INTERACTION OF THE LOWER ATMOSPHERE AND UPPER OCEAN: LES PROCESS STUDIES

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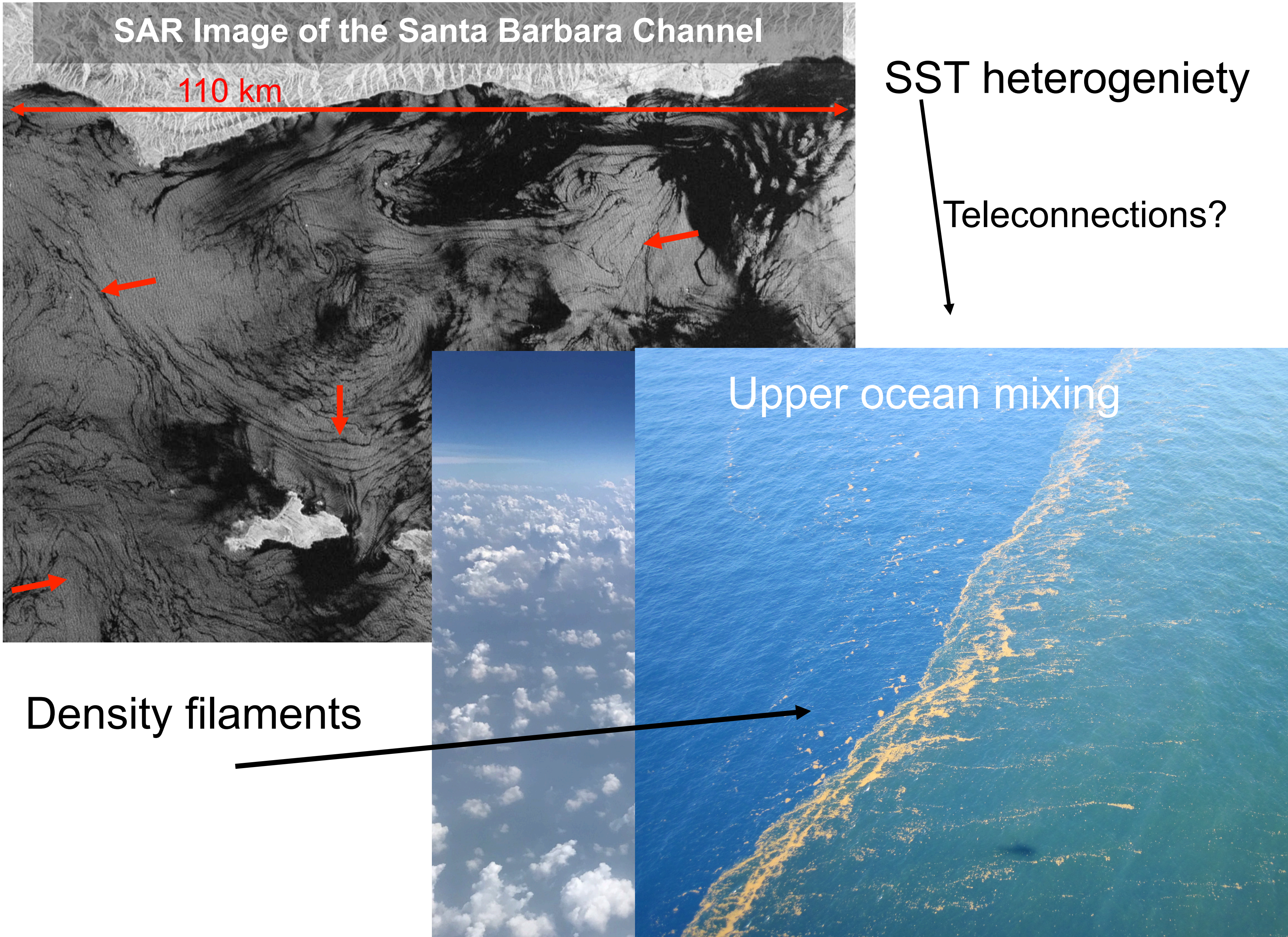

SAR Image of the Santa Barbara Channel
110 km
SST heterogeneity
Teleconnections?
Upper ocean mixing
Density filaments

IMPACTS OF HETEROGENEITY ON THE ABL AND OBL

Motivation:

- Ocean eddies, fronts, filaments (mesoscale/submesoscale turbulence) $\rightarrow$ strong heterogeneous horizontal buoyancy gradients and currents at varying scales

LES APPLICATIONS AND PROCESS STUDIES

Atmospheric BLs:

- Spatially homogeneous BLs
- Coupling with a spectrum of moving water waves
- Passive scalars
- Dispersion/diffusion with Lagrangian particles
- Boundary layer clouds

Oceanic BLs:

- Wave effects using Craik-Leibovich asymptotics
- Submesoscale density filaments + BLs
- Coupling with measured winds, fluxes, and WW3
- Stochastic breakers, bubbles, ...
- Idealized hurricane boundary layers

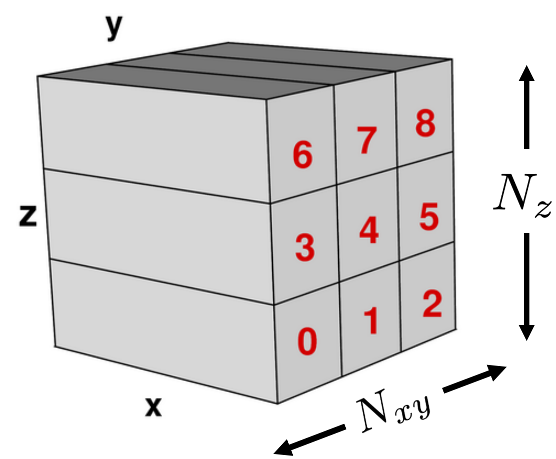
Meshes:

- 10^9 to 10^{10} gridpoints

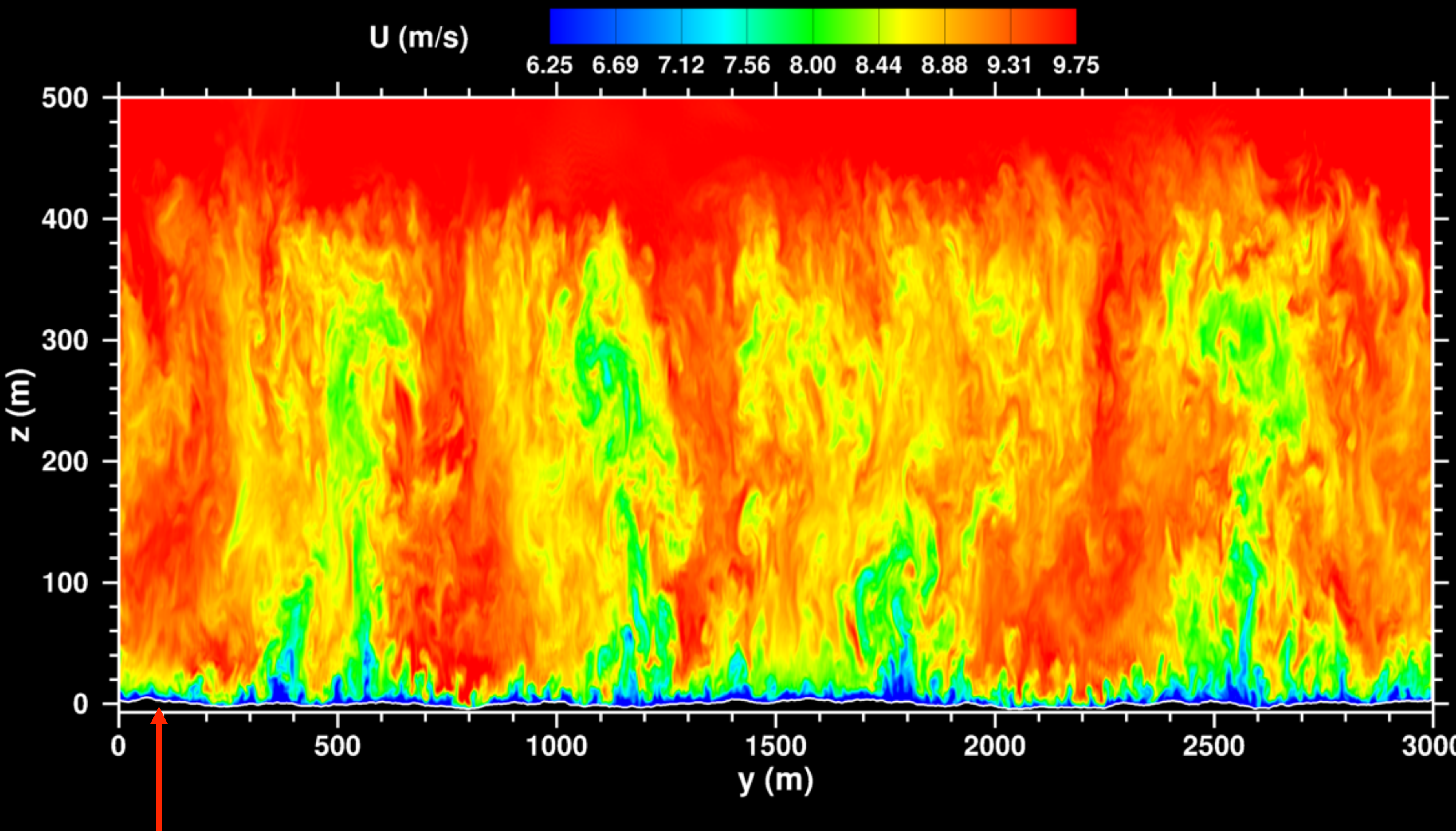
LES 2D MPI decomposition

Core count $N_{tot} = N_z \times N_{xy}$

Parallelization of $\nabla^2 p = s$



U Contours in yz-plane, Ug = 10 m/s, Q_* = 0.01 K m/s
Shear-convective rolls, homogeneous SST



Wavy boundary: Hs ~ 6 m **Grid mesh: dx~3 m, dz~1 m**

ABL PLANS FOR ATOMIC/EUREC^{4}A

LES process studies:

- At what scale(s) does the marine ABL "feel" ocean SST?
- Impact of SST variability on:
  - Entrainment
  - Top-down and bottom-up scalar transport
  - Horizontal variation of vertical fluxes
  - Surface fluxes
  - Momentum and scalar budgets
- Role of wind magnitude and direction
- Role of boundary-layer depth z_i and stability z_i/L
- Role of currents?
- Role of surface waves?
- Site simulations using measured forcing(s)?

LES OF A SPATIALLY EVOLVING ABL: FRINGE METHOD

Developers:

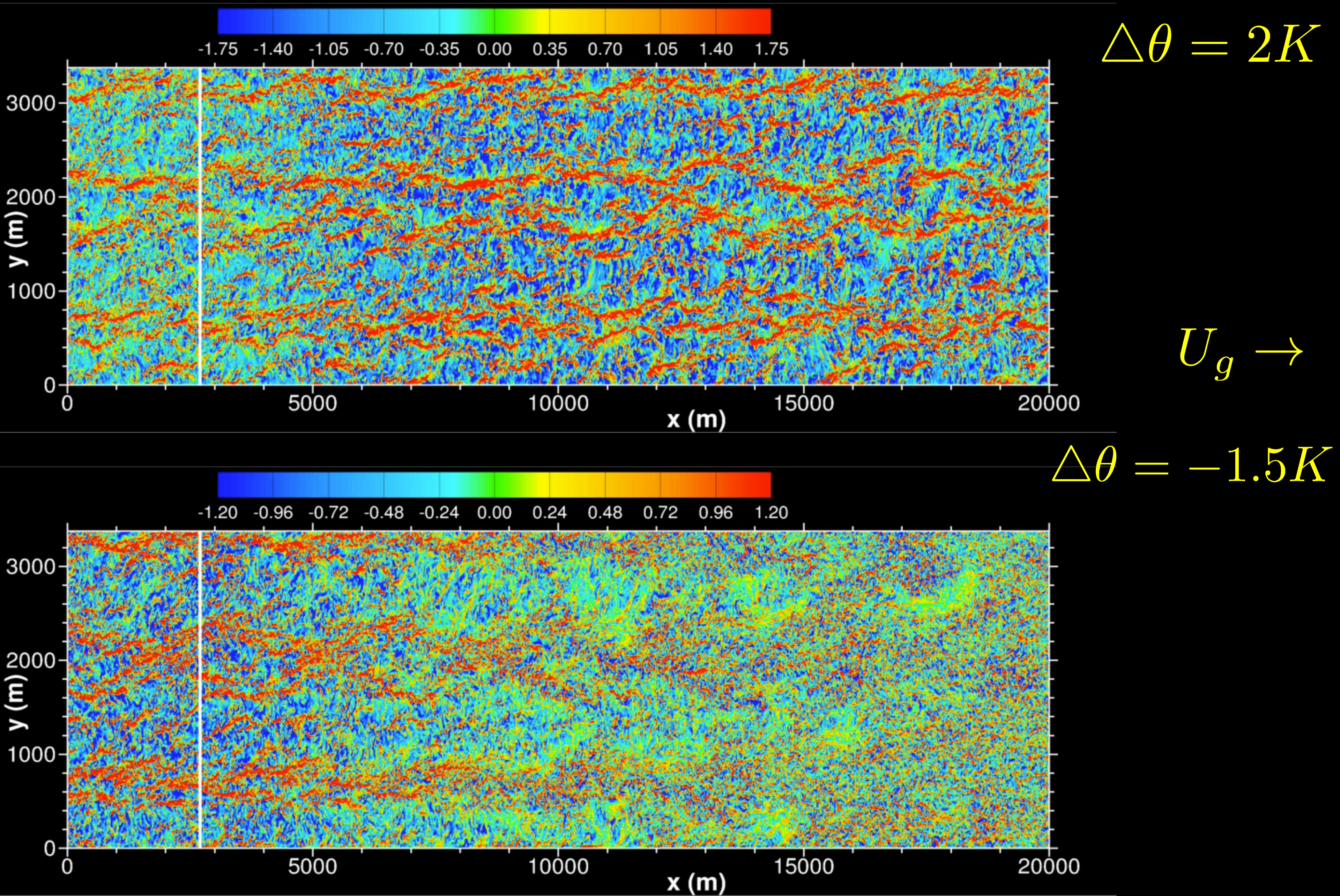
- Spalart & Watmuff (JFM, 1993), Nordström *et al* (SIAM, 1999), Inoue *et al* (MWR, 2014), + others

Fringe method basics:

- Run two LES in different size periodic domains and *artfully* blend the solutions!

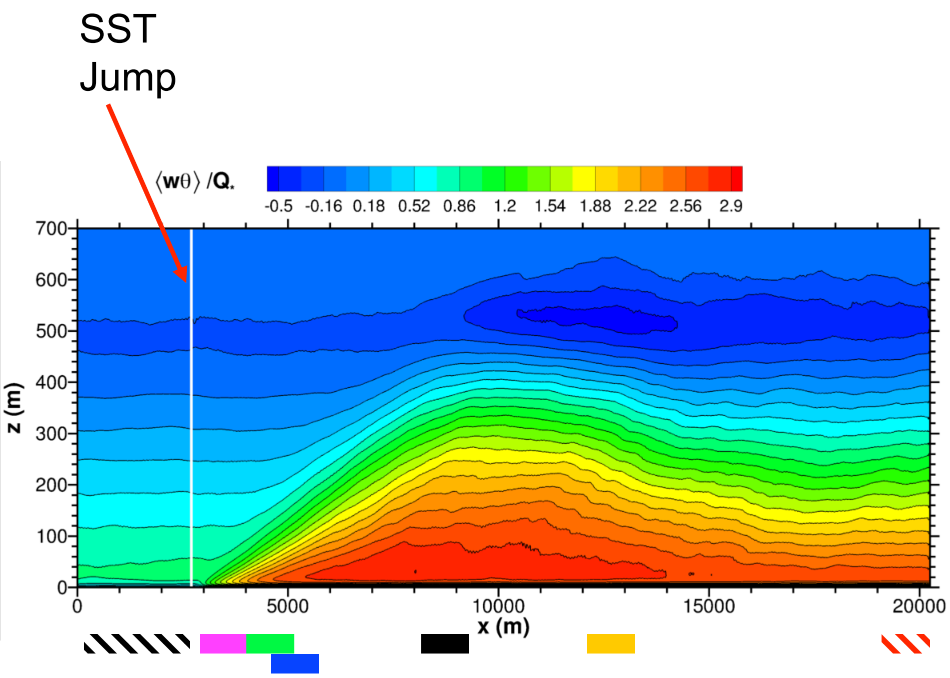
VERTICAL VELOCITY DOWNSTREAM OF AN SST JUMP (WHITE LINE), Z = 41 m

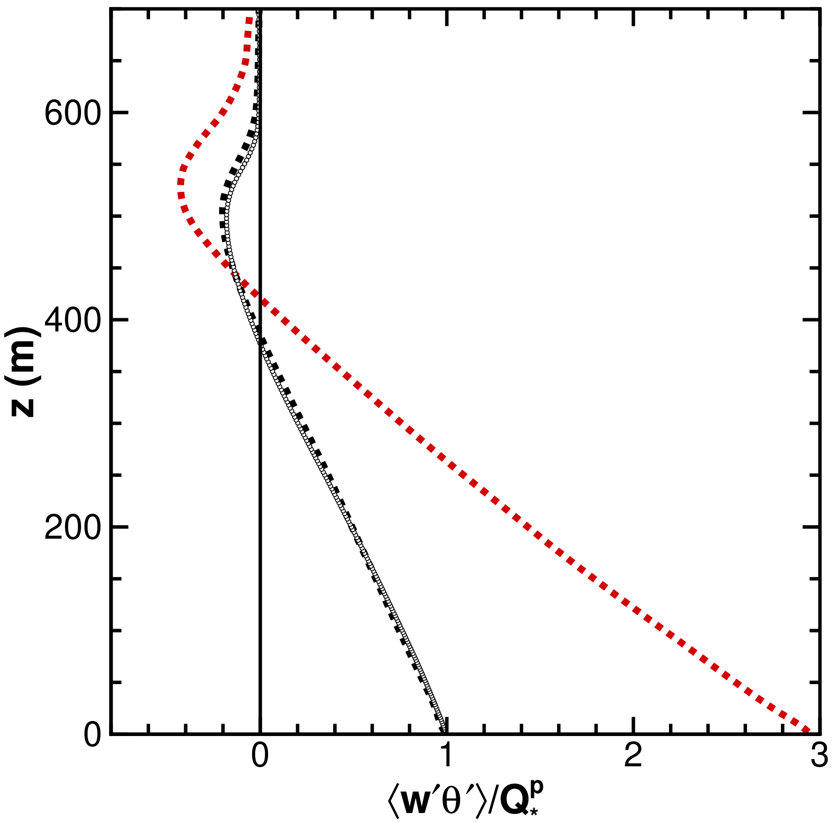
MESHES $(768^2 \times 384)$, $(5376 \times 768 \times 384)$



CROSSFRONT EVOLUTION OF SCALAR FLUX

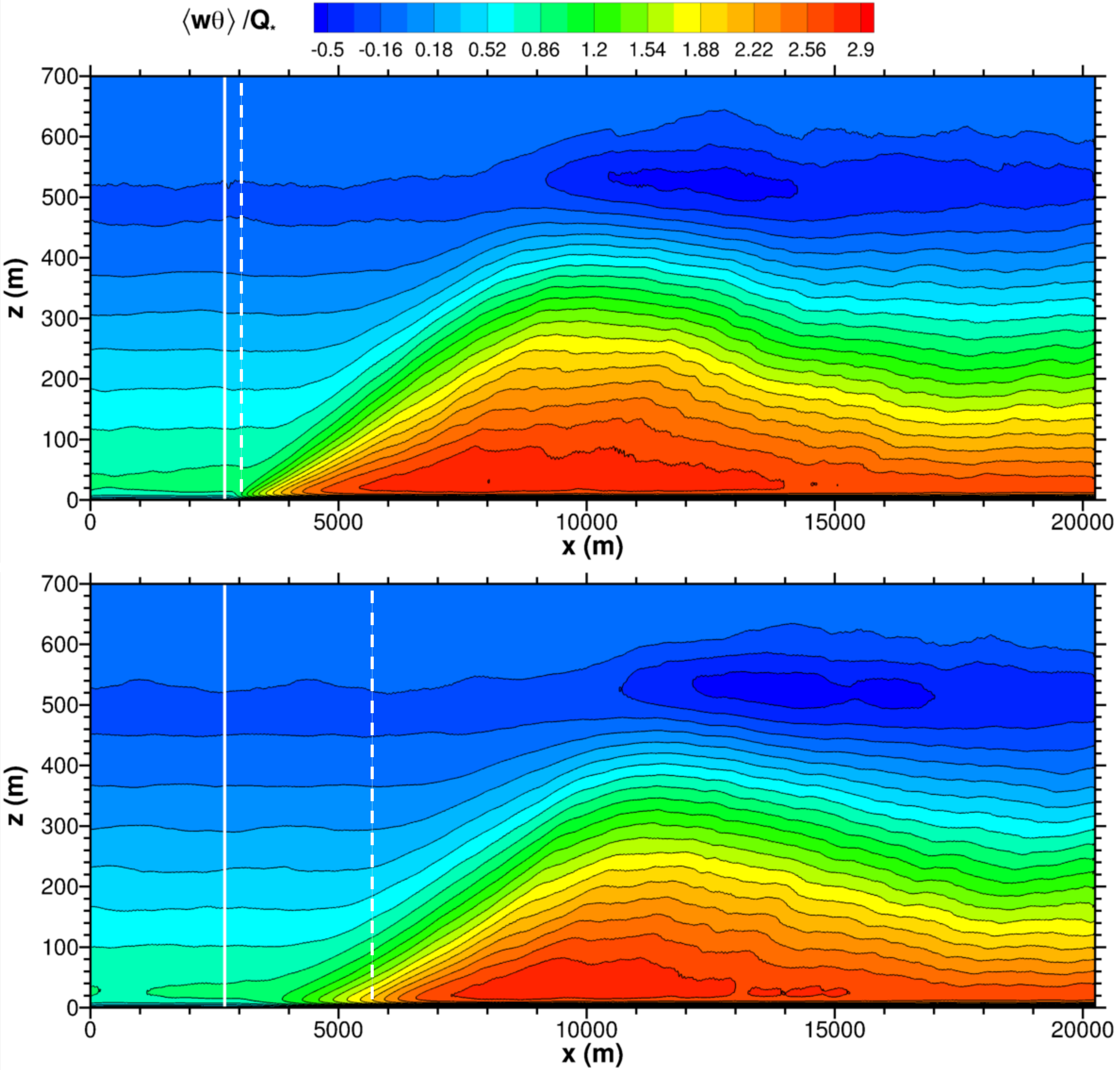
$U_g = 10\,\mathrm{m\,s^{-1}}$, $\triangle\theta = 2\,\mathrm{K}$, SST width $\ell = 100\,\mathrm{m}$





Runs have $\nabla \times \tau$, $\nabla \cdot \tau$

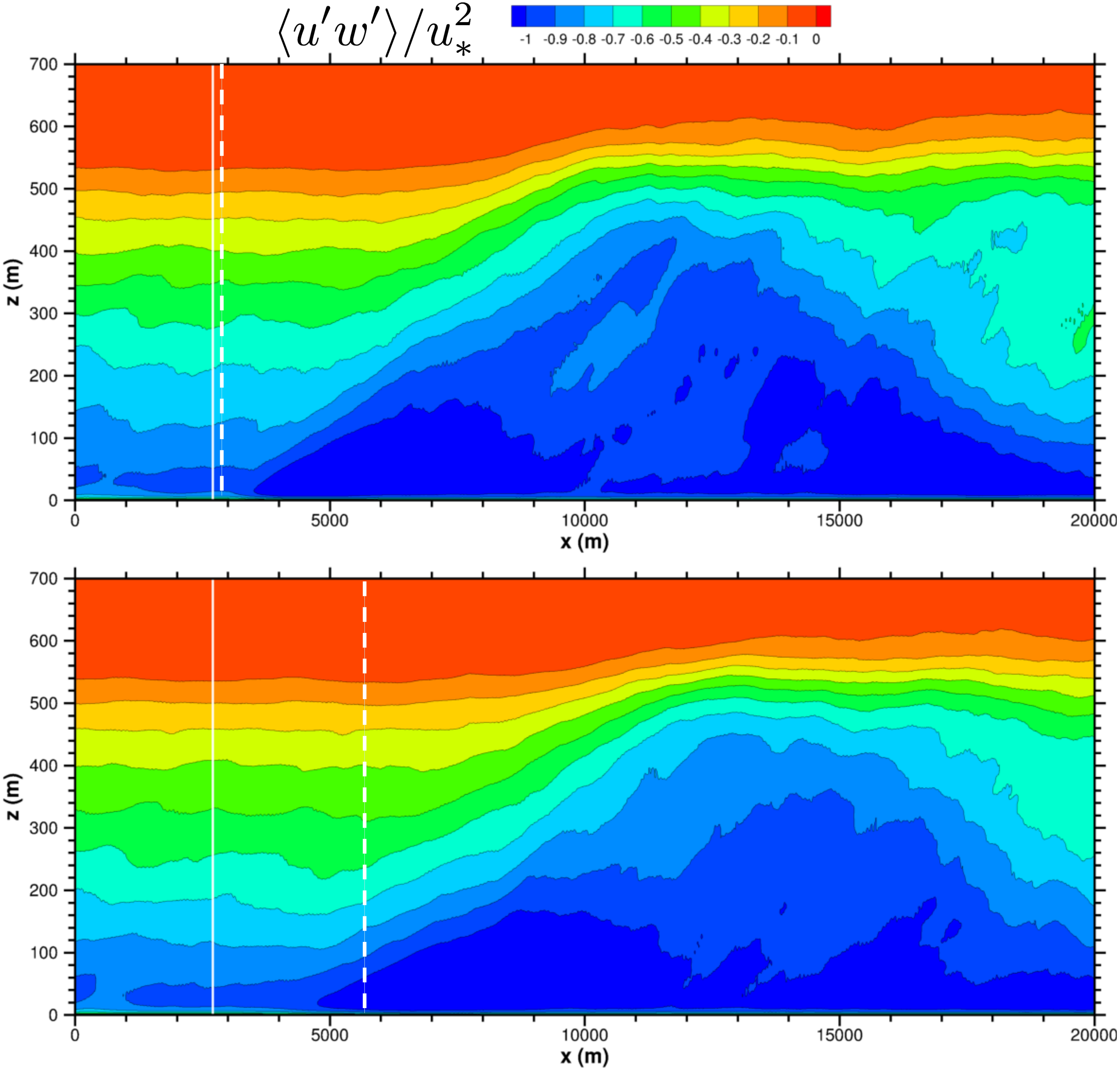
Impact of front width



$$\frac{\triangle\theta}{\ell} = \frac{2K}{100\,m}$$

$$\frac{\triangle\theta}{\ell} = \frac{2K}{3000\,m}$$

Patterns shift to the east with increasing ℓ



Momentum flux

$$\frac{\triangle\theta}{\ell} = \frac{2K}{100\,m}$$

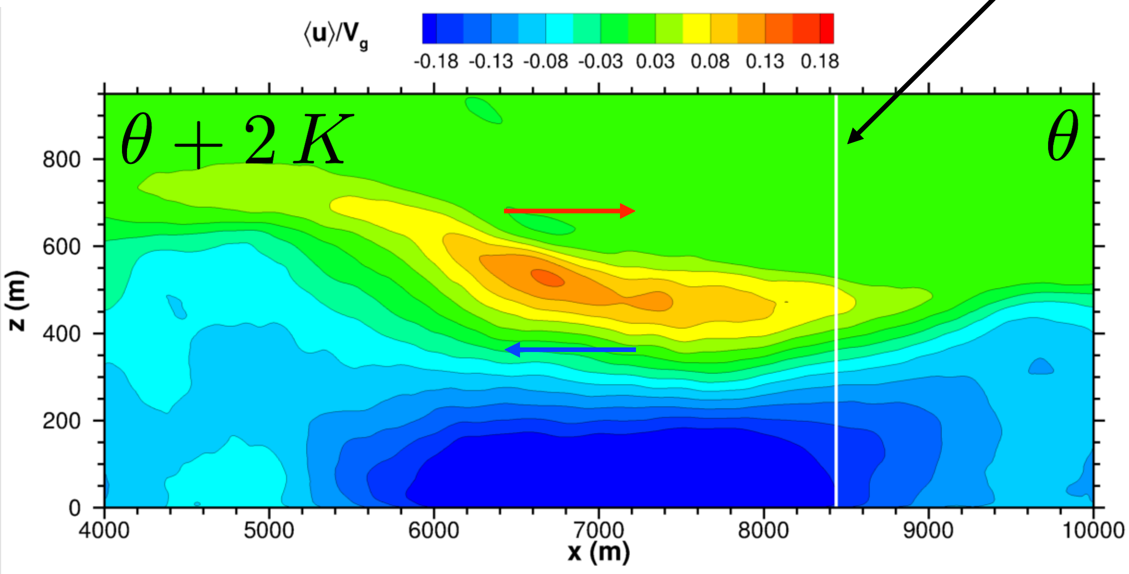
Impact of front width

$$\frac{\triangle\theta}{\ell} = \frac{2K}{3000\,m}$$

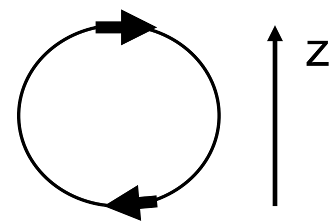
Patterns shift to the east with increasing ℓ

DOWNFRONT WINDS V_G AND SECONDARY CIRCULATIONS

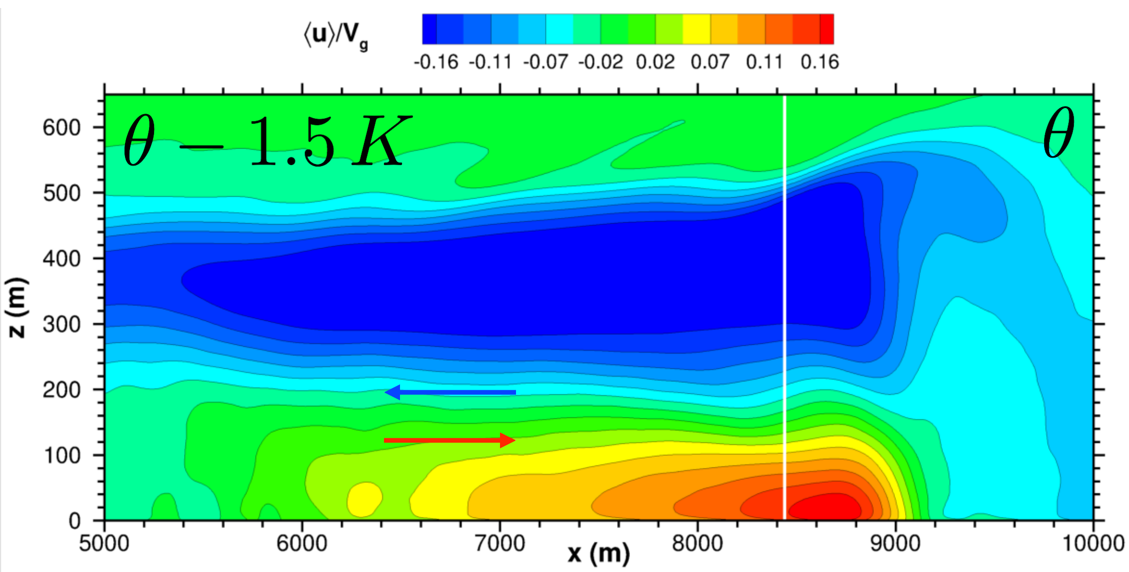
SST front

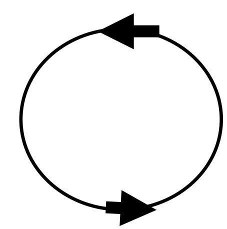


Ekman transport to the west



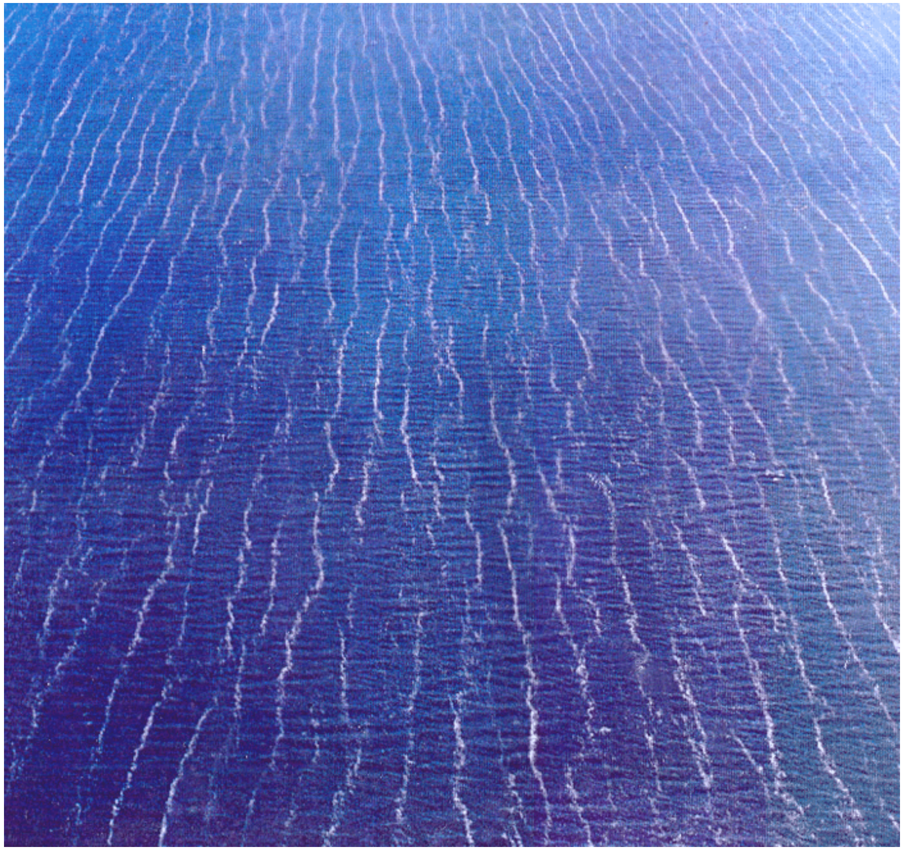
Baroclinic effect reverses sign of surface stress!





Secondary circulations

Frontogenesis and frontal arrest in the OBL with winds and surface waves



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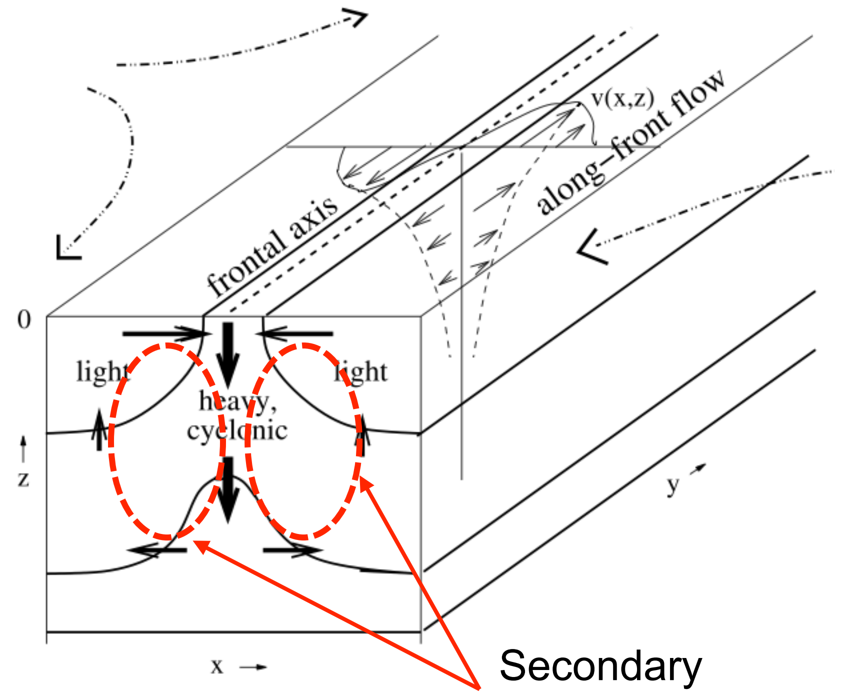
Sullivan & McWilliams (JFM, 2018; to be submitted 2019)

OBL PLANS FOR ATOMIC/EUREC^{4}A

LES process studies:

- Lifecycle of cold filament submesoscale frontogenesis:
  - Role of turbulence
  - Role of winds, cross-front versus down-front
  - Role of surface waves
  - Impact of background turbulence strength (weak, moderate, strong)
  - Variation in filament strength
  - Variation in mixed layer depth
- Lifecycle of single-sided fronts
- Time varying surface forcing?
- Coupled ABL-OBL?

FRONTOGENESIS AND ARREST OF DENSE FILAMENTS IN A WAVY OBL

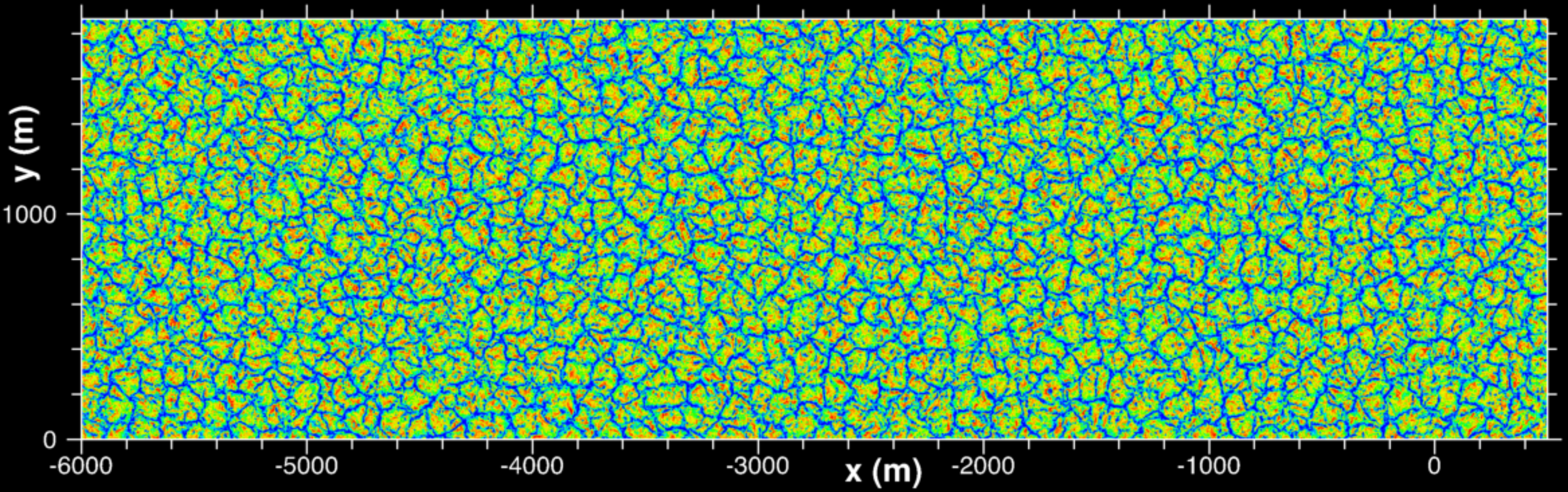


Secondary circulations

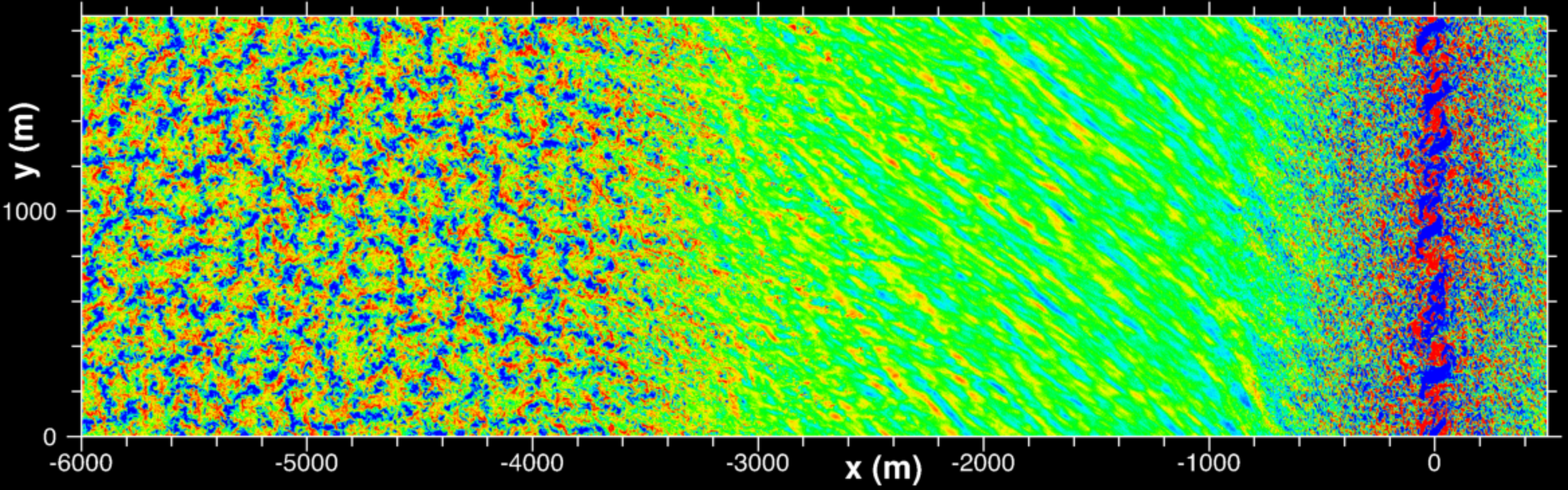
Cold filamentary intensification, McWilliams *et al*, (GRL, 2009)

LES OF FILAMENT FRONTOGENESIS DRIVEN BY SURFACE COOLING: VERTICAL VELOCITY

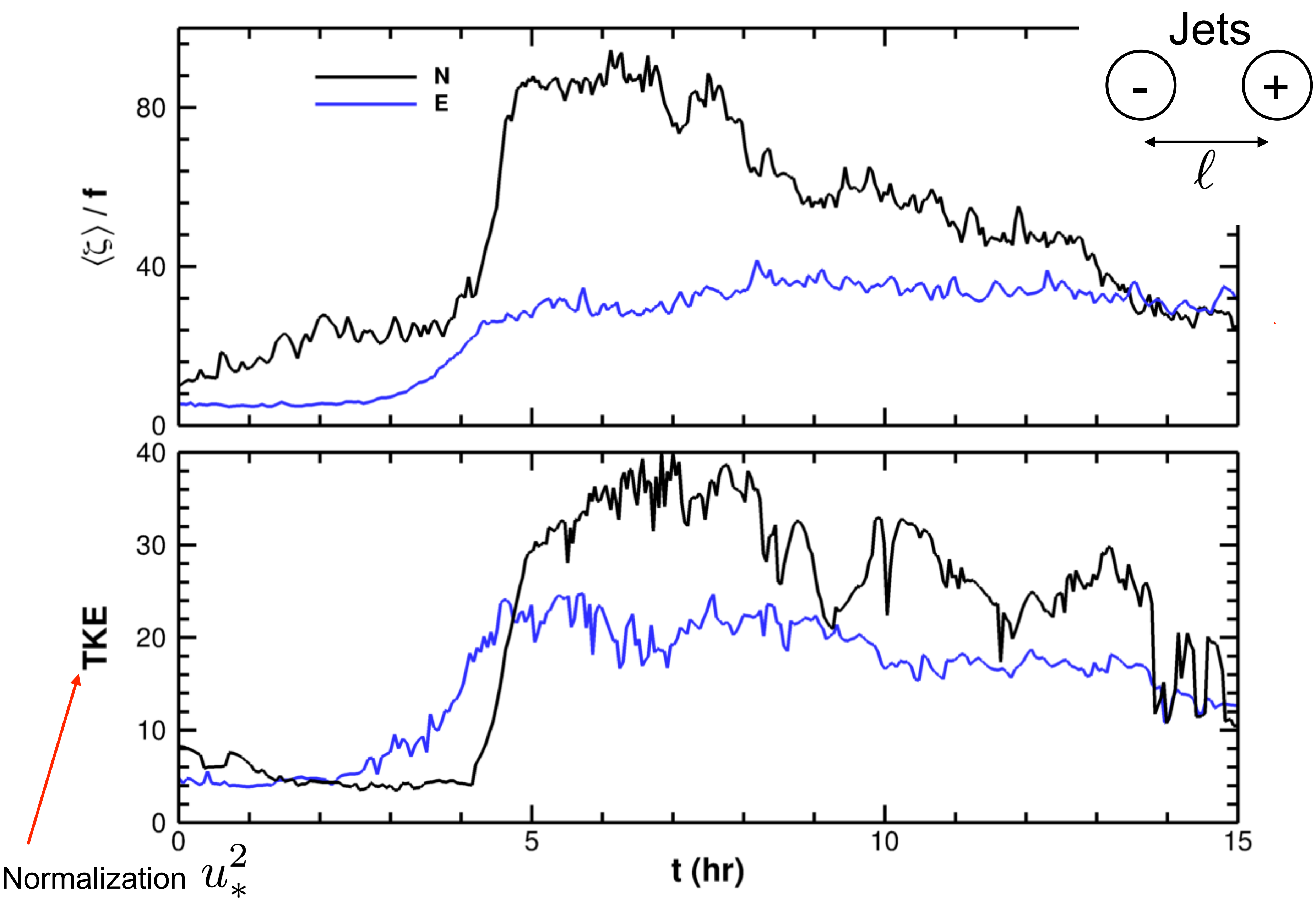
FULLY DEVELOPED TURBULENCE, z = -3 m



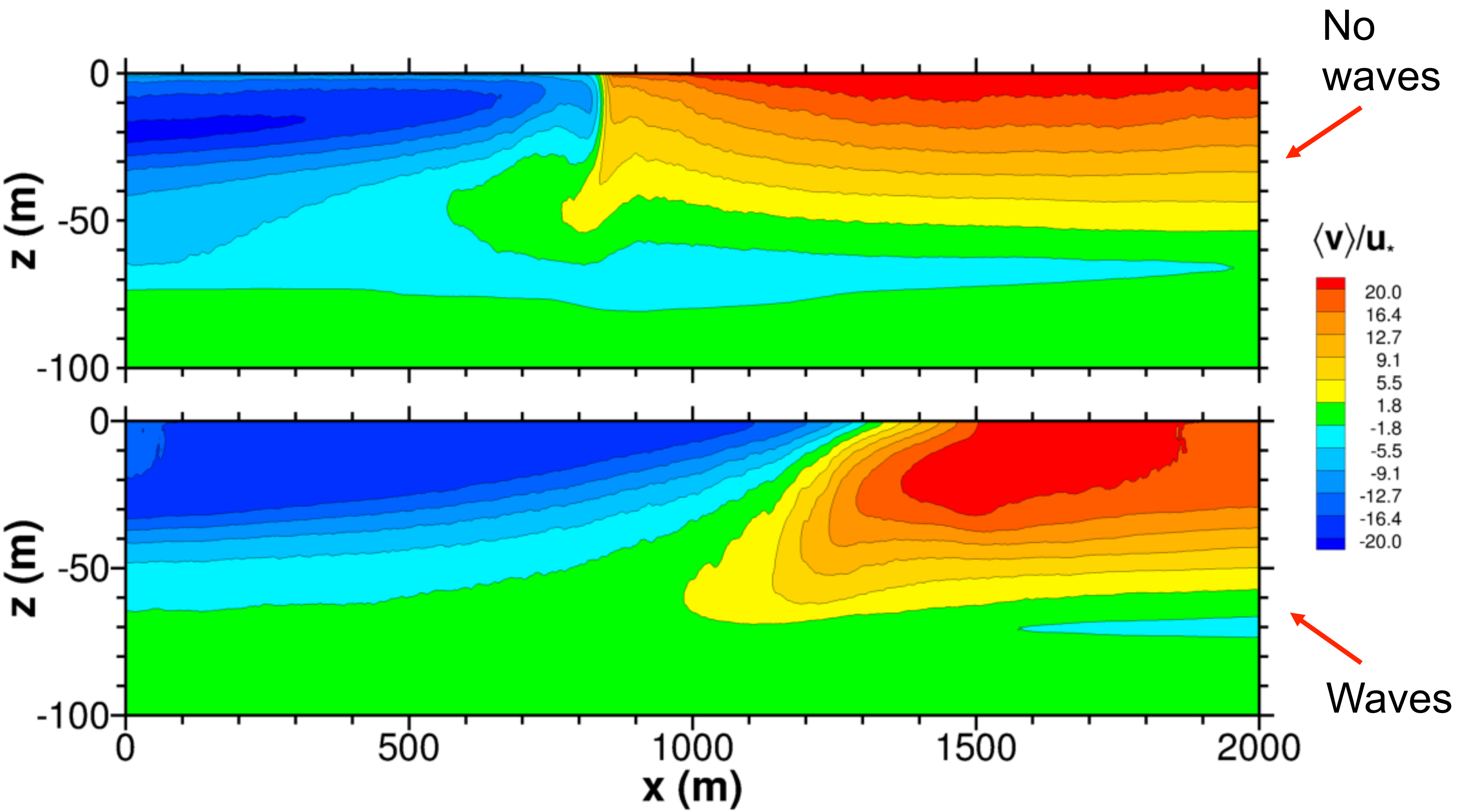
FRONTOGENETIC TURBULENCE, t = 6.1 Hrs, z = -3 m



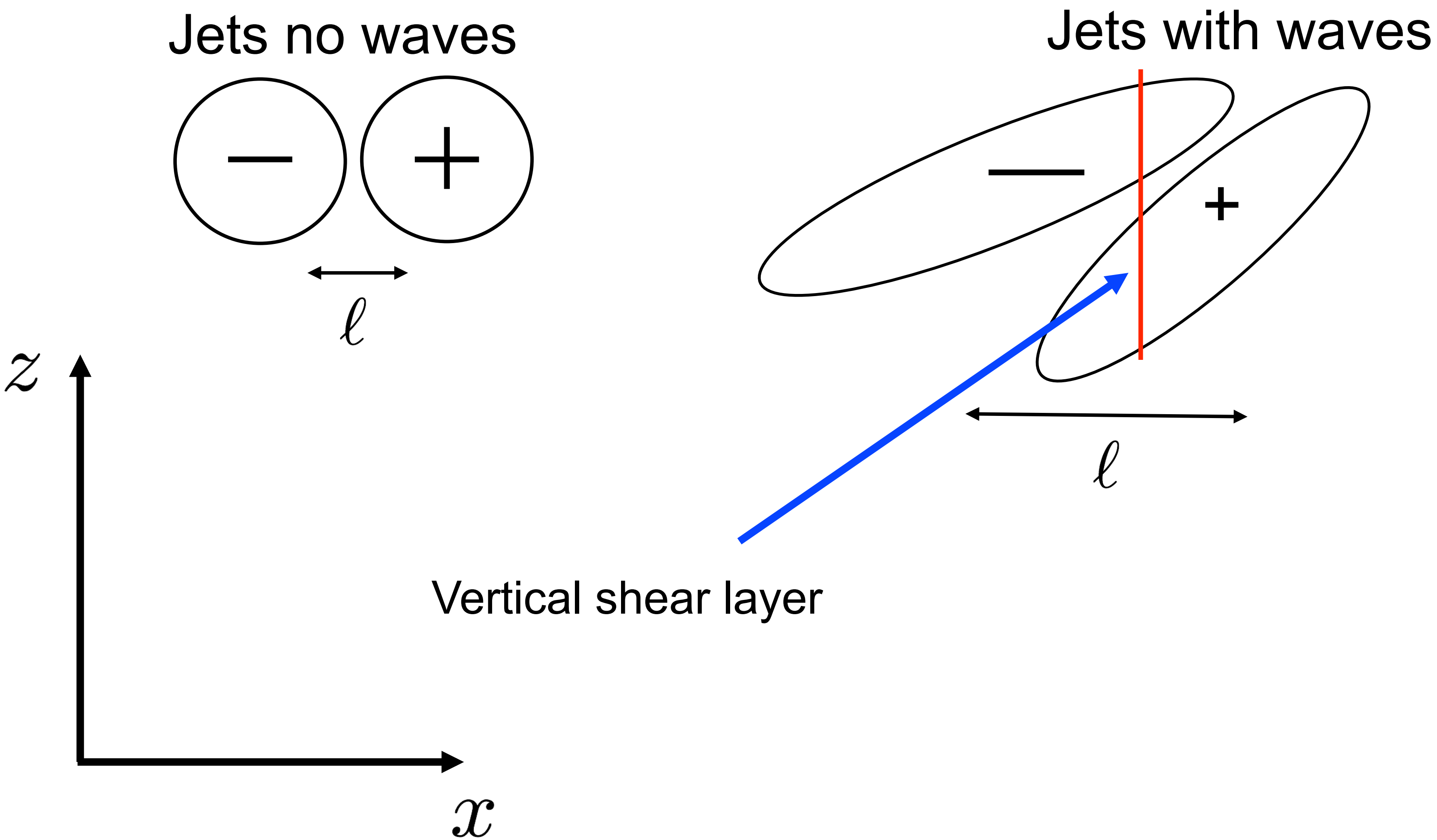
TIME HISTORY OF VERTICAL VORTICITY AND TKE



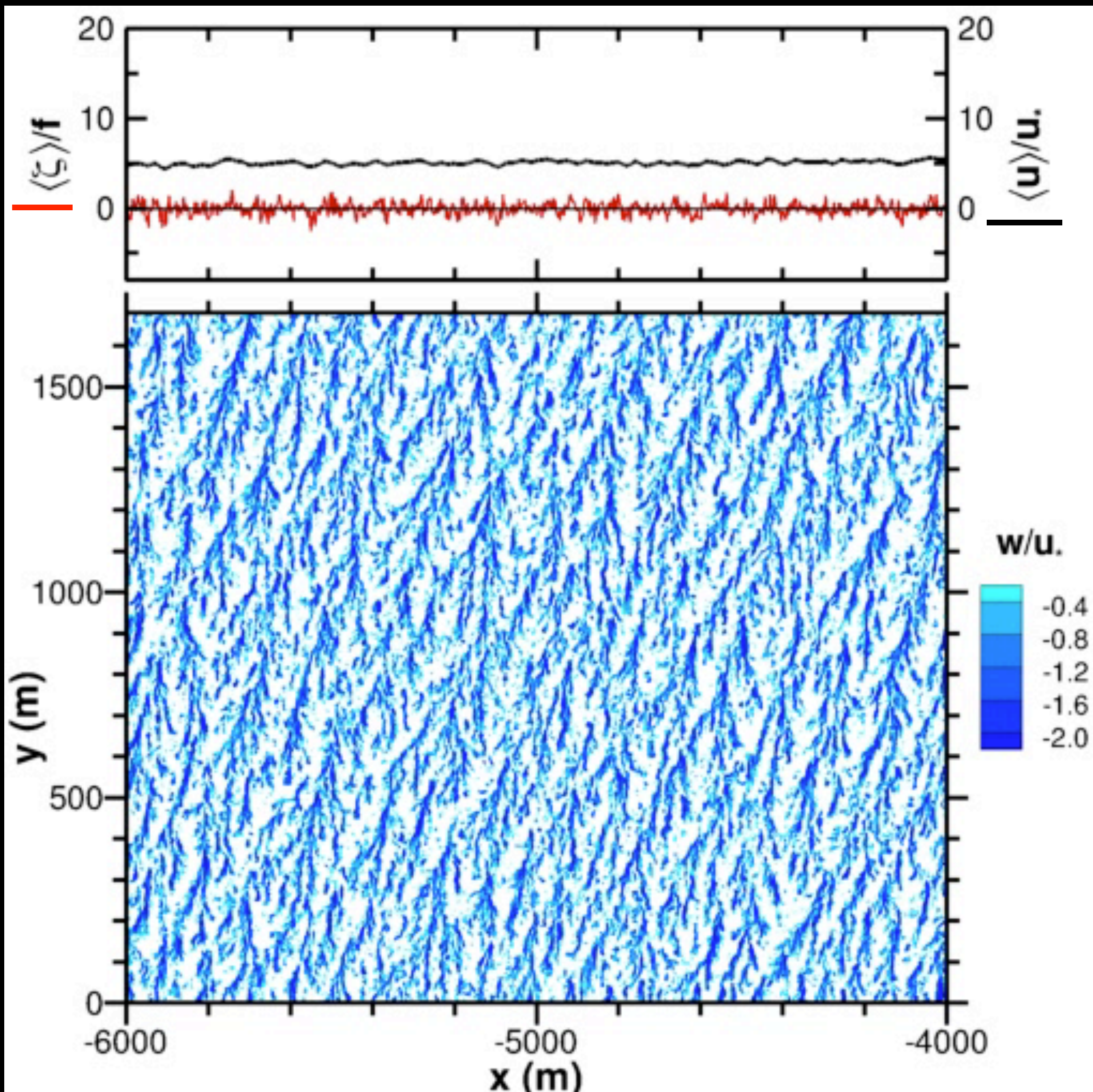
NORTH (DOWN-FRONT) SURFACE WINDS, PEAK FRONTOGENESIS

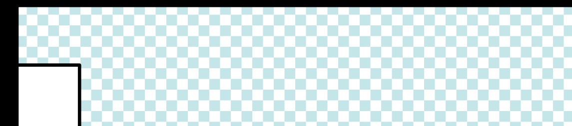


IMPACT OF DOWN-FRONT WAVES ON FRONTOGENESIS: WAVE EFFECTED CURRENTS



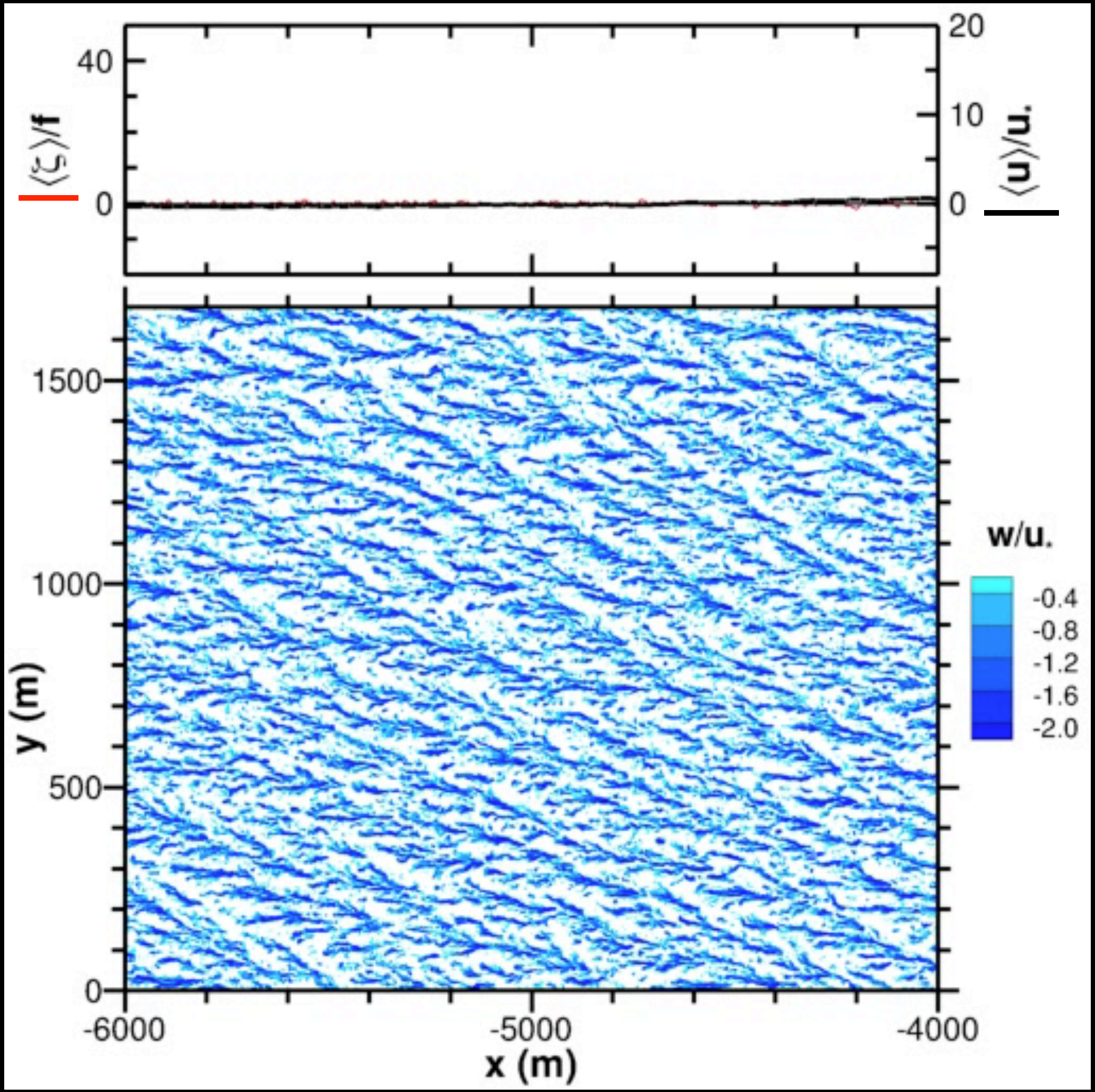
Spatial evolution of downwelling velocity w at z = -10 m: Surface forcing by down-front winds and waves





Winds, waves

Spatial evolution of downwelling velocity w at z = -10 m: Surface forcing by cross-front winds and waves



Winds, waves

LES-OBSERVATIONAL DISCUSSION TOPICS

ABL results for isolated fronts:

- Impressive evolution distance
- Distance to equilibrium depends on $(U, \pm\triangle\theta, \ell)$
- Differences for crossfront versus downfront winds
- Non-monotonic variation of vertical fluxes with x
- Response time of surface fluxes, Q_* versus u_*^2
- Modifies Ekman transport, surface stress, mean budgets
- Dynamics and scalar transport at ABL top, role of surface currents?

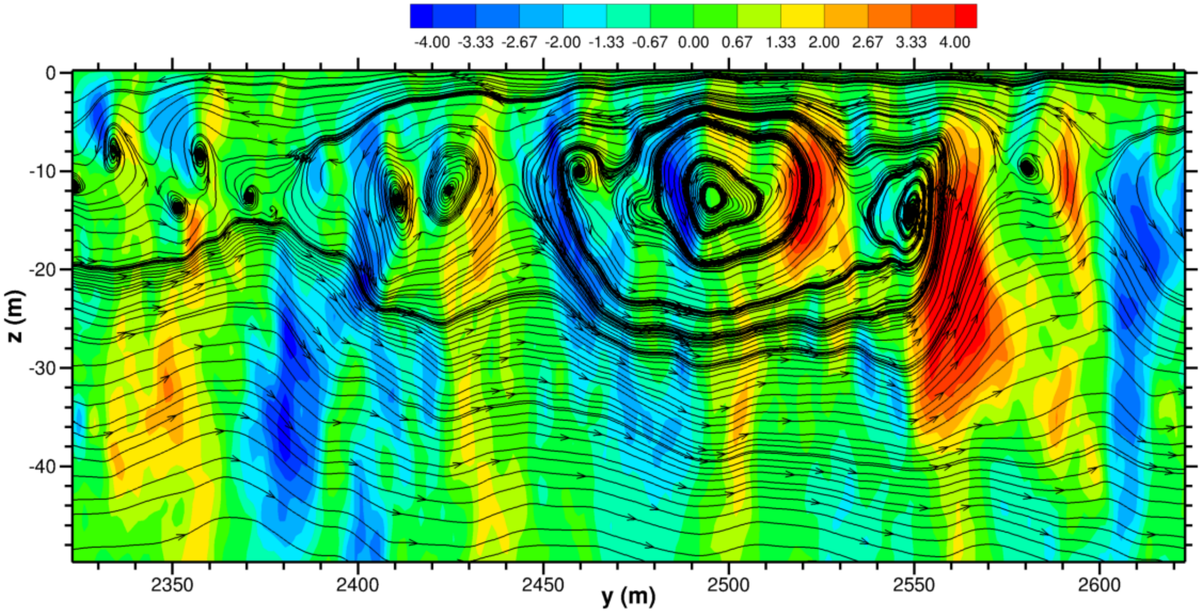
OBL results for filaments:

- Impressive impact of surface waves on filament frontogenesis
- Down-front spectra measurements
- Wavefield measurements
- Variance measurements (u', v', w')
- Dynamics for single-sided fronts?
- Scalar transport?

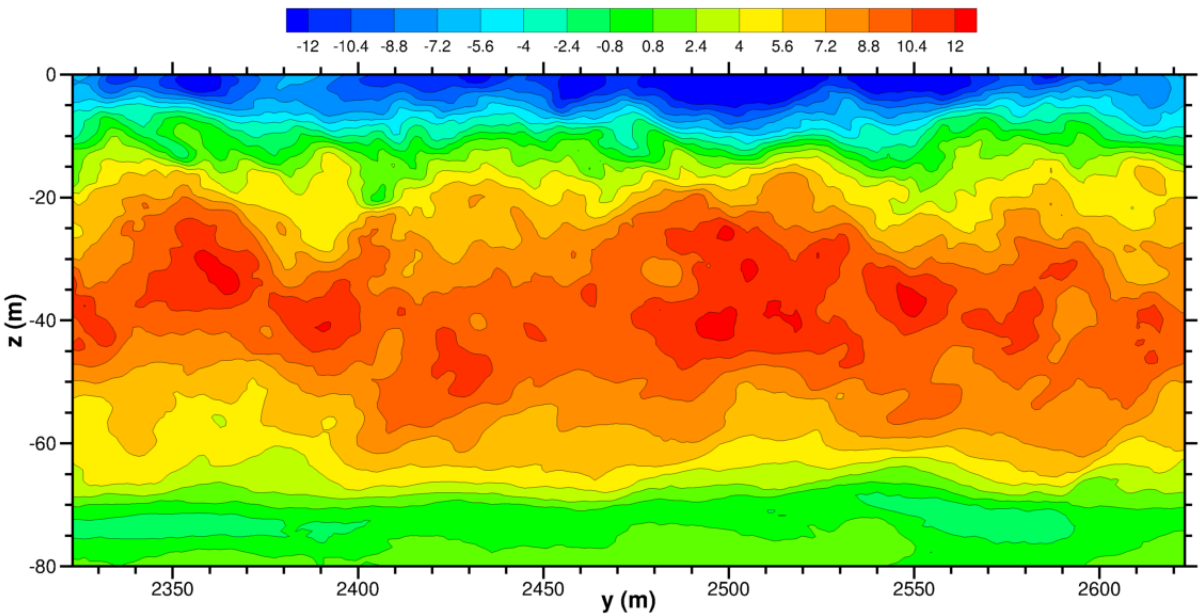
Fringe method:

- Template for coupled LES of the ABL and OBL

Down front winds and waves
Currents (w, v) in y-z plane at x = 1200 m

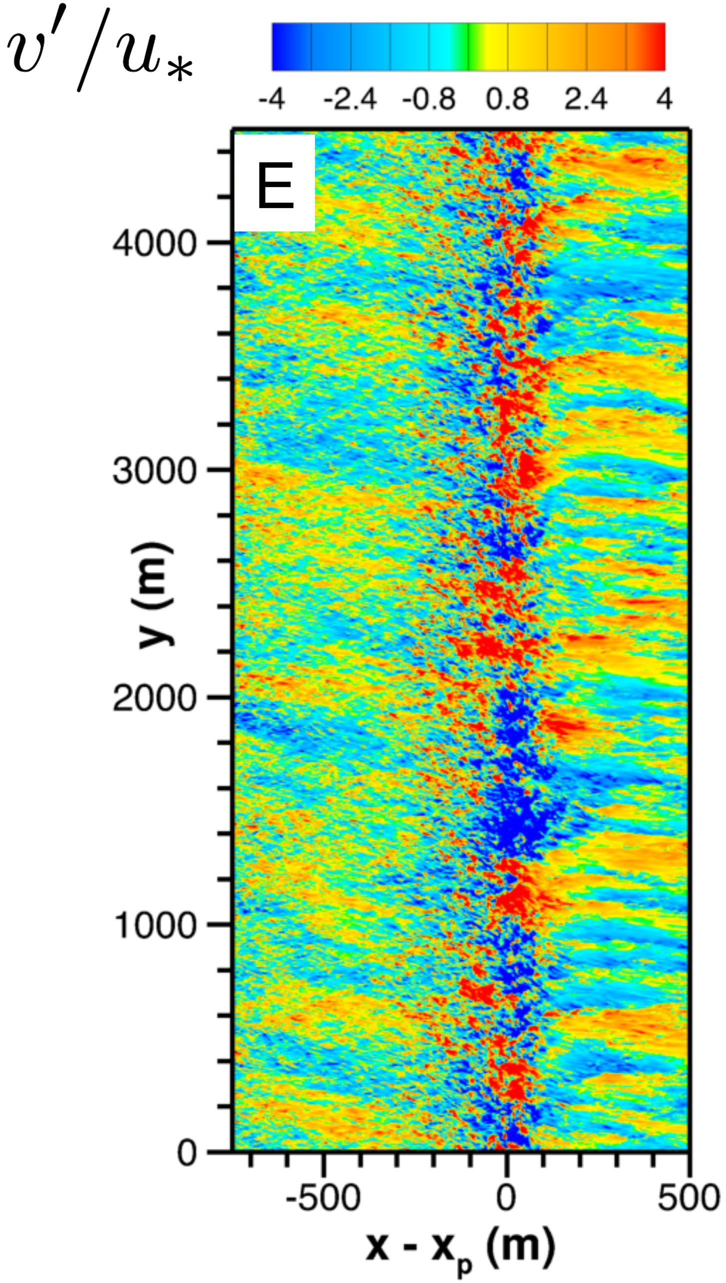


w/u_*



v/u_*

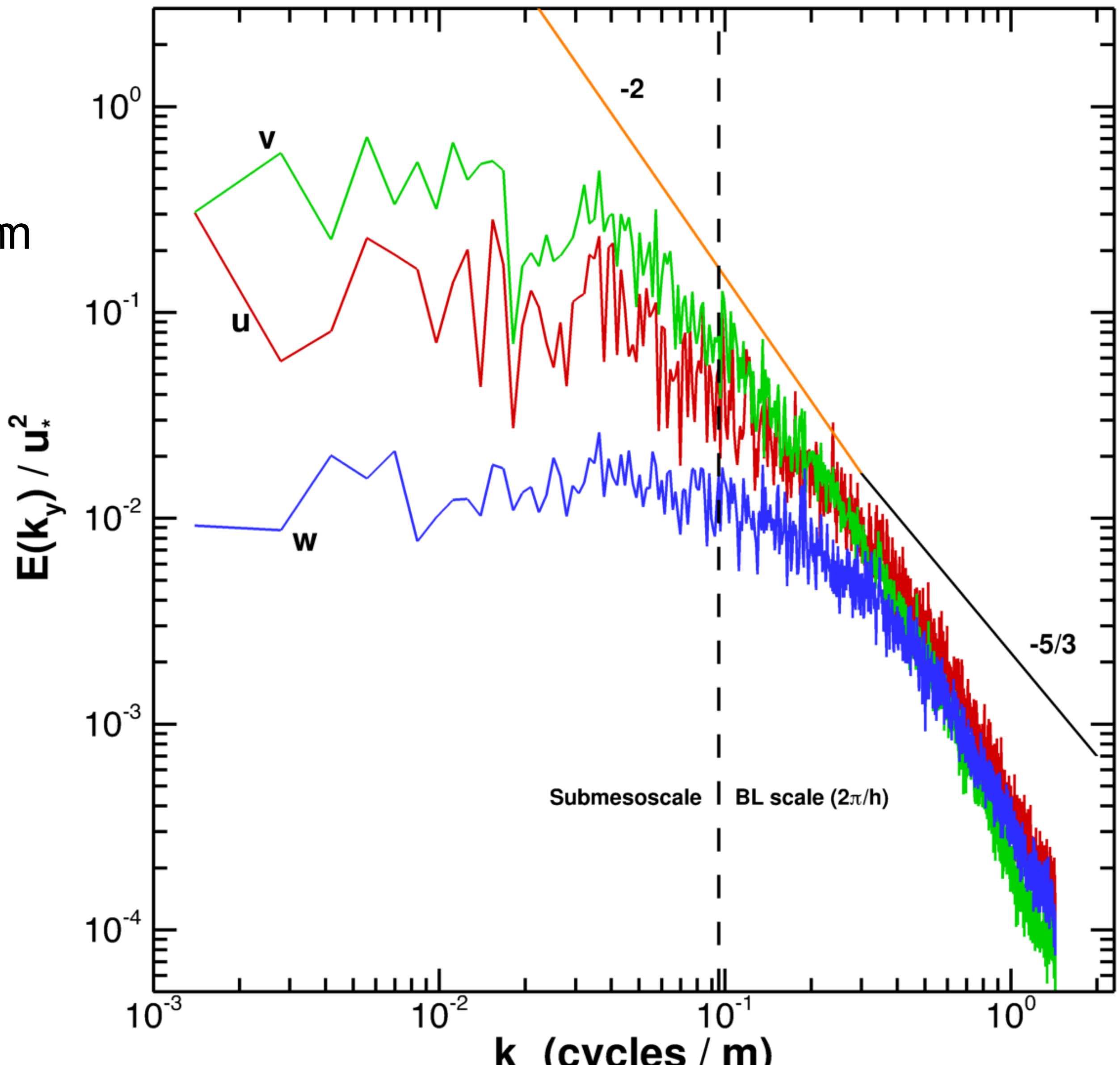
FLOW STRUCTURES AT LATE TIME t ~ 9 hr

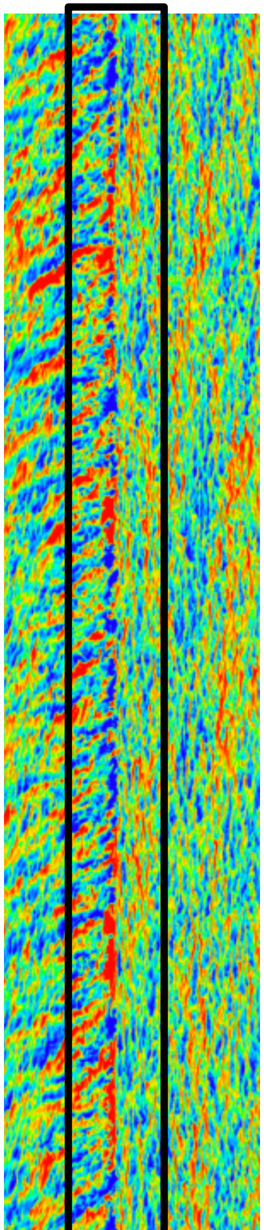


POWER SPECTRA OF (U, V, W) FOR NORTH WINDS

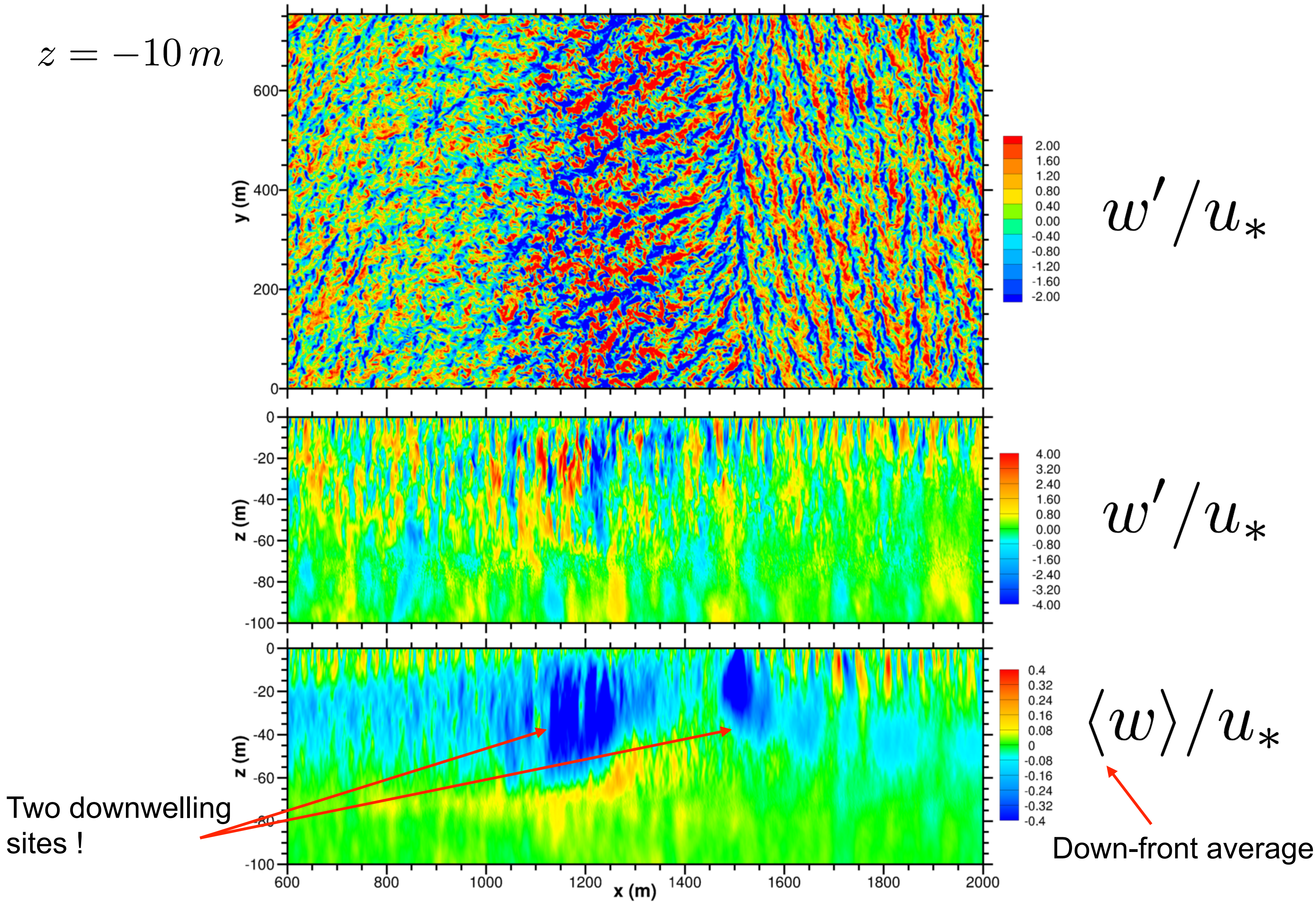
T = 6.1 HR

z = -2.56m

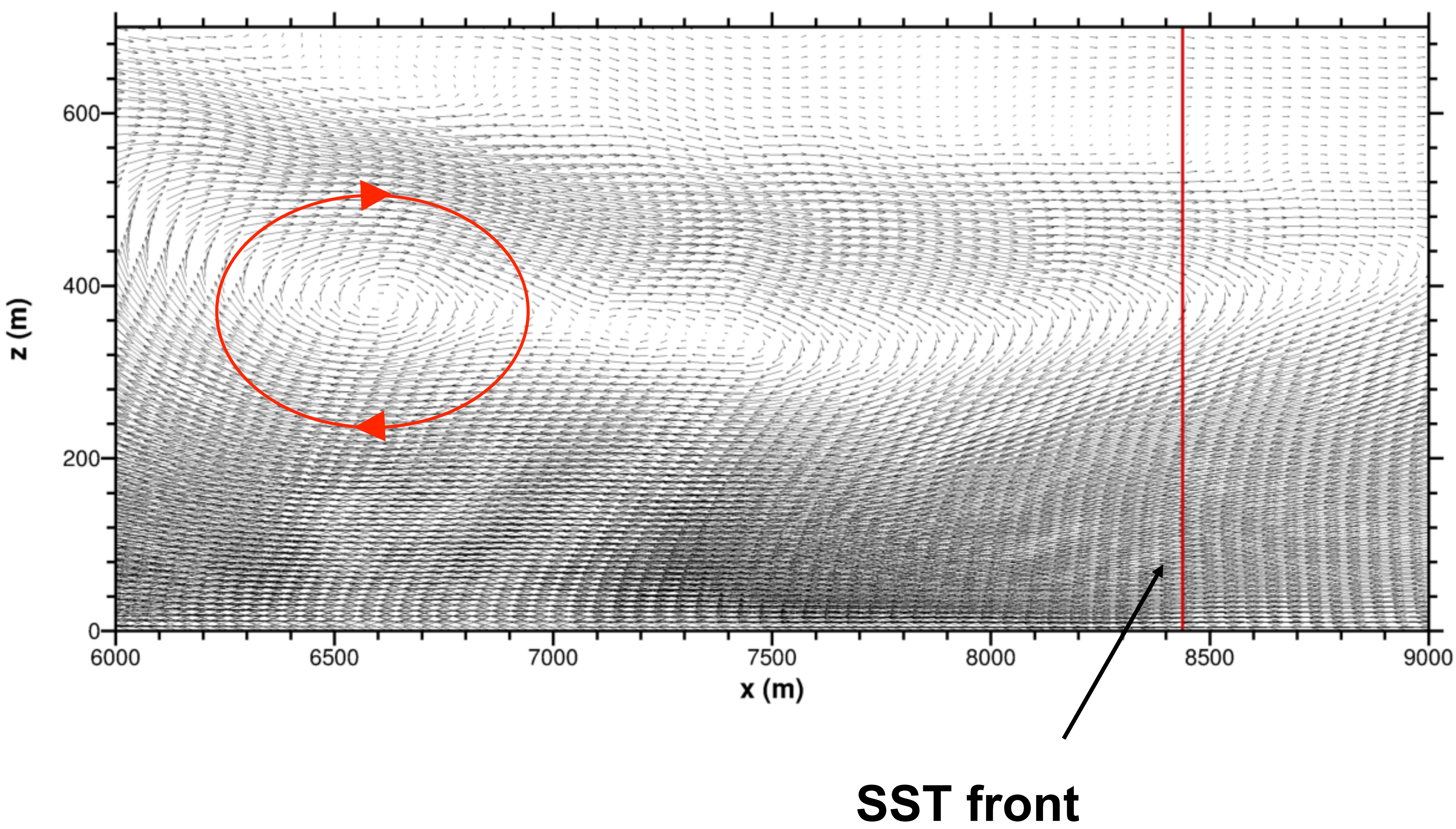




NORTH WINDS PLUS WAVES: VERTICAL VELOCITY

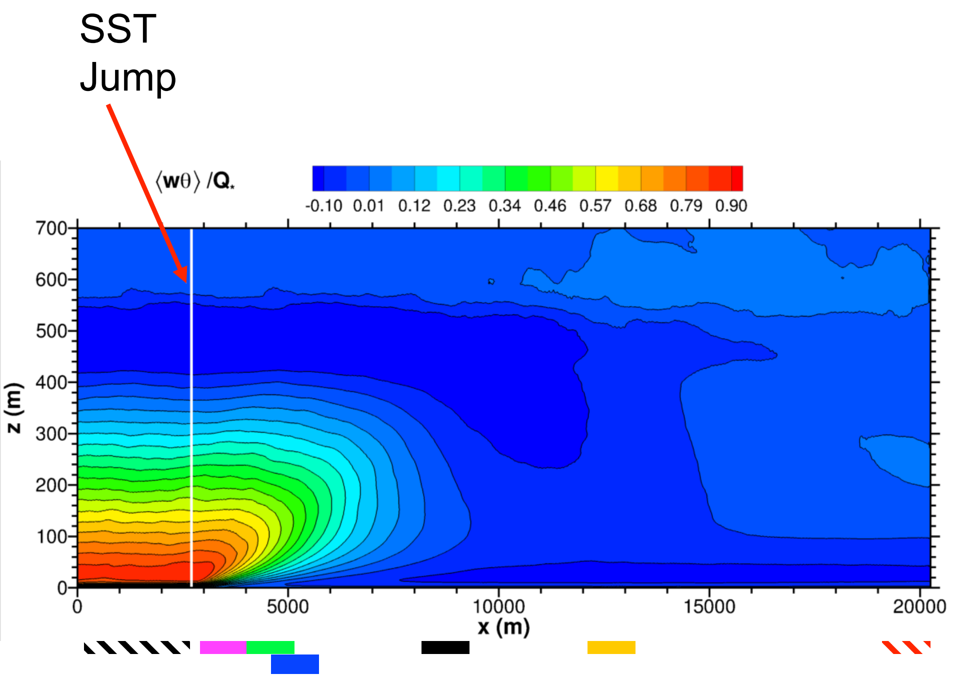


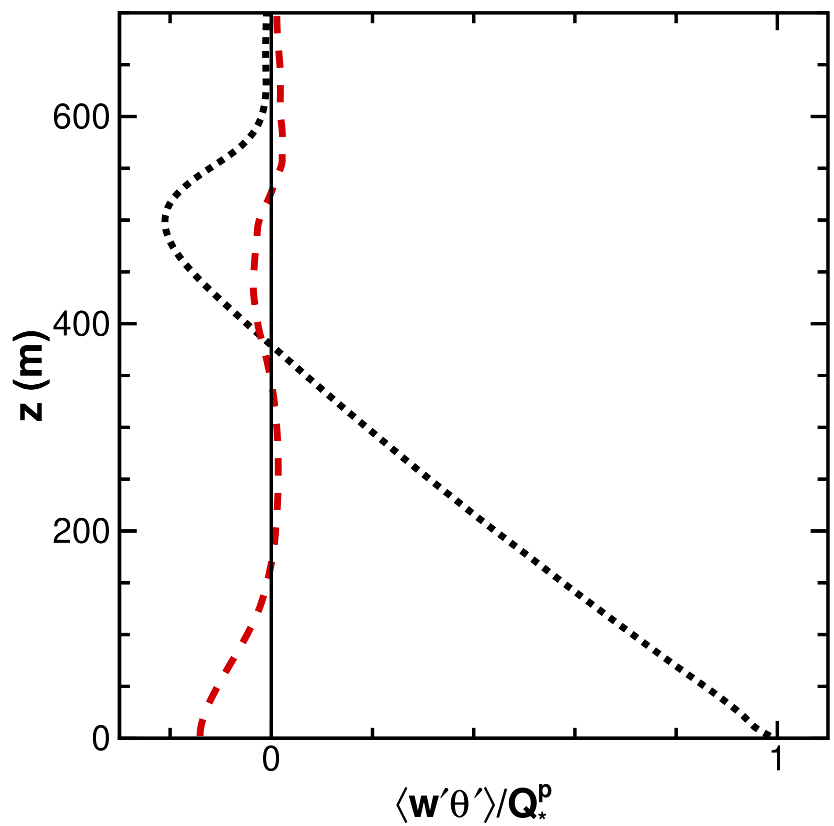
SECONDARY CIRCULATIONS WITH DOWN FRONT WINDS



CROSSFRONT EVOLUTION OF SCALAR FLUX

$$U_g = 10\, m\, s^{-1}, \quad \triangle\theta = -1.5\, K, \quad \ell = 100\, m$$





ABL AND OBL COUPLING

Motivation:

- Ocean eddies, fronts, filaments of varying scale $\rightarrow$ strong heterogeneous horizontal buoyancy gradients and currents

Objective:

- How does ocean submesoscale turbulence impact the OBL and ABL in MISO-BoB regimes?

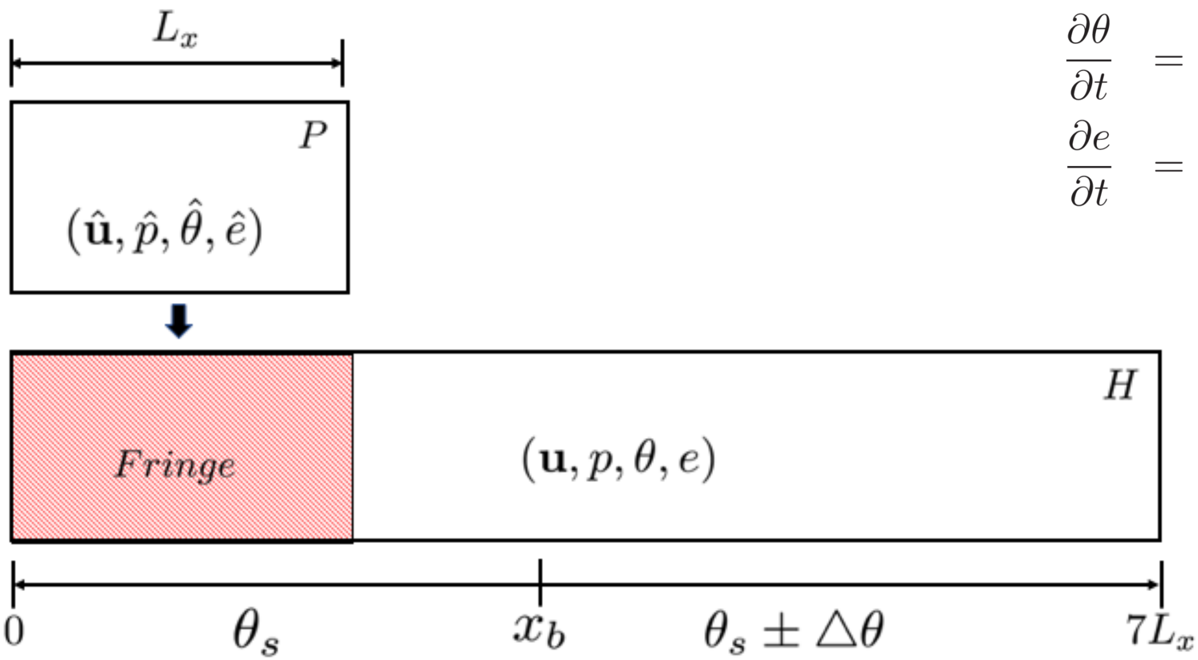
Approach:

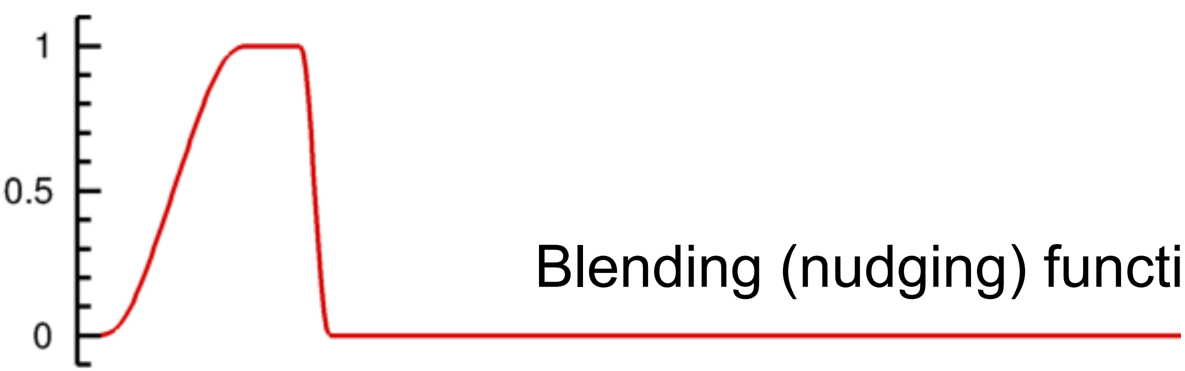
- LES process studies in the OBL and ABL
- Longer term develop a coupled ABL-OBL LES model

(ABL, OBL) = (Atmospheric, Oceanic) Boundary Layer

FRINGE METHOD DETAILS

$$
\begin{aligned}
\frac{\partial u_i}{\partial t} &= \mathcal{R}(u_i,\theta) - \frac{\partial p}{\partial x_i} + \lambda(x)\,(\hat{u}_i - u_i) \\
\frac{\partial \theta}{\partial t} &= \mathcal{S}(u_i,\theta) + \lambda(x)\left(\hat{\theta} - \theta\right), \\
\frac{\partial e}{\partial t} &= \mathcal{T}(u_i,\theta) + \lambda(x)\,(\hat{e} - e)
\end{aligned}
$$





Blending (nudging) function $\lambda(x)\; s^{-1}$

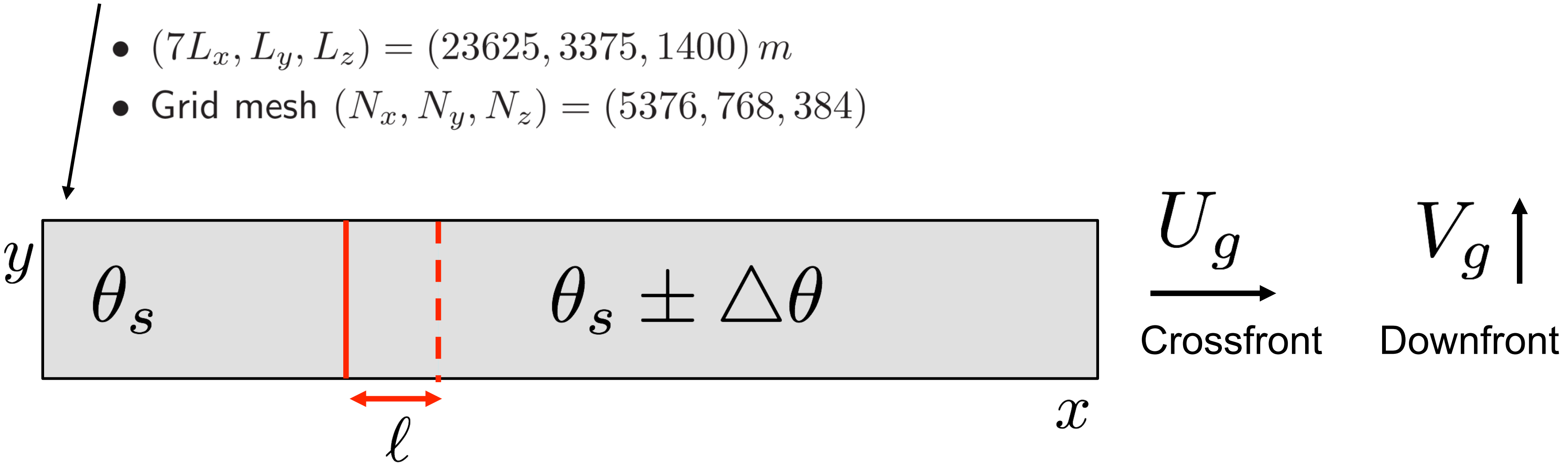
LES OF THE ABL WITH SST GRADIENTS

P-domain:

- $(L_x, L_y, L_z) = (3375, 3375, 1400)\, m$
- Grid mesh $(N_x, N_y, N_z) = (768, 768, 384)$

H-domain:

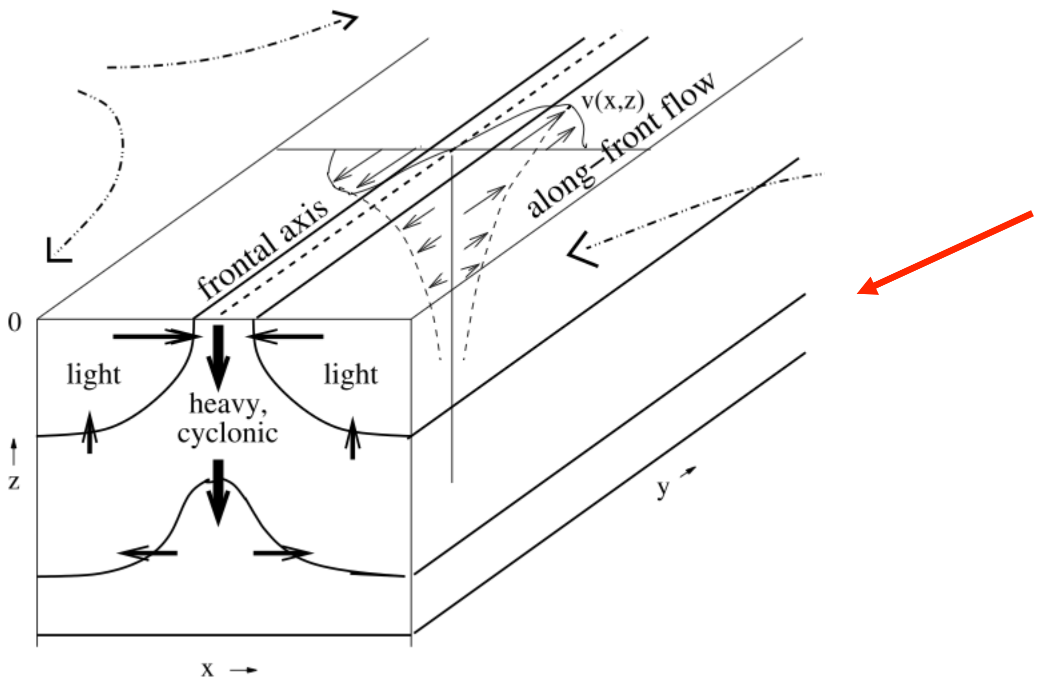
- $(7L_x, L_y, L_z) = (23625, 3375, 1400)\, m$
- Grid mesh $(N_x, N_y, N_z) = (5376, 768, 384)$



Experiments:

$$U_g = (5, 10, 15)\mathrm{m\,s^{-1}}, \quad V_g = 5\mathrm{m\,s^{-1}}$$
$$\triangle\theta = (2, -1.5)\,\mathrm{K}, \quad \ell = (100, 1000, 3000)\,\mathrm{m}, \quad z_i \sim 450\mathrm{m}$$

FRONTOGENESIS AND ARREST OF DENSE FILAMENTS IN A WAVY OBL



Idealized cold filamentary intensification, McWilliams *etal*, 2009

LES:

- Surface forcing: cross-front winds E, down-front winds N, cooling
- Wave effects, $La_t = 0.32$ (wind-wave equilibrium)
- $(L_x, L_y, L_z) = (12000, 4500, -250)$ m
- $(N_x, N_y, N_z) = (8192, 3072, 256) \quad \sim 6.4 \cdot 10^9$ gridpoints
- $(\triangle x, \triangle y, \triangle z) = (1.46, 1.46, [0.5 - 1.58])\, m$

ATMOSPHERIC BL RESPONSE TO SST GRADIENTS

LES results:

- Impressive evolution distance
- Distance to equilibrium depends on wind speed
- Asymmetrical response, $+\triangle\theta$ changes $\neq -\triangle\theta$ changes
- Scalar flux profile has an intermediate maximum, not monotonic
- Front "width" $\ell = [100 - 3000]$ m shifts results downstream
- Surface scalar flux, fast response $Q_* \sim \triangle\theta(x - x_o)/\ell$
- Momentum fluxes, slow response because of pressure (?)
- Differences for crossfront versus downfront winds
  - Modifies Ekman transport and surface stress
- Mean θ budget: horizontal advection $=$ vertical flux divergence
- Mean u budget:
  - crossfront winds horizontal advection $\sim$ vertical flux divergence
  - downfront winds horizontal pressure gradient $\sim$ vertical flux divergence

MPI Fringe algorithm:

- Works well for heterogeneous ocean surfaces
- Template for coupled LES of the ABL and OBL

SUMMARY

- Marine boundary-layers and the connecting wavy interface remain in a state of discovery
- Observational challenges are (very) high because of the broadband dynamics
- LES and DNS process studies are providing insights and observational targets, $e.g.$, role of Langmuir turbulence, wave driven winds, drag of steep waves, ...
- Mechanics of sea surface drag? non-separated sheltering, critical layers, separation, wave unsteadiness, micro-breaking, ...
- Advance the understanding of drag using targeted simulations and observed time varying spatial maps of the sea surface
- Simulations of loose and tightly coupled air-water boundary layers are feasible on large parallel machines
- Role of submesoscale ocean turbulence in marine boundary layer dynamics is largely unknown and needs to be explored