



CEE Fluid Mechanics Seminar
29 April 2026

From billows to braids: new perspectives on stratified mixing in environmental flows



Observations:



Chris Bassett



Dan Plotnick



Andone Lavery



Rocky Geyer

Adrien Lefauve

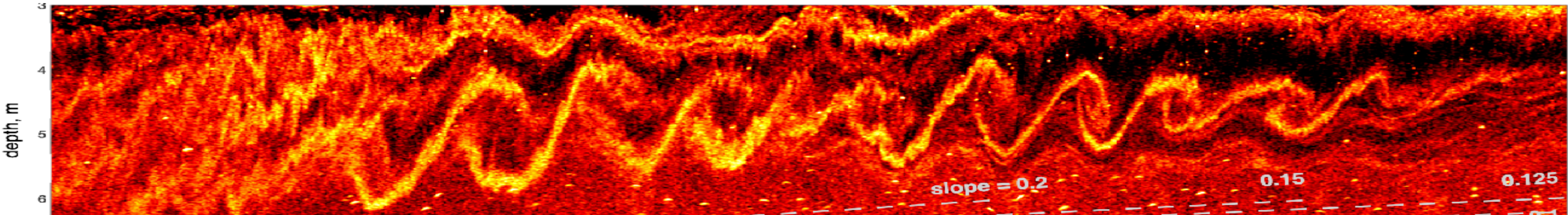


Theory:

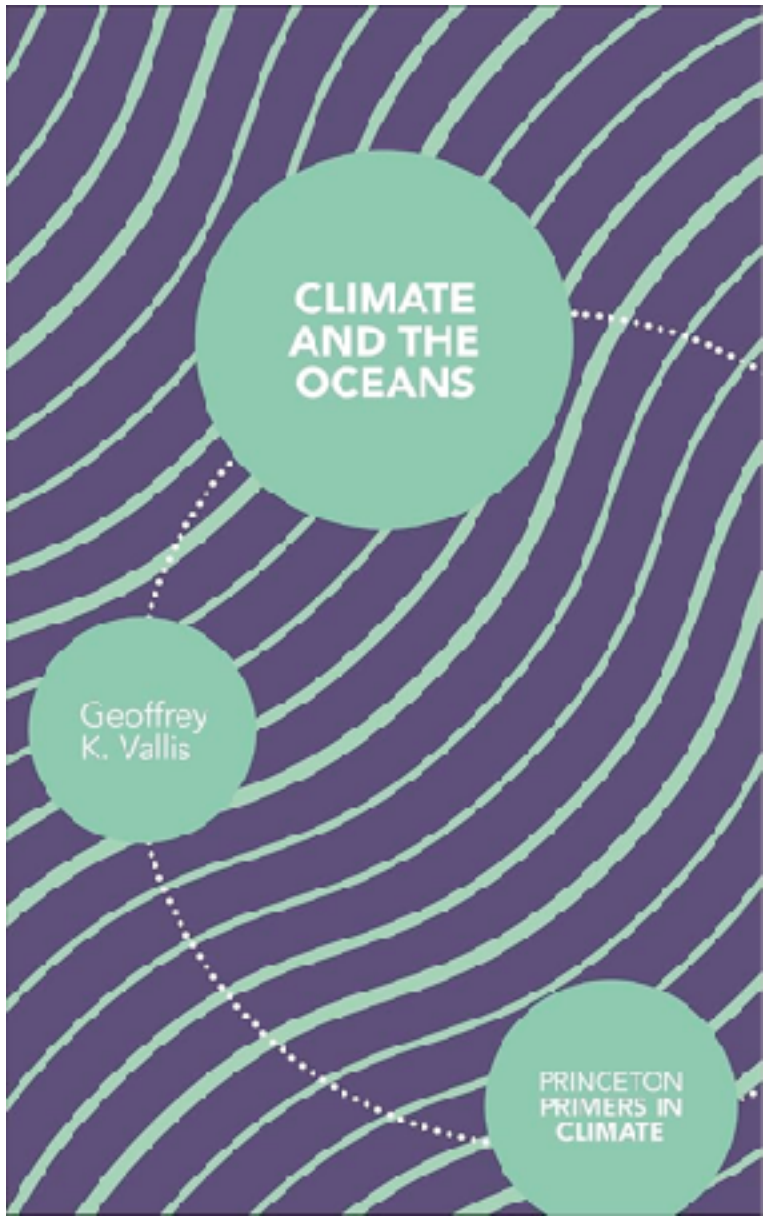
Sam Lewin



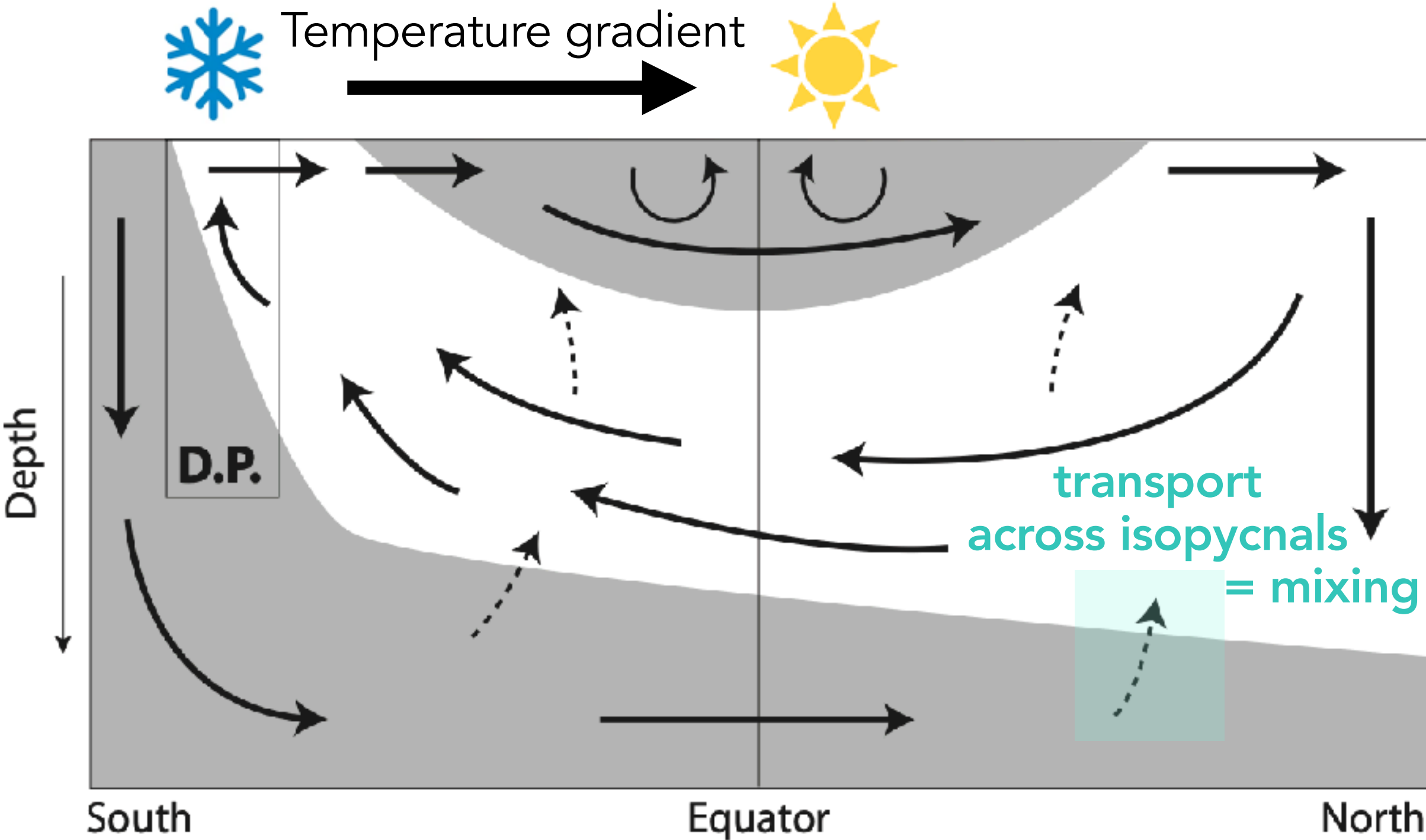
Emma Bouckley



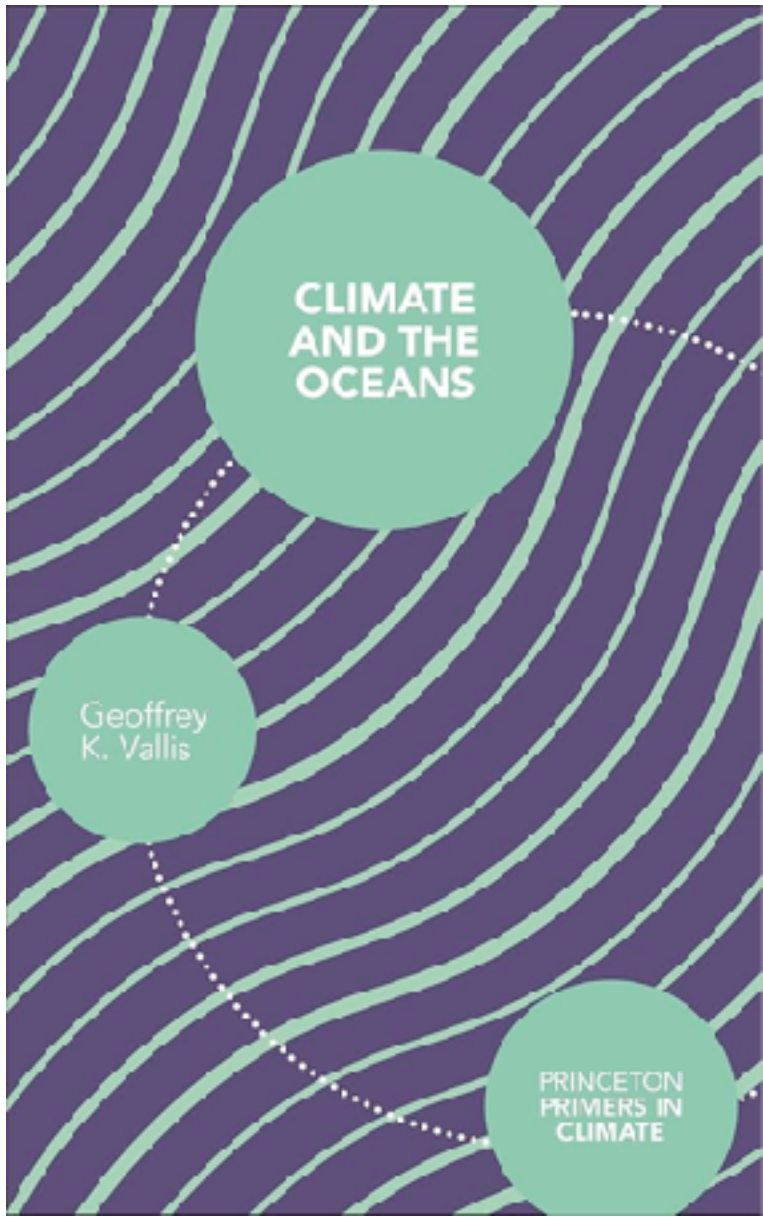
Turbulent mixing is key to the large-scale ocean circulation



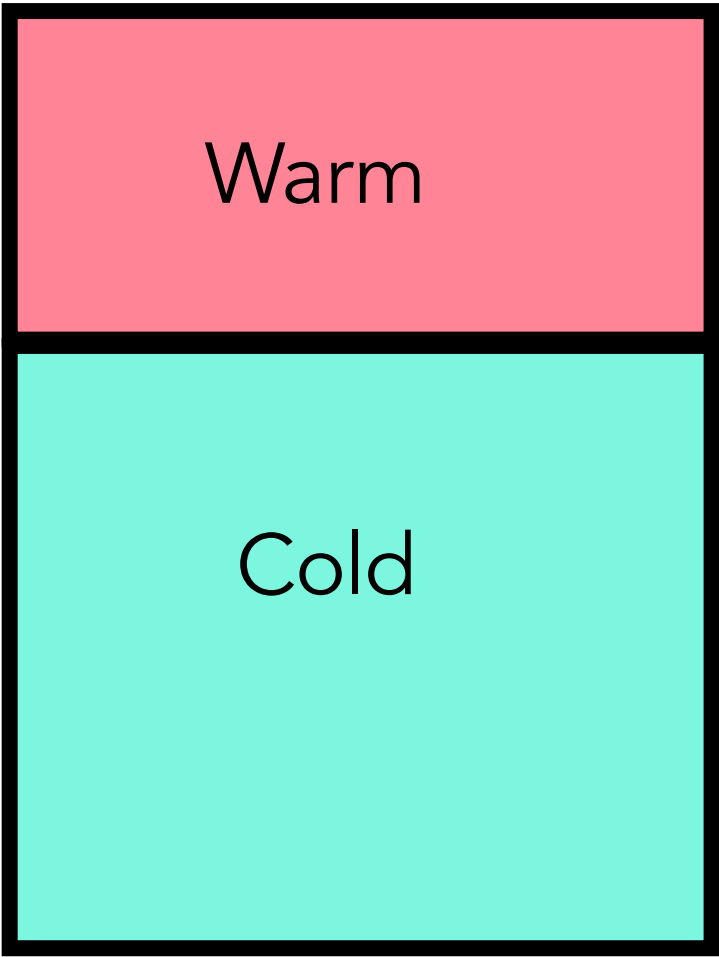
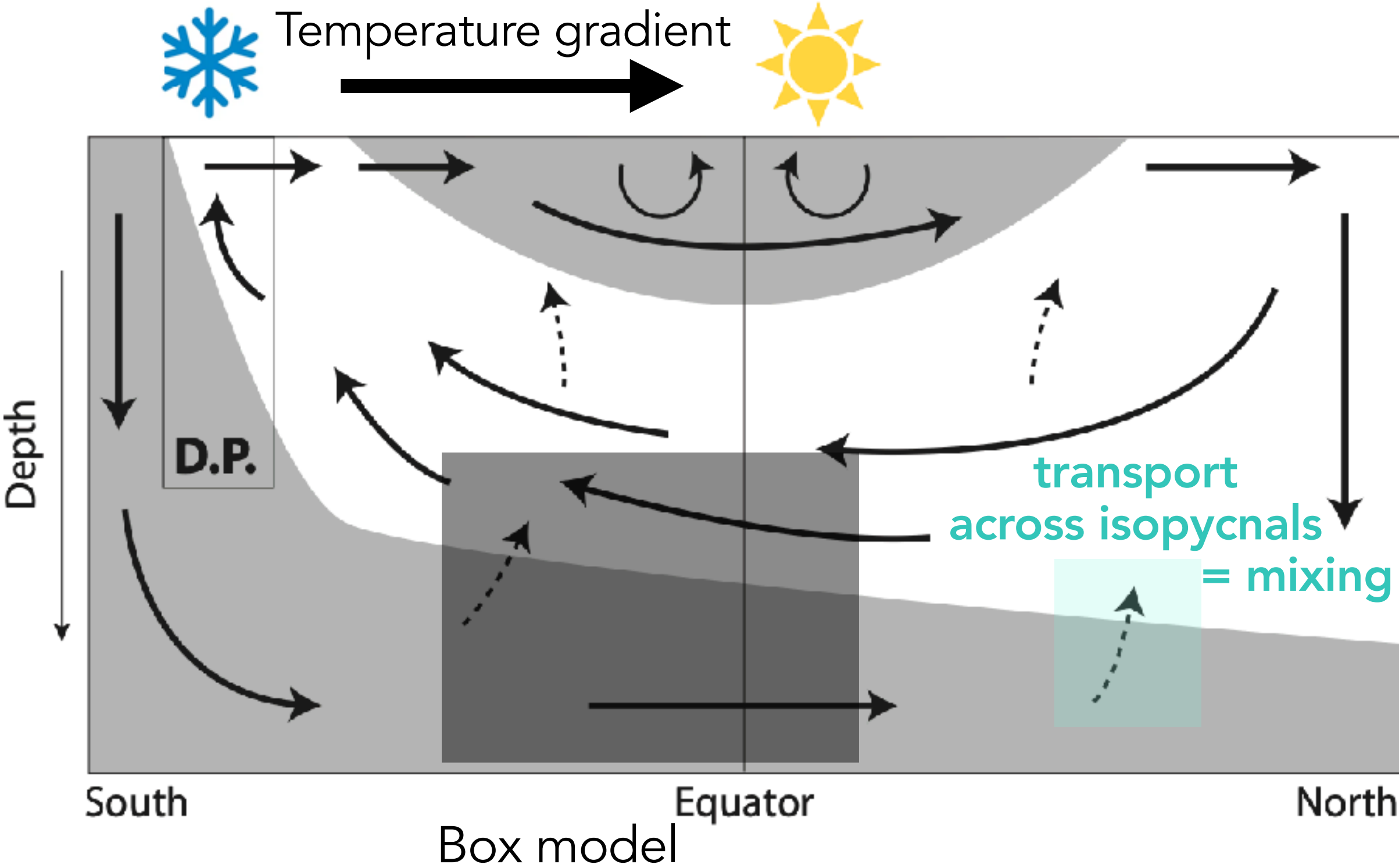
G. K. Vallis



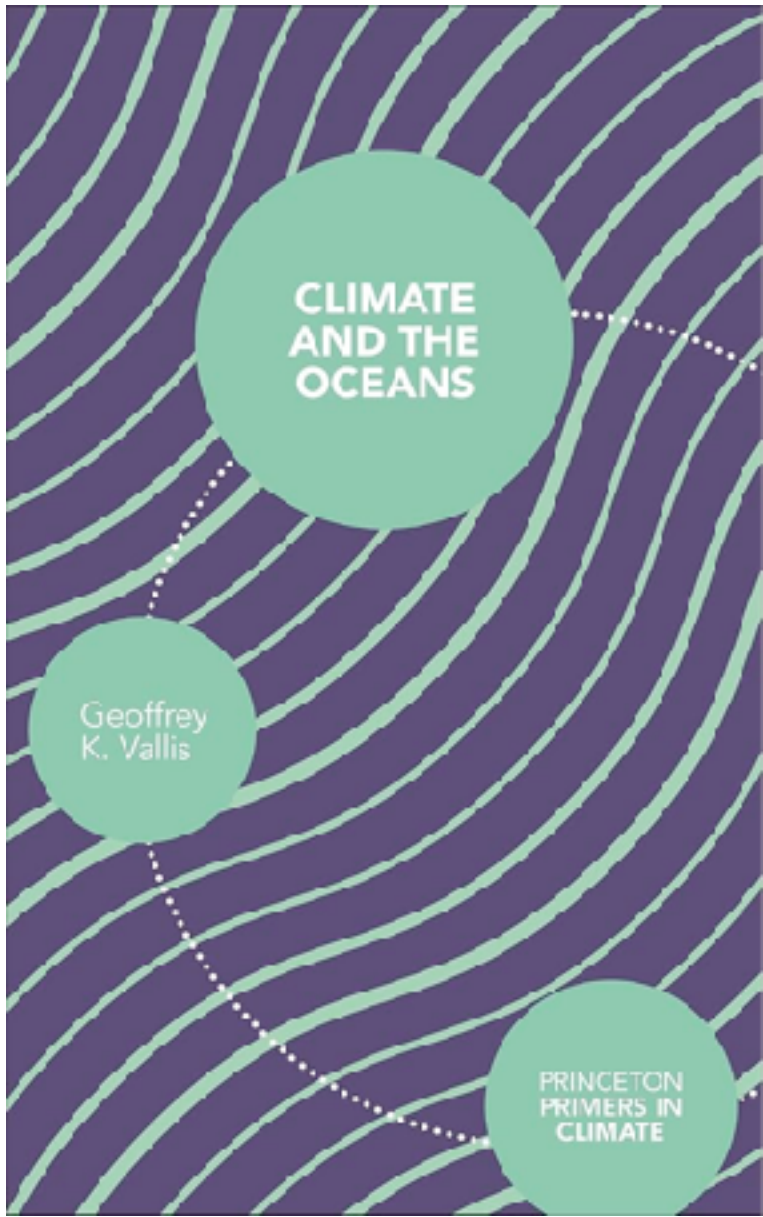
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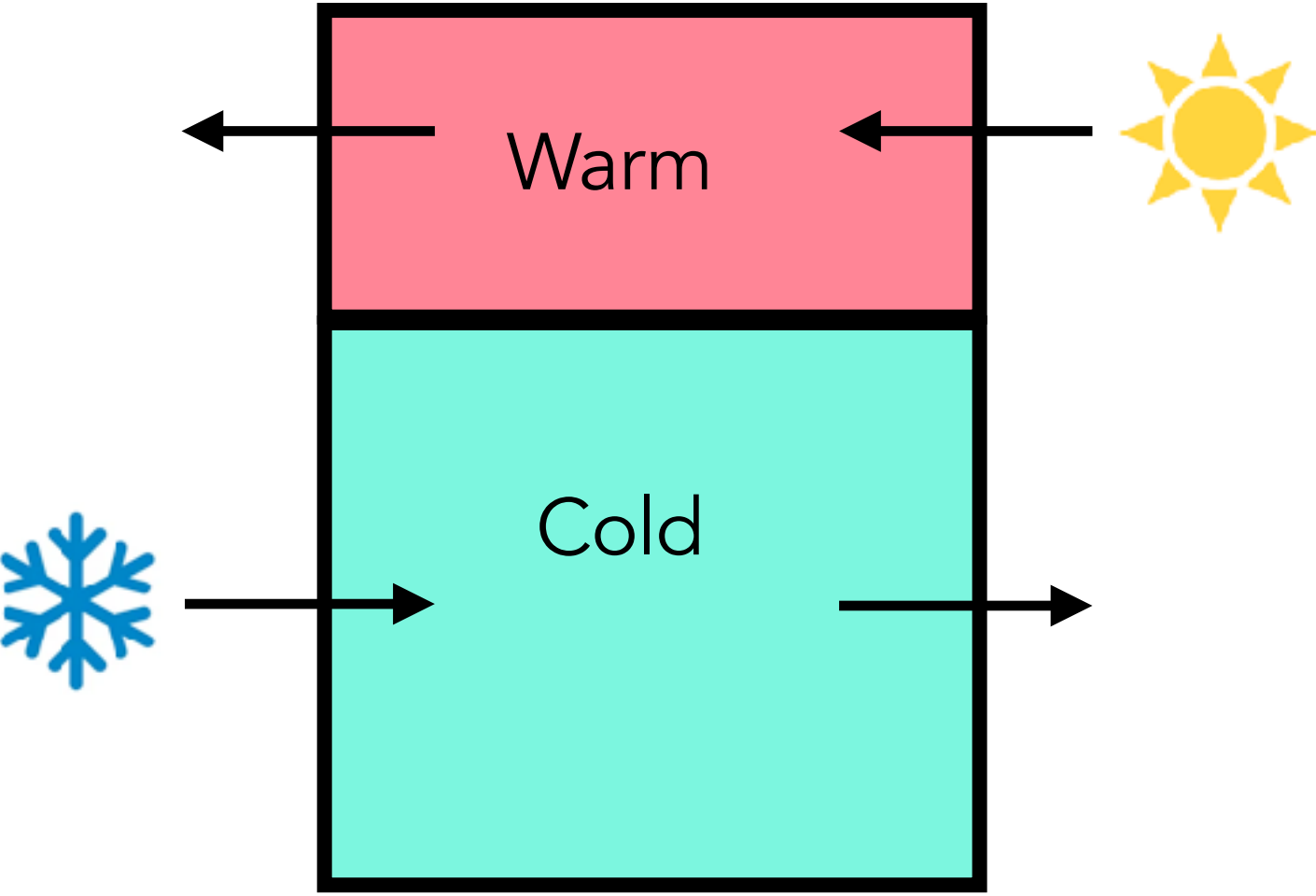
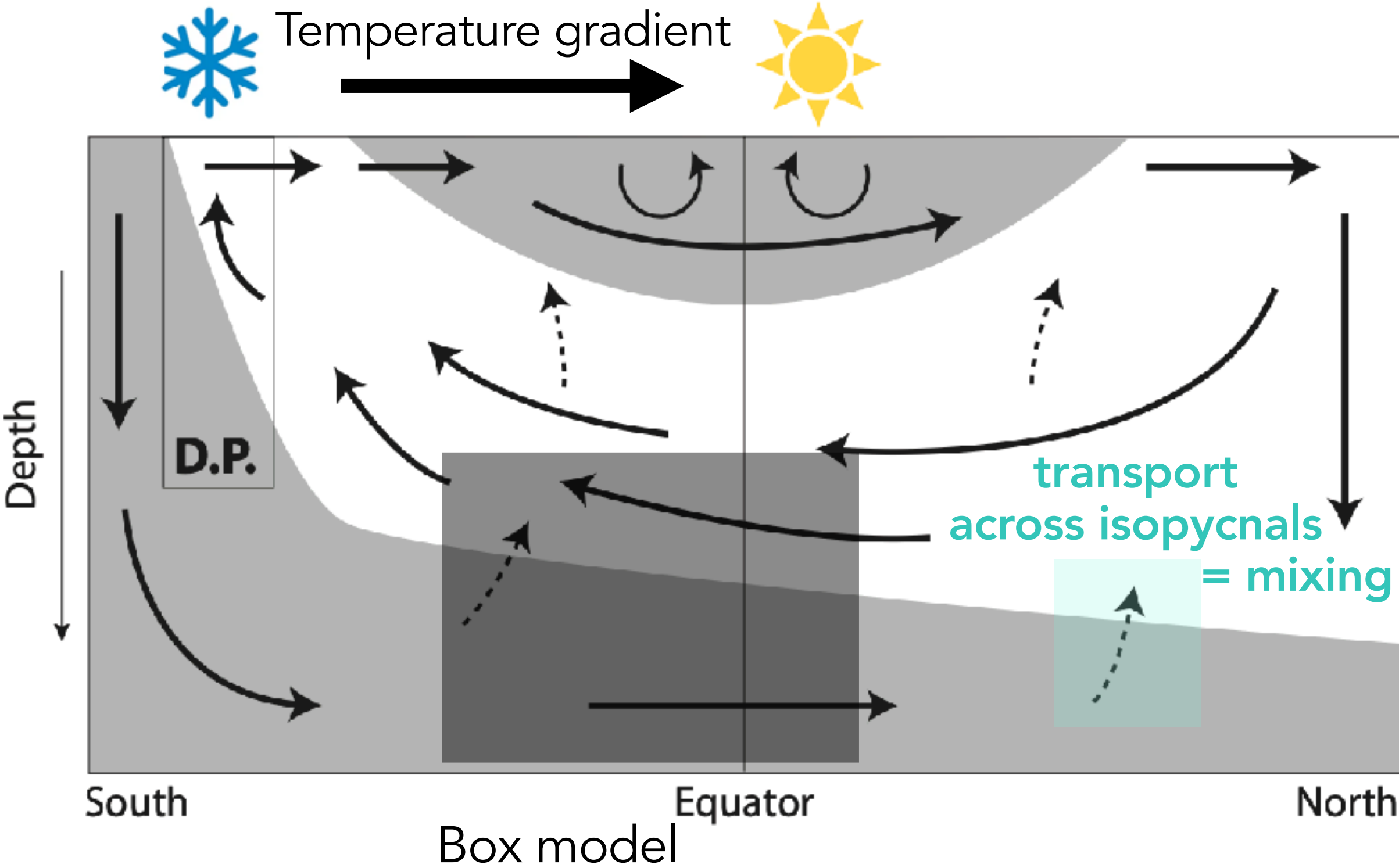
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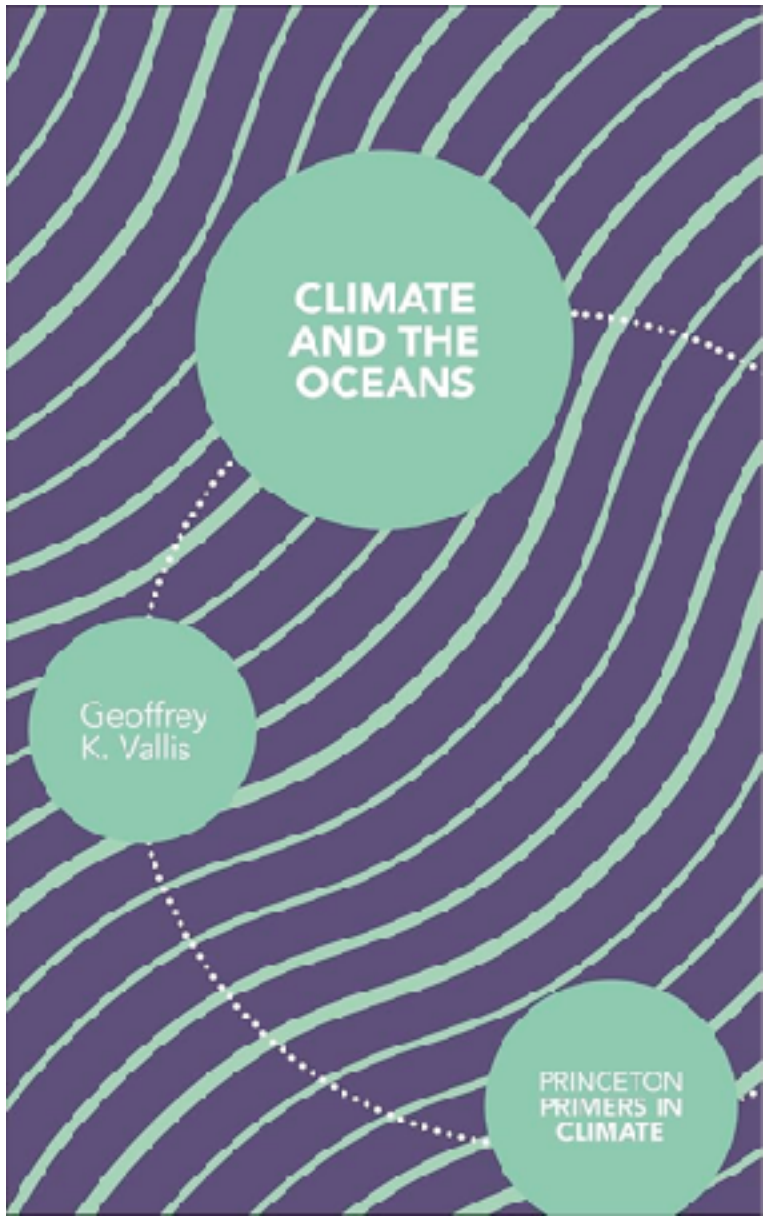
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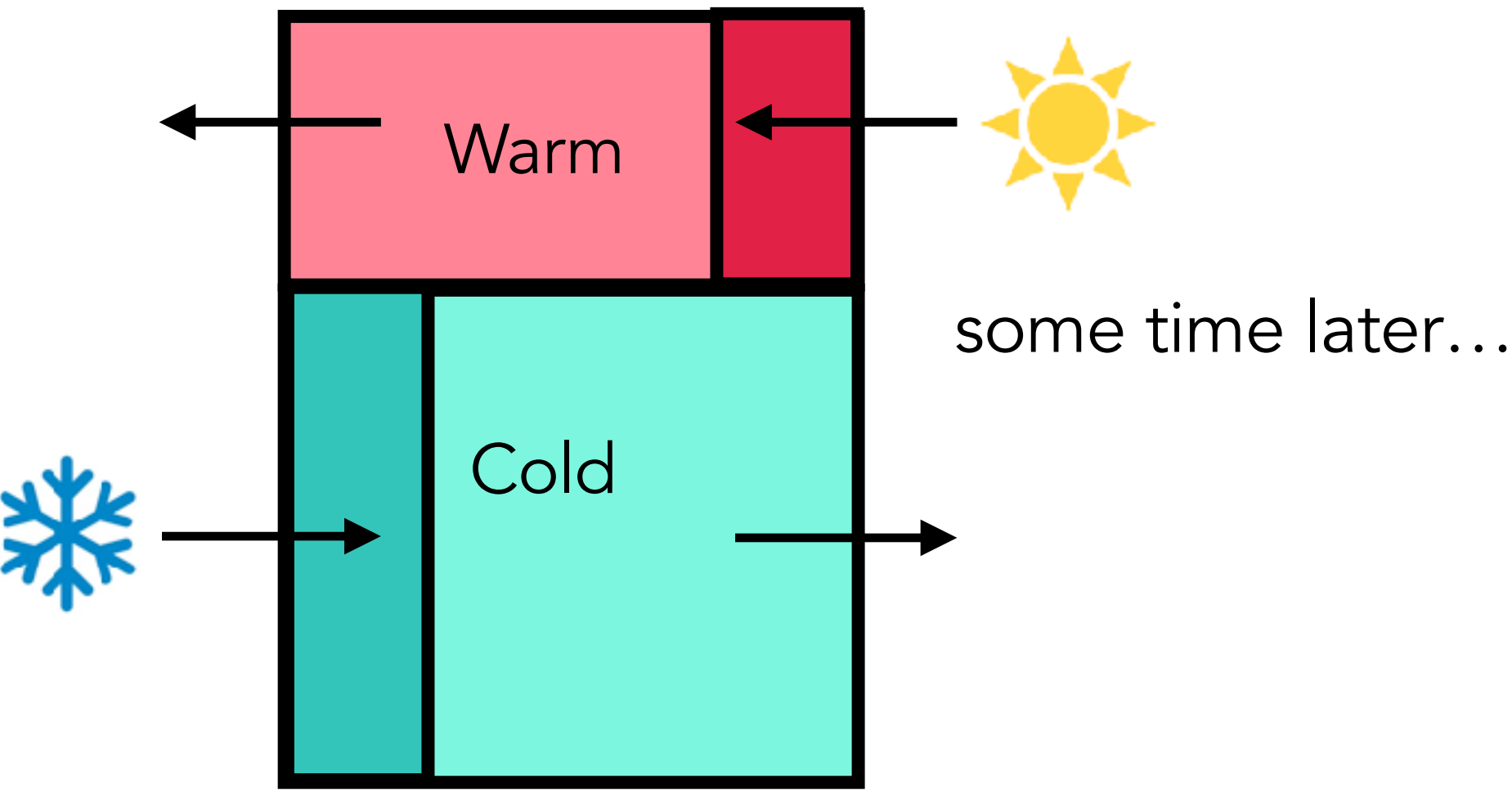
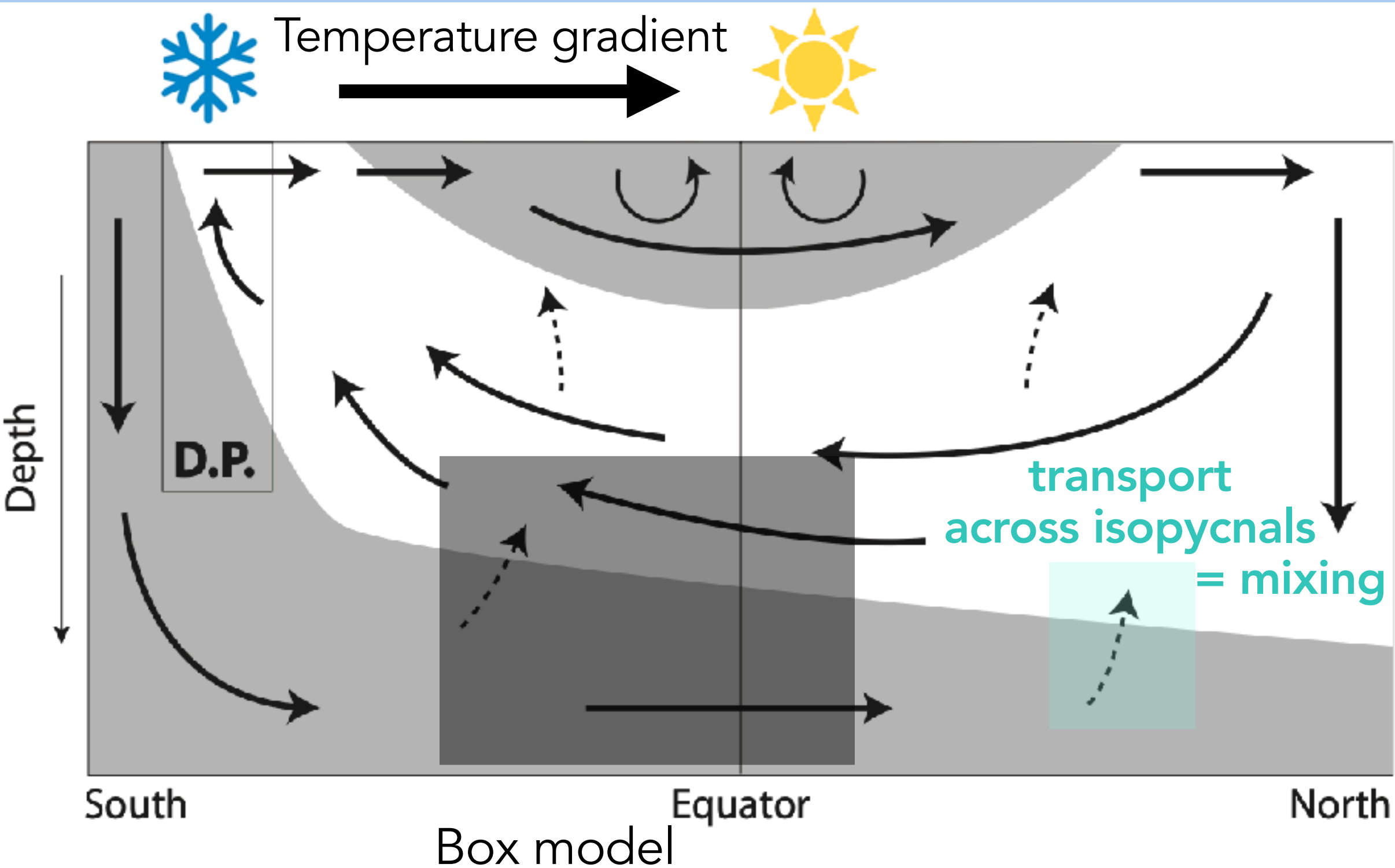
G. K. Vallis



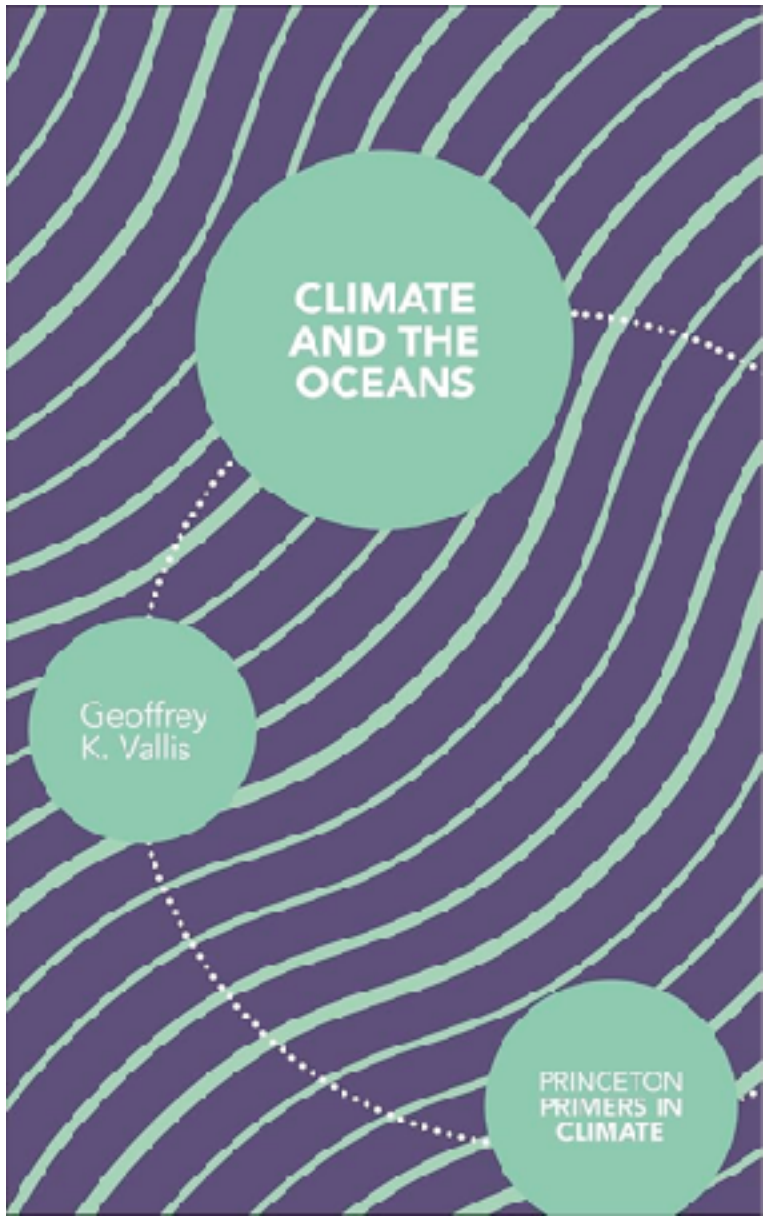
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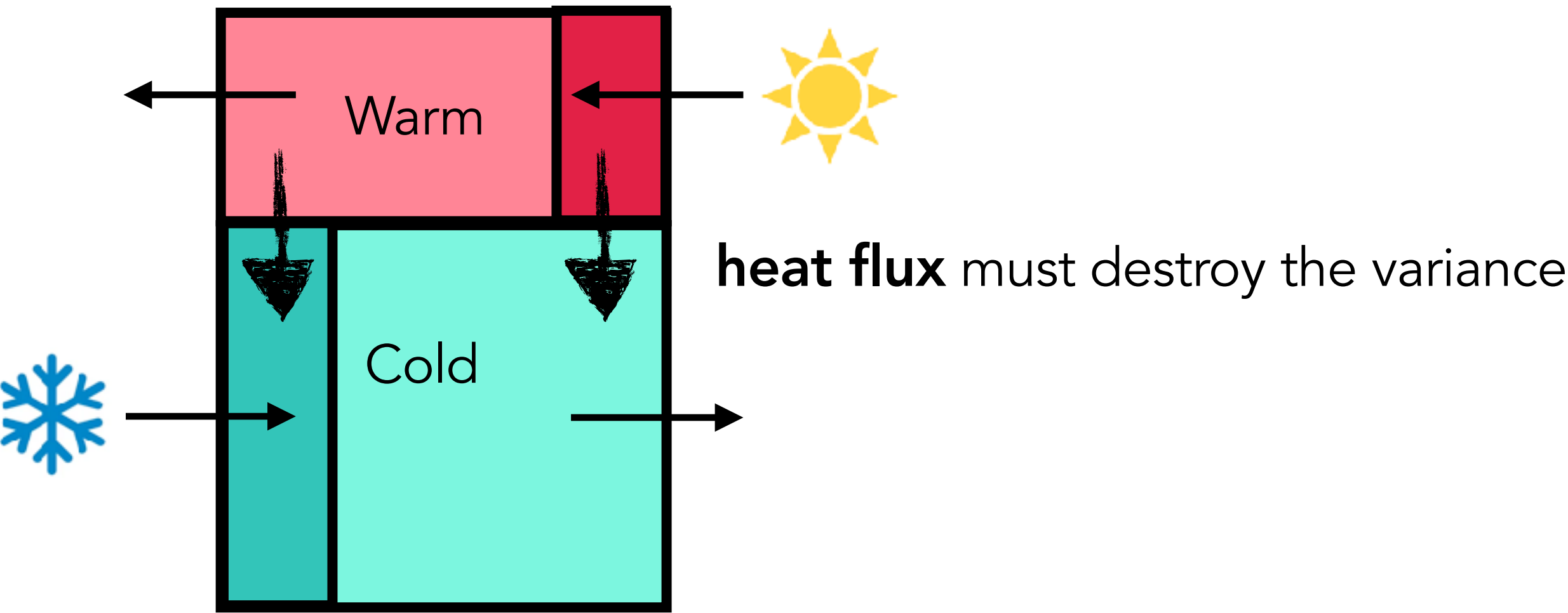
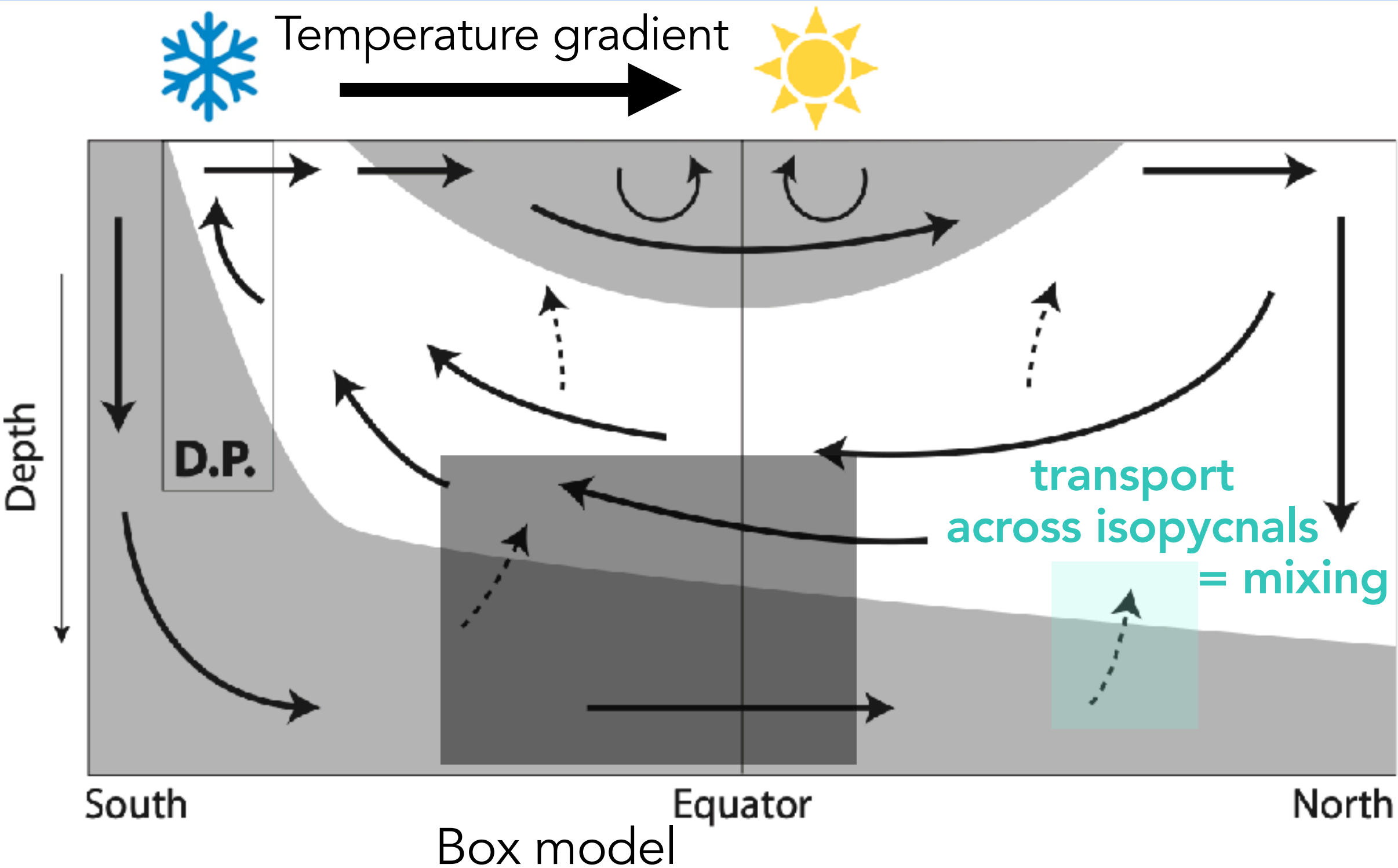
G. K. Vallis



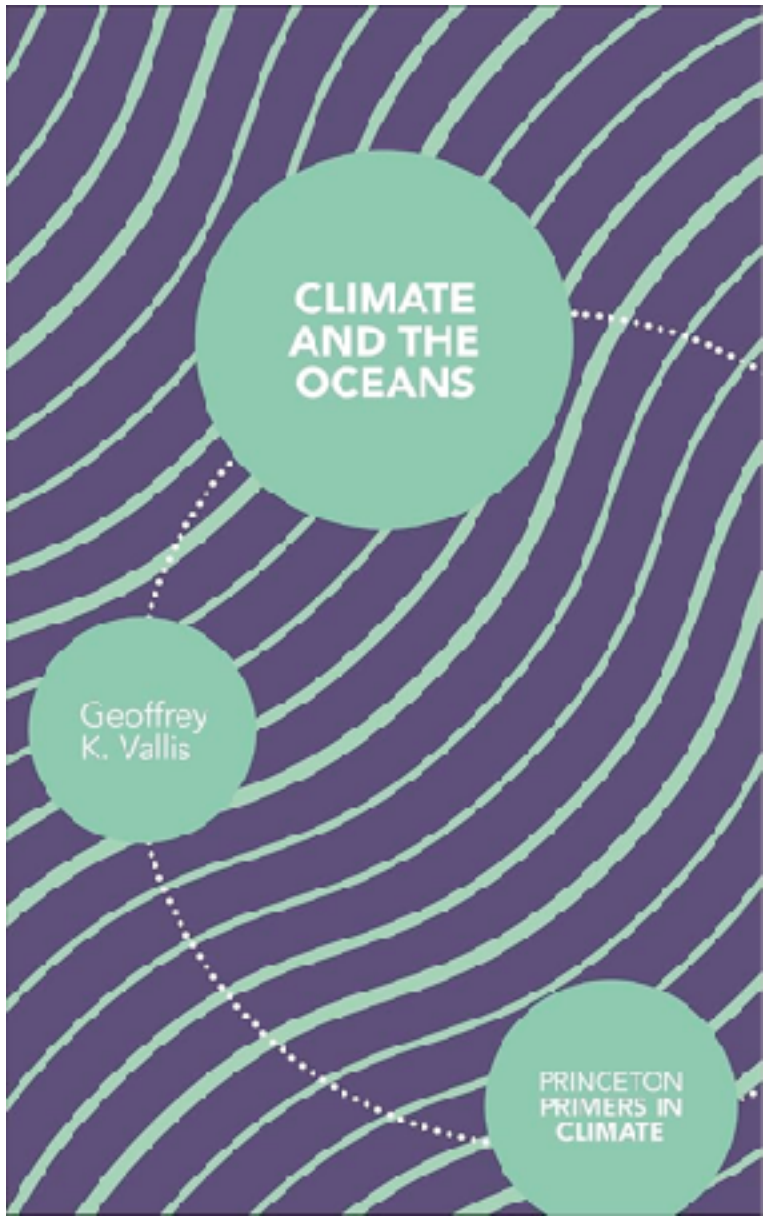
Turbulent mixing is key to the large-scale ocean circulation



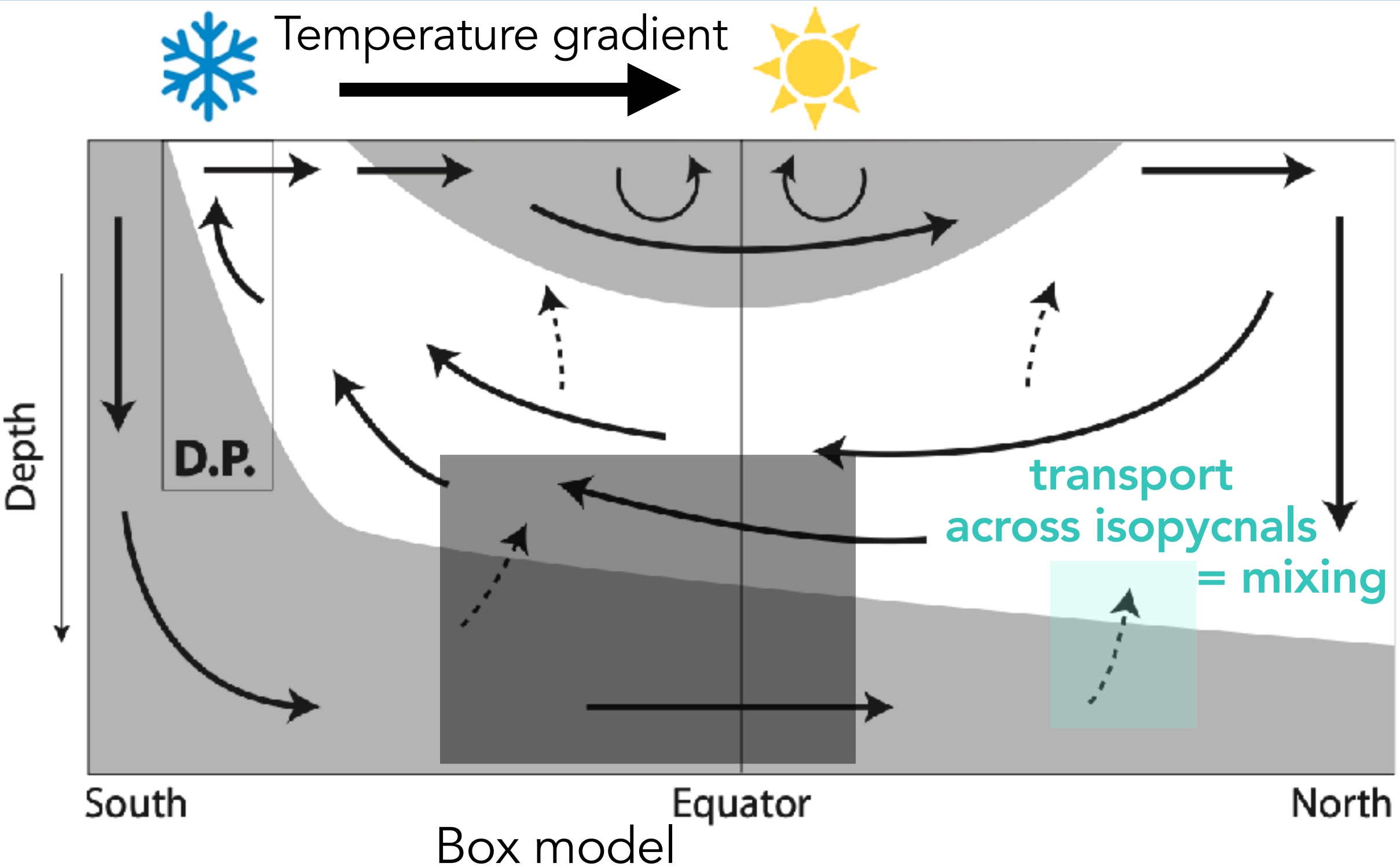
G. K. Vallis



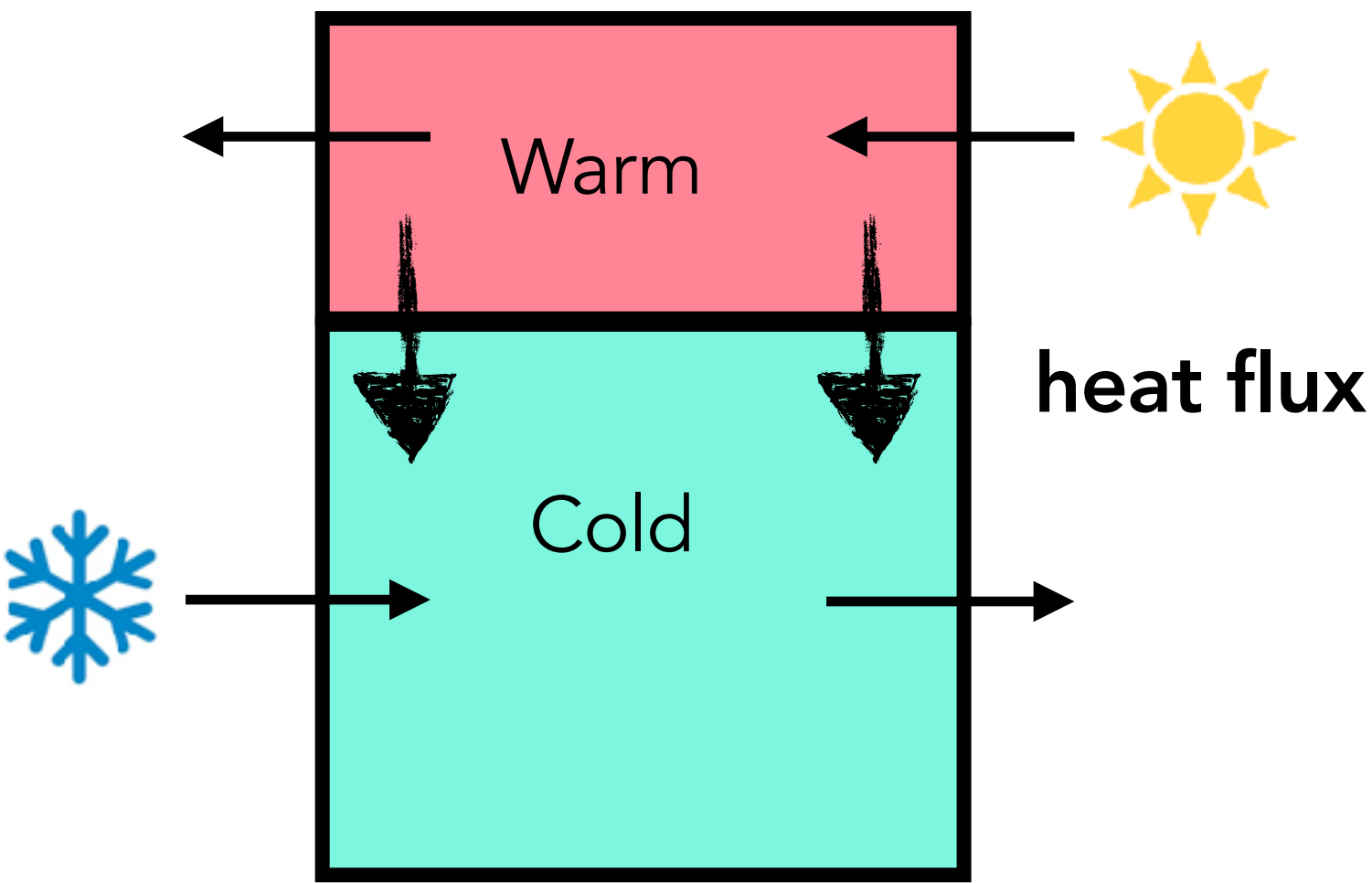
Turbulent mixing is key to the large-scale ocean circulation



G. K. Vallis

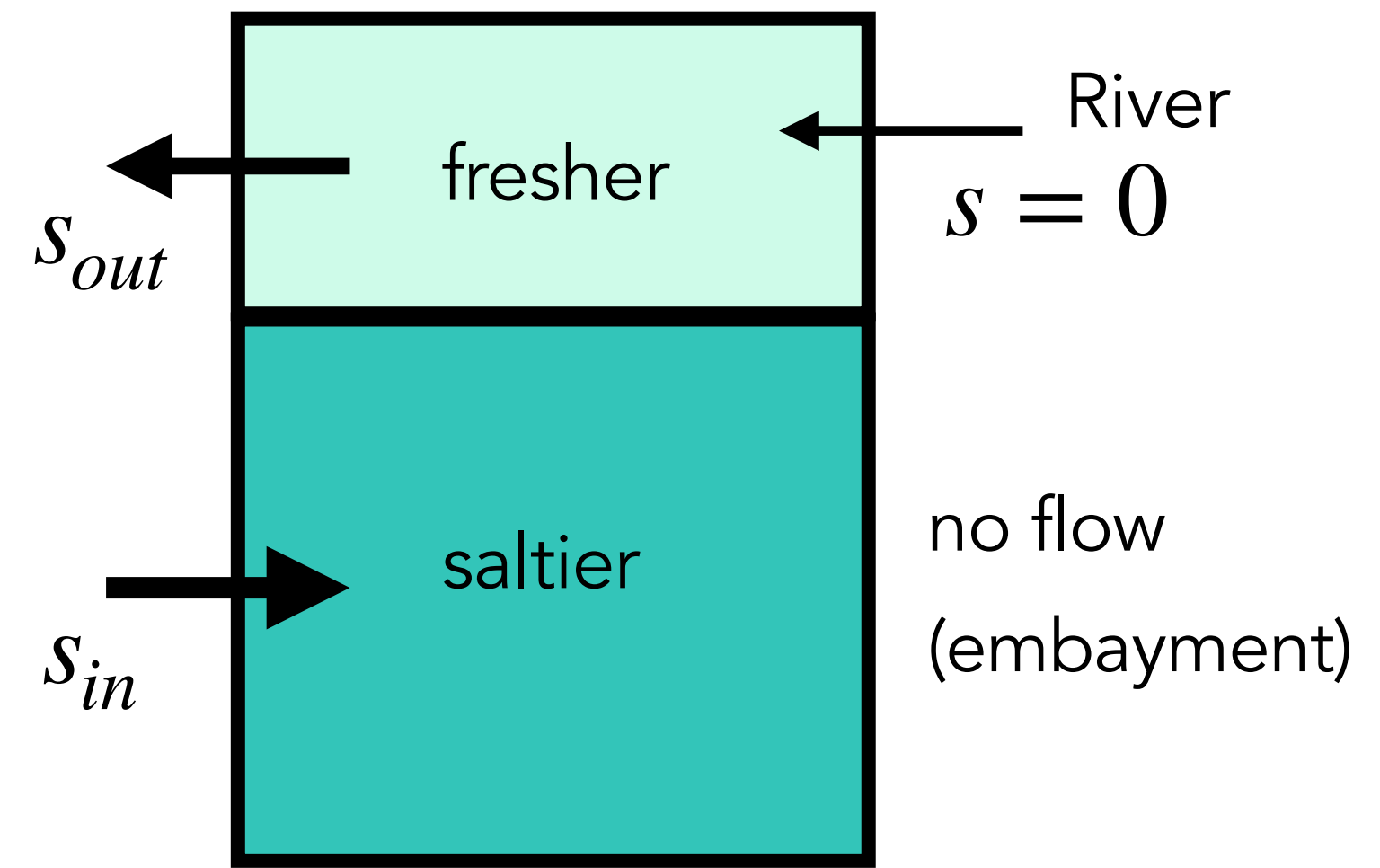
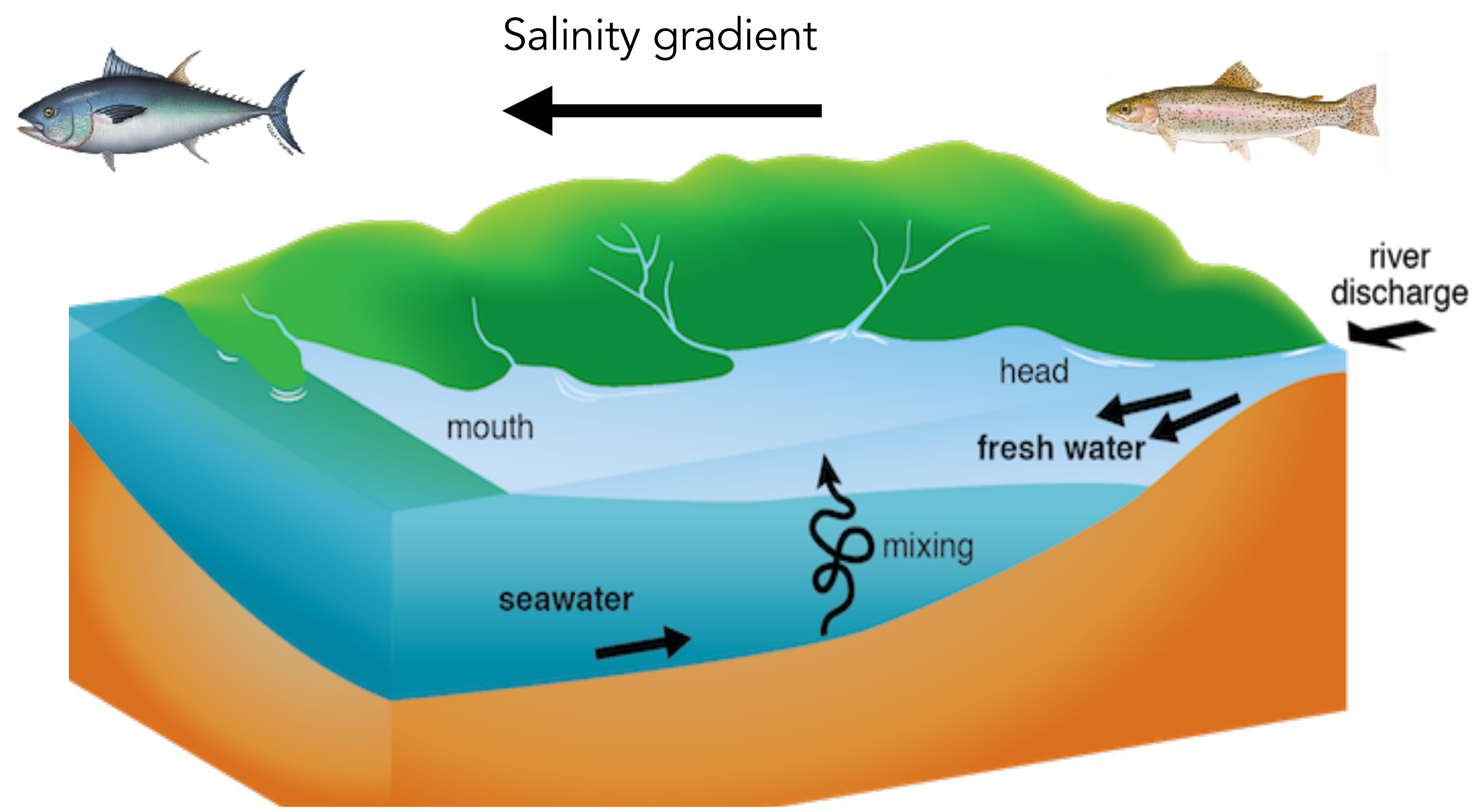


Controls the rate of meridional heat transport, carbon sequestration...

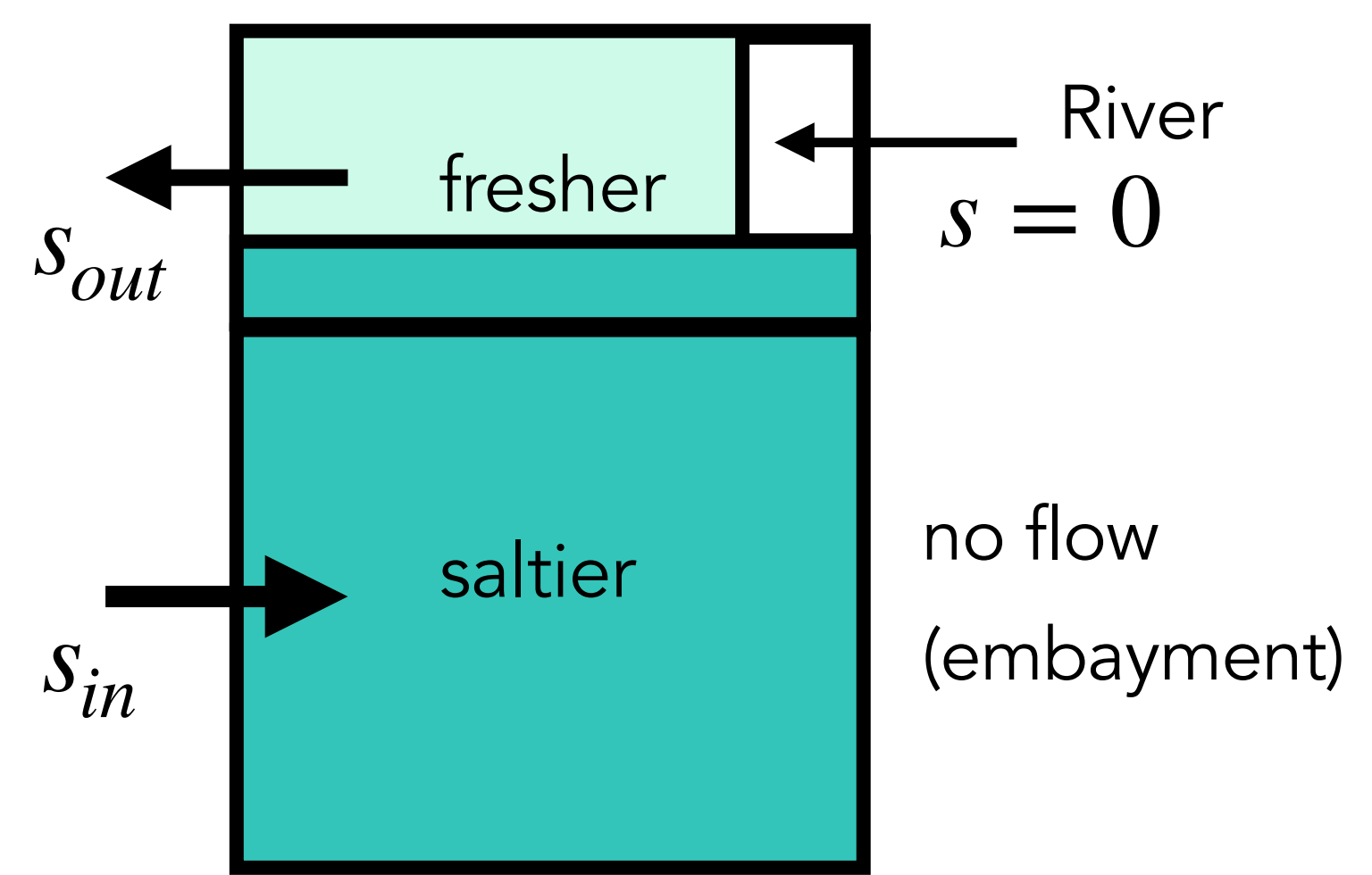
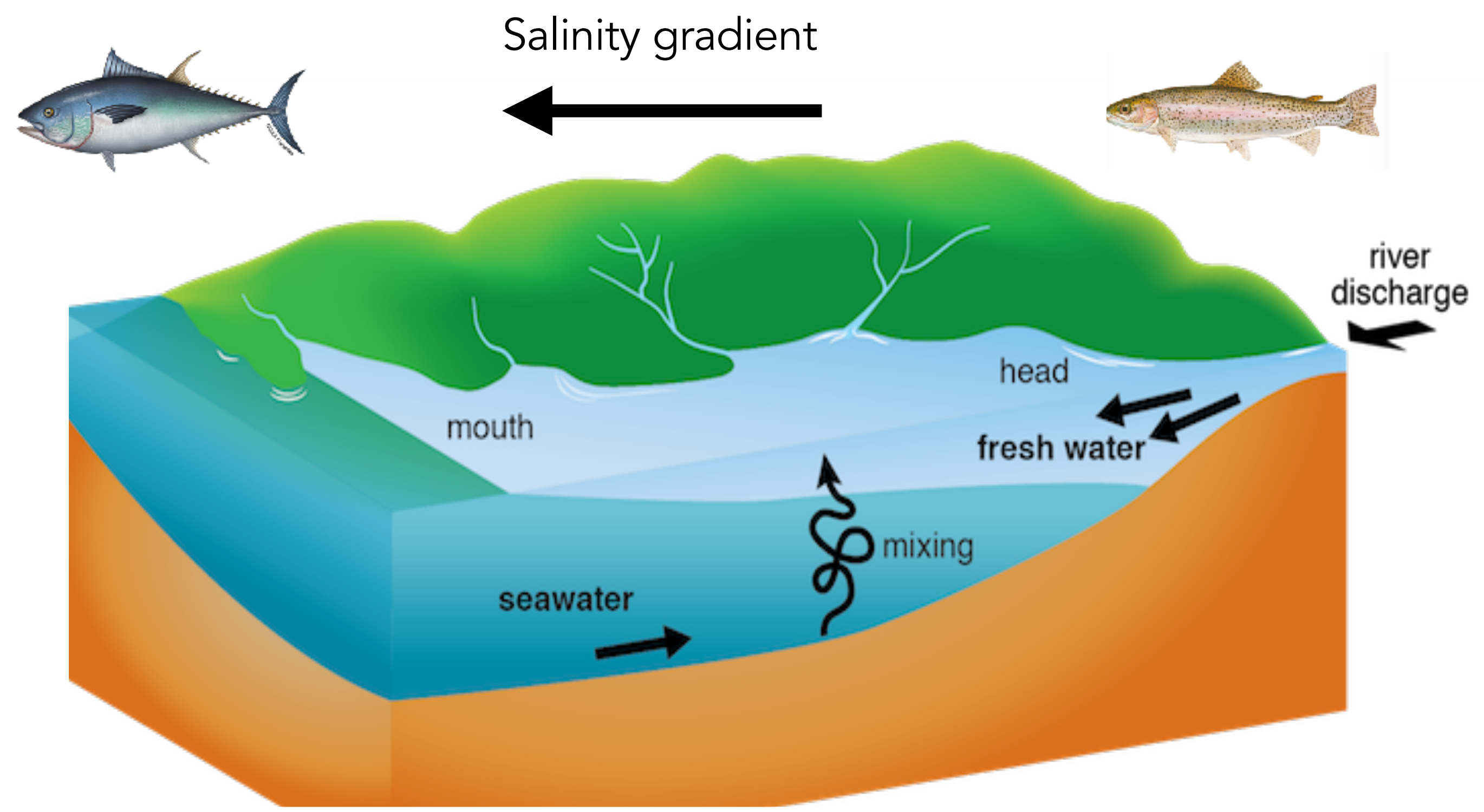


In the presence of a **sustained horizontal buoyancy gradient**,
a **steady-state stable vertical stratification**
requires **diapycnal mixing**
= **destruction of scalar variance**
by small-scale turbulence

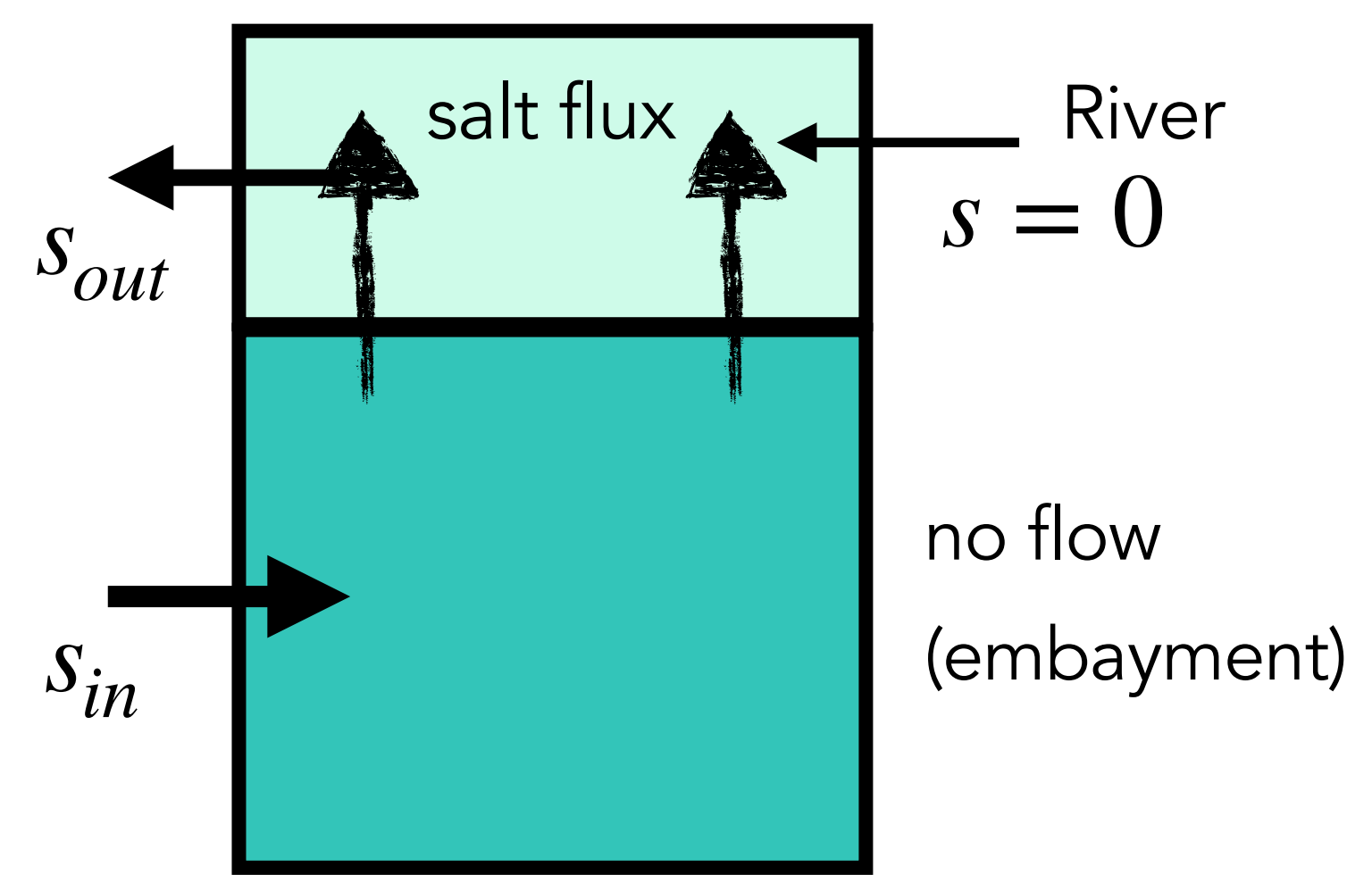
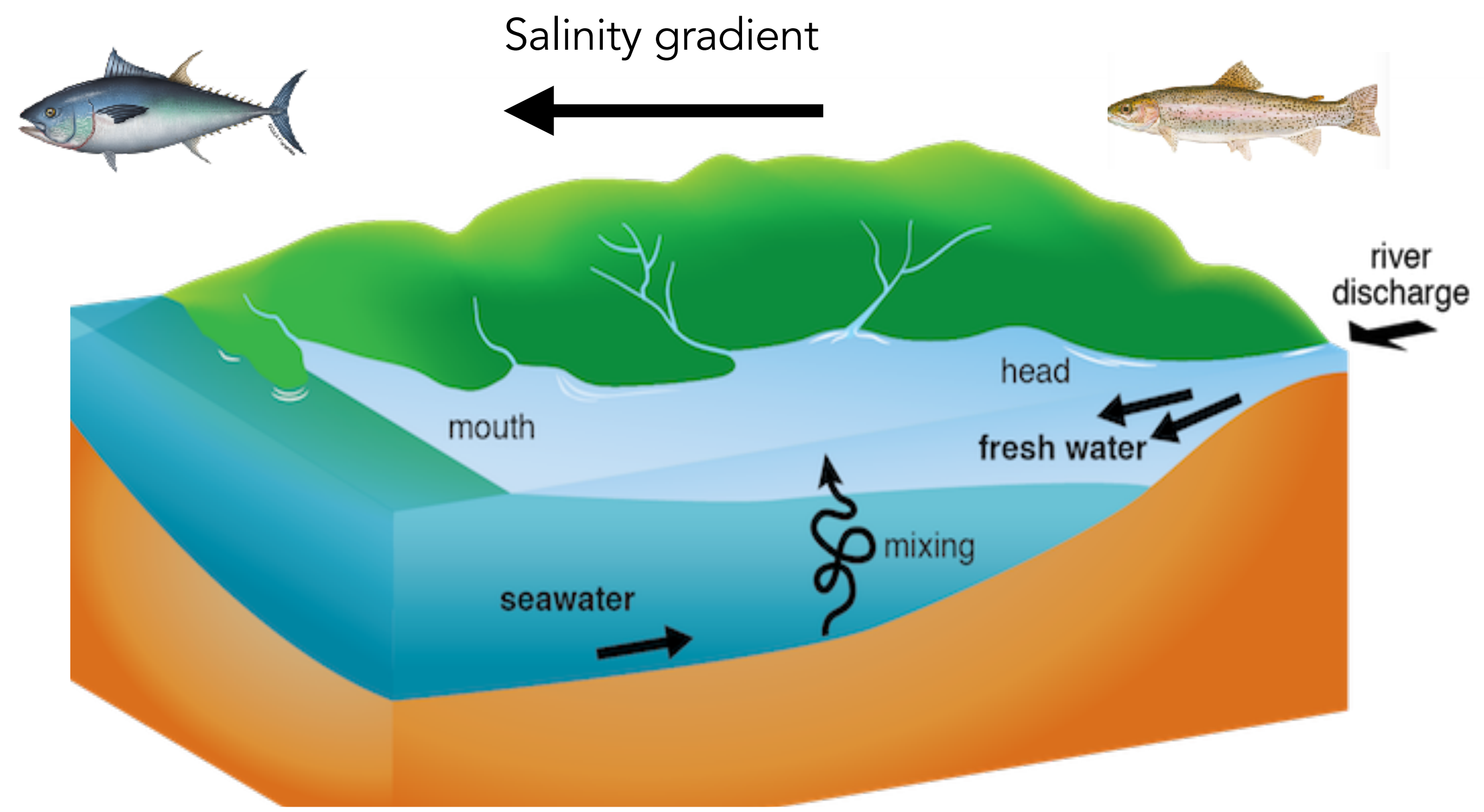
Turbulent mixing is also key to coastal waters



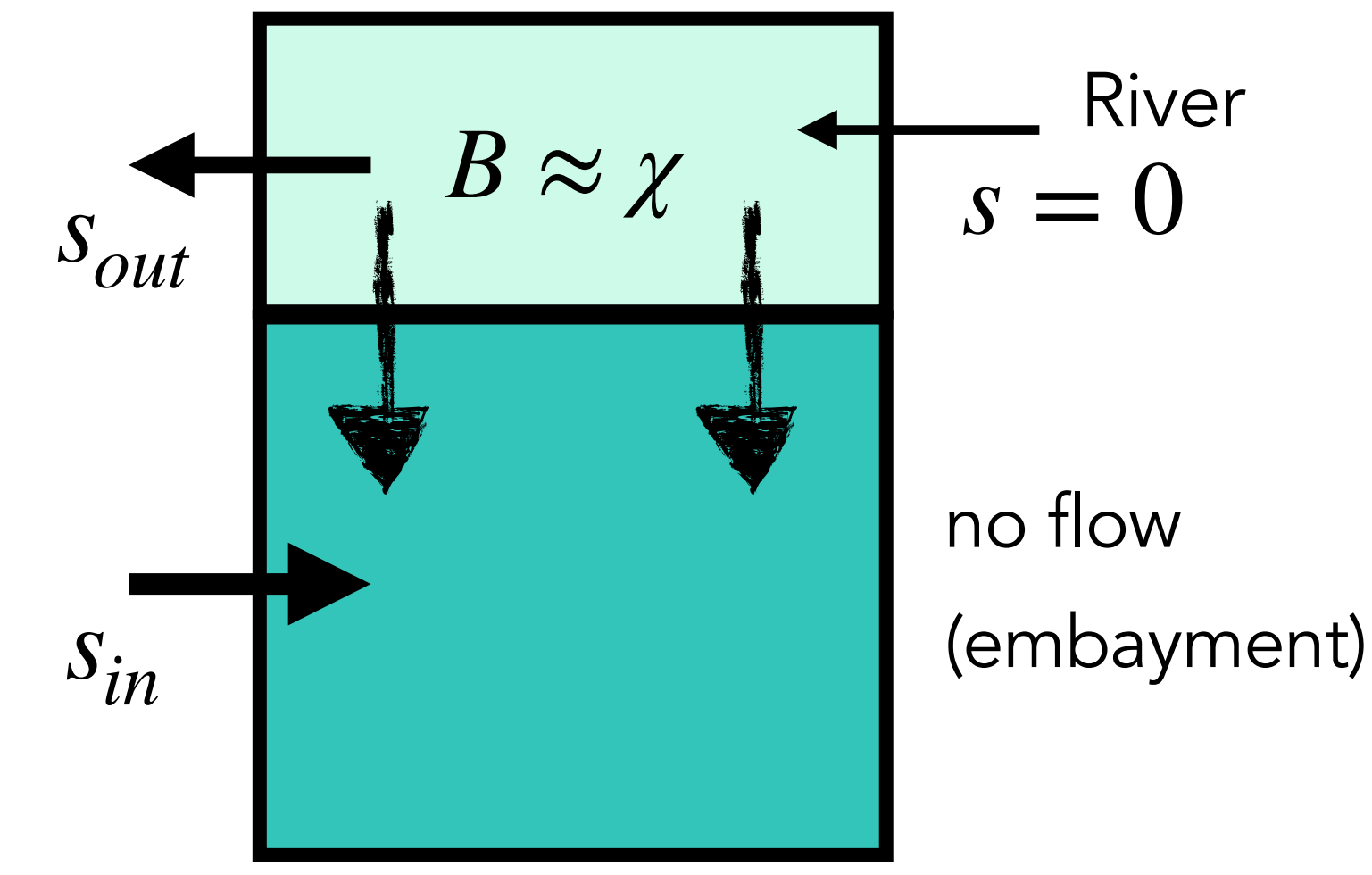
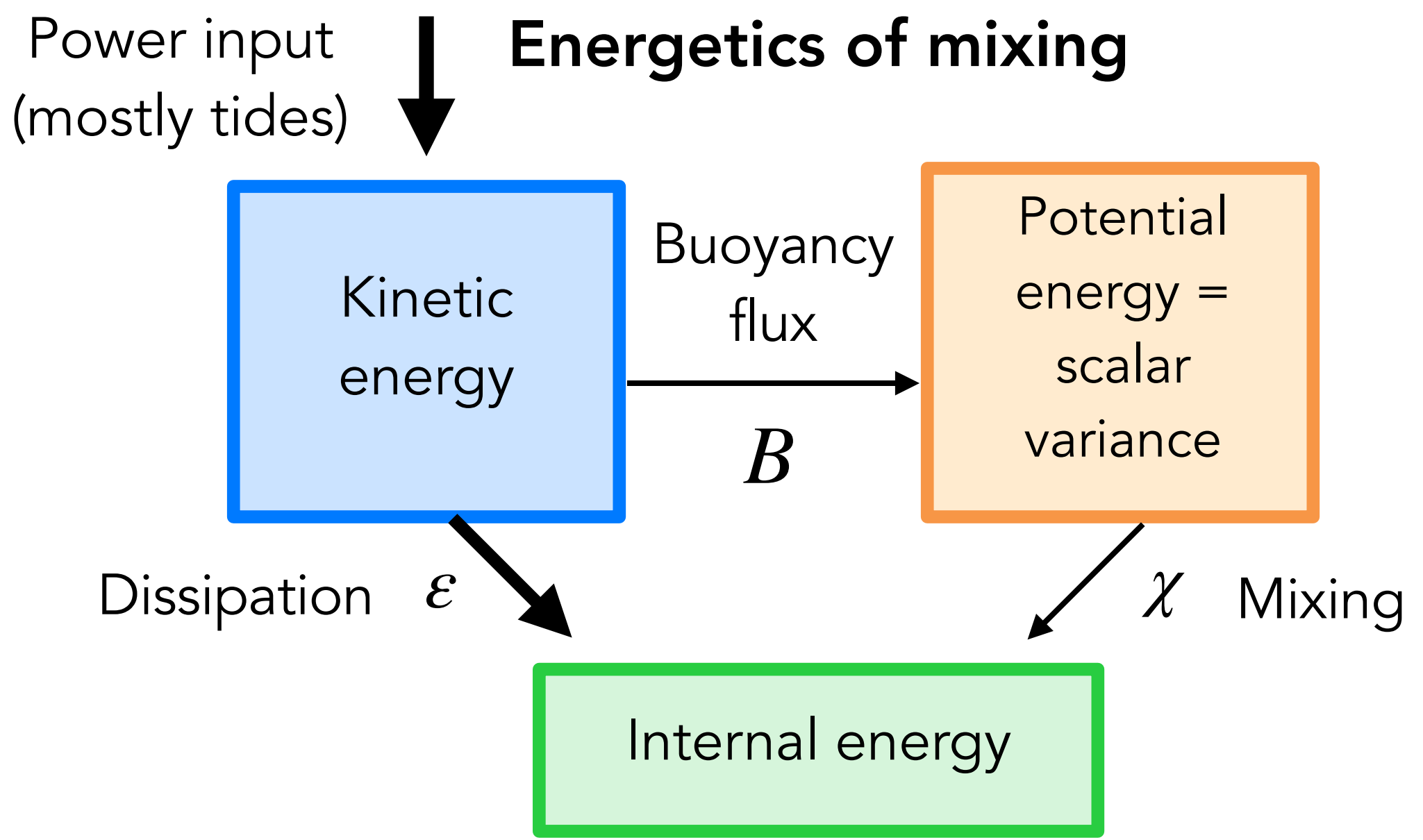
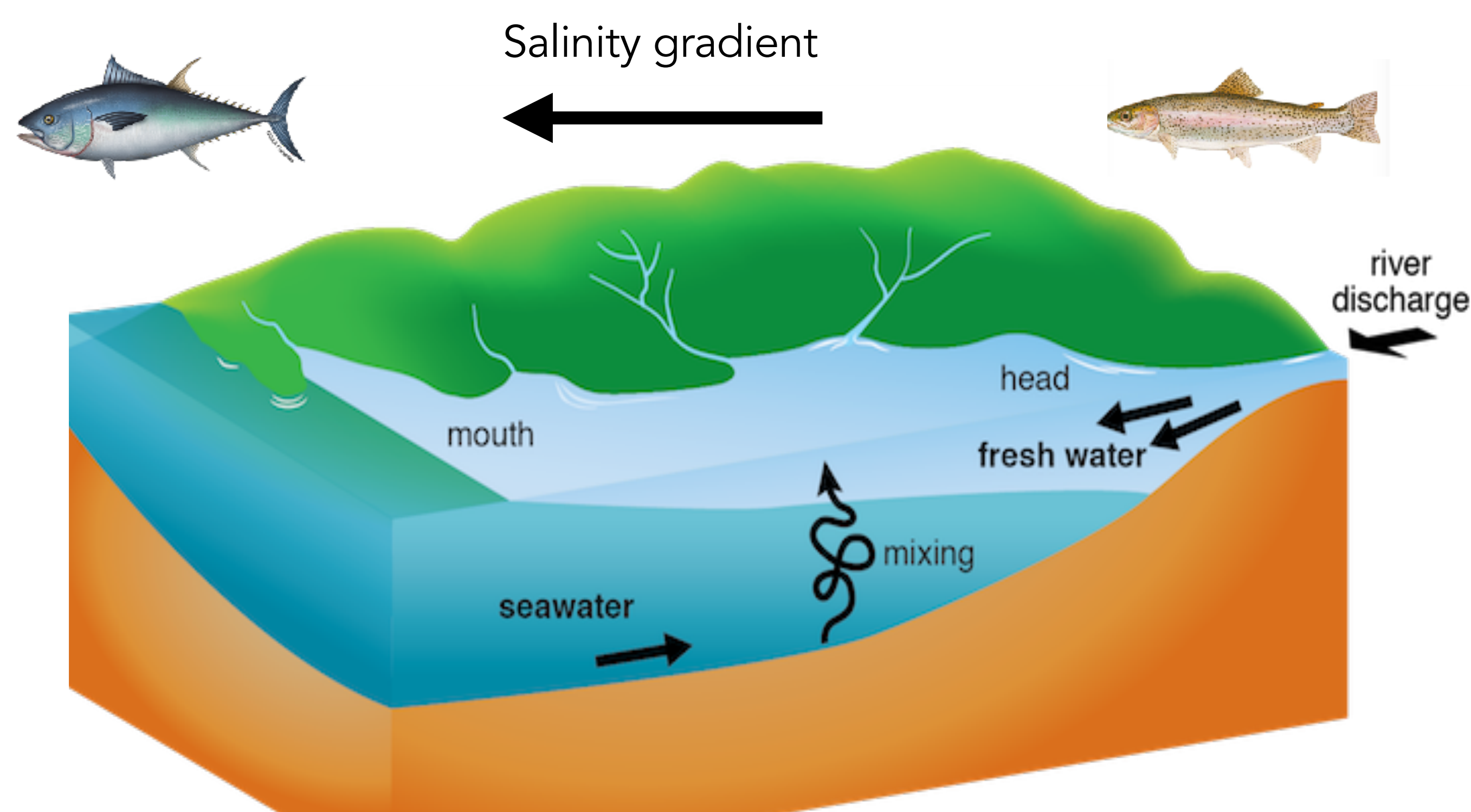
Turbulent mixing is also key to coastal waters



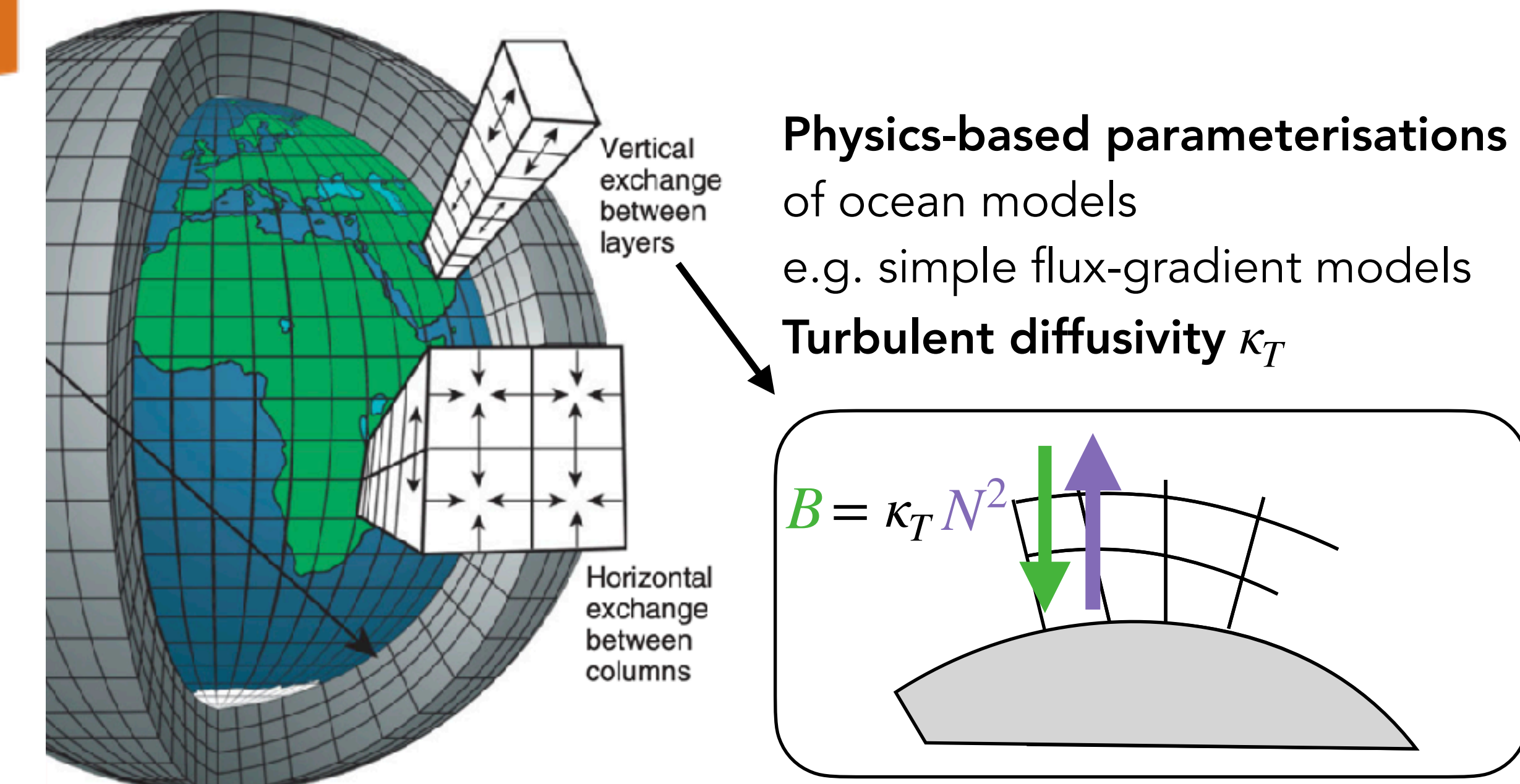
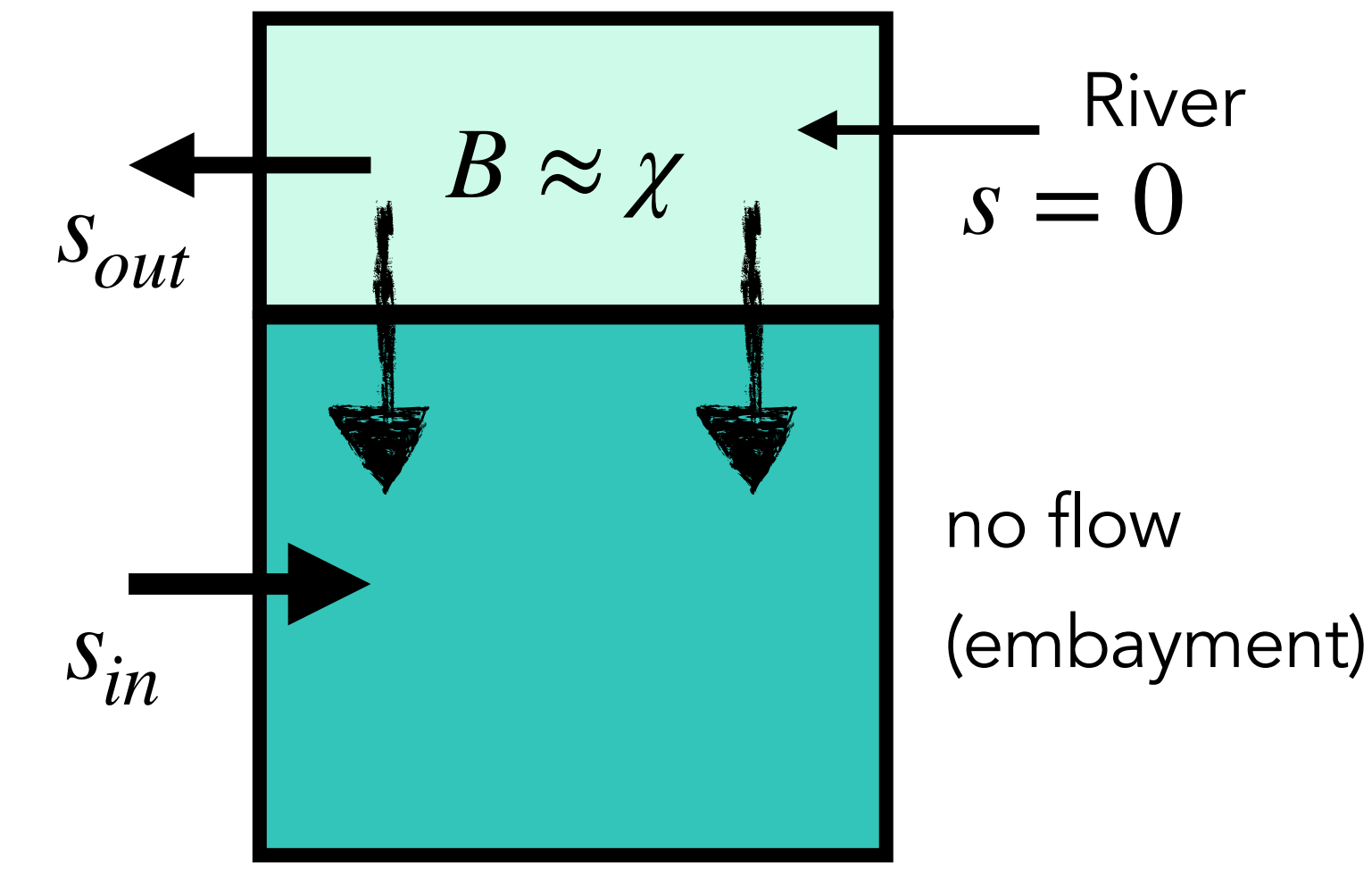
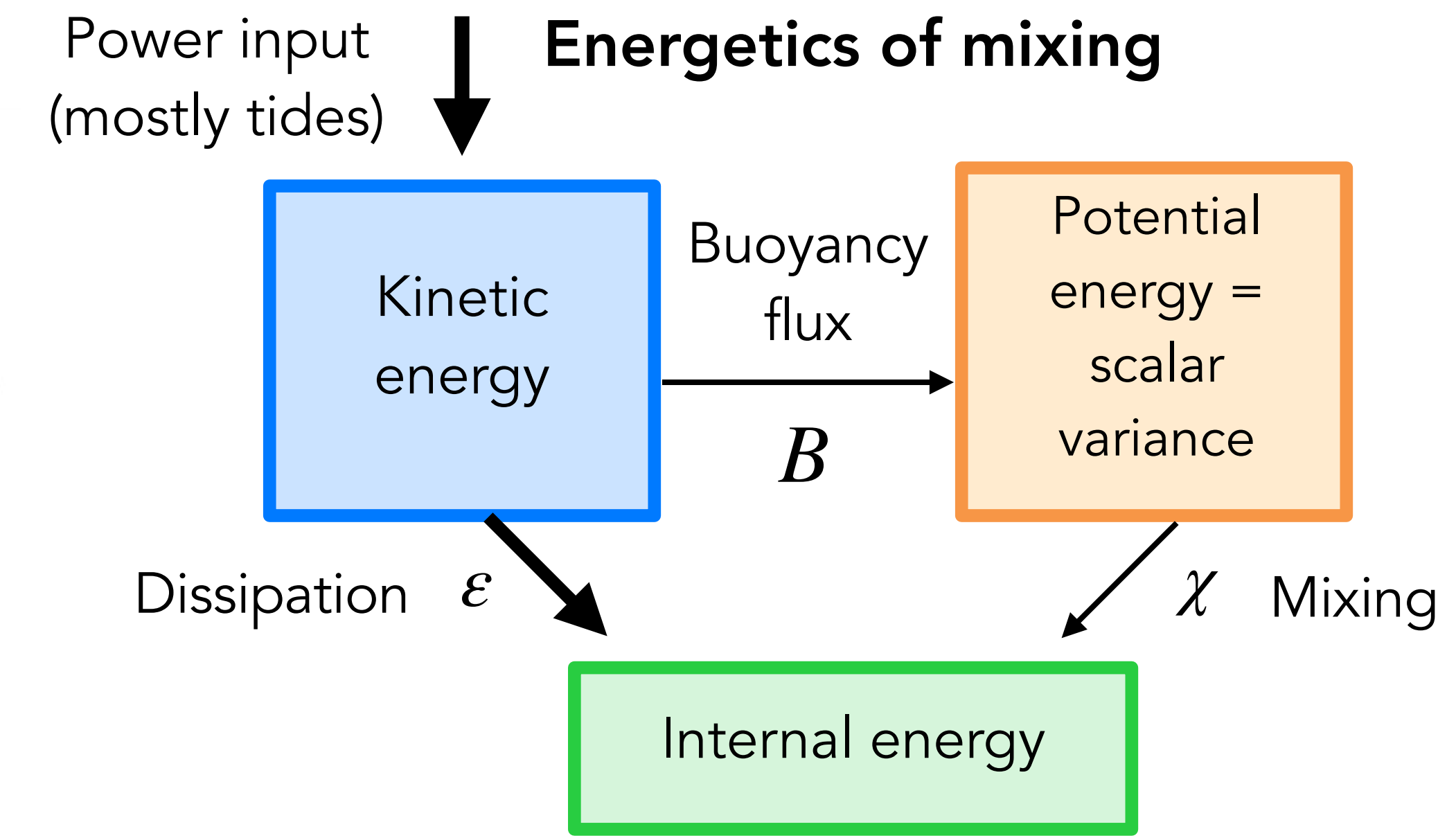
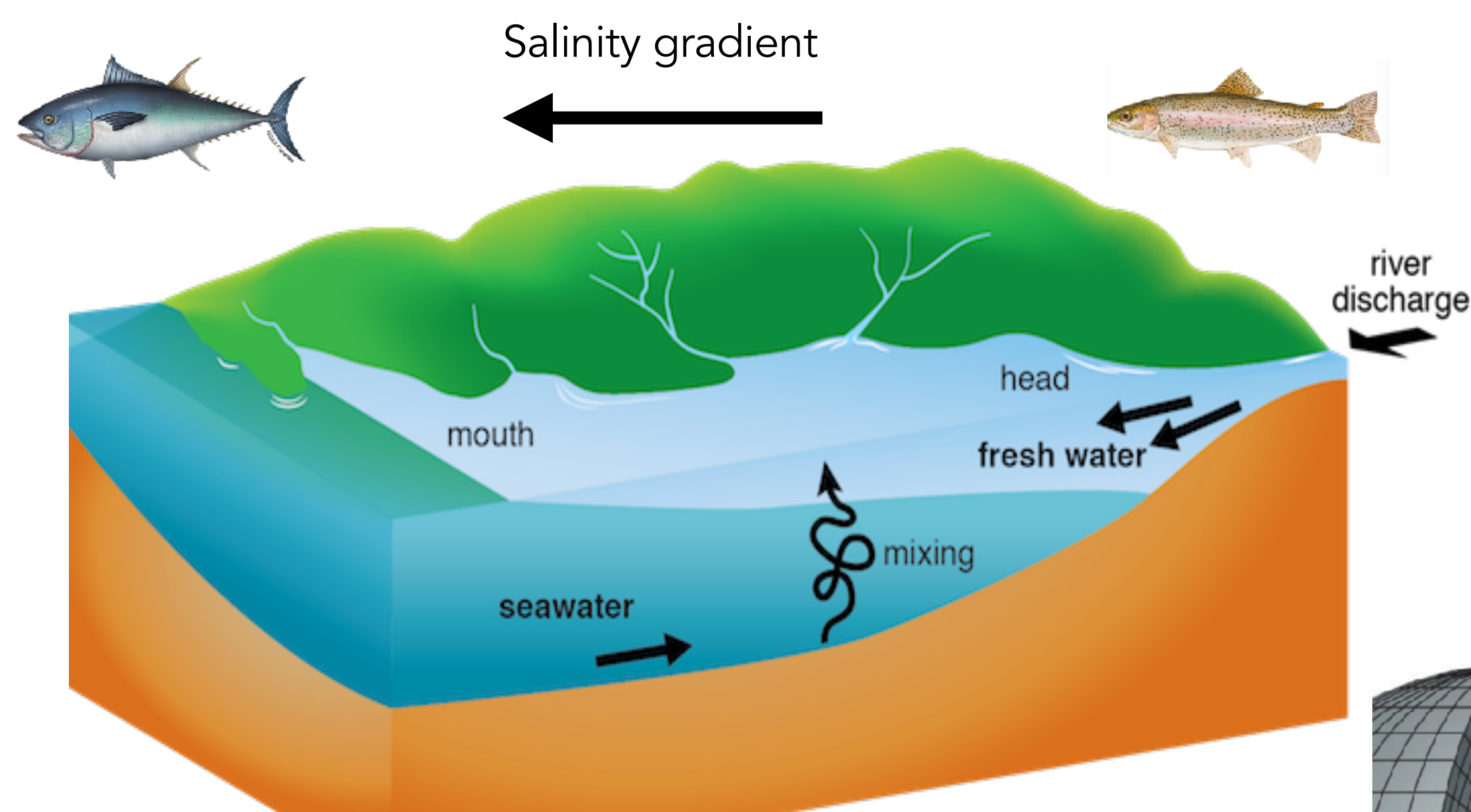
Turbulent mixing is also key to coastal waters



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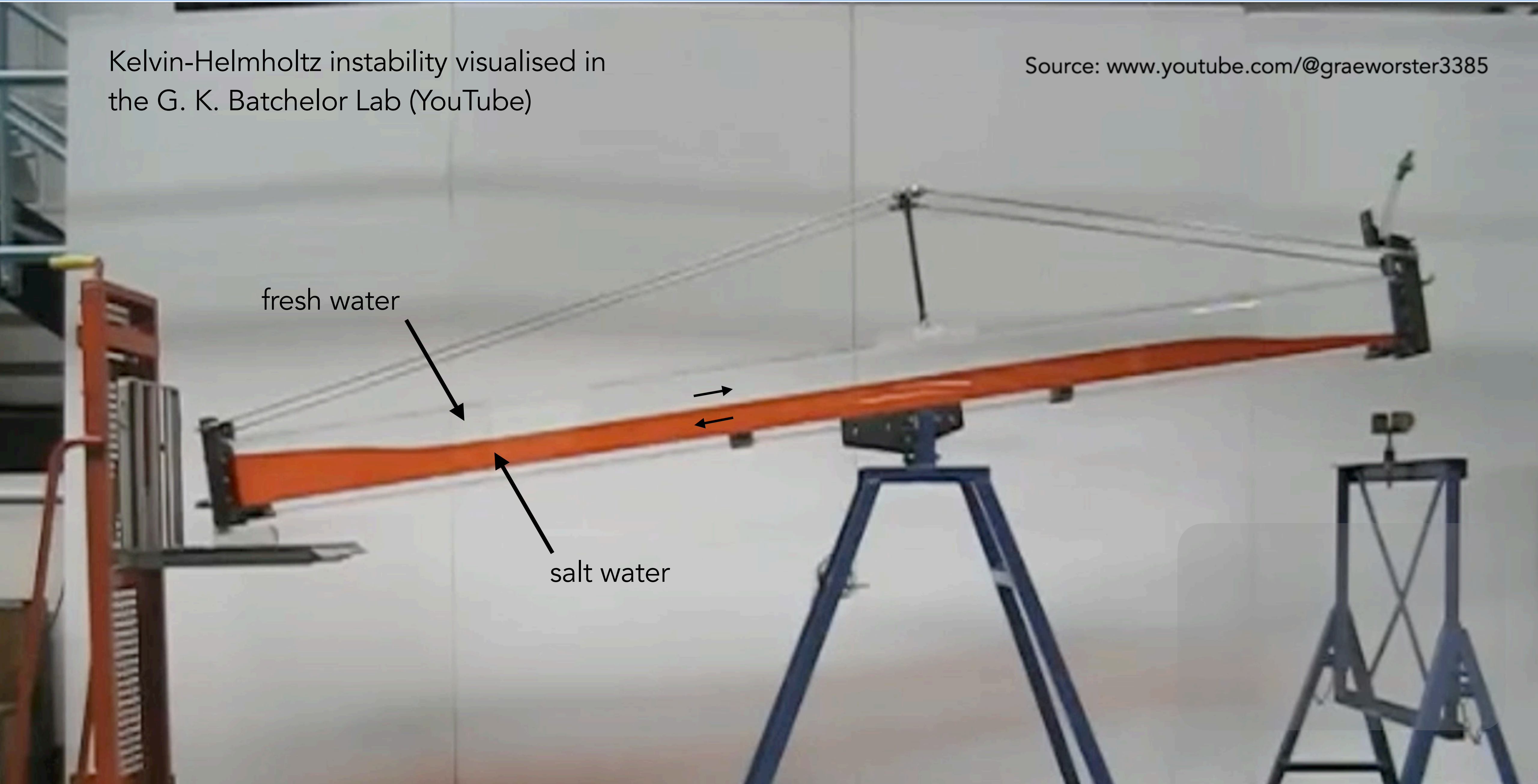
Turbulent mixing is also key to coastal waters



Shear instabilities are a key route to stably-stratified mixing

Kelvin-Helmholtz instability visualised in the G. K. Batchelor Lab (YouTube)

Source: www.youtube.com/@graeworster3385

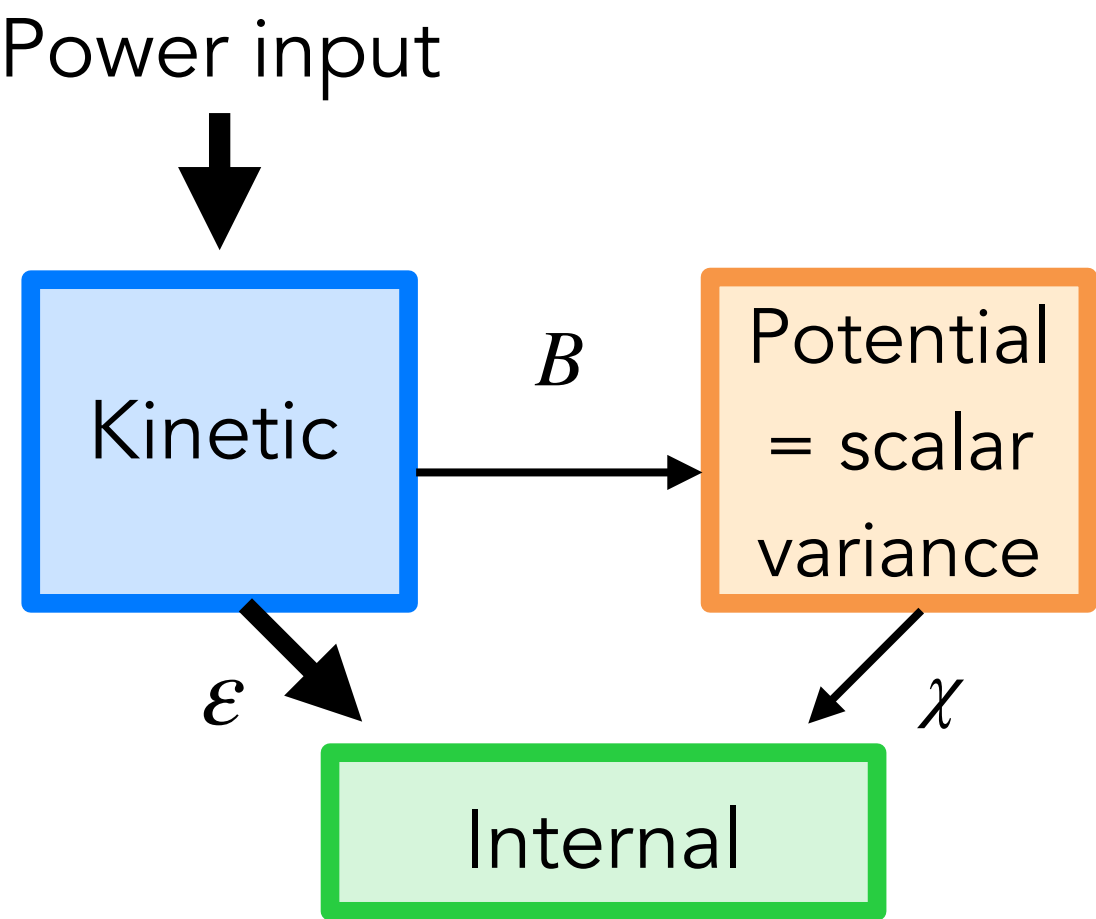


FOCUS TODAY: where and how does turbulent mixing occur?

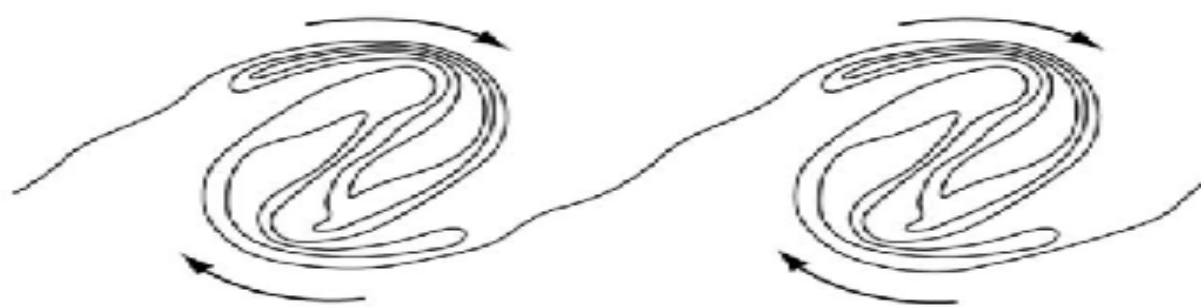


Shear instability requires a low Richardson number

$$Ri_g = \frac{N^2}{S^2} < 0.25$$



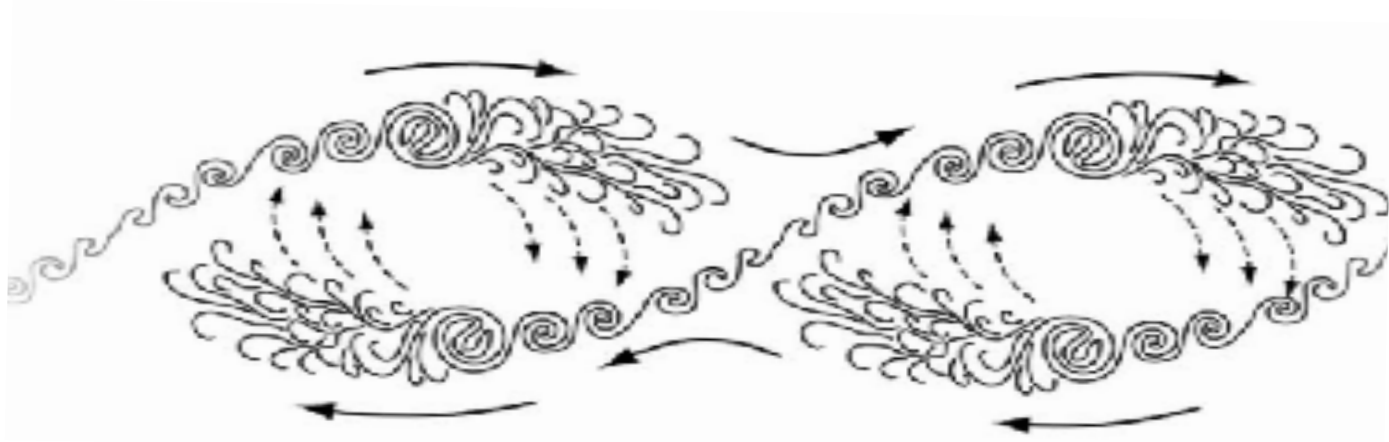
Mixing at the lab scale $Re \sim 10^3 - 10^4$



large-scale overturn,
statically unstable,
collapse, mixing

≠

Mixing in the ocean $Re > 10^5$



secondary instabilities?
smaller-scale, faster,
sheared overturns

Hypothesis already in Geyer et al., *Geophys. Res. Lett.* (2010)

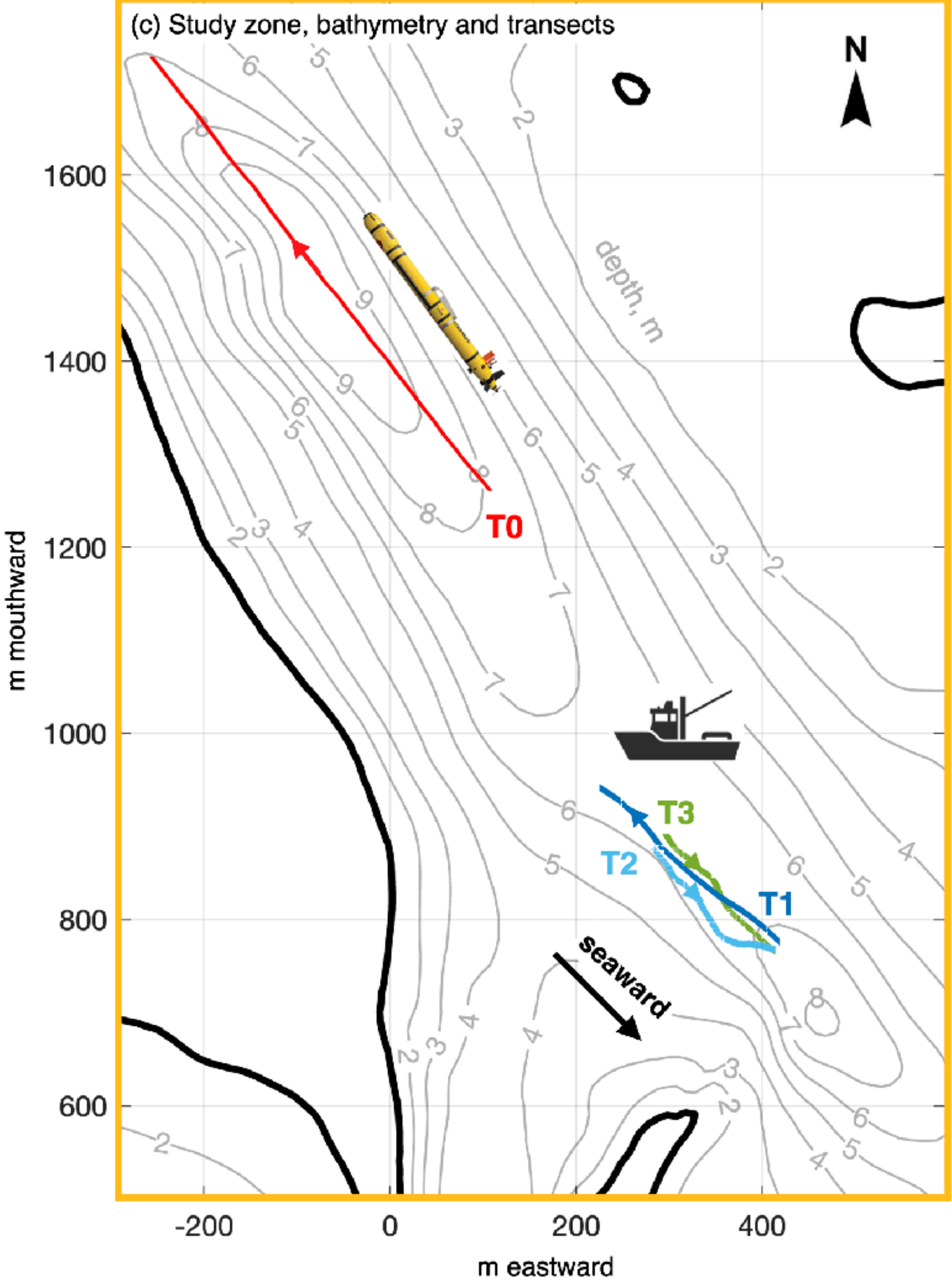
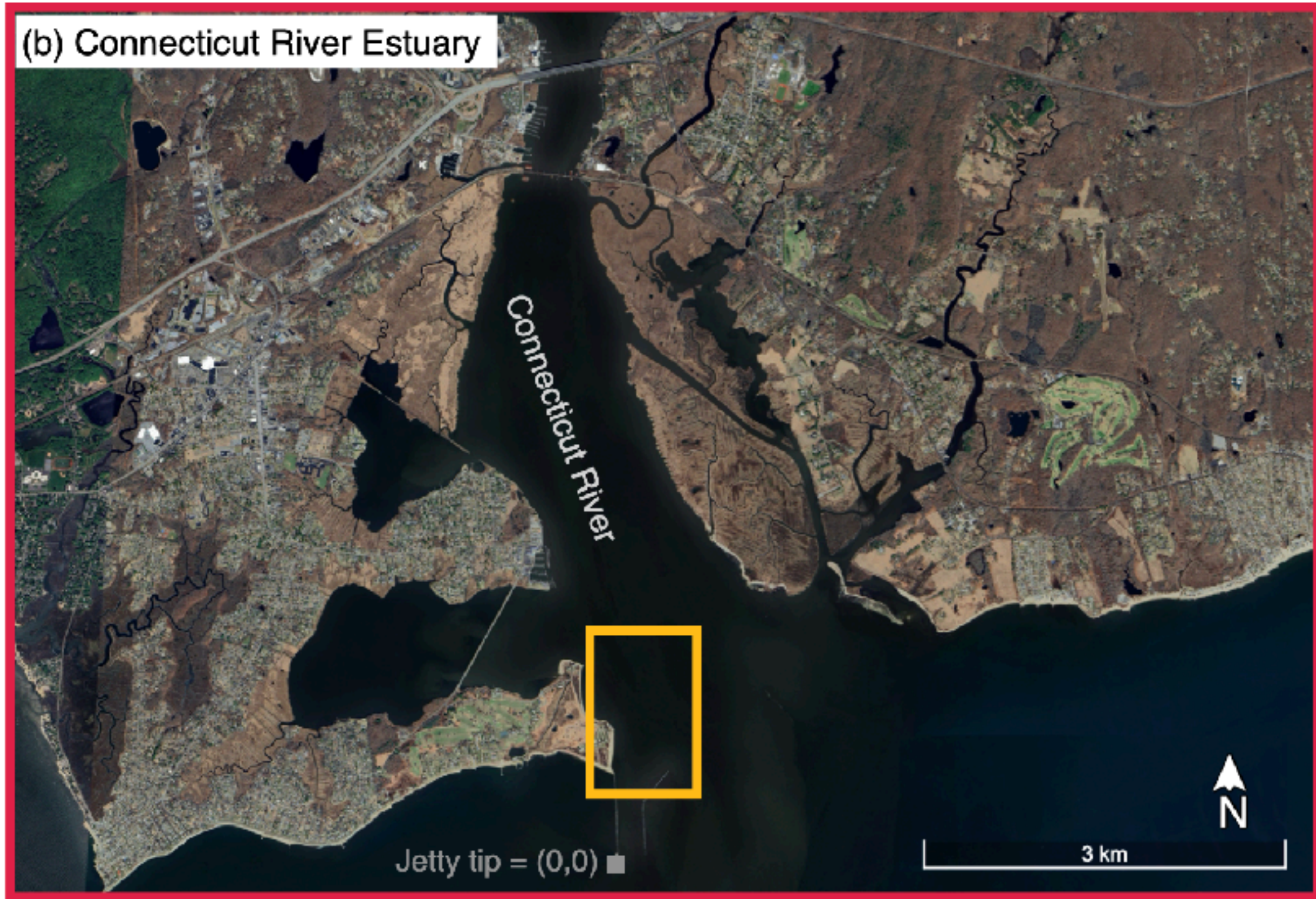
The site

June 2017

Cruise by
Rocky Geyer,
Andone Lavery



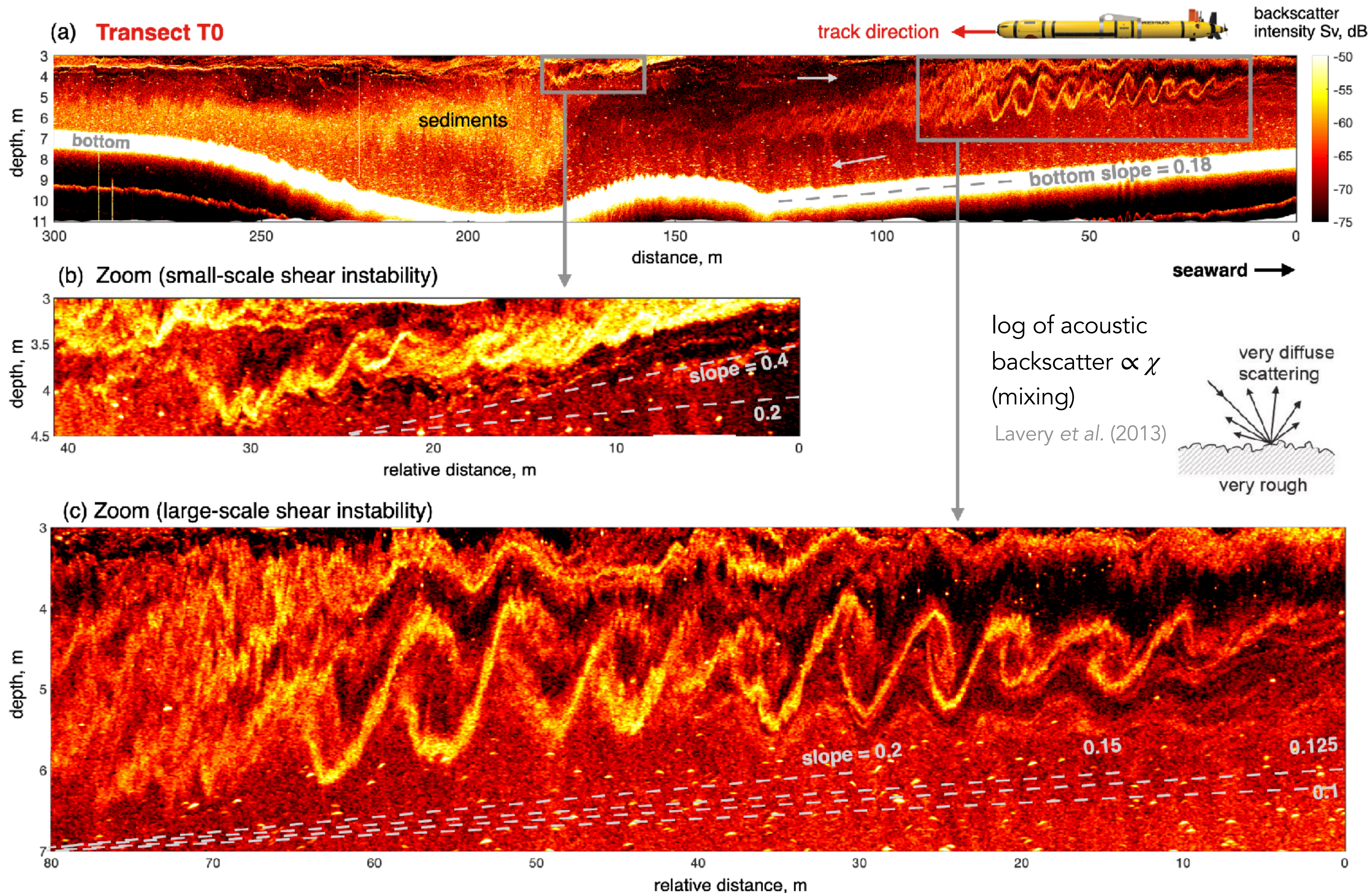
Strongly-
stratified
estuary



Acoustics

Remus Autonomous Underwater Vehicle (AUV)

Vertical
exaggeration
= 5 in all figures



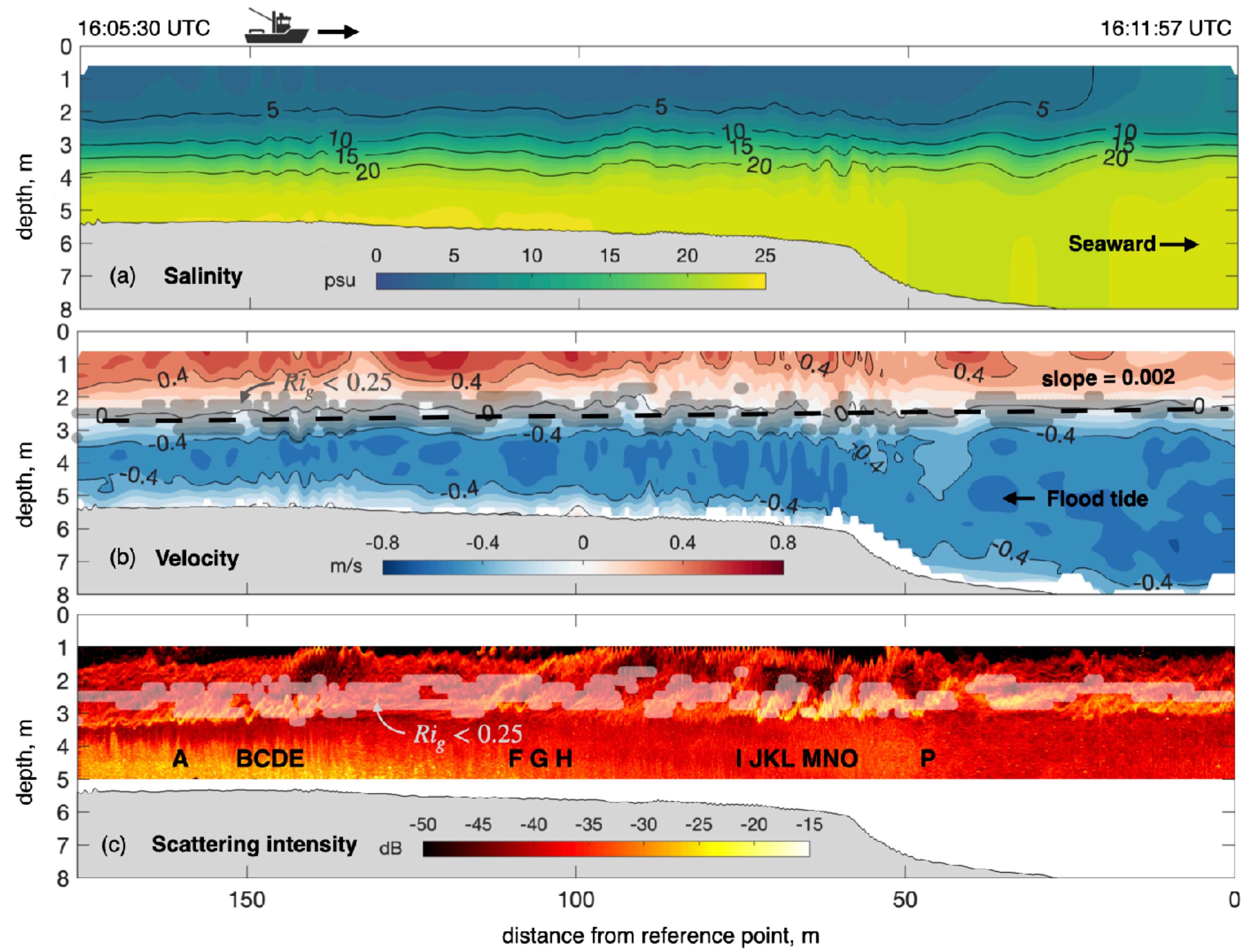
Shipboard transect T2

Salinity-stratified flow
(temperature negligible)

Tidal forcing creates
tilted pycnoclines and
shear layer

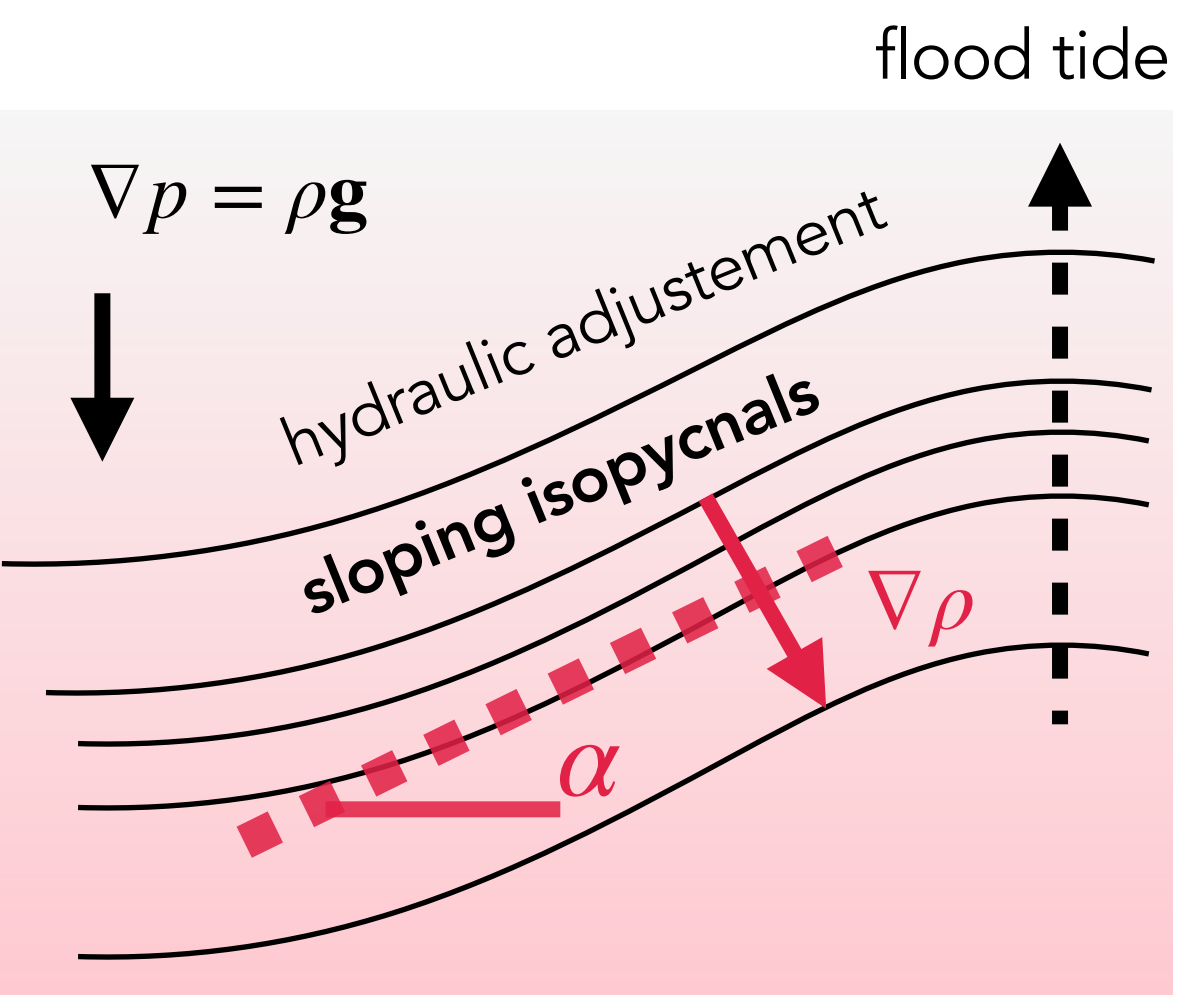
Reynolds number $Re \approx 8 \times 10^5$

Shear instabilities are well
predicted by $Ri_g < 0.25$



Why shear instability?

Continuous tidal forcing



Inviscid vorticity equation

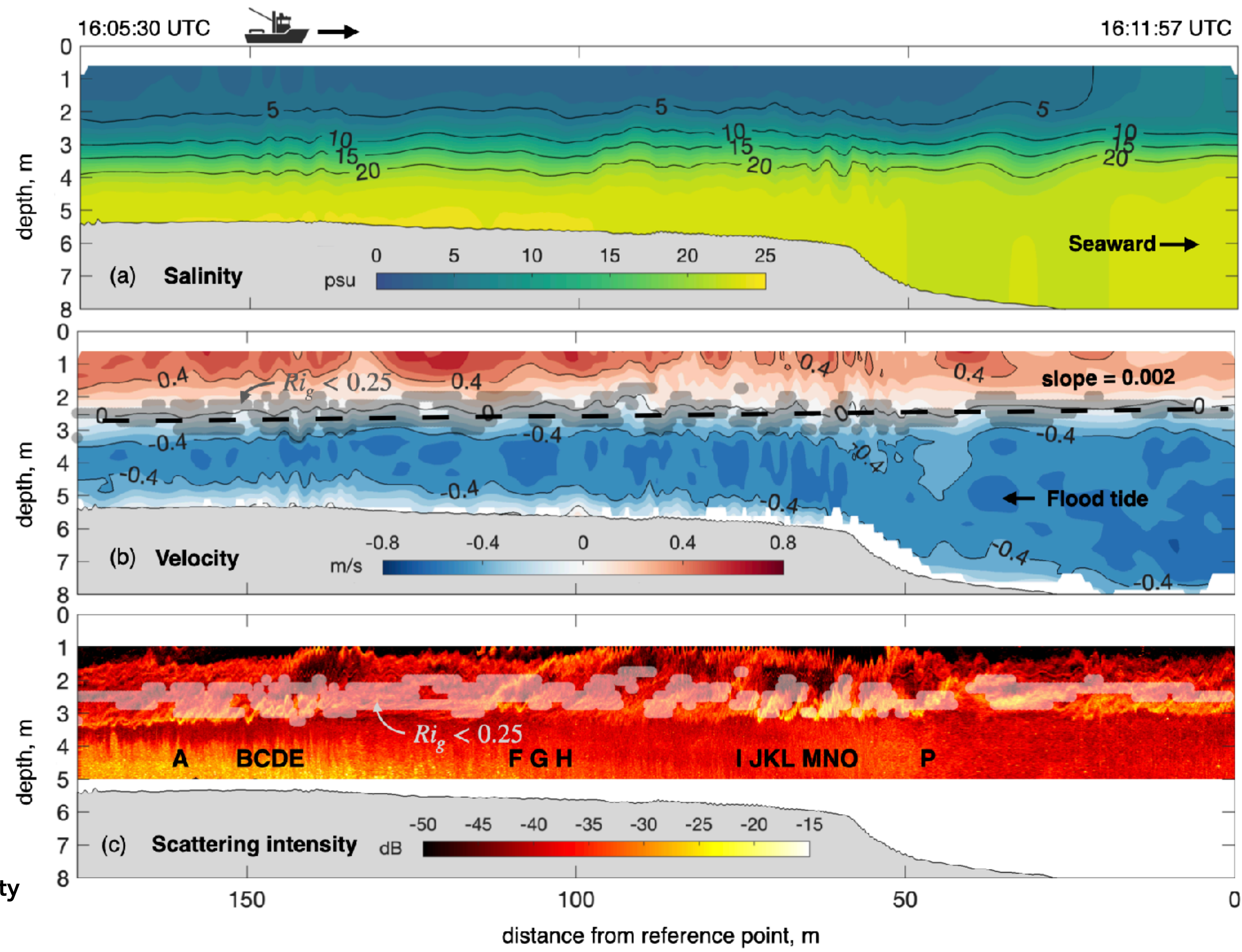
$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)\mathbf{u} + \frac{1}{\rho_0^2} \nabla \rho \times \nabla p$$

stretching baroclinic

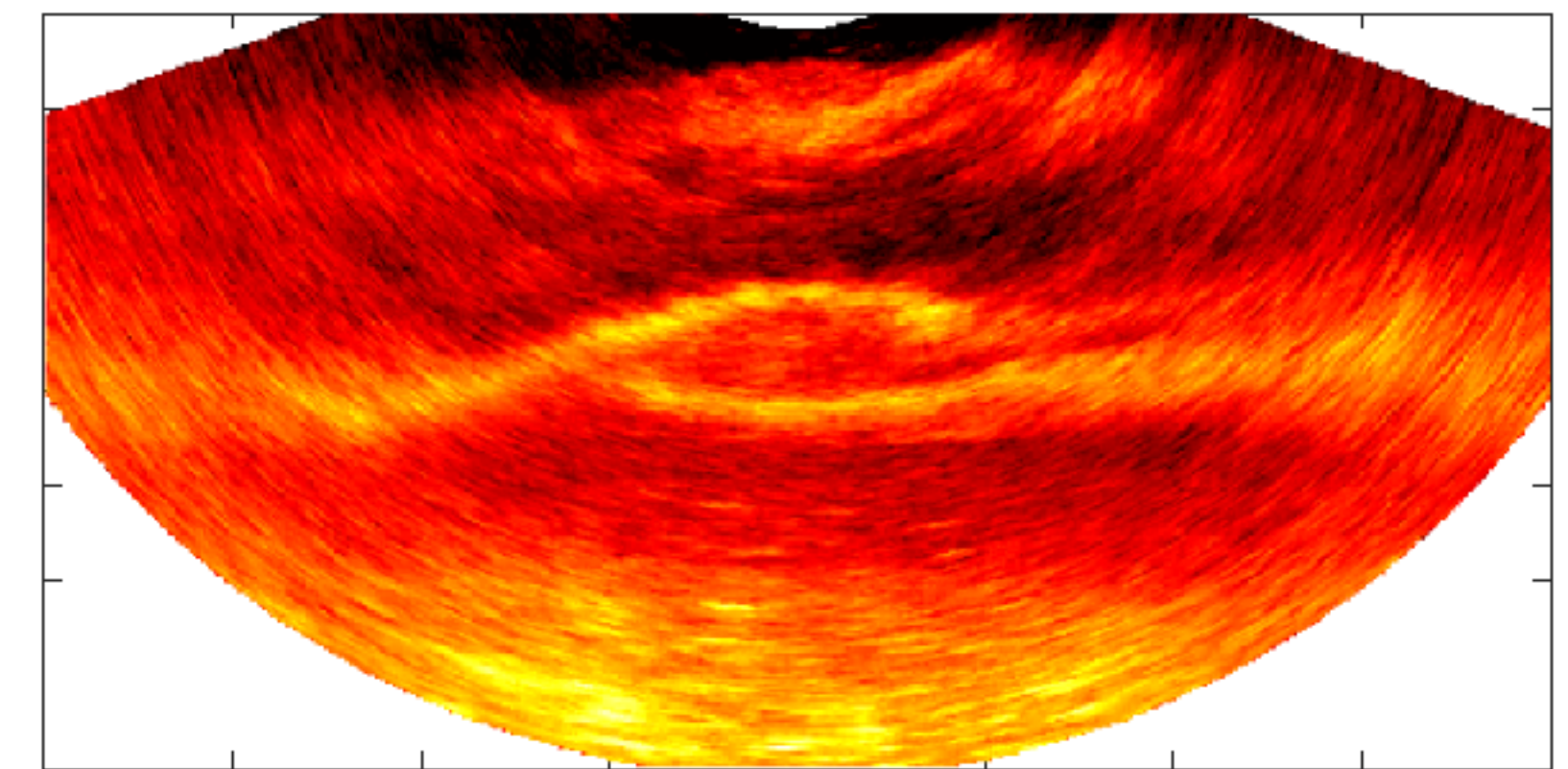
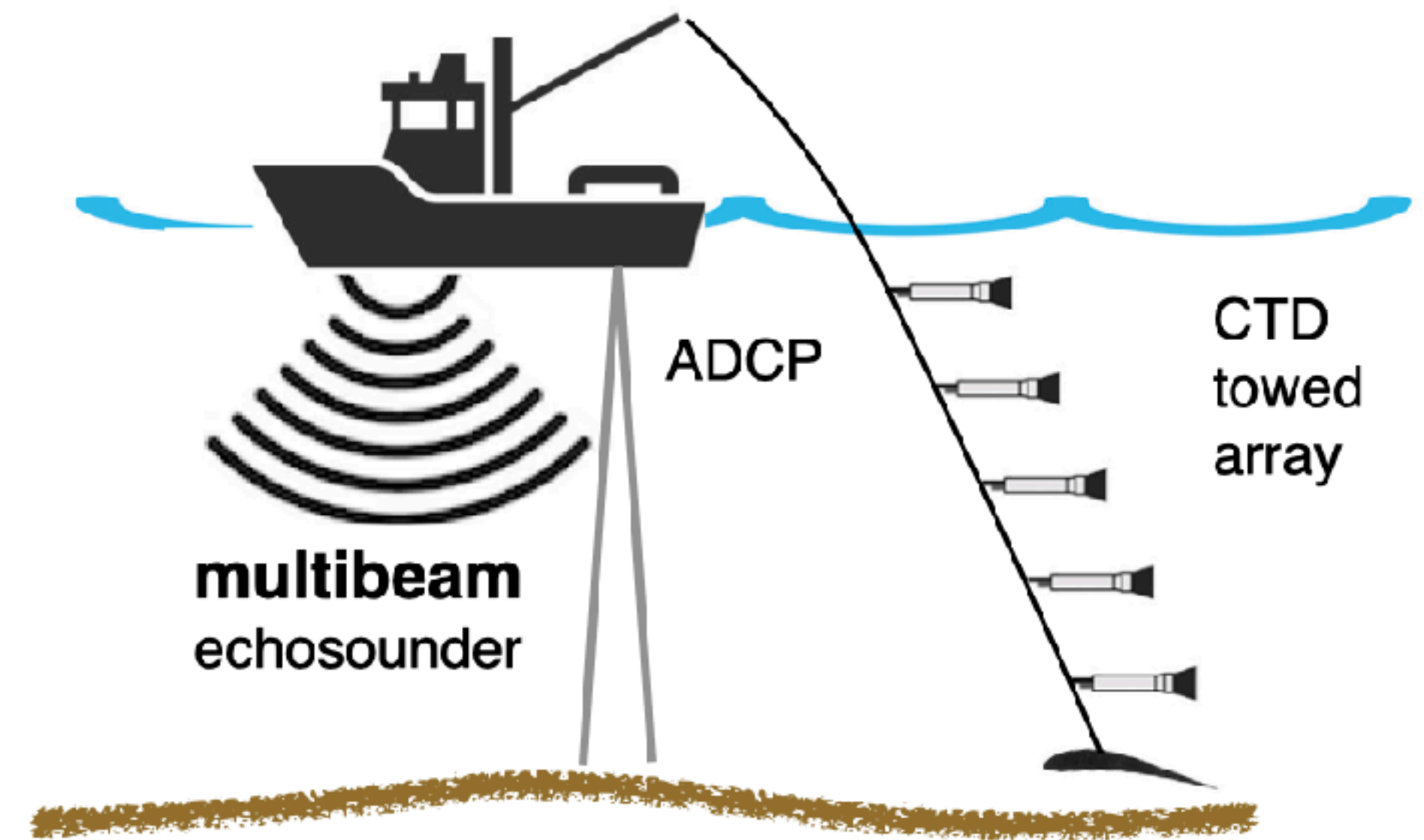
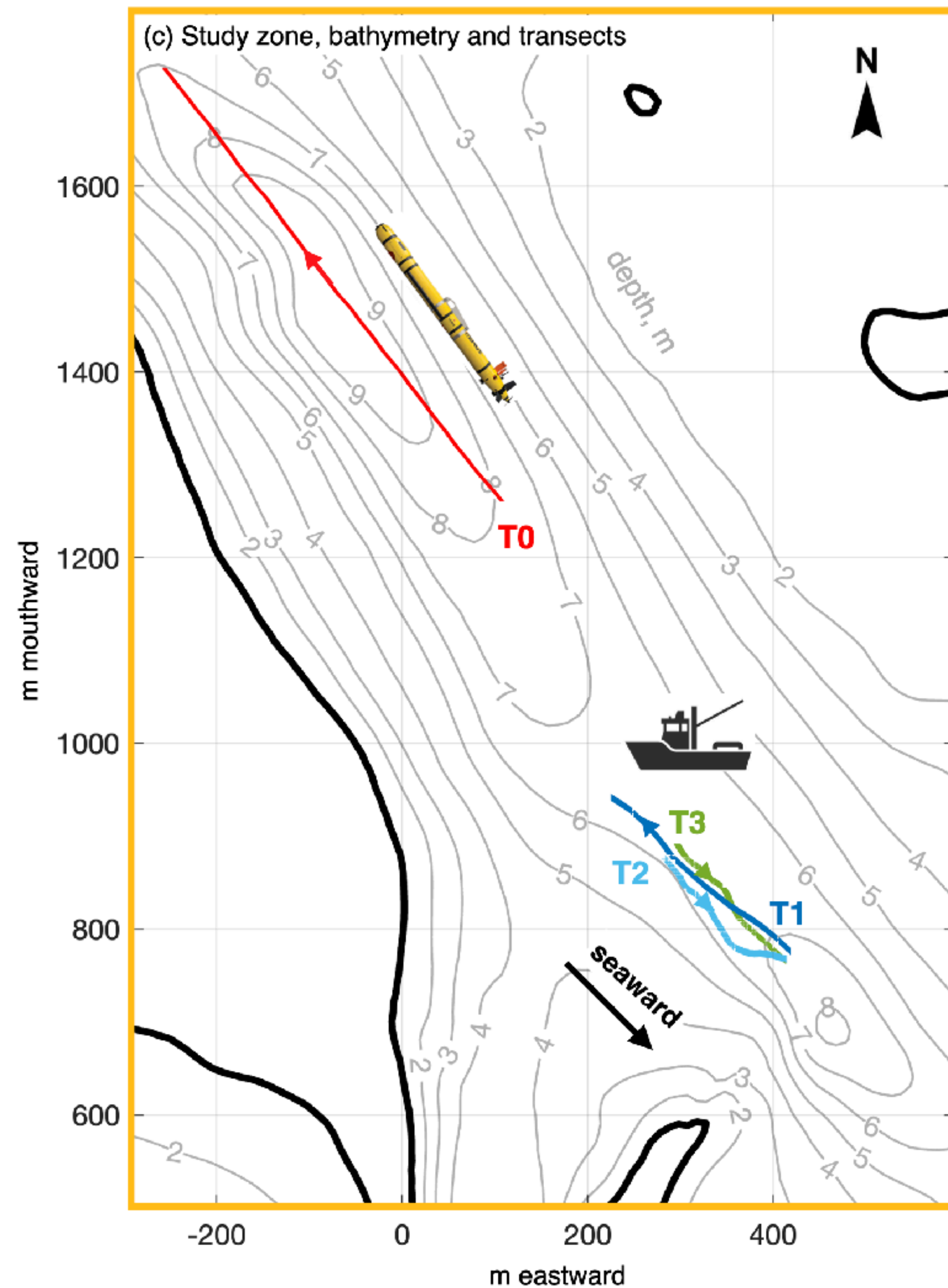
Baroclinic shear production

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

$\rightarrow Ri_g = \frac{N^2}{S^2}$ drops $\rightarrow$ instability



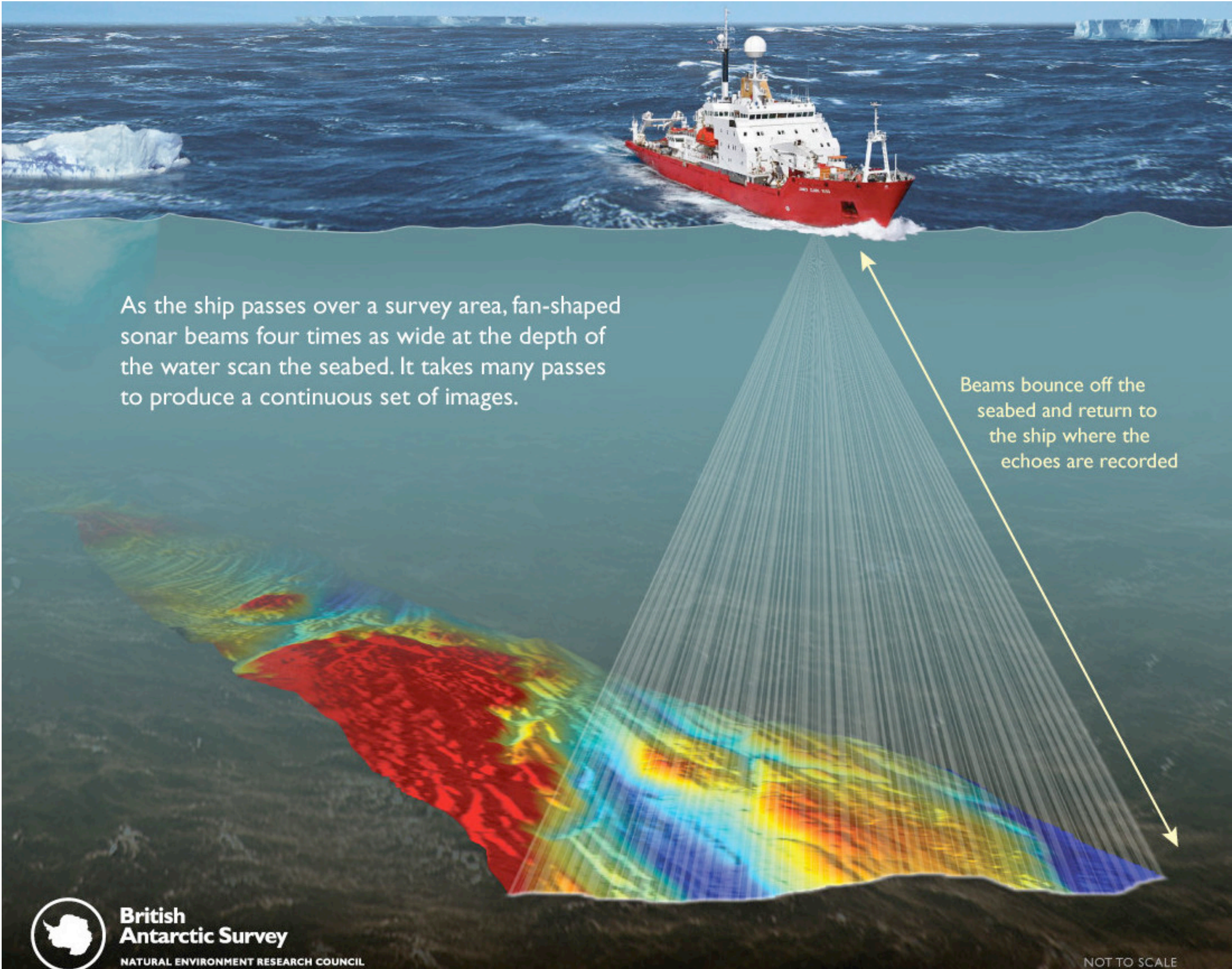
Shipboard transects: add velocity and salinity measurements



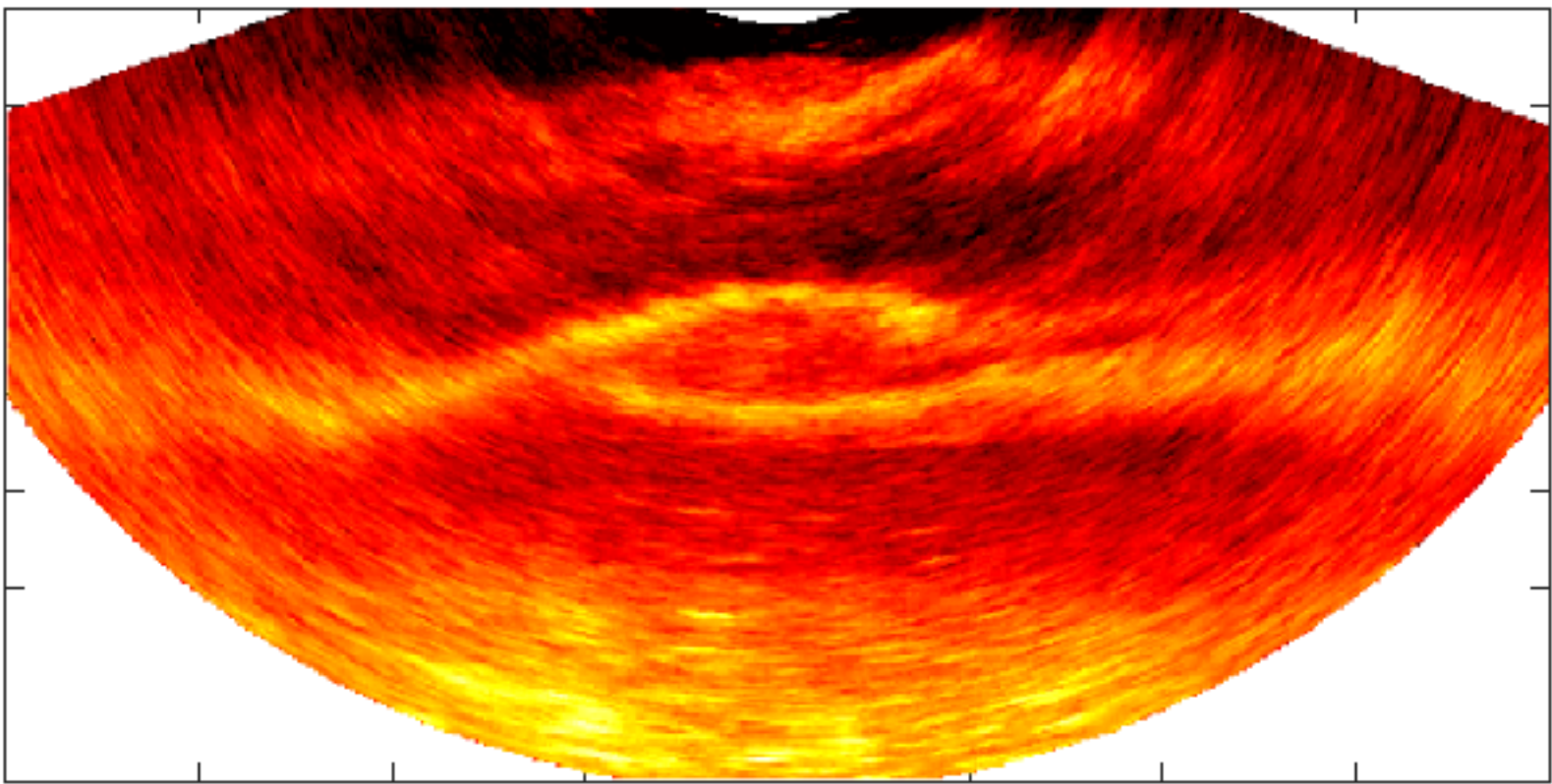
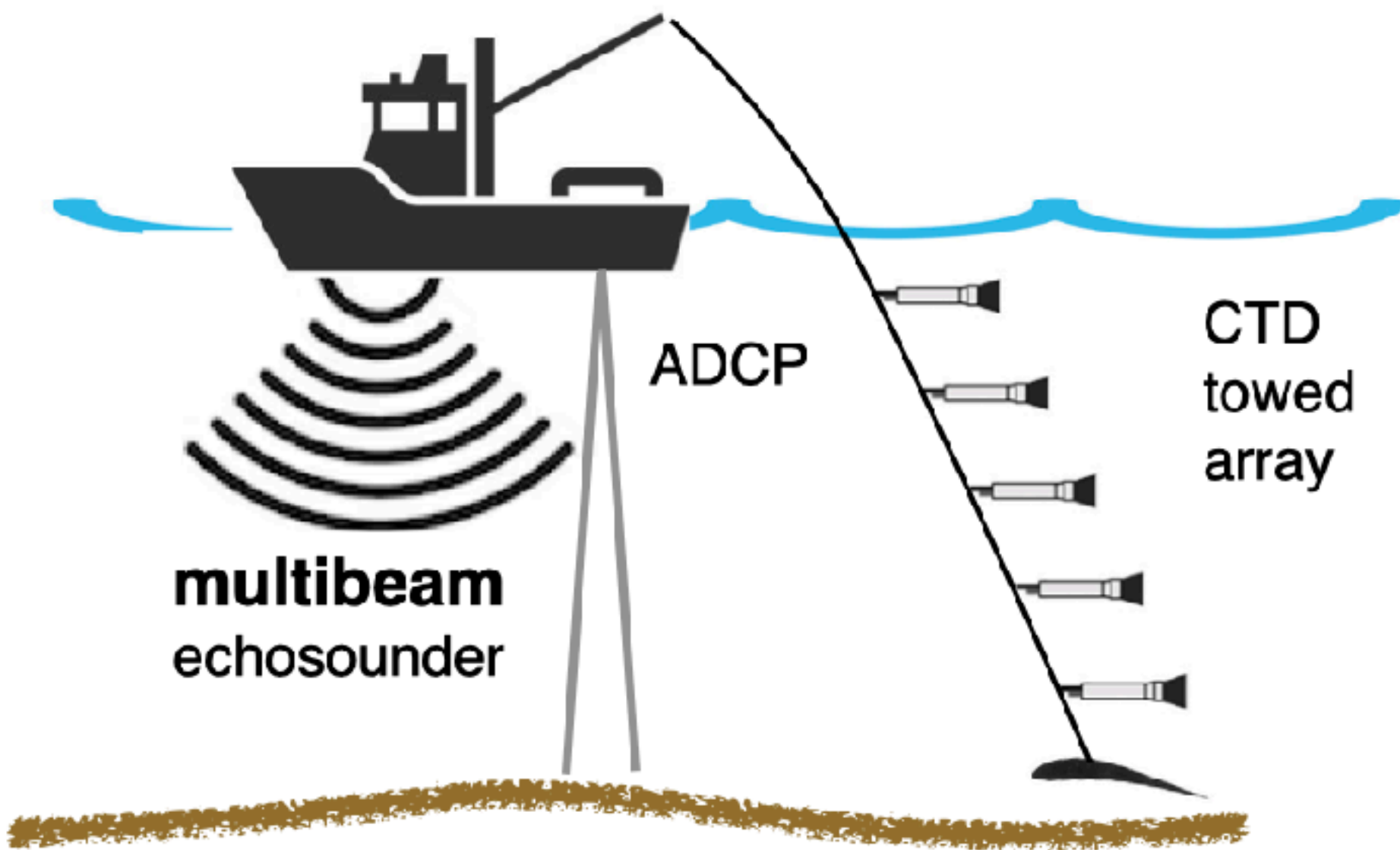
Combine 75 beams to create a 120 degree fan

Game changer: MULTIBEAM echosounder

Typical bathymetric survey: cross-track alignment

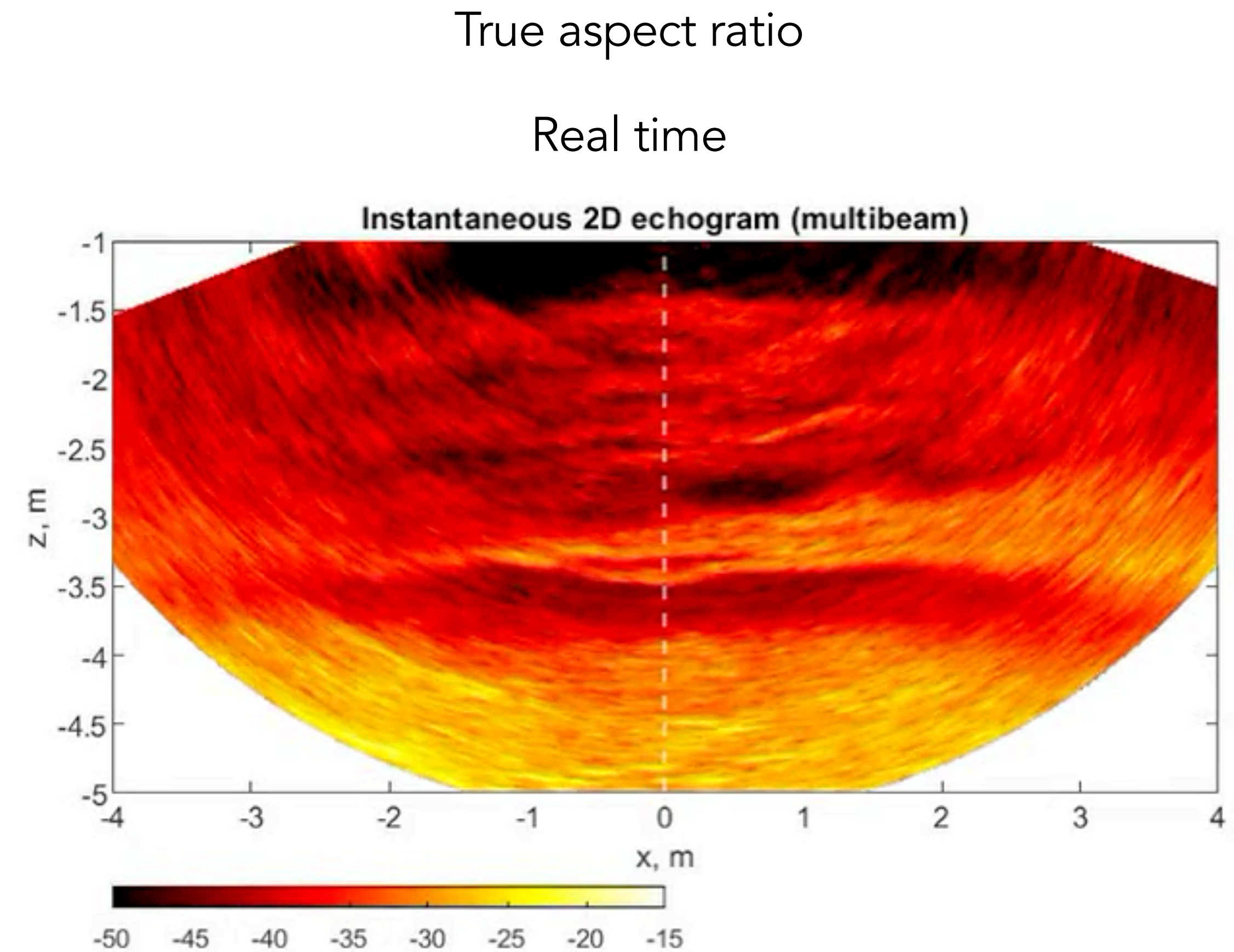
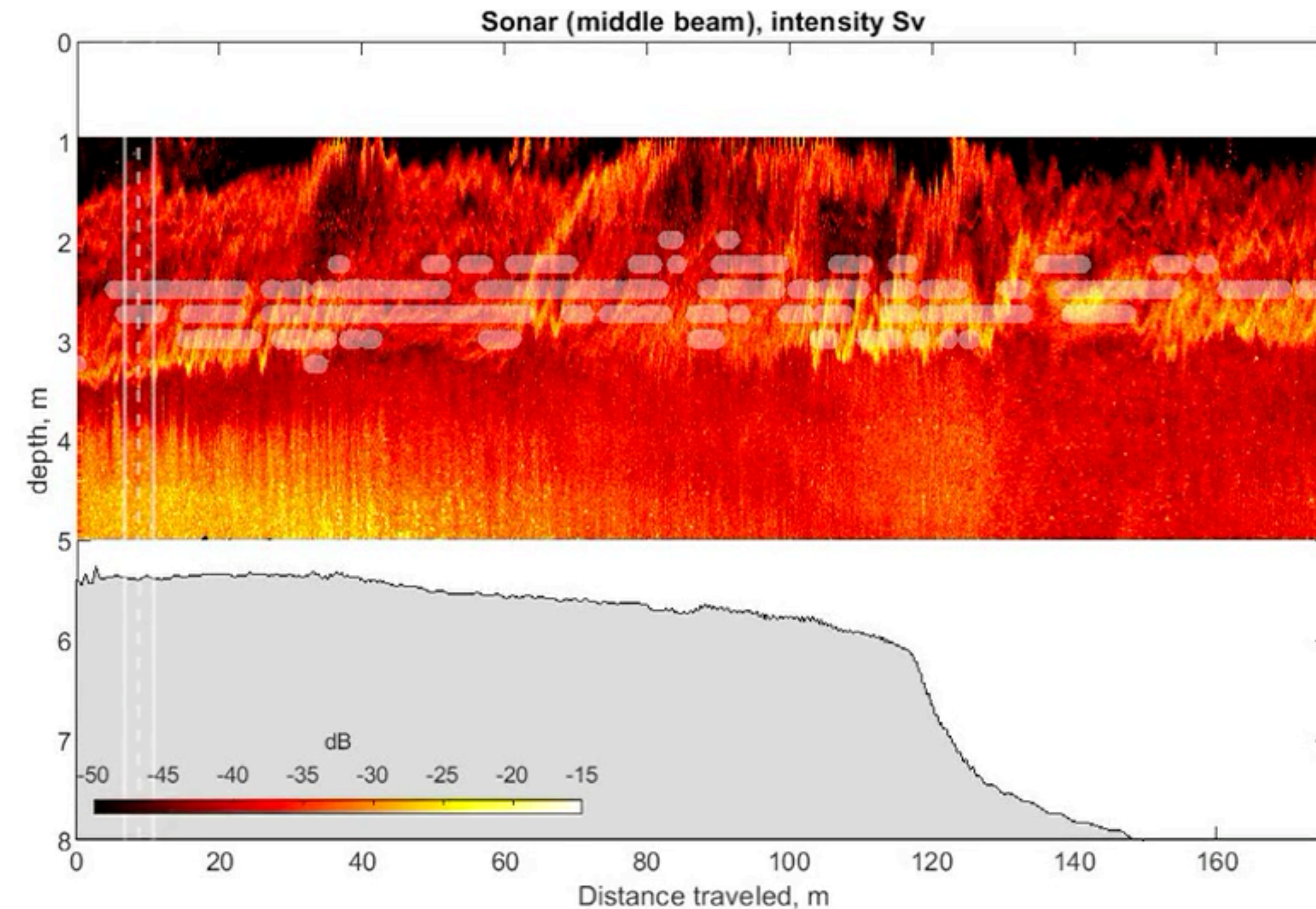


Our setup for shear instabilities: fore-aft alignment



Combine 75 beams to create a 120 degree fan

Key observations: bright braids, dark cores,
moderate braid slopes, rare overturns



MULTIBEAM echosounder to reveal the true structure of mixing

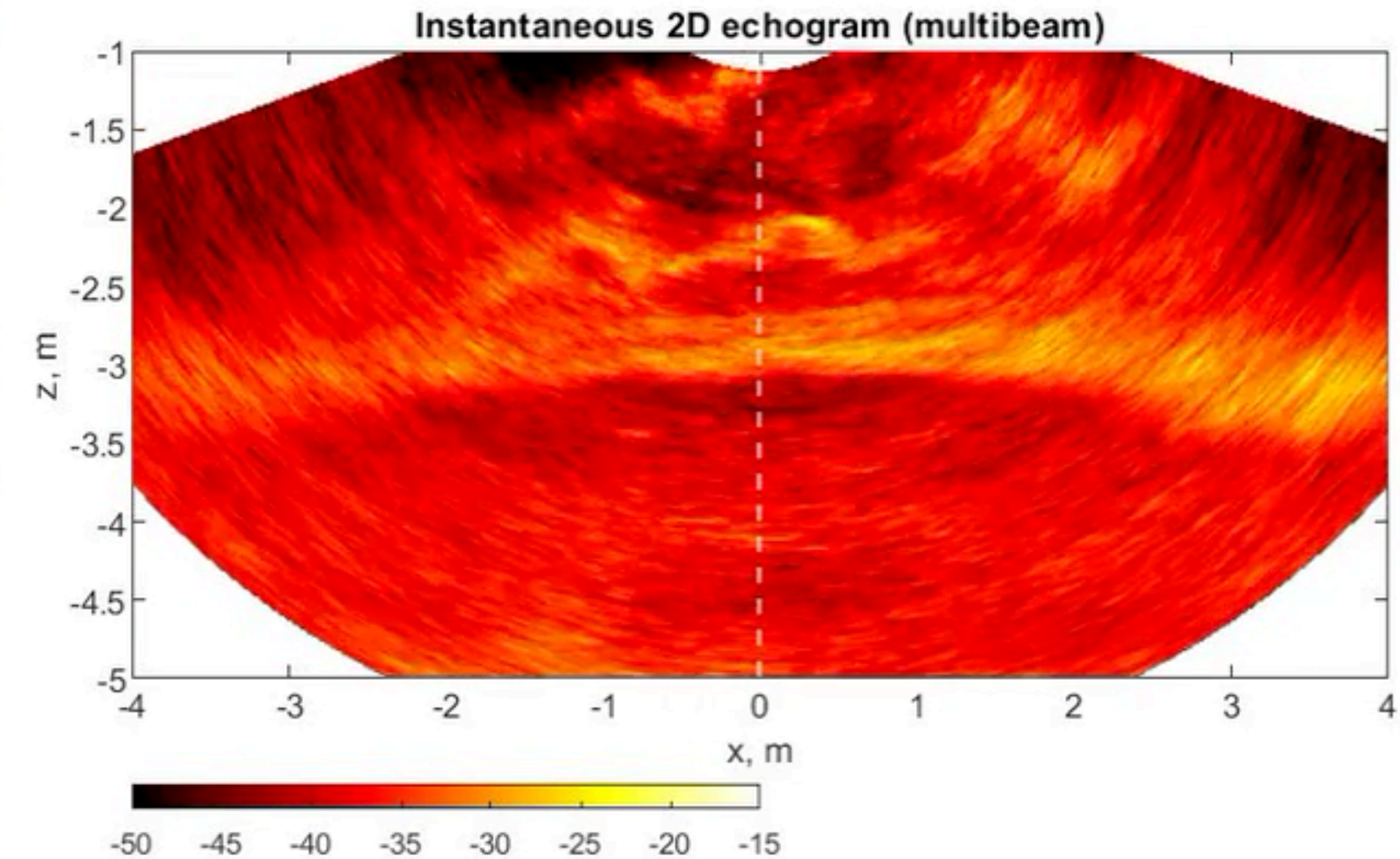
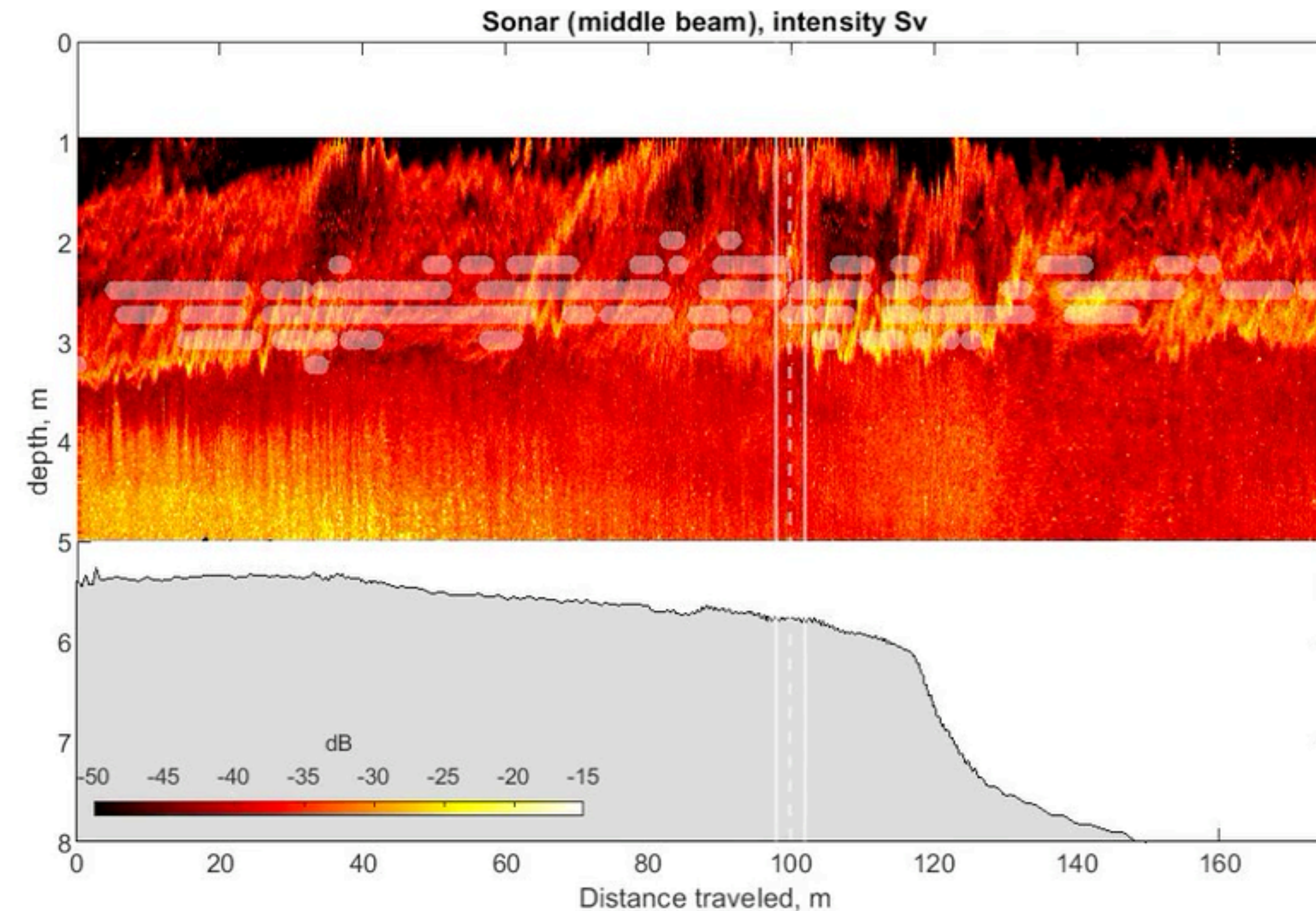
Sequence 2

Key observations: bright braids, dark cores, moderate braid slopes, rare overturns



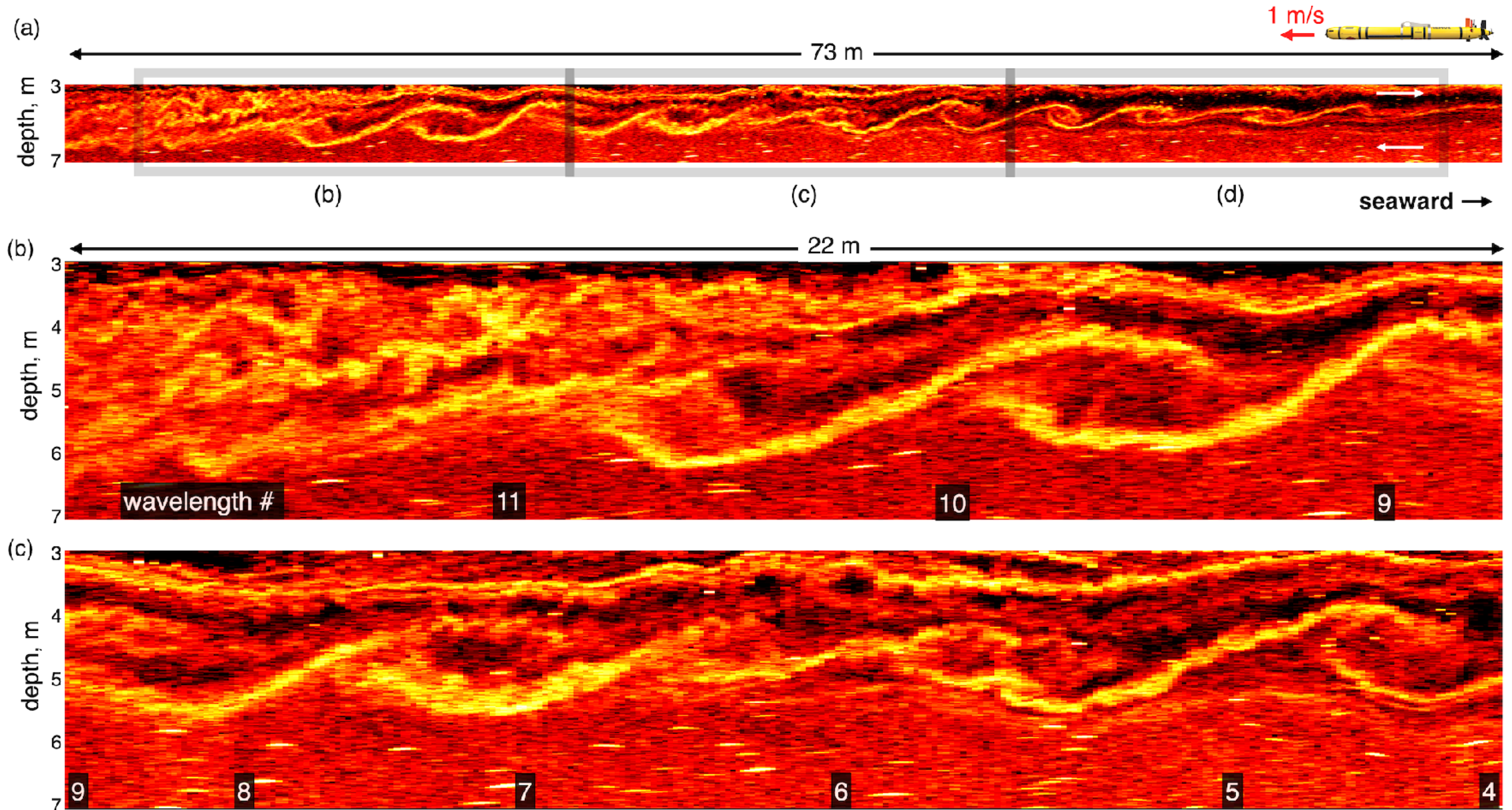
True aspect ratio

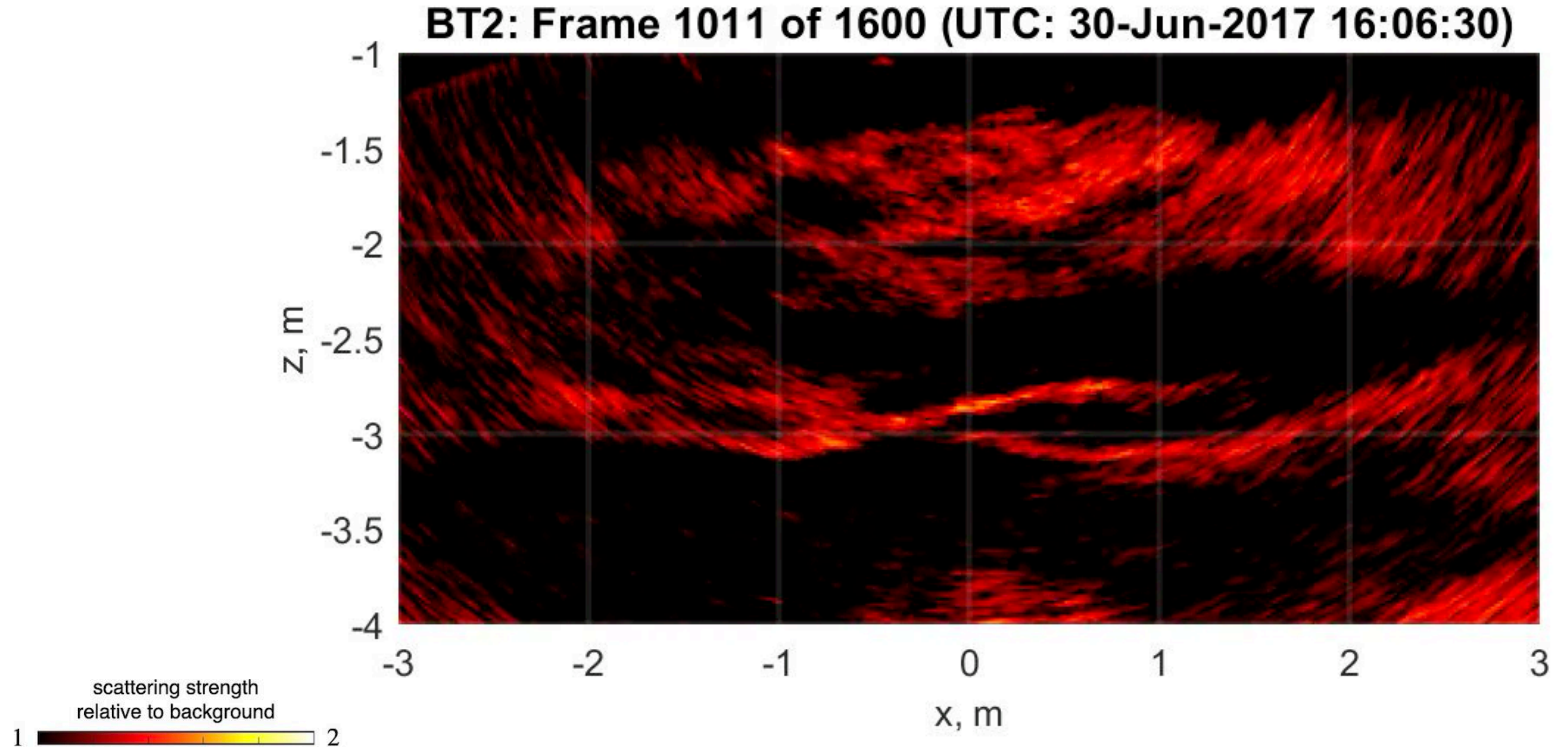
Real time



Evidence of secondary shear instability

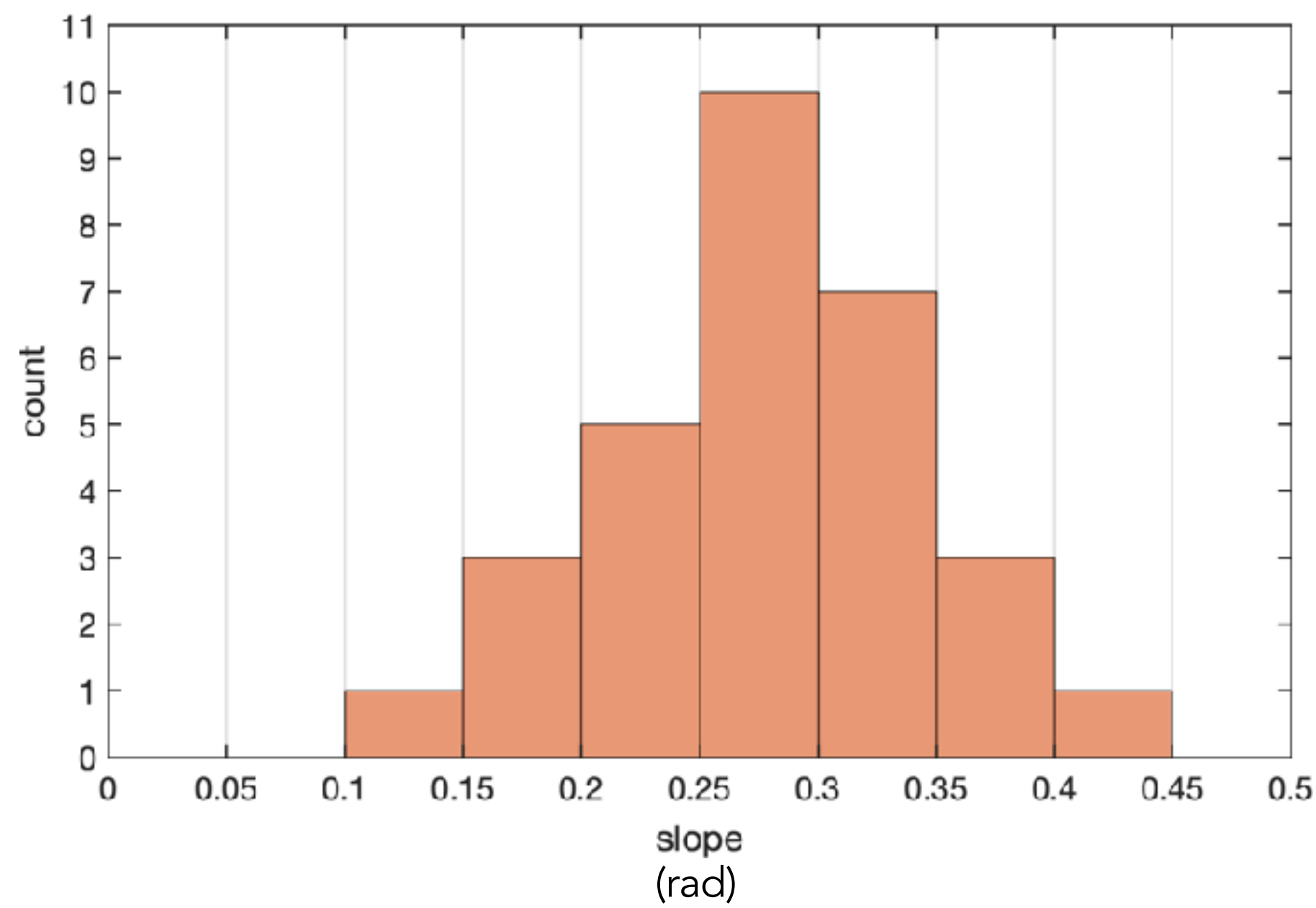
Back to the AUV data



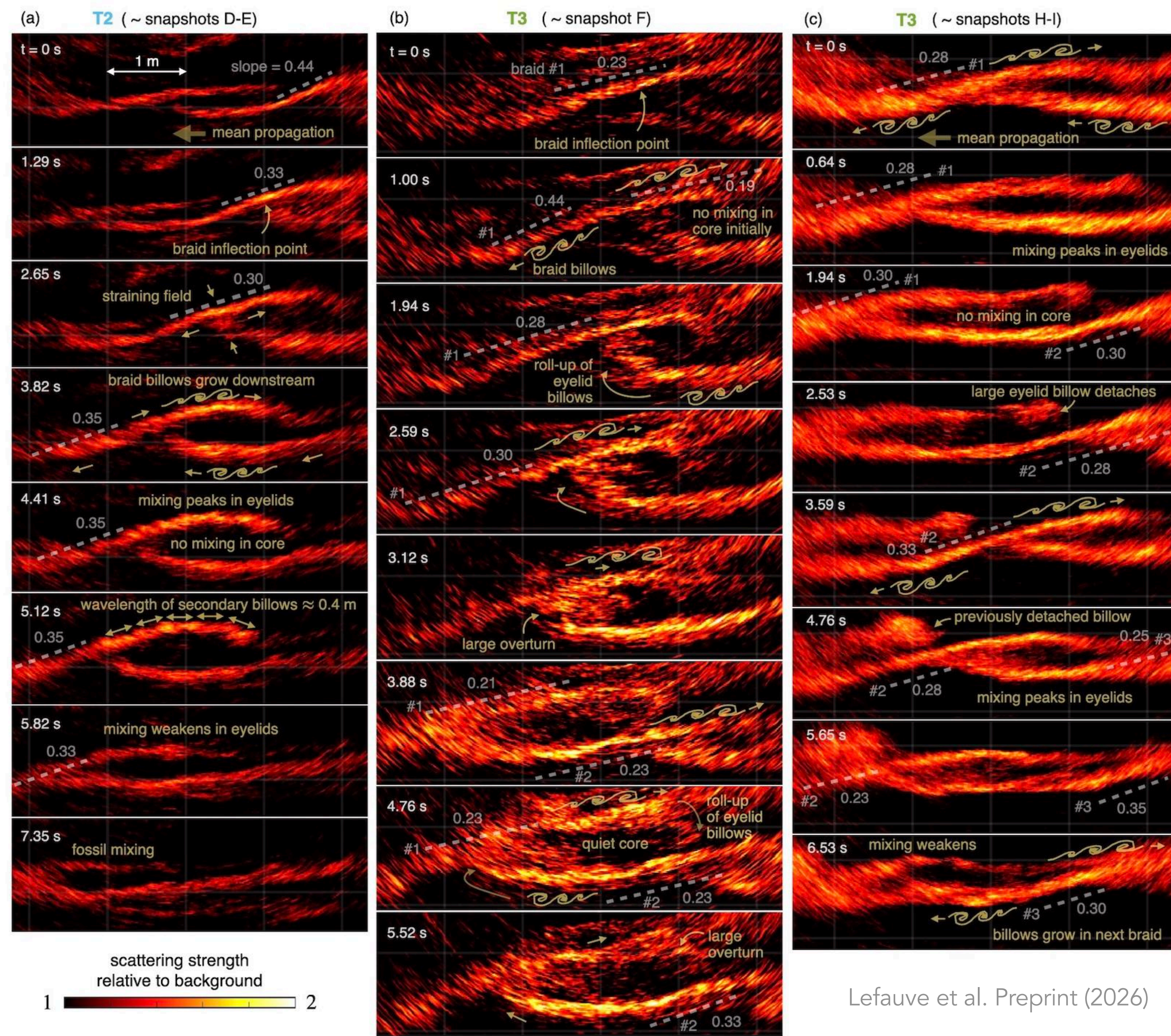


Lifecycle of shear instabilities

Measured slopes in 30 shear instabilities
→ braids remain **too shallow to overturn**

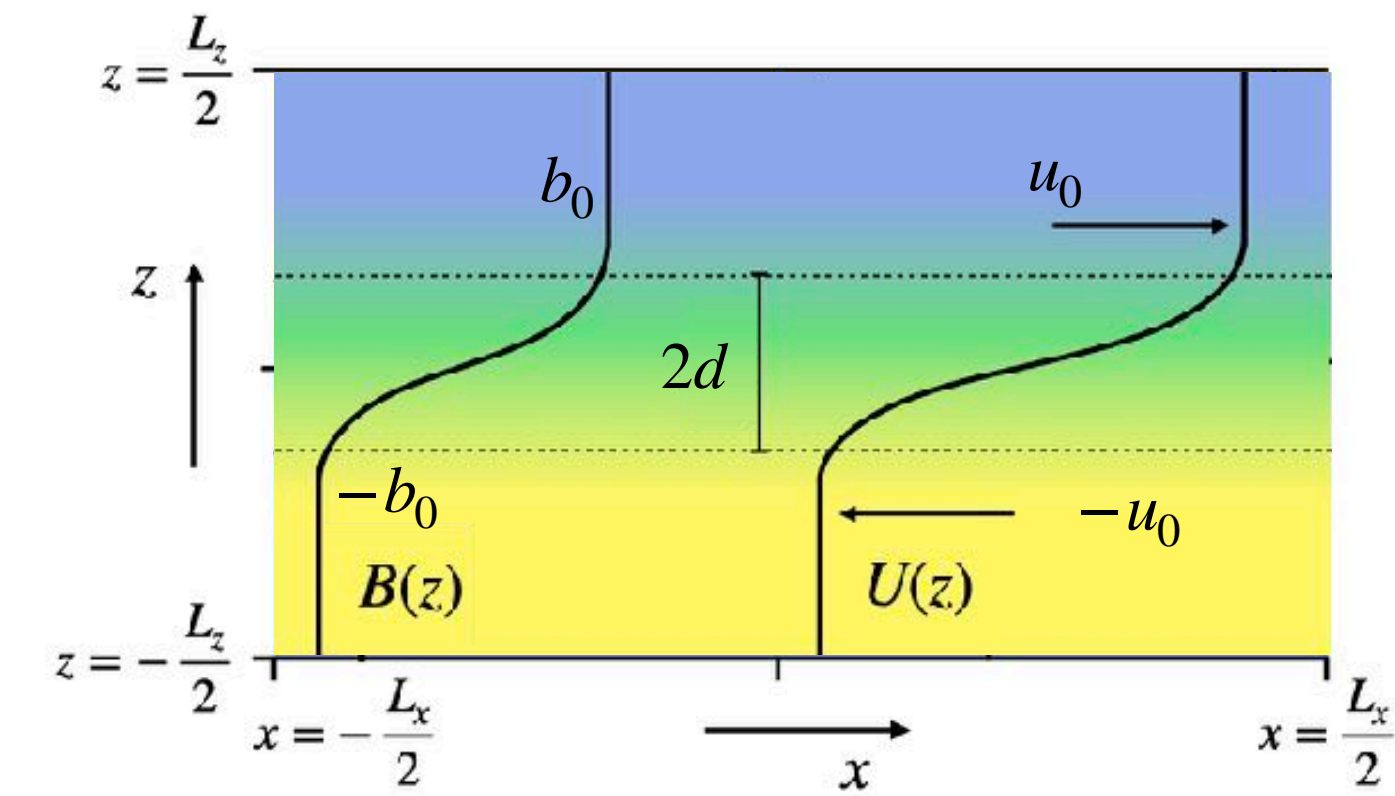


Second part of the talk:
Why are secondary shear instabilities triggered early and cause braid turbulence and mixing **before** primary core overturn?



Two-dimensional simulations of Kelvin-Helmholtz instability at high Reynolds number

Flow and domain



Dimensionless parameters

Reynolds	Richardson	Prandtl
$\text{Re} = \frac{u_0 d}{\nu}$,	$\text{Ri} = \frac{b_0 d}{u_0^2}$,	$\text{Pr} = \frac{\nu}{\kappa} = 1$,

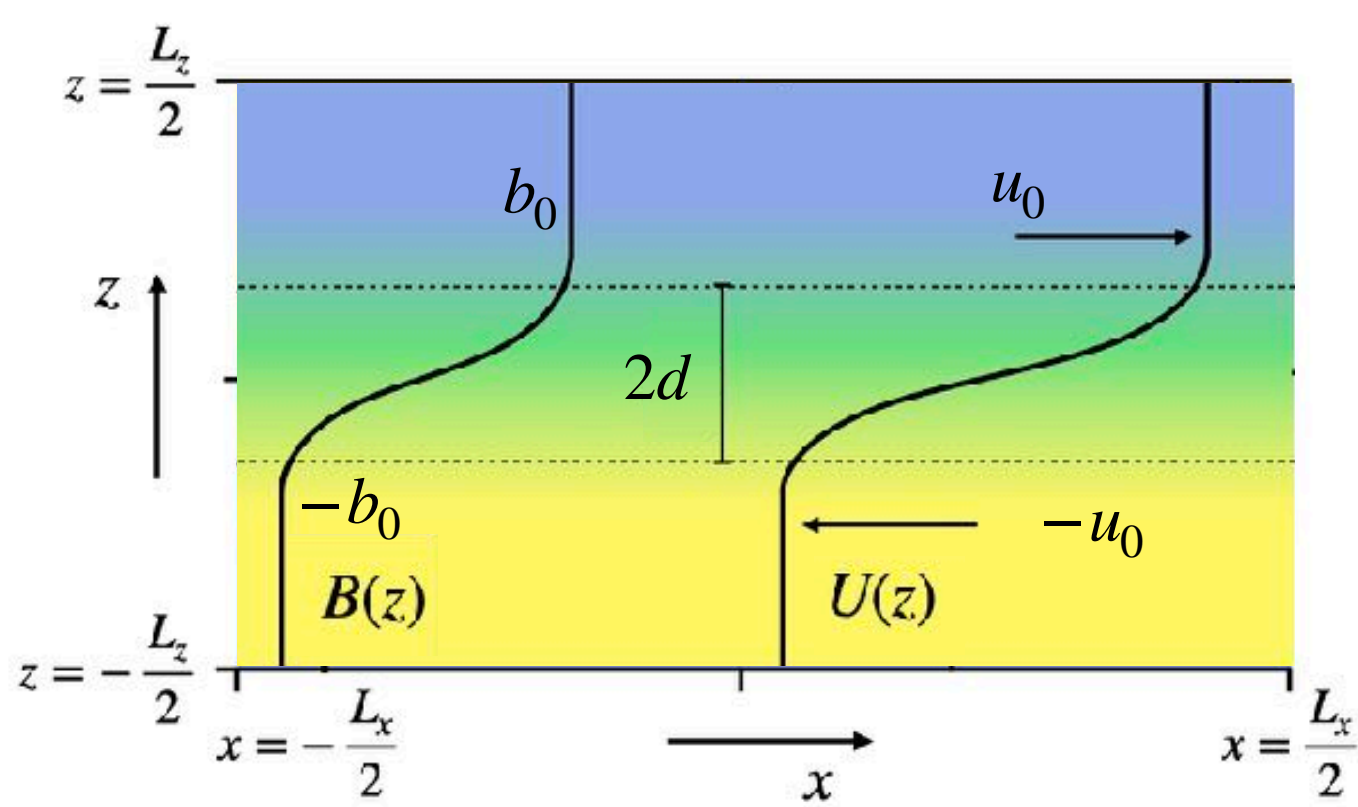
Governing equations

$$\nabla \cdot \mathbf{u} = 0, \quad \frac{D\mathbf{u}}{Dt} = -\nabla p + \text{Ri} \, b \, \hat{\mathbf{z}} + \frac{1}{\text{Re}} \nabla^2 \mathbf{u},$$
$$\mathbf{u}(z, t = 0) = \tanh(z) \, \hat{\mathbf{x}},$$

$$\frac{Db}{Dt} = \frac{1}{\text{Re} \, \text{Pr}} \nabla^2 b,$$
$$b(z, t = 0) = \tanh(z).$$

Two-dimensional simulations of Kelvin-Helmholtz instability at high Reynolds number

Flow and domain



Dimensionless parameters

Reynolds

Richardson

Prandtl

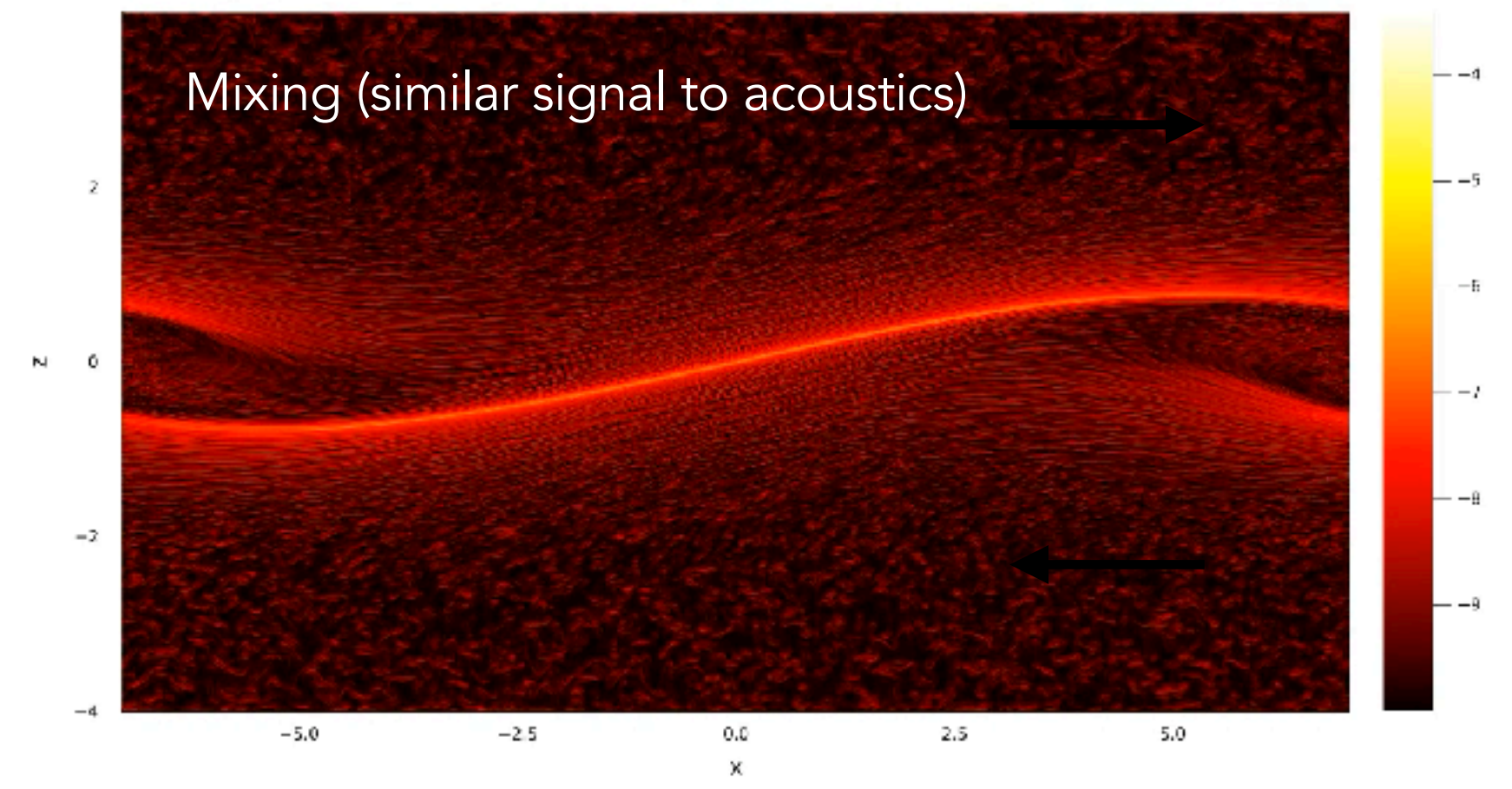
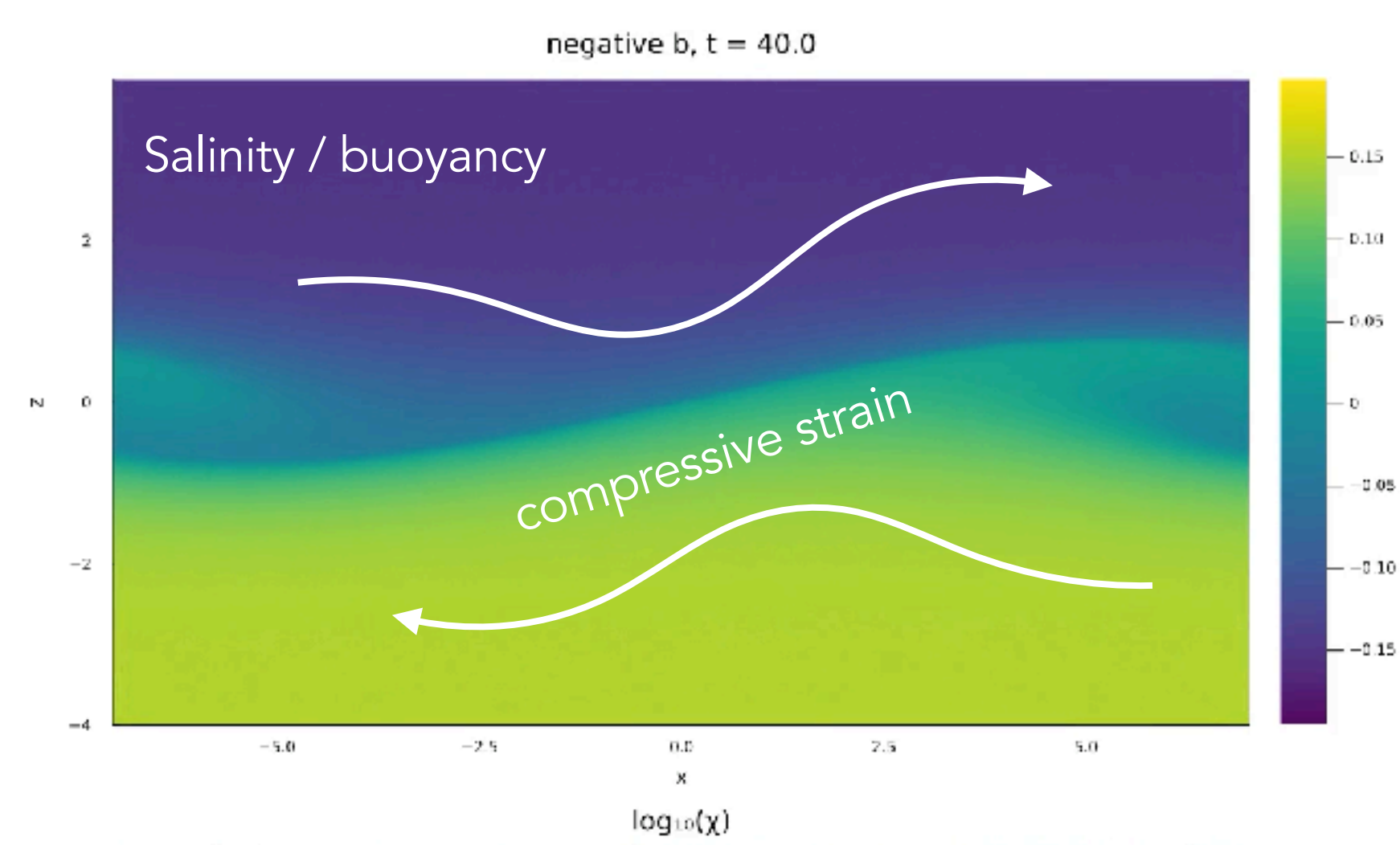
$$\text{Re} = \frac{u_0 d}{\nu}, \quad \text{Ri} = \frac{b_0 d}{u_0^2}, \quad \text{Pr} = \frac{\nu}{\kappa} = 1,$$

Governing equations

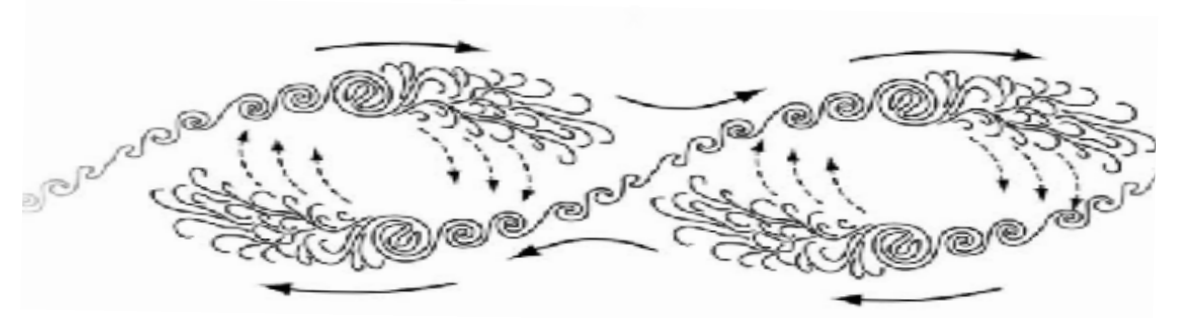
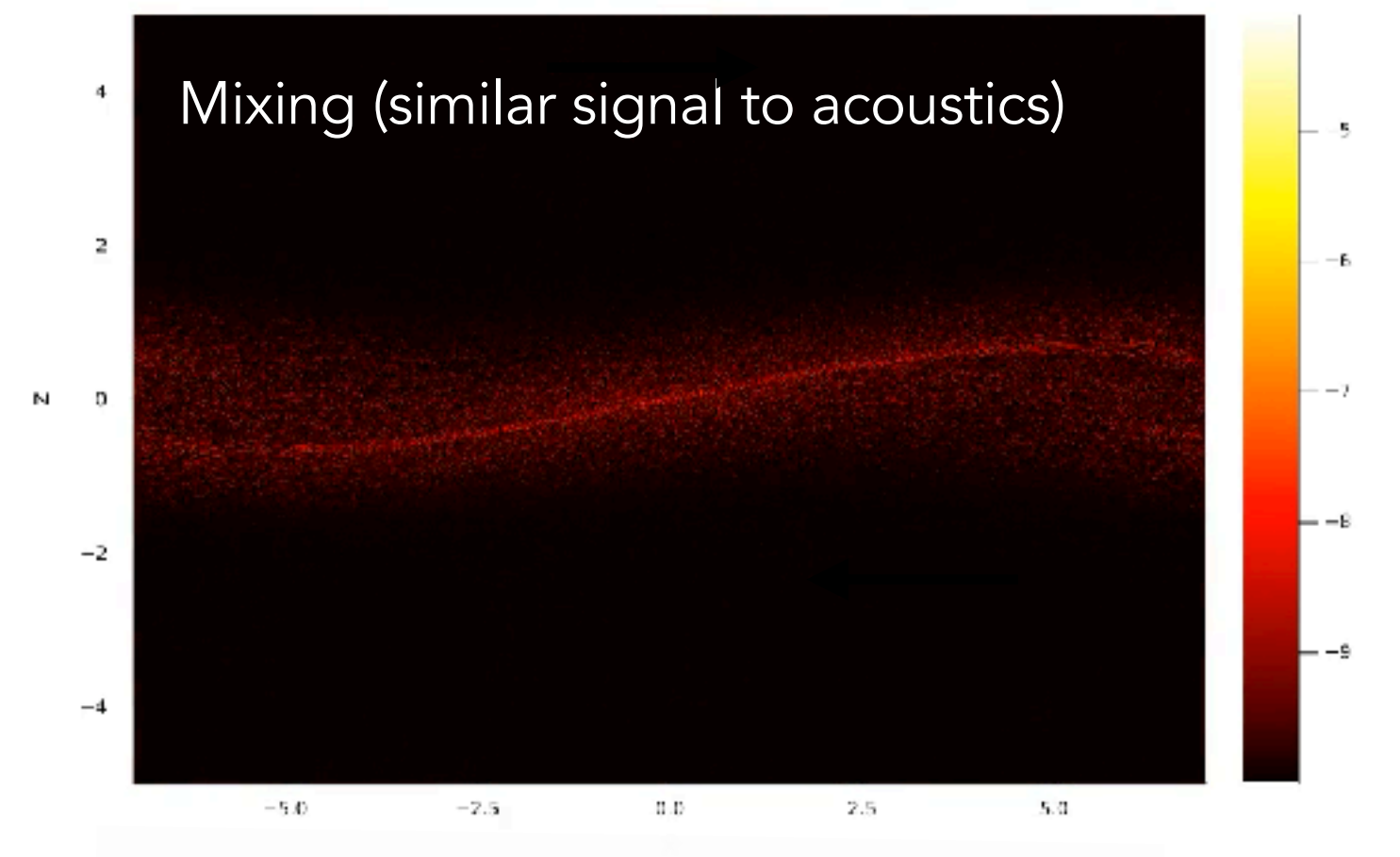
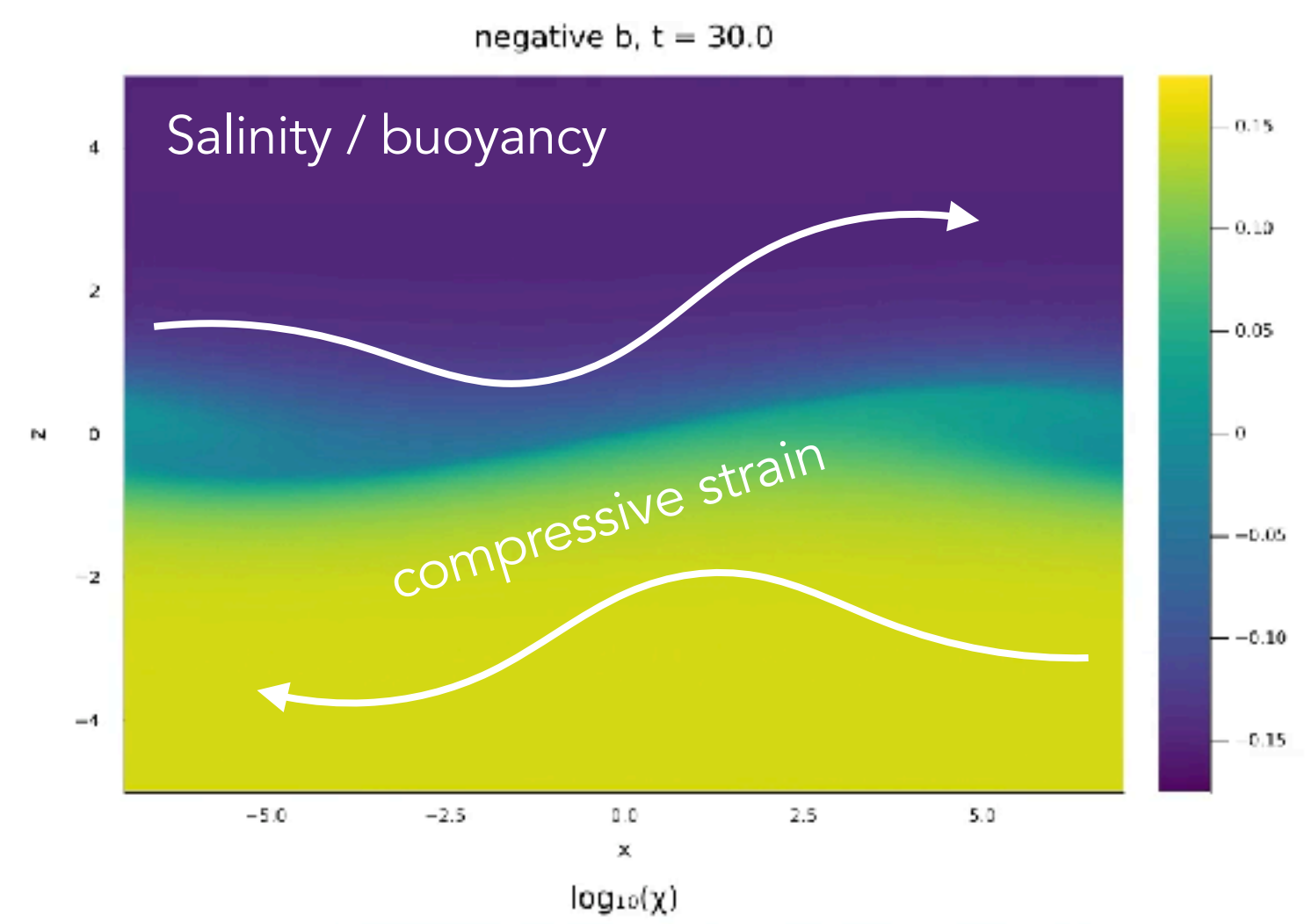
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$$\mathbf{u}(z, t = 0) = \tanh(z) \, \hat{\mathbf{x}},$$

$$\frac{Db}{Dt} = \frac{1}{\text{Re} \, \text{Pr}} \nabla^2 b,$$
$$b(z, t = 0) = \tanh(z).$$

Low Reynolds number

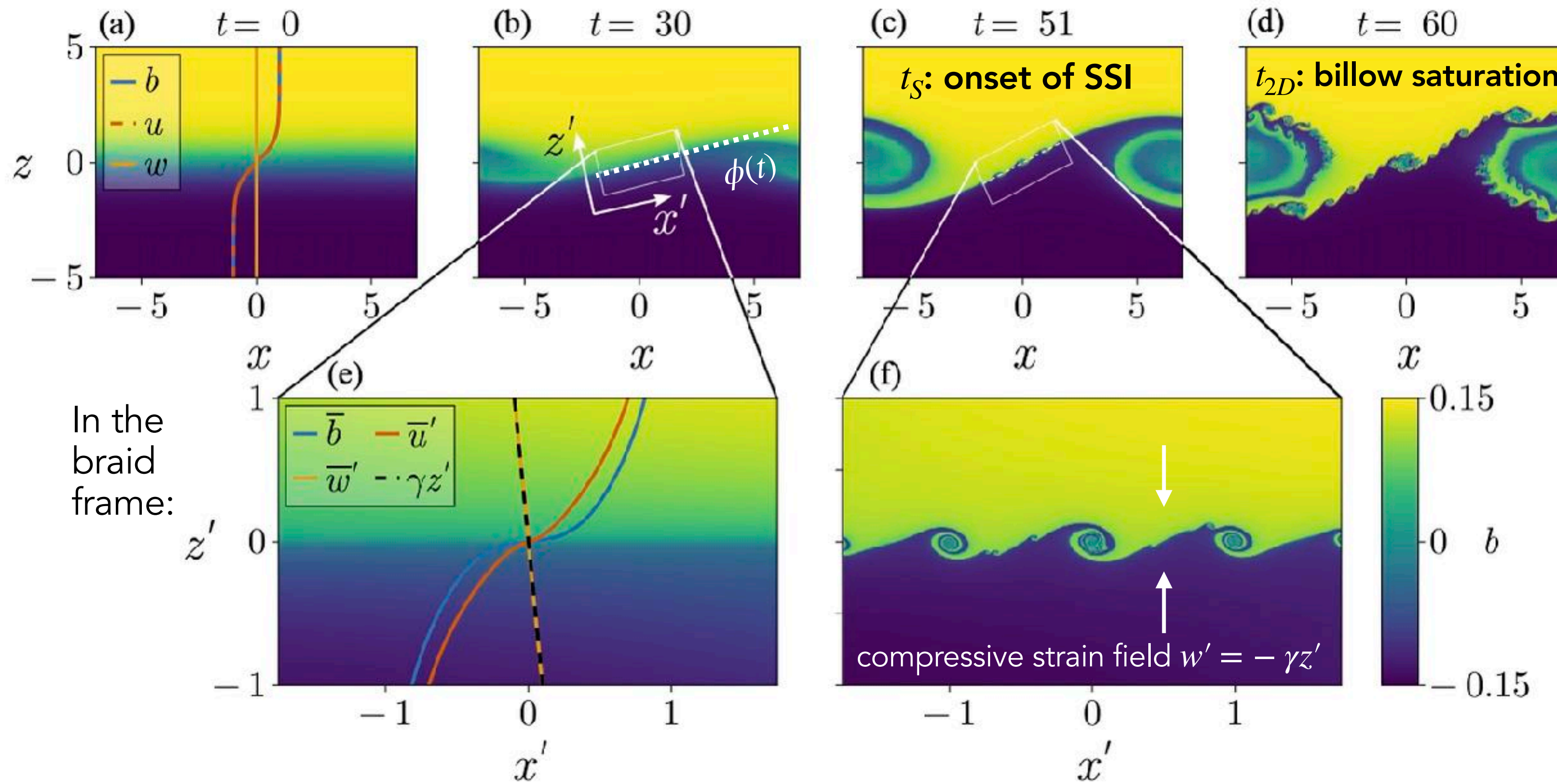


High Reynolds number



Braid evolution model

Existing literature on secondary shear instability focused on equilibrium at t_{2D} , not the braid evolution



As the braid steepens:

Local buoyancy field

$$\frac{\partial b}{\partial t} \approx \underbrace{\gamma z'}_{\text{strain}} \frac{\partial b}{\partial z'} + \underbrace{\frac{1}{\text{Re Pr}} \frac{\partial^2 b}{\partial z'^2}}_{\text{diffusivity}},$$

Local vorticity (shear)

$$\frac{\partial \Omega}{\partial t} \approx \underbrace{\gamma z'}_{\text{strain}} \frac{\partial \Omega}{\partial z'} + \underbrace{\text{Ri} \sin \phi \frac{\partial b}{\partial z'}}_{\text{baroclinicity}} + \underbrace{\frac{1}{\text{Re}} \frac{\partial^2 \Omega}{\partial z'^2}}_{\text{viscosity}}.$$

Inviscid model (similarity solution)

$\text{Re} \rightarrow \infty$

$$b = F\left(\frac{z'}{\delta(t)}\right) \quad \Omega = S(t) F'\left(\frac{z'}{\delta(t)}\right) \quad \text{where}$$

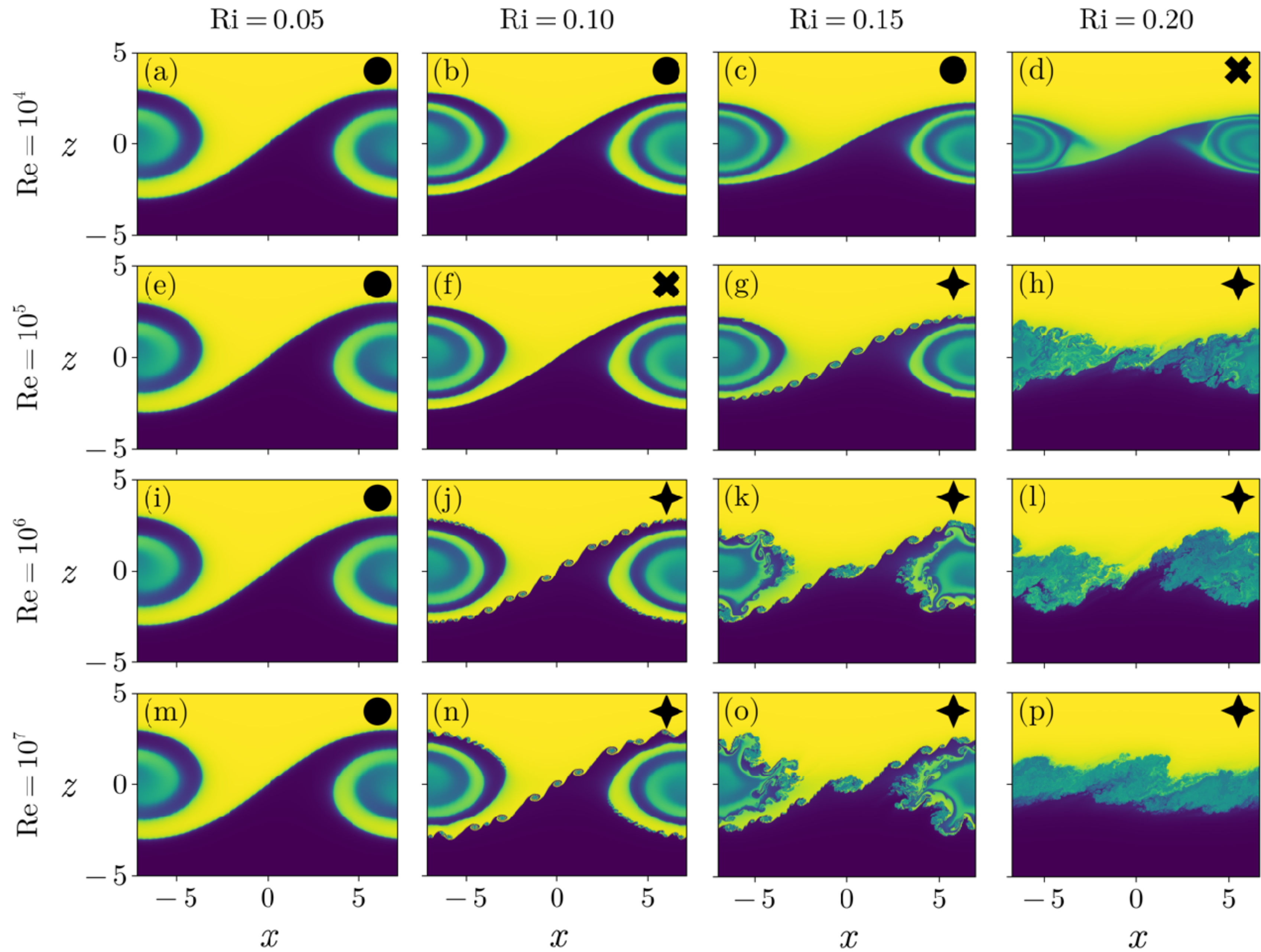
$$\frac{\partial \delta}{\partial t} = -\gamma \delta, \quad \frac{\partial S}{\partial t} = \frac{\text{Ri} \sin \phi}{\delta}.$$

Assume $\gamma(t) = \gamma_1 t + \gamma_0$ and $\phi(t) = \phi_1 t + \phi_0$

$$\left\{ \begin{array}{ll} \text{Braid thickness} & \delta(t) = \exp \left[- \int_0^t \gamma(\tau) d\tau \right] = \exp \left[-\frac{1}{2} \gamma_1 t^2 - \gamma_0 t \right], \\ \text{Braid shear} & S(t) = S(0) + \int_0^t \text{Ri} \sin(\phi_1 \tau + \phi_0) \exp \left[\frac{1}{2} \gamma_1 \tau^2 + \gamma_0 \tau \right] d\tau. \end{array} \right.$$

Outcome in (Re, Ri) space

All images at time t_{2D} (billow saturation)



$$\frac{\partial \delta}{\partial t} = -\gamma \delta,$$

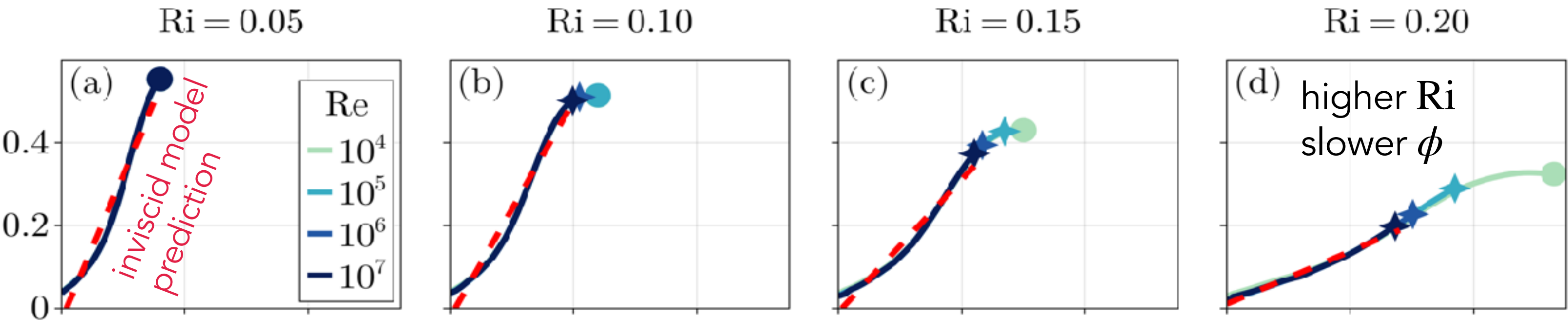
$$\frac{\partial S}{\partial t} = \frac{\text{Ri} \sin \phi}{\delta}.$$

SSI sets on
when
 $\frac{\gamma}{S} < 0.02$

(already suggested
in past studies)
Most likely a “non-
normal” instability
(transient growth)

The key physics
are inviscid

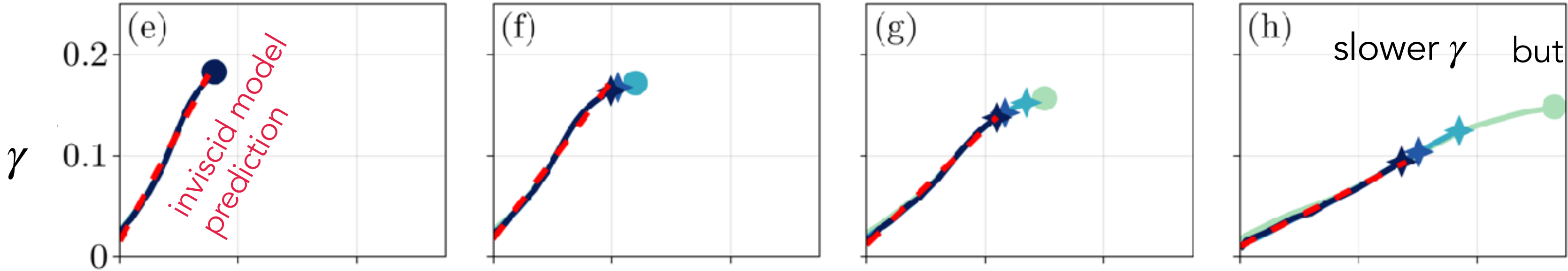
Braid angle



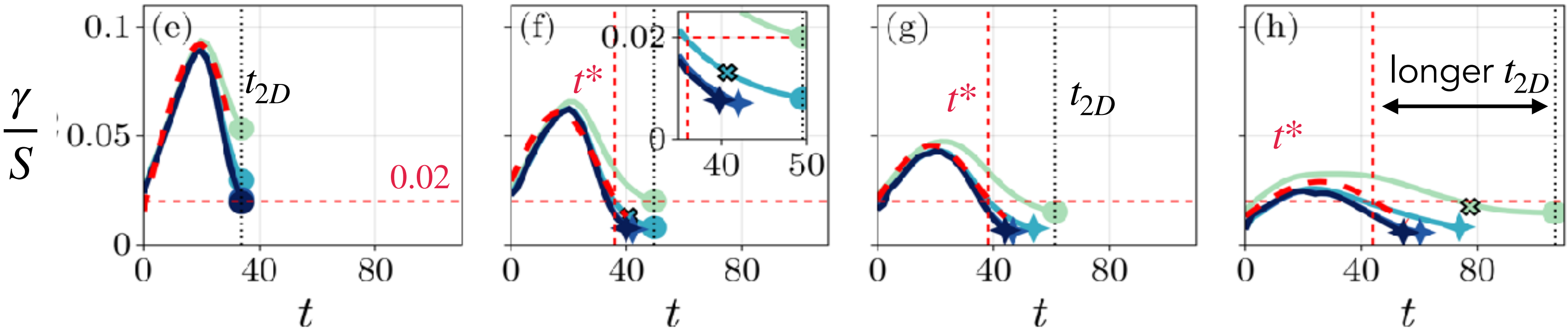
Inviscid model:

$$\frac{\partial S}{\partial t} = \frac{Ri \sin \phi}{\delta}.$$

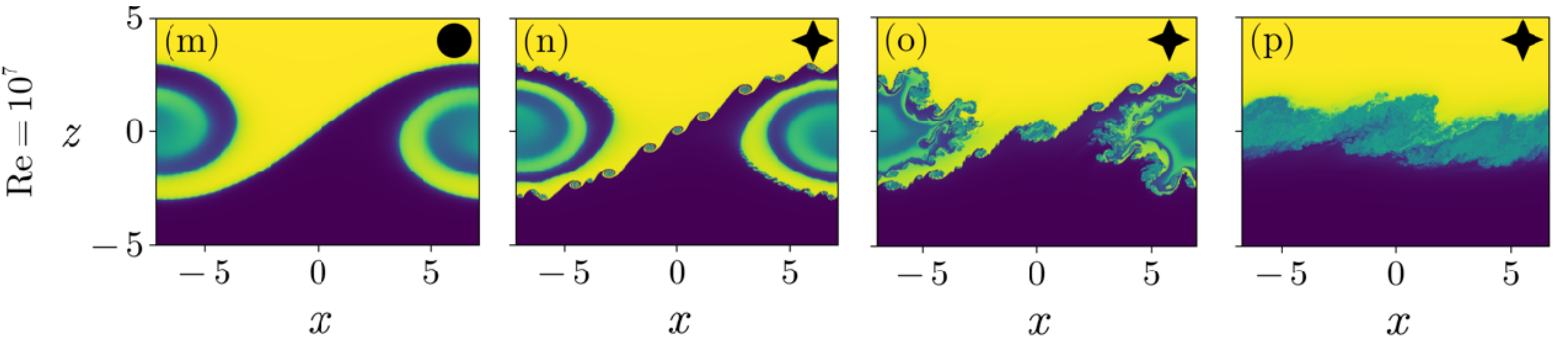
Braid strain



Strain-to-vorticity
ratio



Outcome at t_{2D}



→ at higher Ri
more time for SSI to
grow and transition
to turbulence
BEFORE t_{2D}

Effect of Reynolds number

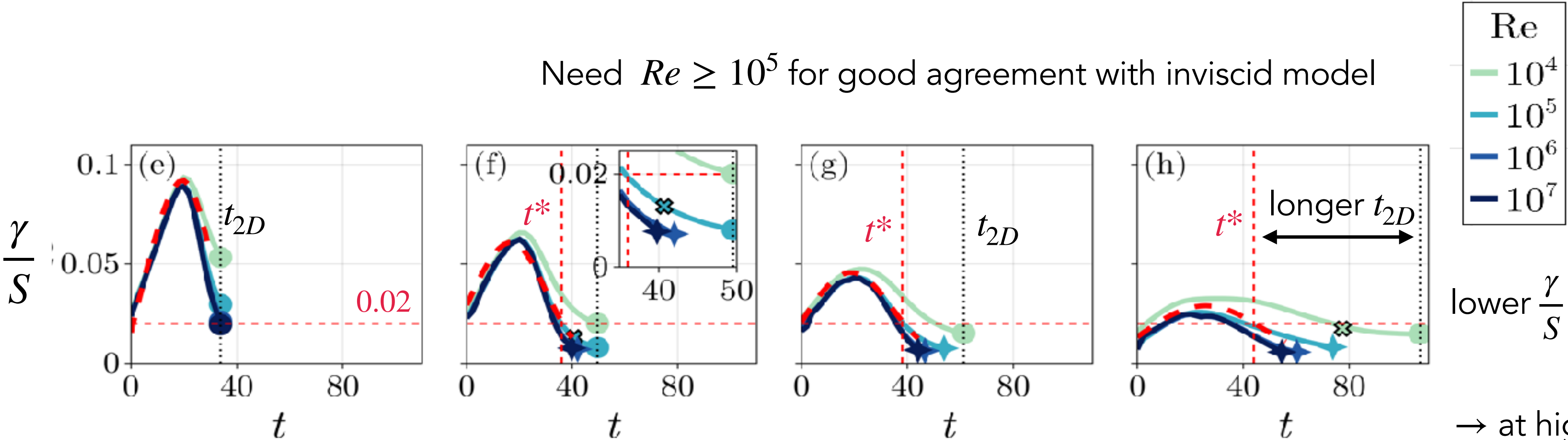
Inviscid model

$$\left\{ \begin{array}{l} \frac{\partial \delta}{\partial t} = -\gamma \delta, \\ \frac{\partial S}{\partial t} = \frac{\text{Ri} \sin \phi}{\delta}. \end{array} \right.$$

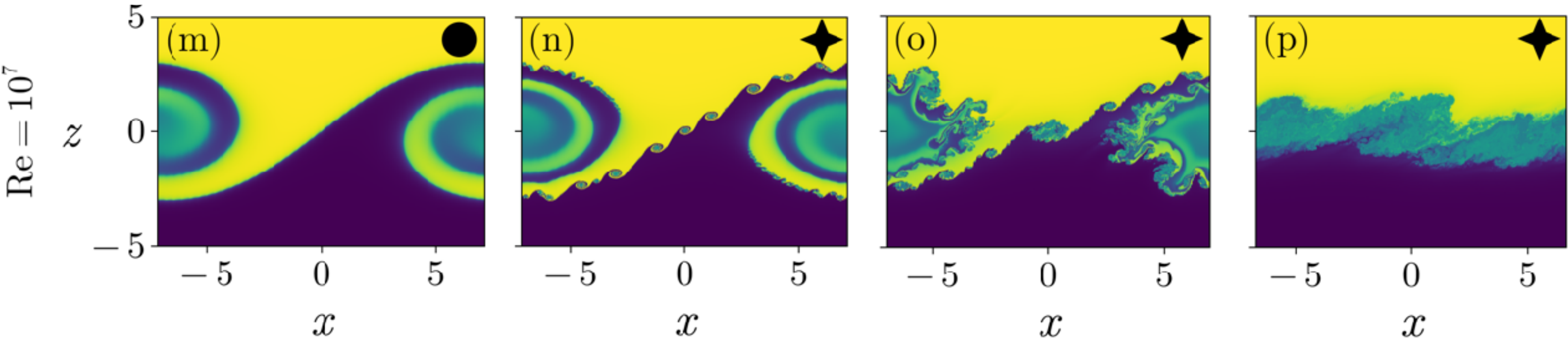
but **viscosity slows down and can halt the thinning of δ** $\rightarrow$ limits amplification of S and $\frac{\gamma}{S}$

Need $Re \geq 10^5$ for good agreement with inviscid model

Strain-to-vorticity ratio

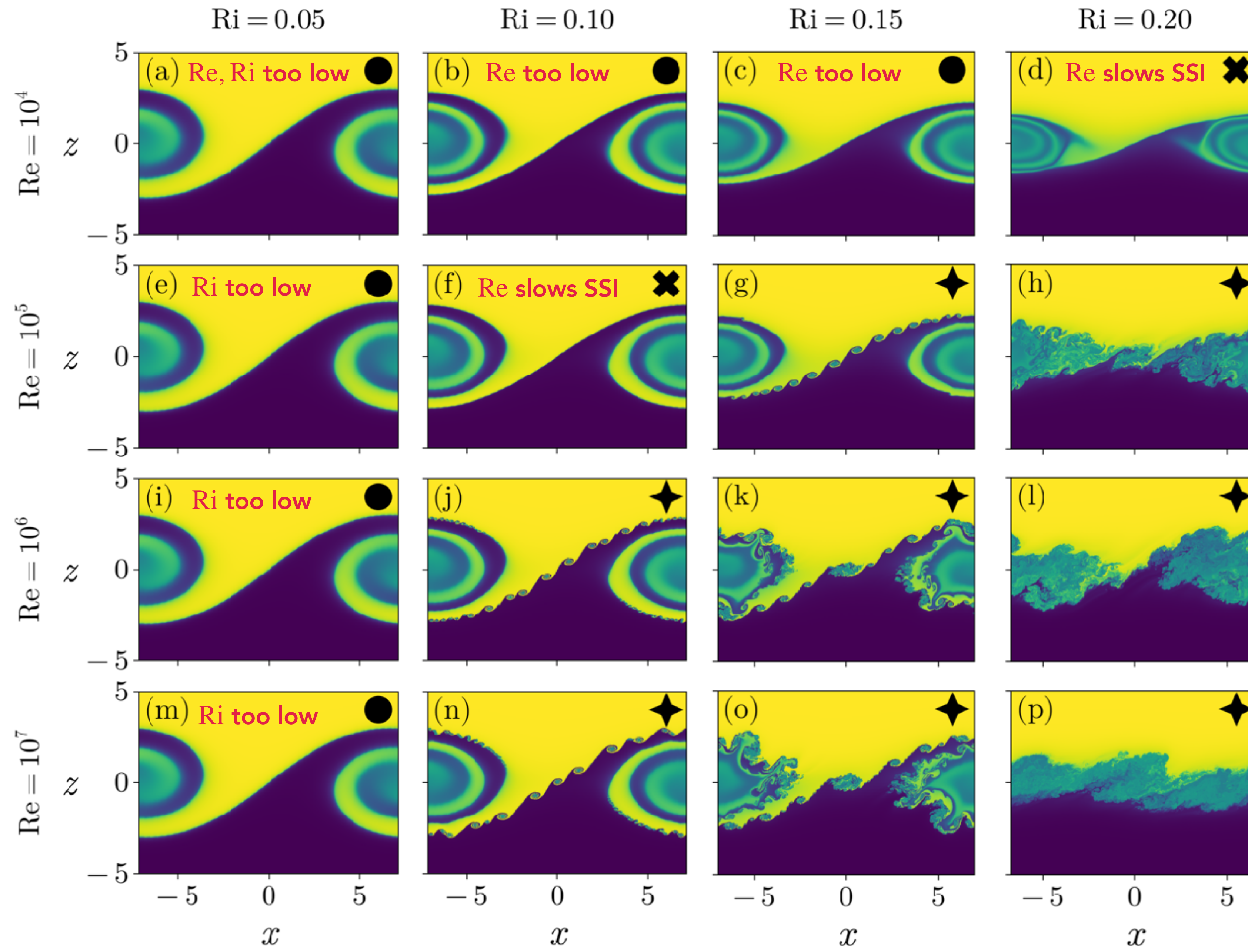


Outcome at t_{2D}



$\rightarrow$ at higher Ri
more time for SSI to
grow and transition
to turbulence
BEFORE t_{2D}

We can now understand the outcome in (Re, Ri) space

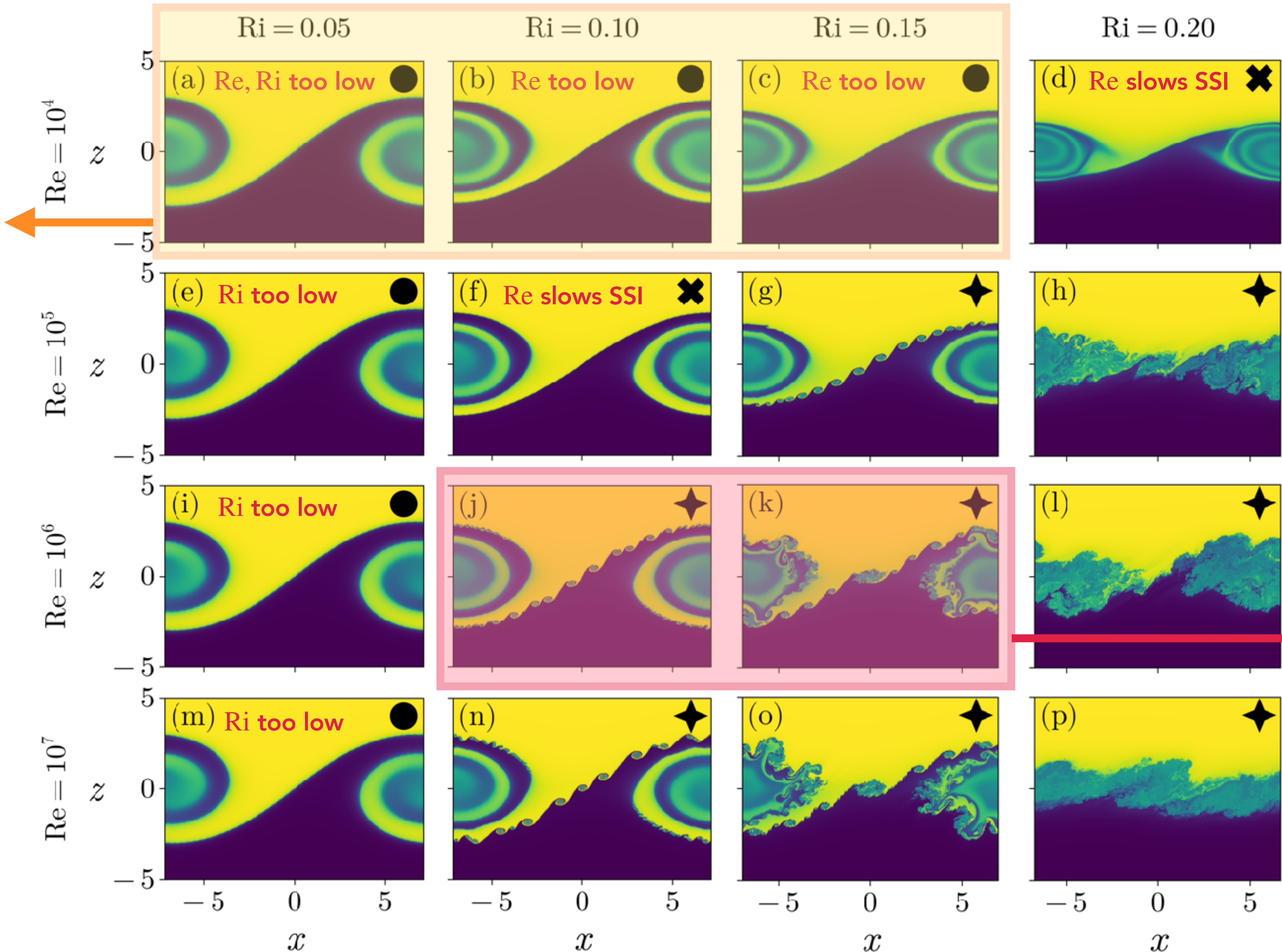


We can now understand the outcome in (Re, Ri) space

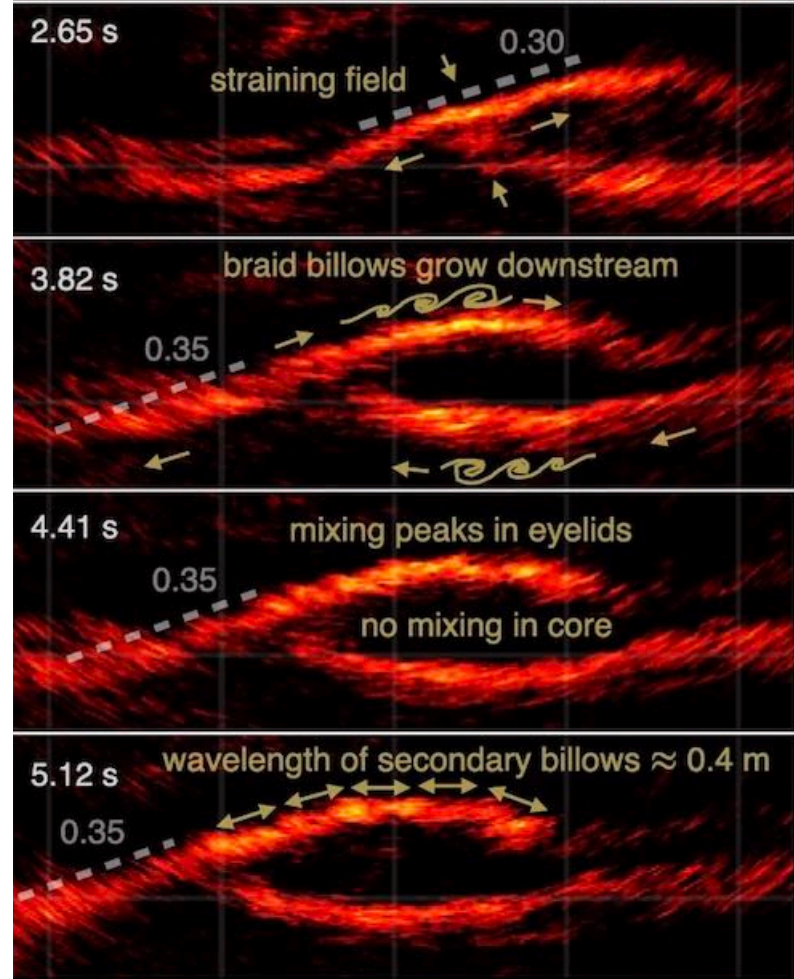
lab experiments



SSI is not expected



estuarine observations



early onset of SSI is expected

Bouckley, Lewin & Lefauve, arXiv (2026)

Braid mixing seems generic

Compilation of observations:

Shear layer thickness $d \sim 0.5 - 200$ m

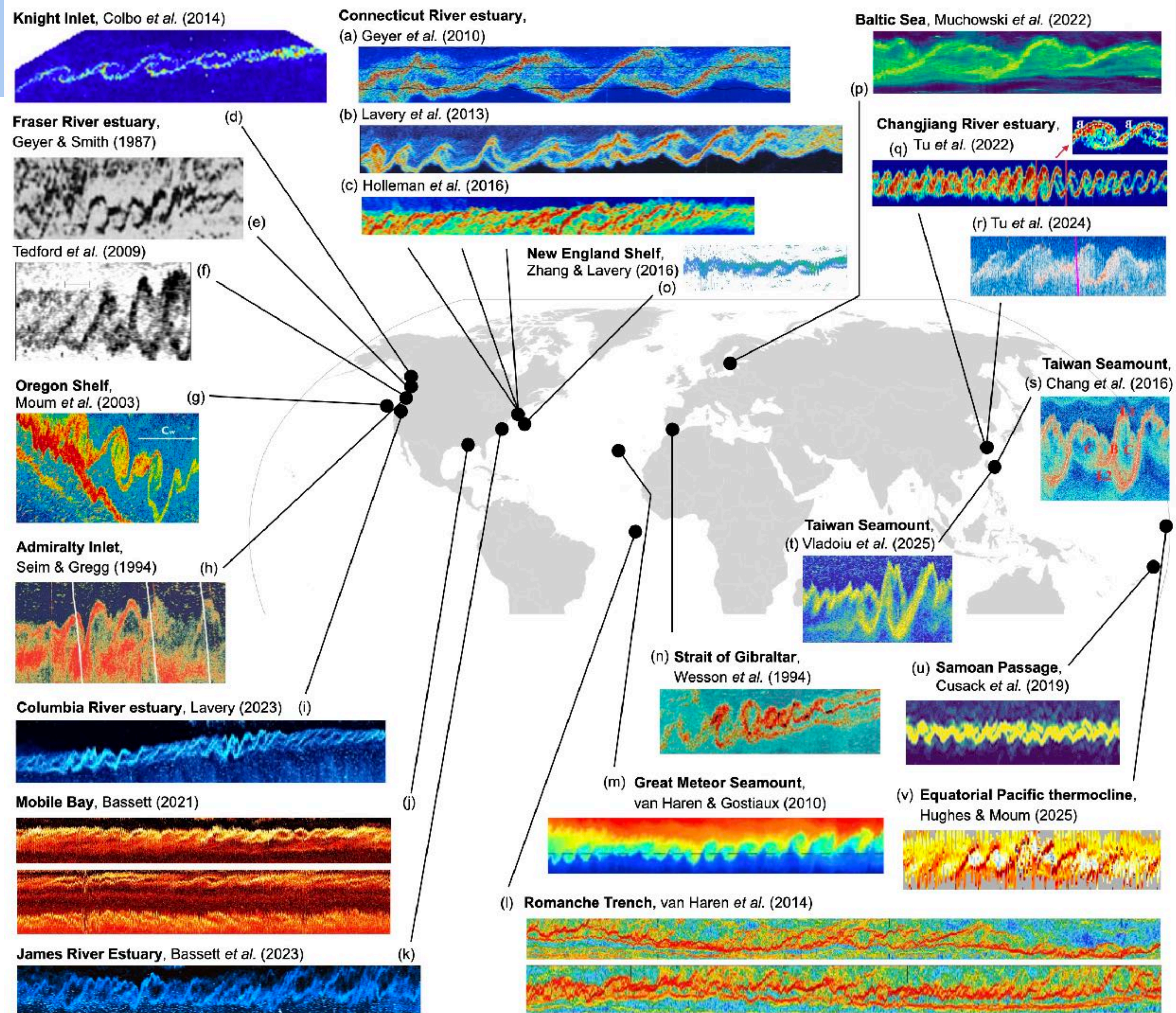
Reynolds number $Re \sim 10^5 - 10^8$

Found in all types of stratification:

Salinity: pycnoclines
in estuaries, fjords and straits...
(panels a,c,d,e,f,h,i,j,k,n,r)

Temperature: thermoclines
in continental shelves, marginal seas,
seamounts, deep overflows, equatorial
surface current...
(panels g,o,l,m,p,s,t,u)

Turbidity: lutoclines
in highly turbid estuaries (panel q)



Implication: new practical estimates of braid energetics and mixing

Estimating energy dissipation along a turbulent sloping braid

$\partial_t U = -\partial_x p + \partial_z \overline{u'w'}$ Reynolds averaged streamwise momentum
 ∂_z : shear

$\partial_t S = N^2 \sin \alpha - |\partial_{zz} \overline{u'w'}| \approx 0$ Assume approx. steady state
baroclinic turbulence

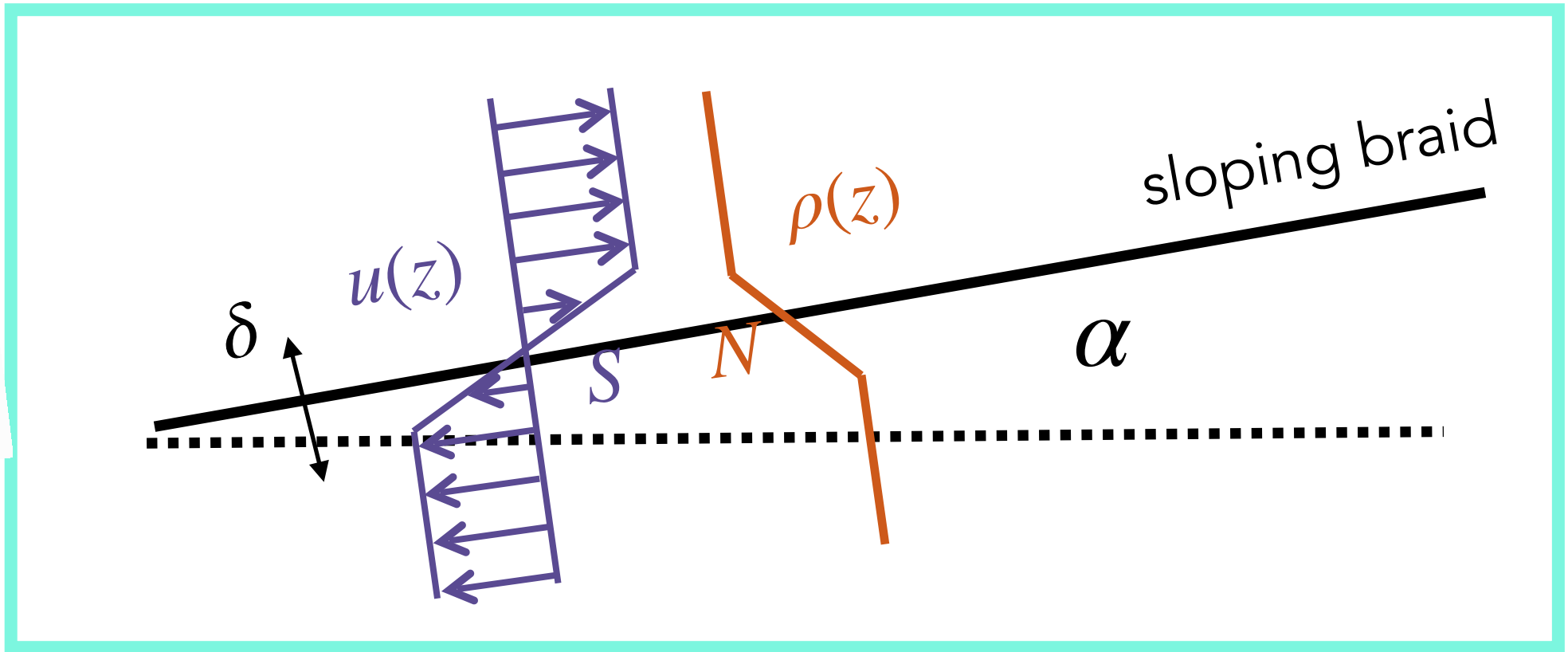
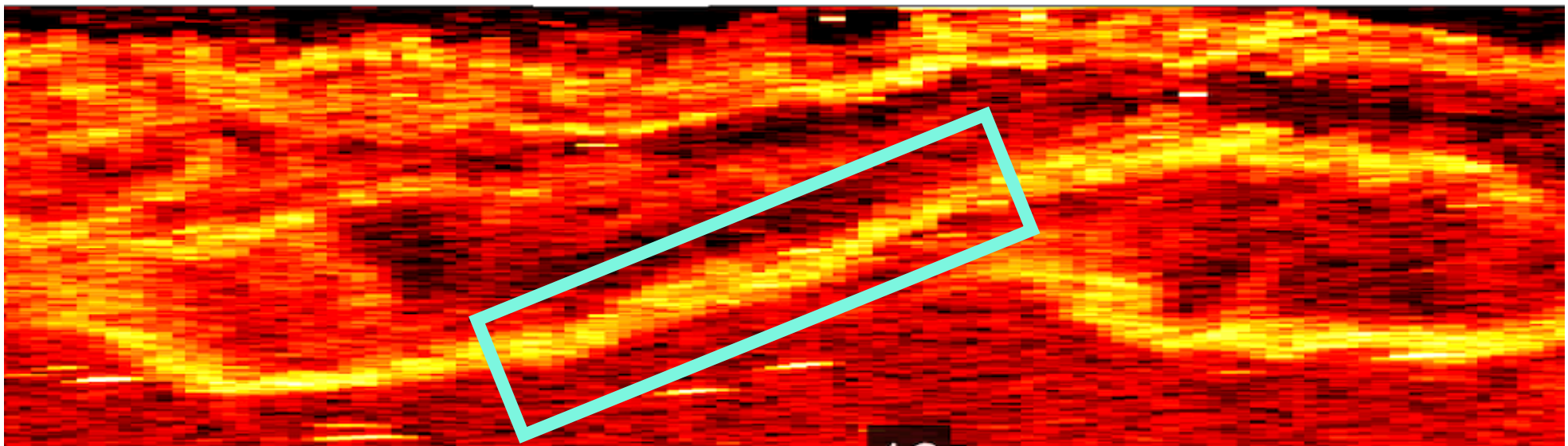
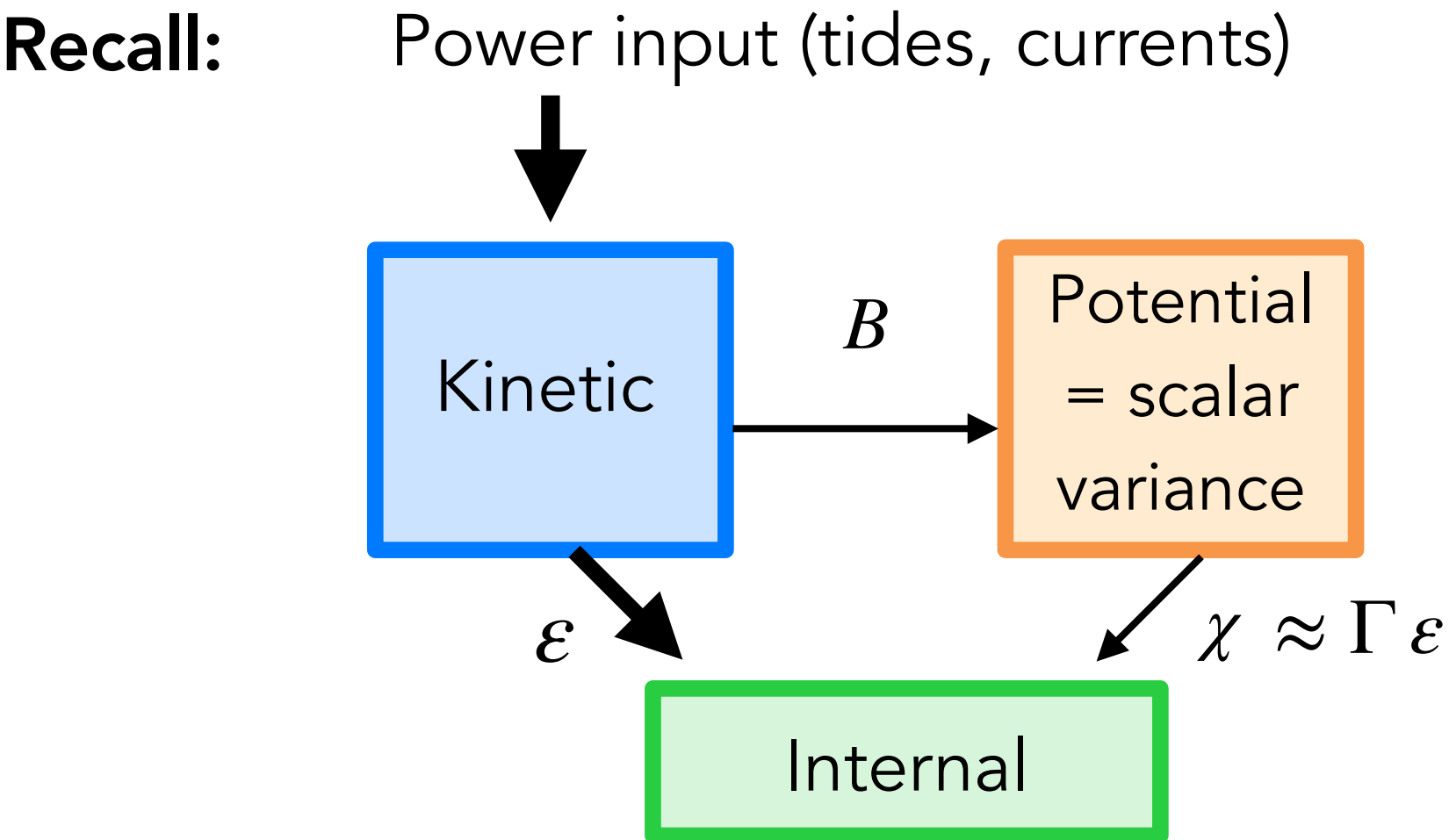
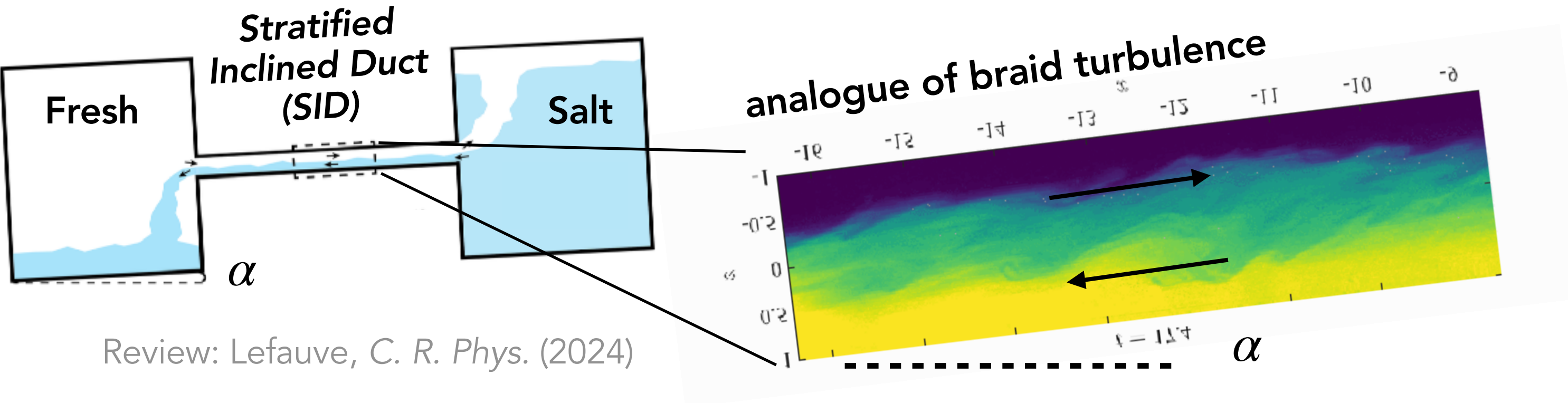
$\overline{u'w'} \approx \alpha N^2 z(z - \delta)$ Reynolds stress

$P = \overline{u'w'} S$ Production rate of TKE by shear

$\varepsilon \approx P \propto \alpha \delta^2 N^2 S \propto \alpha \text{ Ri } \delta^2 S^3$ Dissipation rate of TKE

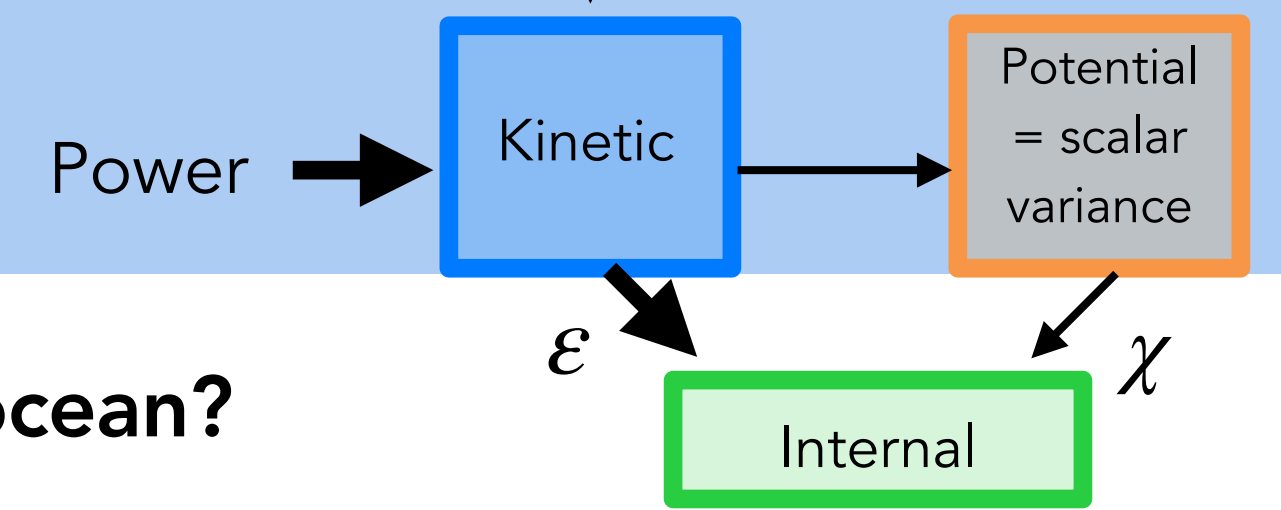
Lab experiments confirm the scaling and provide the pre-factor

3D velocity + density data: $\varepsilon \approx 0.05 \alpha \text{ Ri } \delta^2 S^3$



Conclusions

Mixing controls the stratification and circulation of our oceans



Question: Physics of stratified turbulence and mixing in large-scale shear instabilities in the ocean?

Takeaways:

1. A train of **primary Kelvin-Helmholtz instability** emerges due to strong tidal forcing and/or interaction with topography that leads to the baroclinic generation of shear and $Ri < 0.25$ (linear stability threshold). The mechanism is generic to a variety of environments in the ocean.
2. At $Ri \gtrsim 0.1$ and $Re \gtrsim 10^5$, **fast secondary shear instabilities precede and pre-empt primary overturns** due to the baroclinic amplification of shear at the braid scale (high Ri), unhindered by low viscosity (high Re) and able to overcome the stabilising braid strain. **Ocean $\neq$ laboratory!**
3. **Braid turbulence and mixing forced by local braid slope and shear** is different from classical primary overturn mixing, and we propose a **new parameterisation of energetics ϵ, χ as functions of local braid slope α , thickness δ and shear S** , which are easier to measure in the field than ϵ, χ .

Focus: estuarine flow (better data than open ocean)

