Langmuir Turbulence in the Oceanic Mixed Layer

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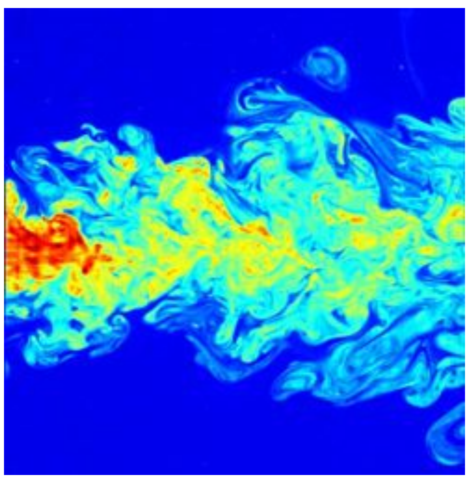
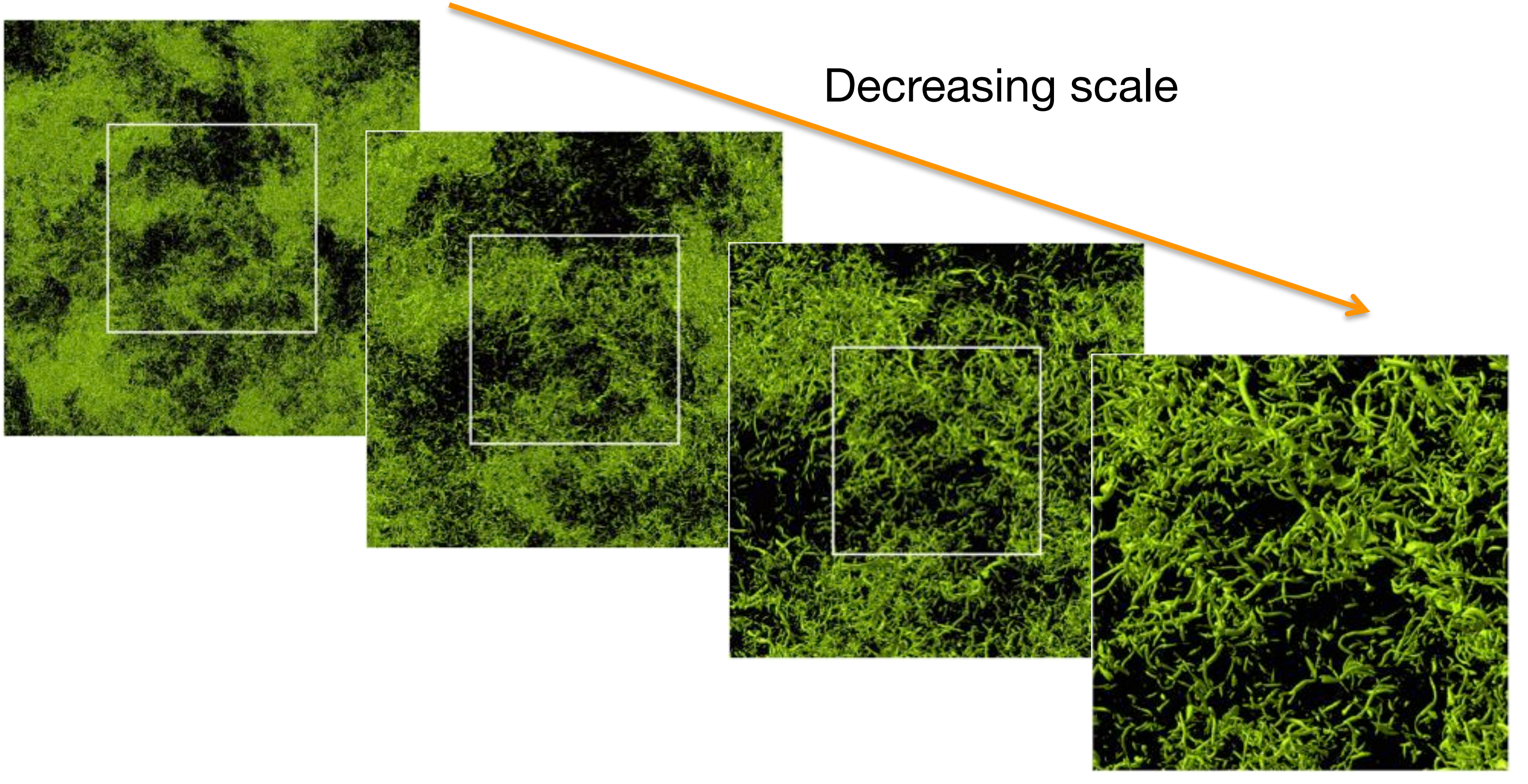
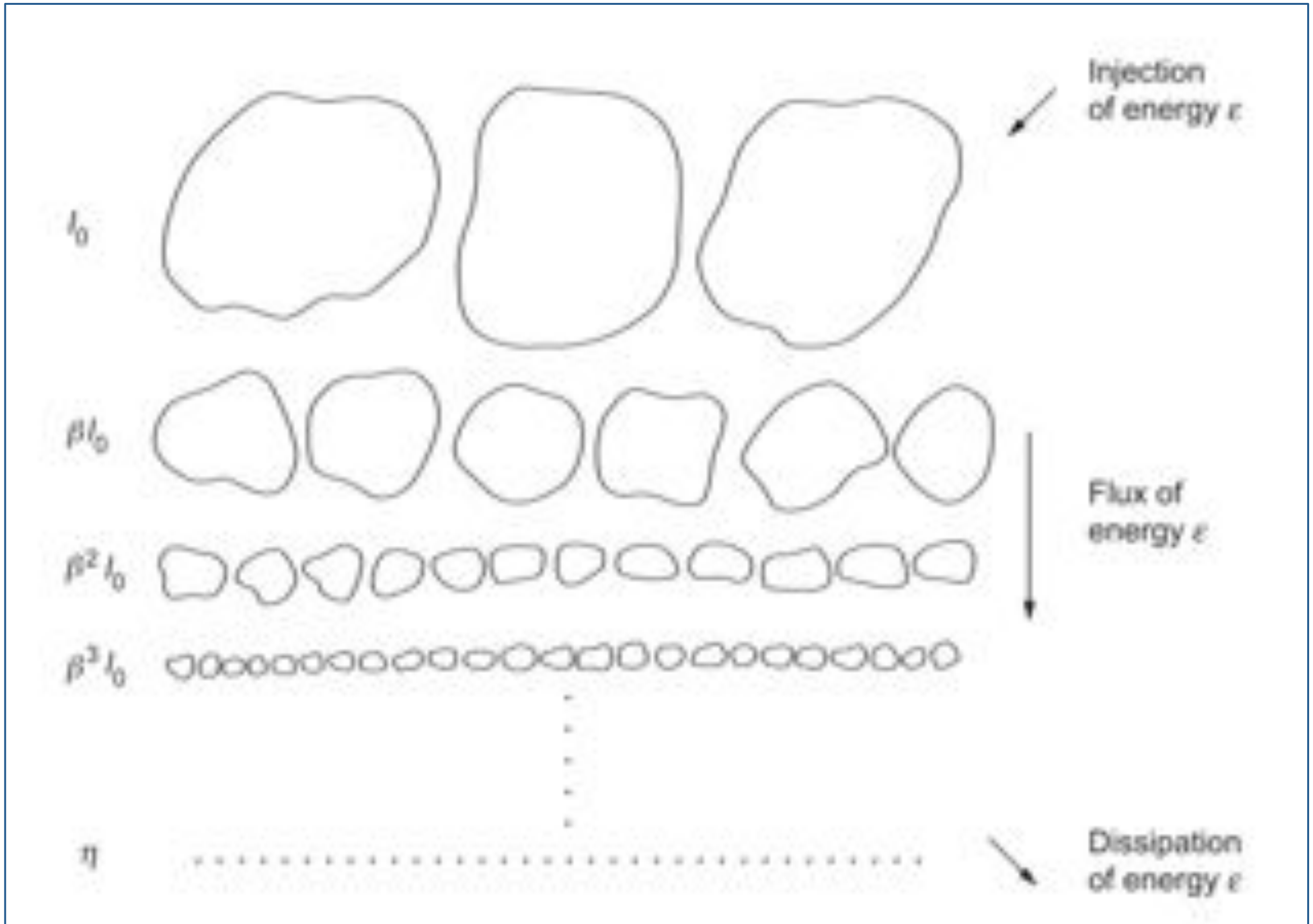
Turbulent Flows



Spatial and Temporal Scale Ranges



The Energy Cascade



Reynolds Number

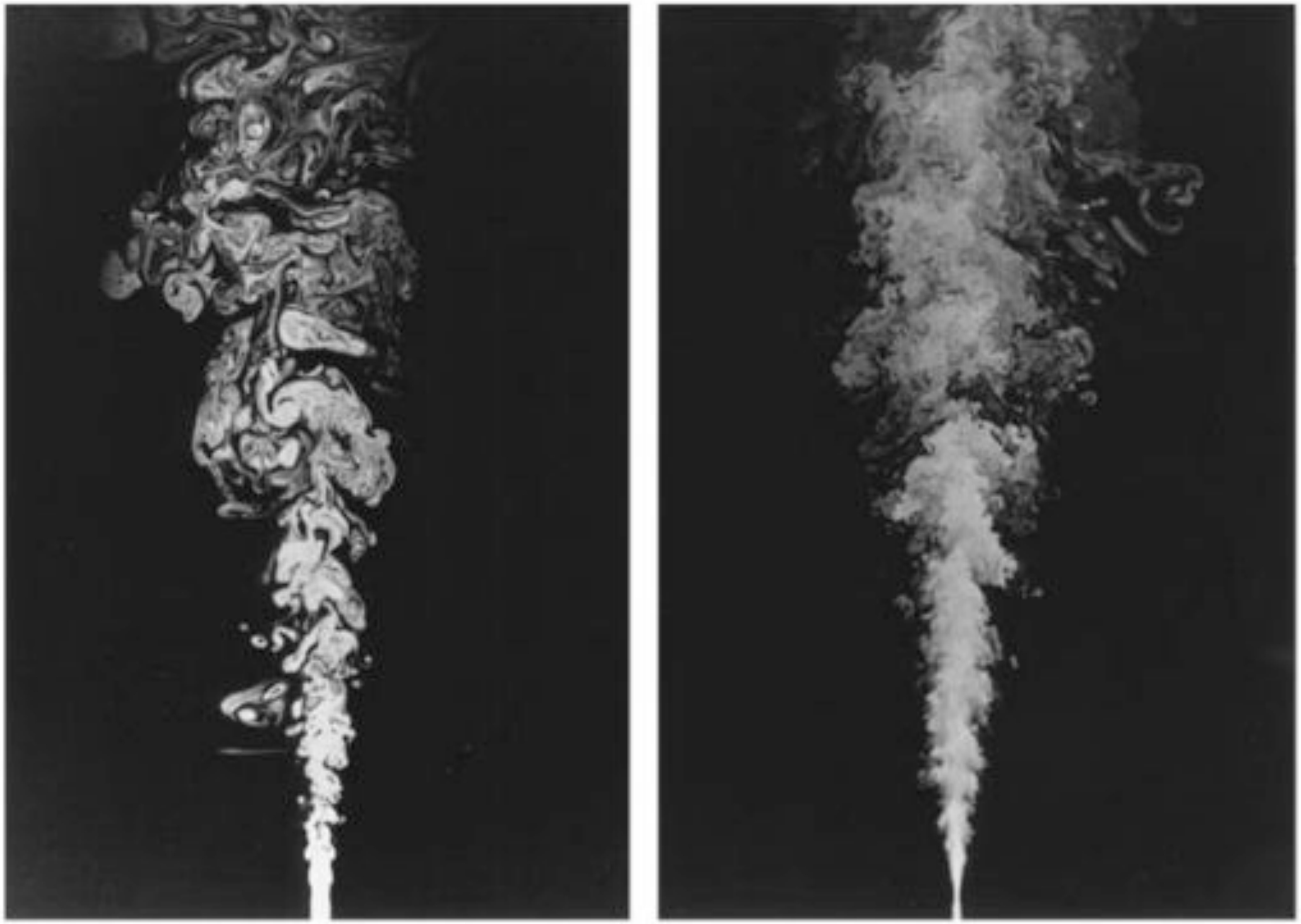
Three dimensional turbulent eddies are stretched and torn by nonlinear inertial processes, creating smaller and smaller scales until velocity gradients become large enough and viscous dissipation becomes strong enough for kinetic energy to be transferred into heat.

Reynolds number:

Re = Nonlinear Inertial Processes / Viscous Processes = UL/v

Spatial and temporal scale ranges ~ $Re^{3/4}$

Turbulence and Reynolds Number



Geophysical Scale Ranges

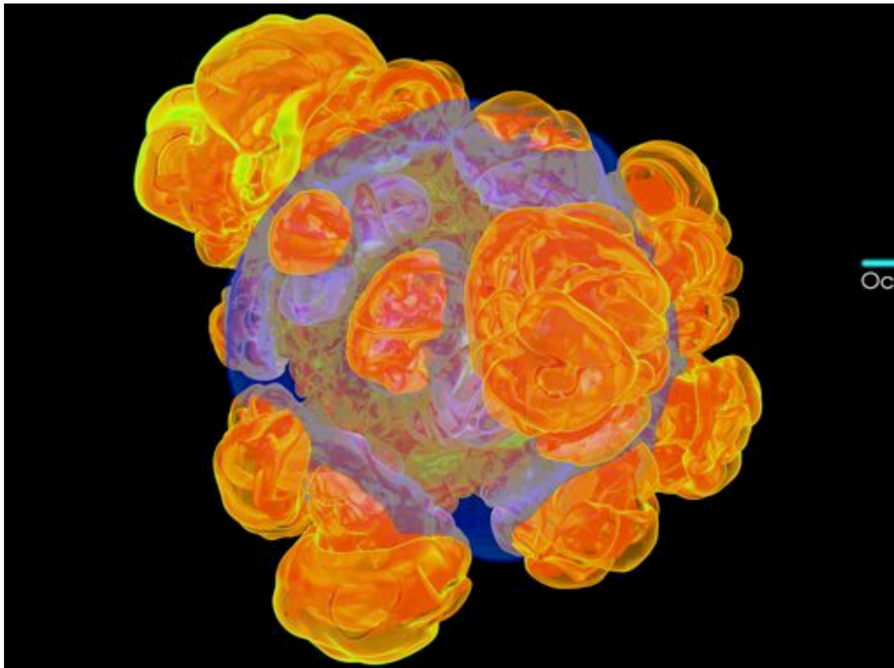
Largest scale motions ~ 1 x 10^6 m
Smallest scale motions ~ 1 x 10^{-3} m

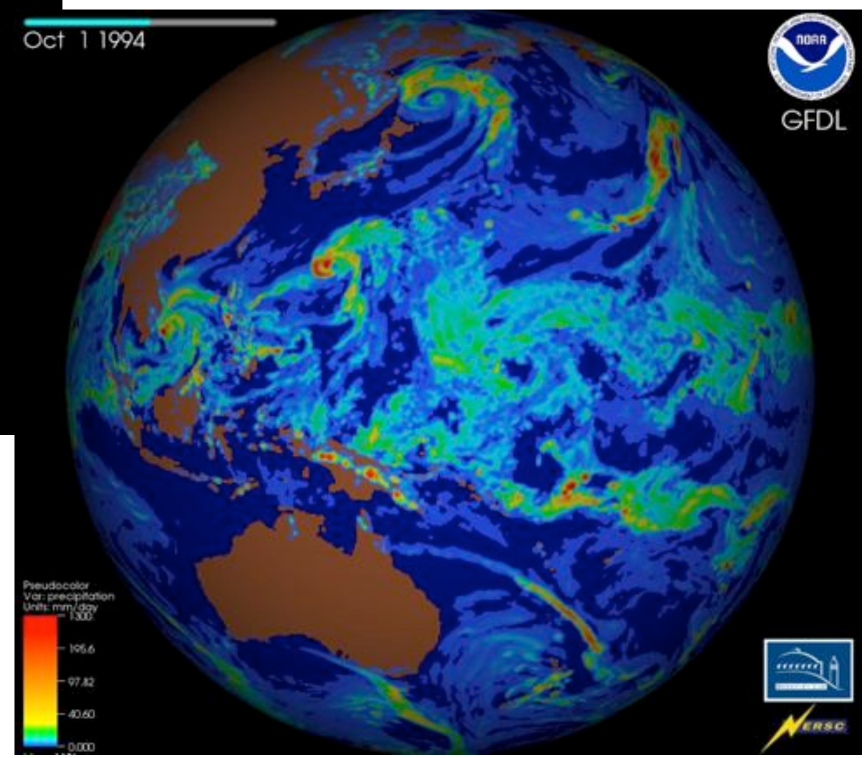
Nine orders of magnitude!

Computational Simulations of Turbulence

The wide range of scales is a big problem for computational simulations of turbulent flows

Computational Simulations of Turbulence





The Computational Challenge

Earth surface area ~ 5×10^{14} m^2
Atmosphere height ~ 1×10^3 m
Ocean depth ~ 1×10^3 m

Total simulation volume ~ 1×10^{18} m^3
Grid cell volume ~ 1×10^{-9} m^3

Total number of grid cells ~ 1×10^{27}

1 day simulation ~ 1×10^5 s
Time step ~ 0.1 s

Total number of time steps ~ 1×10^6

The Computational Challenge Continued

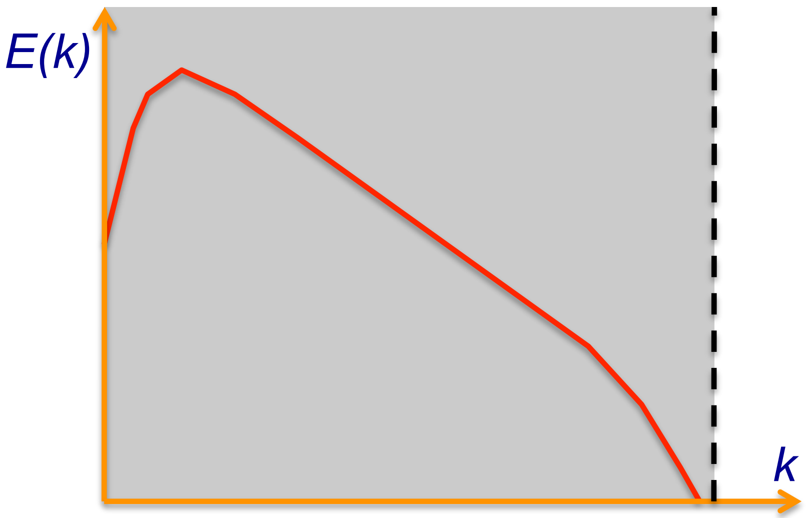
Total number of grid cells ~ 1 x 10^{27}
Total number of time steps ~ 1 x 10^{6}

Consider a "quantum" computer that can calculate one cell at one step in the time it takes for light to cross a hydrogen atom (~1 x 10^{-19} s)

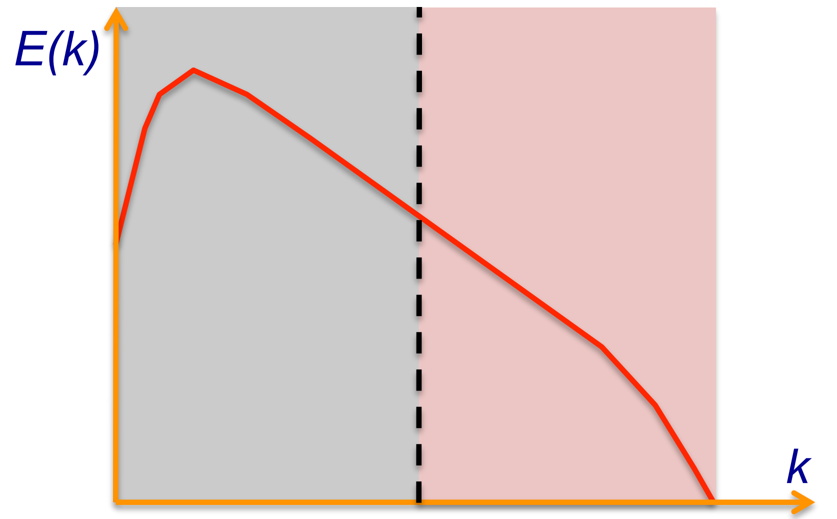
Total simulation time ~ 1 x 10^{6} years!

Turbulence Modeling

Direct numerical simulation (DNS):
Solve all scales, high cost, high fidelity

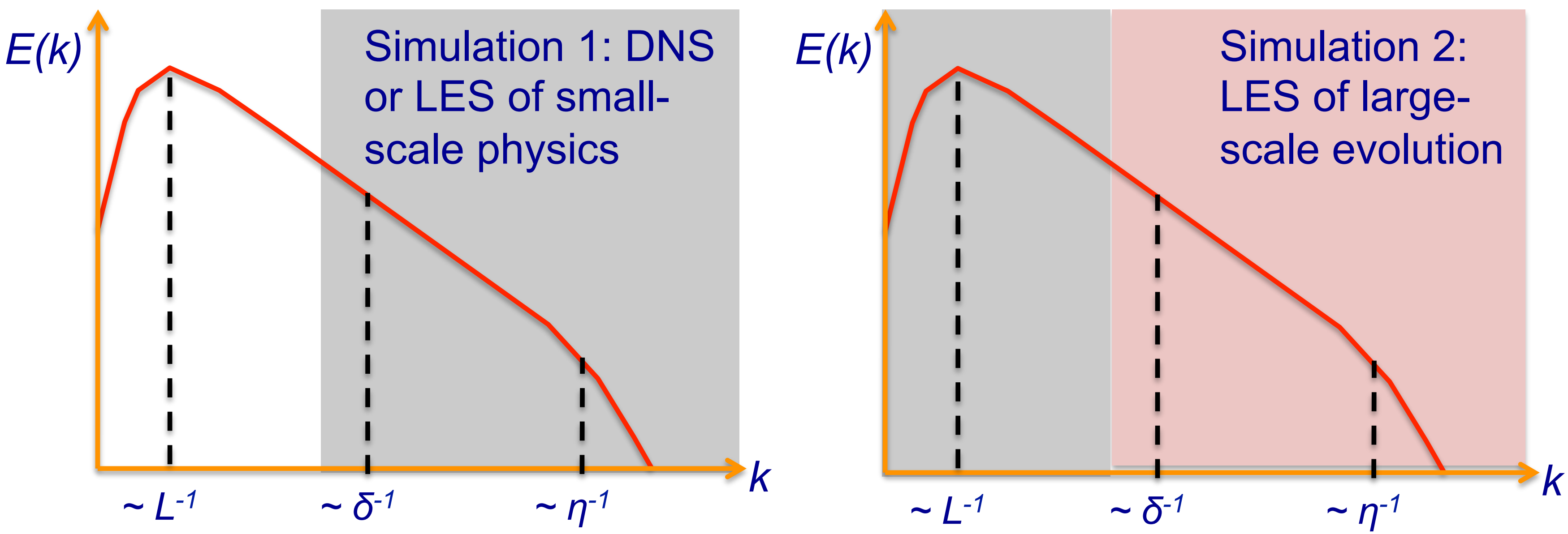


Large eddy simulation (LES):
Resolve only large scales, intermediate cost and fidelity

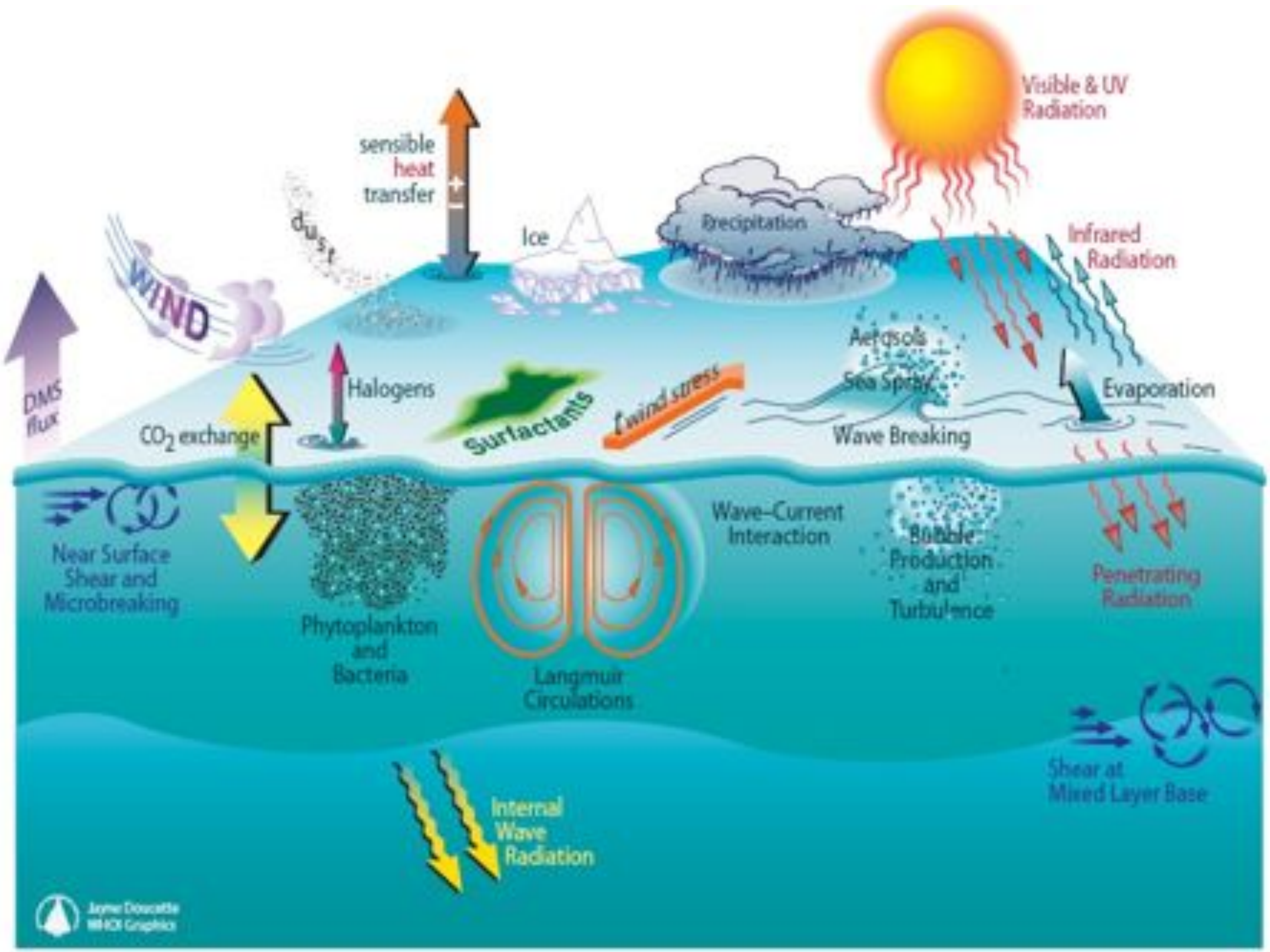


Model Development

Develop subgrid scale models based on physics, exact governing equations, and simulations of reduced scale ranges



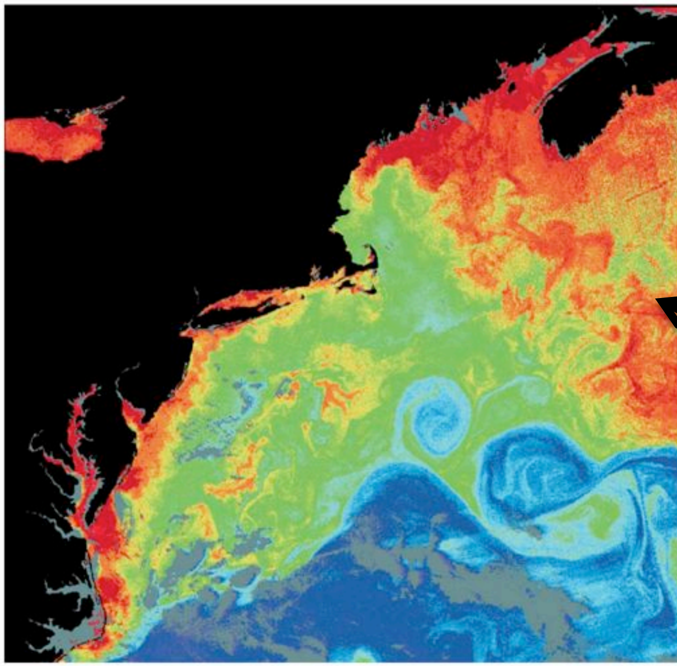
The Oceanic Mixed Layer



Langmuir Turbulence

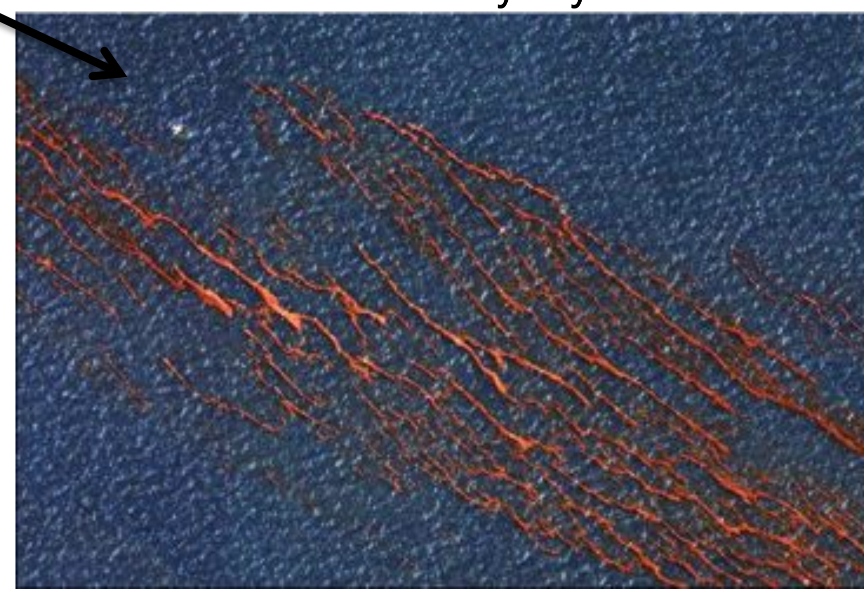
Langmuir-Submesoscale Interactions

What are the interactions between Langmuir cells and large submesoscale (~1-10 km) eddies?

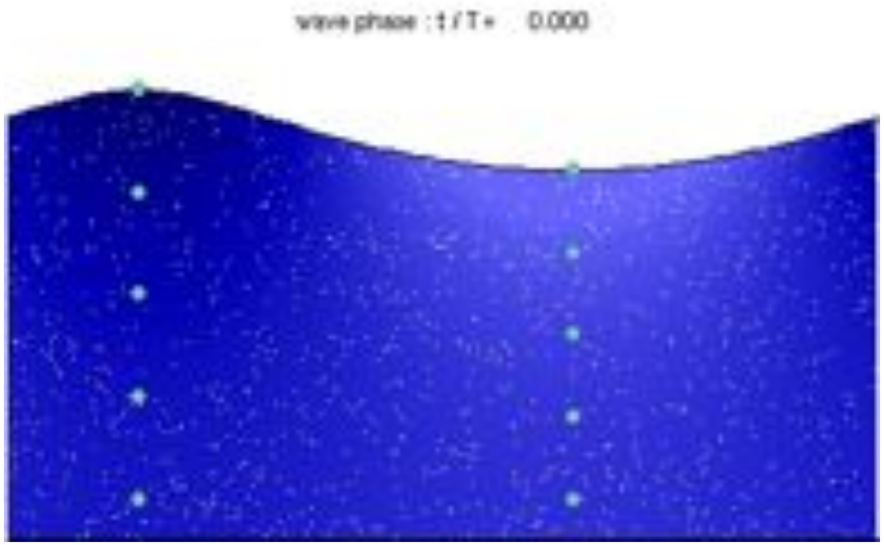


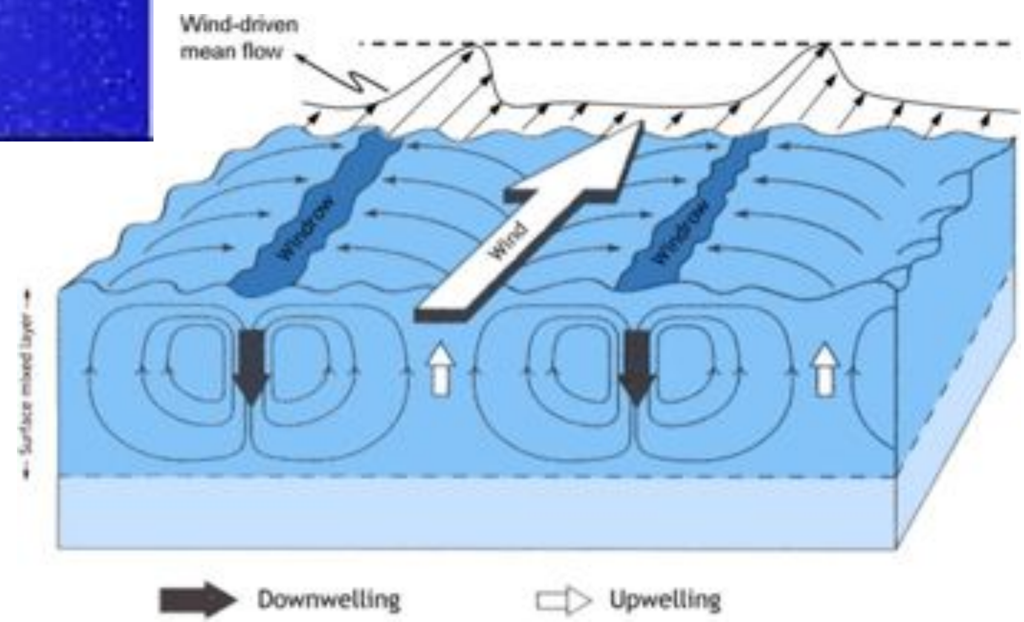
Submesoscale eddies form from fronts and filaments and restratify boundary layer; associated with symmetric instability

Small-scale turbulence mixes and destratifies boundary layer



Stokes Drift and Langmuir Cells





The Craik-Leibovich Equations

The Craik-Leibovich Boussinesq (CLB) equation is the wave or phase-averaged Boussinesq equation

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{\omega} + \boldsymbol{f}) \times \boldsymbol{u}_L = -\nabla\left(p + \frac{1}{2}|\boldsymbol{u}_L|^2\right) + b\hat{\boldsymbol{z}}$$

$$\frac{\partial b}{\partial t} + \boldsymbol{u}_L \cdot \nabla b = 0$$

$$\nabla \cdot \boldsymbol{u} = 0$$

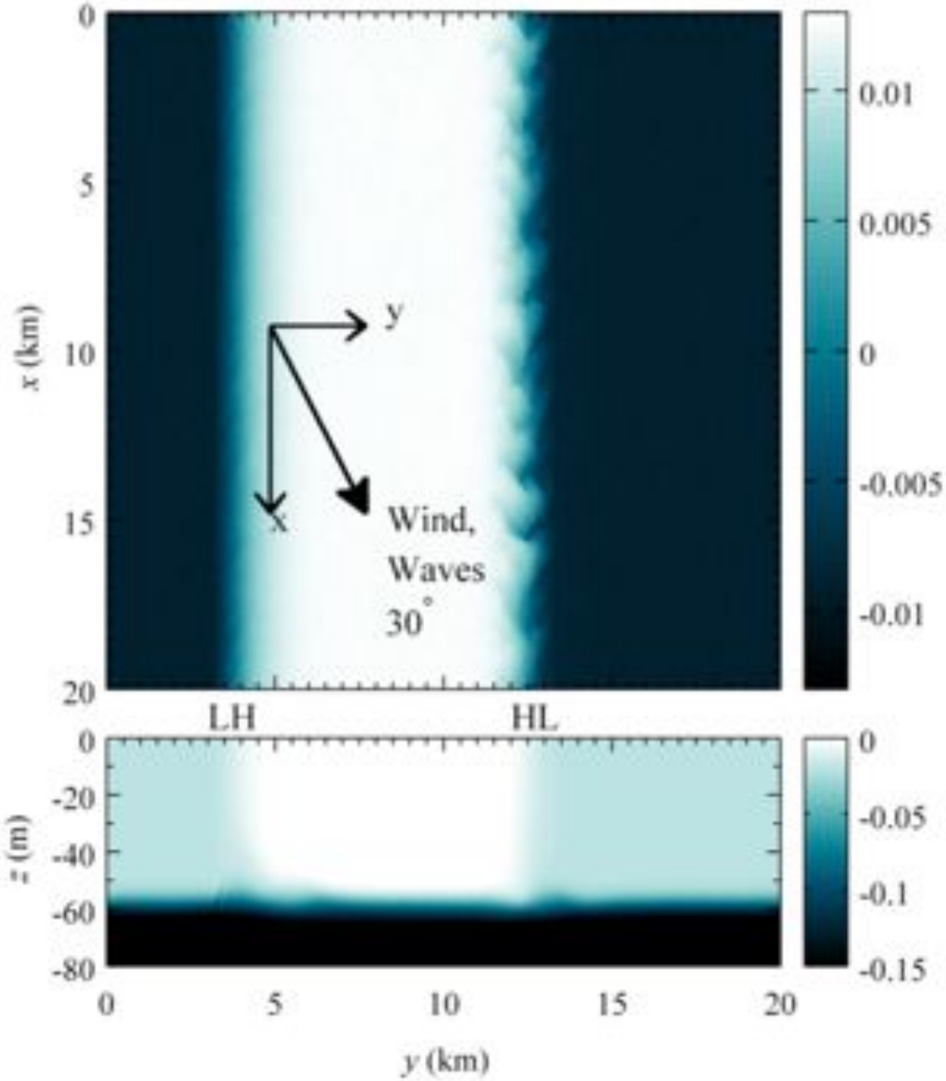
The Lagrangian velocity replaces the Eulerian velocity

$$\boldsymbol{u}_L \equiv \boldsymbol{u} + \boldsymbol{u}_s \qquad \boldsymbol{u}_s = u_s(z)\left[\cos(\vartheta_s)\hat{\mathbf{x}} + \sin(\vartheta_s)\hat{\mathbf{y}}\right]$$

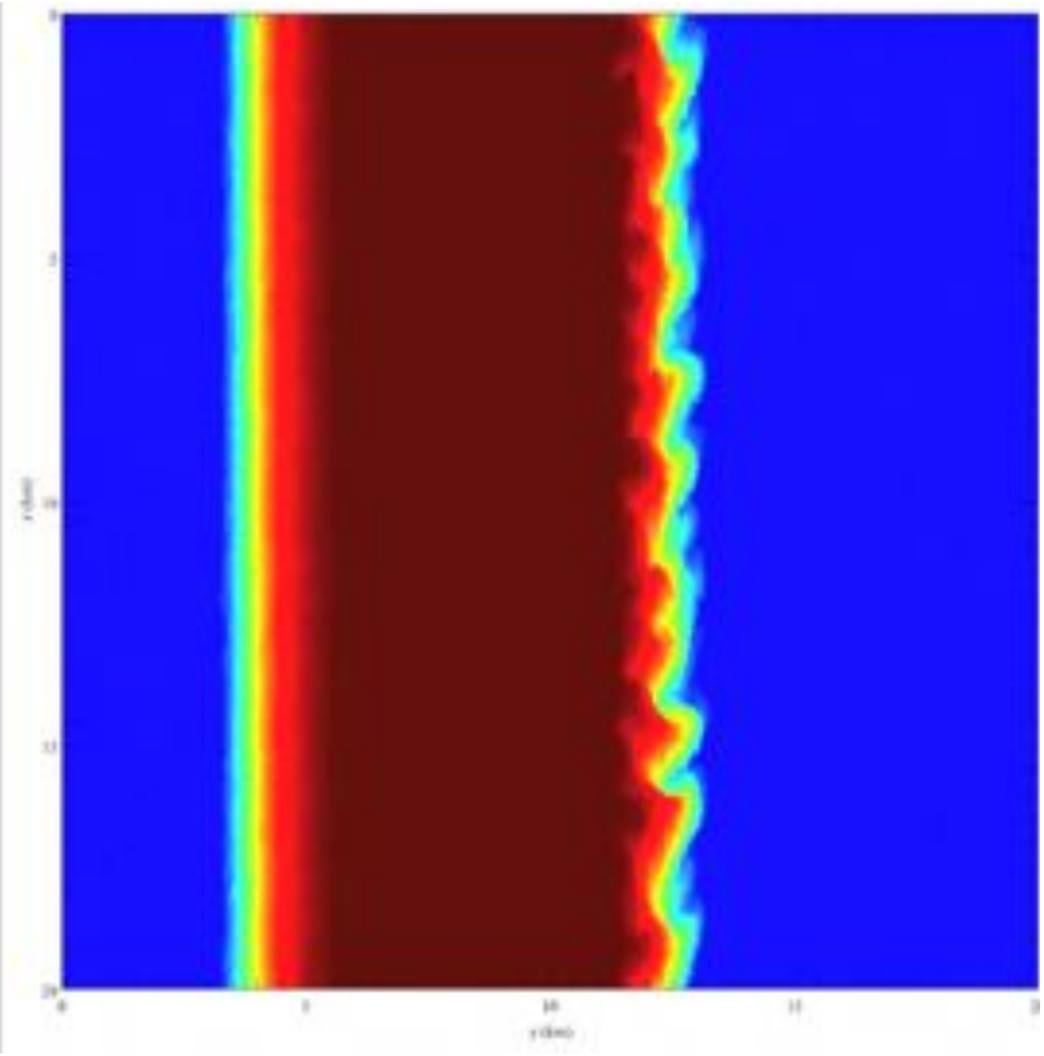
Simulations of Langmuir Turbulence

	LT	ST
Physical domain size, $L_x \times L_y \times L_z$	20km×20km×-160m	20km×20km×-160m
Computational grid size, $N_x \times N_y \times N_z$	$4096 \times 4096 \times 128$	$4125 \times 4125 \times 128$
Grid resolution, $\Delta_x \times \Delta_y \times \Delta_z$	4.9m×4.9m×1.25m	4.9m×4.9m×1.25m
Reference temperature, θ_0	290.16K	290.16K
Reference density, ρ_0	1000kg/m^3	1000kg/m^3
Coriolis parameter, $\boldsymbol{f}$	$0.729 \times 10^{-4}\text{s}^{-1}\hat{\mathbf{z}}$	$0.729 \times 10^{-4}\text{s}^{-1}\hat{\mathbf{z}}$
Initial mixed layer depth, $H_{ML,0}$	50m	50m
Friction velocity, u^*	$5.46 \times 10^{-3}\text{m/s}$	$5.46 \times 10^{-3}\text{m/s}$
Surface wind stress magnitude, τ	$0.025\ \text{N m}^{-2}$	$0.025\ \text{N m}^{-2}$
Surface wind angle, ϑ_w	30°	30°
Initial surface temperature cooling, $\overline{w'\theta'}(z=0)$	-5W/m^2	-5W/m^2
Horizontal buoyancy gradient, $M^2 = \lvert\partial b/\partial y\rvert$	$4f^2 = 2.1 \times 10^{-8}\text{s}^{-2}$	$4f^2 = 2.1 \times 10^{-8}\text{s}^{-2}$
Thermocline stratification, $N^2 = \partial b/\partial z$	$5.3\times10^{-9}\text{s}^{-2}$	$5.3\times10^{-9}\text{s}^{-2}$
Surface stokes drift, $U_s(z=0m)$	0.063m/s	–
Stokes drift angle, ϑ_s	30°	–
Turbulent Langmuir number, $La_t = \sqrt{u^*/U_s(0)}$	0.29	–

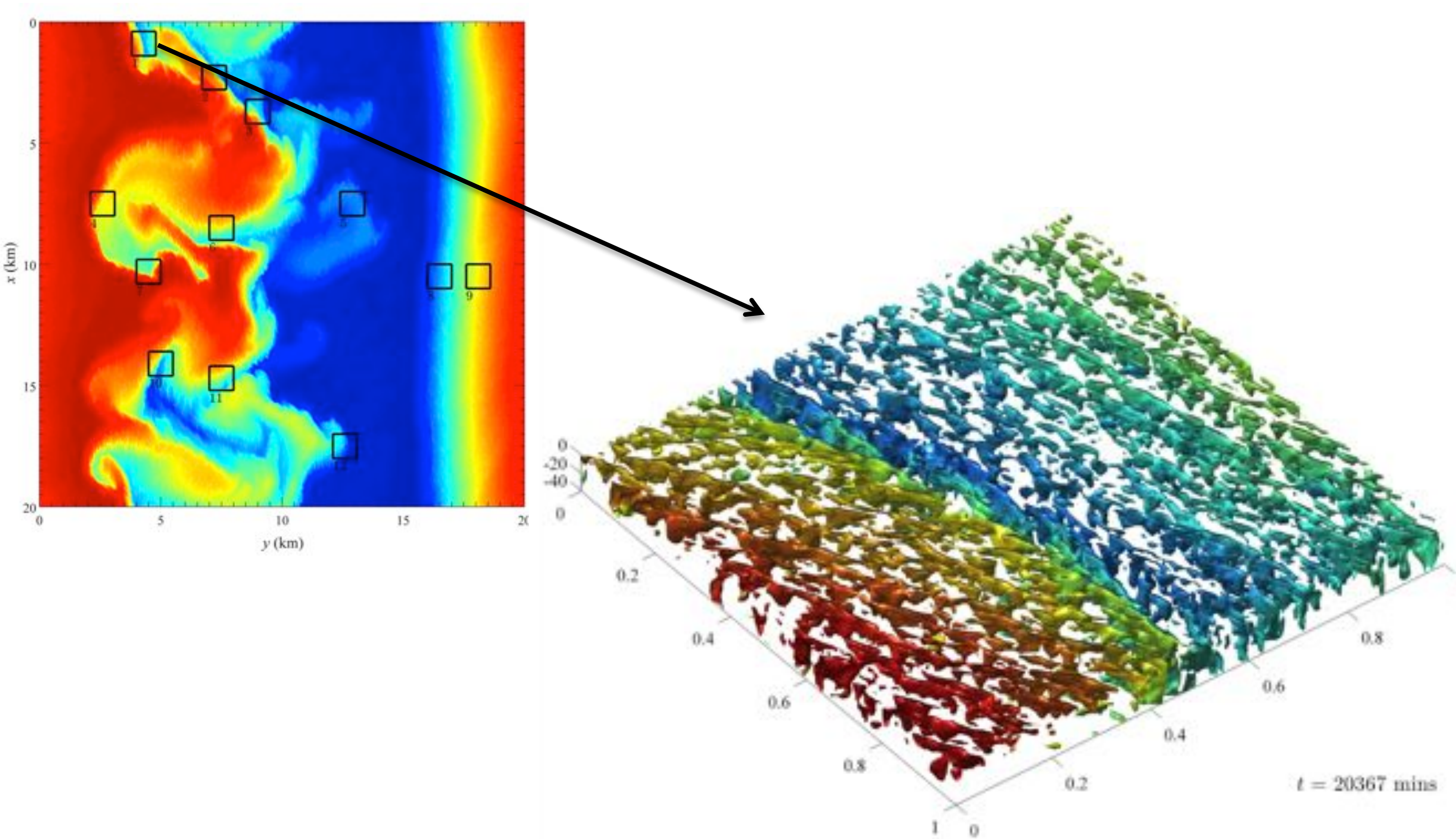
Initial Condition



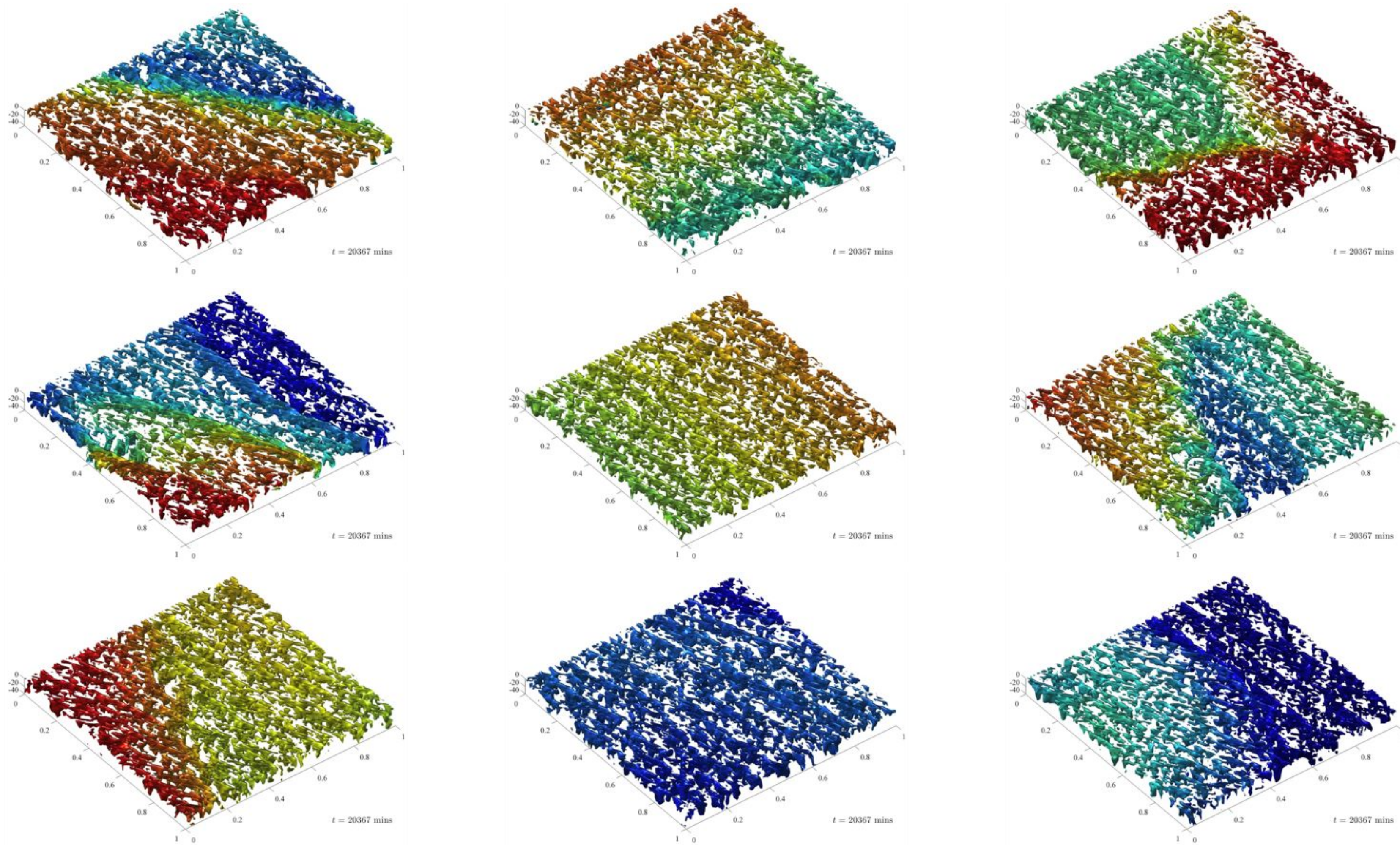
Submesoscale Evolution



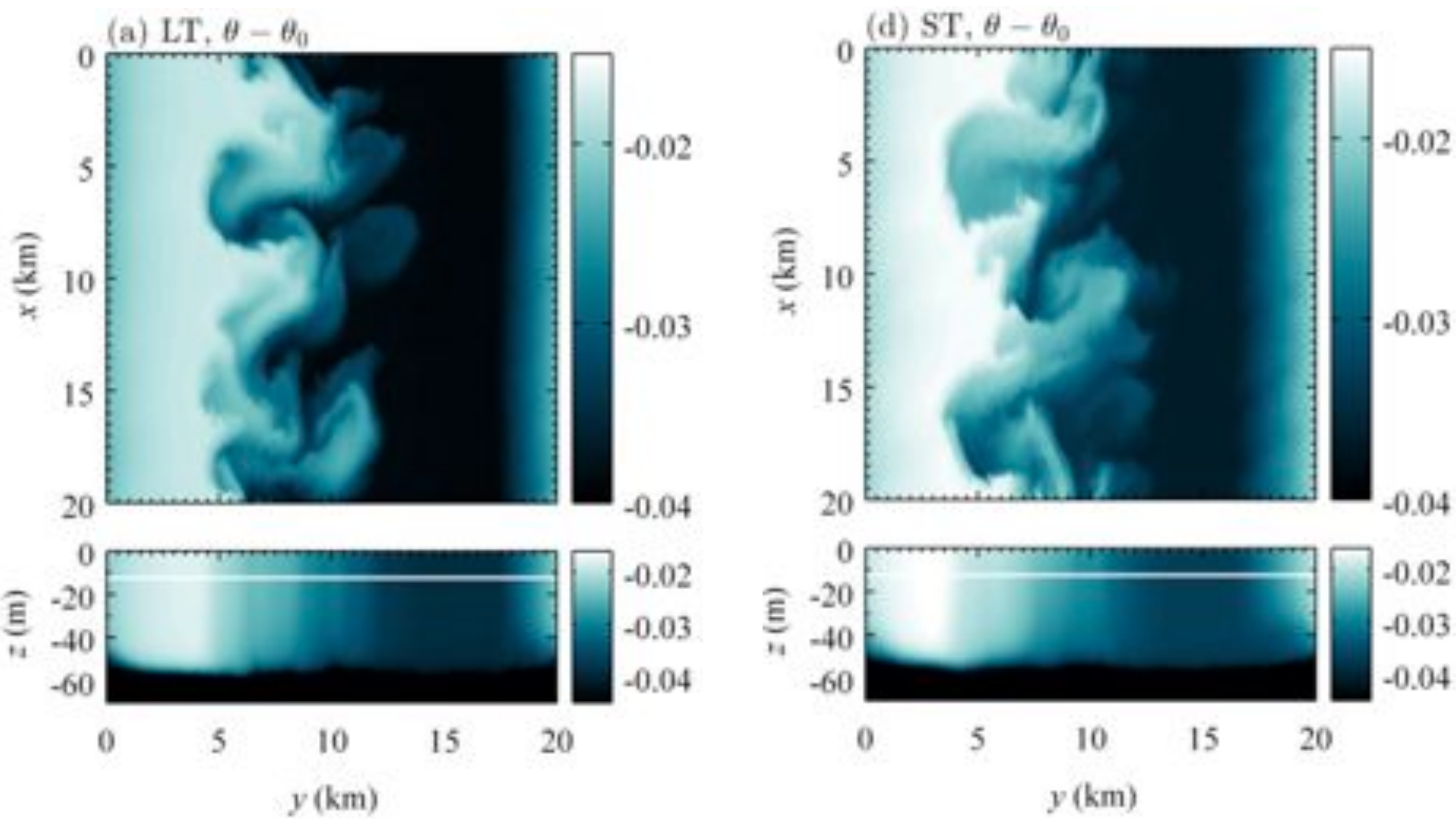
Small-Scale Evolution



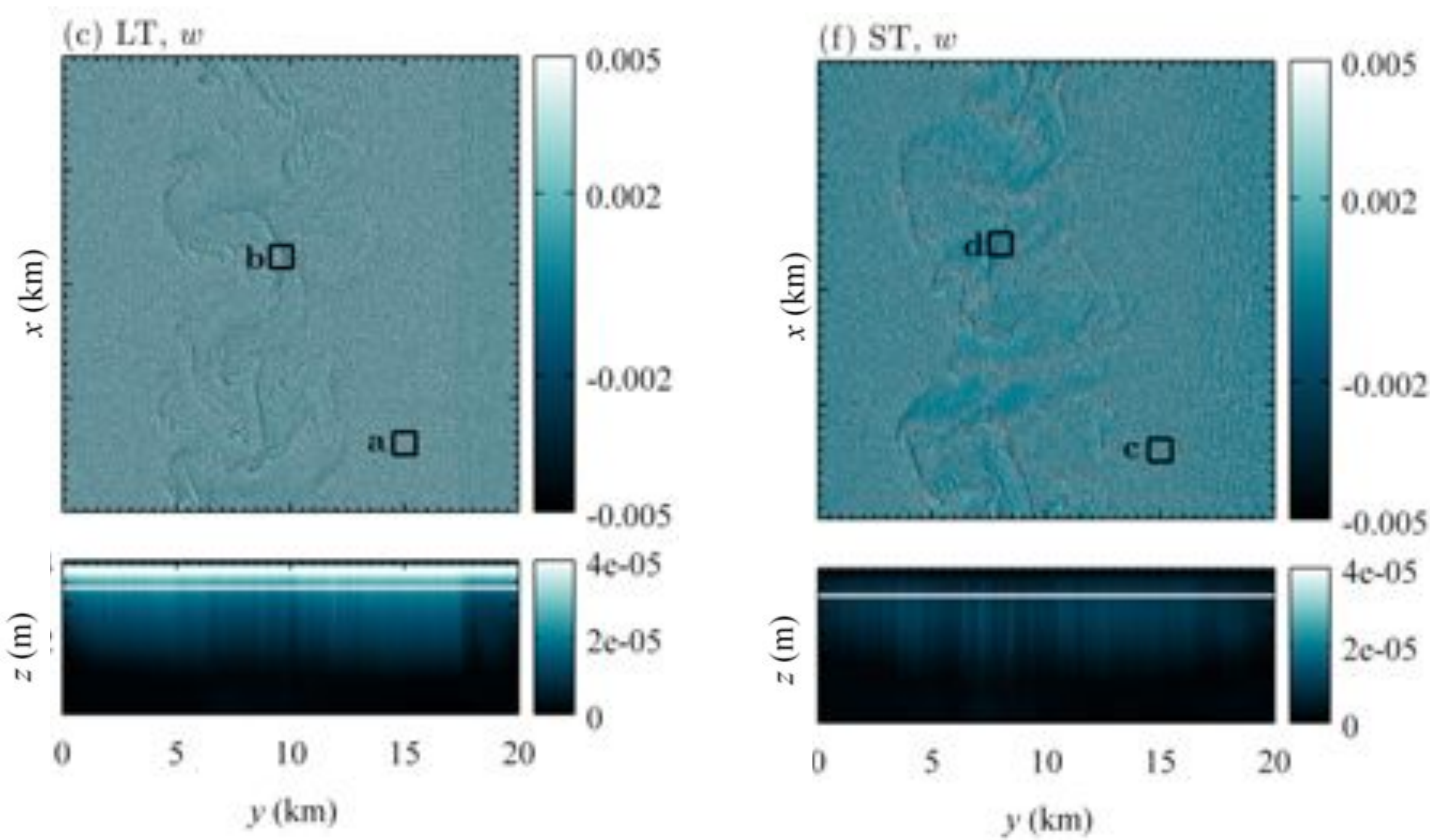
Small-Scale Evolution



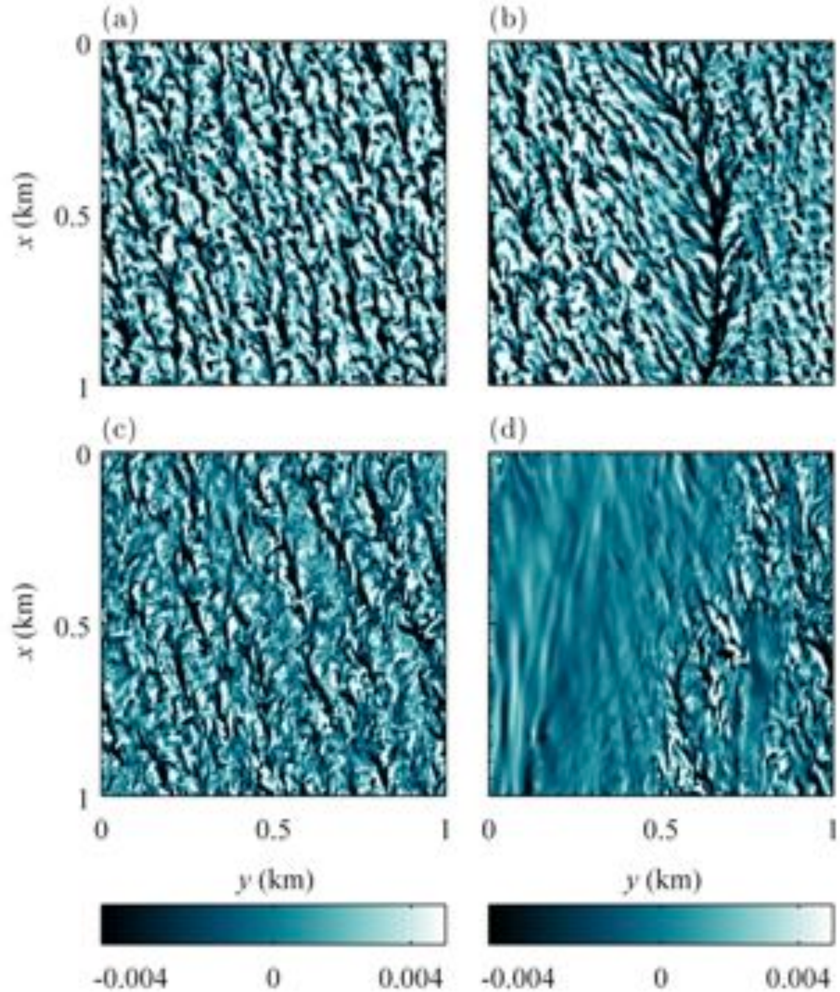
Temperature



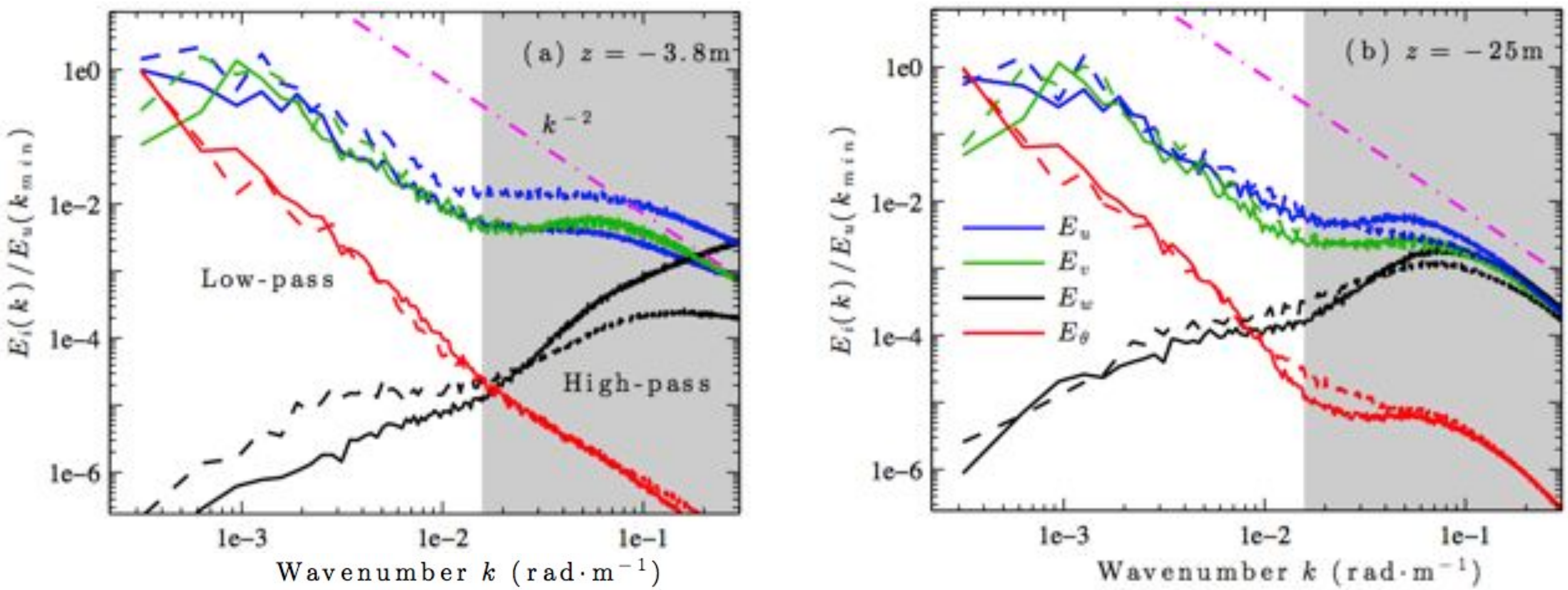
Vertical Velocity



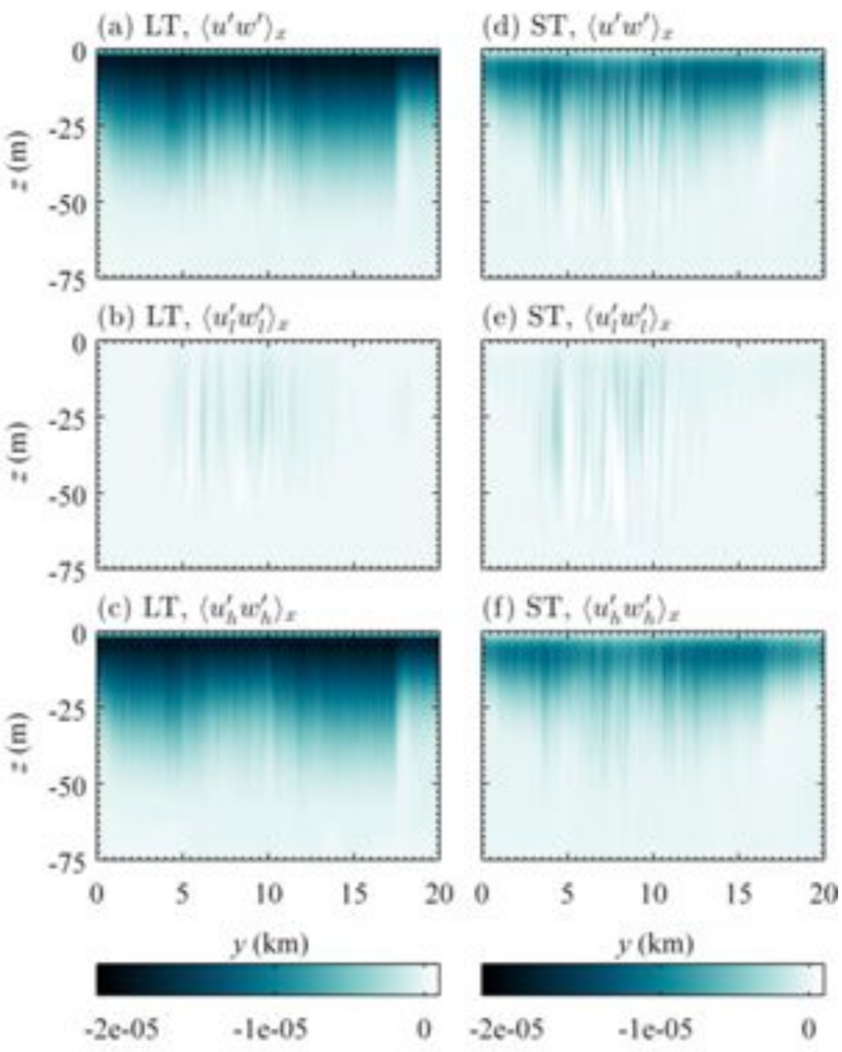
A Closer Look at Vertical Velocity

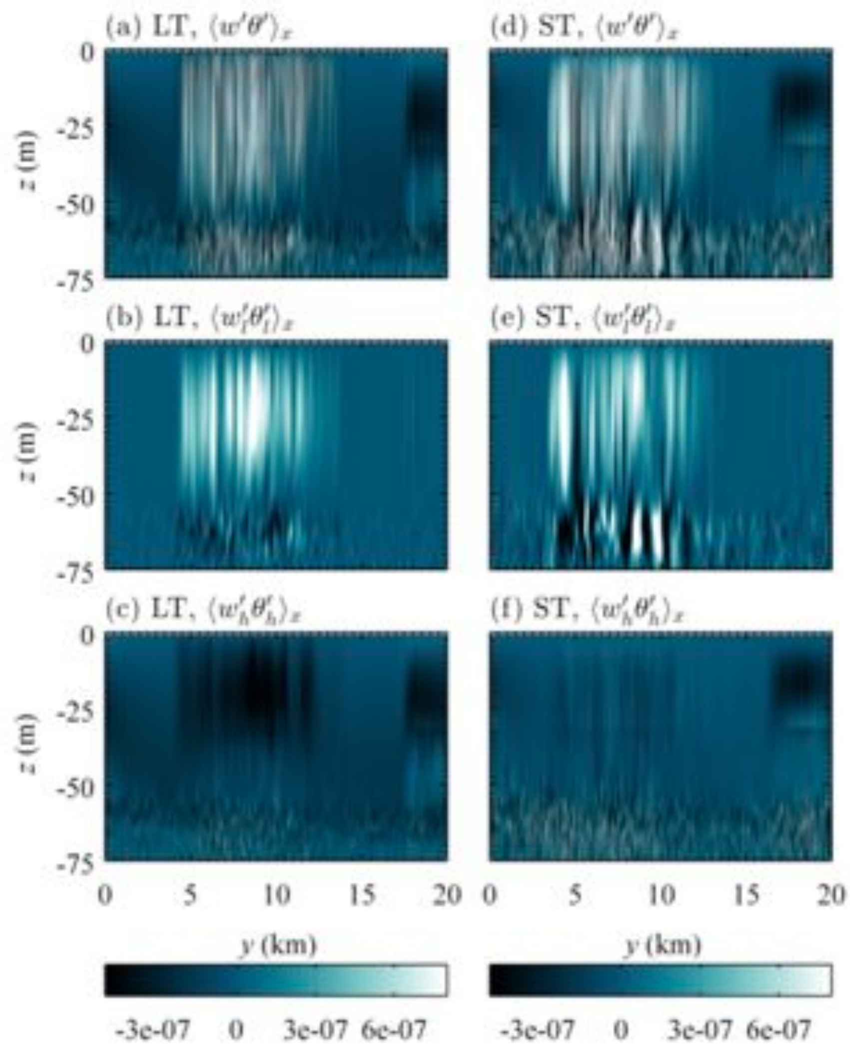


Kinetic Energy Spectra

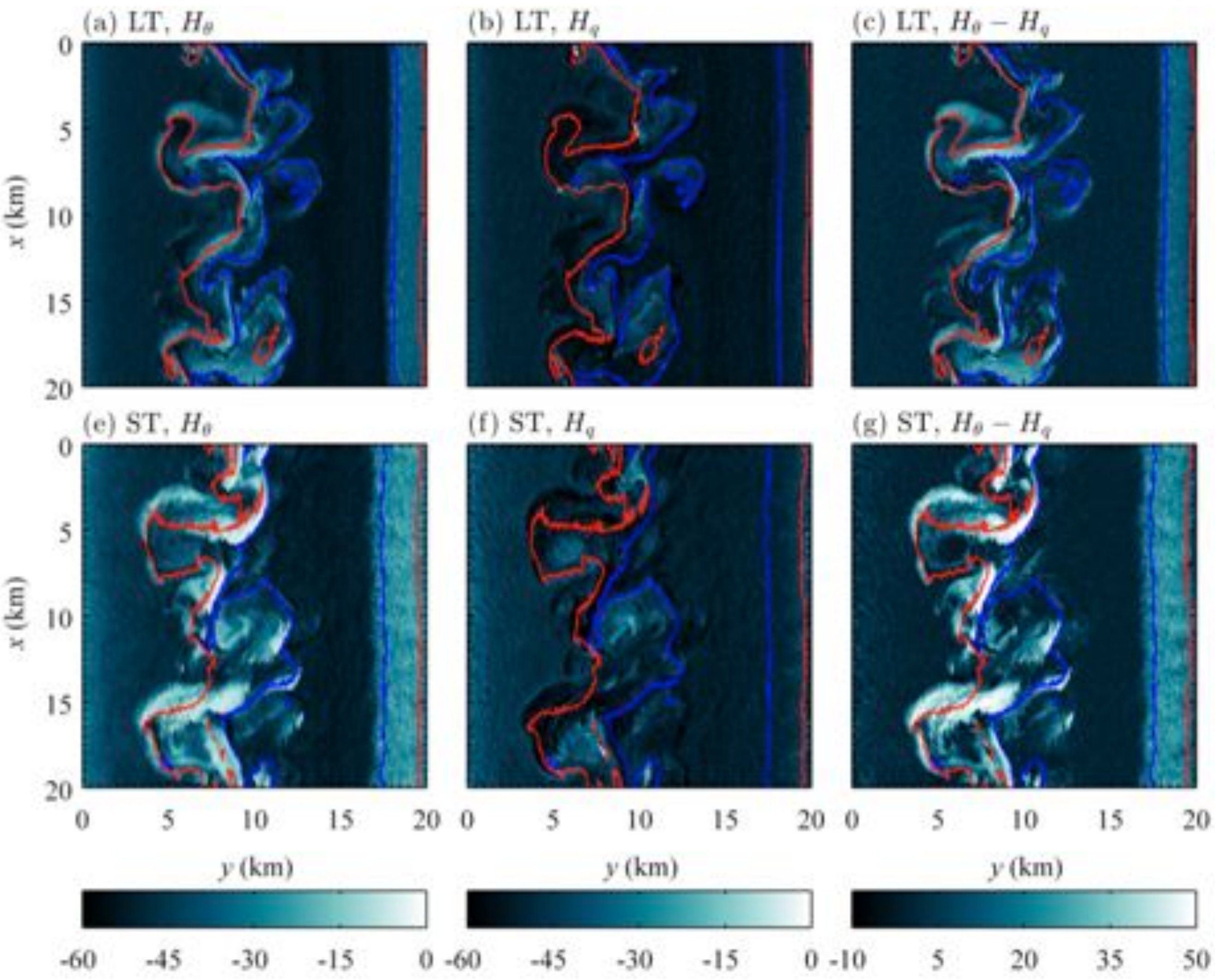


Momentum and Temperature Fluxes





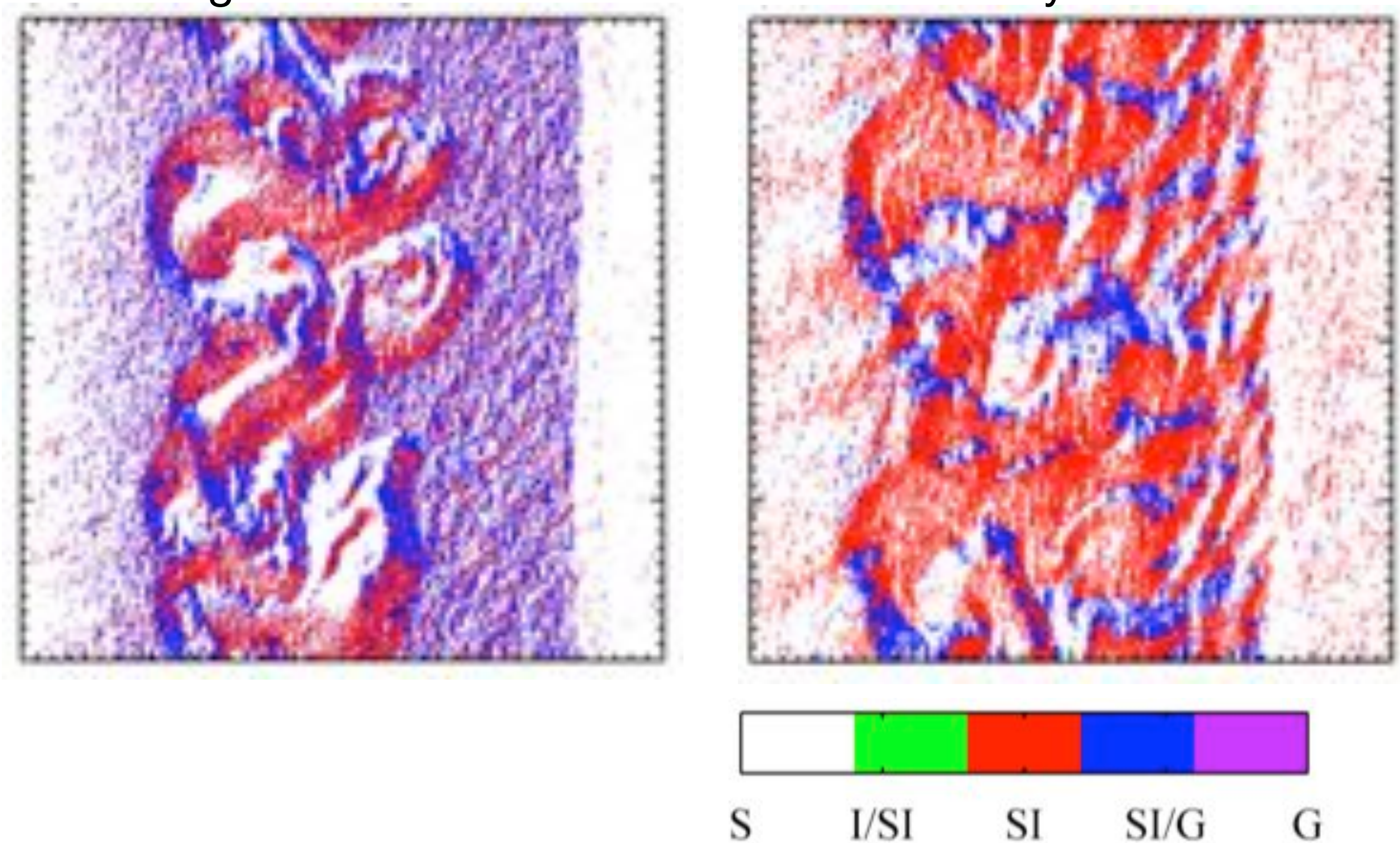
Mixed Layer Depth



Instabilities

Langmuir Turbulence

Shear-Only Turbulence



Summary and Conclusions

- Turbulent flows are enormously difficult to understand and simulate computationally
- In geophysical flows we attempt to reduce the computational load through subgrid scale modeling
- There are weak effects of Langmuir turbulence on submesoscale motions
- Submesoscale motions themselves have a substantial effect on Langmuir turbulence
- Langmuir turbulence should be parameterized in larger scale climate and weather simulations

Collaborators: Baylor Fox-Kemper, Keith Julien, Greg Chini, Luke Van Roekel, Sean Haney

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