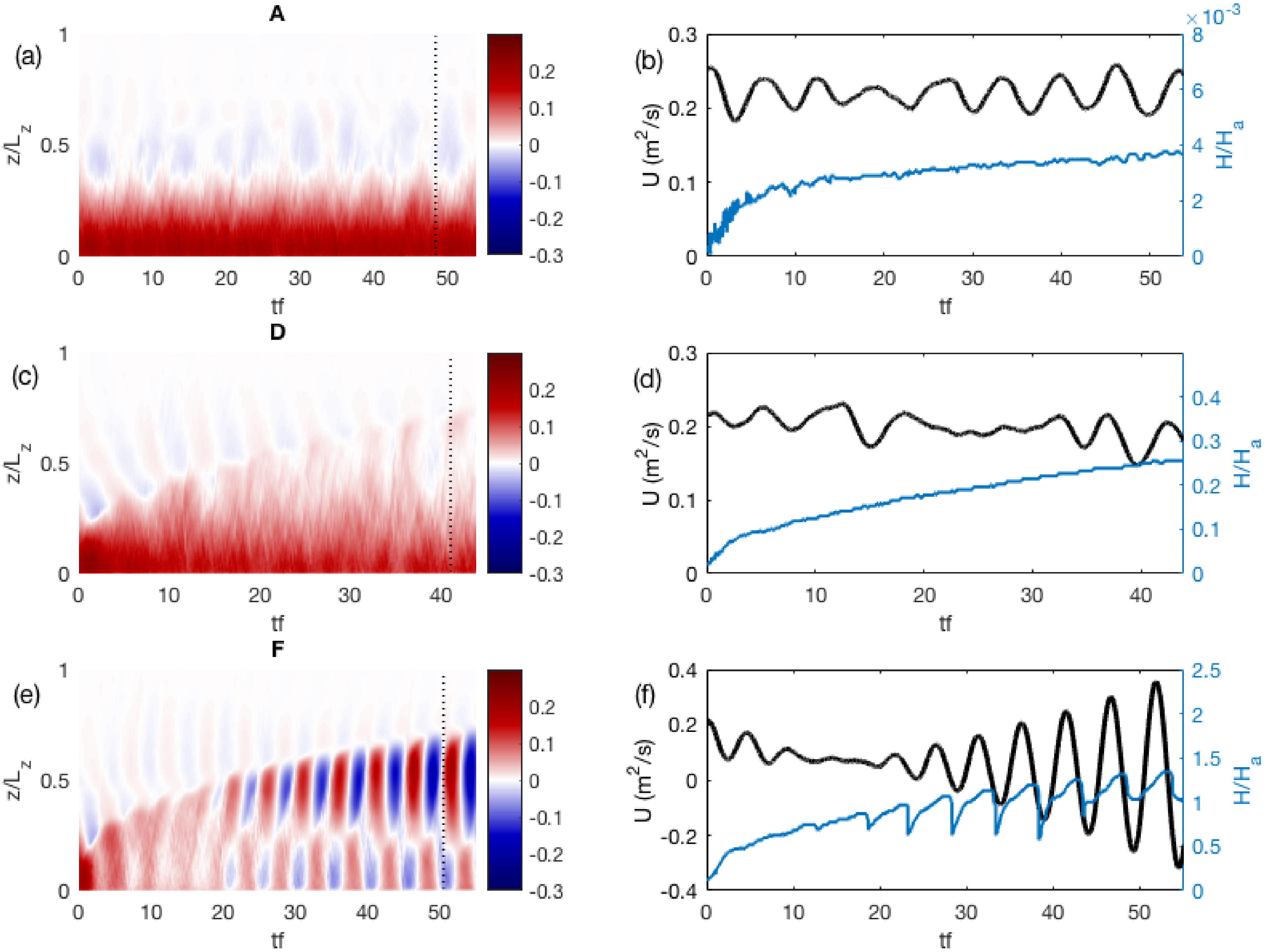
- $H/H_a \approx 1$

  - Stratification penetrates from above.
  - Prominent oscillations although time-averaged transport approaches Ekman state.



Ruan *et al.* (2018, submitted)

Cross-slope transport



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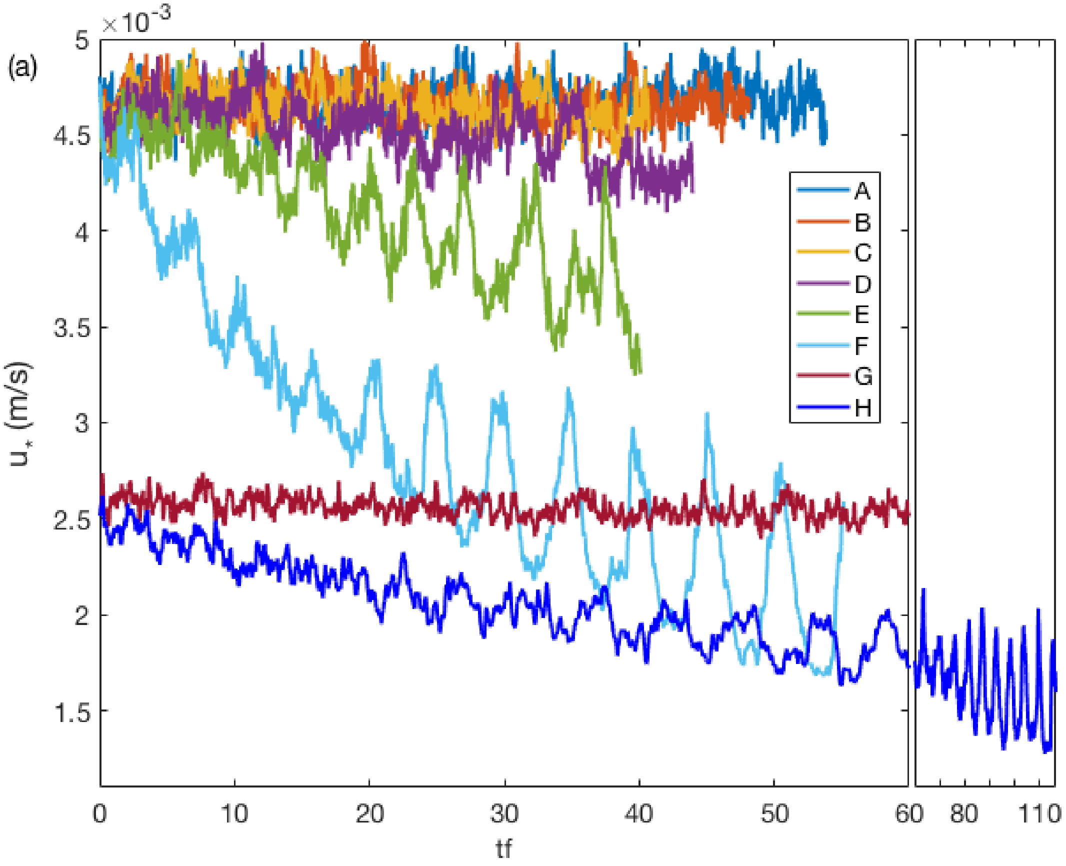
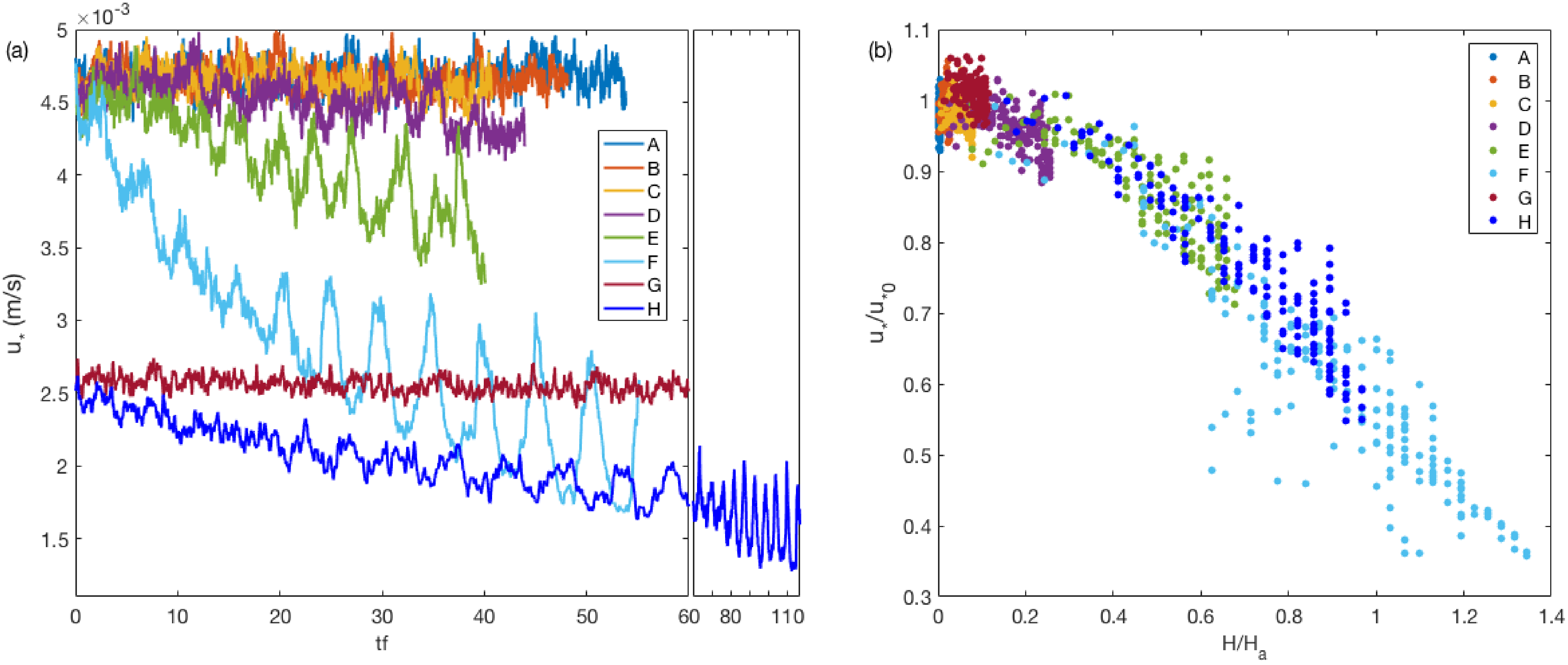
LES simulations



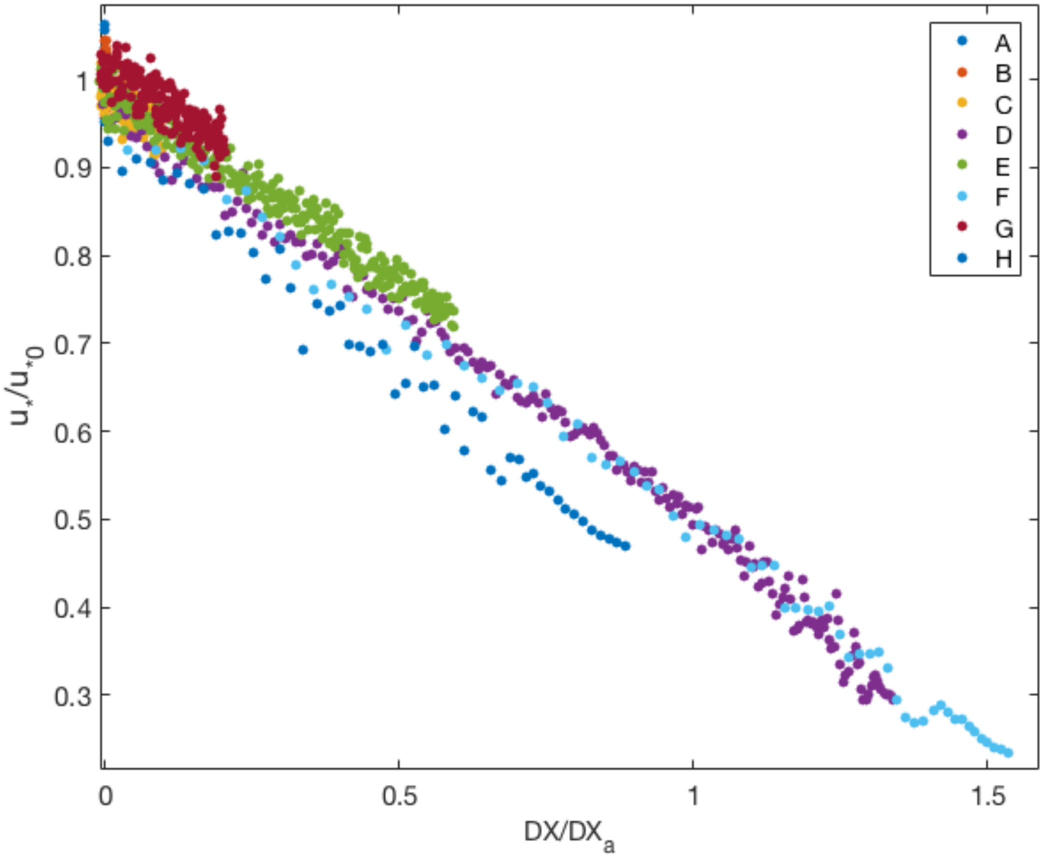
LES simulations



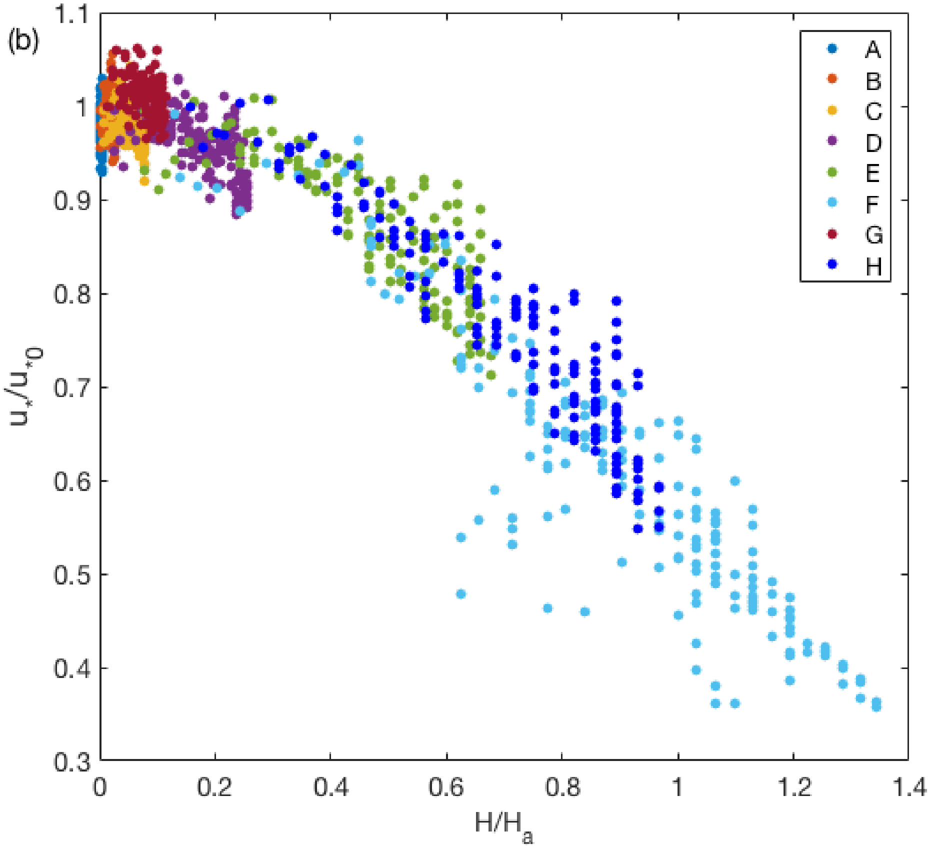
Ruan *et al.* (2018, submitted

LES simulations

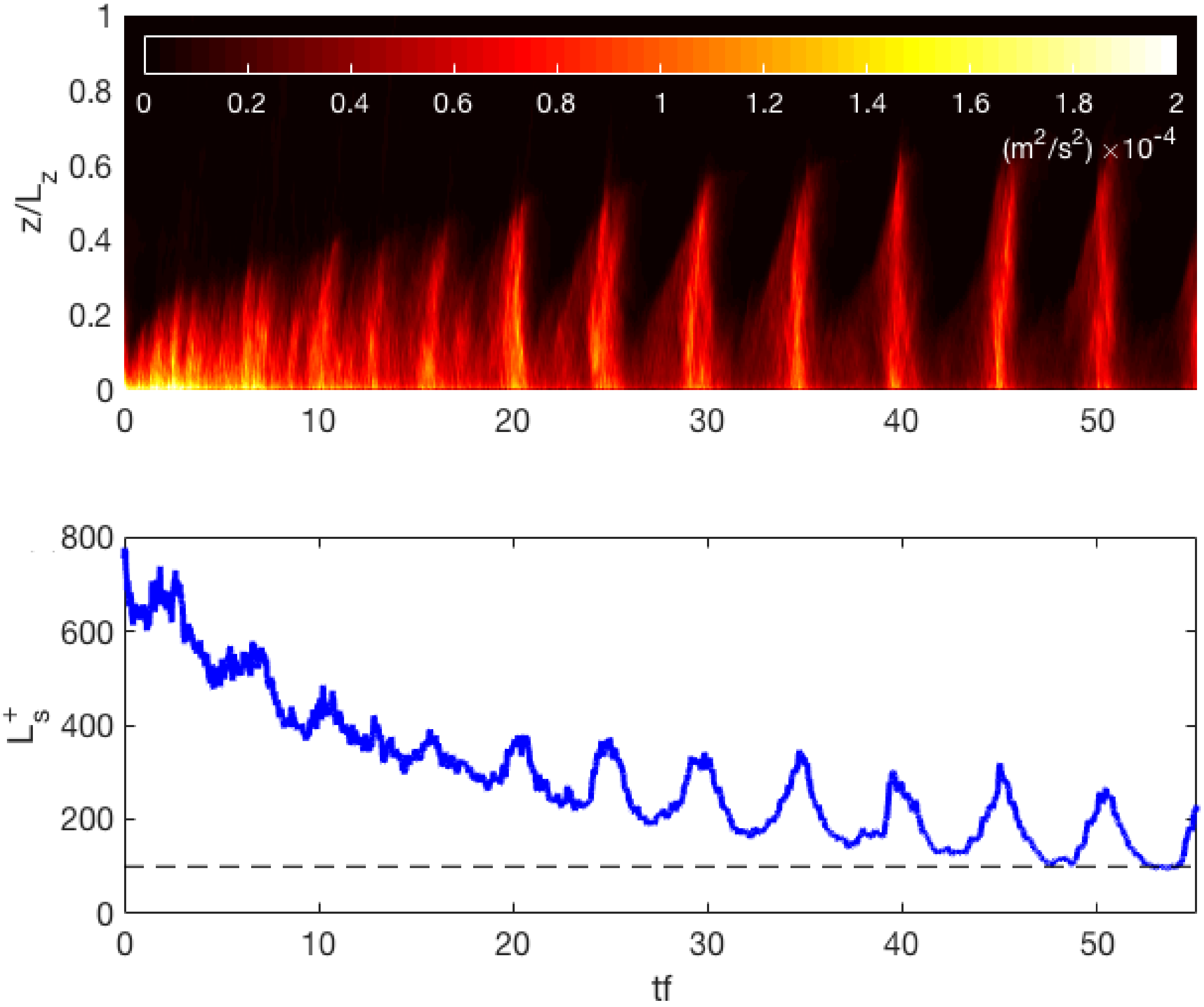
Upwelling case



Downwelling case



Ekman arrest?



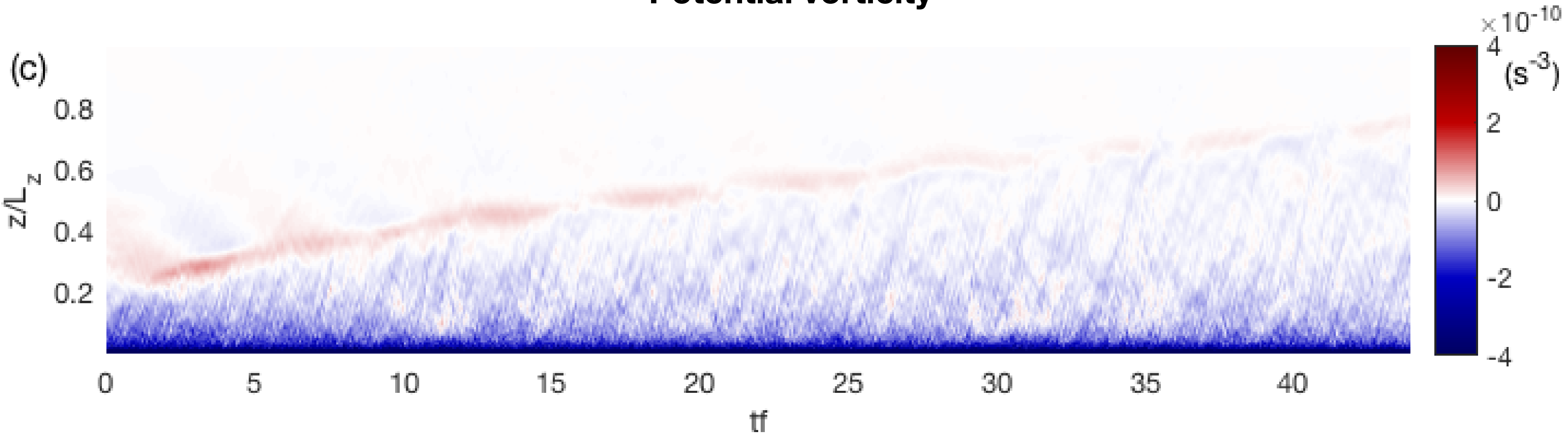
Inertial oscillations give rise to intermittent bursts of TKE, even as the time-averaged transport approaches the arrested value [see also Umlauf *et al.* (2015)]

Ruan *et al.* (2018, submitted)

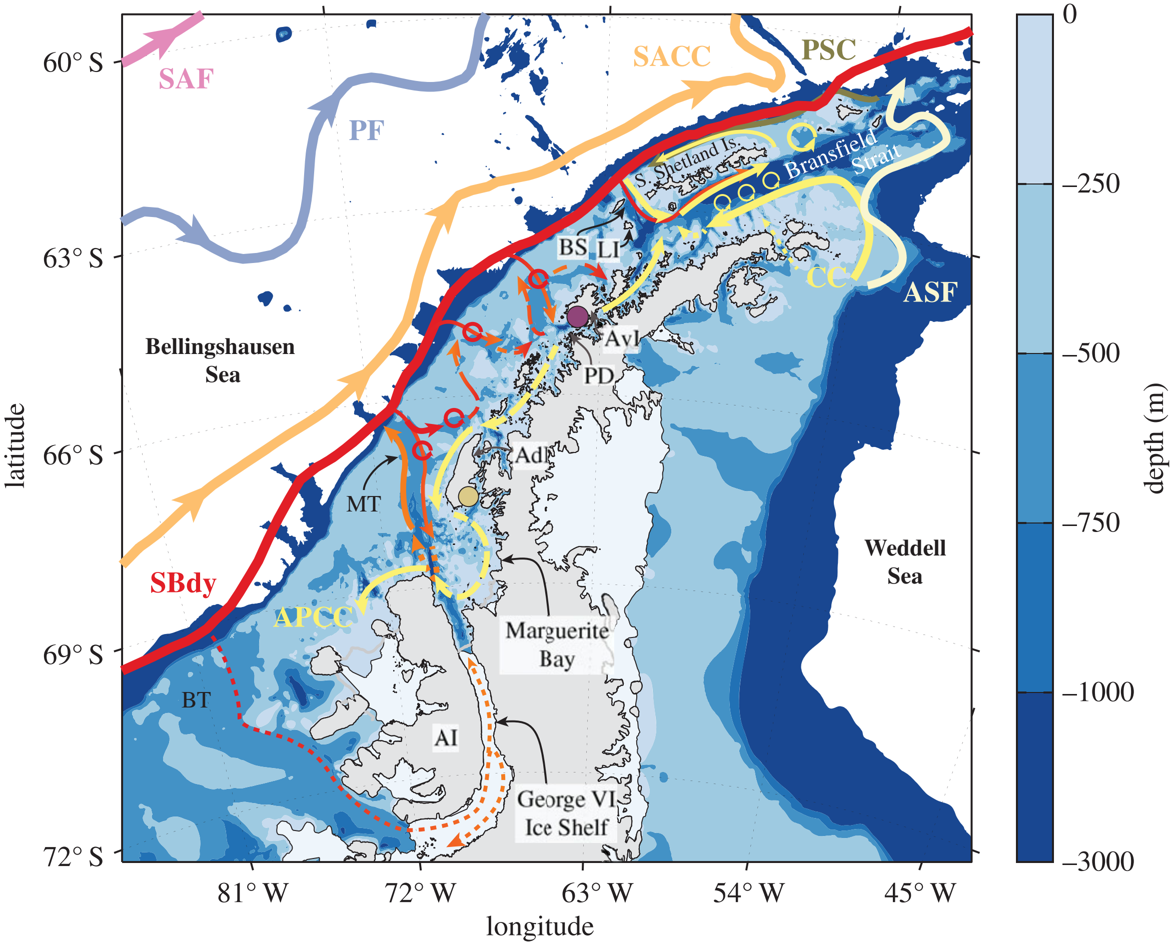
Future work

- A global distribution of Ekman arrest height (or E_{arr})?
- Prediction of friction velocity (based on H/H_a); improved parameterizations in GCMs?
  - More effective estimates of V_b
- Expand to larger domains to explore other active physical processes.

Potential vorticity



Bottom boundary layer turbulence in the Antarctic Circumpolar Current



California Institute of Technology • Scripps Institution of Oceanography

Changes in Stratification at the Antarctic Peninsula

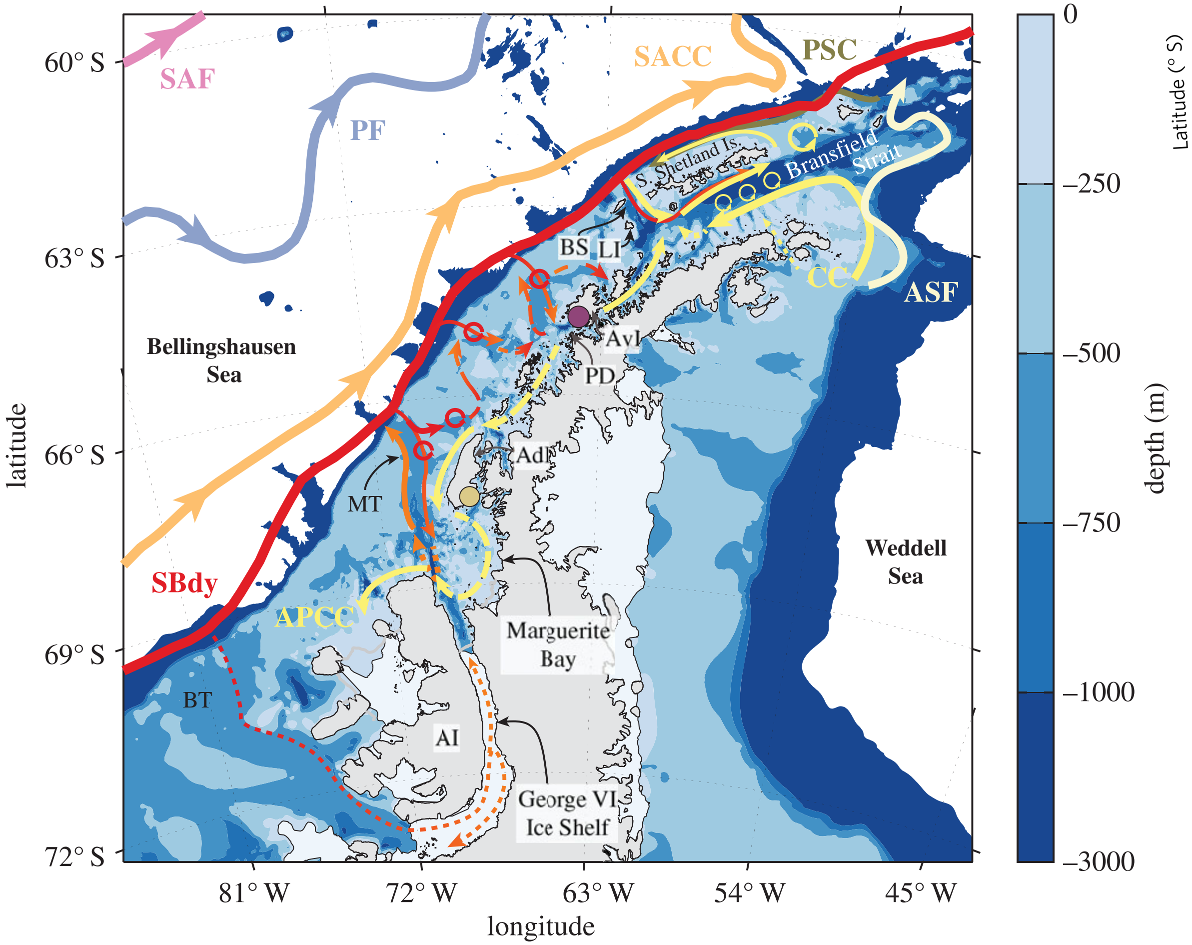
ChinStrAP

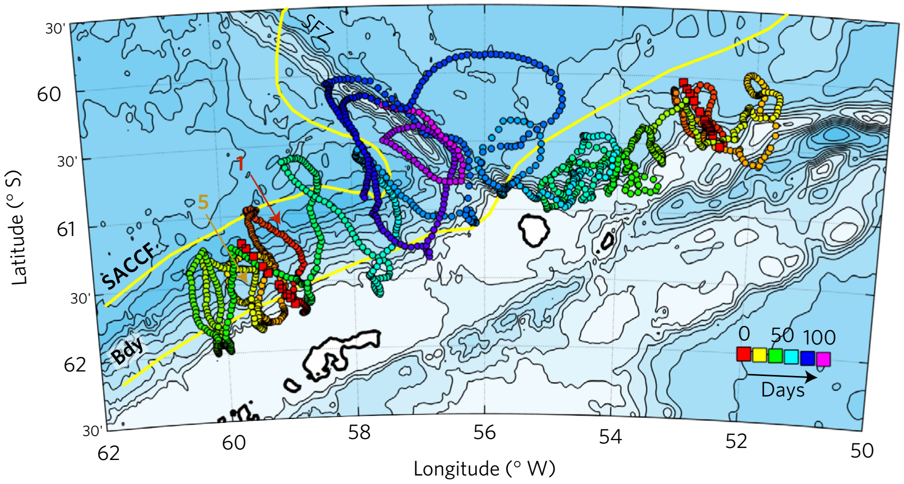
R/V L.M. Gould • Drake Passage

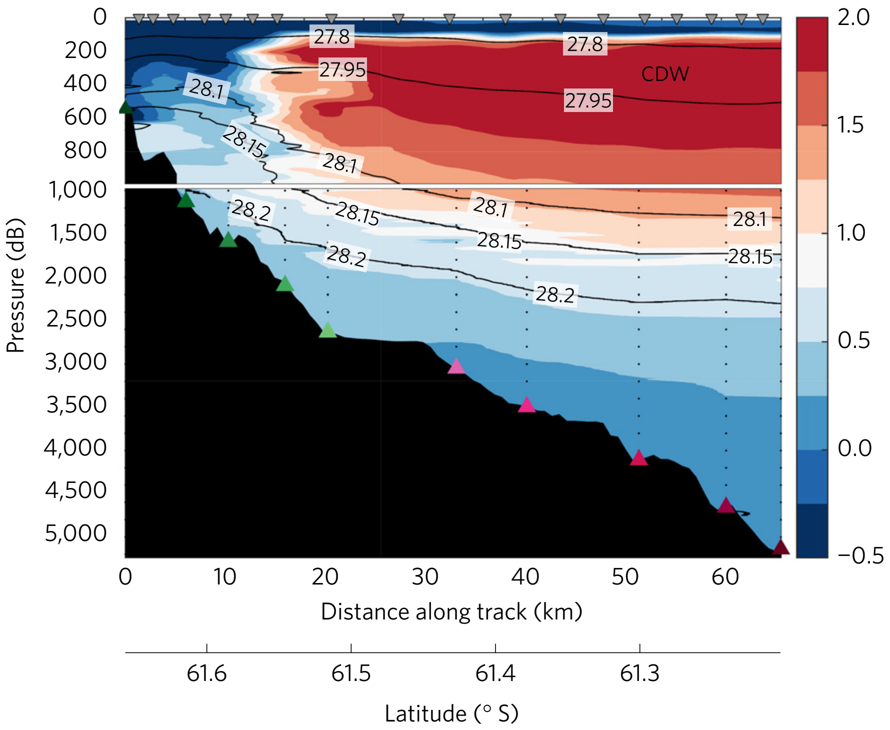
December 2014

Council for Scientific and Industrial Research, South Africa

Bottom boundary layer turbulence in the Antarctic Circumpolar Current



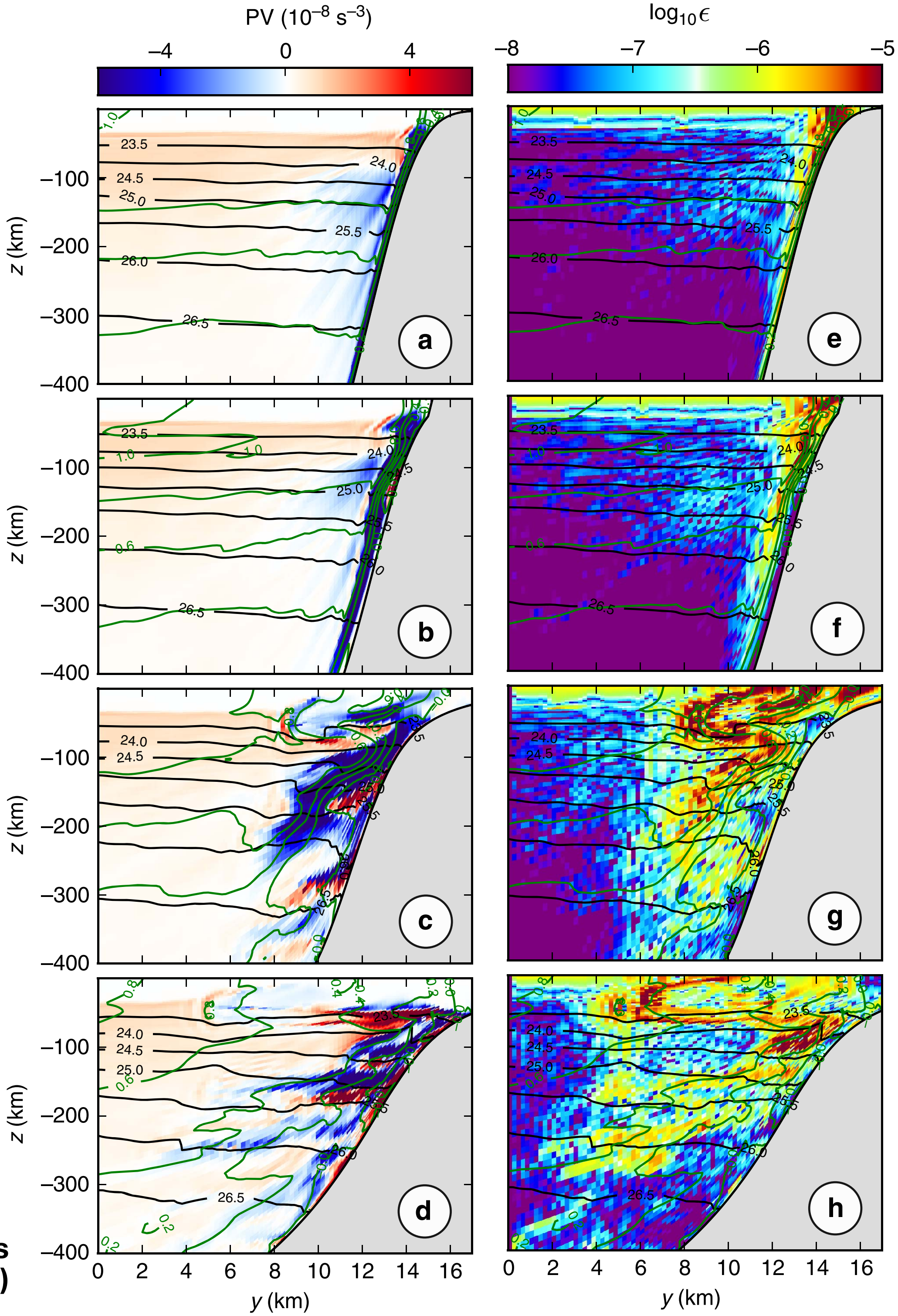




Bottom boundary layer turbulence & interactions with sloping topography

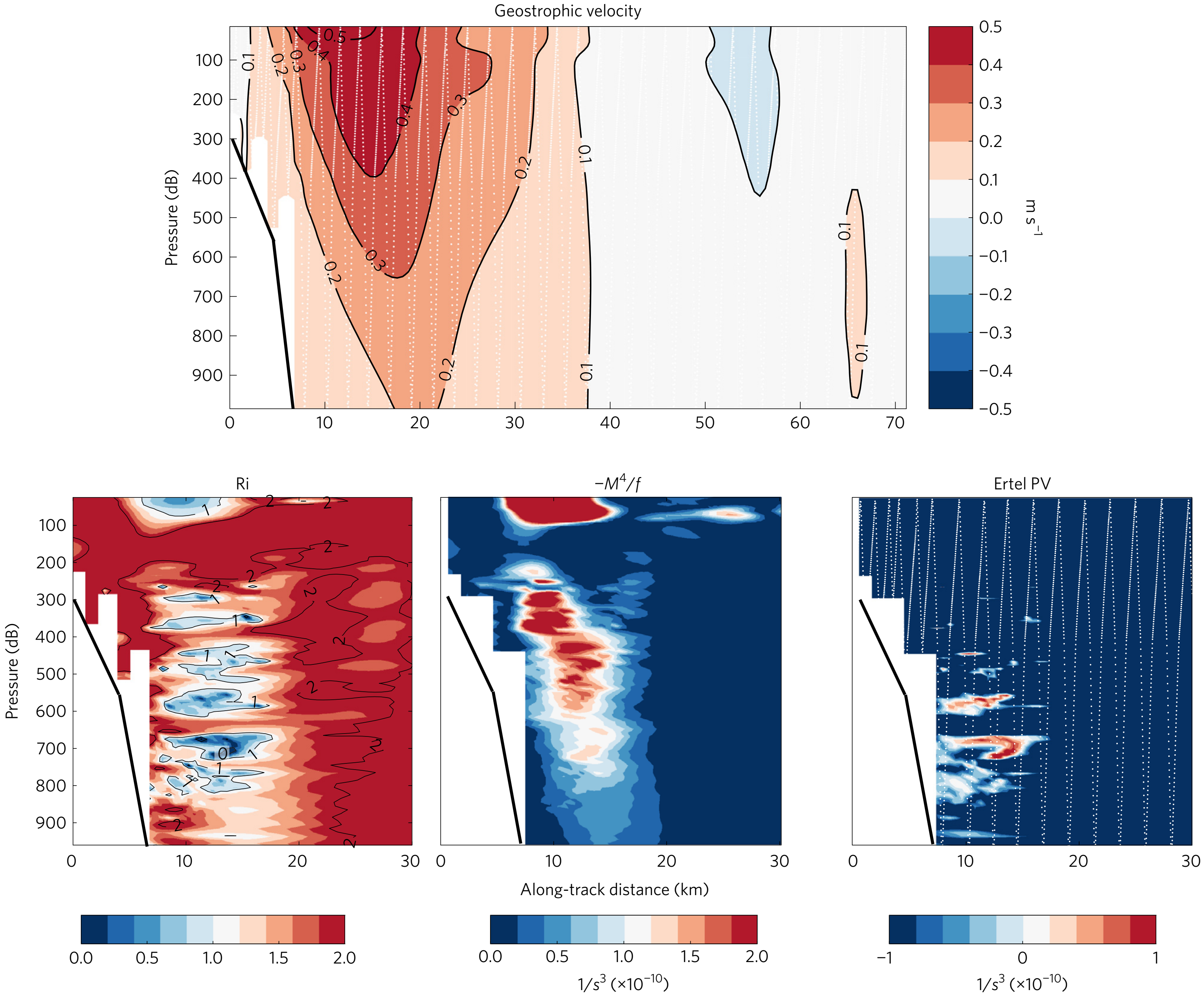
- High-resolution numerical models show evidence of small-scale instabilities that enhance dissipation.

- These dynamics are linked to the injection of PV anomalies into the interior along isopycnals.



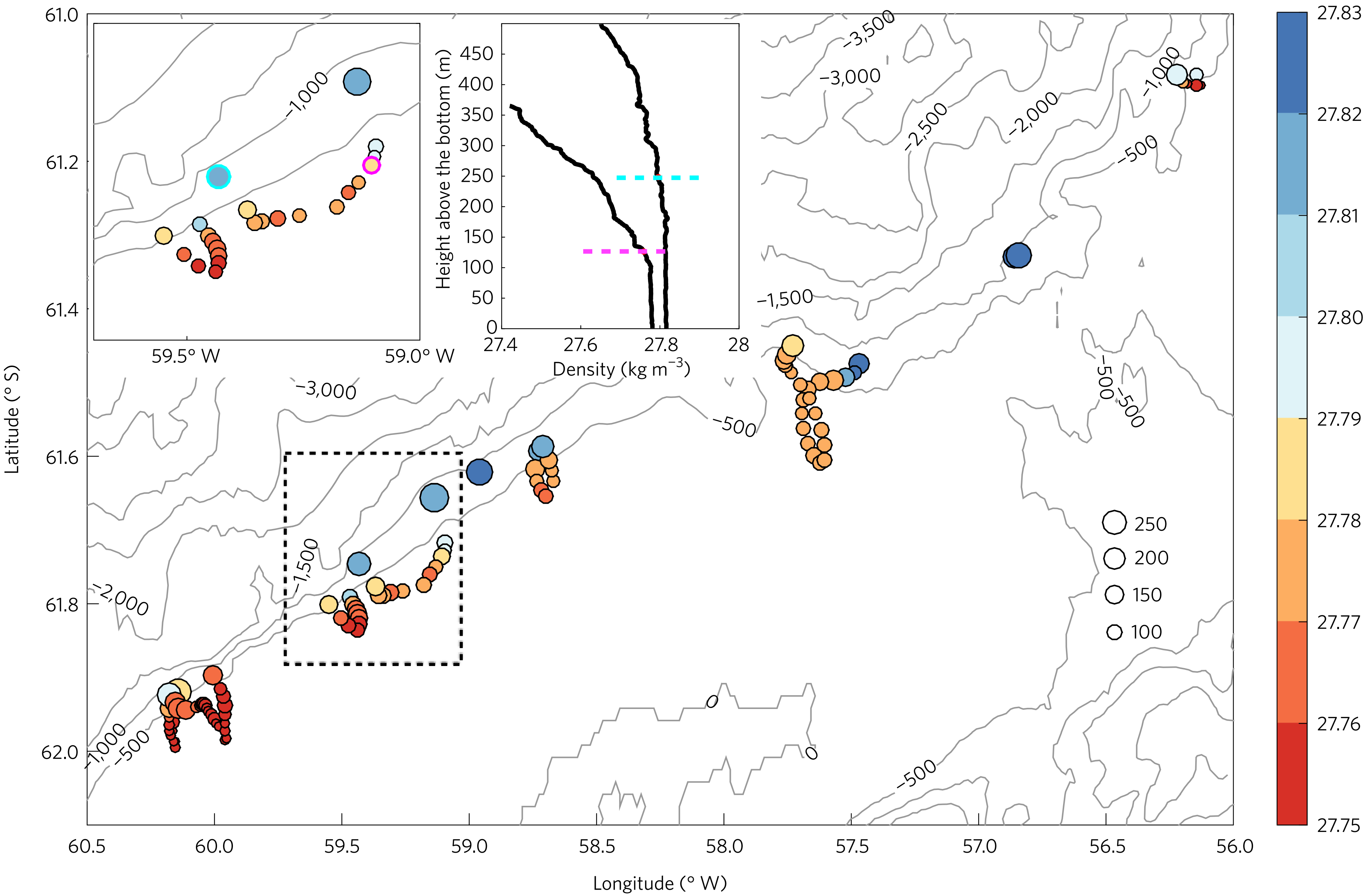
Simulation of the Florida Straits
Gula *et al*. (2016)

The southern boundary of the ACC in Drake Passage



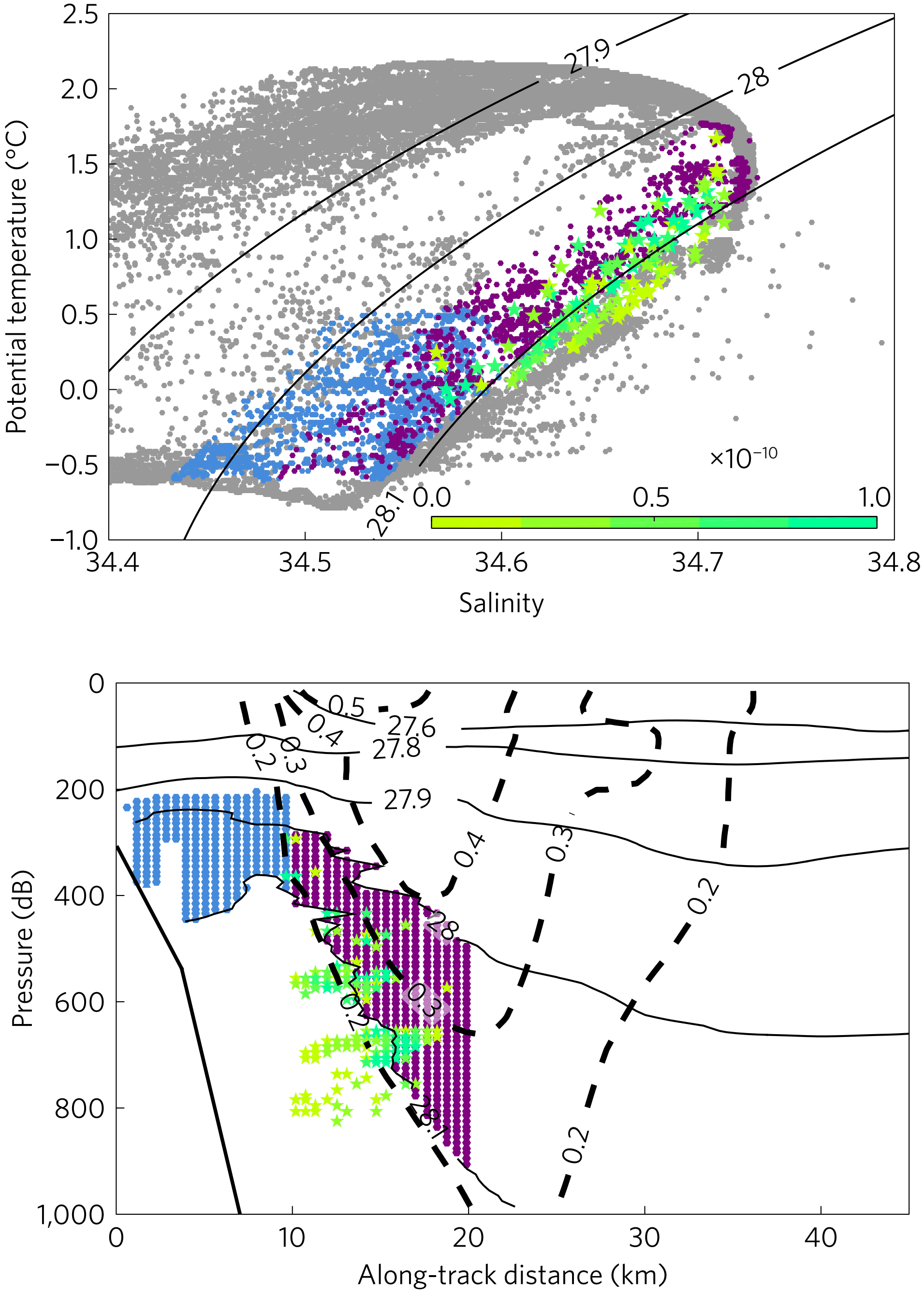
Ruan *et al.* (2017)

Boundary layer thickness



Ruan *et al.* (2017)

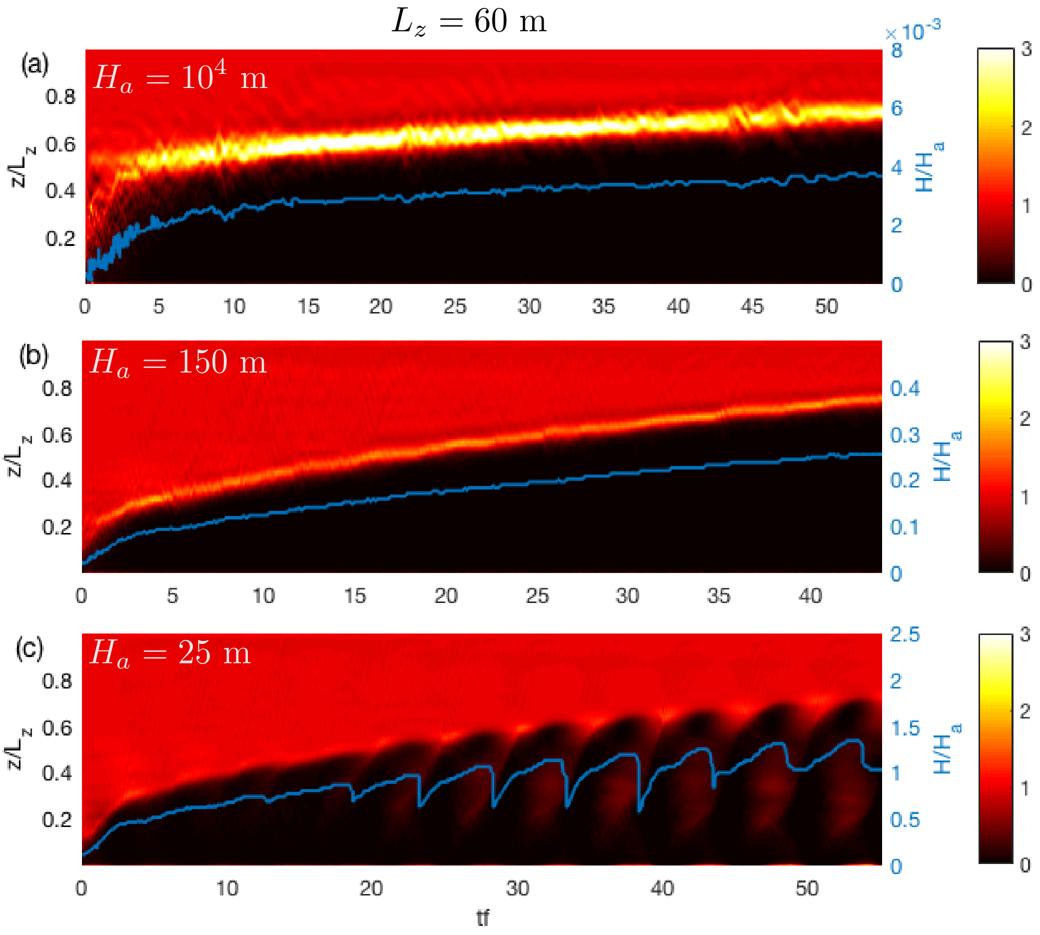
Water mass transformation

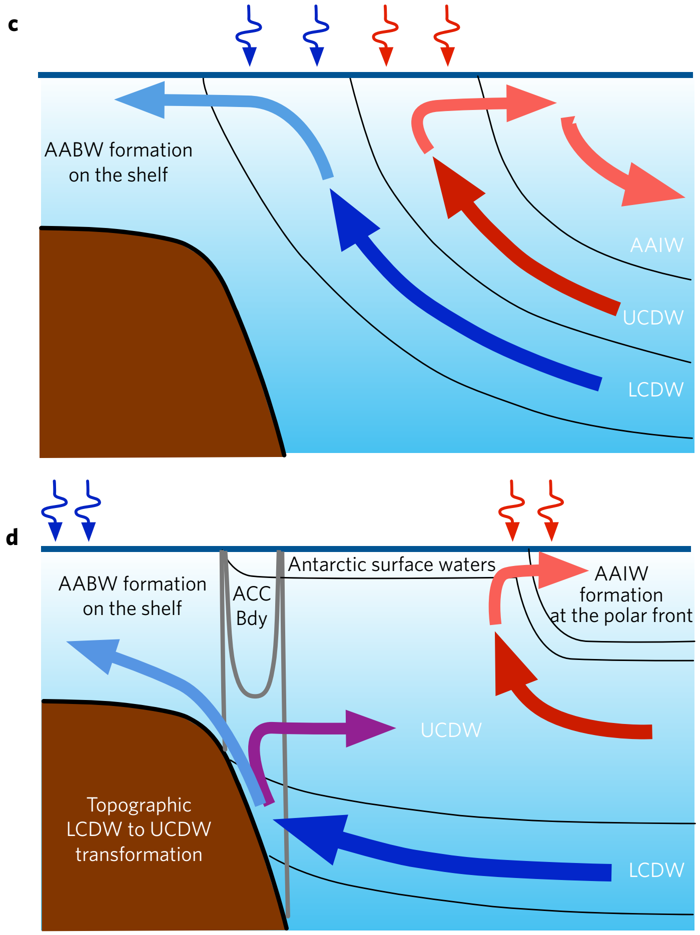


Ruan *et al.* (2017)

Conclusions

- LES simulations show that scalings for an arrested Ekman layer depth is useful for characterizing turbulence;
- Observational evidence suggest that submesoscale stabilities can catalyze water mass transformation in BBLs.





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Ruan, X., A.F. Thompson, M.M. Flexas & J. Sprintall, 2017. Contribution of topographically-generated submesoscale turbulence to Southern Ocean overturning. *Nat. Geosci.*, **10**, 840-846.