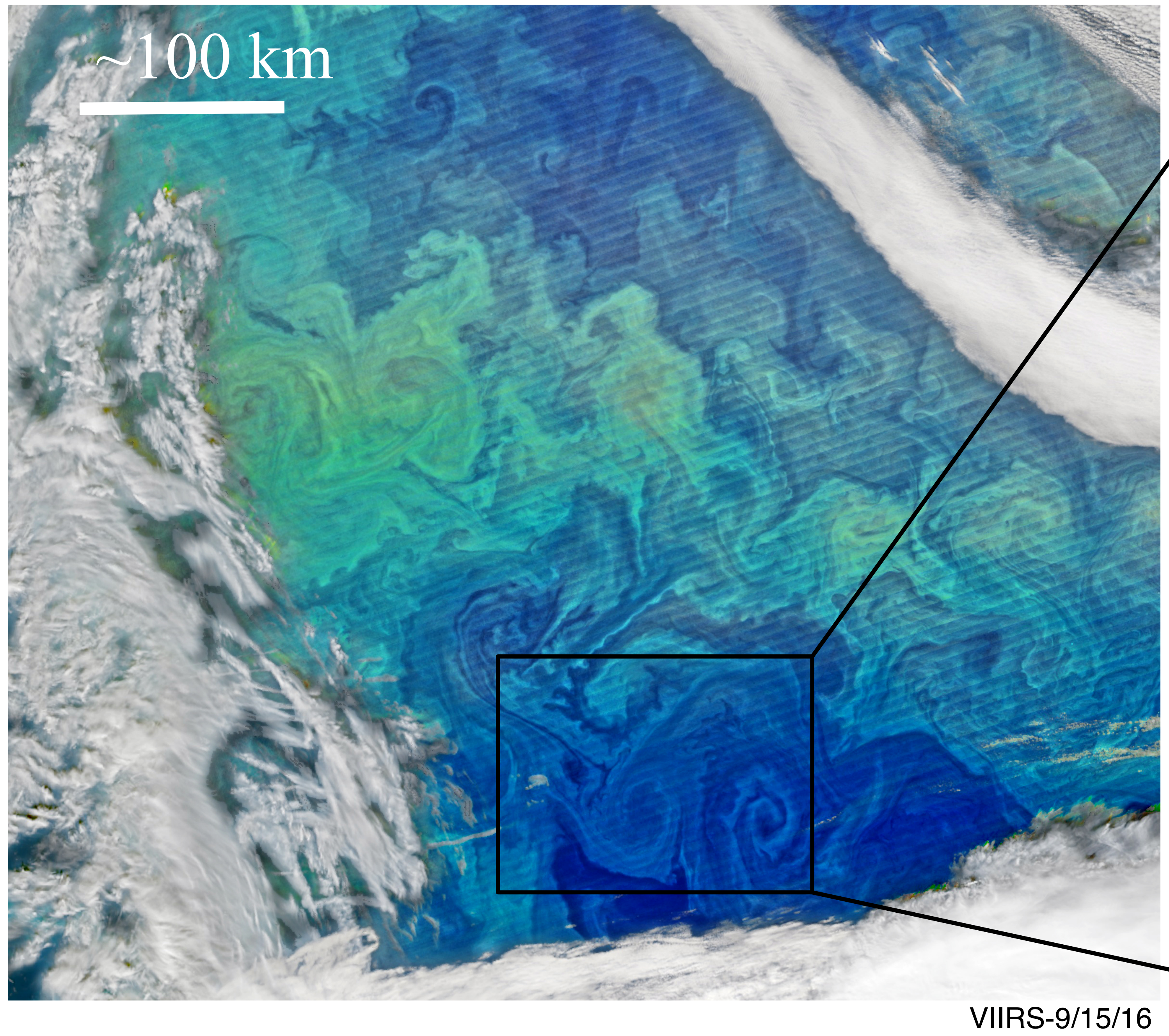
US CLIVAR Mesoscale and frontal-scale air-sea interaction workshop

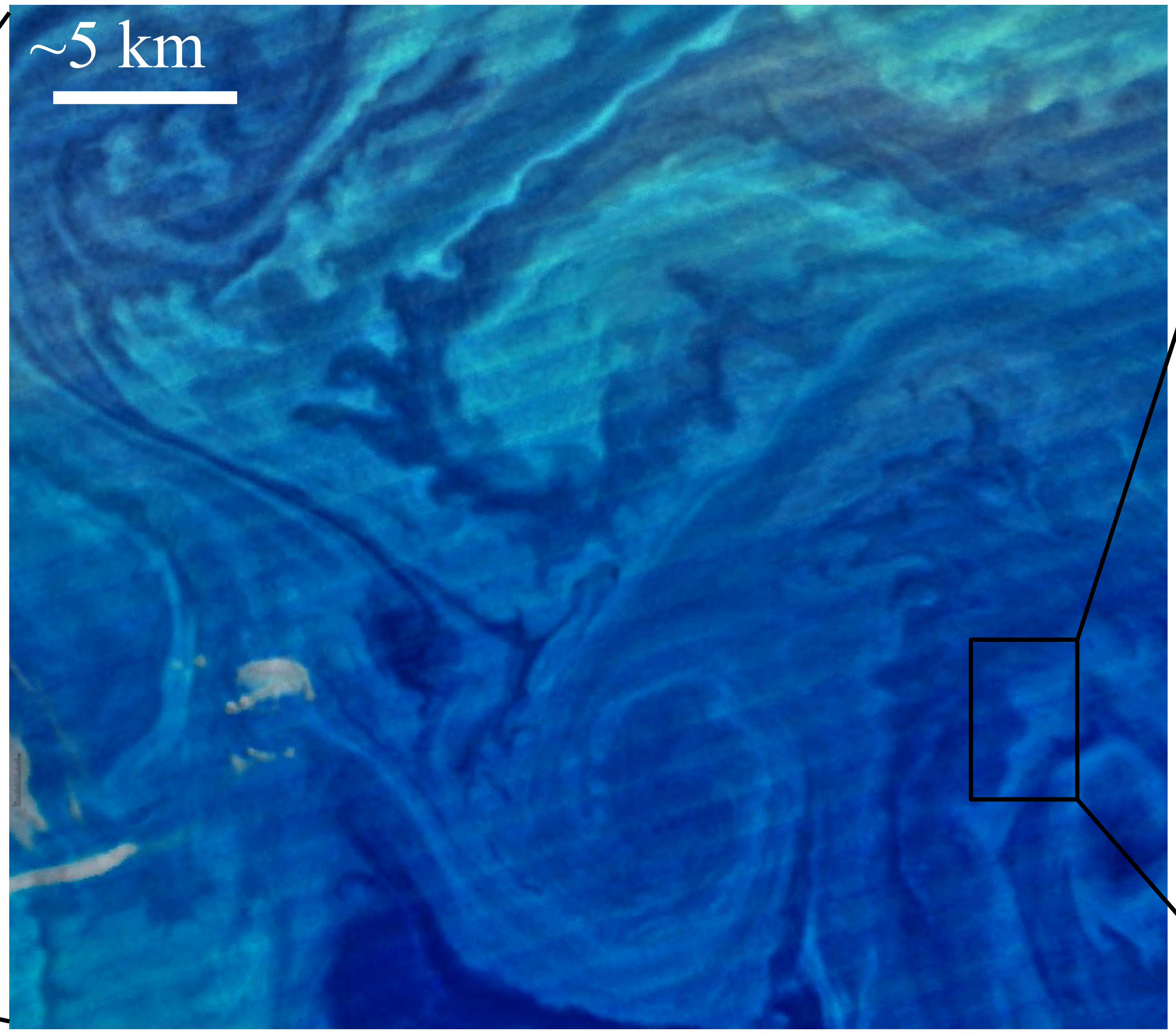
More than a length scale: Air-sea interaction at submesoscale fronts

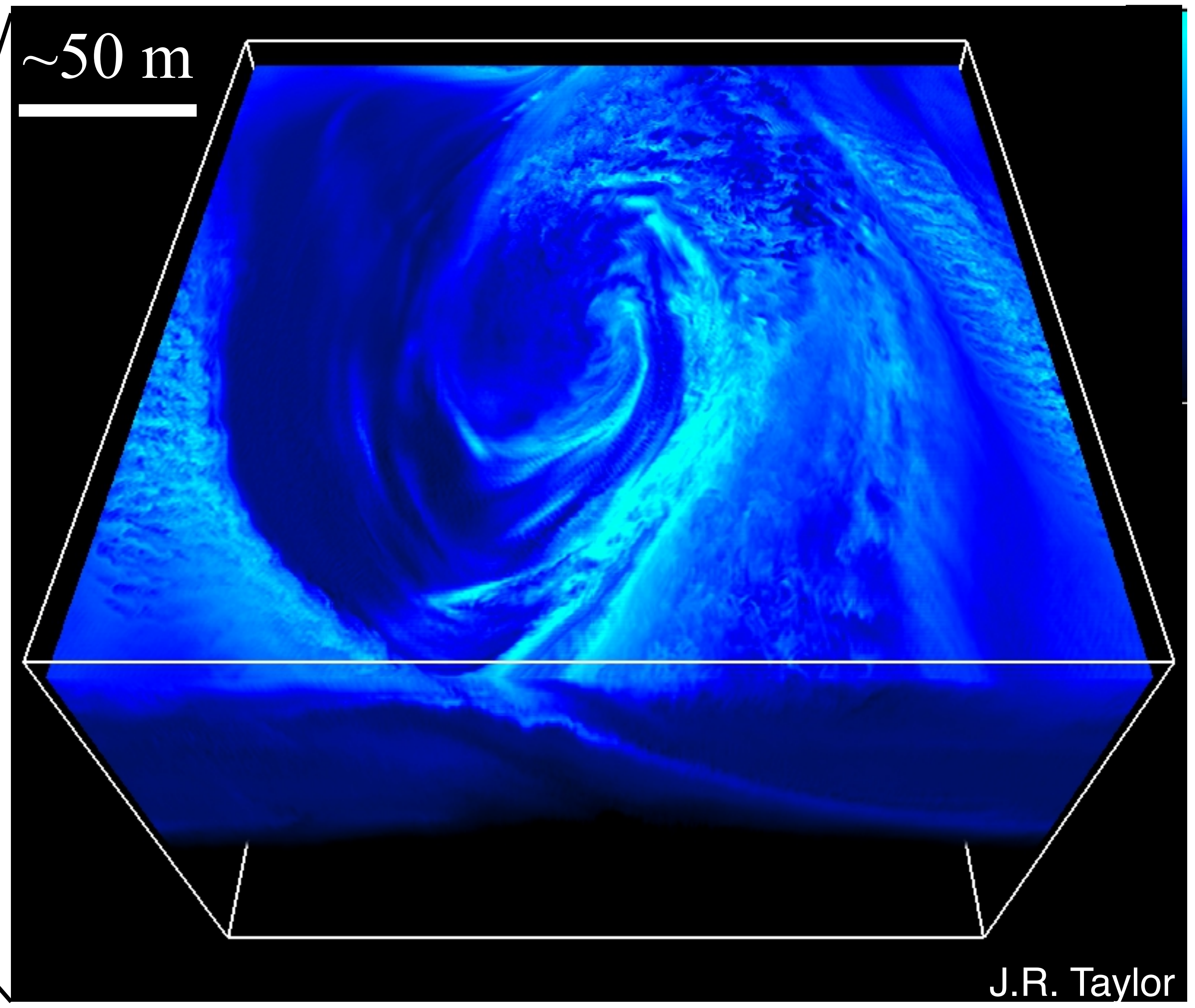
Jacob Wenegrat
University of Maryland, College Park

wenegrat.github.io

Submesoscales are dynamically unique





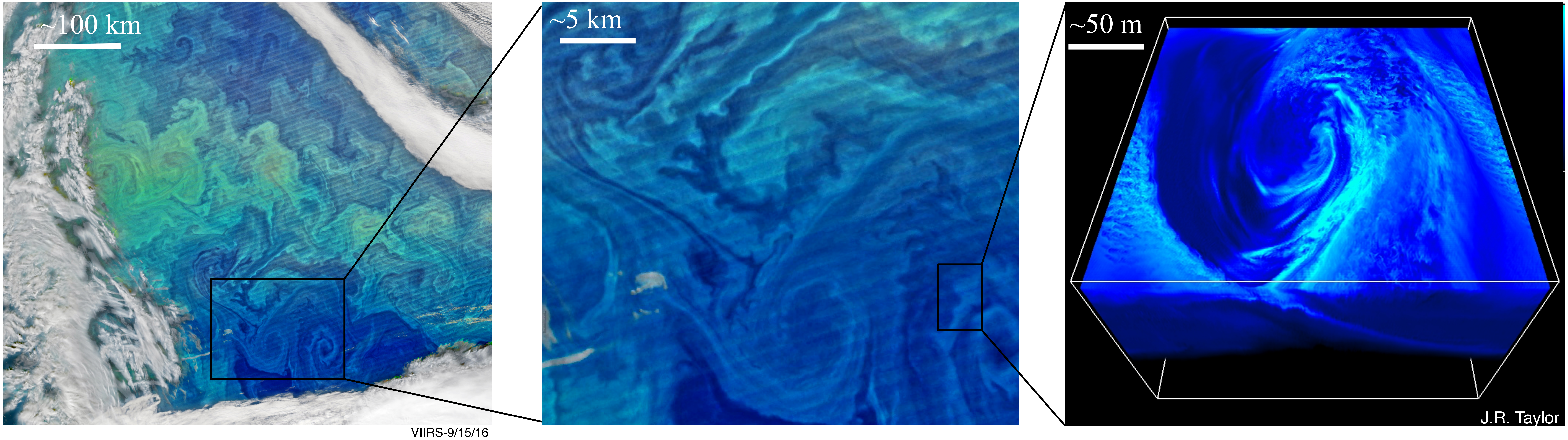


Mesoscale

Submesoscale

Small-scale mixing

Submesoscales are dynamically unique



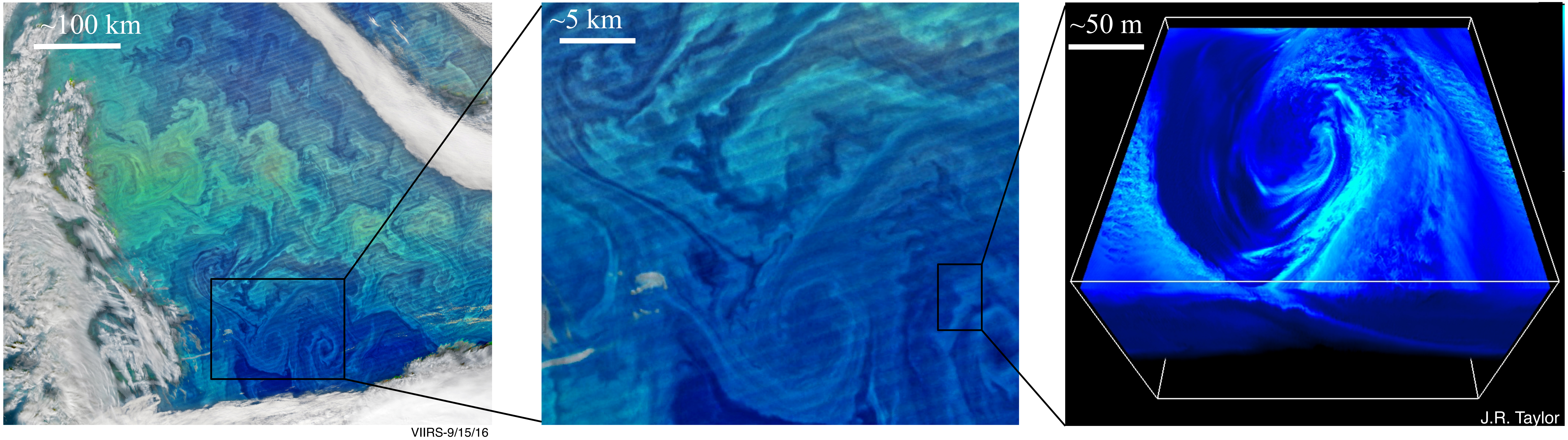
Mesoscale | Submesoscale | Small-scale mixing

100 km ← 10 km — 100 m → 1 m

Rossby number: $Ro \sim \frac{U}{fL}$ Richardson number: $Ri \sim \frac{N^2}{U_z^2}$

U - velocity scale, f - Coriolis frequency, L - horizontal length scale, N^2 - vertical buoyancy gradient

Submesoscales are dynamically unique



Mesoscale | Submesoscale | Small-scale mixing

100 km — 10 km — 100 m — 1 m

Planetary rotation, nonlinearity, and stratification are all important

$Ro \ll 1, Ri \gg 1$ | $Ro \sim 1, Ri \sim 1$ | $Ro \gg 1, Ri < 1$

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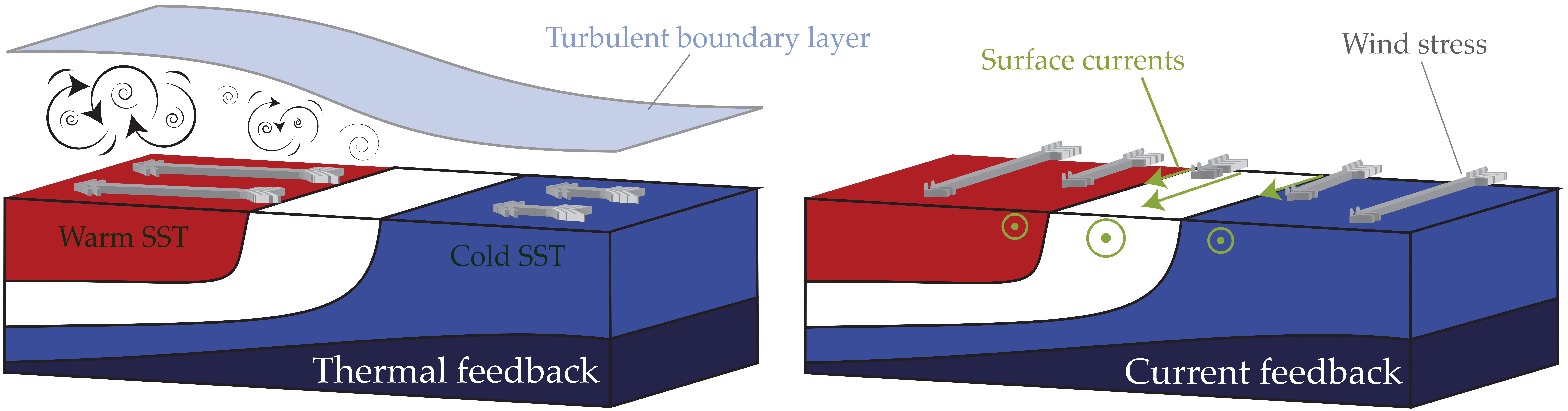
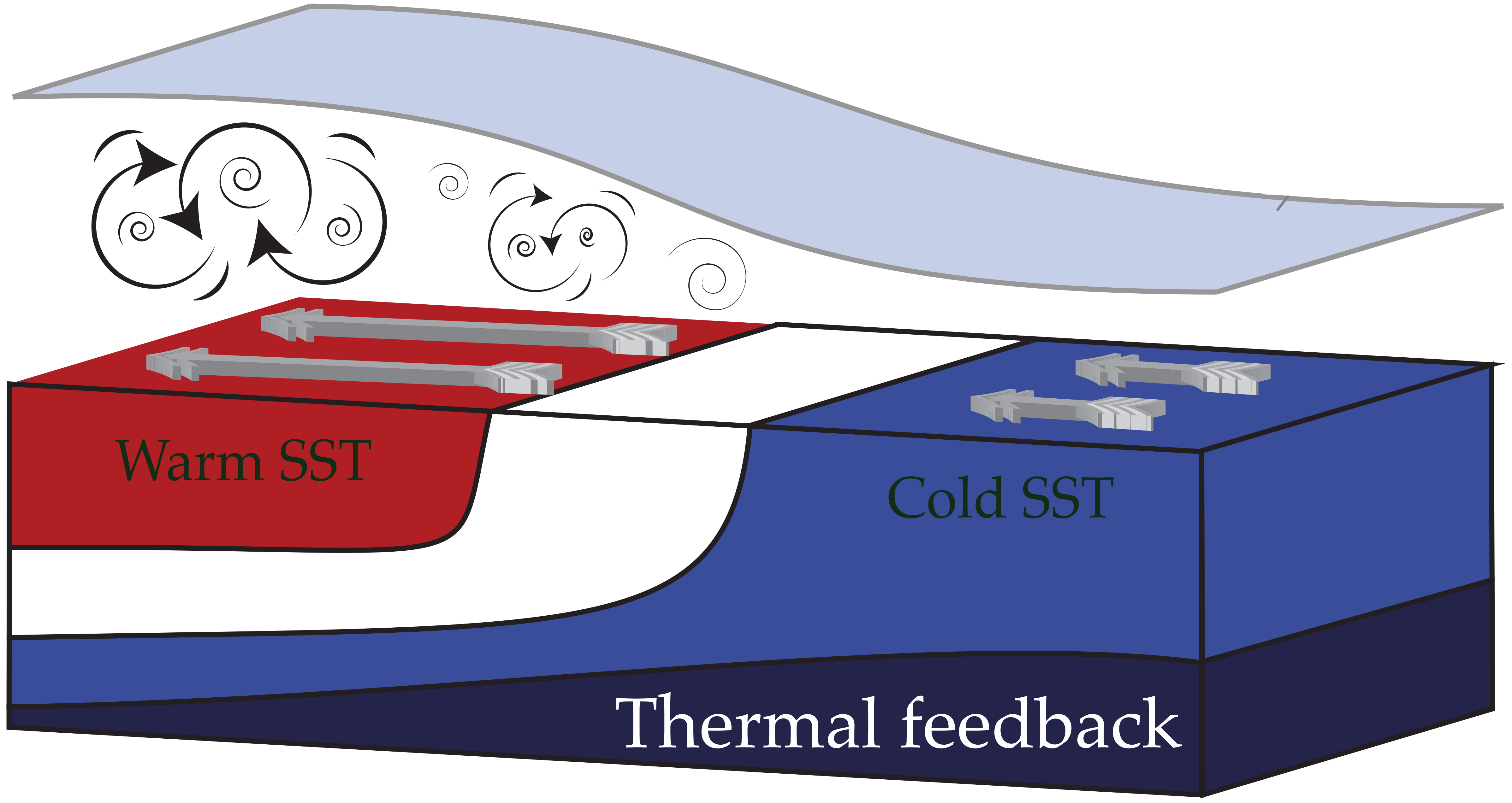
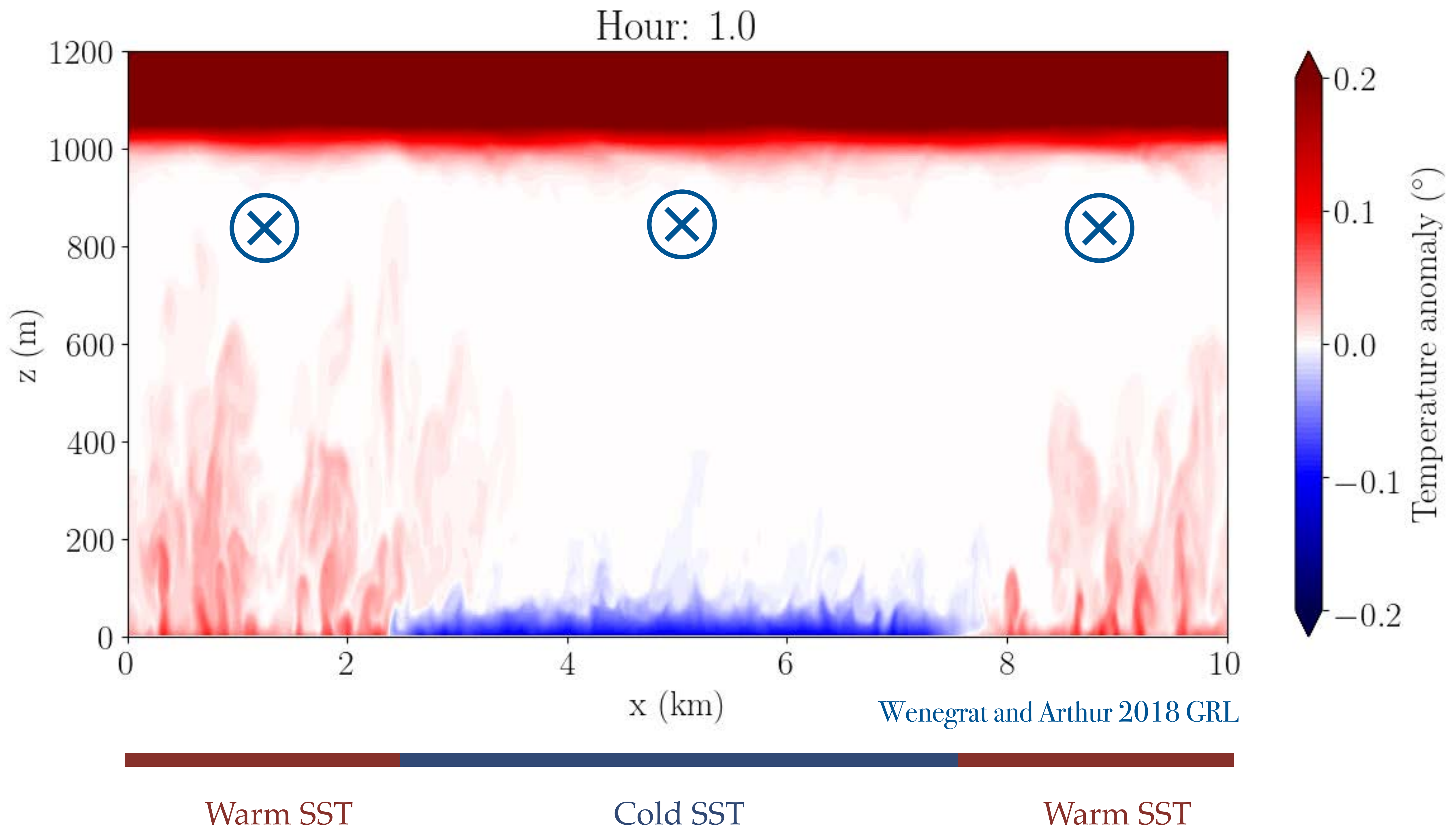
What are the mechanisms of submesoscale air-sea interaction?



Physical mechanisms of *mesoscale* air-sea interaction also active at *submesoscale*

What are the mechanisms of submesoscale air-sea interaction?





LES suggests strong response of ABL (including winds) to submesoscale fronts

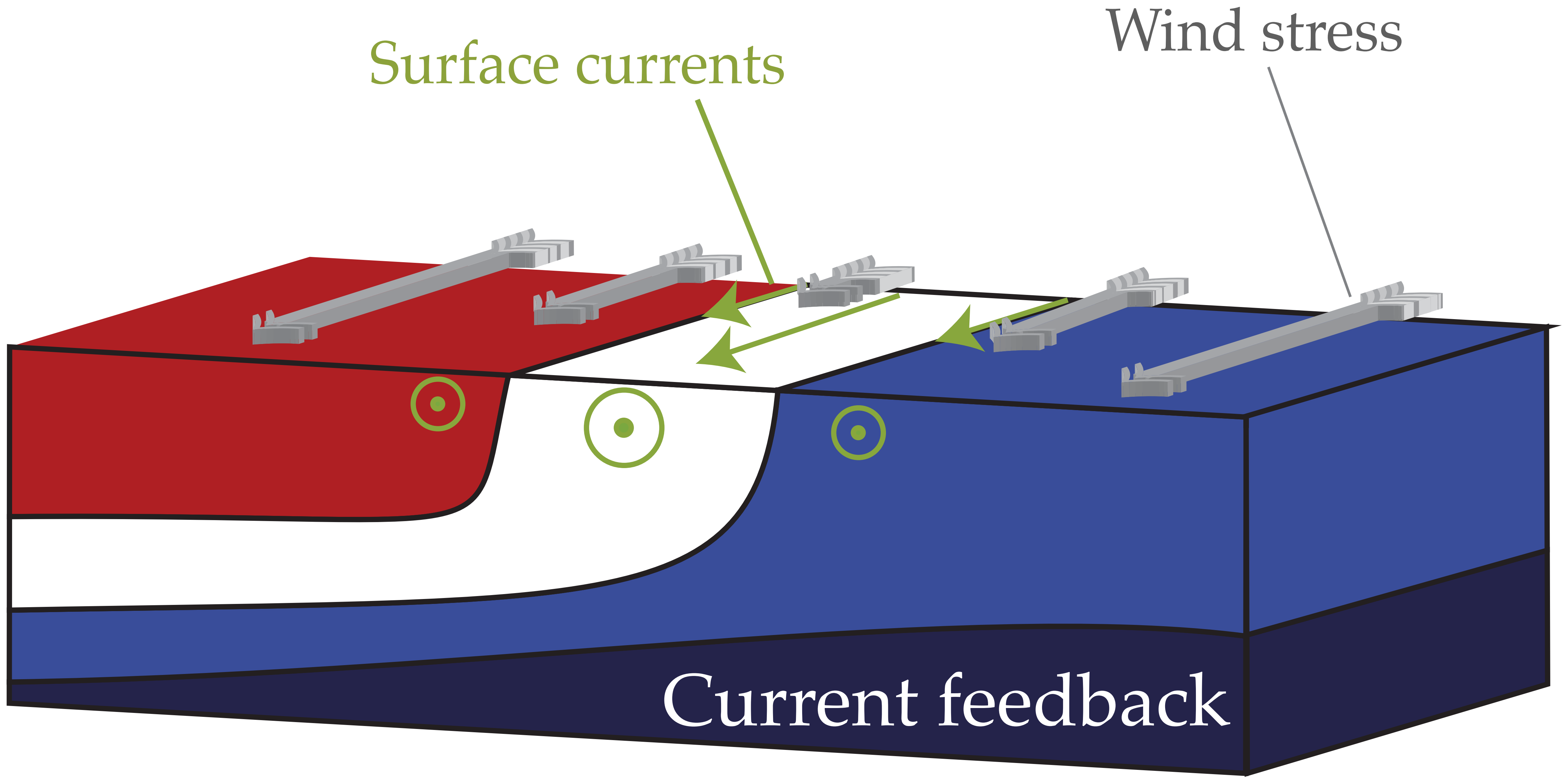
To what extent does this hold for realistic submesoscale turbulence? Always in a large Rossby number regime ($\frac{U_a}{fL_{SST}} \gg 1$)

Heat fluxes also generate a direct flux of eddy potential energy (see poster by Igor Uchoa!)

What are the mechanisms of submesoscale air-sea interaction?

$$\tau = \rho_a c_d |\boldsymbol{U_a} - \boldsymbol{u_o}| (\boldsymbol{U_a} - \boldsymbol{u_o})$$

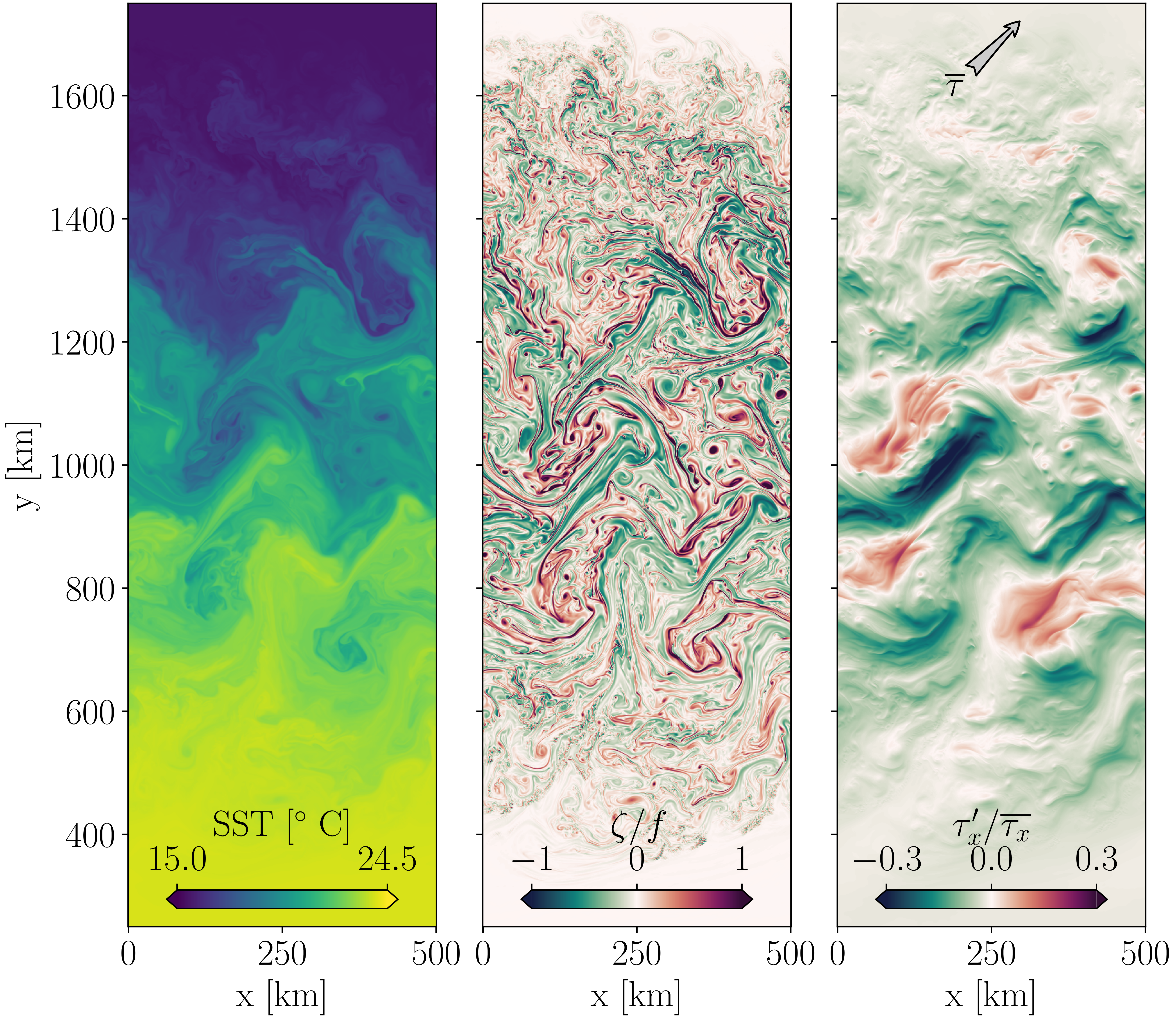
$$\tau' = \tau - \underbrace{\rho_a c_d |\boldsymbol{U_a}| \boldsymbol{U_a}}_{\overline{\tau}}$$



Surface currents also introduce a *current feedback on stress (CFB)*

Definition is entirely local, mechanism is robust at all scales

Current feedback introduces small-scale variability in stress



Re-entrant channel

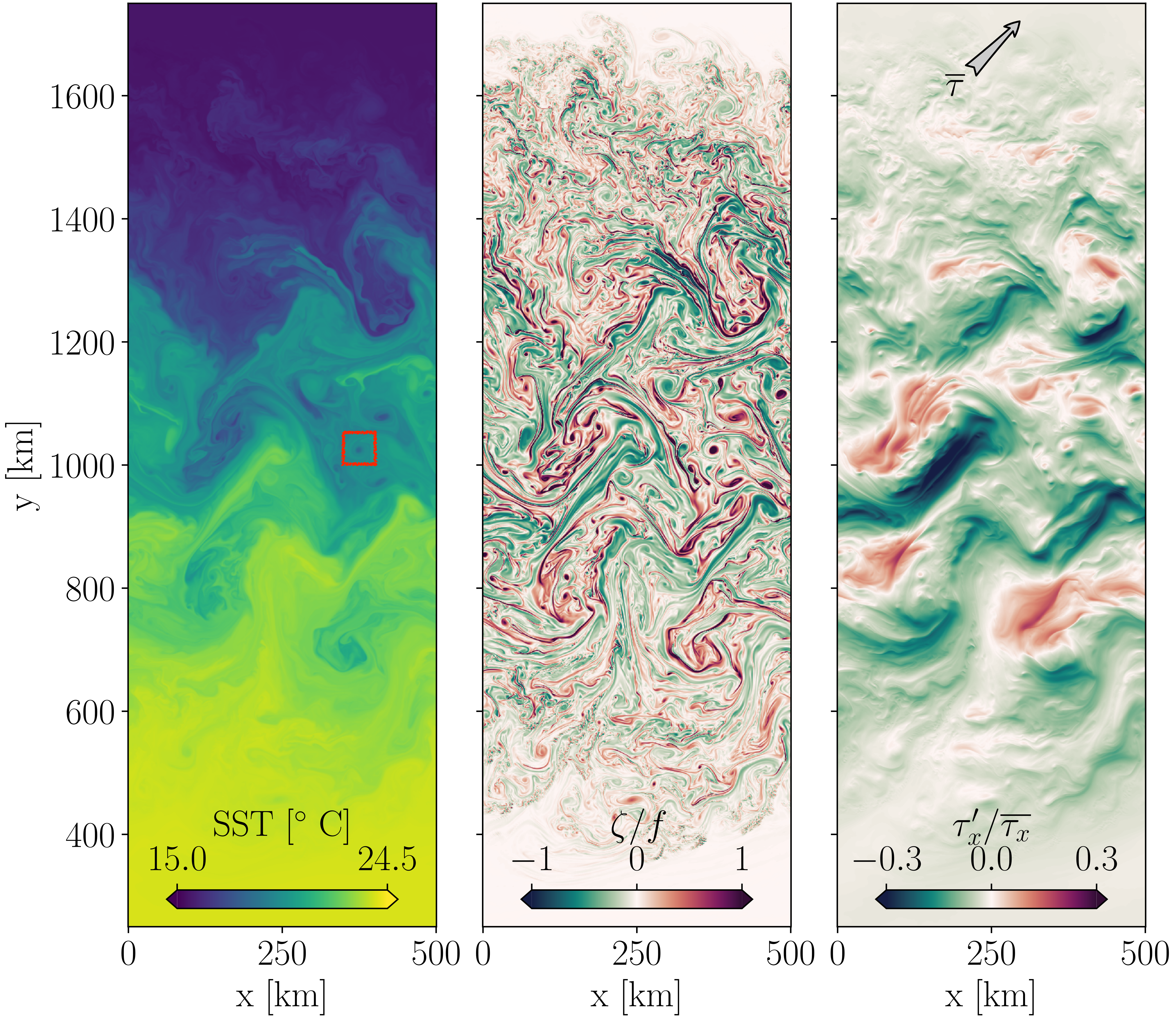
$\Delta x = \Delta y = 500$ m

Moderate wind towards NE (7 ms^{-1})

Surface buoyancy loss (25 Wm^{-2})

Spun-up for 360 days at lower res.

Current feedback introduces small-scale variability in stress



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Stress anomalies oppose the surface currents

Anti-correlation between currents and stress important for wind-work, eddy energetics.

eg. Renault et al. 2018

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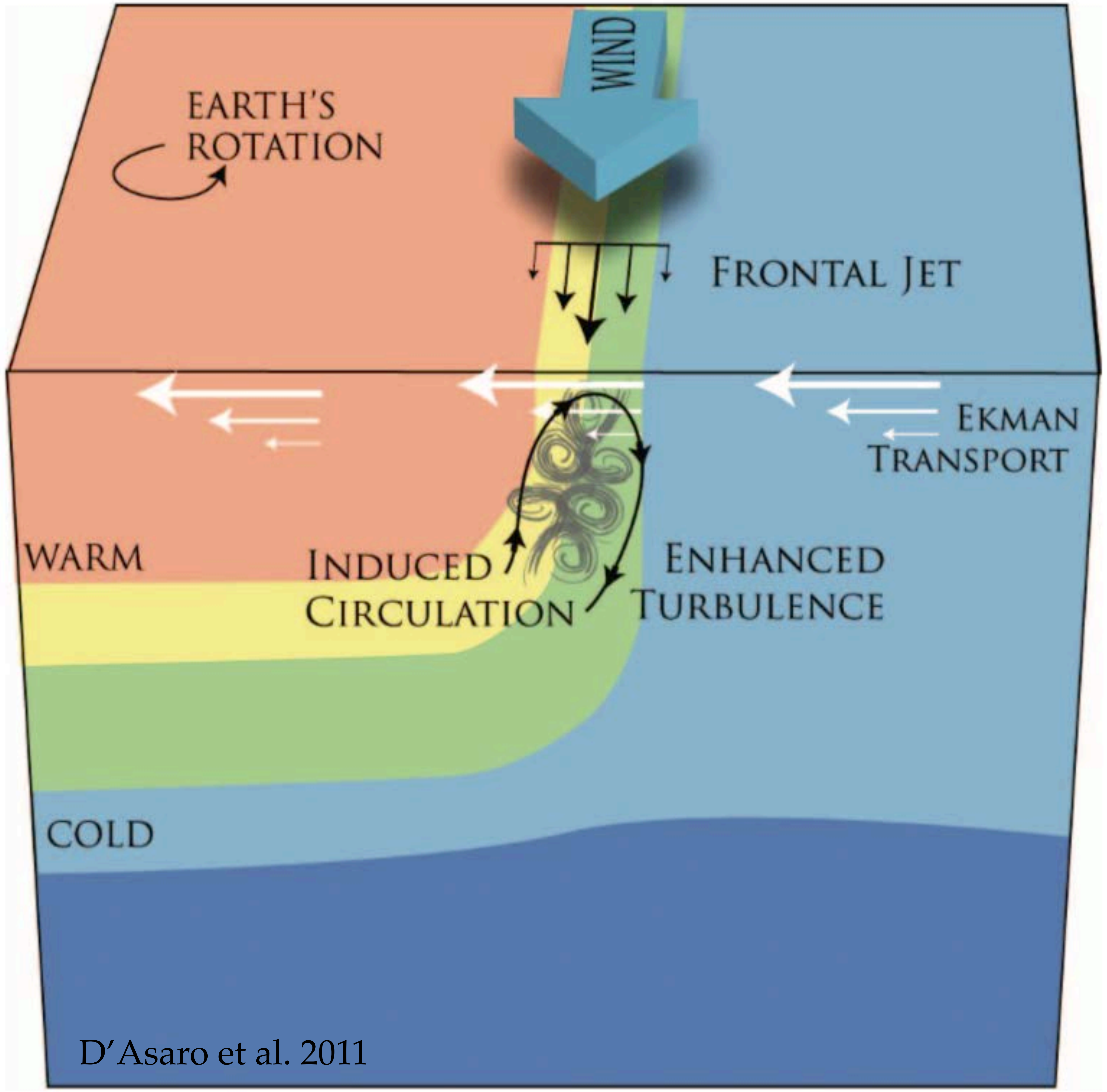
Correlation with buoyancy gradient will affect the Ekman buoyancy flux at fronts!

Current feedback modifies the Ekman buoyancy flux



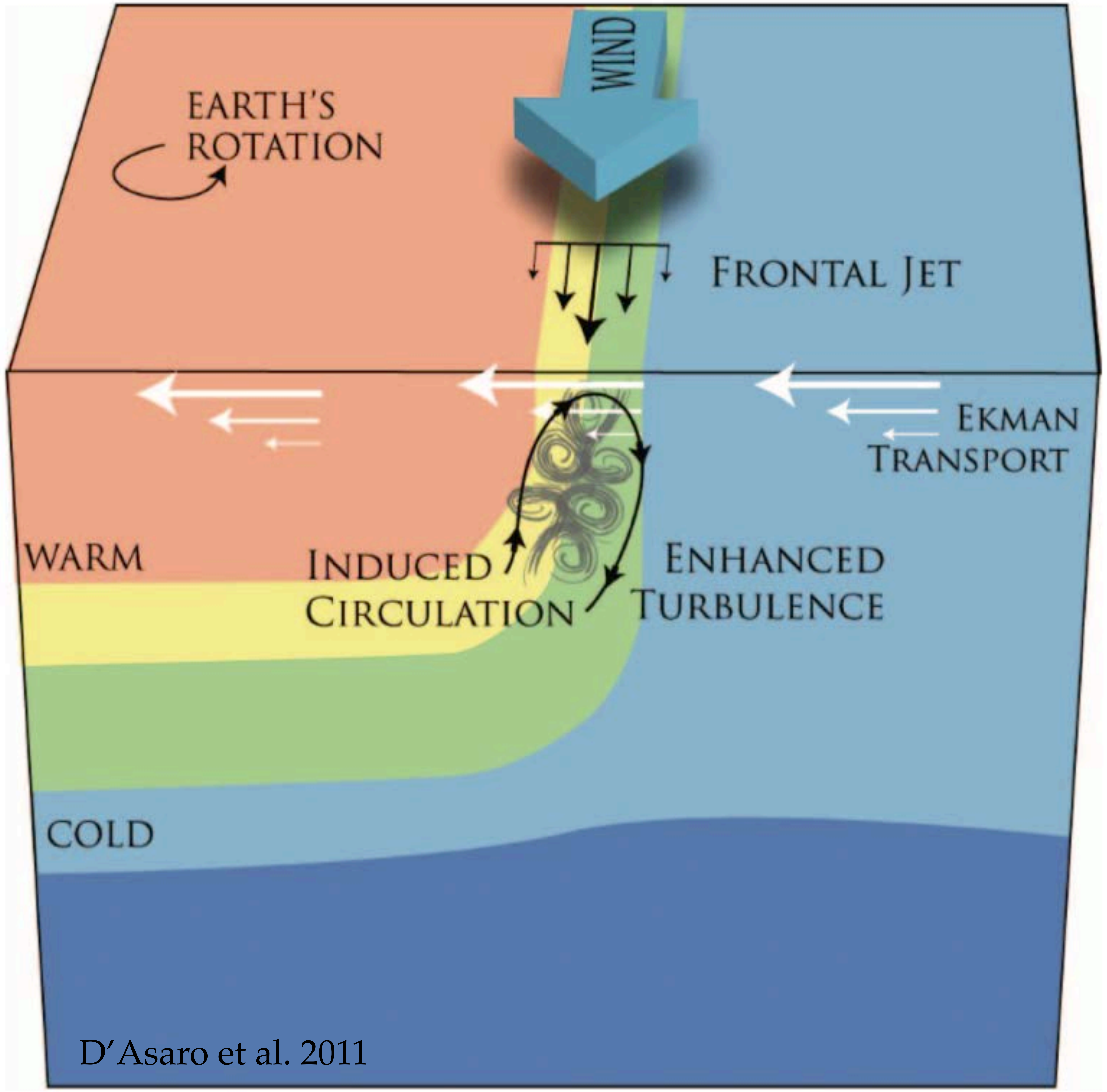
Ekman transport advects buoyancy at fronts:

$$EBF = \frac{\boldsymbol{\tau} \times \hat{k}}{\rho_o f} \cdot \nabla_h b$$

Observed values equivalent to O(10,000 Wm^{-2}) surface heat fluxes!

Also generates a flux of *potential vorticity*.

Current feedback modifies the Ekman buoyancy flux



Ekman transport advects buoyancy at fronts:

$$EBF = \frac{\boldsymbol{\tau} \times \hat{k}}{\rho_o f} \cdot \nabla_h b$$

Can be expanded as a *mean* and *CFB* component:

$$EBF = \underbrace{\frac{\bar{\boldsymbol{\tau}} \times \hat{k}}{\rho_o f} \cdot \nabla_h b}_{EBF_{\bar{\tau}}} + \underbrace{\frac{\boldsymbol{\tau}' \times \hat{k}}{\rho_o f} \cdot \nabla_h b}_{EBF_{\tau'}}$$

Submesoscale symmetric instability

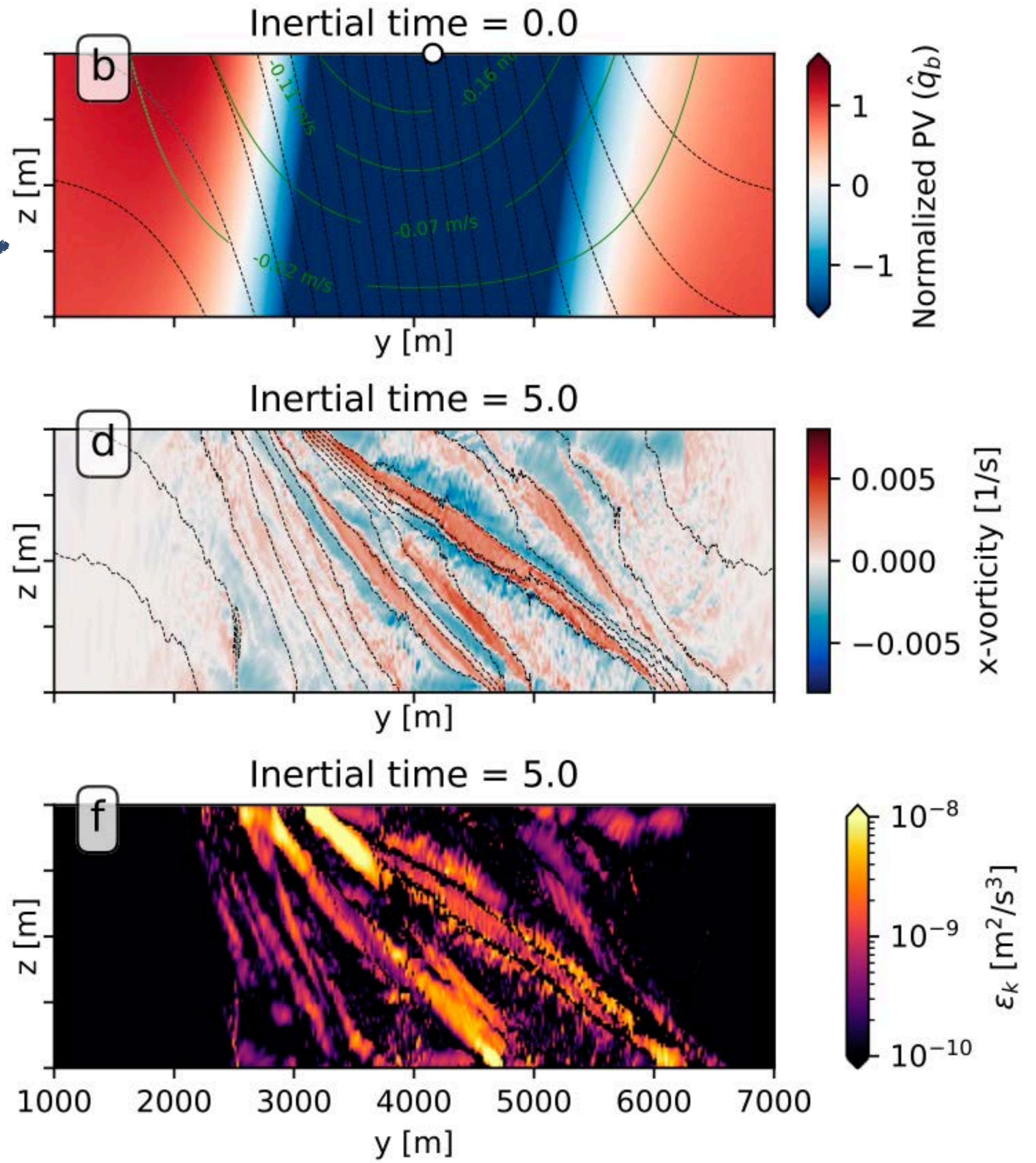
Background thermal wind flow

Turbulent kinetic energy

EBF

destroys/injects PV

sets the rate of energy extraction
(geostrophic shear production)



Chor, Wenegrat, and Taylor, 2022 JPO

A forward cascade of energy to turbulence

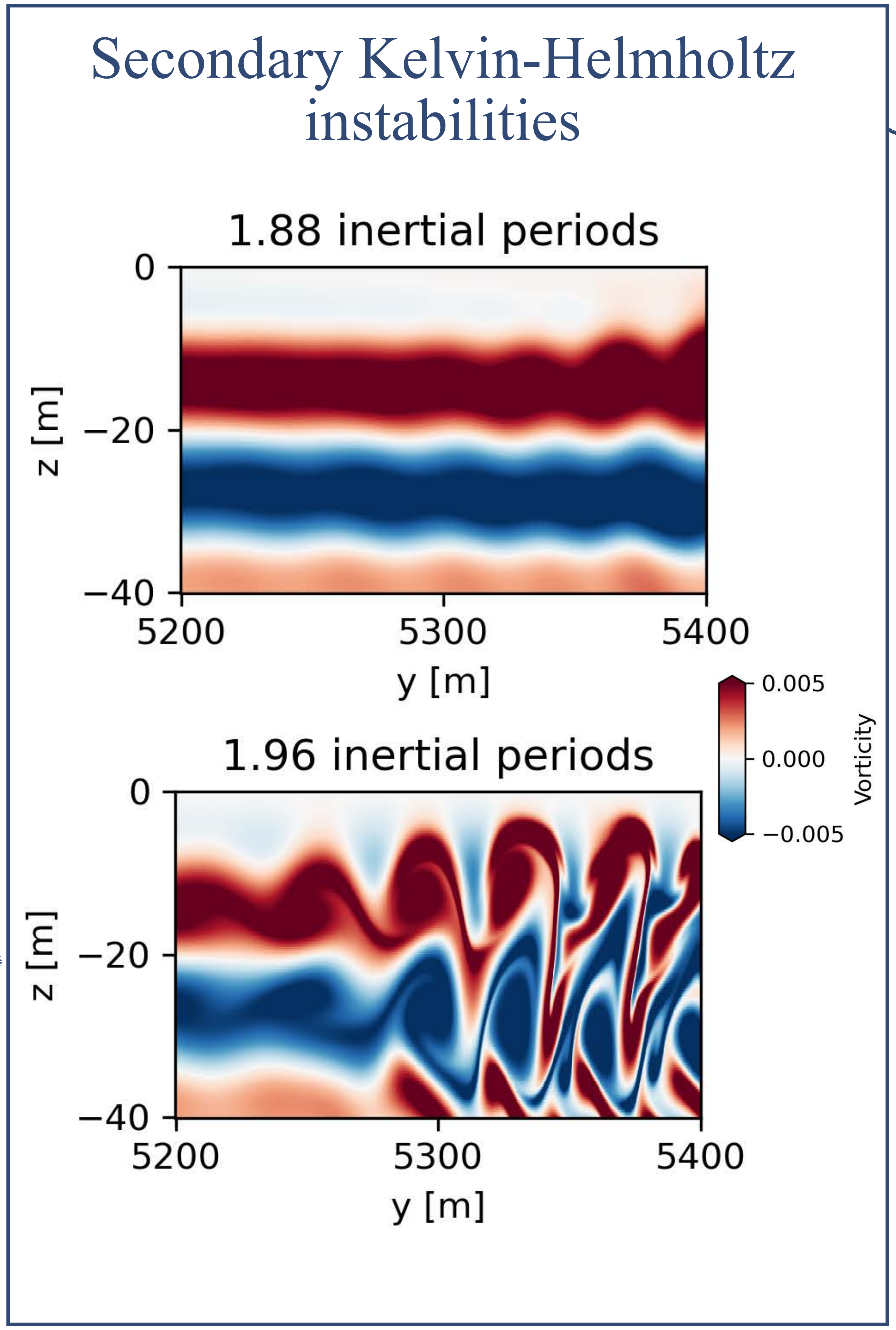
Background thermal wind flow

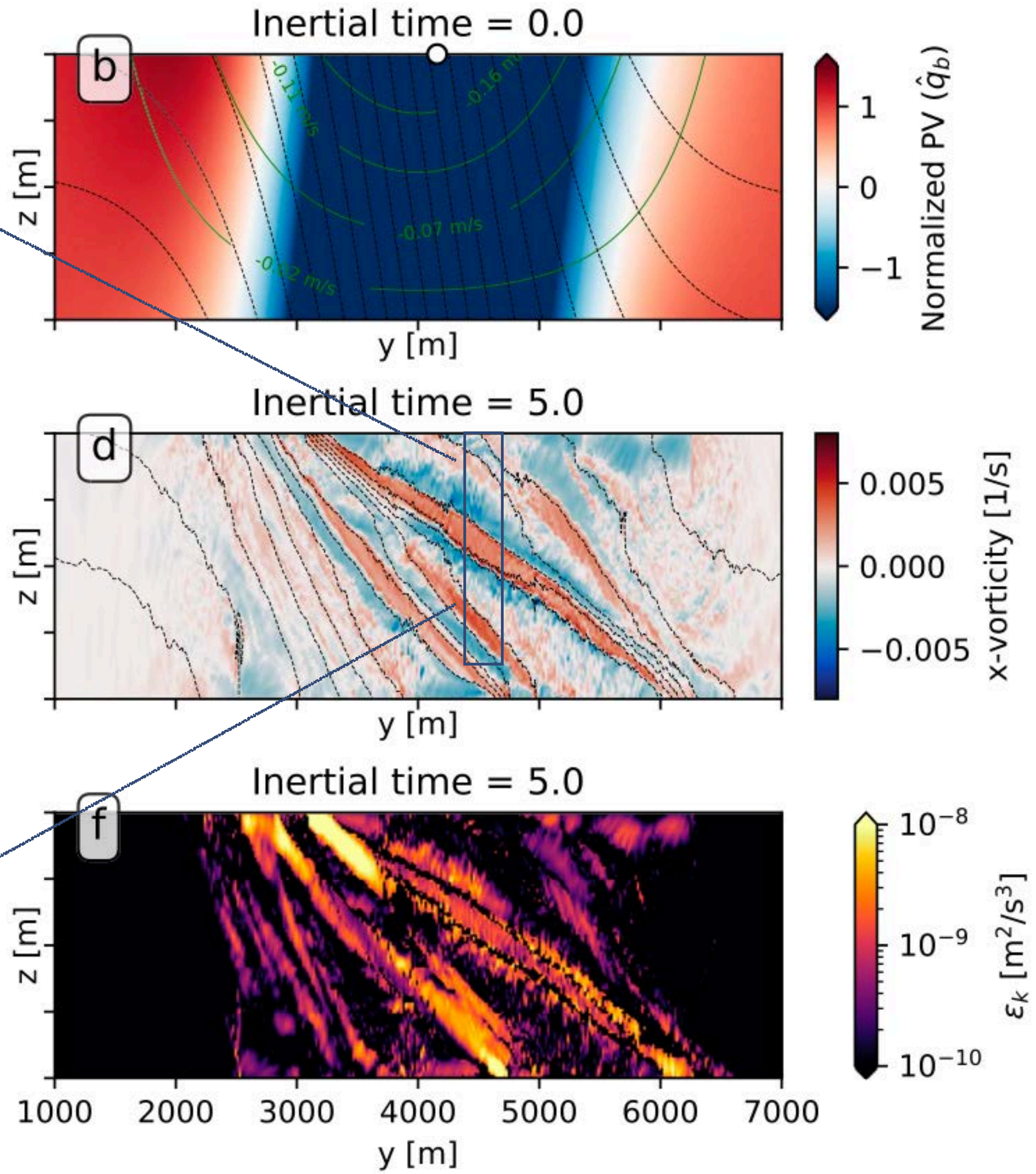
↓ Geostrophic shear production

Turbulent kinetic energy

↓

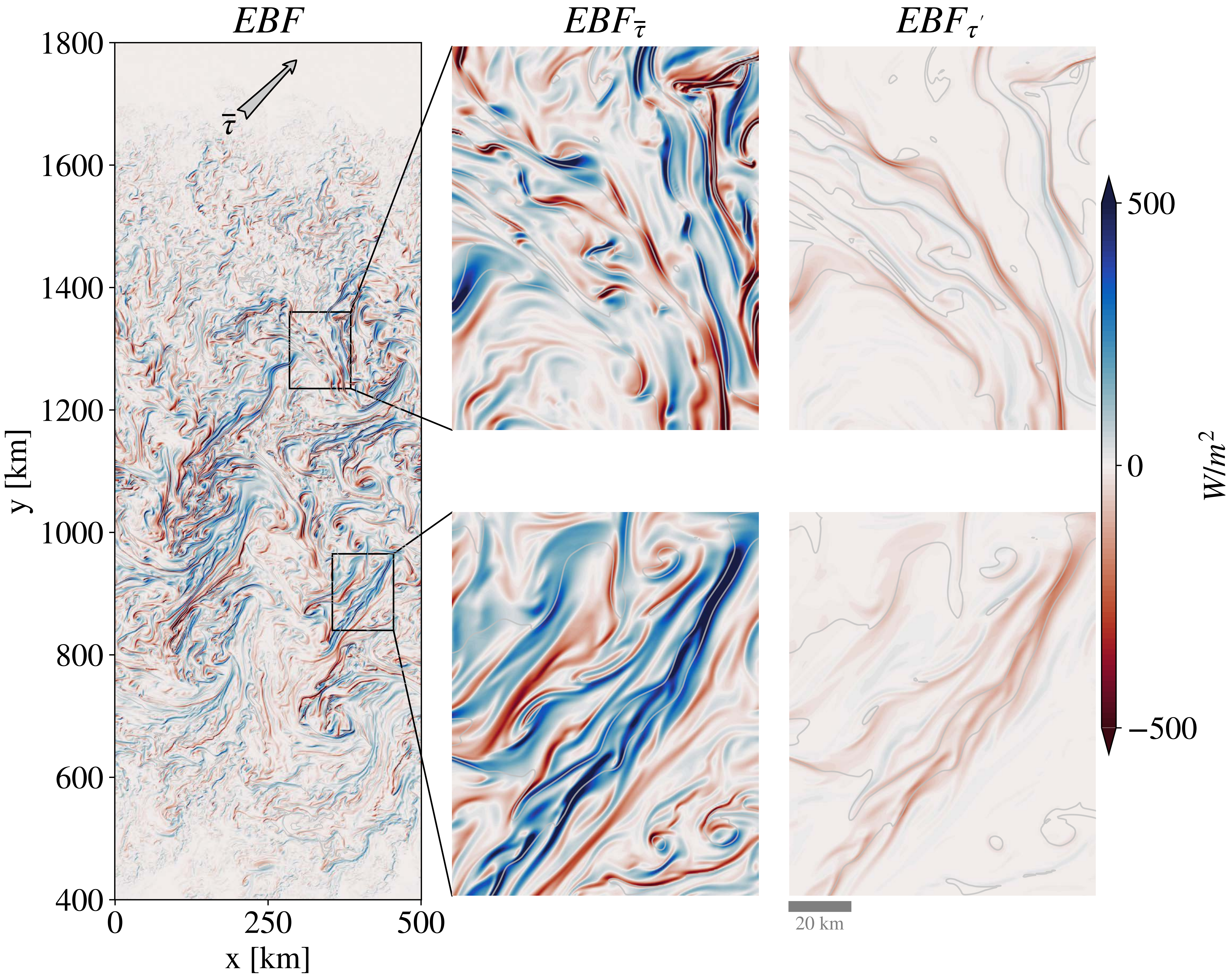
Dissipation (ϵ) and mixing (ϵ_ρ)





Chor, Wenegrat, and Taylor, 2022 JPO

Significant modification to Ekman buoyancy flux



Ratio of current feedback to mean EBF:

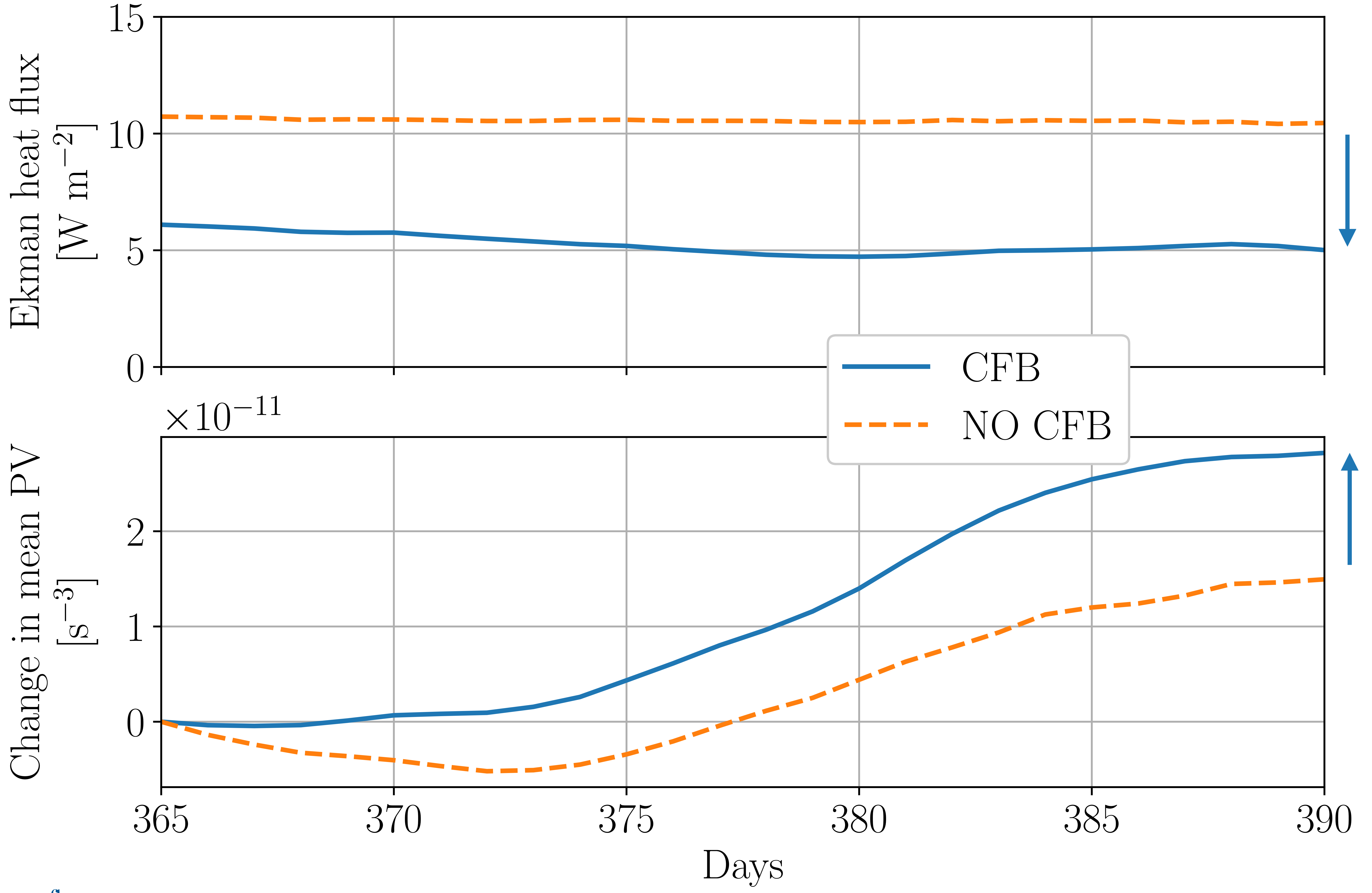
$$\frac{EBF_{\tau'}}{EBF_{\bar{\tau}}} \sim -\frac{U_o}{U_a \cos \psi}$$

where U_o scales the surface currents, U_a scales the wind speed, and ψ is the angle between the wind and the surface thermal wind shear

Large contribution when:

- Surface velocities are large
- Winds are weak
- Winds are misaligned with fronts (eg. Wenegrat et al. 2018 JPO)

Current feedback acts as buoyancy & PV *source*

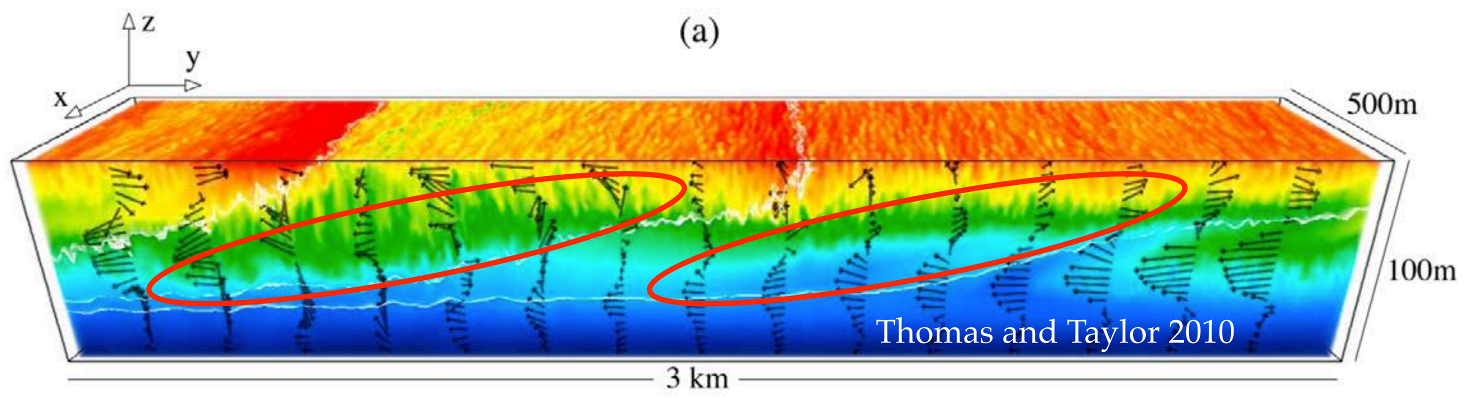


50% decrease in mean EBF

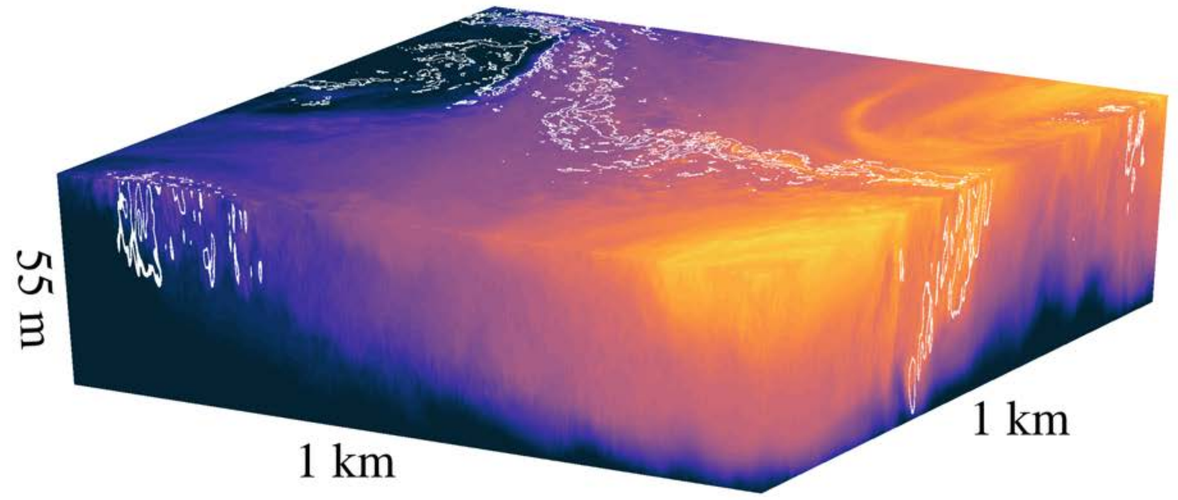
50% increase in PV injection

* simulations without buoyancy flux

A potential pathway for modifying energetics



Symmetric instability



Baroclinic instability

Background kinetic energy

Eddy potential energy

Geostrophic shear production

Buoyancy production

Eddy kinetic energy

Secondary instabilities

3D Turbulence

Dissipation (ϵ)

Mixing

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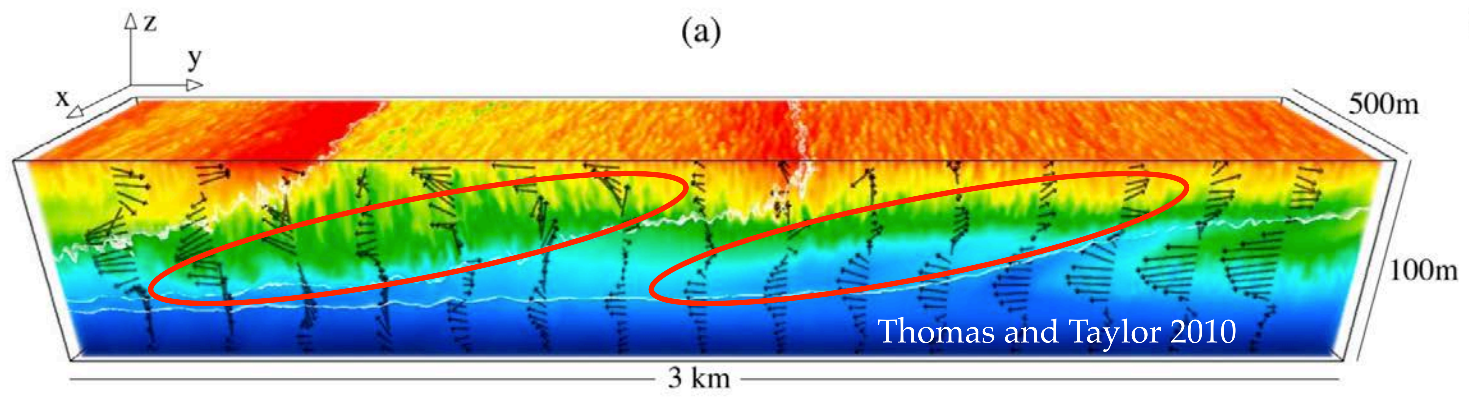

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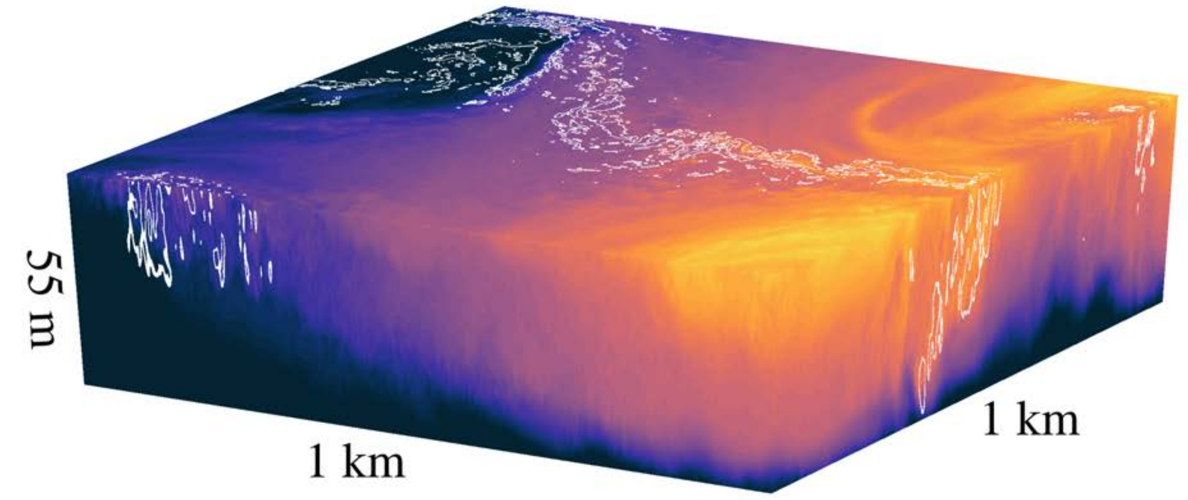

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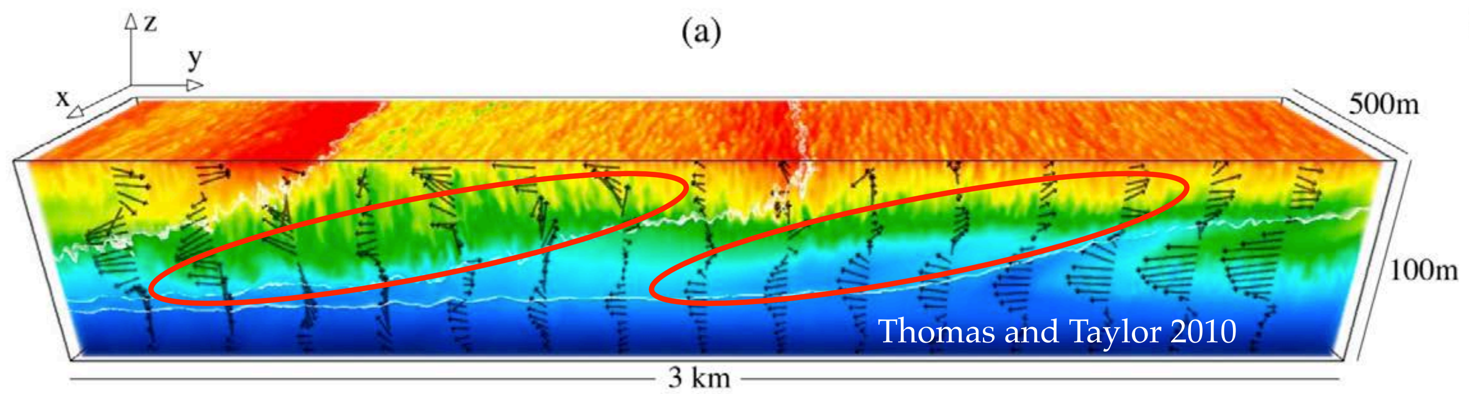
'Eddy killing' effect on mixed-layer KE:

$$\frac{\boldsymbol{\tau}' \cdot \boldsymbol{u}_o}{\rho_o} \sim -\underbrace{\left(\frac{u_*^2}{U_a}\right)}_{\textit{damping}} U_o^2$$

A potential pathway for modifying energetics



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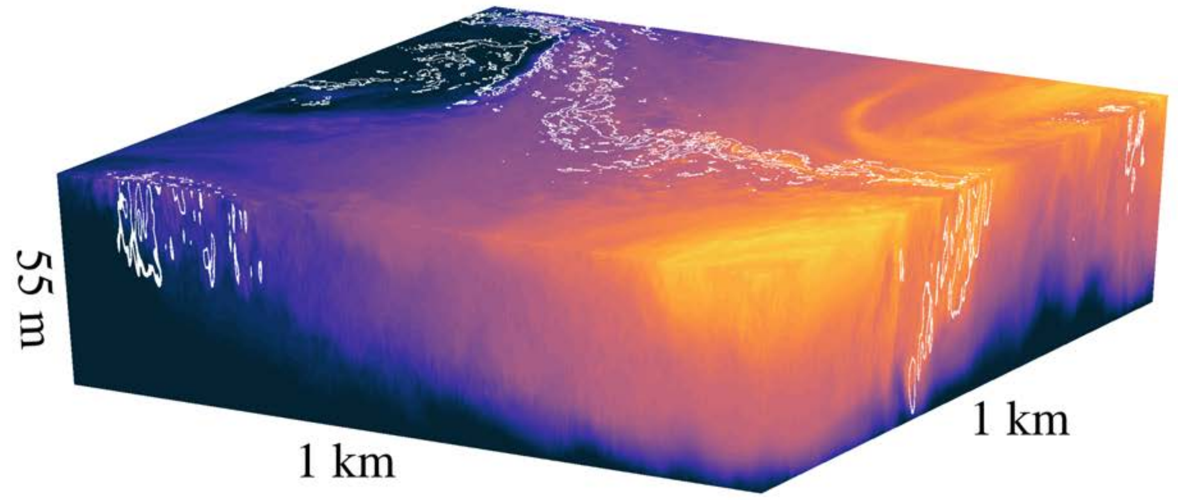

Baroclinic instability

Geostrophic shear production

Buoyancy production

Current feedback effect on EBF-geostrophic shear production:

$$\overline{GSP_{\tau'}} \sim -\left(\frac{u_*^2}{U_a}\right) U_o \Delta U_g$$

ΔU_g is the change in geostrophic velocity across the mixed-layer depth.

Eddy kinetic energy

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Secondary instabilities

3D Turbulence

Dissipation (ϵ)

Mixing

More than a length scale: submesoscale air-sea interaction

- Submesoscale is a **dynamical regime,** may promote the importance of alternate air-sea interaction mechanisms
- The current feedback on stress acts as a source of **Ekman buoyancy flux**, reduces PV destruction by winds
- Modifies the **geostrophic shear production**, effects on energetics may be comparable to the surface wind-work ('eddy-killing')

Wenegrat, J., 2023: The surface current feedback on stress modifies the Ekman buoyancy flux. *In review for JPO.*

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- **Open challenges:** model resolution, cross-scale effects (direct and indirect changes), shared parameter dependencies for many submesoscale processes…

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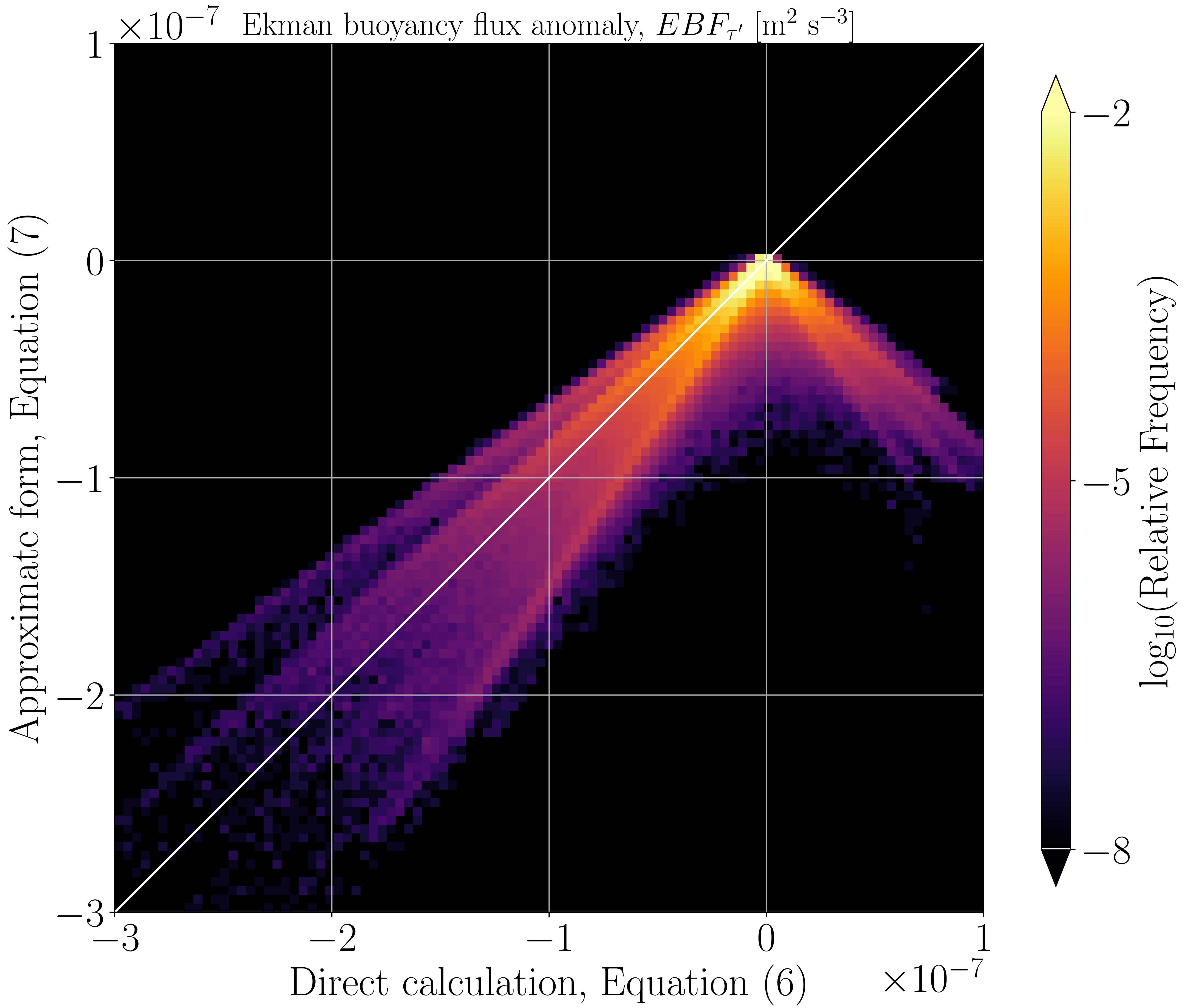
Extras

Current feedback modifies the Ekman buoyancy flux

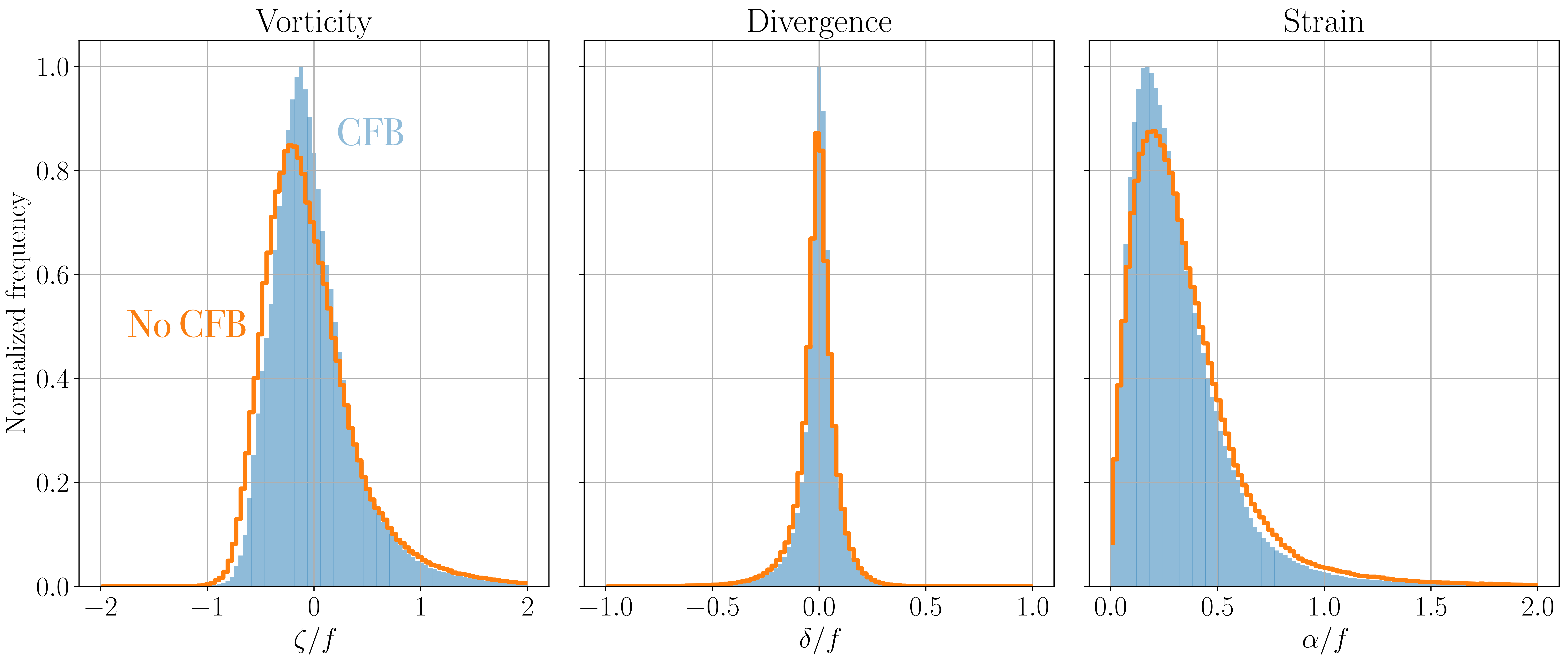


Perturbation Ekman buoyancy flux:

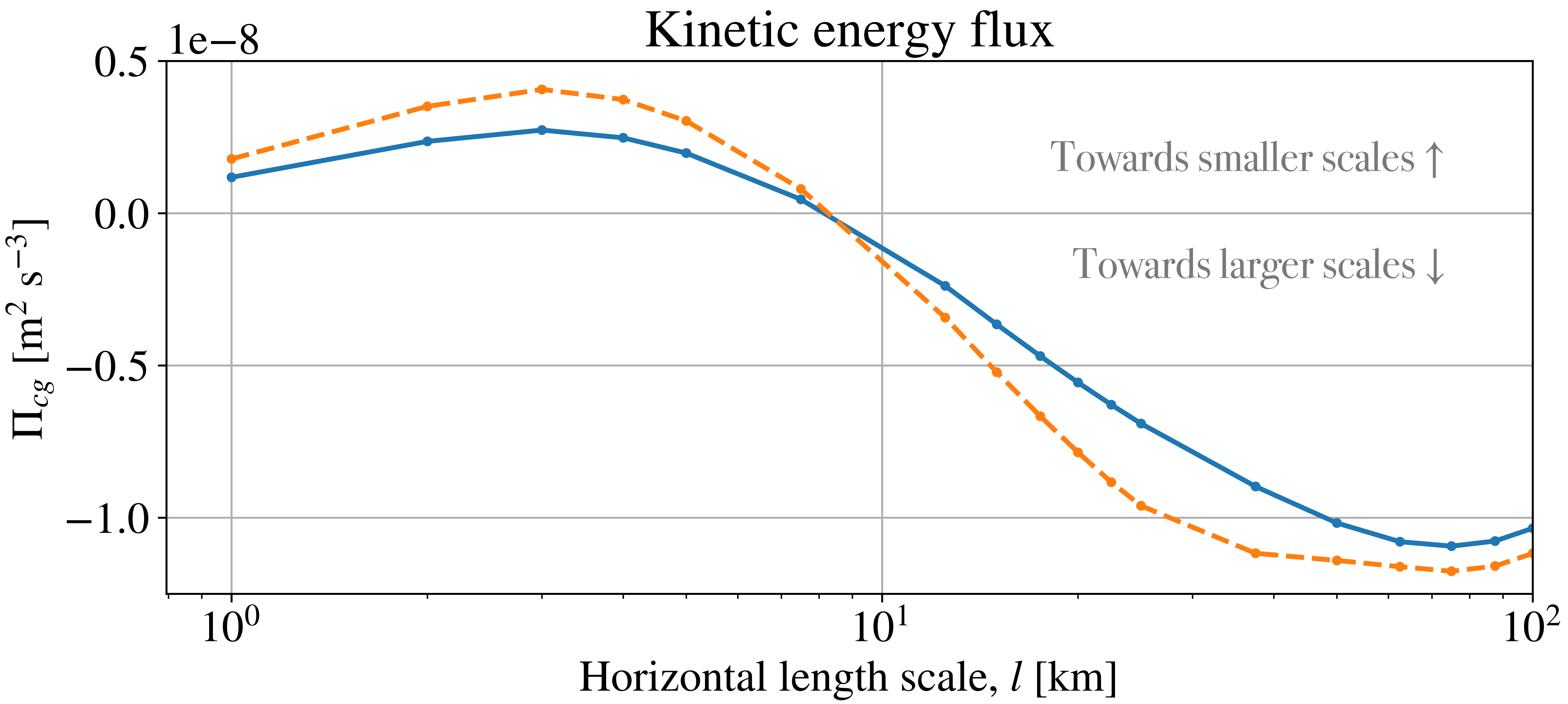
$$EBF_{\tau'} \approx -\frac{3}{2}\frac{\rho_a}{\rho_o}\frac{c_d}{f}|\boldsymbol{U_a}||\boldsymbol{u_o}||\nabla_h b|$$

Suggests the current feedback acts to generate a *source* of buoyancy and PV to the mixed-layer

Current feedback weakens submesoscales

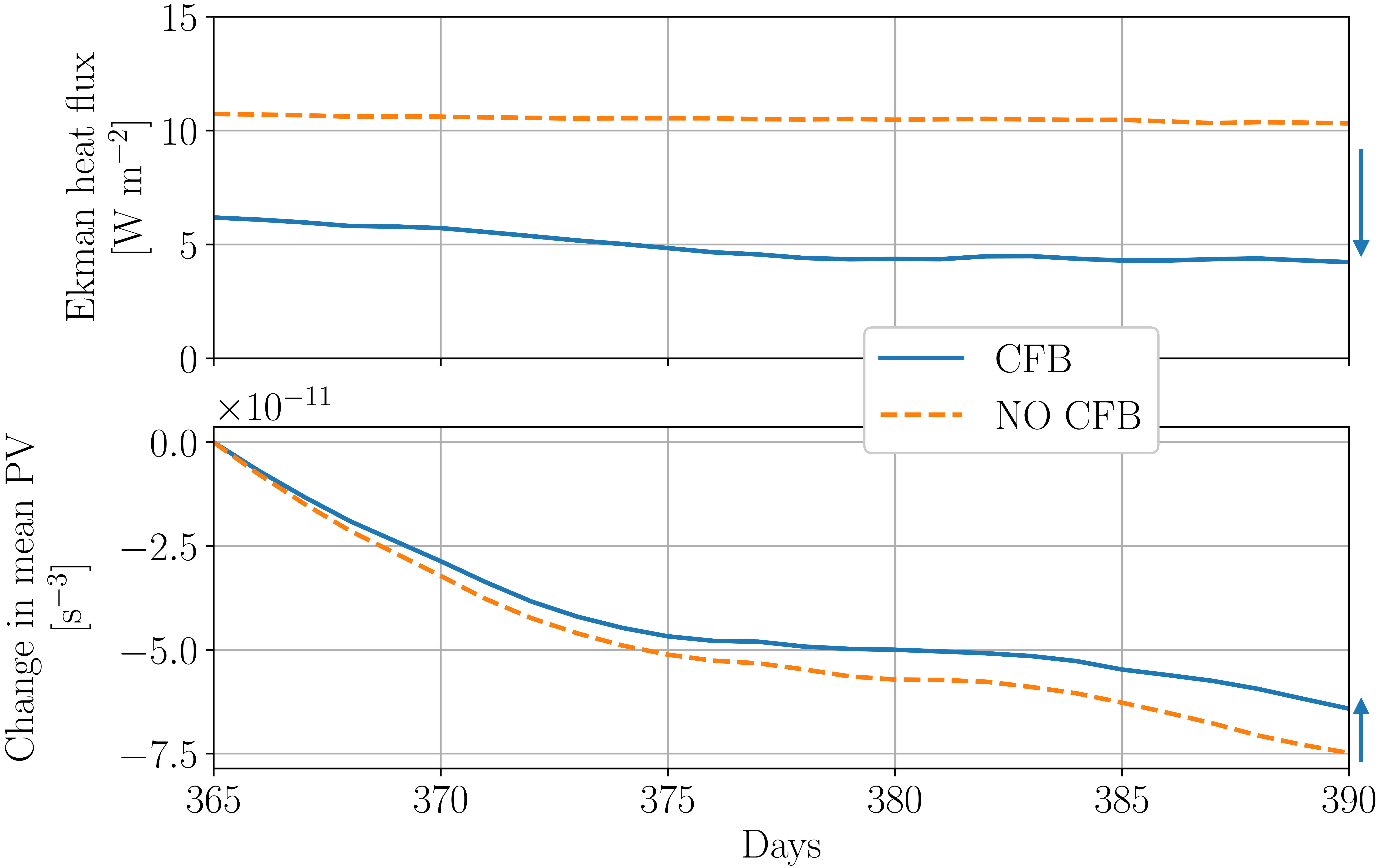


Cross-scale effects of air-sea interaction



- Air-sea interaction modifies all scales.
- Many submesoscale processes share parameter dependencies (eg. MLI, EBF, SI, TTW)
- Indirect effects of air-sea interaction may be as important as direct effects.

Current feedback acts as buoyancy & PV *source*



50% decrease in mean EBF

15% decrease in PV destruction

(Includes diabatic contributions)

*simulations without buoyancy flux