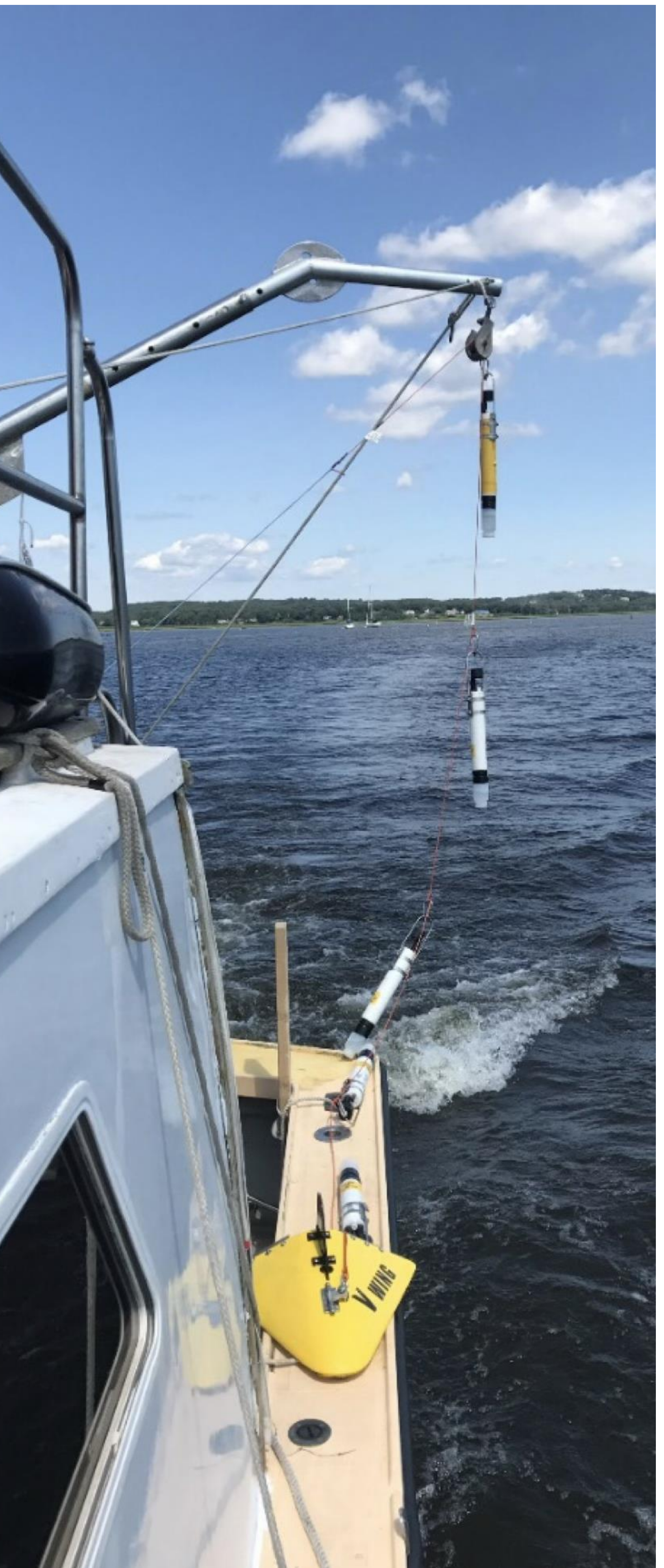
The structure and lifecycle of stratified mixing by shear instability in continuously forced shear flows

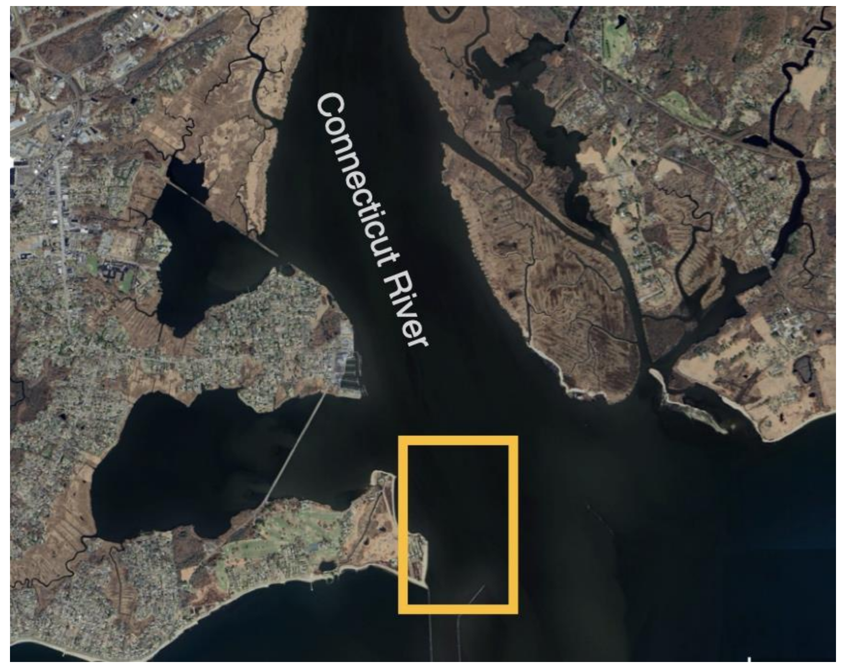
Adrien Lefauve
Chris Bassett
Dan Plotnick
Andone Lavery
Rocky Geyer

IMPERIAL
University of Washington
PennState
Oregon State University
Woods Hole Oceanographic Institution

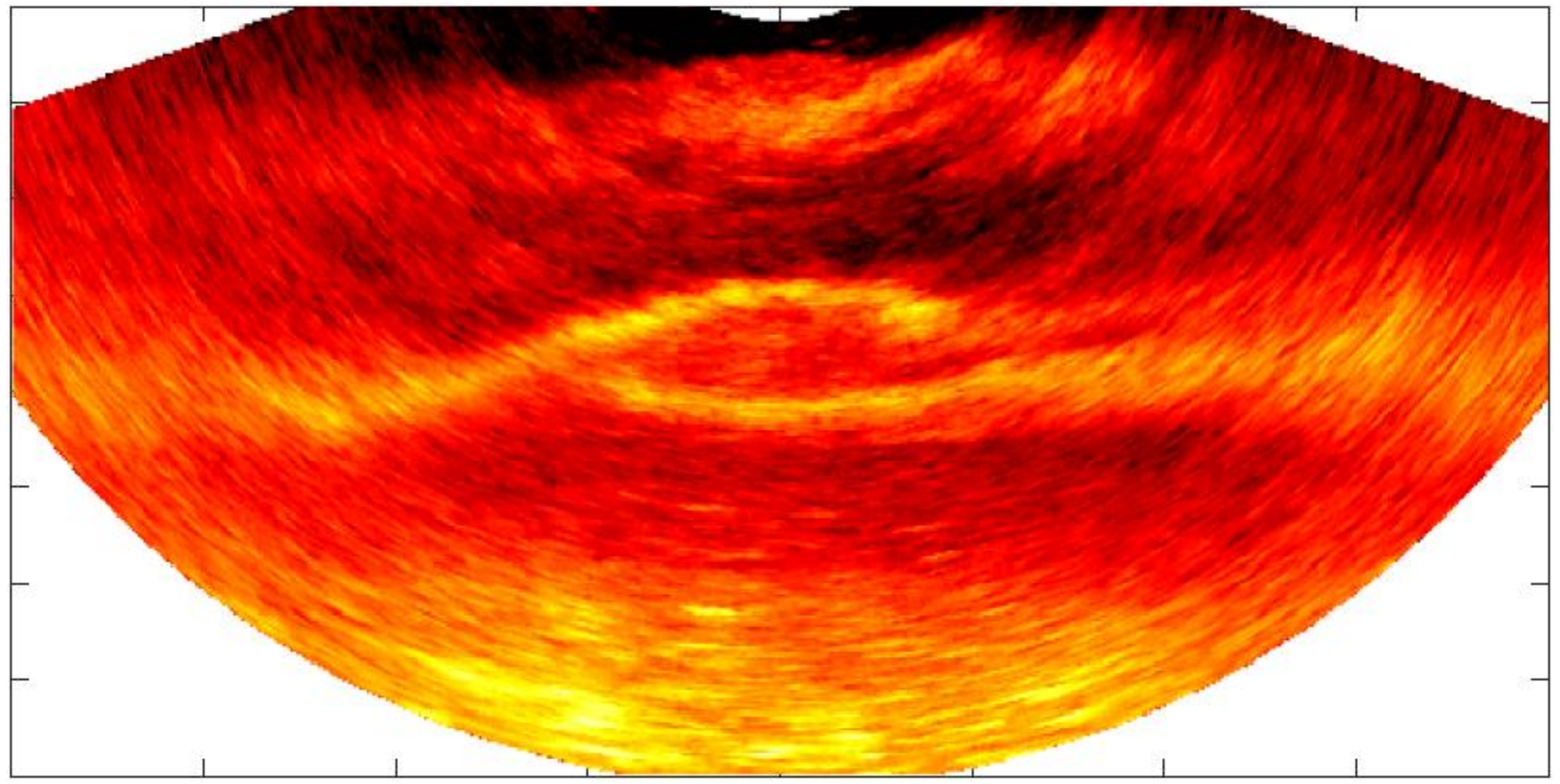
UKRI Natural Environment Research Council
Office of Naval Research Science & Technology

strongly-stratified estuary



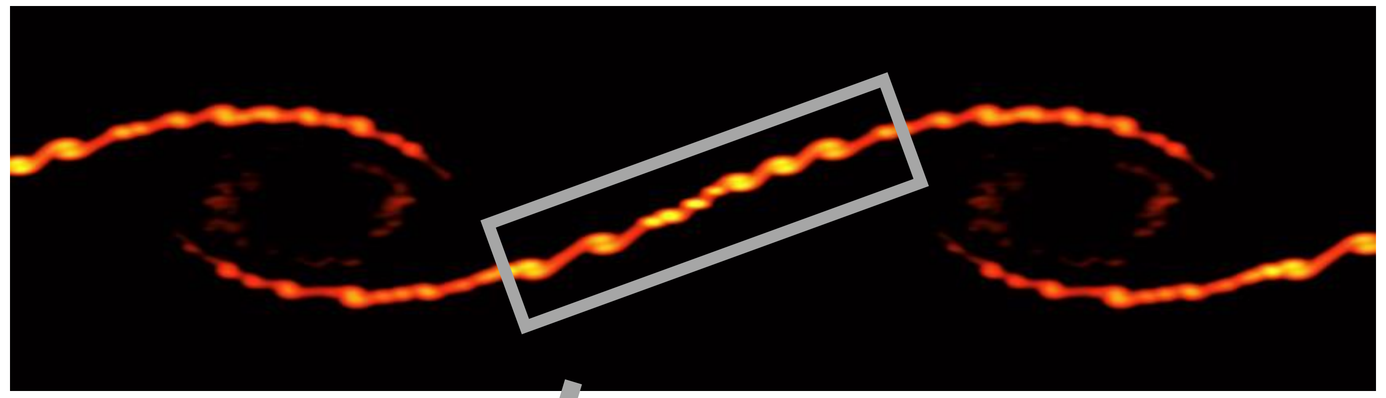


multibeam sonar



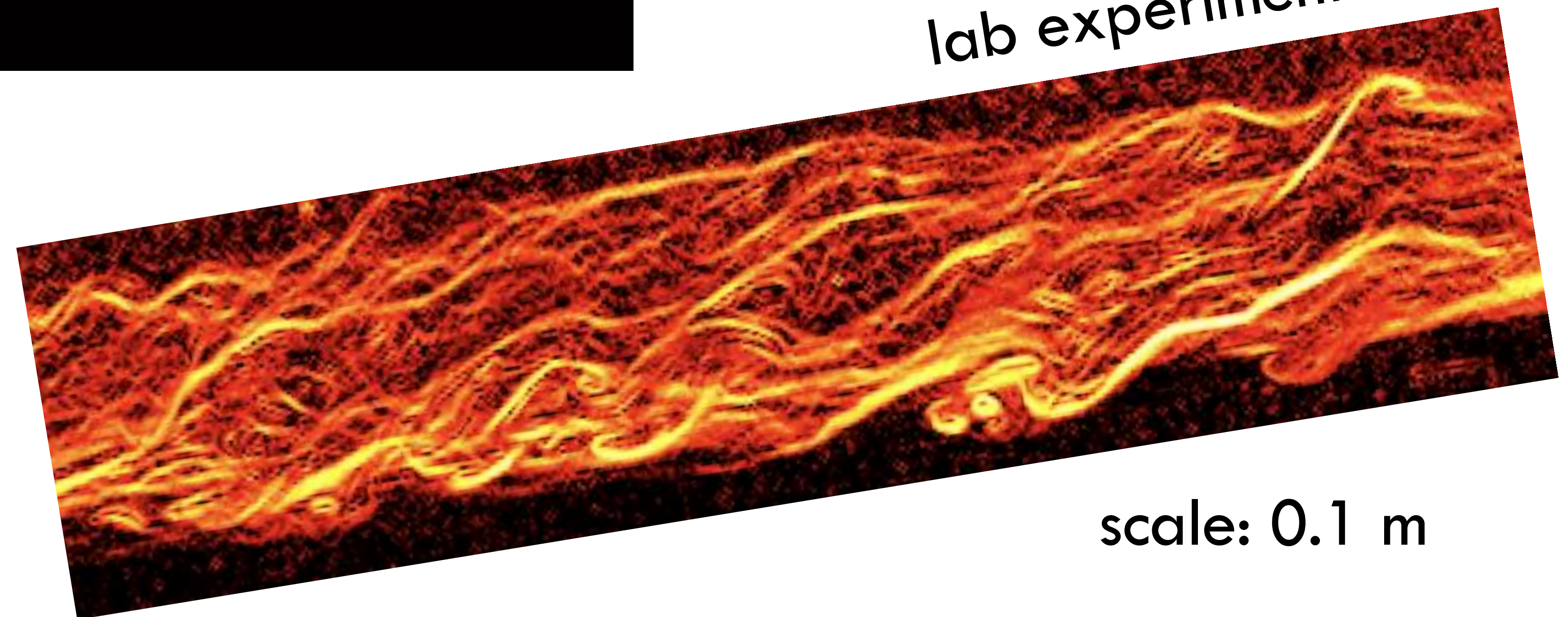
Signal: diapycnal mixing rate of salinity χ_s

numerical modelling



scale: 1 m

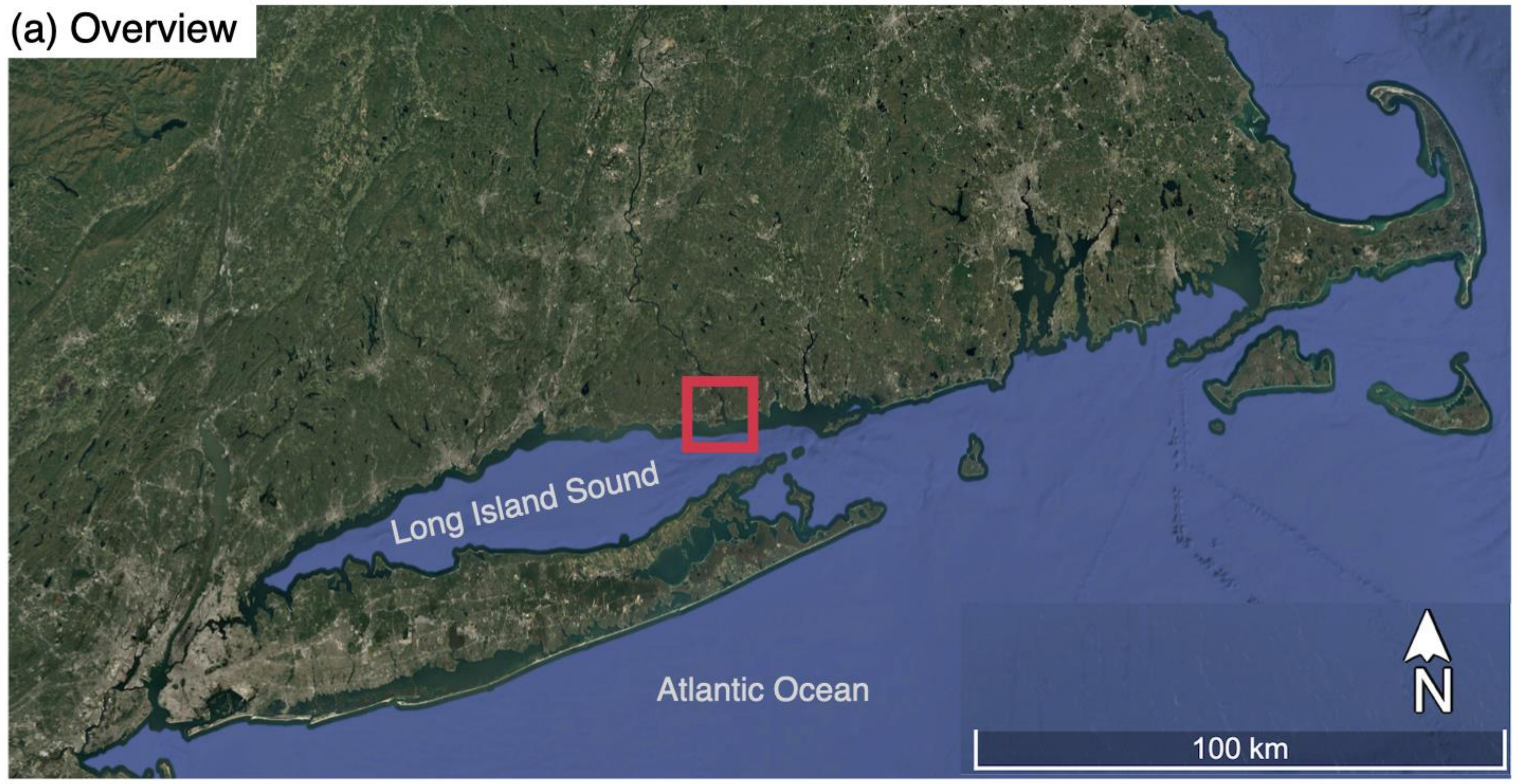
lab experiment

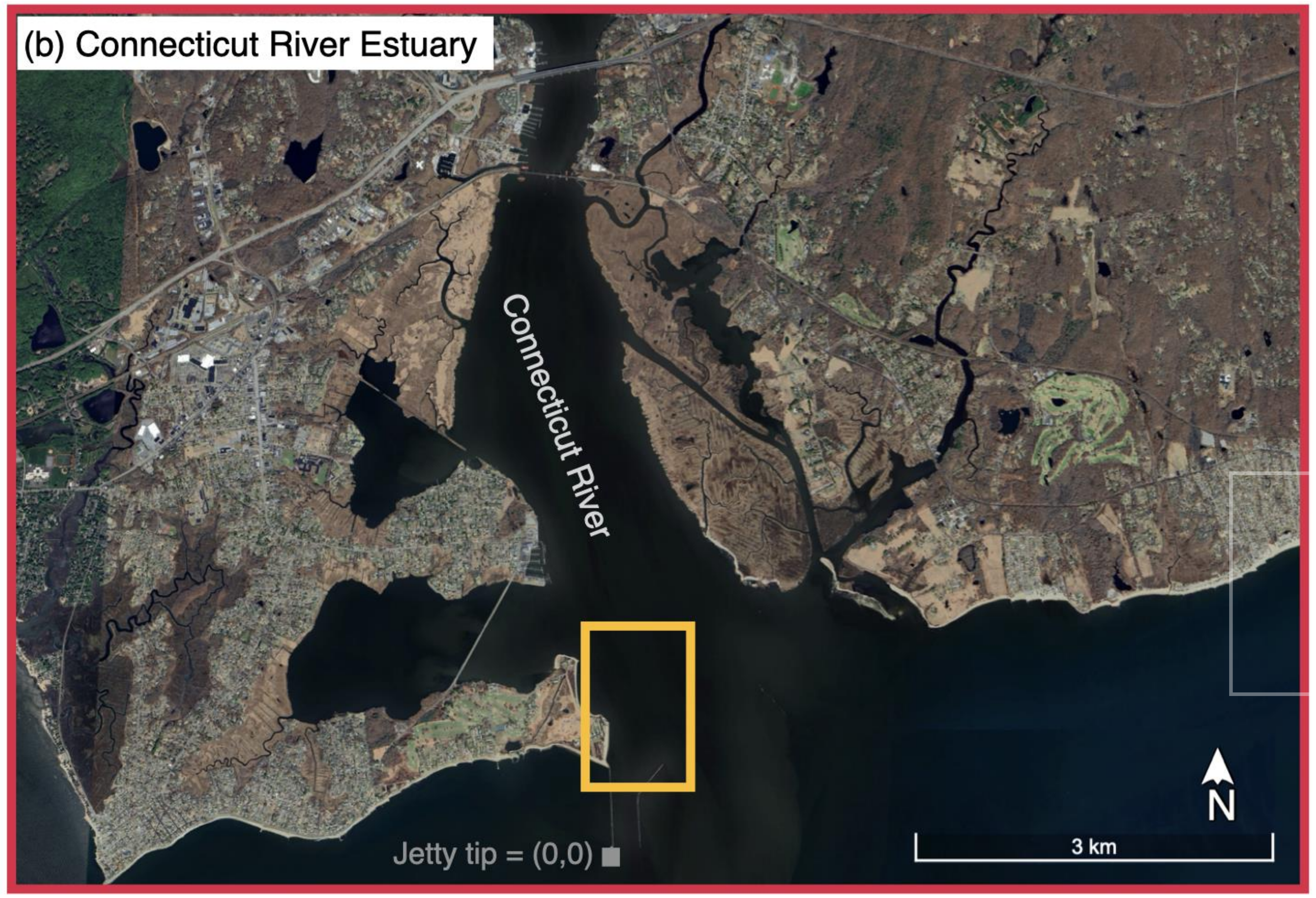


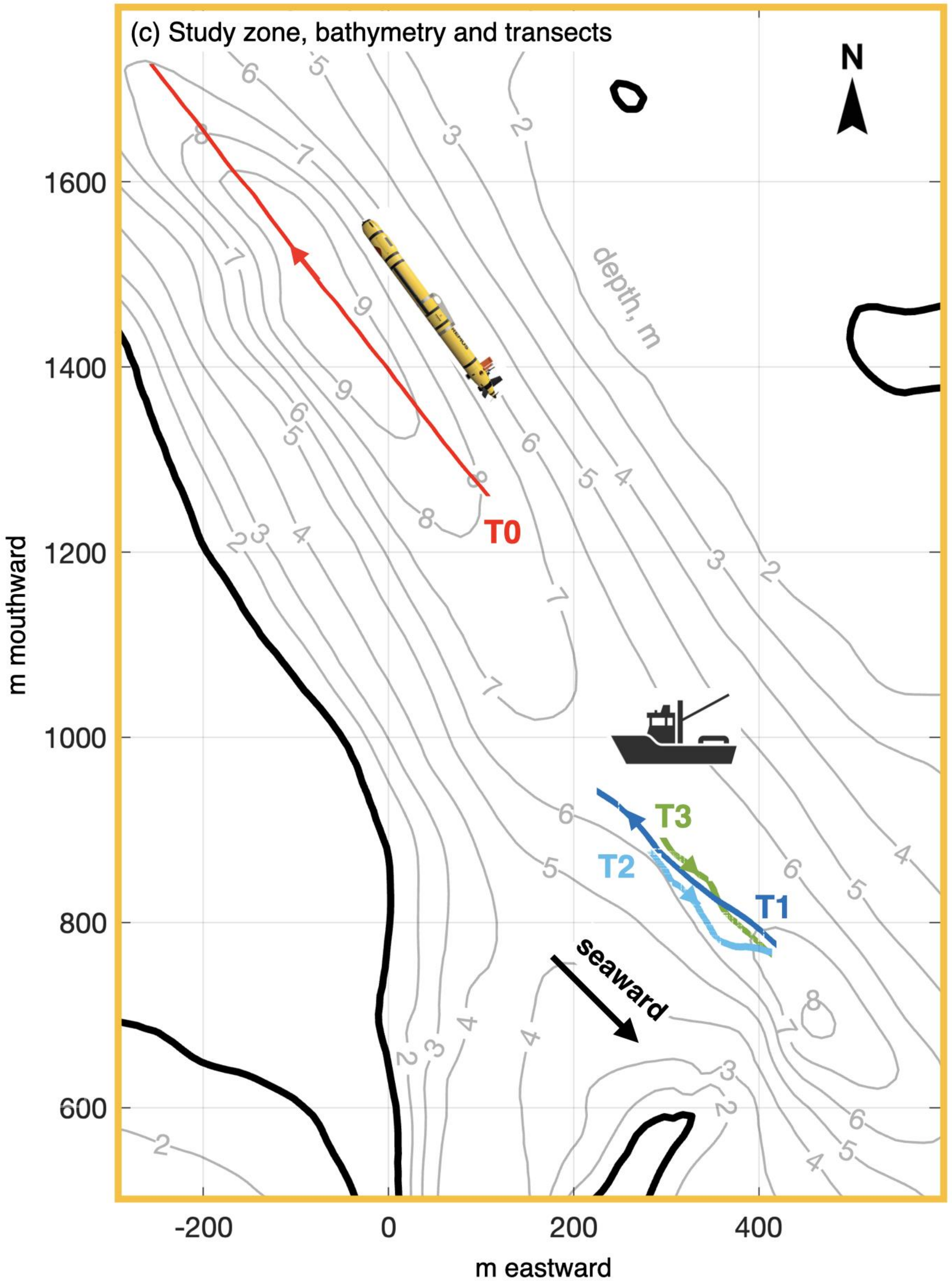
scale: 0.1 m

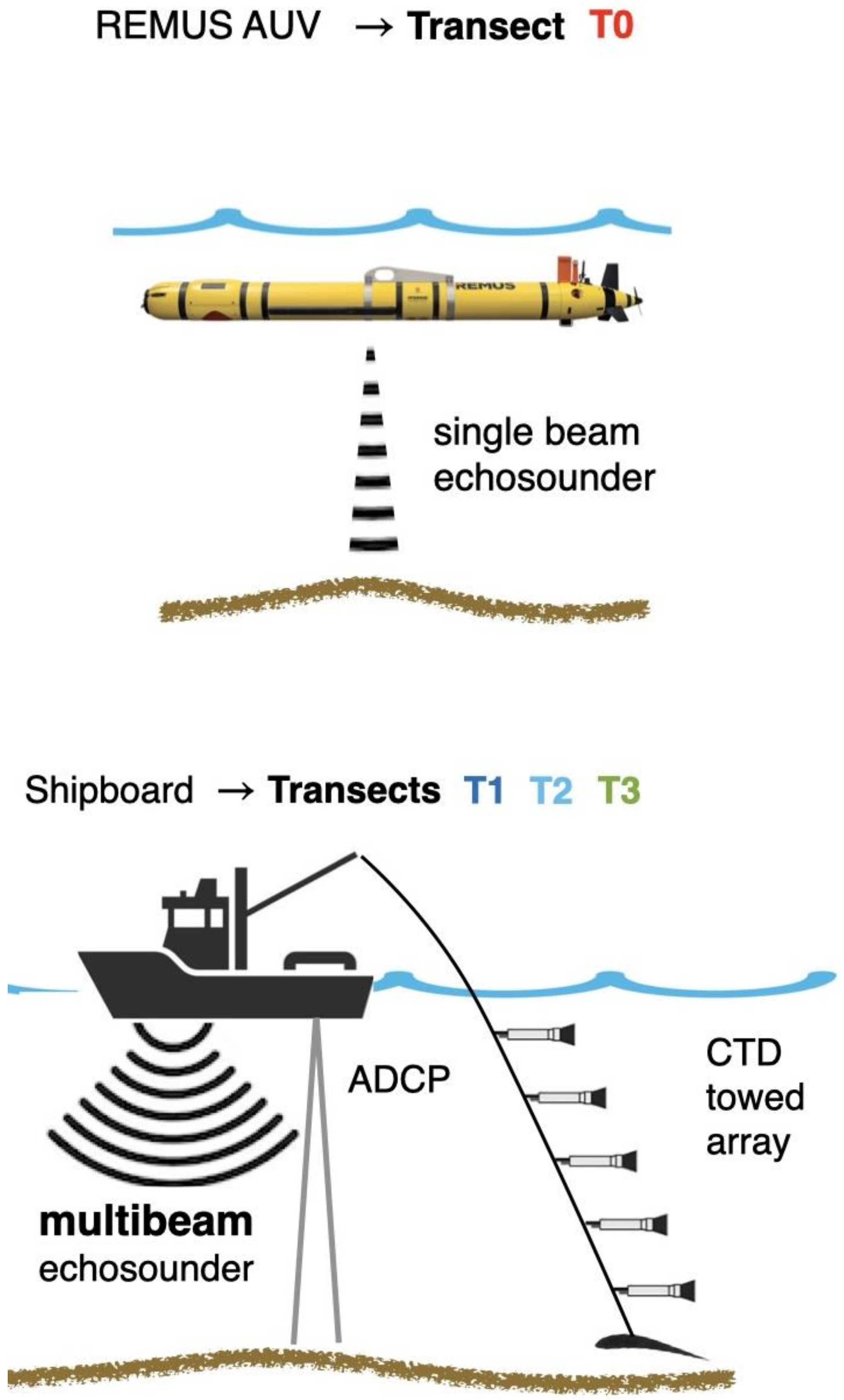
The site, transects and instruments

Fieldwork by Rocky Geyer & Andone Lavery (June 2017)



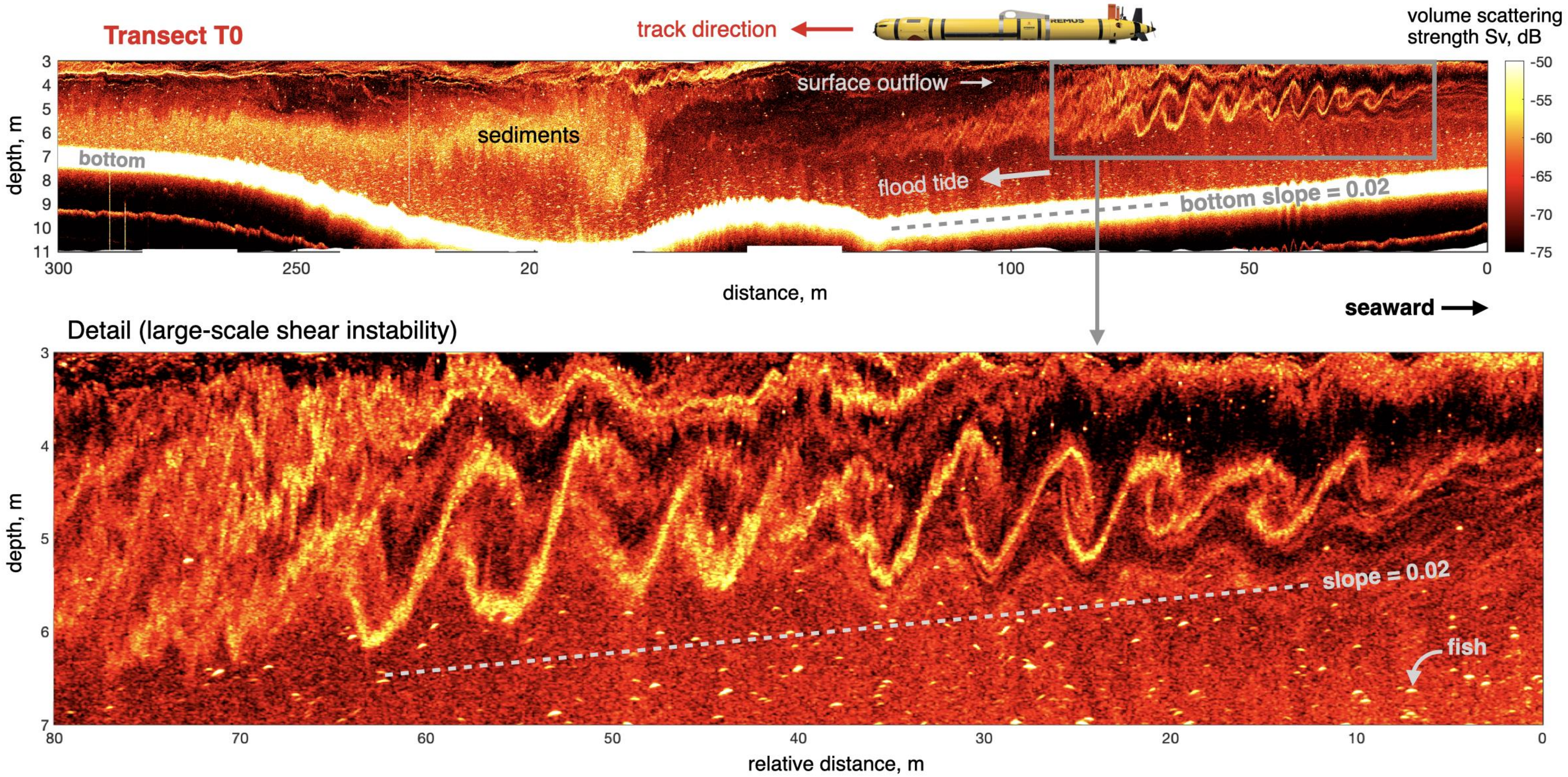






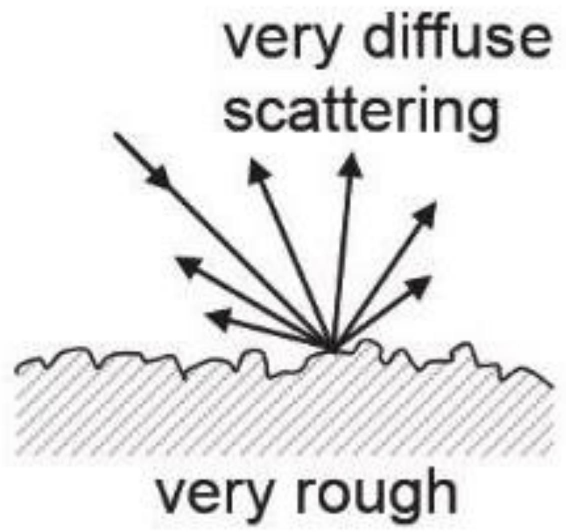
Instability train at the pycnocline revealed by echosounder

Remus
Autonomous
Underwater
Vehicle
(AUV)



Vertical exaggeration = 5

Principle:
Bragg scattering



Acoustic backscatter is a proxy for mixing rate

$$S_V = 5 \log_{10} \chi_s + \text{const.}$$

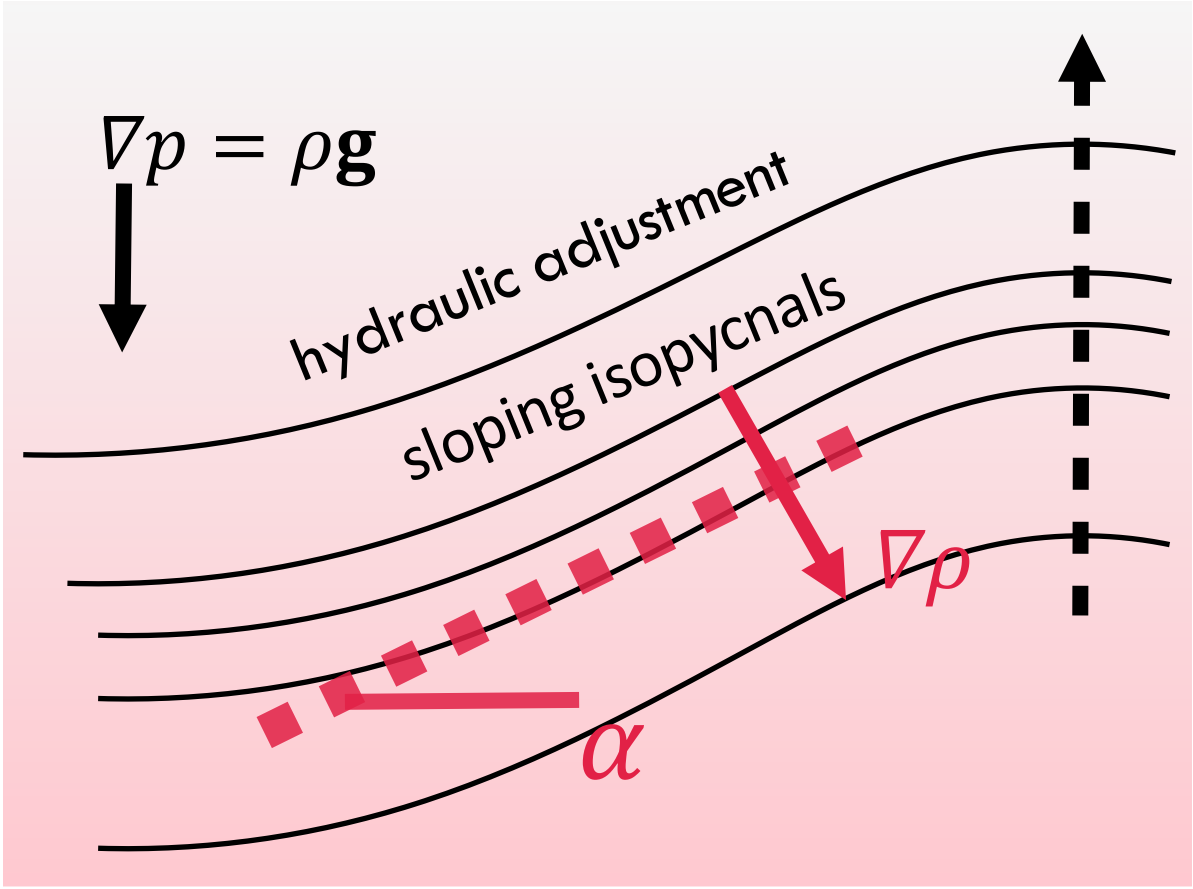
$\chi_s = 2D_s|\nabla s'|$ dissipation rate of salinity variance
~ diapycnal mixing rate

Lavery, Geyer & Scully, J. Acous. Soc. Am. (2013)

Continuous shear forcing

Salinity-stratified flow (temperature negligible)

Tidal forcing → **baroclinic shear** generation



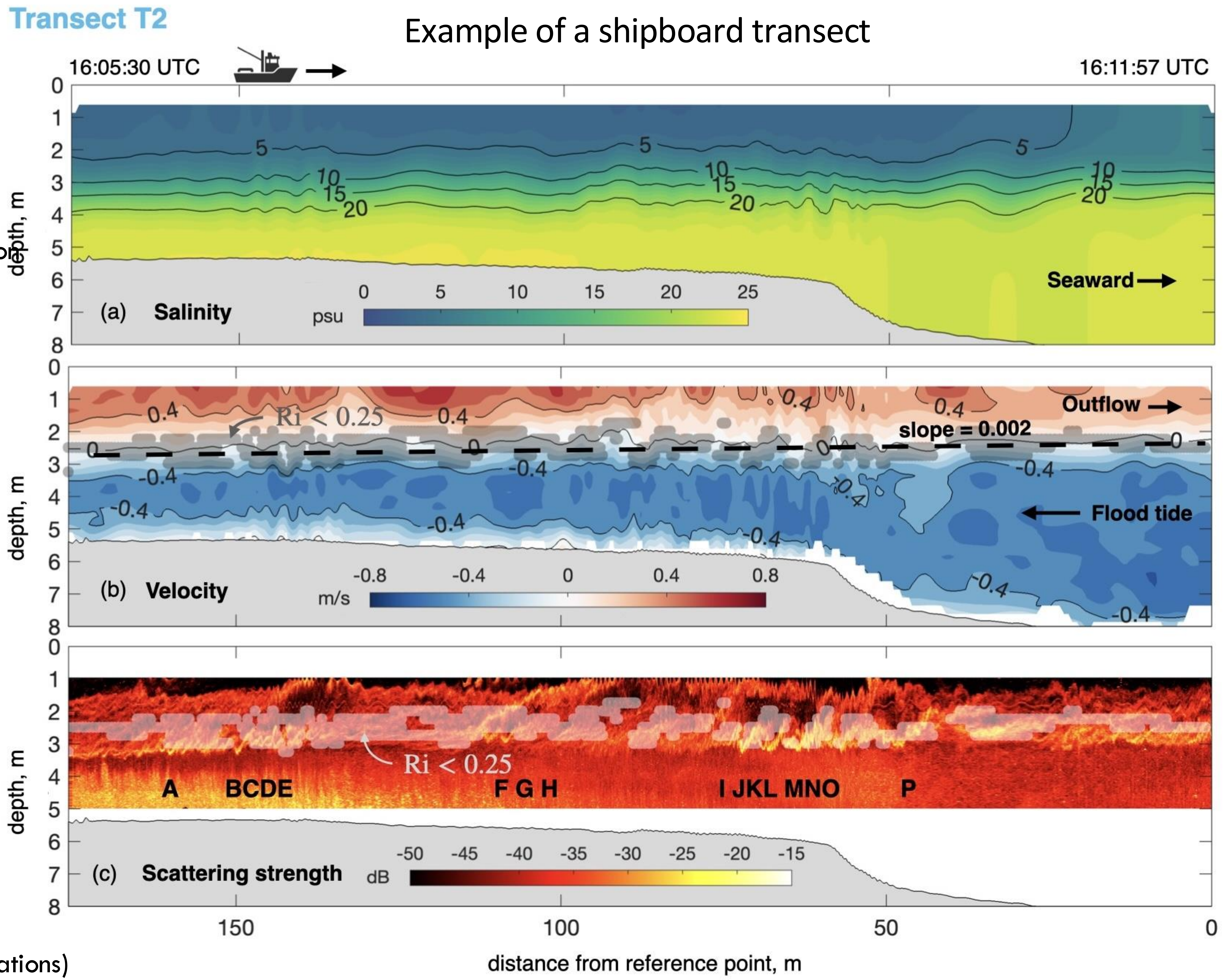
$$\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} + \frac{1}{\rho_0^2}\nabla\rho \times \nabla p$$

$$\frac{\partial S}{\partial t} \approx \mathrm{N}^2 \sin\alpha \approx \alpha\,\mathrm{N}^2$$

Drop in $\mathrm{Ri} = \frac{\mathrm{N}^2}{S^2} < 0.25$

→ **KH instability** (predictions match observations)

Example of a shipboard transect



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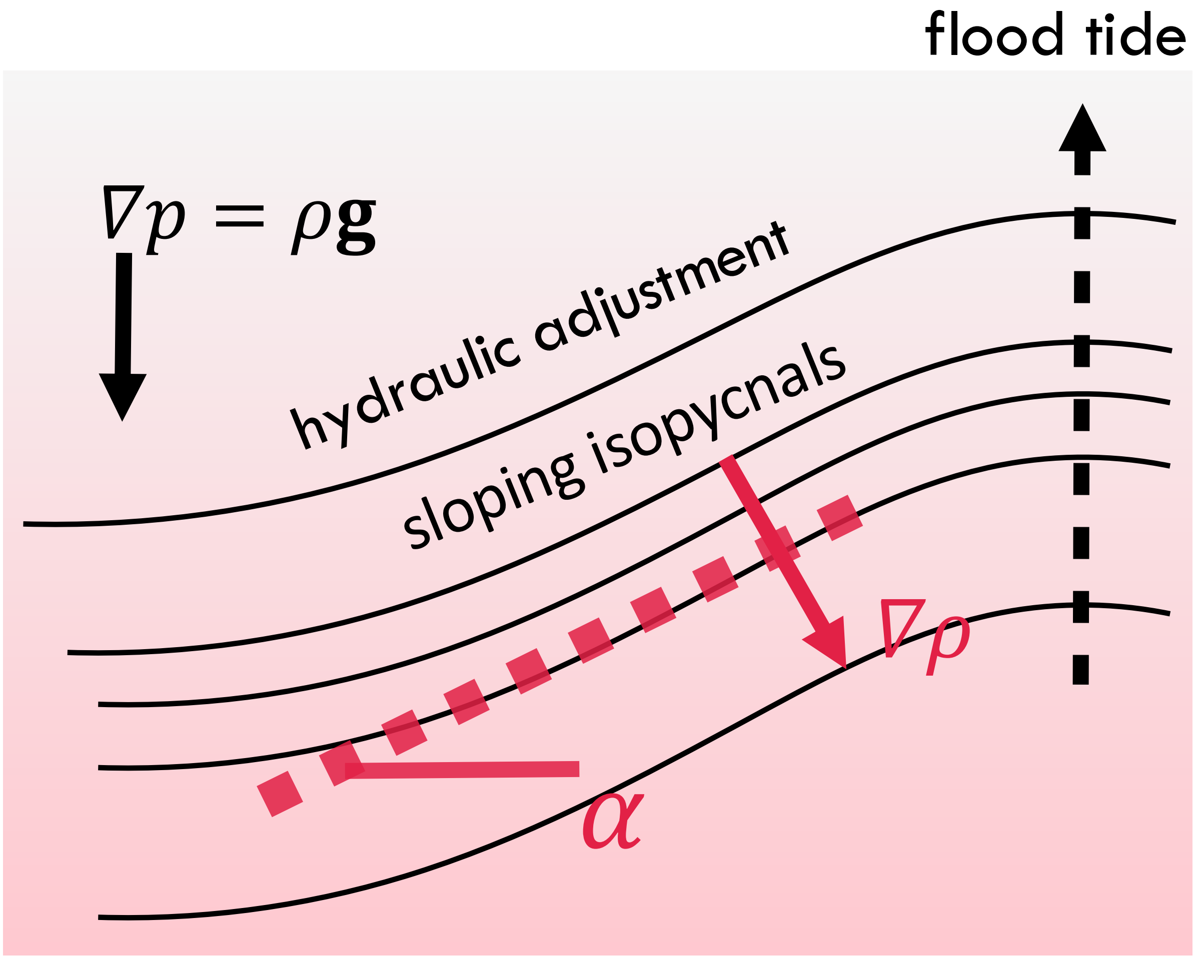
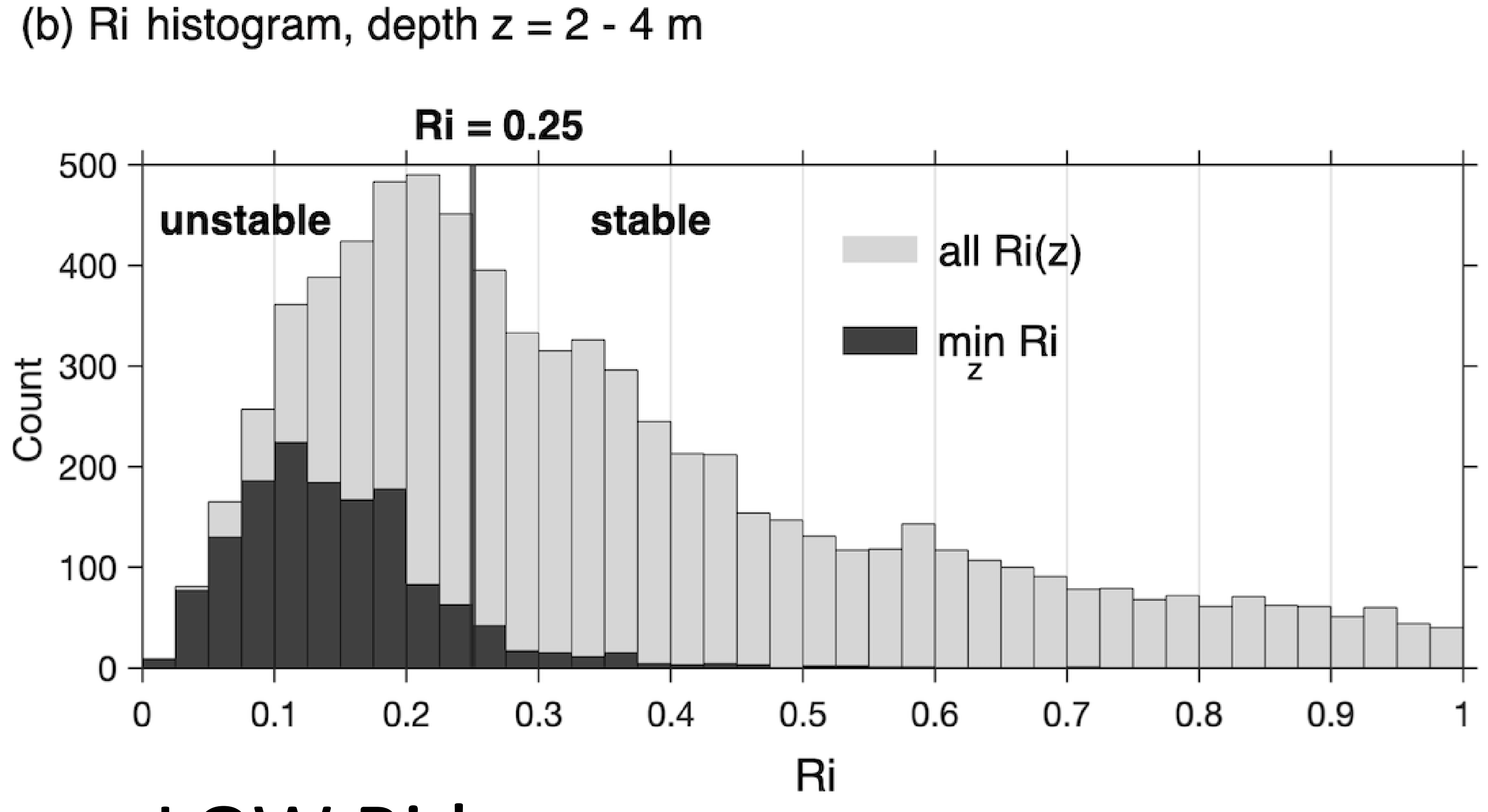
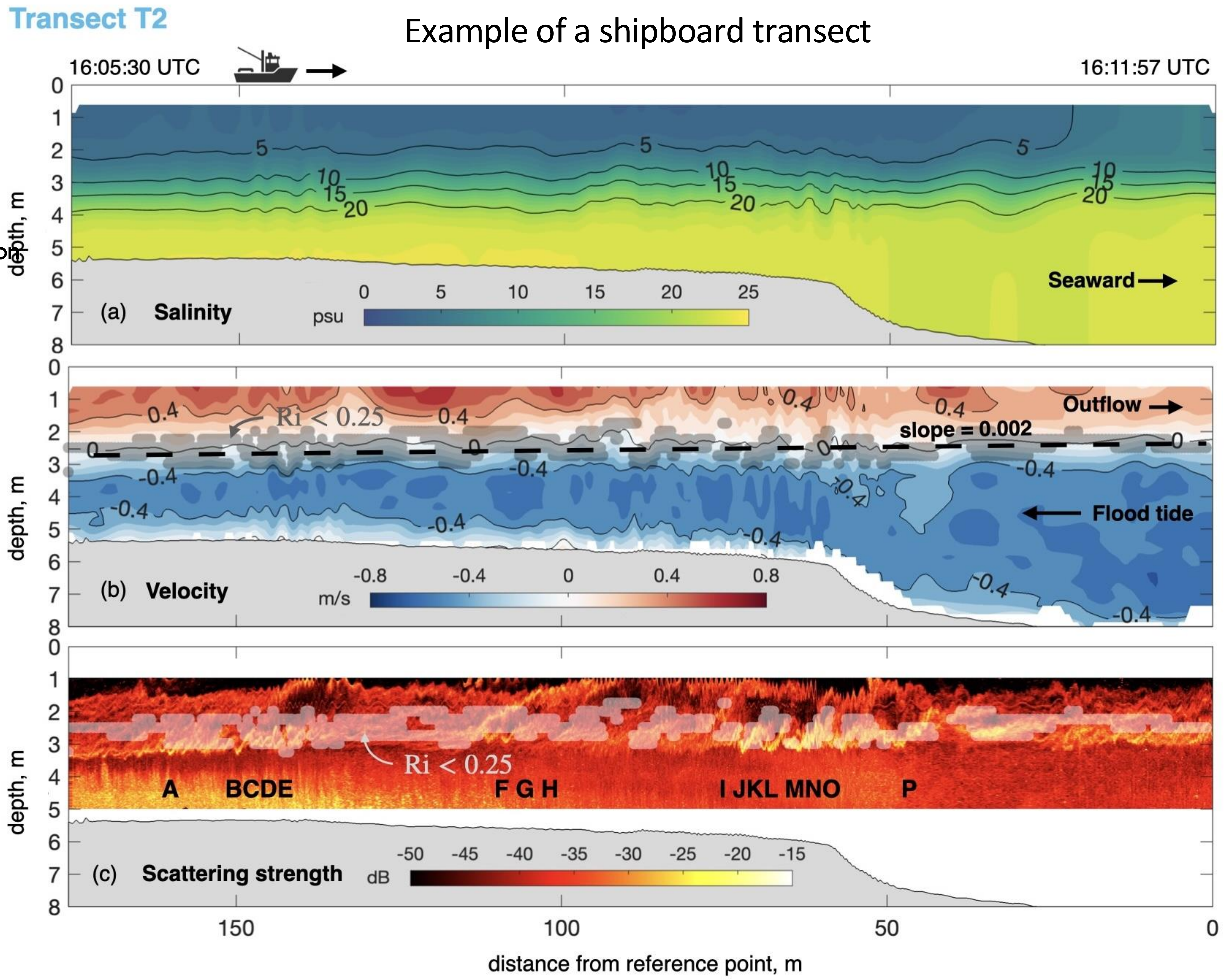




LOW Ri !

Example of a shipboard transect

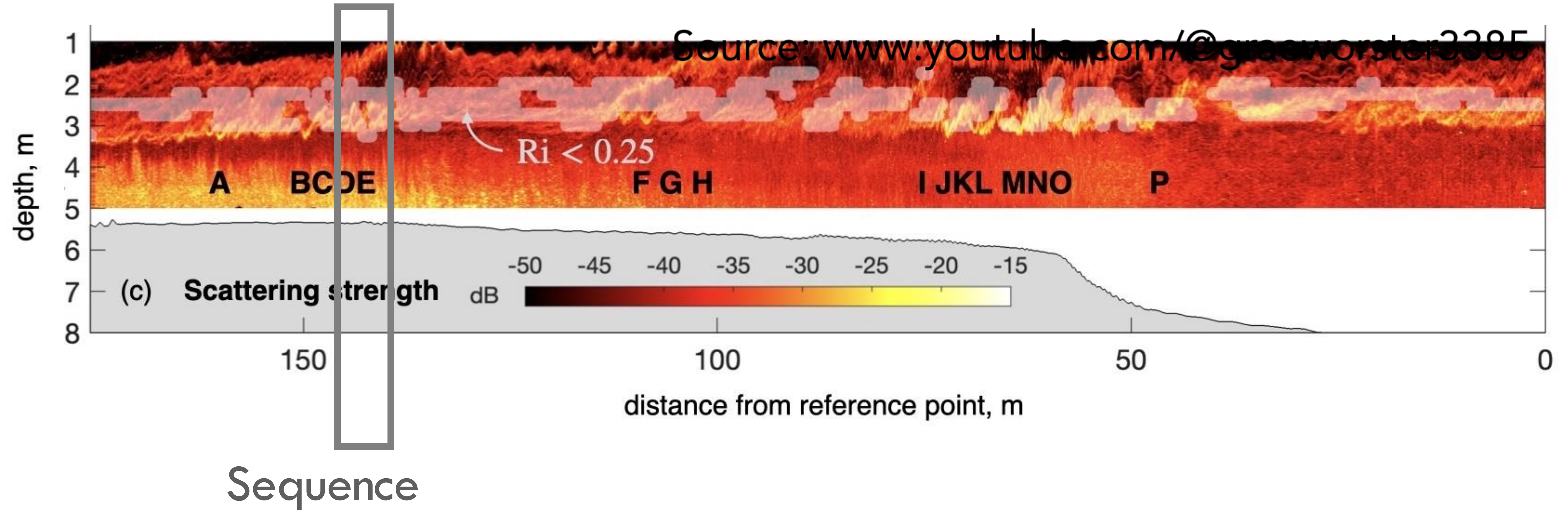


Multibeam reveals the spatial structure and lifecycle of instabilities

Combine 75 individual beams →120-degree fan

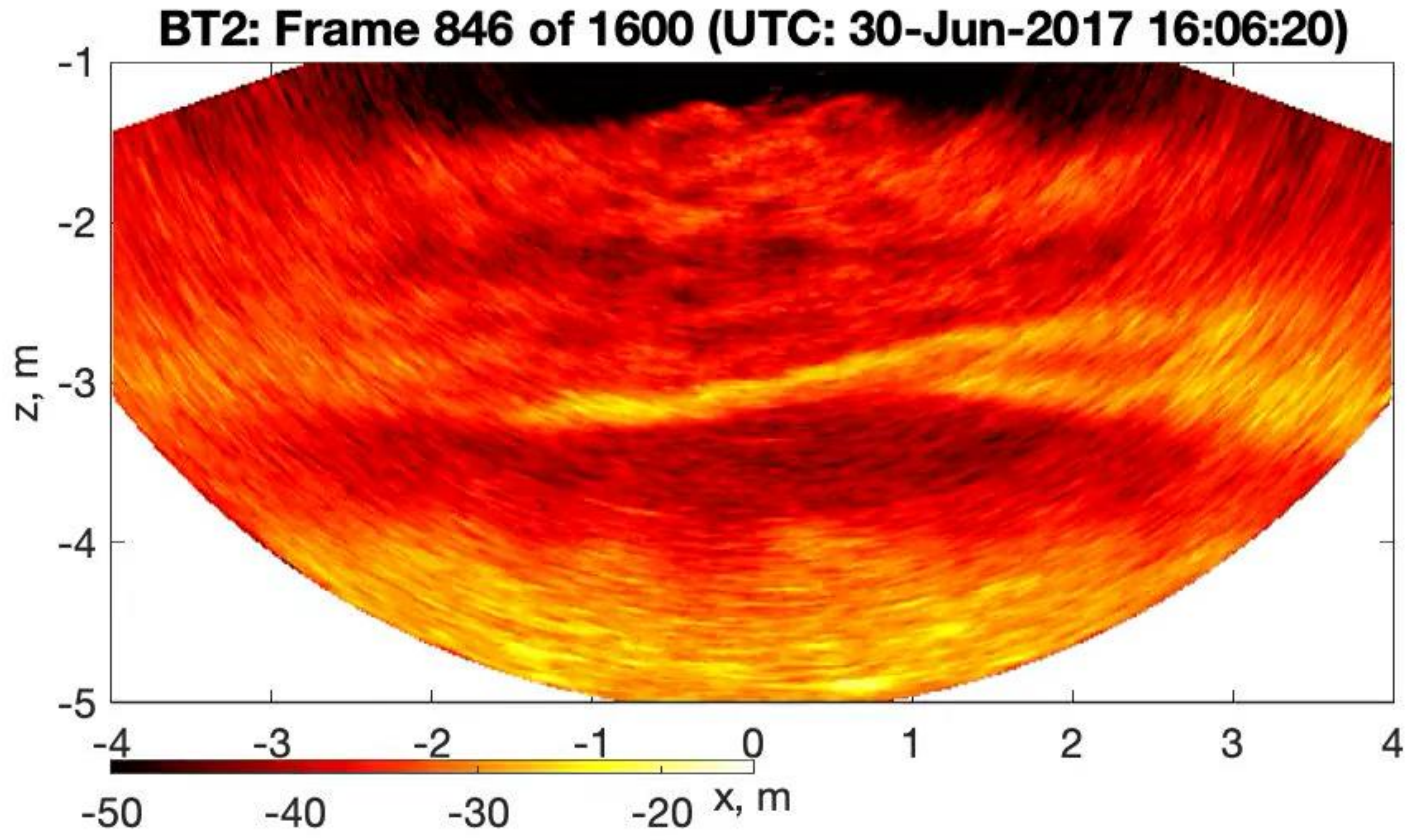
Motion correction (boat heave, pitch and roll)

Multibeam disentangles space and time



1:1 aspect ratio

Real speed



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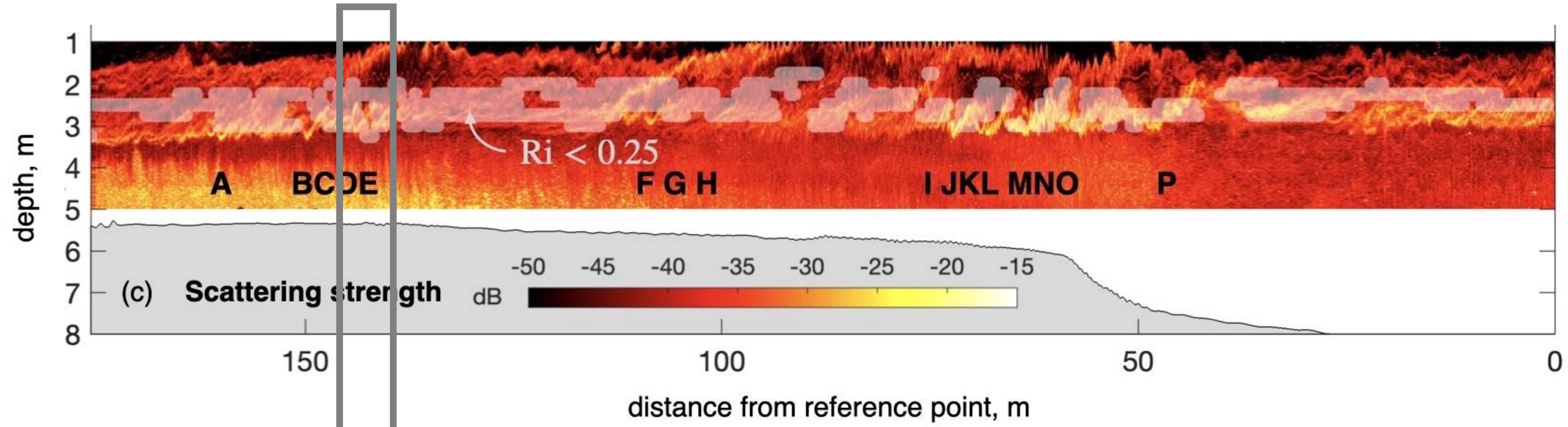
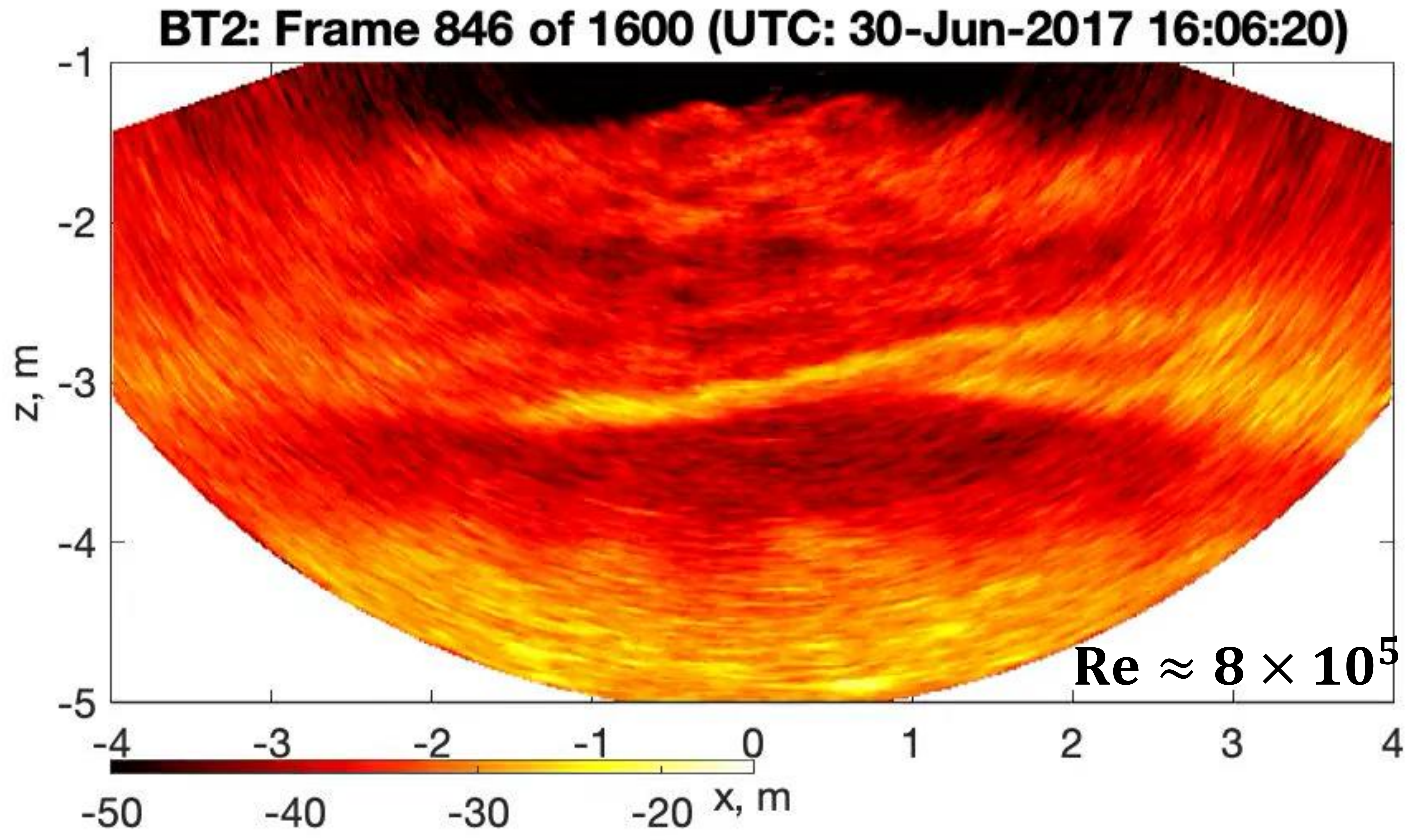


Sequence

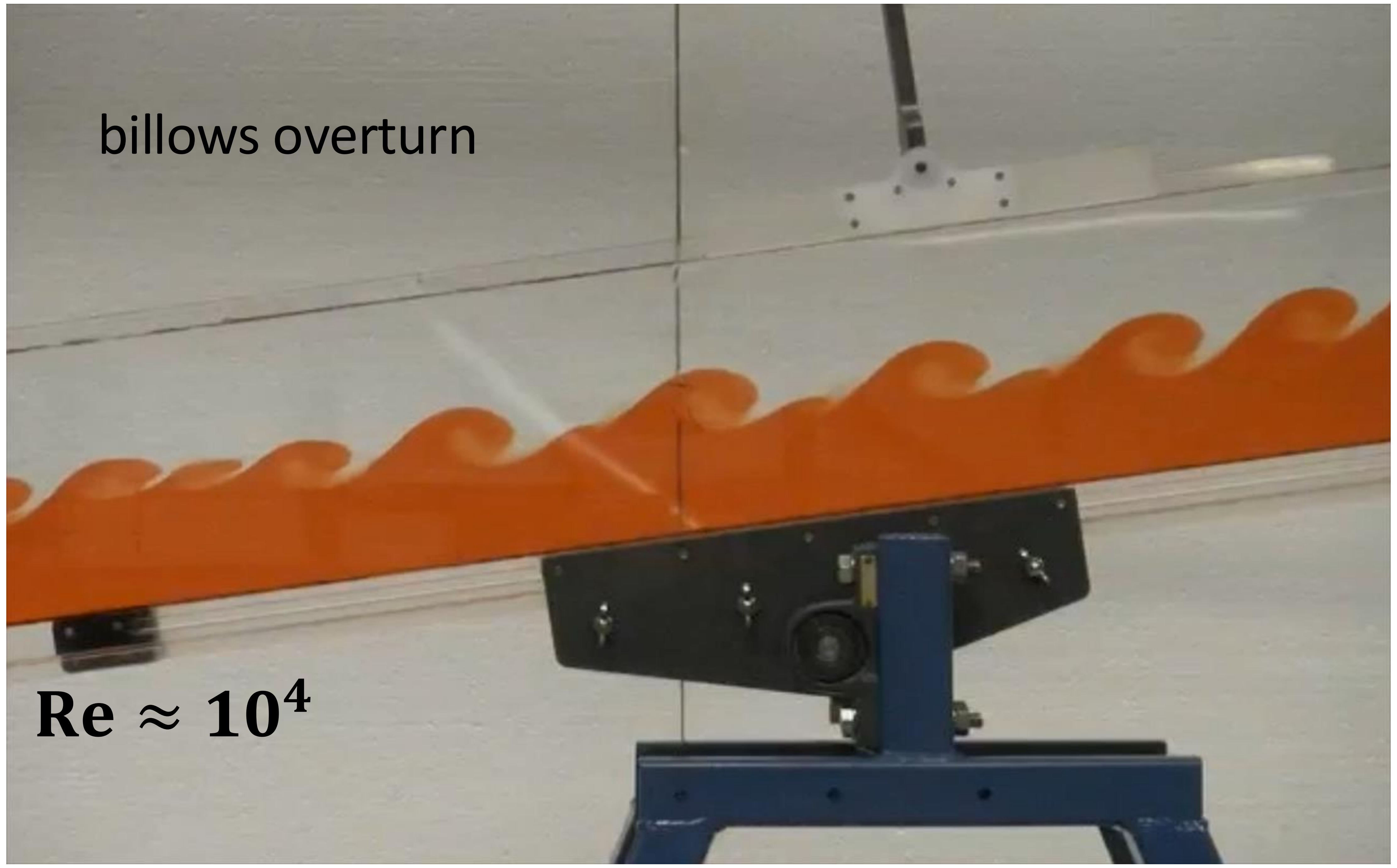
1:1 aspect ratio

Real speed



$\mathbf{Re} \approx 8 \times 10^5$

Contrast with KH breaking in the lab



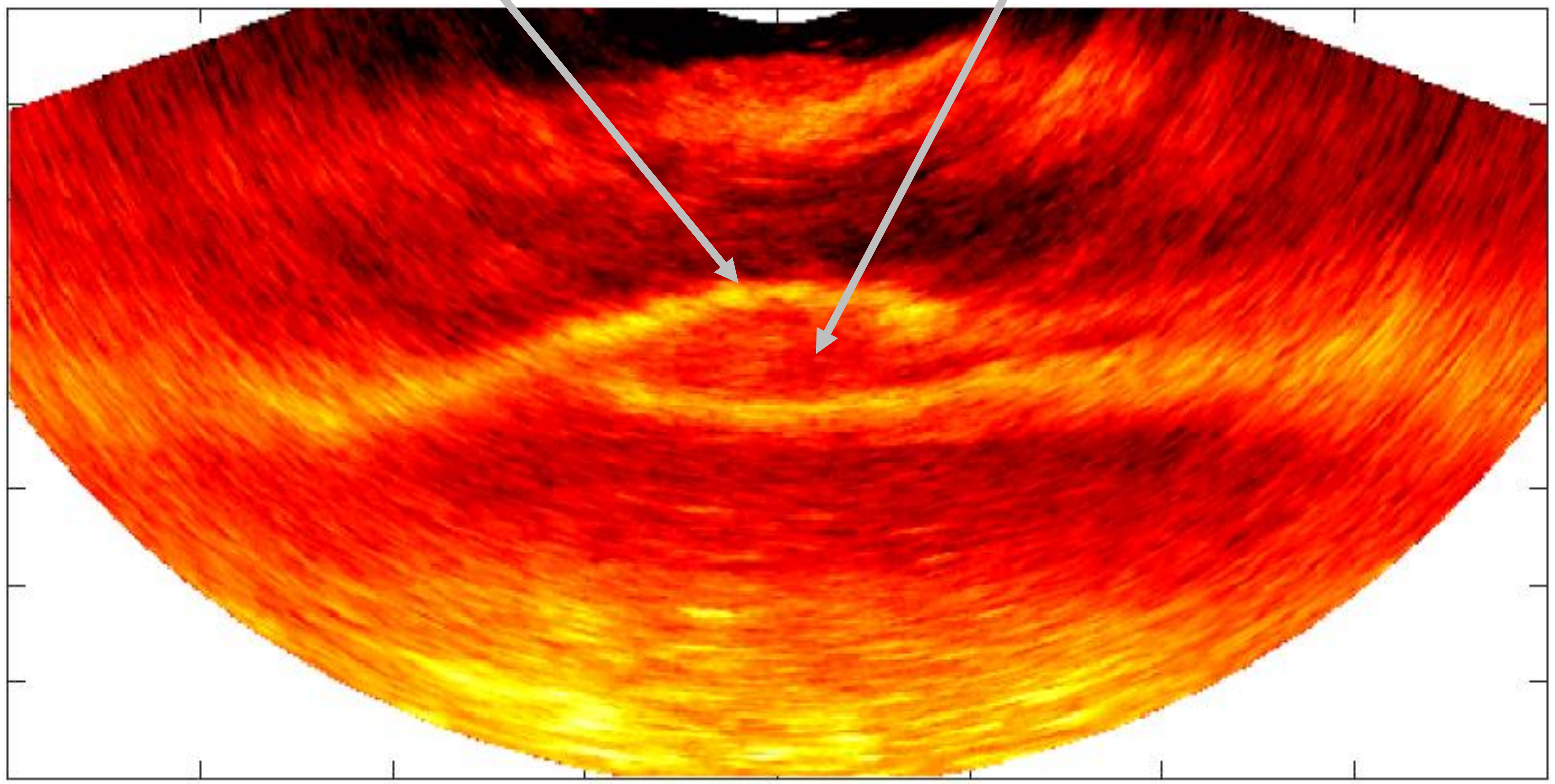
$\mathbf{Re} \approx 10^4$

Source: www.youtube.com/@graeworster3385

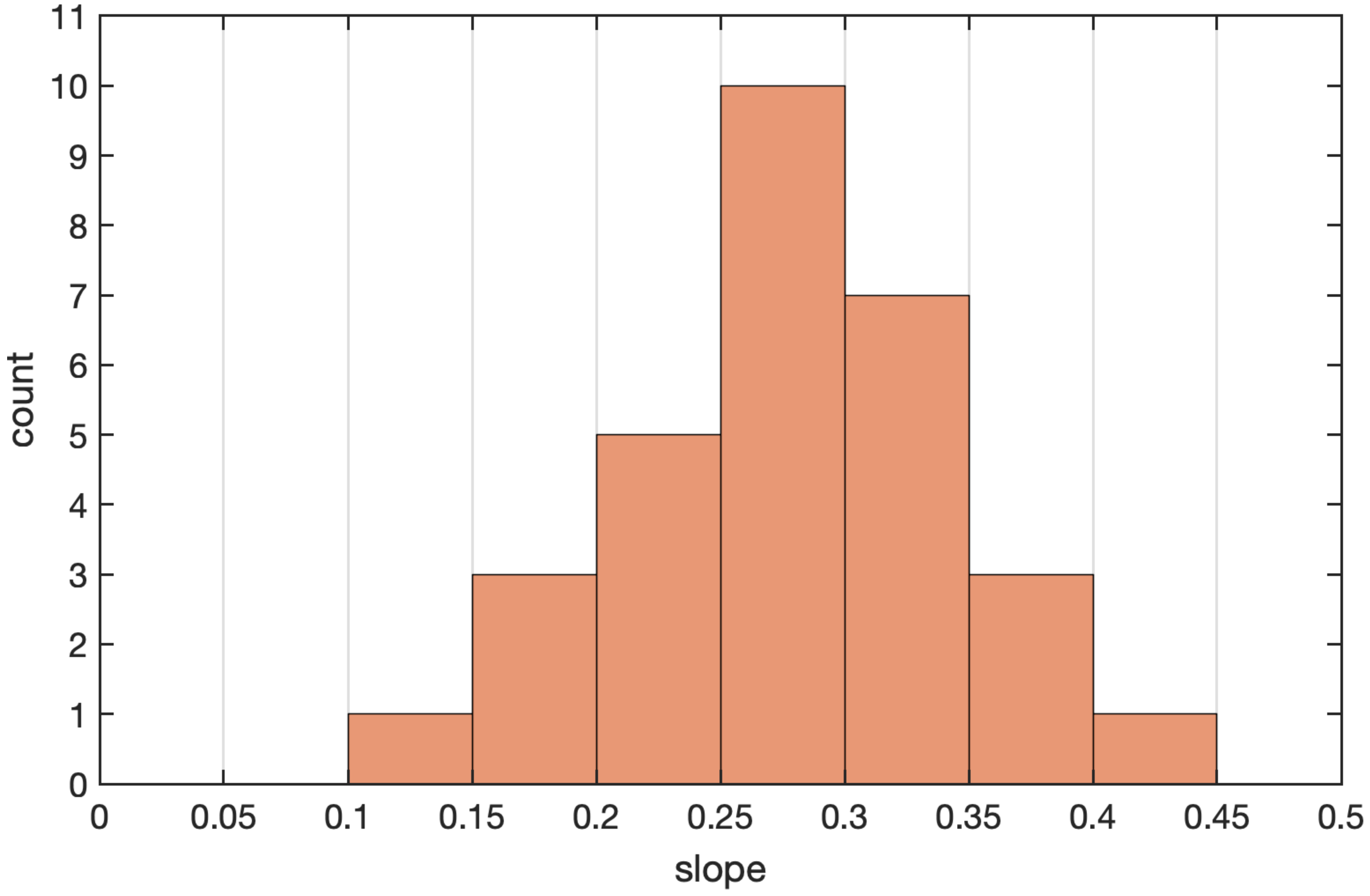
Turbulent BRAID mixing without CORE overturn

mixing in the 'braids' or 'eyelids'

no elevated mixing in the core



Slopes measured in 30 events from multibeam:



moderate slopes → too shallow to overturn

Why braid turbulence?

Why no core overturn?

Mechanism: secondary stratified shear instability at high Re

2D simulations

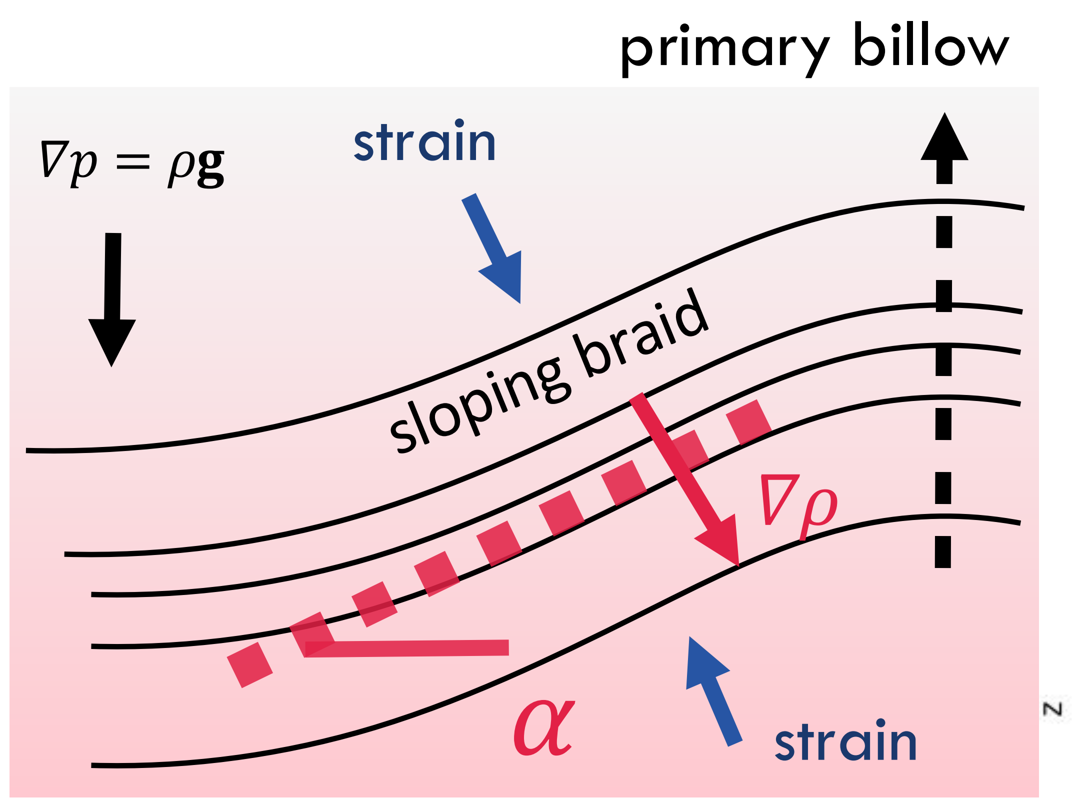
FIELD

$$\mathbf{Re = 8 \times 10^5}$$

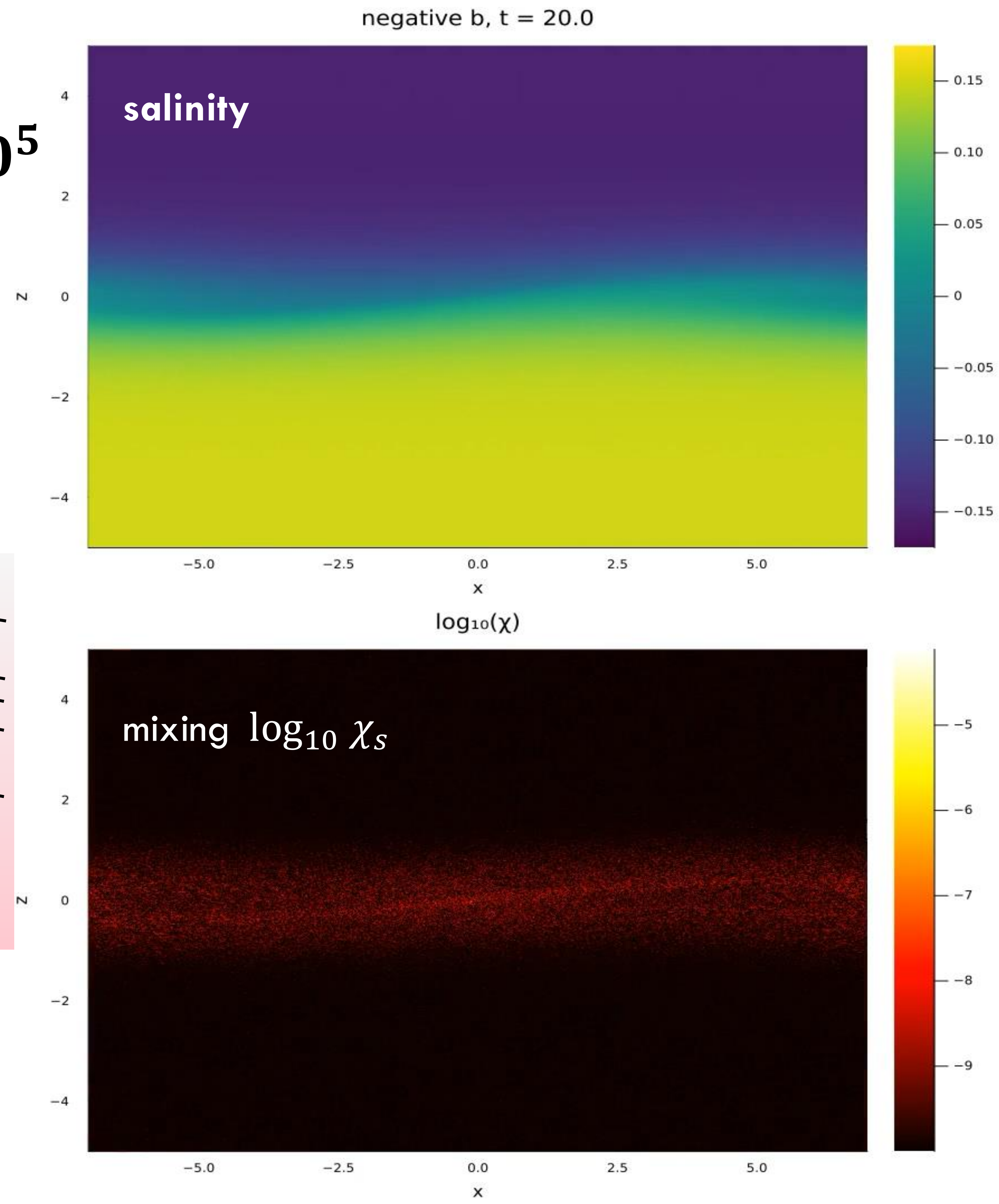
Ri = 0.15,

Pr = 700

Baroclinic shear intensification:



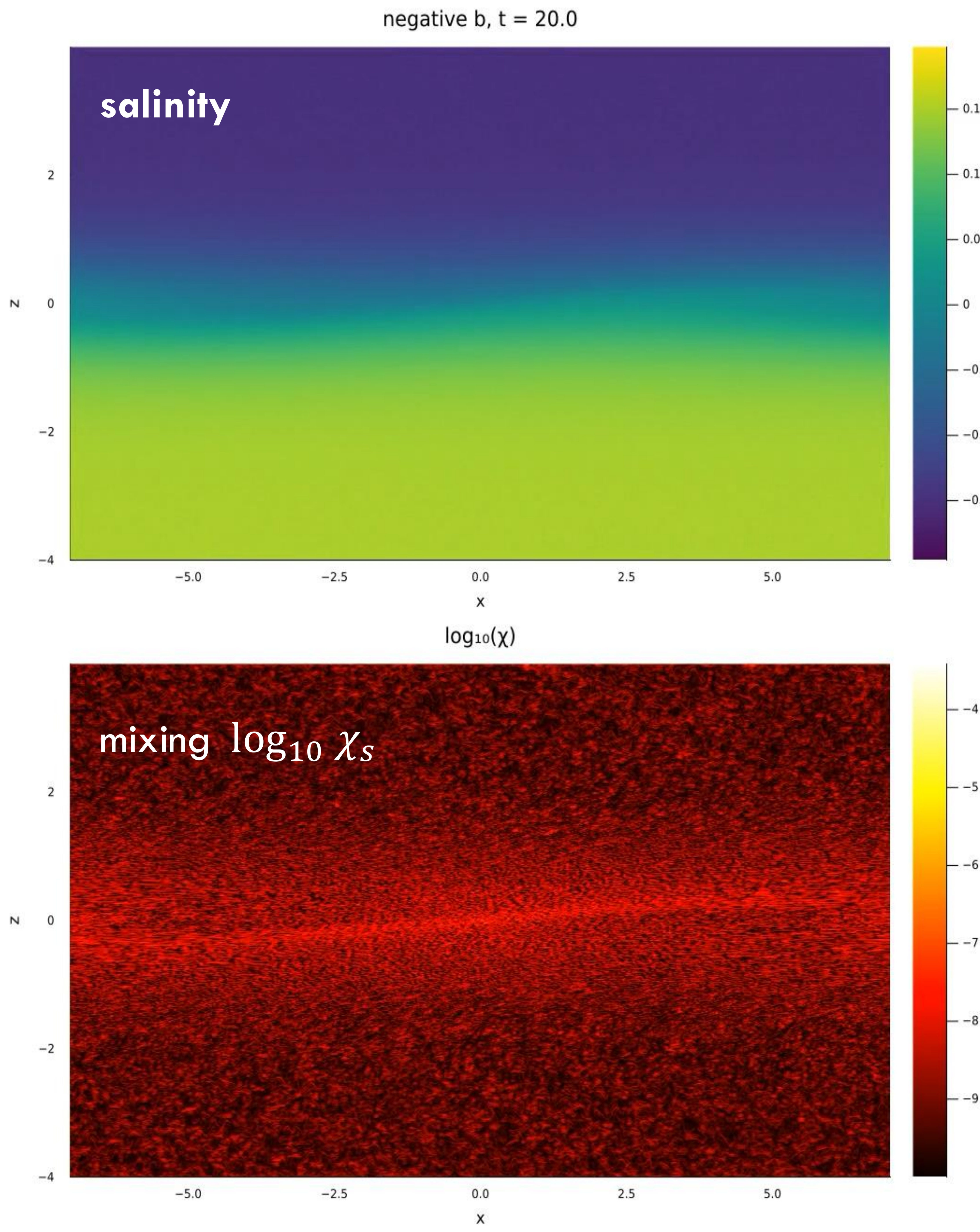
Corcos & Sherman, J. Fluid Mech. (1976)
Dritschel et al. J. Fluid Mech. (1991)
Staquet,, J. Fluid Mech. (1995)
Smyth, J. Fluid Mech. (2003)

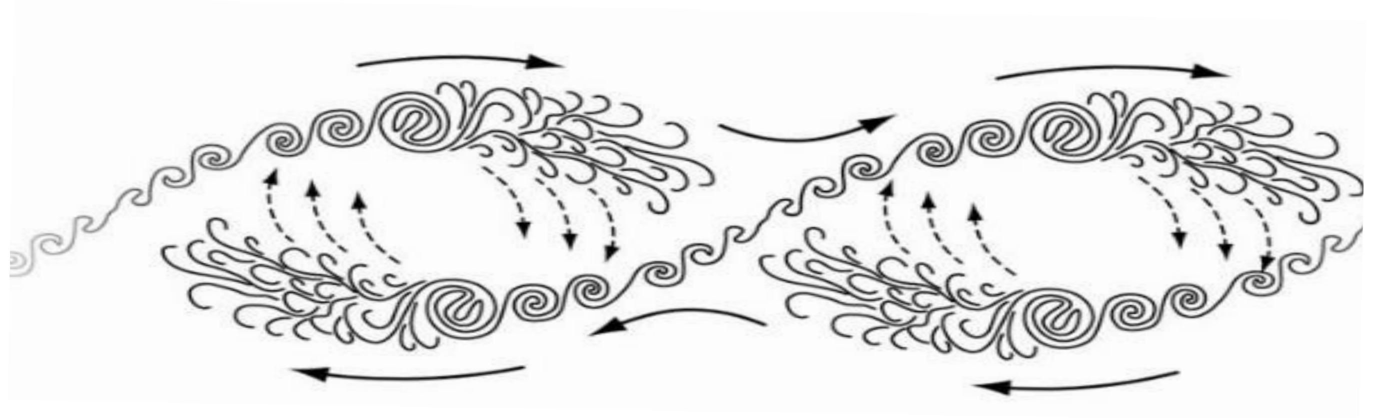


LAB

$$\mathbf{Re = 10^4}$$

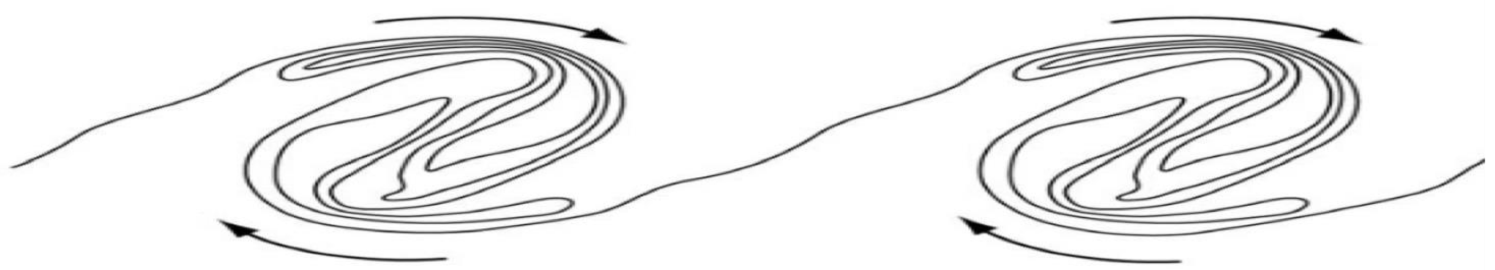
same Ri, Pr





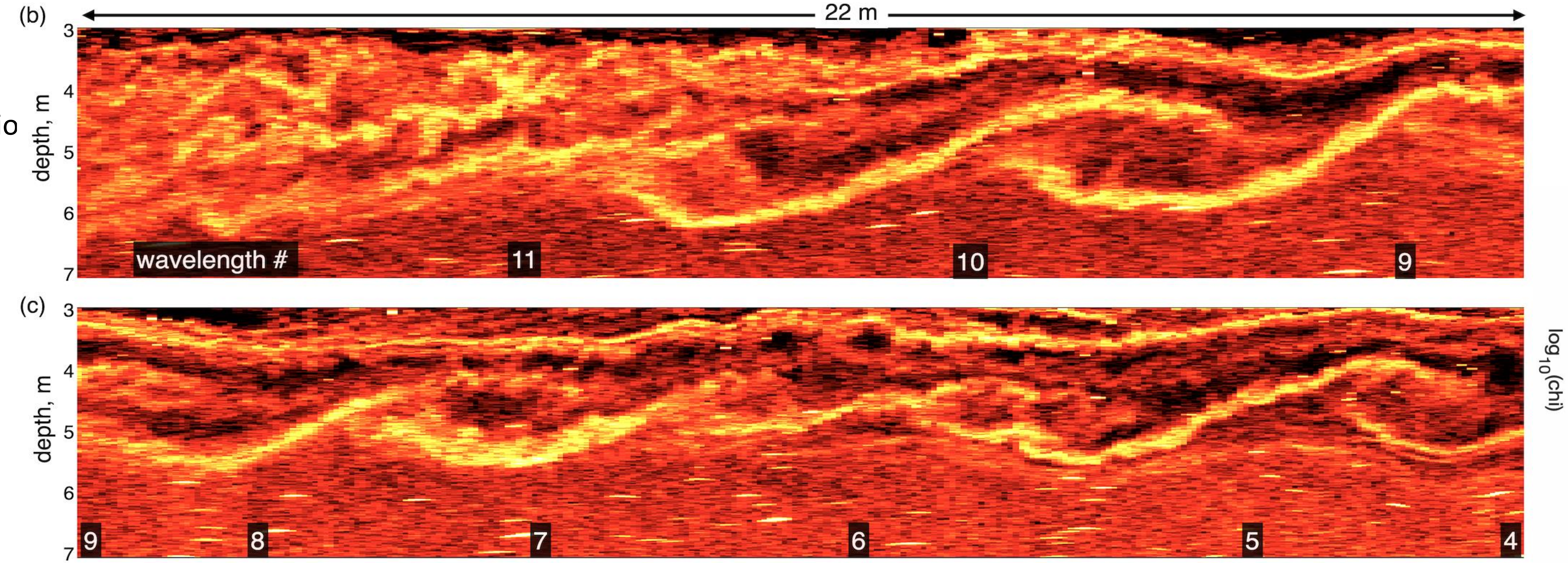
already proposed by

Geyer et al. Geophys. Res. Lett. (2010)



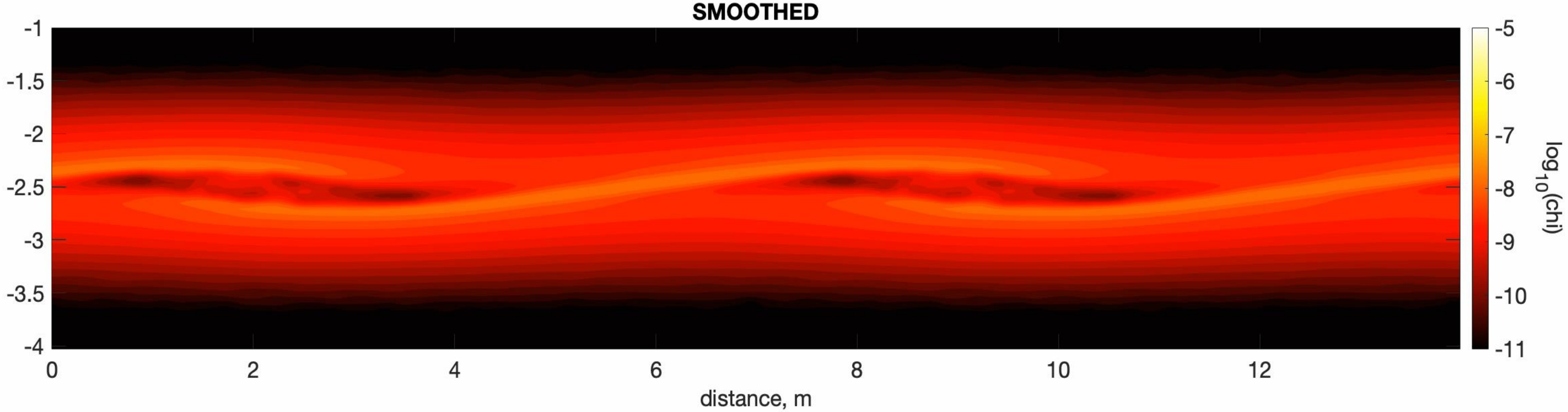
Further evidence of braid secondary shear instability

AUV
echosounder
1:1 aspect ratio



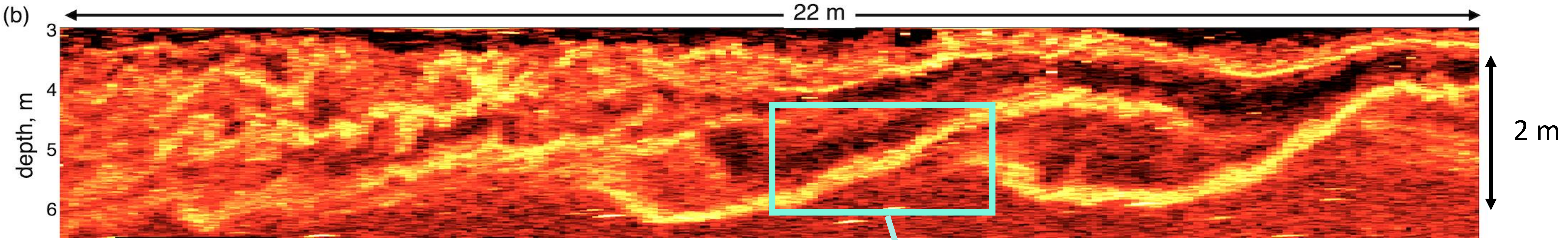
2D simulation

smoothed to simulate acoustic backscatter



Modelling the braid mixing rate and its small-scale structure

Pycnocline scale:

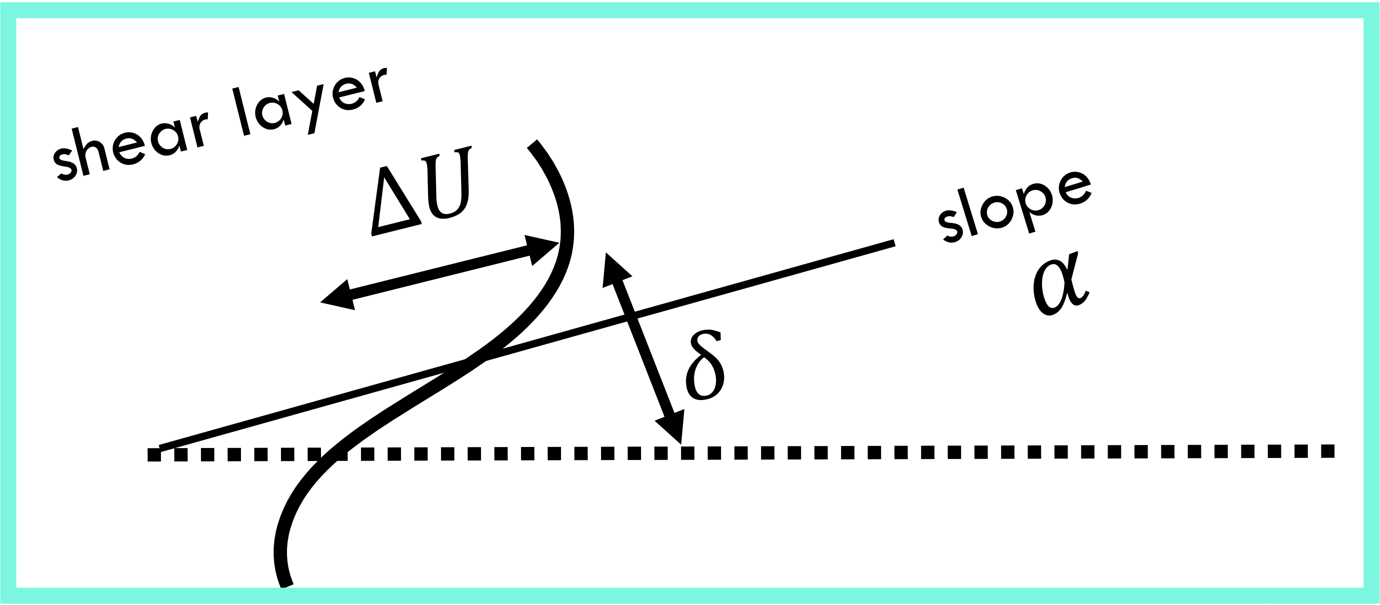


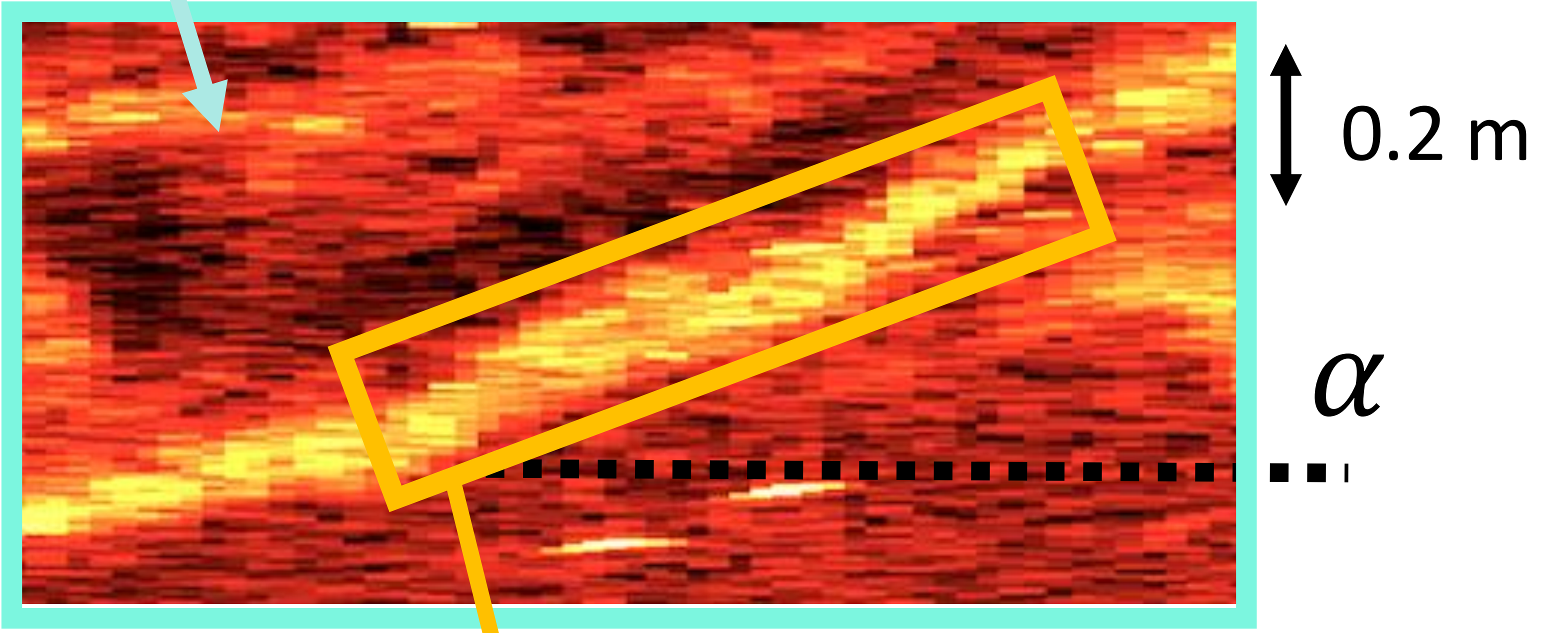
Braid scale:

same **baroclinic forcing**
and Ri ~ 0.10 - 0.15

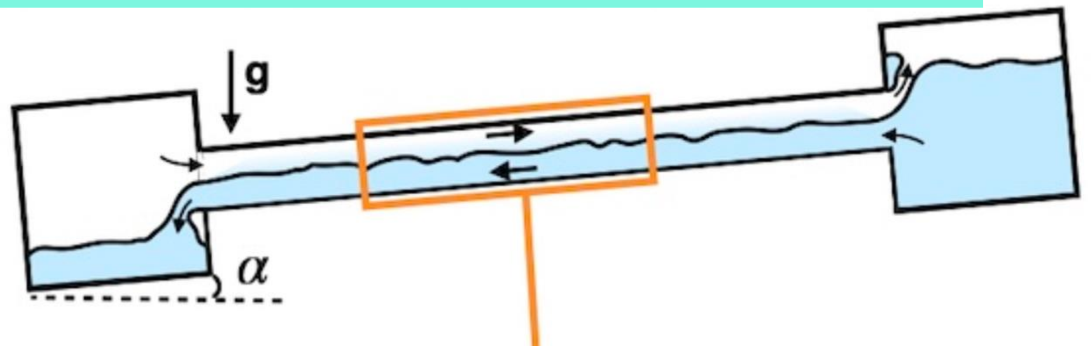
$$\partial_t S = \alpha N^2 - |\partial_{zz}\overline{u'w'}| \approx 0$$

baroclinic production | turbulent diffusion





pycnocline
↓
braid
↓
extreme χ_s filaments



Dissipation:

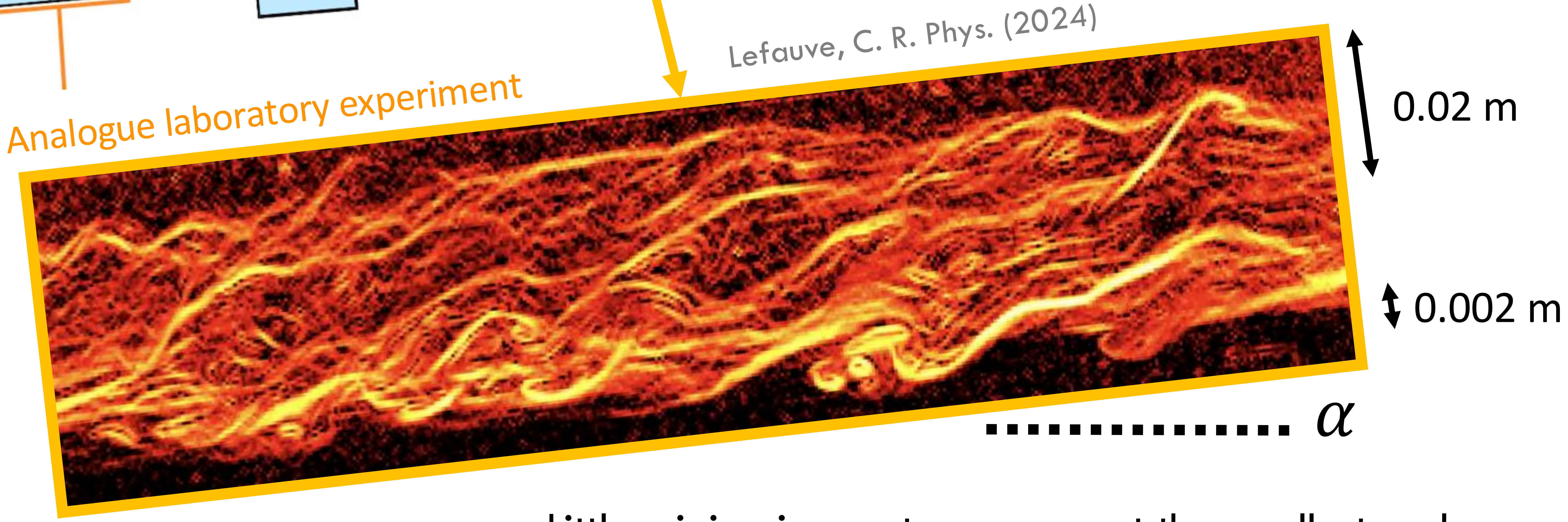
$$\epsilon \approx 0.05\,\alpha\,\mathrm{Ri}\,\frac{(\Delta U)^3}{\delta} \approx 0.007\,\alpha\,\delta^2\,S^3$$

x 10 - 100 in braid

Mixing:

$$\chi_s \approx \frac{N^2}{(g\beta)^2}\Gamma_\chi\,\epsilon \approx 0.001\,(g\beta)^{-2}\,\alpha\,\delta^2\,N^2\,S^3$$

x 100 – 10 000 in braid



Validated by laboratory experiments

Consistent with prior ϵ, χ_s measurements in this estuary

Little mixing in overturns, even at the smallest scales

Takeaways

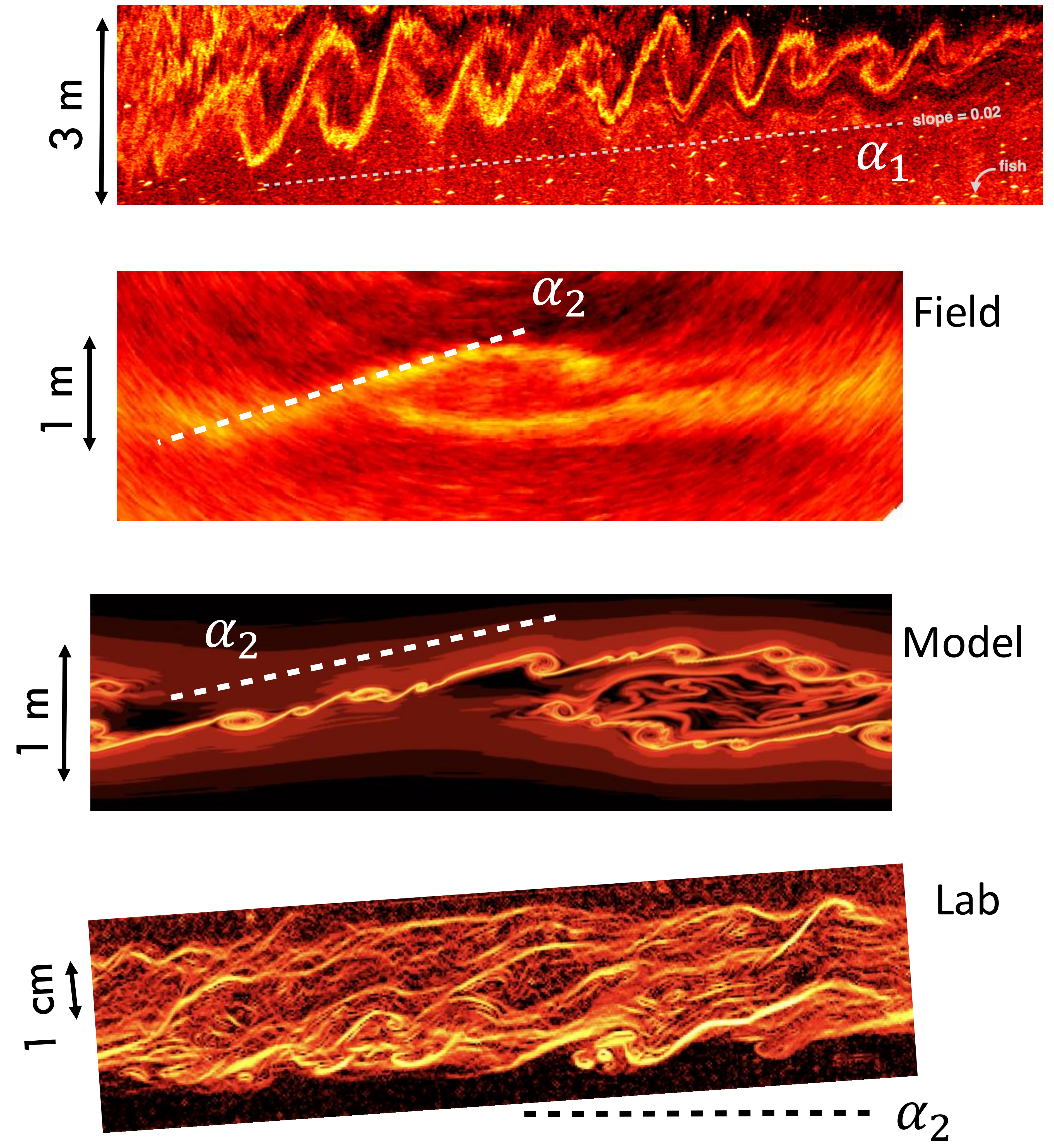
1. Shear instability under continuous shear forcing ($\mathbf{Ri} \approx \mathbf{0.1 - 0.15}$) mix along thin, sloping braids rather than through large overturns

2. Multibeam echo-sounding disentangles spatial and temporal evolution, confirming shallow braid slopes $\alpha \approx 0.2 - 0.4$

3. At high Re, stratified braid baroclinicity triggers fast secondary shear instabilities and turbulence that pre-empt primary overturn

4. A simple baroclinic production–dissipation balance predicts ϵ and χ_s at both pycnocline and braid scales as a function of local α, δ, S, N

5. Elevated braid ϵ and χ_s predictions match the field, and lab data reveal extreme χ_s in fine sub-mm filaments, not overturns



Find out more: preprint

Gallery of shear instabilities