

BOUNDARY-LAYER INDUCED FRONTOGENESIS IN THE OCEAN SURFACE LAYER

Peter P. Sullivan¹ , James C. McWilliams²

¹National Center for Atmospheric Research

²University of California Los Angeles



ENERGY FLOW IN THE OCEANIC GENERAL CIRCULATION

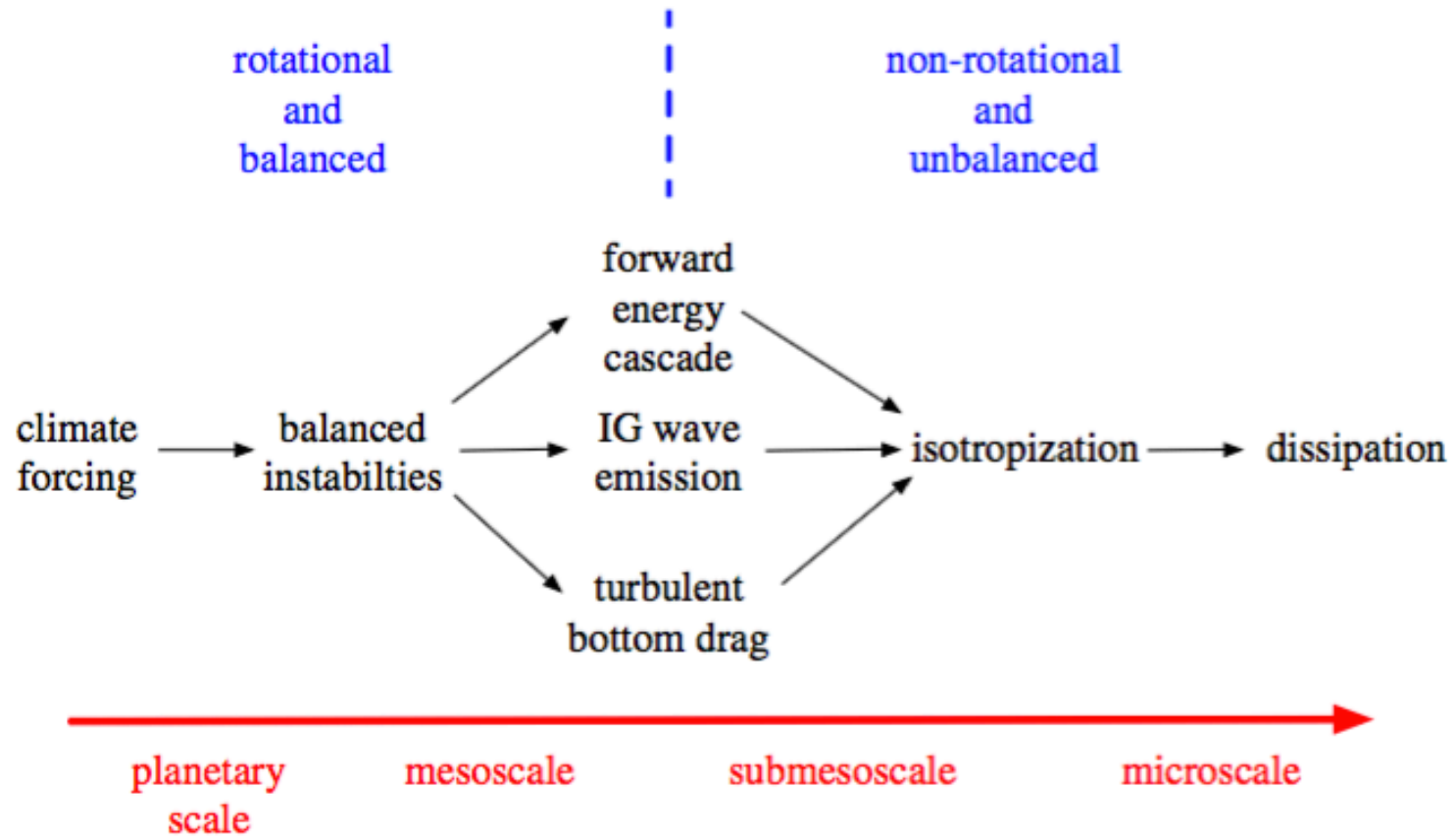


Figure 1. Stages in the oceanic general circulation from planetary-scale forcing to microscale dissipation and mixing. The dynamical parameters Ro and Fr pass through $\mathcal{O}(1)$ values within the submesoscale regime.

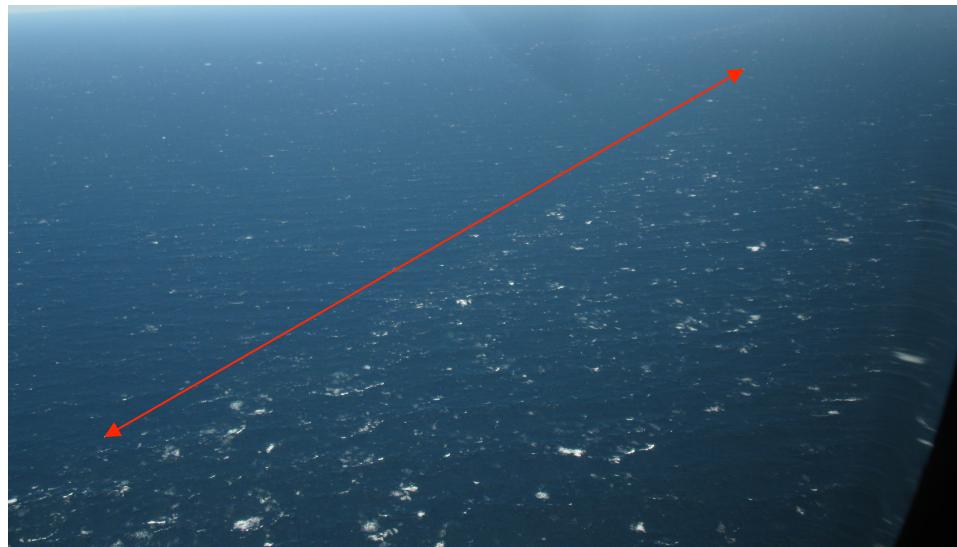
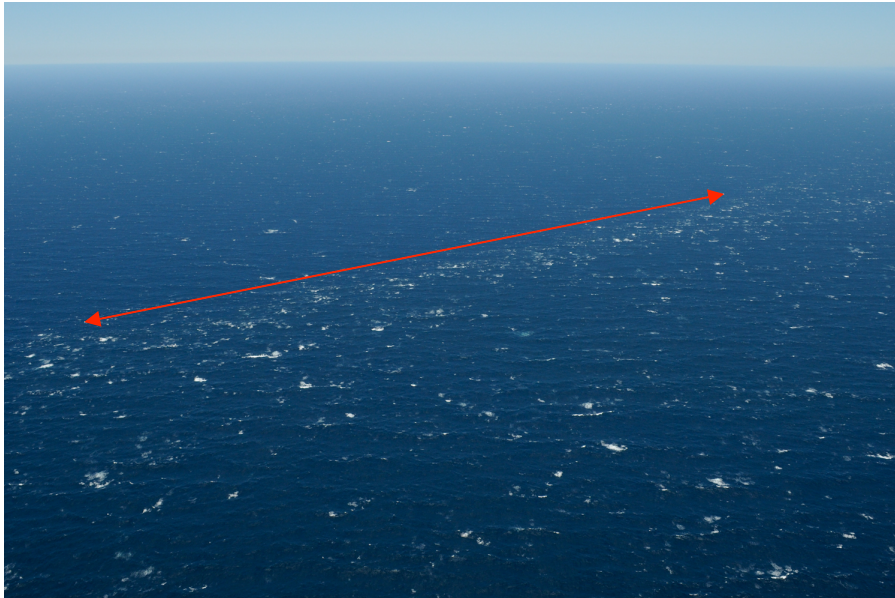
McWilliams, 2016: *Submesoscale currents in the ocean*

LANDSAT8 Image of cyanobacteria bloom in the Baltic Sea, Aug. 11, 2015

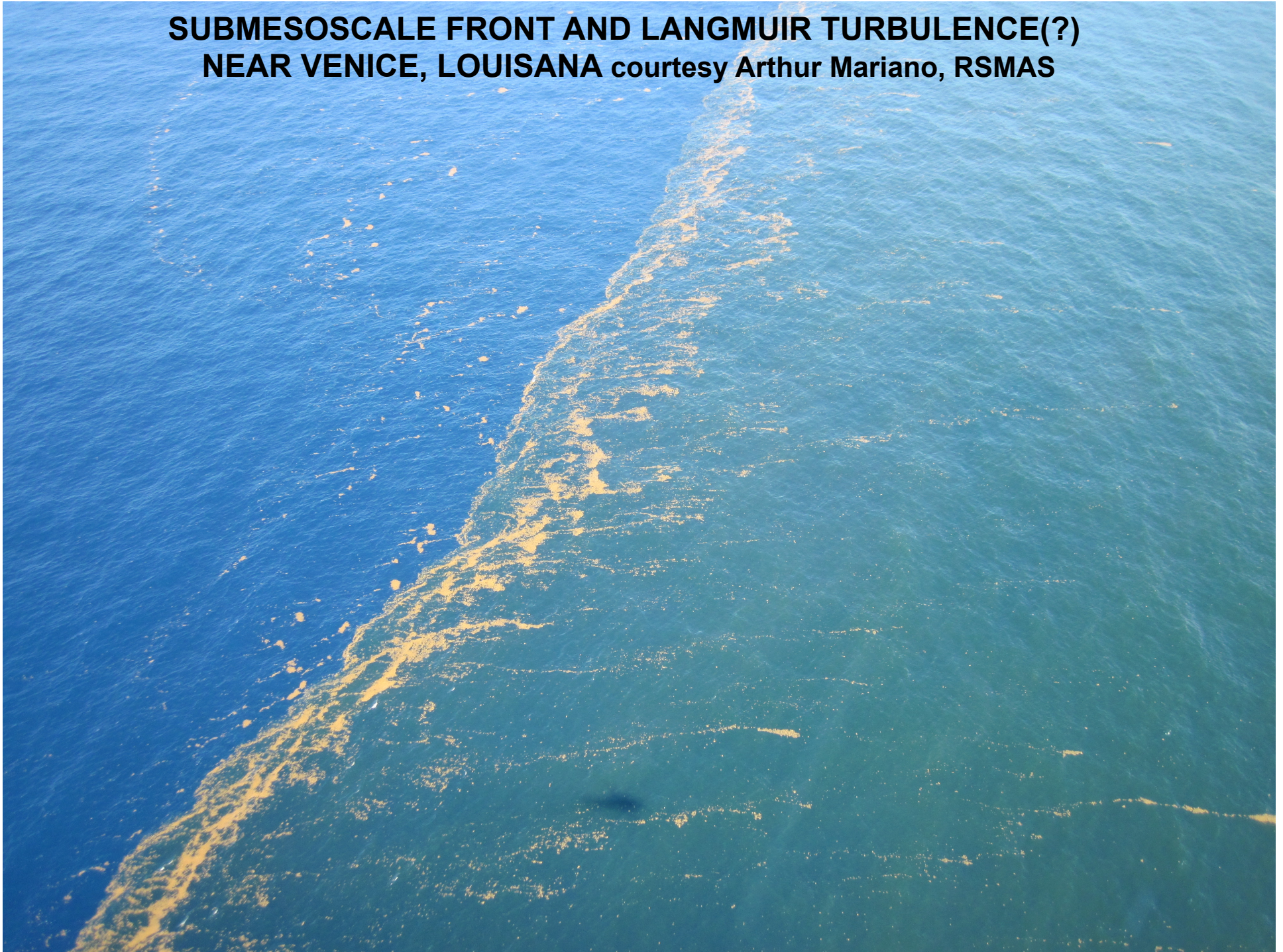


HI-RES Experiment June 2010, Courtesy Ken Melville, Scripps Institution of Oceanography

Wave-current interaction and ocean fronts



**SUBMESOSCALE FRONT AND LANGMUIR TURBULENCE(?)
NEAR VENICE, LOUISIANA courtesy Arthur Mariano, RSMAS**




COLD FILAMENT FRONTOGENESIS (CFF) AND FRONTAL TURBULENCE

WHY COLD FILAMENTS:

- Filament \Rightarrow a closely spaced pair of warm-cold cold-warm fronts
- Super exponential rate of intensification (McWilliams *et al.* 2009,b)
- Prevalence, *e.g.*, in the Gulf Stream

CFF LIFECYCLE:

- Role of winds, cooling, surface waves
- Turbulent Thermal Wind (TTW) balance
- Turbulence ! 

APPROACH:

- Large domain Large Eddy Simulation (LES) with fine spatial meshes, 6.4×10^9 gridpoints
- LES design after McWilliams *et al.* (2015)
“*Filament frontogenesis by boundary layer turbulence*”

LES SETUP FOR A 2-D FILAMENT

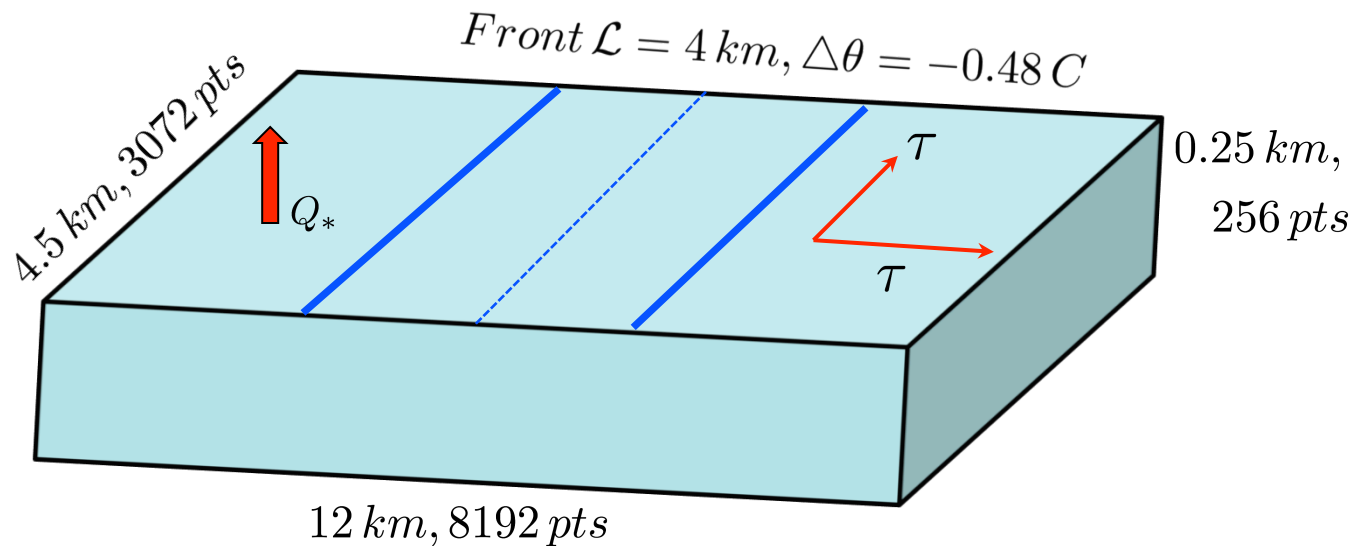
LES MODEL:

- Wave-averaged Boussinesq plus baroclinic pressure gradients

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} = \dots + \mathbf{u}_s \times (f \hat{\mathbf{z}} + \bar{\boldsymbol{\omega}}) + f \hat{\mathbf{z}} \times \mathbf{u}_g$$

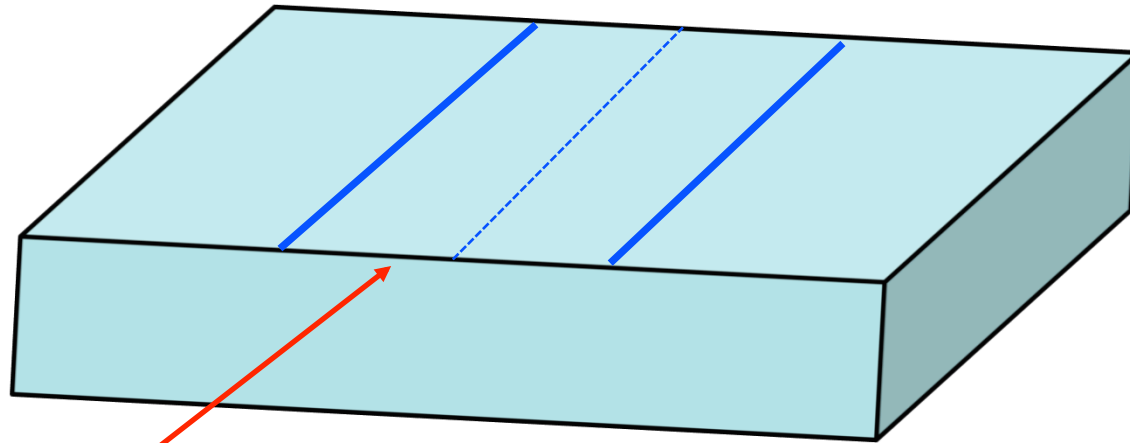
CASES:

- Seven simulations: east winds, north winds, cooling, surface waves

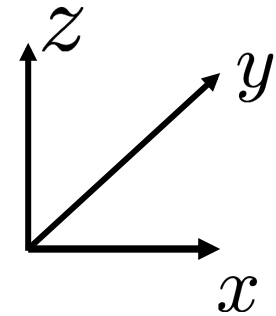


$$(\Delta x = \Delta y, \Delta z) = (1.46, [0.5 - 1.58]) \text{ m} \quad N_x \cdot N_y \cdot N_z = 6.4 \cdot 10^9 \text{ pts}$$

FLOW DECOMPOSITION: MEANS AND FLUCTUATIONS



2D density filament



Along-front average

$$\langle f \rangle(x, z) = \int f(x, y, z) dy$$

$$u = \langle u \rangle + u'$$

$$v = \langle v \rangle + v'$$

$$w = \langle w \rangle + w'$$

$$b = \langle b \rangle + b'$$

LES ALONG-FRONT AVERAGE EQUATIONS WITH WAVE EFFECTS

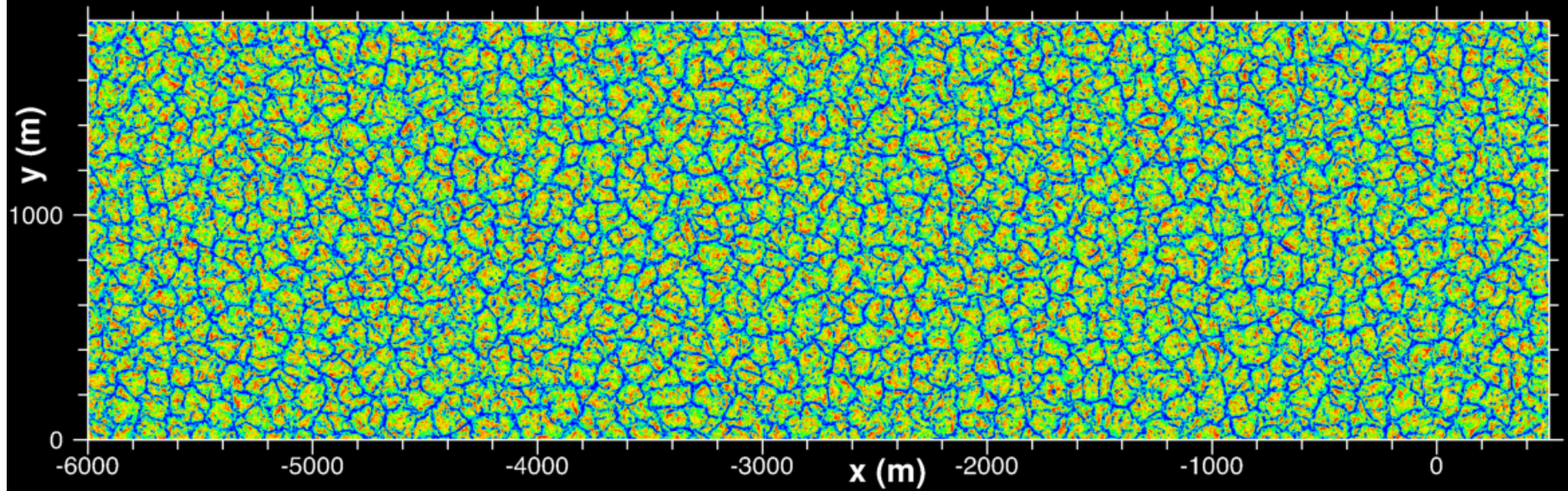
$$\begin{aligned}
 \frac{\partial}{\partial t} \langle u \rangle &= \cancel{-\frac{\partial}{\partial x} (u^L \langle u \rangle + \langle u' u' \rangle + \frac{\langle p \rangle}{\rho_o} + \frac{2 \langle e \rangle}{3} + \langle \tau_{11} \rangle)} \\
 &\quad - \frac{\partial}{\partial z} (\langle u \rangle \langle w \rangle + \langle u' w' \rangle + \langle \tau_{13} \rangle) + f(v^L - v_g) \\
 \frac{\partial}{\partial t} \langle v \rangle &= \cancel{-\frac{\partial}{\partial x} (u^L \langle v \rangle + \langle u' v' \rangle + \langle \tau_{12} \rangle)} \\
 &\quad - \frac{\partial}{\partial z} (\langle v \rangle \langle w \rangle + \langle v' w' \rangle + \langle \tau_{23} \rangle) - f u^L \\
 \frac{\partial}{\partial t} \langle w \rangle &= \cancel{-\frac{\partial}{\partial x} (u^L \langle w \rangle + \langle u' w' \rangle + \langle \tau_{13} \rangle)} \\
 &\quad - \frac{\partial}{\partial z} (\langle w \rangle \langle w \rangle + \langle w' w' \rangle + \langle \tau_{33} \rangle + \frac{\langle p \rangle}{\rho_o} + \frac{2}{3} \langle e \rangle) \\
 &\quad + \langle b \rangle - \left(u^L \frac{\partial u_s}{\partial z} - v^L \frac{\partial v_s}{\partial z} \right) \\
 \frac{\partial}{\partial t} \langle b \rangle &= \cancel{-\frac{\partial}{\partial x} (u^L \langle b \rangle + \langle u' b' \rangle + \langle \tau_{1b} \rangle)} \\
 &\quad - \frac{\partial}{\partial z} (\langle w \rangle \langle b \rangle + \langle w' b' \rangle + \langle \tau_{3b} \rangle)
 \end{aligned}$$

No front

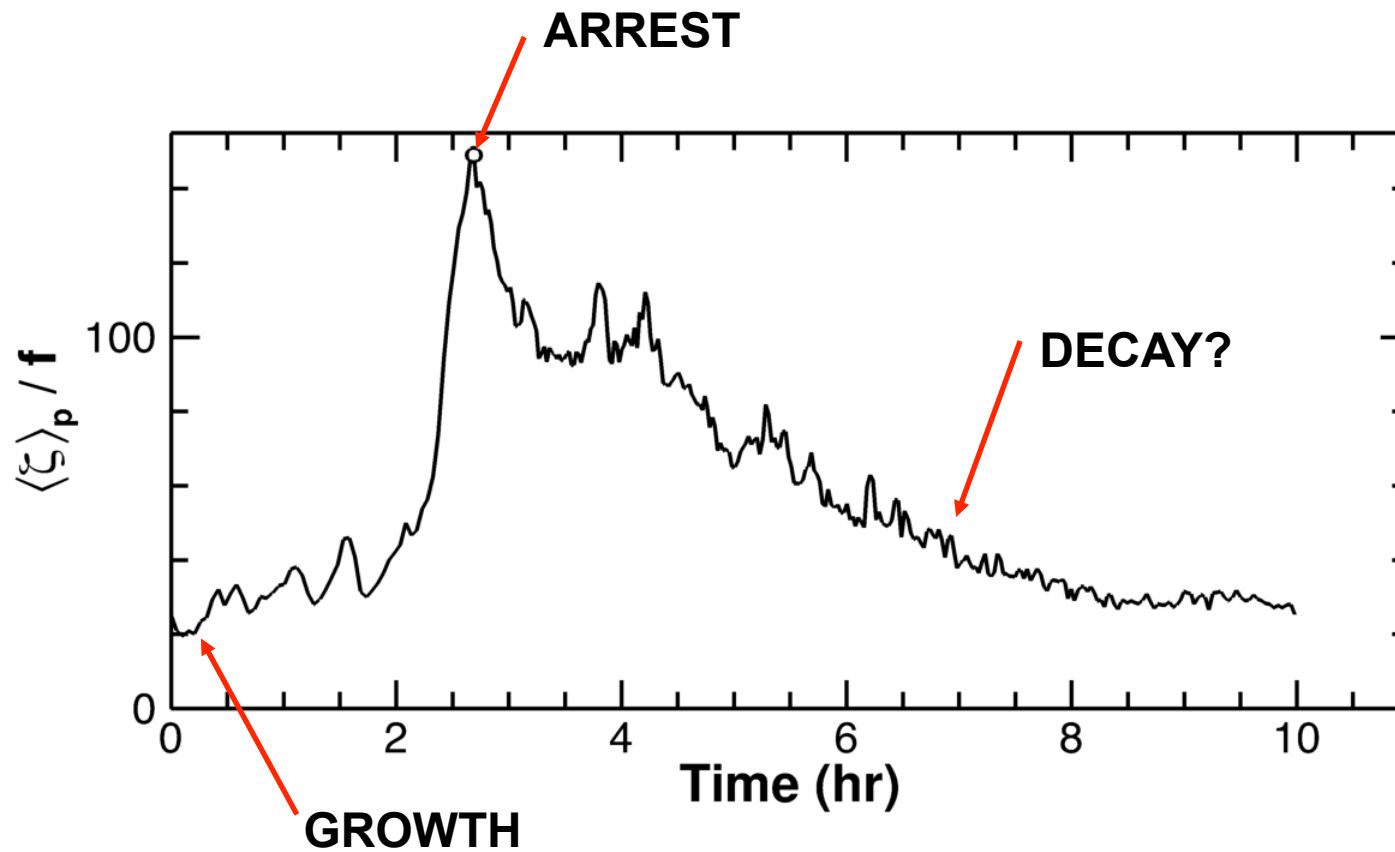
Wave effects

VERTICAL VELOCITY IN LES OF CFF WITH COOLING

FULLY DEVELOPED TURBULENCE, $z = -3\text{ m}$



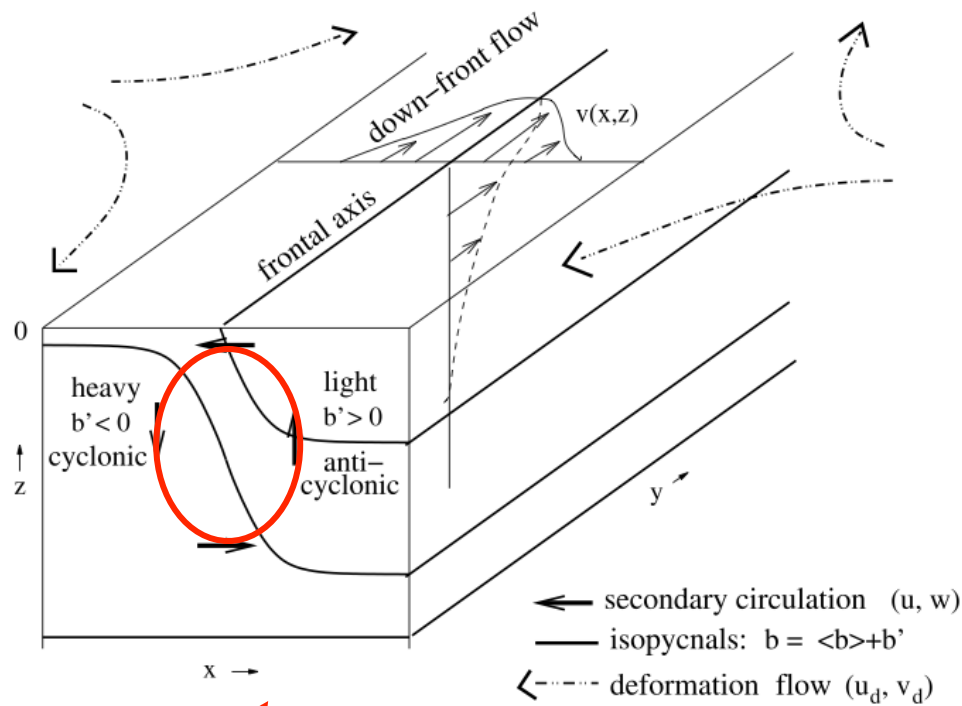
TIME HISTORY OF FRONTOGENESIS AND FRONTOLYSIS AVERAGE VERTICAL VORTICITY



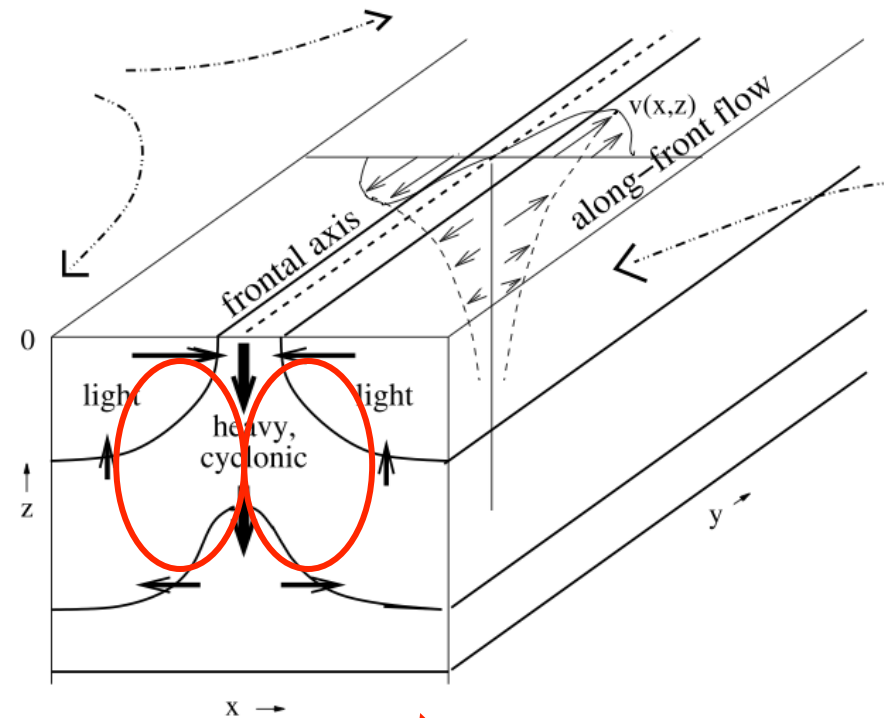
$$\langle \zeta \rangle_p = \partial_x \langle v \rangle_{peak}$$

BOUNDARY-LAYER INDUCED FRONTOGENESIS

IDEALIZED FRONT AND FILAMENT FRONTOGENESIS



One-sided surface frontogenesis, Hoskins, 1982



Cold filament frontogenesis, McWilliams et al, 2009

TURBULENT THERMAL WIND (TTW)

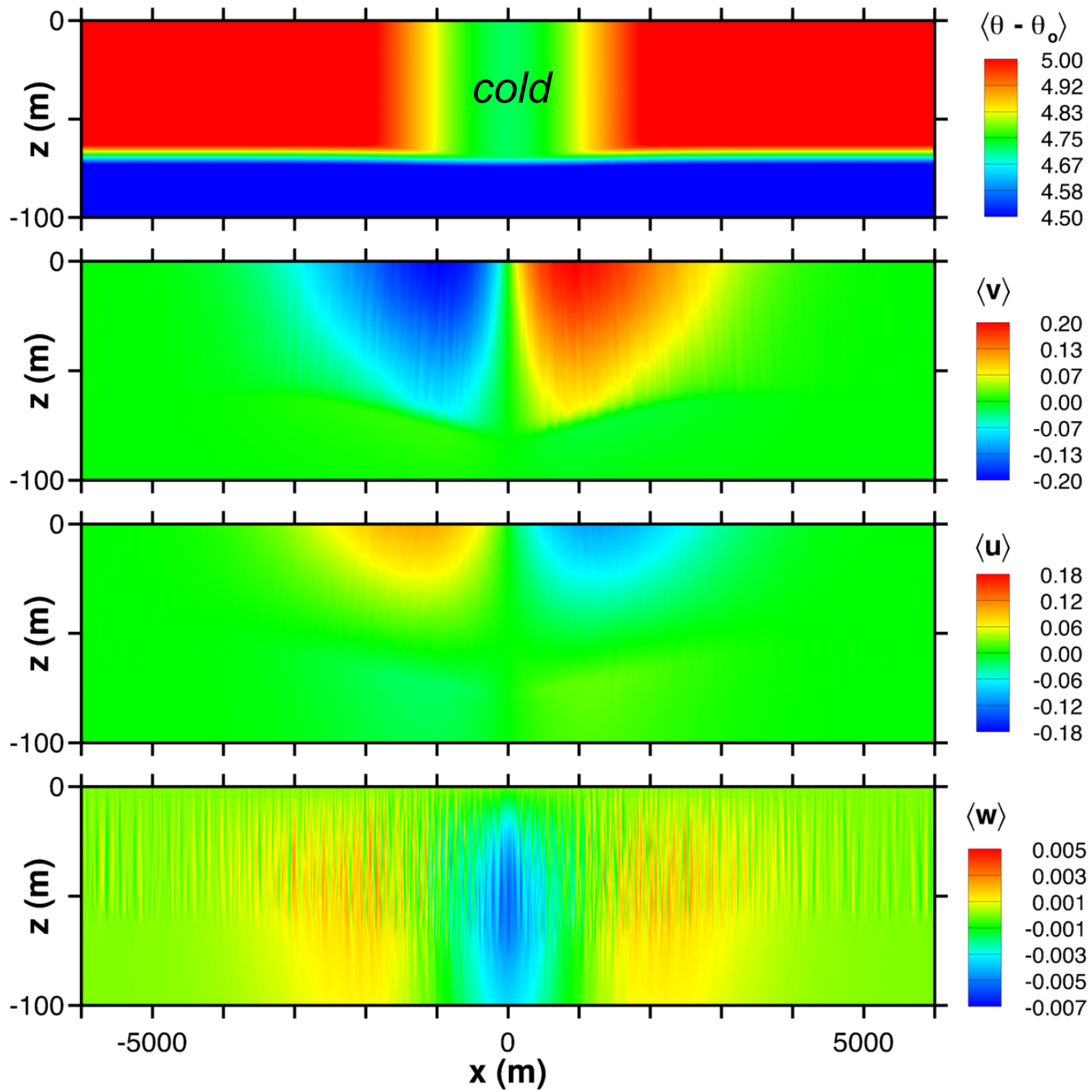
A quasi-steady, linear momentum balance, that combines hydrostatic, geostrophic and Ekman boundary layer dynamics is called *turbulent thermal wind* (TTW), McWilliams *et al.* (2015, JPO)

$$f \frac{\partial v_g}{\partial z} = \frac{\partial b}{\partial x}, \quad \langle u \rangle = 0, \quad \langle w \rangle = 0$$

far field

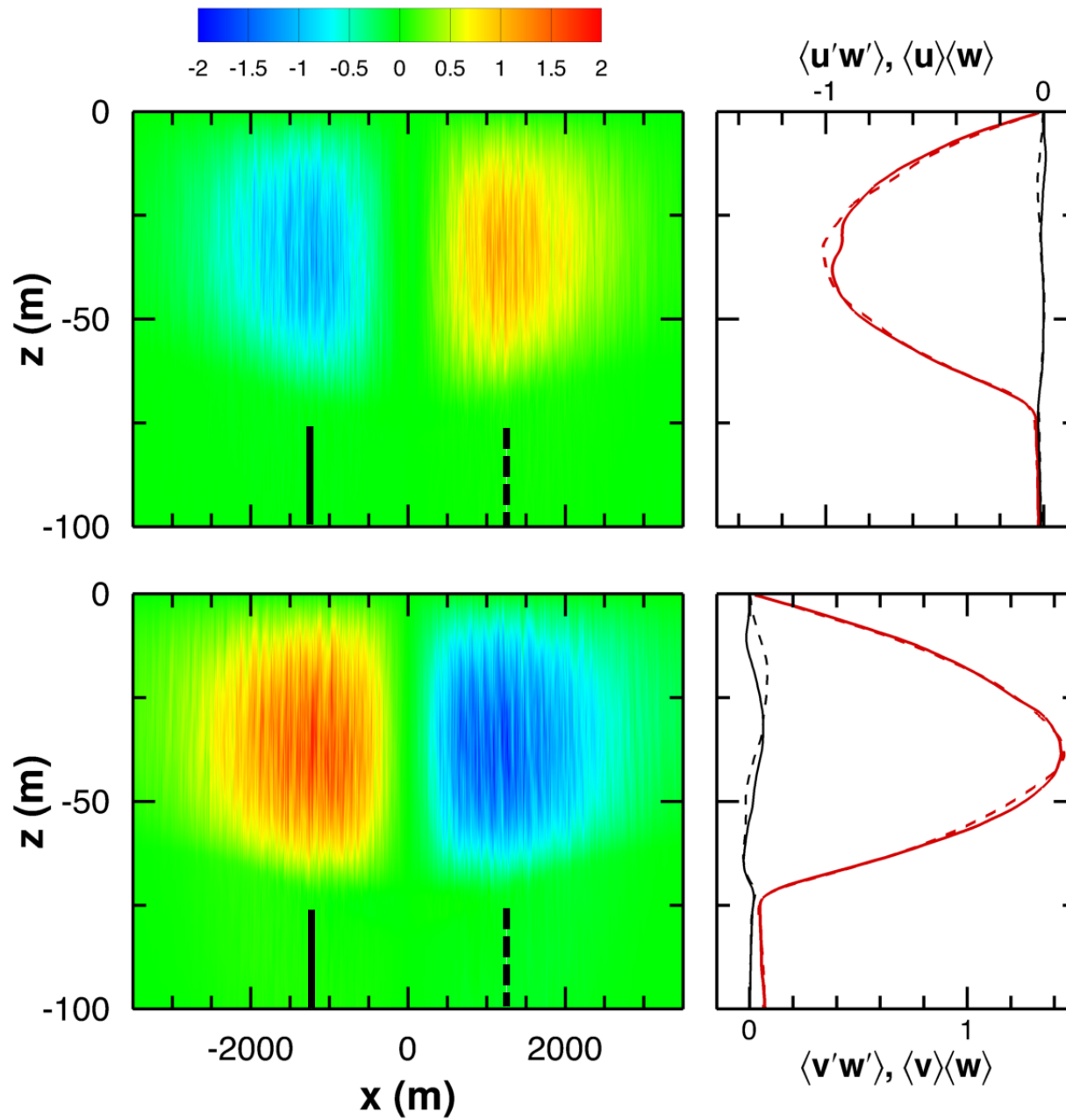
\mathbf{u} = currents, b = buoyancy, v_g = geostrophic current, f = Coriolis parameter
 $\langle \rangle$ = average, $()'$ = fluctuation

CROSS-FRONT FIELDS WITH SURFACE COOLING



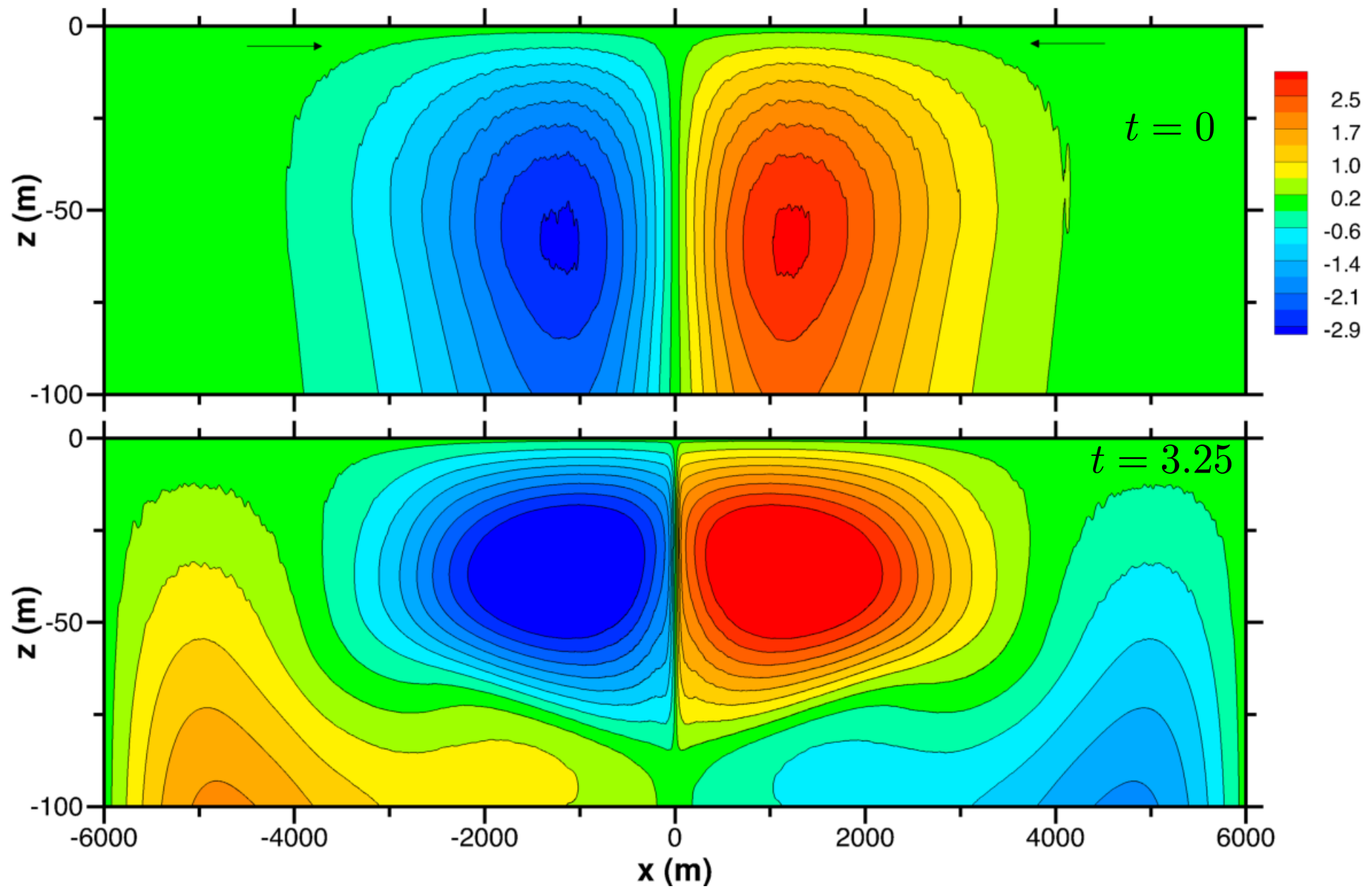
$t = 0$

MOMENTUM FLUXES IN TTW DRIVEN BY COOLING

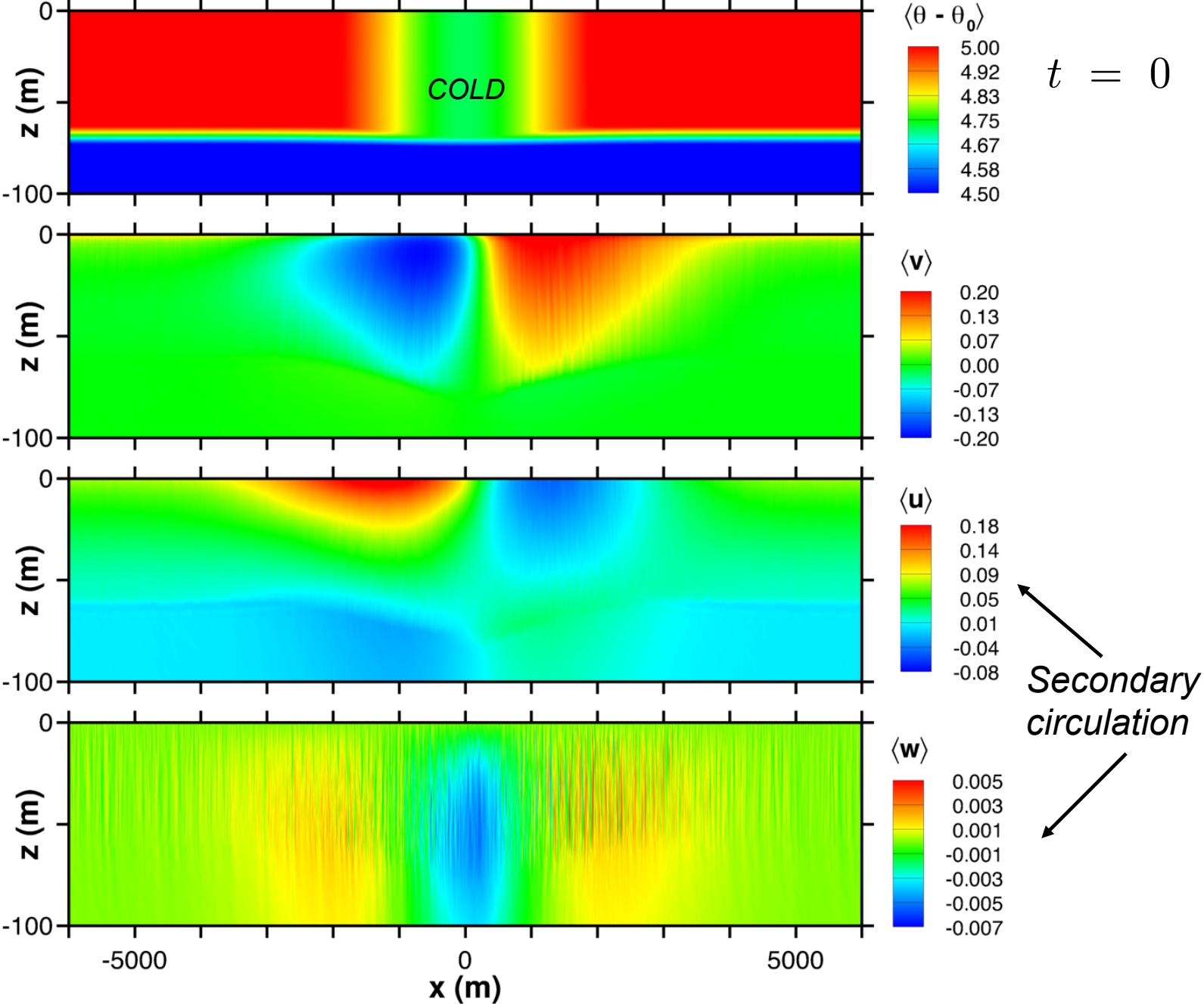


$t = 0$

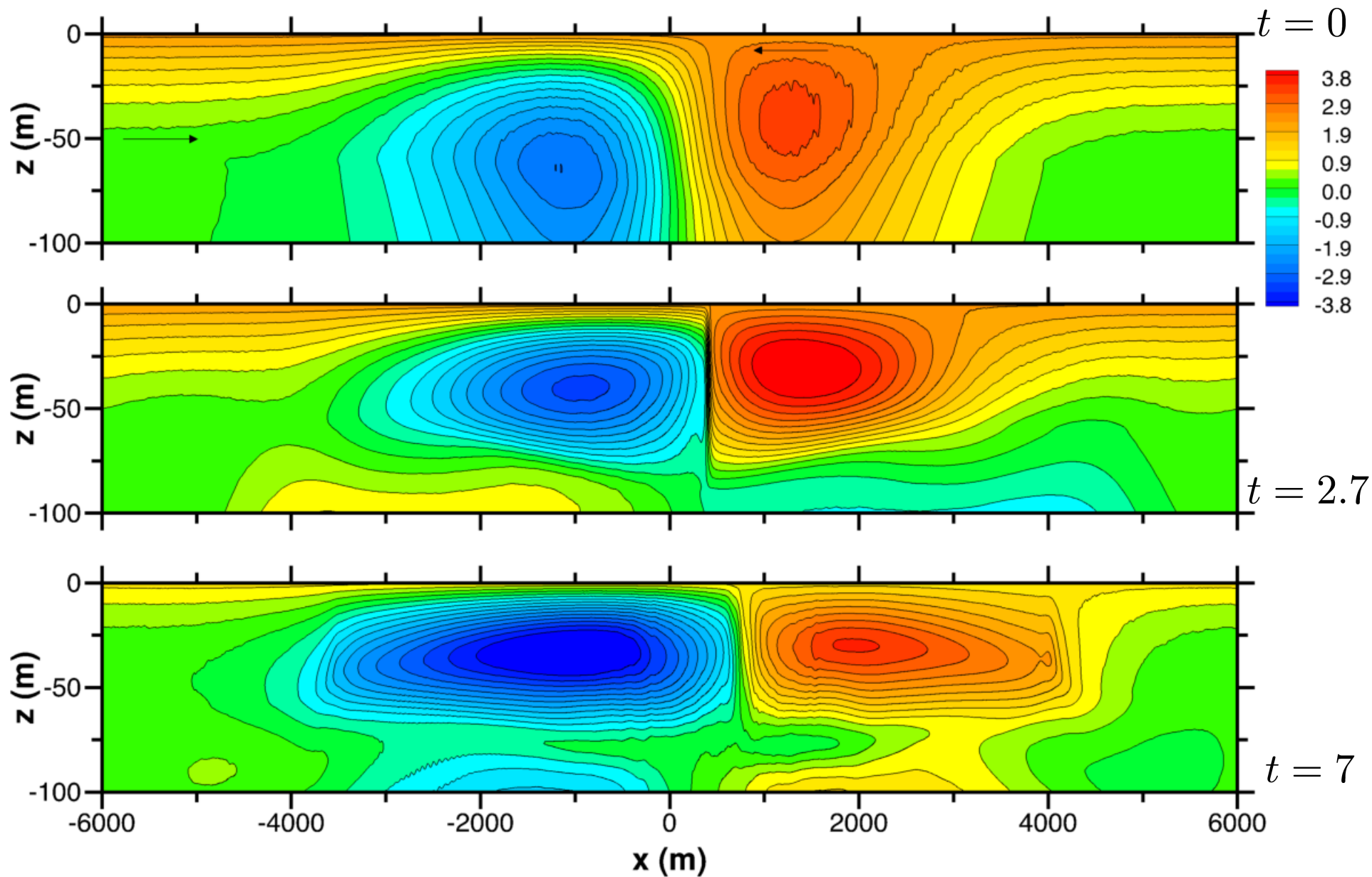
CROSS-FRONT STREAMFUNCTION WITH COOLING



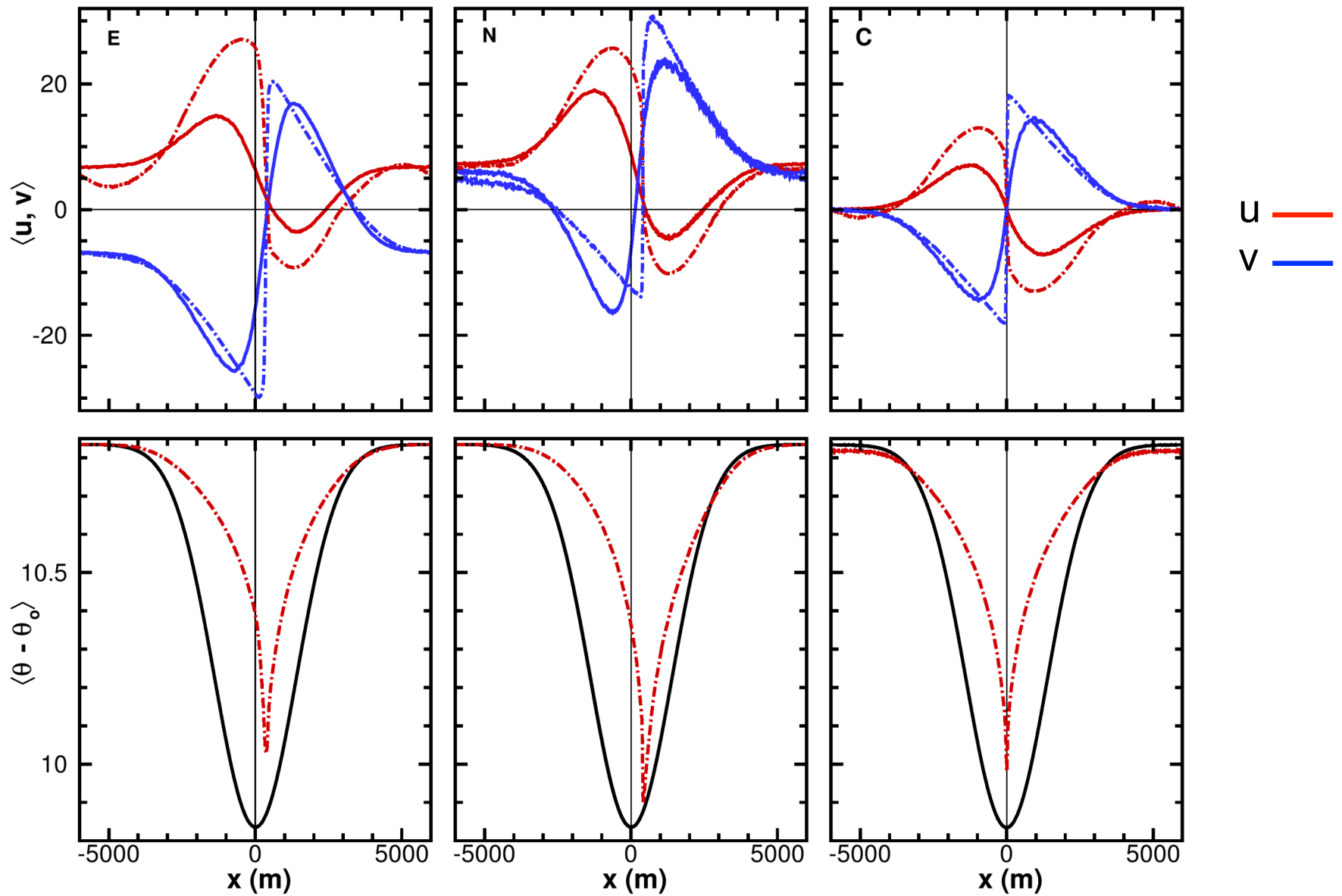
CROSS-FRONT FIELDS WITH NORTH WIND



CROSS-FRONT STREAMFUNCTION FOR NORTH WINDS



CROSS FRONT PROFILES OF MEAN CURRENTS AND TEMPERATURE



LIFE CYCLE OF COLD FILAMENT

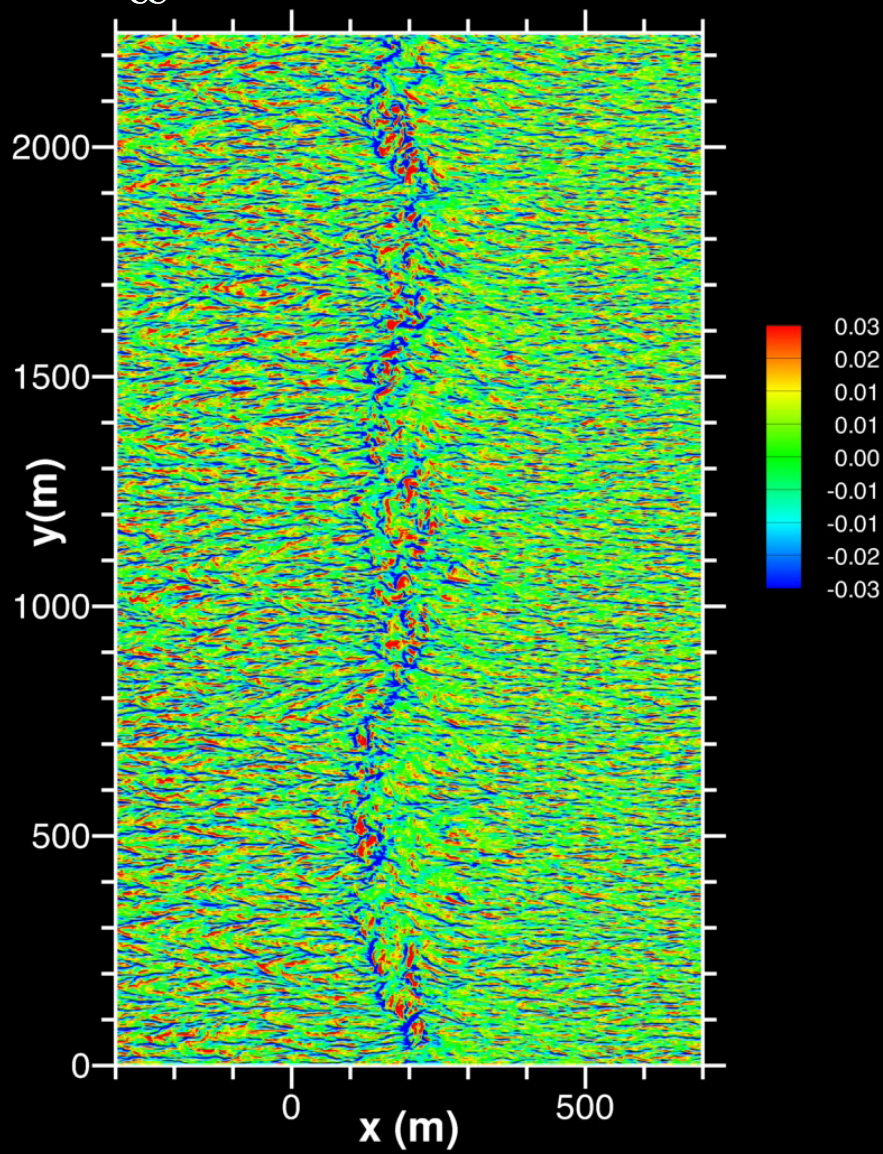
FRONTOGENESIS

Winds + waves

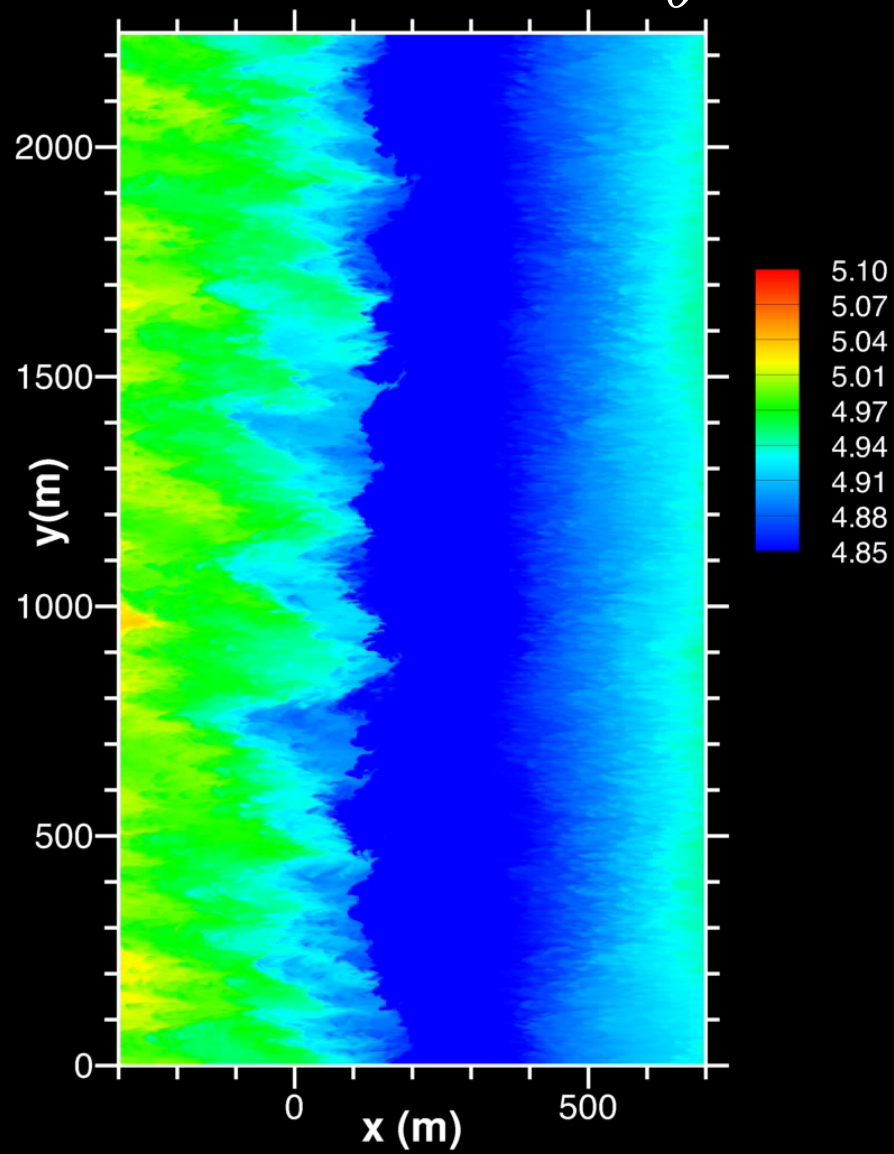


$z = -3 \text{ m}$

w



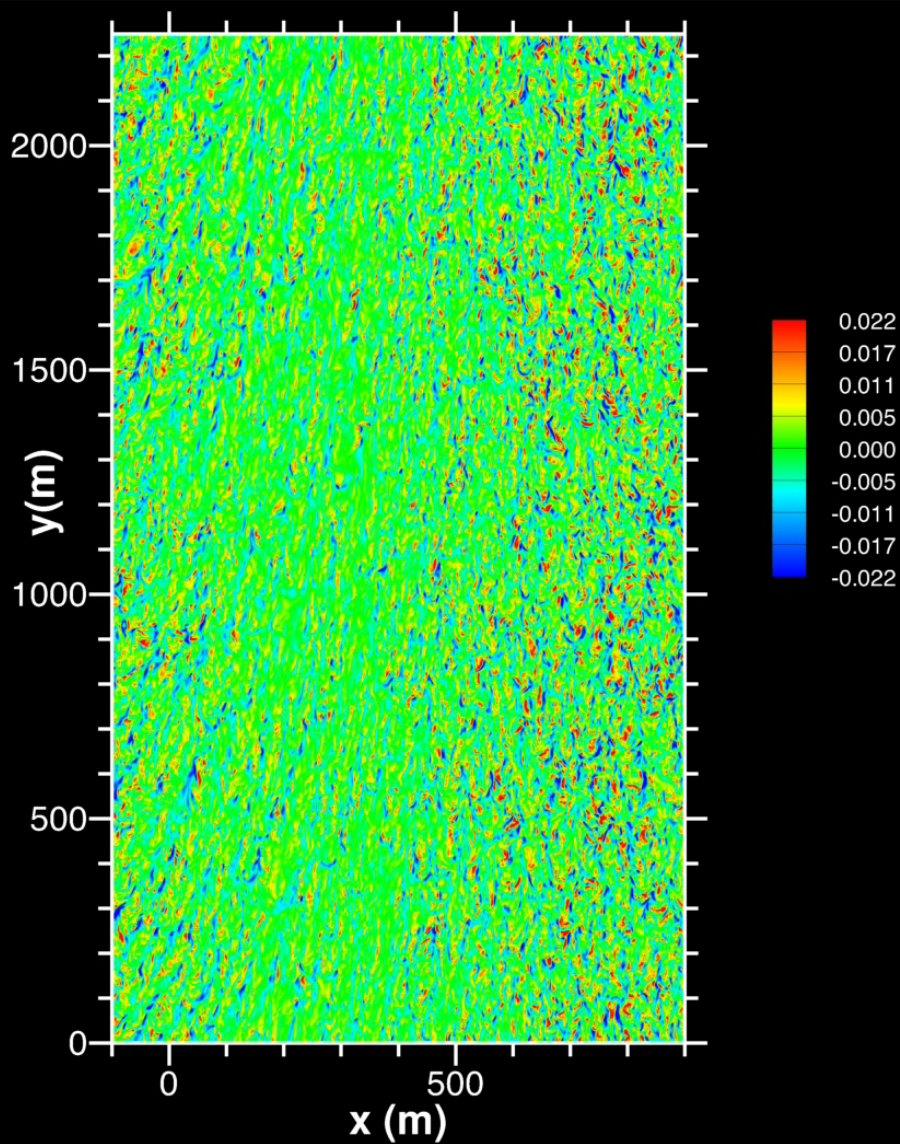
θ



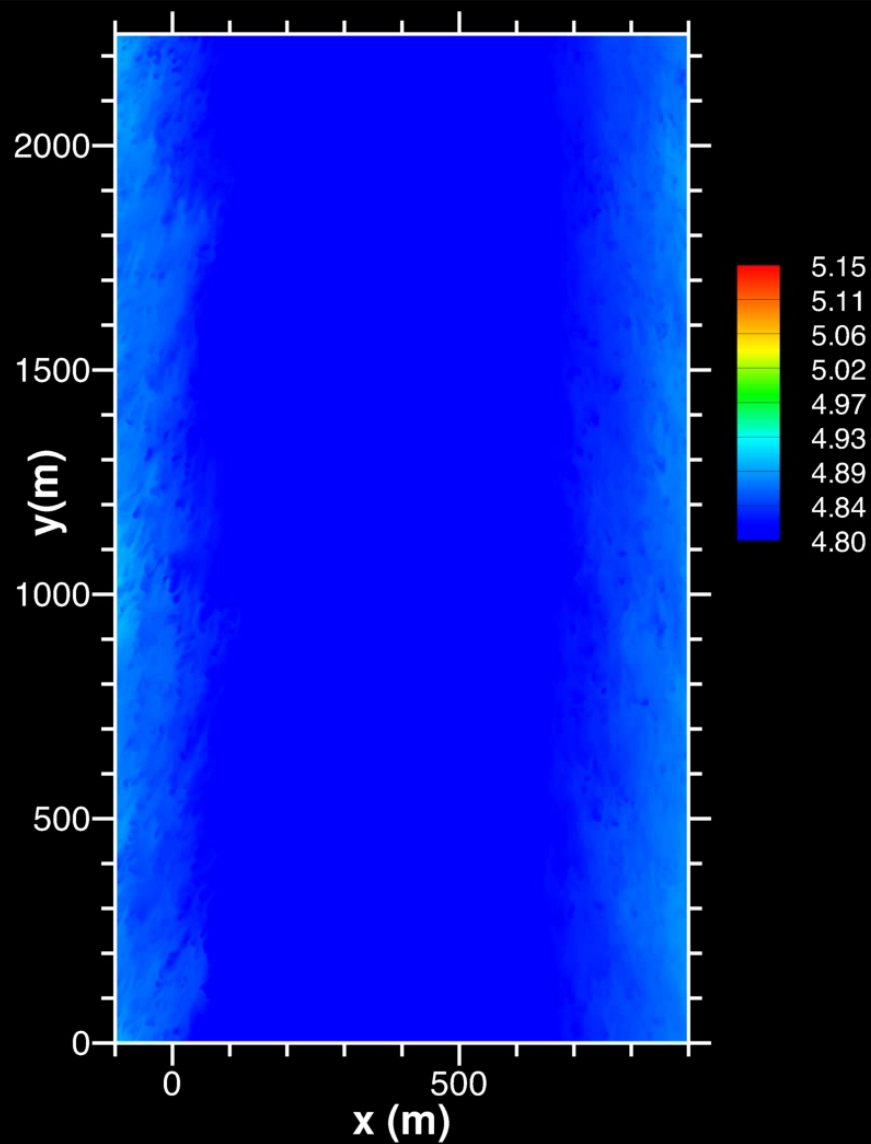
Winds ↑

$z = -3 \text{ m}$

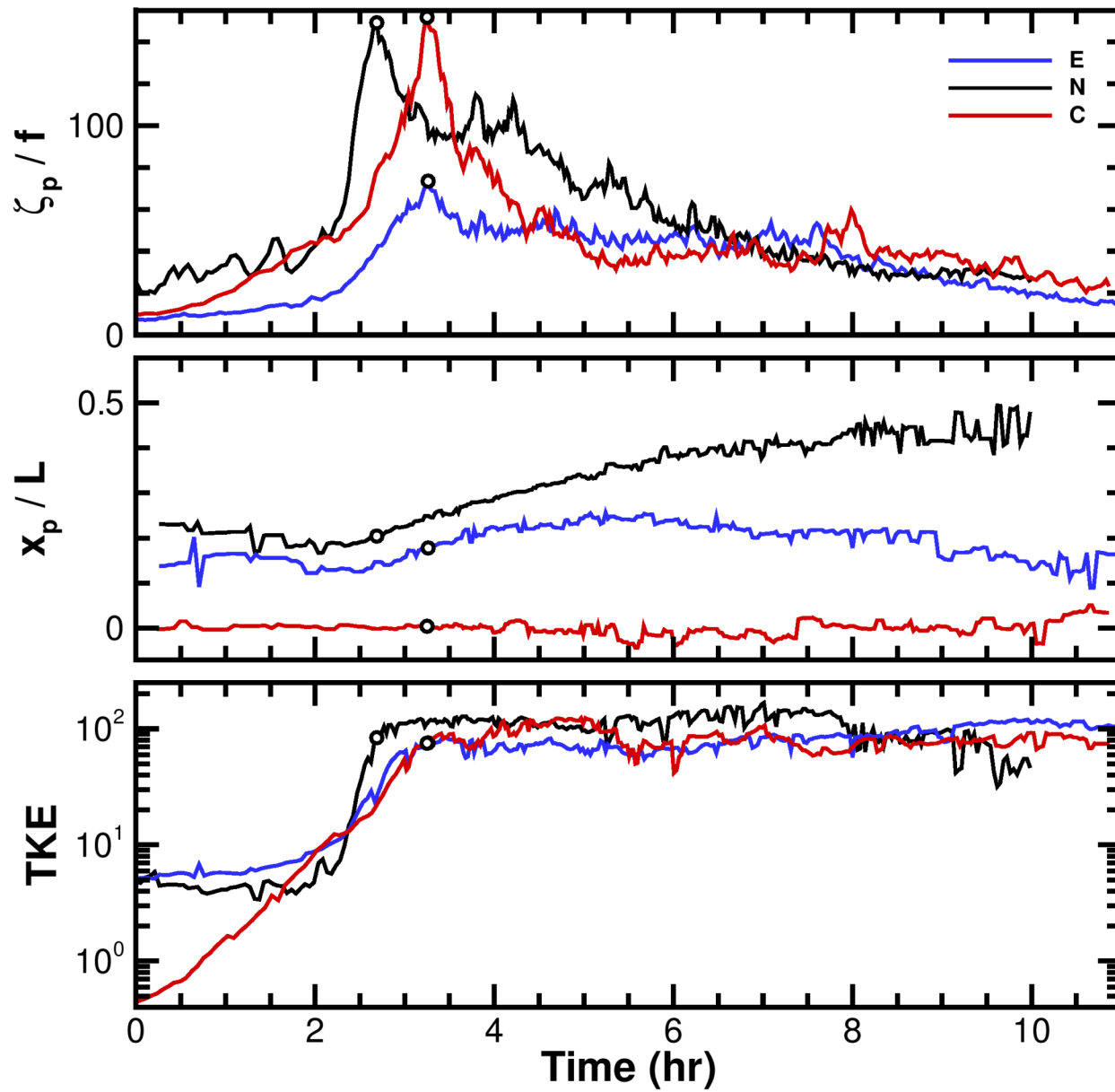
w



θ



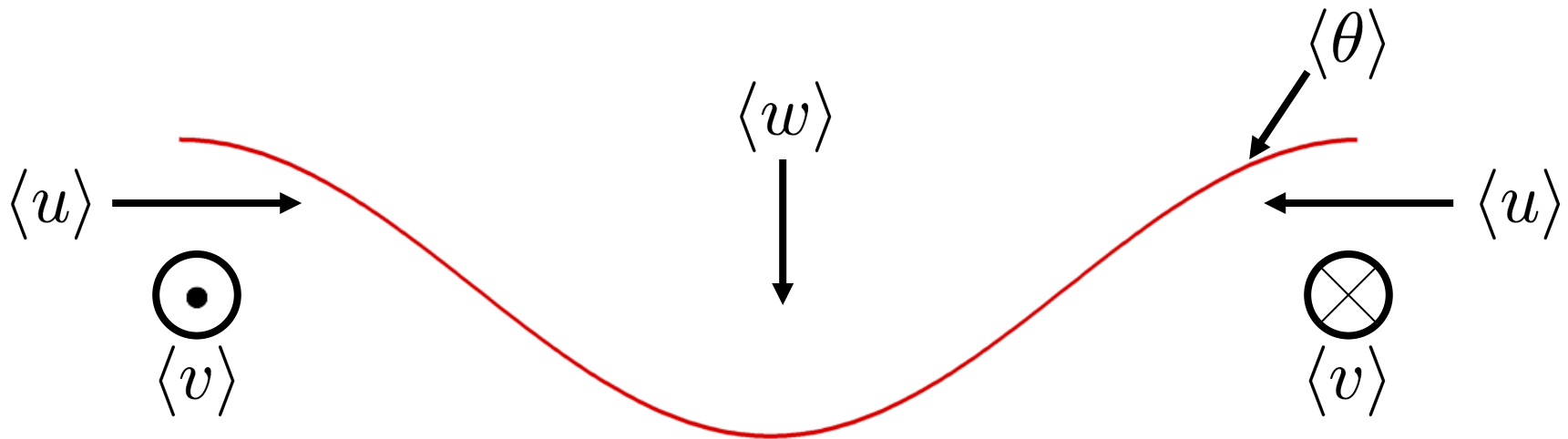
VERTICAL VORTICITY, FRONT LOCATION AND TKE



WHAT DOES THE ARREST?

“The real breakdown of our models is that when gradients become large, ... Kelvin-Helmholtz instability must be expected, and neglected mixing effects must be important.” (Hoskins & Bretherton, 1972)

HORIZONTAL VARIANCES AND CO-VARIANCES



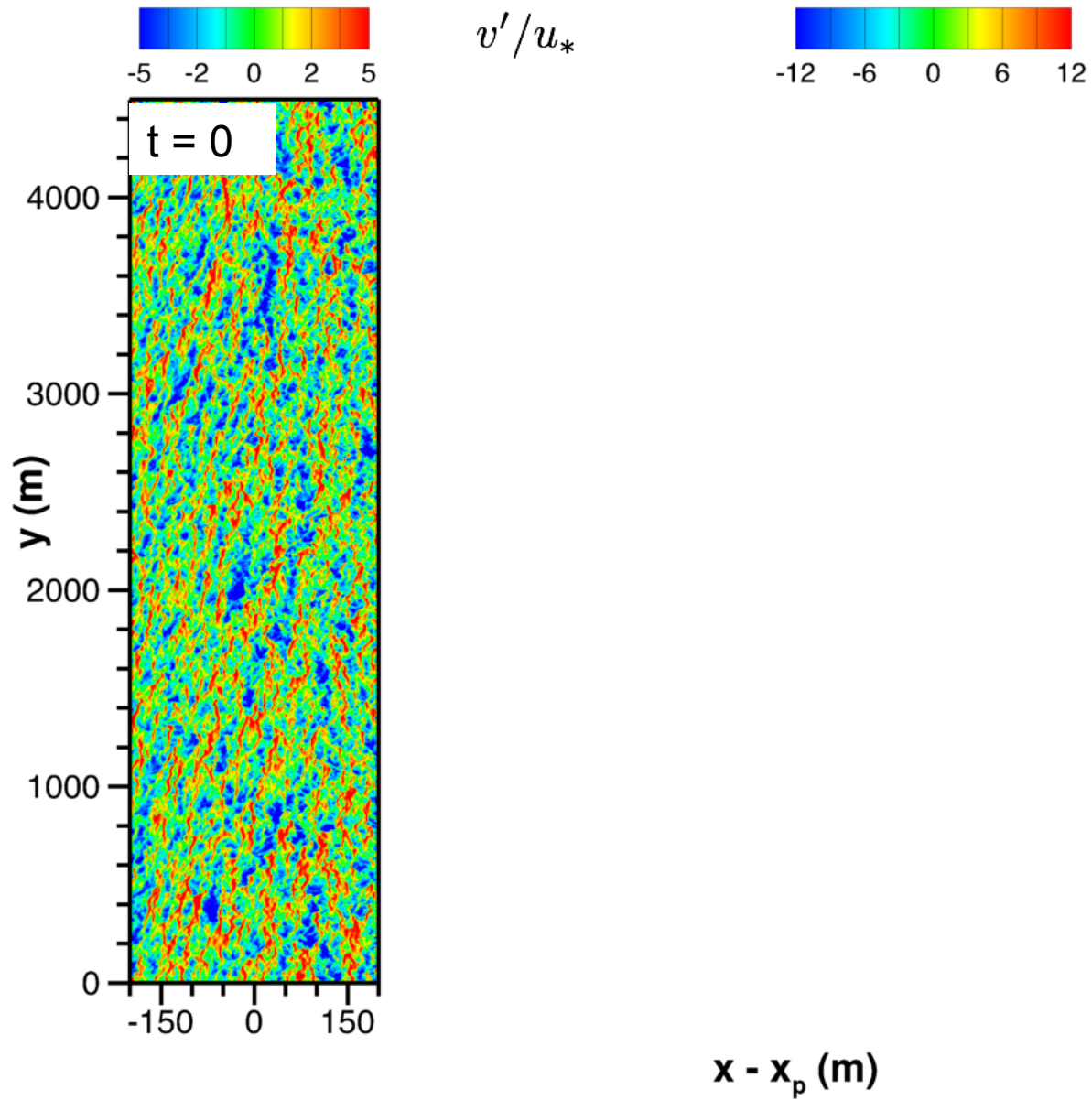
$$\frac{\partial \langle u \rangle}{\partial t} = -\frac{\partial}{\partial x} [\langle u \rangle \langle u \rangle + \langle u' u' \rangle] - \frac{\partial}{\partial z} [\langle u \rangle \langle w \rangle + \langle u' w' \rangle] \dots$$

$$\frac{\partial \langle v \rangle}{\partial t} = -\frac{\partial}{\partial x} [\langle u \rangle \langle v \rangle + \langle u' v' \rangle] - \frac{\partial}{\partial z} [\langle v \rangle \langle w \rangle + \langle v' w' \rangle] \dots$$

$$\langle \mathbf{u} \rangle \cdot \partial_t \langle \mathbf{u} \rangle$$

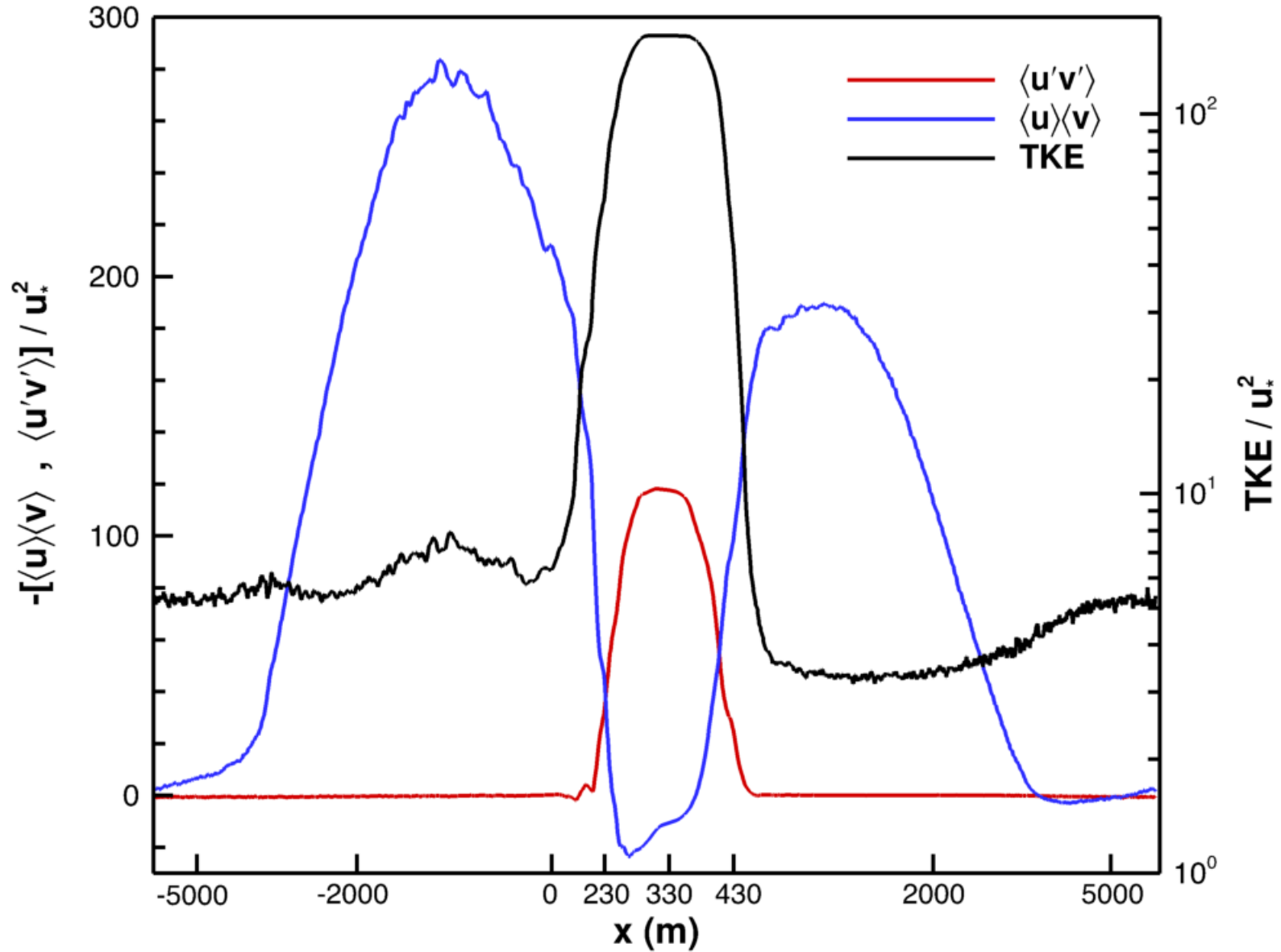
$$TK E_{prod} = -\langle u' u' \rangle \frac{\partial \langle u \rangle}{\partial x} - \langle u' v' \rangle \frac{\partial \langle v \rangle}{\partial x} - \langle u' w' \rangle \frac{\partial \langle u \rangle}{\partial z} - \langle v' w' \rangle \frac{\partial \langle v \rangle}{\partial z}$$

TIME EVOLUTION OF FRONTAL INSTABILITY NORTH WIND

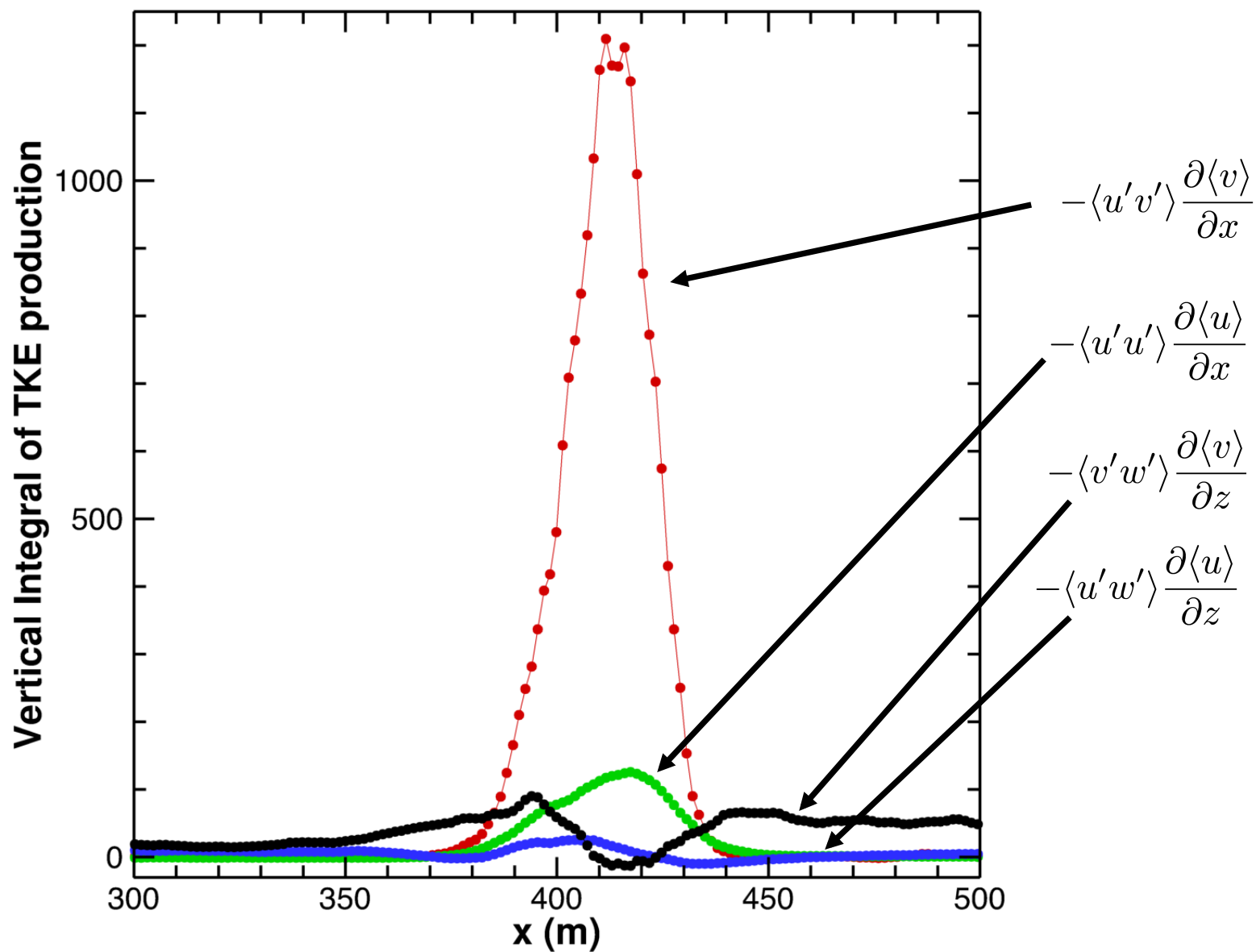


HORIZONTAL FLUXES AND TKE FOR EAST WINDS + WAVES

t = 5.5 hr
z ~ -1.26 m



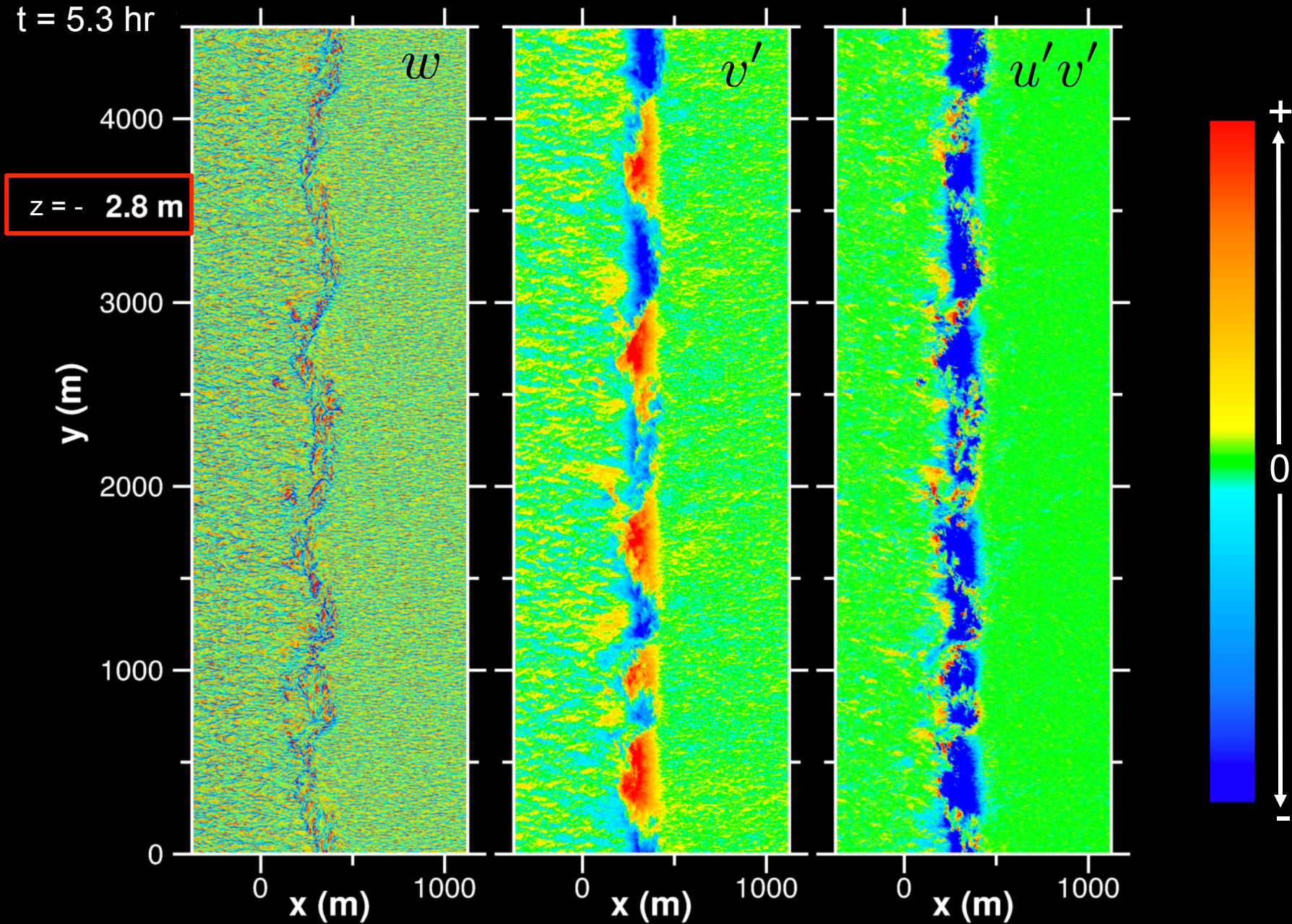
TKE PRODUCTION FOR NORTH WINDS



WHAT'S THE SCALE OF THE ARREST?

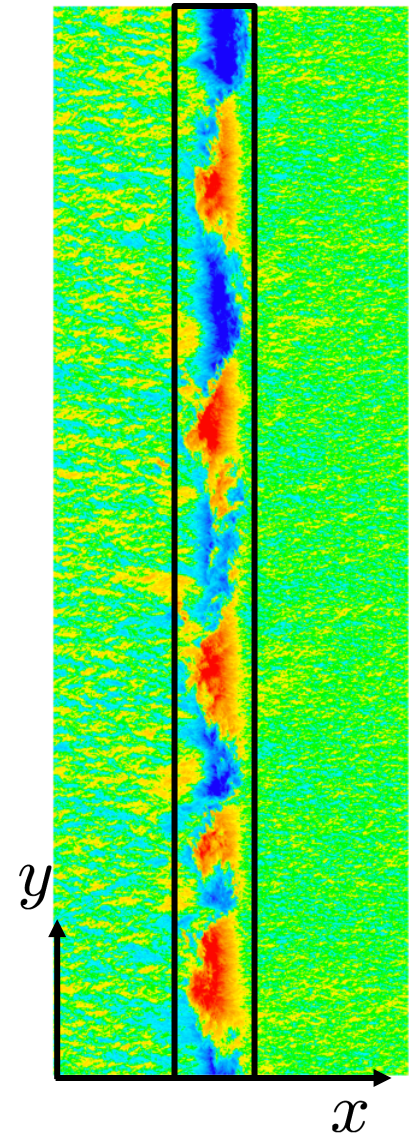
ARRESTING TURBULENCE FOR EAST WINDS + WAVES

t = 5.3 hr

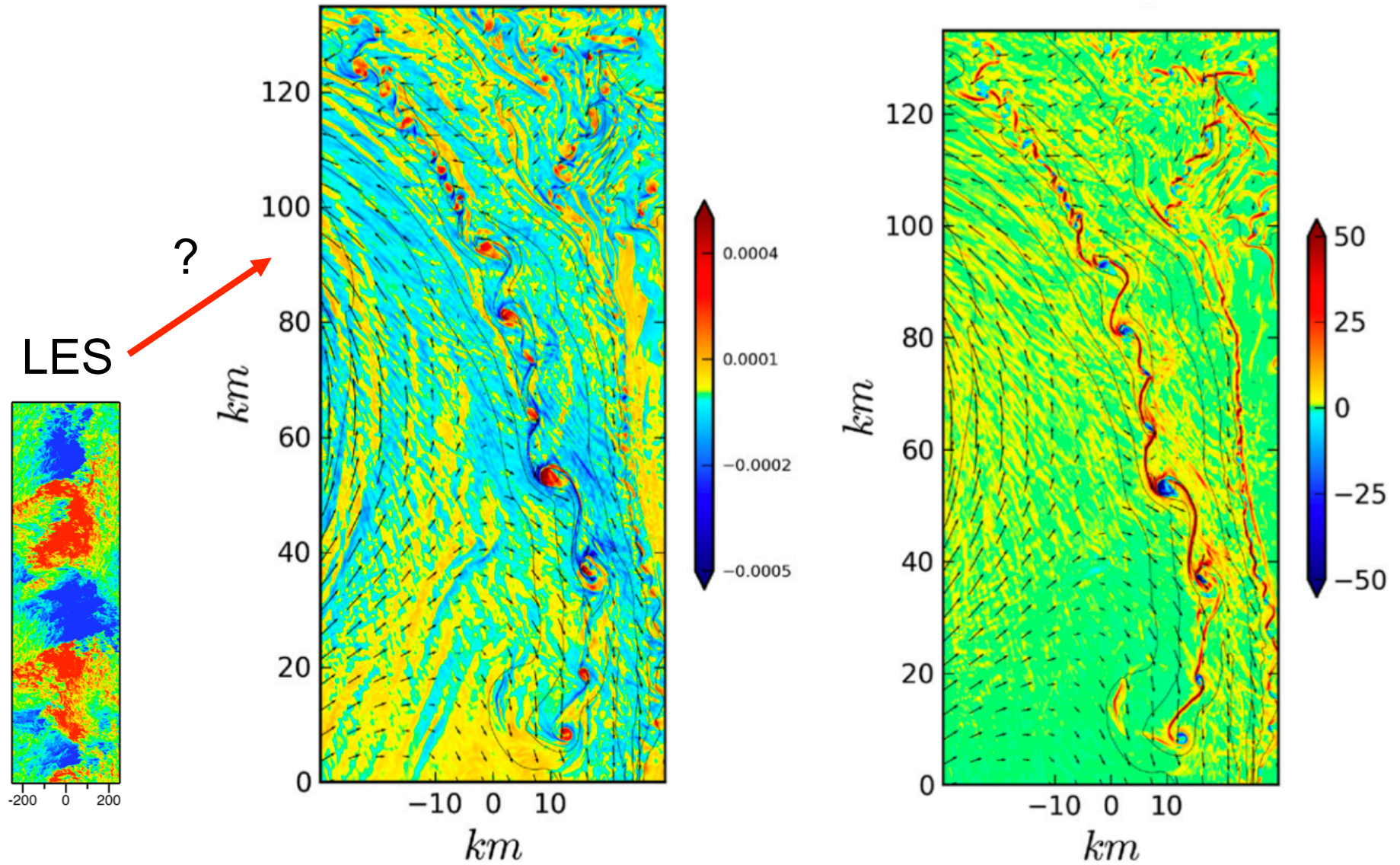


POWER SPECTRA OF (U, V, W) FOR EAST WINDS + WAVES

t = 5.4 hr

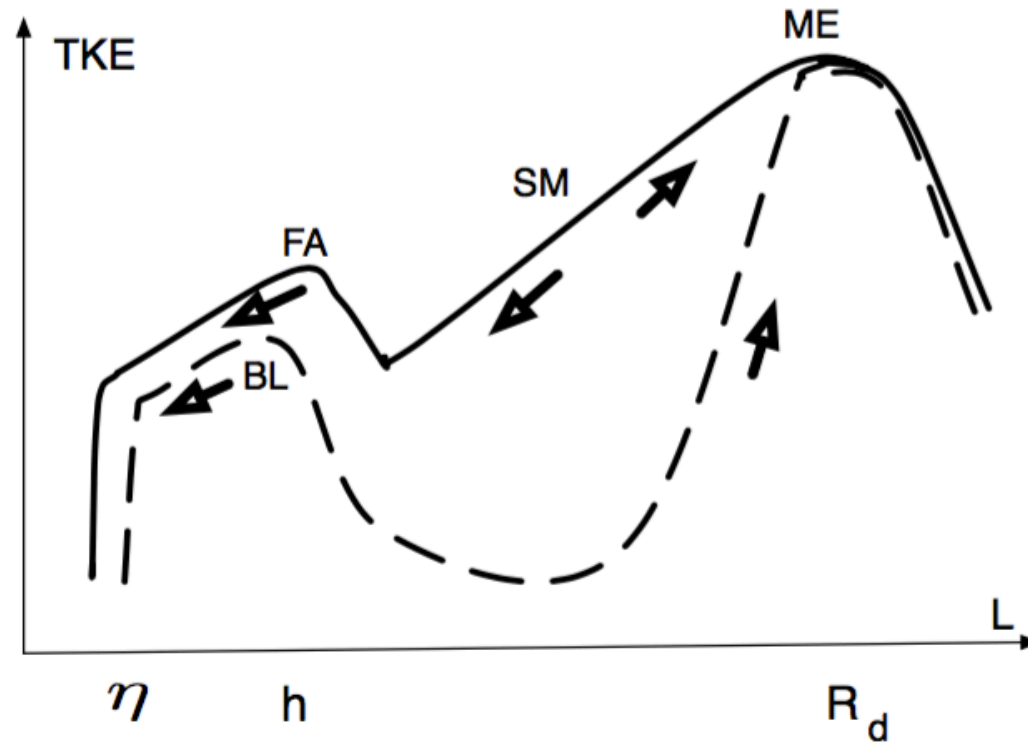


VORTEX FRAGMENTATION OF A DENSITY FILAMENT IN ROMS



GULA *etal* (2014, JPO)

SCHEMATIC OF ENERGY CASCADE IN THE UPPER OCEAN



SUMMARY

LES of Cold Filament Frontogenesis (CFF):

- All the solutions exhibit CFF
- Details dependent on external forcings
- Wind and wave forcing → asymmetrical fronts
- Turbulent Thermal Wind (TTW) balance and secondary circulations

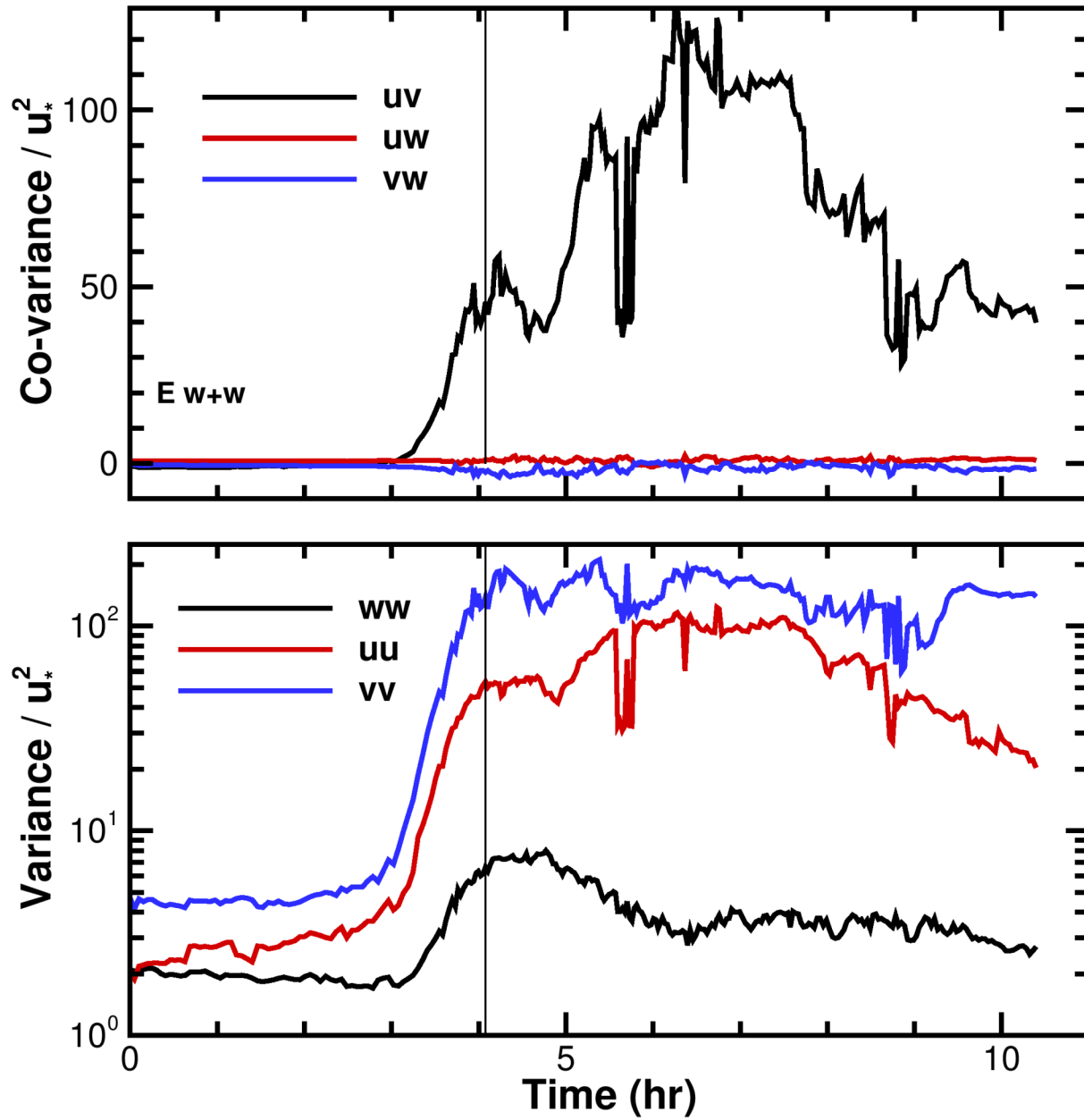
Near surface turbulence:

- Boundary layer turbulence kick-starts frontogenesis
- Arrest by horizontal anisotropic submesoscale turbulence
- Scales of arresting turbulence $\ell_y \gg |h|$, $\ell_x < |h|$
- Variances $v'^2 \sim u'^2 > w'^2$
- Co-variances $-u'v' \gg -u'w', -v'w'$
- Frontal shear instability $\partial v(t)/\partial x$ develops at long time

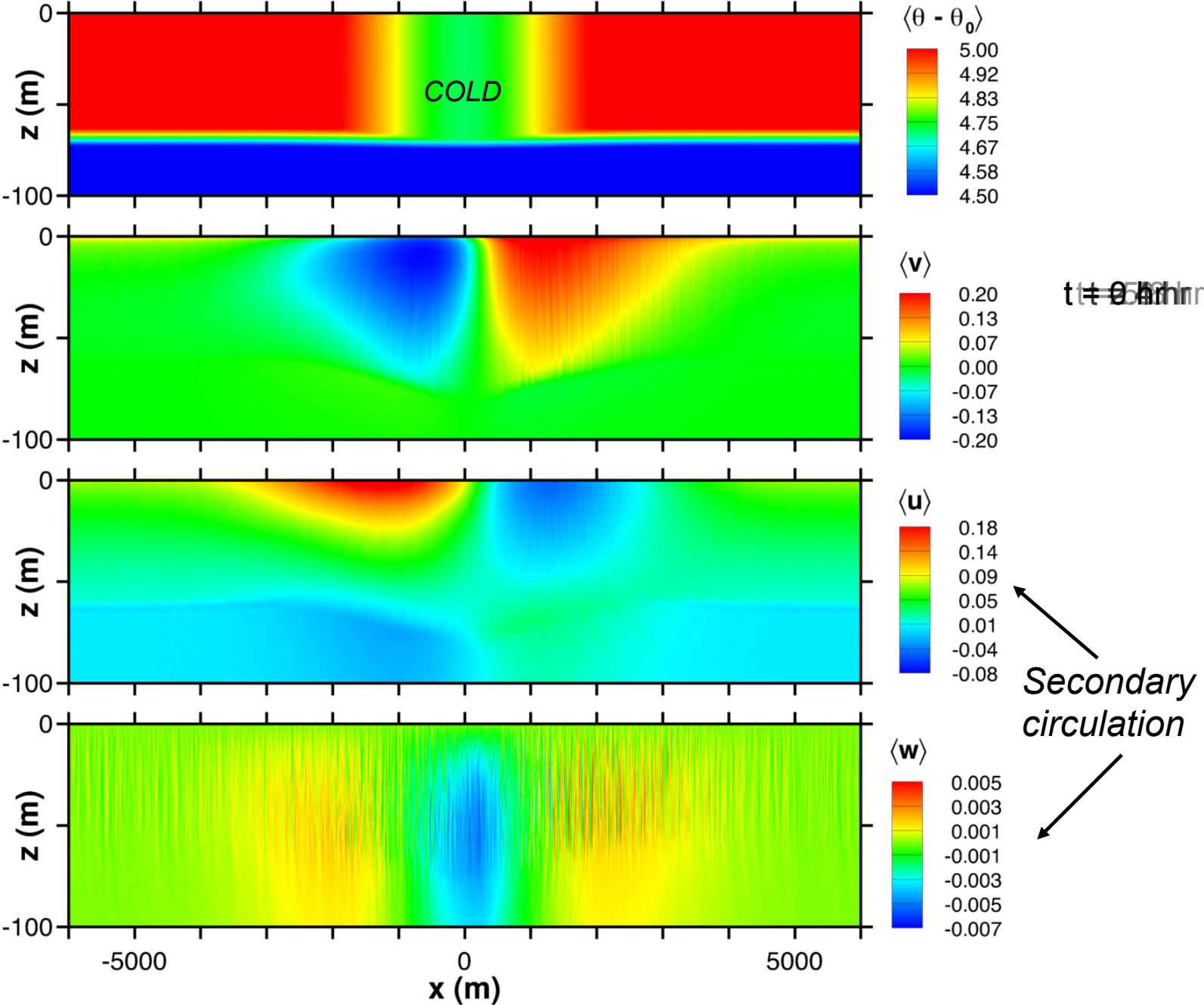
Potential Vorticity (PV) role:

- Small (none?)

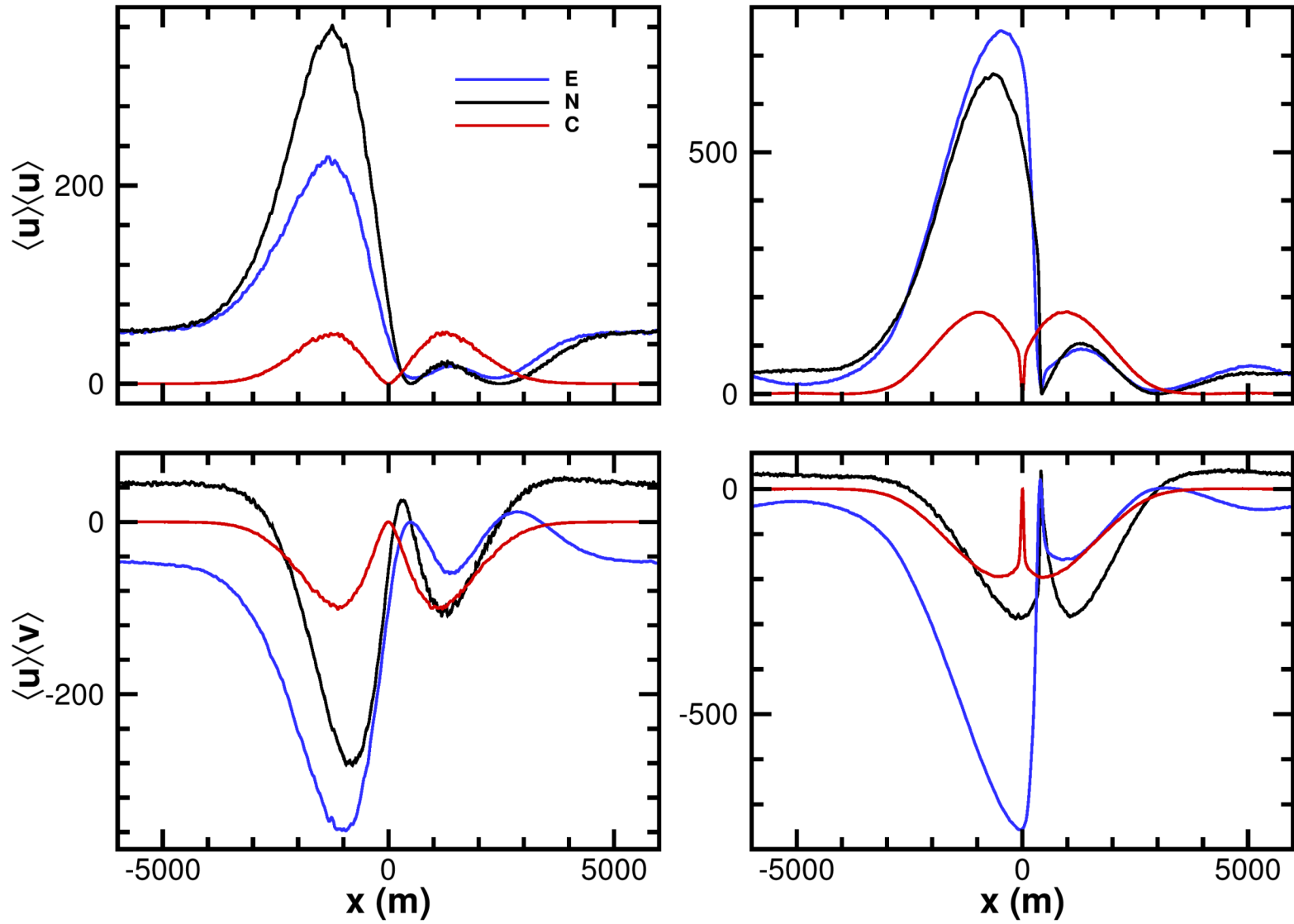
VARIANCES AND CO-VARIANCES AT MAXIMUM $\langle \zeta(x, t) \rangle$



CROSS-FRONT FIELDS WITH NORTH WIND



CROSS FRONT PROFILES OF MEAN HORIZONTAL FLUXES



SUMMARY

Modeling turbulence, surface waves, and submesoscale fronts:

- Multi-scale asymptotic techniques for fast waves on slow currents
- Fine-resolution large-domain large eddy simulations
- Large-scale forcings from Wavewatch III, ROMS

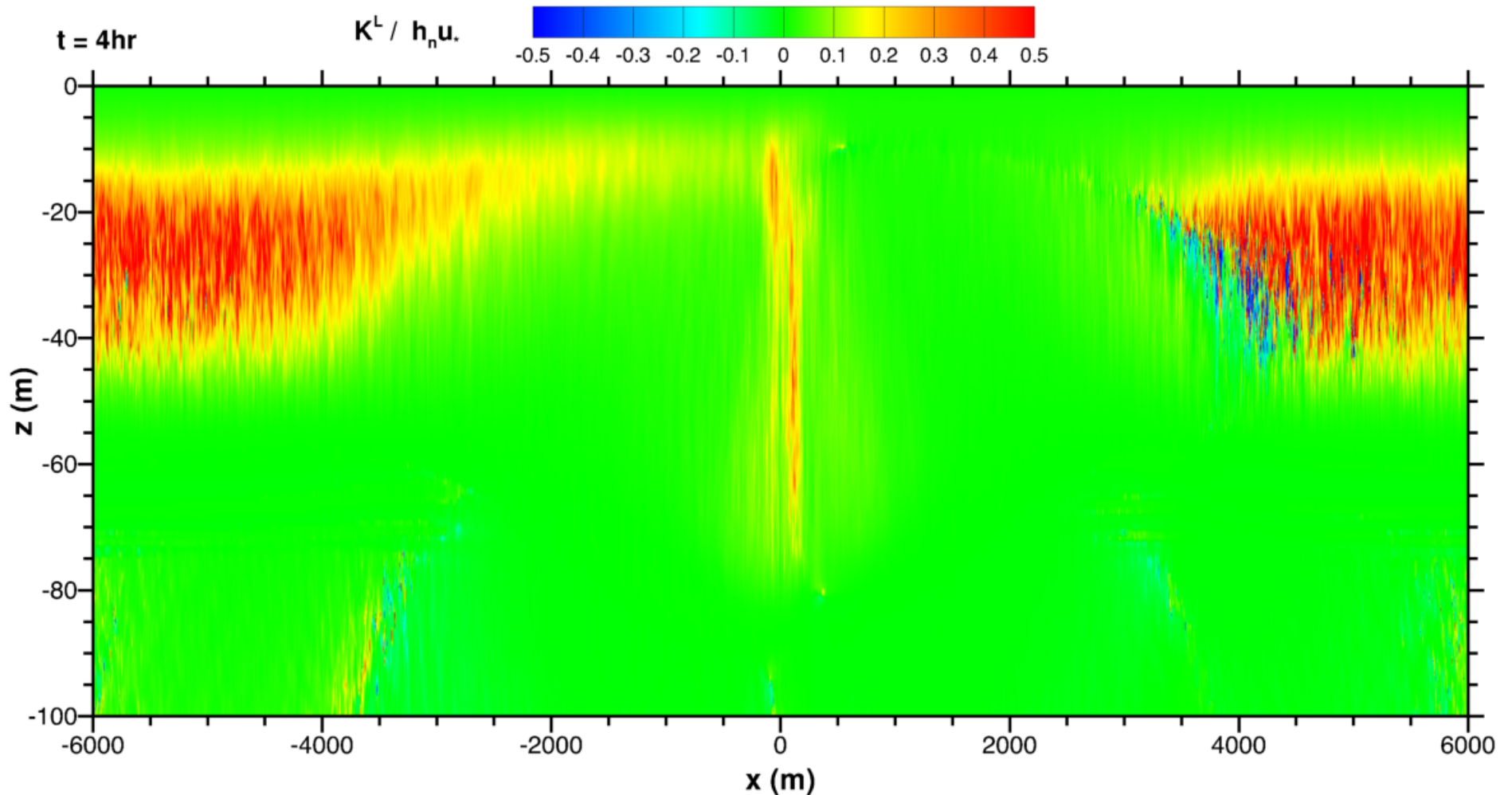
Process level discovery:

- Turbulence, waves, currents, temperature fronts are coupled in the upper ocean
- Cold filament frontogenesis depends on the combination of winds and waves, and wind-wave orientation

Parameterization in large-scale weather and climate models is a challenge:

LAGRANGIAN EDDY VISCOSITY EAST WINDS + WAVES

$$\mathbf{u}'w = K^L \frac{\partial \mathbf{u}^L}{\partial z}$$



Non-equilibrium turbulence!

OBSERVATIONAL TARGETS

Regime dependent:

- Homogeneous conditions?
- Fronts?

Atmosphere:

- Winds and surface fluxes, waves
- Large scale variability *e.g.*, rolls

Ocean:

- OBL turbulence, vertical profiles
- Spatial measurements, *e.g.*, $(x - y)$
- Multi-point correlations to determine Langmuir cell structure
- Connections between wave breaking and LT
- Thermal structure
- Fronts, *e.g.*, co-variance $u'v'$
- Asymmetry left and right of front axis
- Wind and wave orientation relative to front

Observational Targets: Need atmospheric surface layer observations (winds, heat fluxes, turbulence) and wave fields ... Transient wind-wave regimes are interesting. In the OBL, profiles of variances, current and temperature ... spatial measurements, correlation functions to determine cell properties ... Regime with varying winds and waves ... Temperature fronts are especially interesting ... frontogenesis and arrest are functions of winds and waves and their orientation ... really need spatial measurements ... coupling over multiple scales ... for example the variances, co-variance $u'v'$ are interesting and LES suggests that arrest is determined by the latter

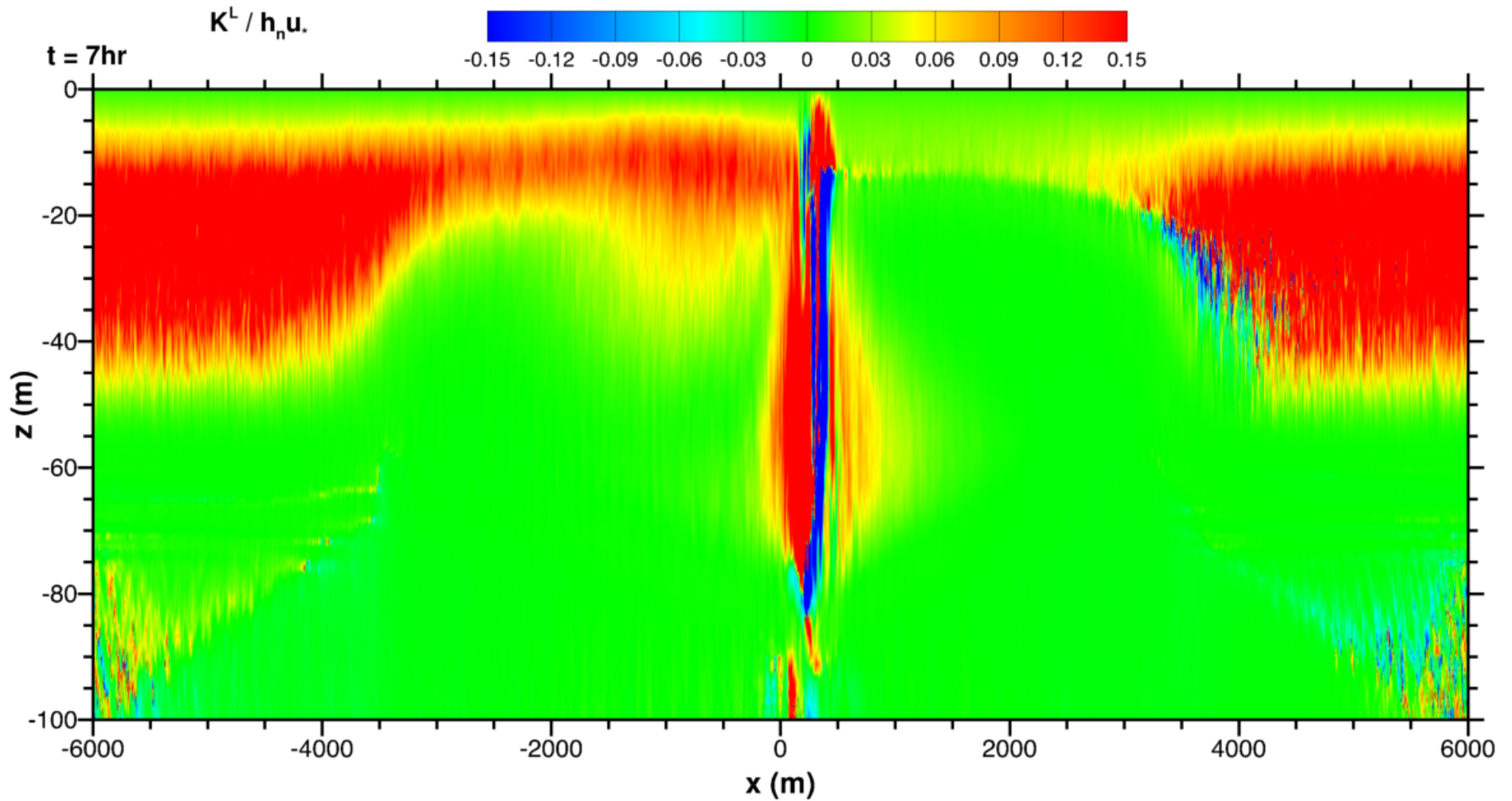
Objectives: Understand the interactions between surface BL turbulence, submesoscale currents and density gradients in the presence of surface gravity waves.

Regimes: Variable large-scale forcing, transient winds, remote swell, density fronts – regimes where LT is active

Approach: Large domain Large-Eddy Simulations with fine spatial meshes to resolve turbulence and include surface wave effects ... transient BL evolution for disequilibrium wind-wave conditions ... since we are interested in time varying winds and waves we will drive the LES mostly with wave fields computed from WaveWatch III with guidance from Leonel Romero (UCSB).

DRI goals: Use LES to guide the planning phase of the observational strategy aid the interpretation of the observations. Understand the adequacy of a single column model to represent LT in complex regimes.

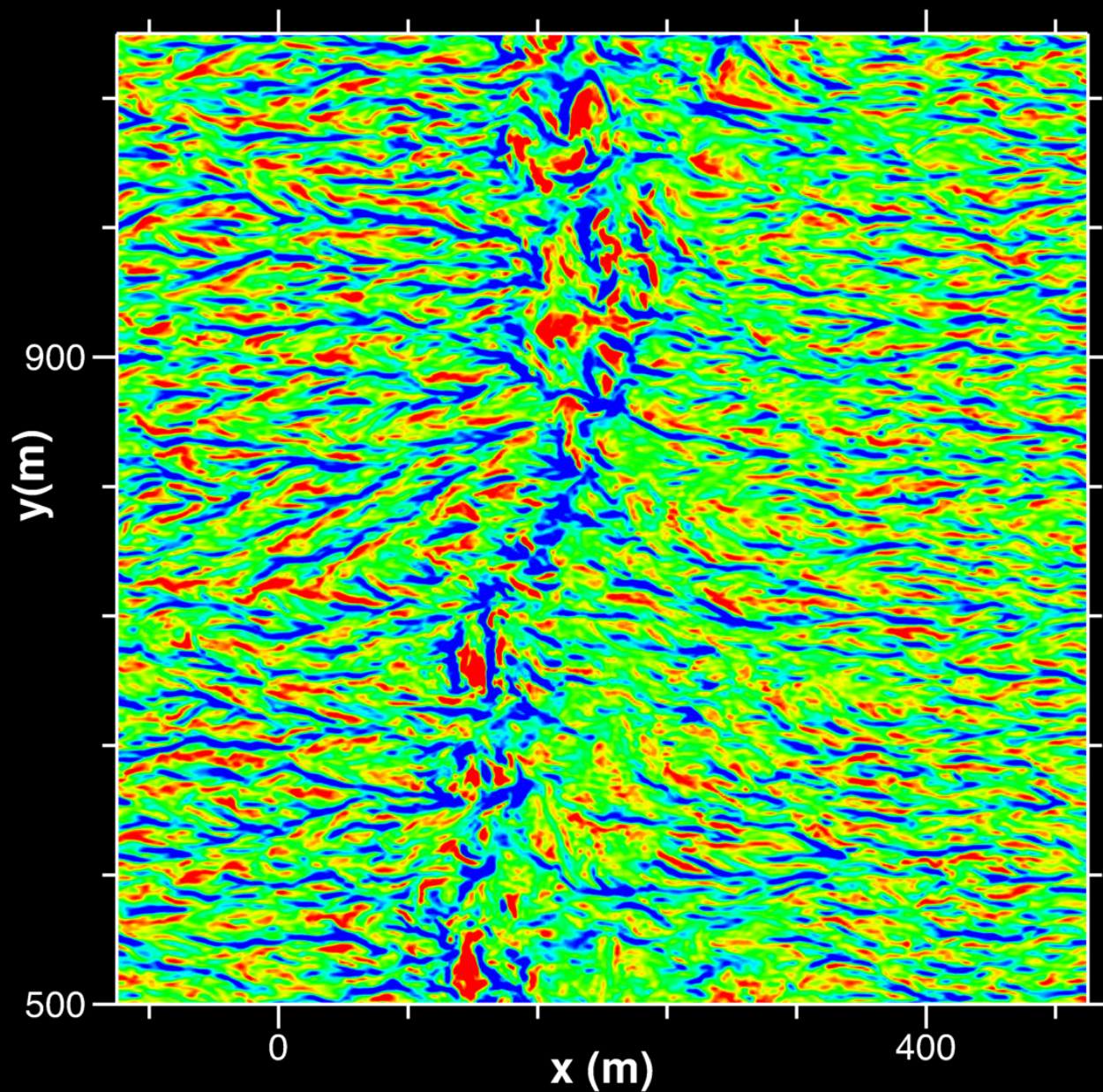
LAGRANGIAN EDDY VISCOSITY EAST WINDS AND WAVES



Cell strength changes across the front

Winds + waves
→

$z = -3 \text{ m}$



TYPICAL SCALES IN THE UPPER OCEAN BOUNDARY LAYER

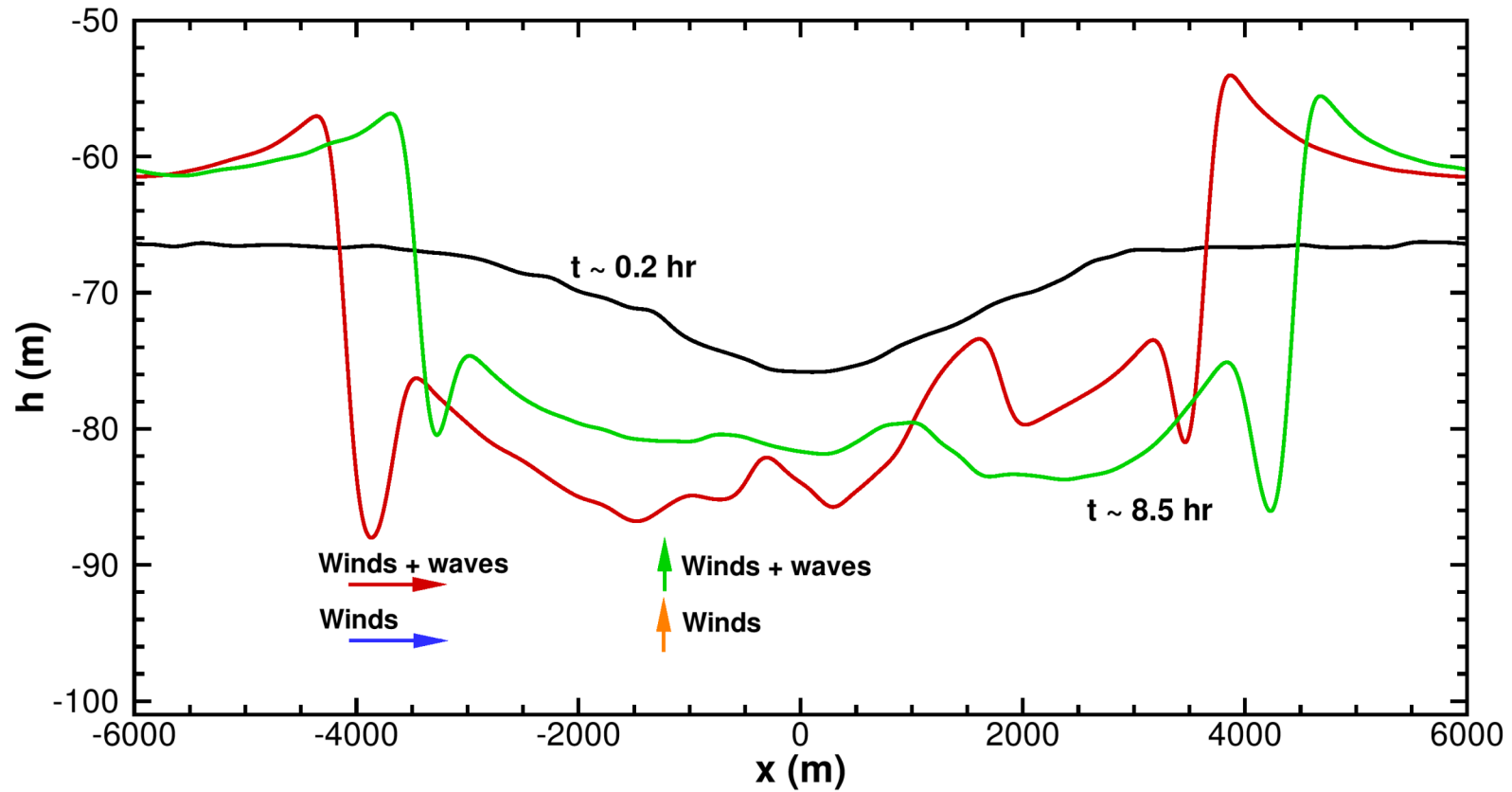
Turbulence (slow):

$$\ell < |h|, |h| \sim \mathcal{O}(30 \text{ m}) \quad \text{OBL depth}$$

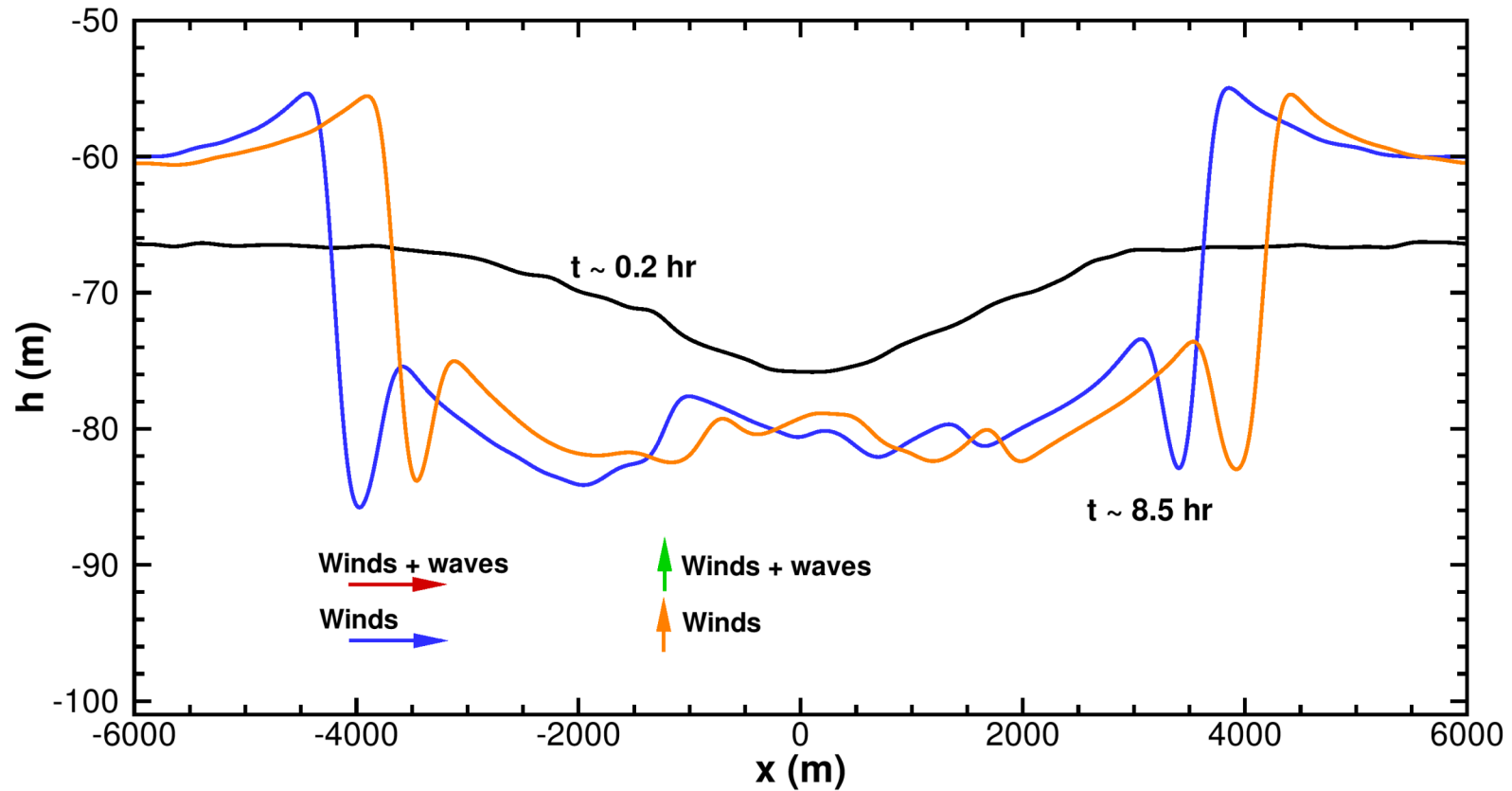
$$u_* = \sqrt{|\boldsymbol{\tau}|/\rho} \sim \mathcal{O}(0.01 \text{ m/s}) \quad \text{friction velocity}$$

$$T_e = \ell/u_* \sim 3000 \text{ s} \quad \text{turnover time}$$

CROSS FILAMENT PROFILE OF OBL THERMOCLINE FOR VARYING WINDS AND WAVES



CROSS FILAMENT PROFILE OF OBL THERMOCLINE FOR VARYING WINDS AND WAVES

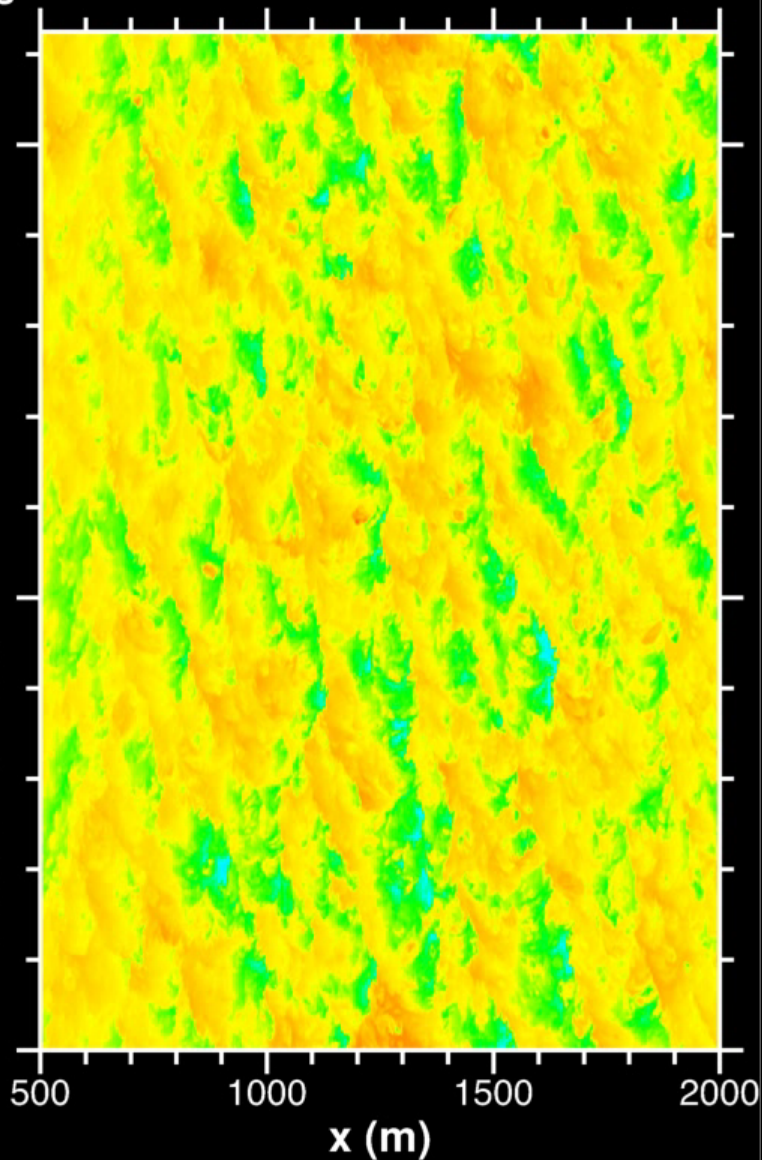
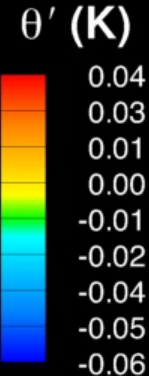
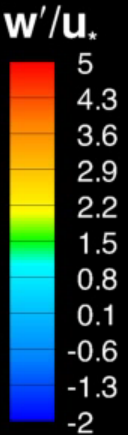
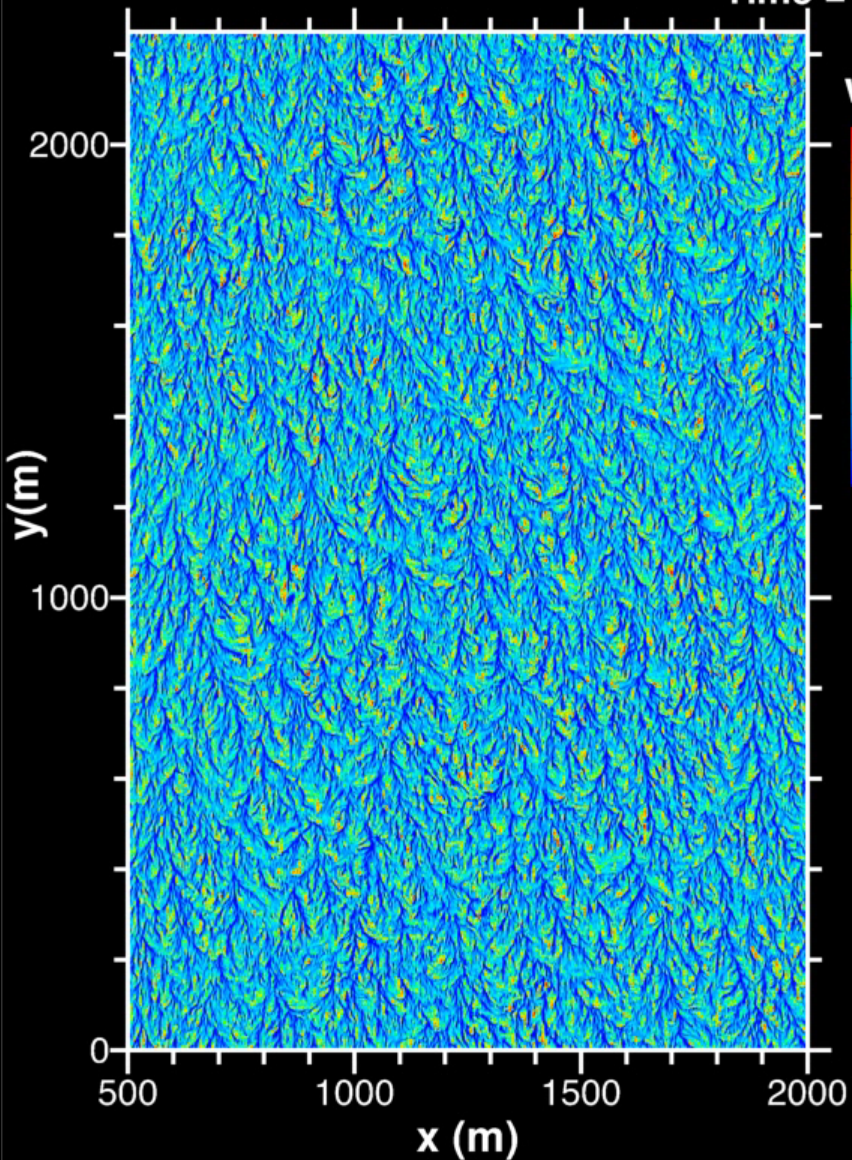


Winds + Waves

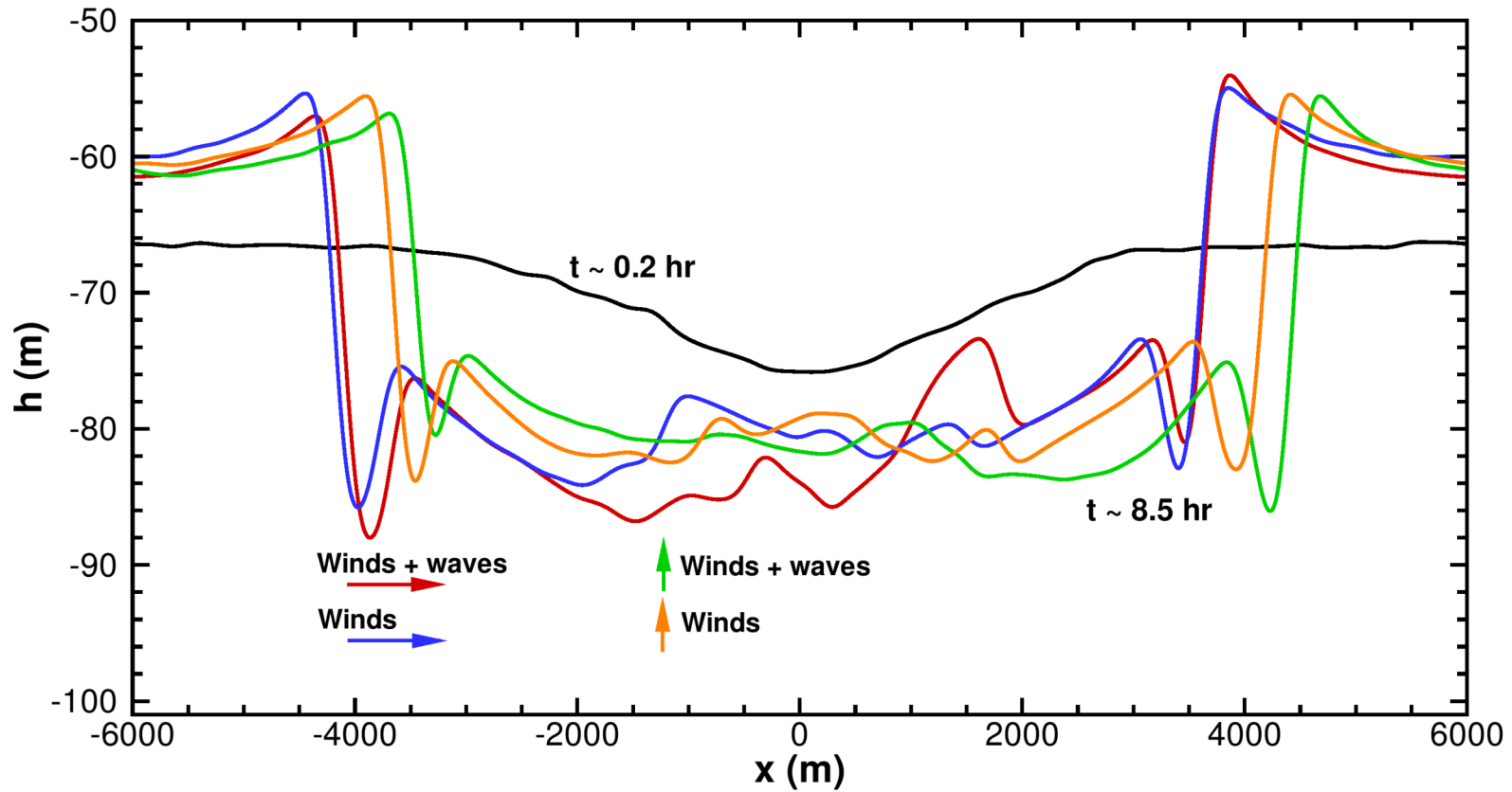


$z = -2.3 \text{ m}$

Time = 1.7 hrs



CROSS FILAMENT PROFILE OF OBL THERMOCLINE FOR VARYING WINDS AND WAVES

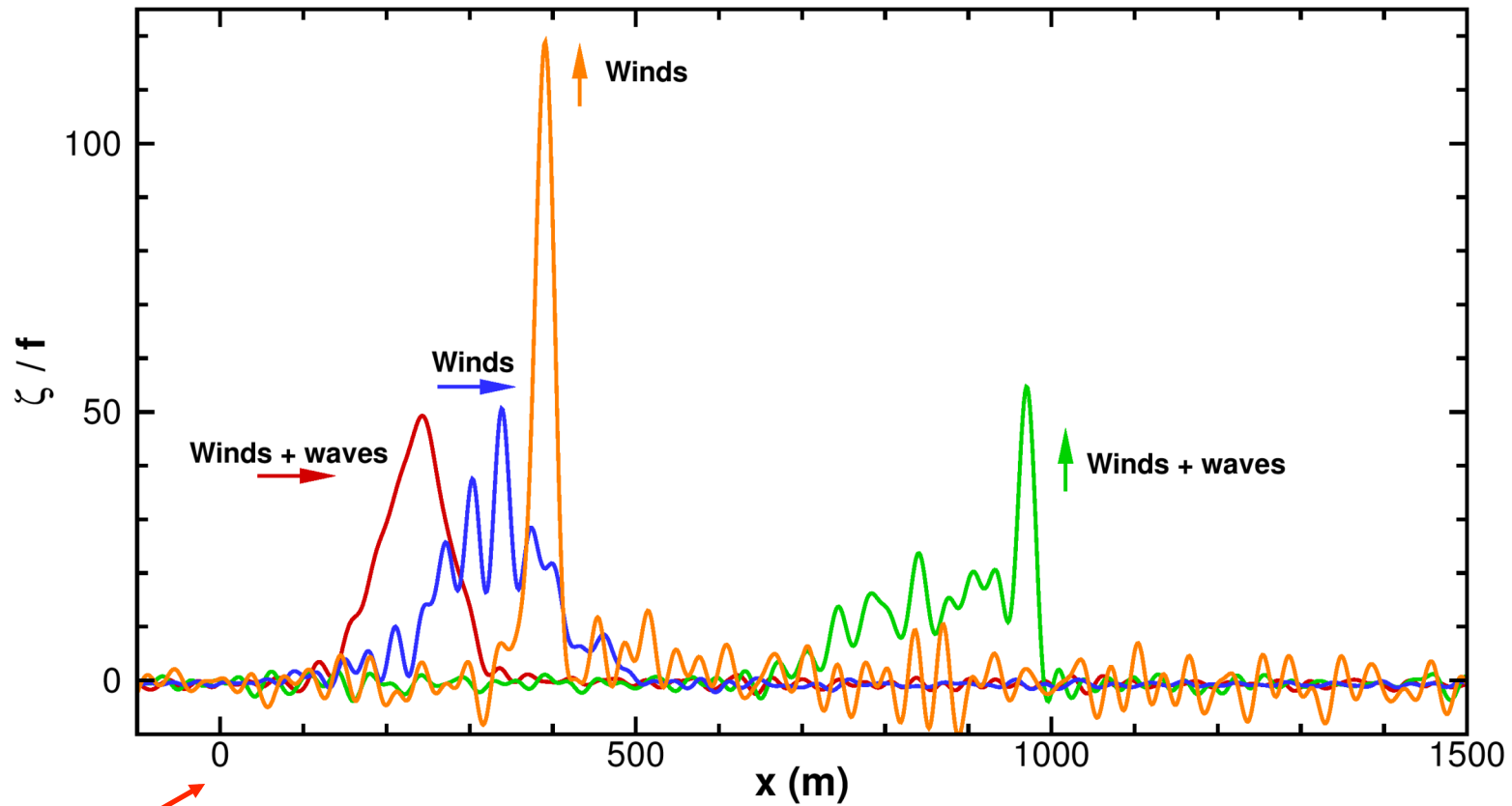


MODELING APPROACH FOR OCEAN TURBULENCE, SURFACE WAVES, AND SUBMESOSCALE FRONTS

Combination of:

- Analytics, a multi-scale asymptotic theory
- External forcings from large scale models Wavewatch III and ROMS
- Laboratory and outdoor measurements of breakers
- Turbulence resolving large-eddy simulations
peta-scale computations

CROSS FILAMENT PROFILE OF AVERAGE VERTICAL VORTICITY $\zeta(x) = \partial\langle v \rangle / \partial x$



FRONT LOCATION AT $t = 0$

*FRONT LOCATION DEPENDS ON EKMAN TRANSPORT,
STOKES-CORIOLIS, VORTEX FORCE*

GOALS AND APPROACH

OBJECTIVE: *Understand the dynamical interactions between upper ocean Langmuir turbulence (LT) and submesoscale currents and density gradients in the presence of surface gravity waves*

THERMAL WIND BALANCE FOR LARGE SCALE GEOSTROPHIC CURRENTS

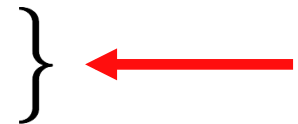
$$f \hat{\mathbf{z}} \times \frac{\partial \mathbf{u}_g}{\partial z} = -\beta \nabla_h \theta \quad \Rightarrow \quad \mathbf{u}_g = \frac{\beta}{f} \int_{-\infty}^z \nabla_h \theta dz'$$

LES OF LANGMUIR TURBULENCE AND SUBMESOSCALE DENSE (COLD) 2-D FILAMENTS

- Winds across and parallel to front axis
- With and without wave effects, $La_t = 0.32$
- $(\Delta x, \Delta y, \Delta z) = (1.46, 1.46, [0.5 - 1.58]) m$
- $\sim 6.4 \cdot 10^9$ gridpoints

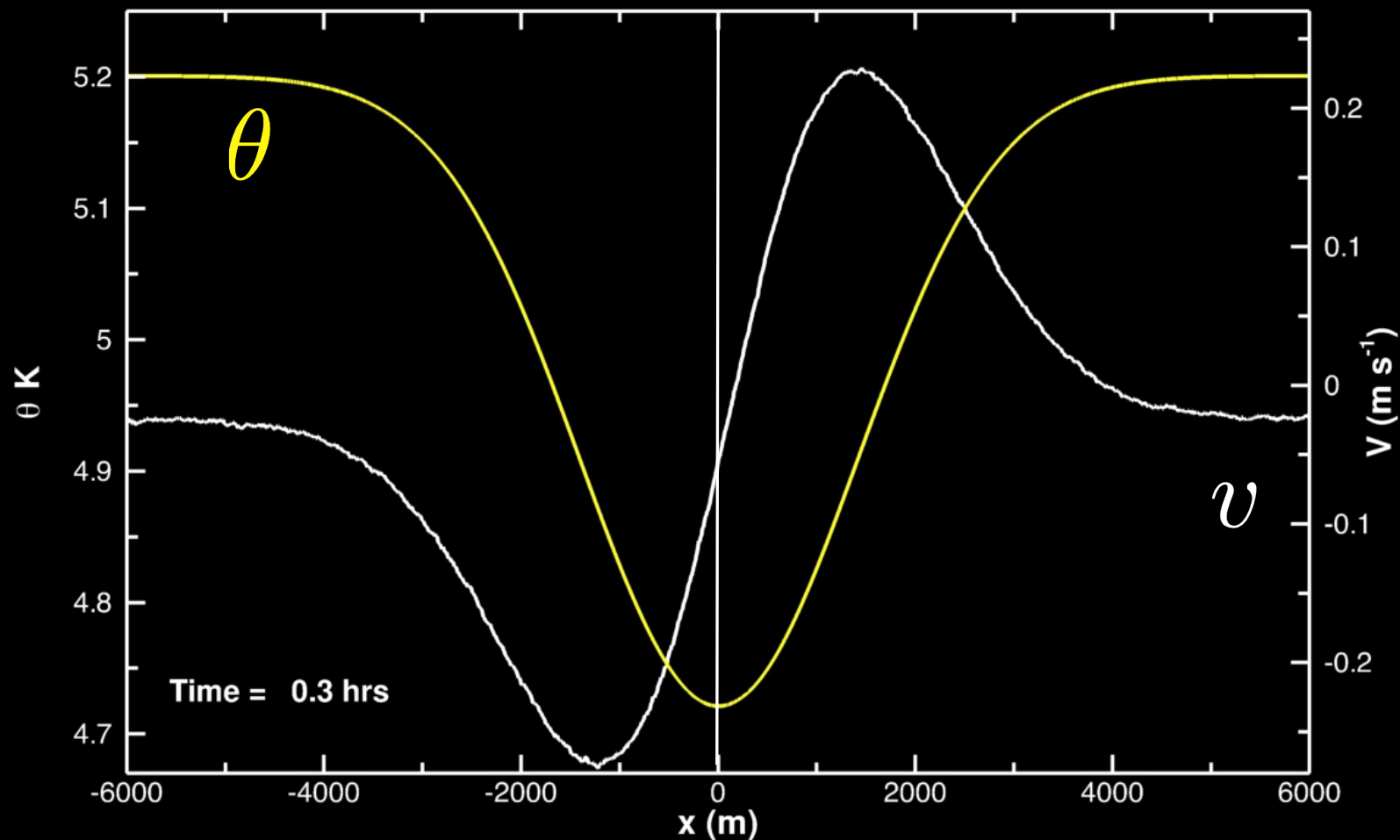
Simulation parameters

Front scale \mathcal{L} (km)	$\Delta\theta$ (C)	(X_L, Y_L, Z_L) (km)	(N_x, N_y, N_z)
2	0.28	(6, 0.56, -0.25)	(4096, 384, 256)
4	0.48	(12, 0.56, -0.25)	(8192, 384, 256)
6	0.69	(18, 0.56, -0.25)	(12288, 384, 256)
4	0.48	(12, 2.25, -0.25)	(8192, 1536, 256)
4	0.48	(12, 4.5, -0.25)	(8192, 3072, 256)

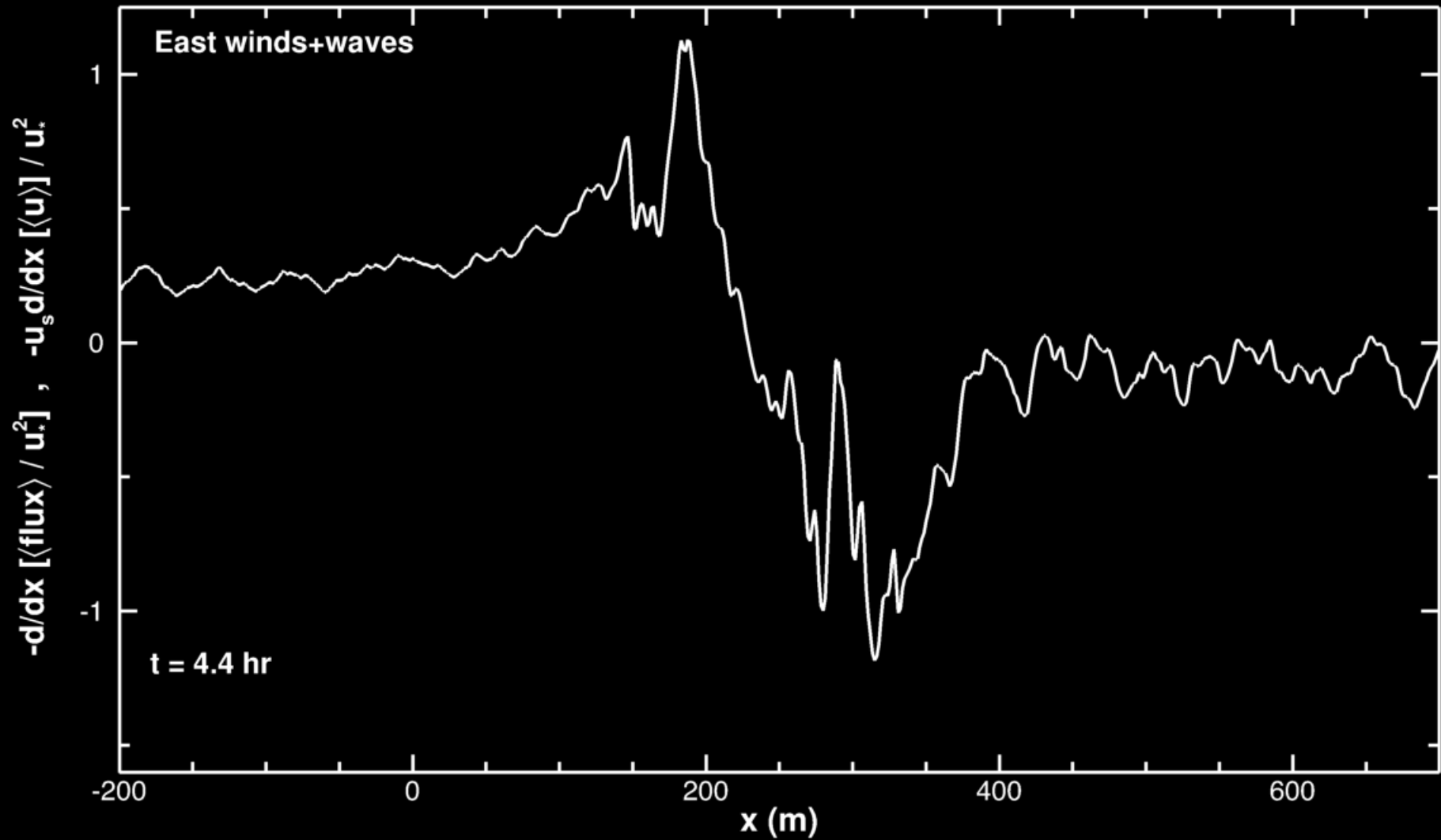


CROSS FILAMENT SURFACE TEMPERATURE AND SPANWISE CURRENT UNDER FRONTOGENESIS $0 < t < 12$ hrs

WINDS + WAVES \longrightarrow



FRONTOGENESIS AND ARREST FLUX DIVERGENCE

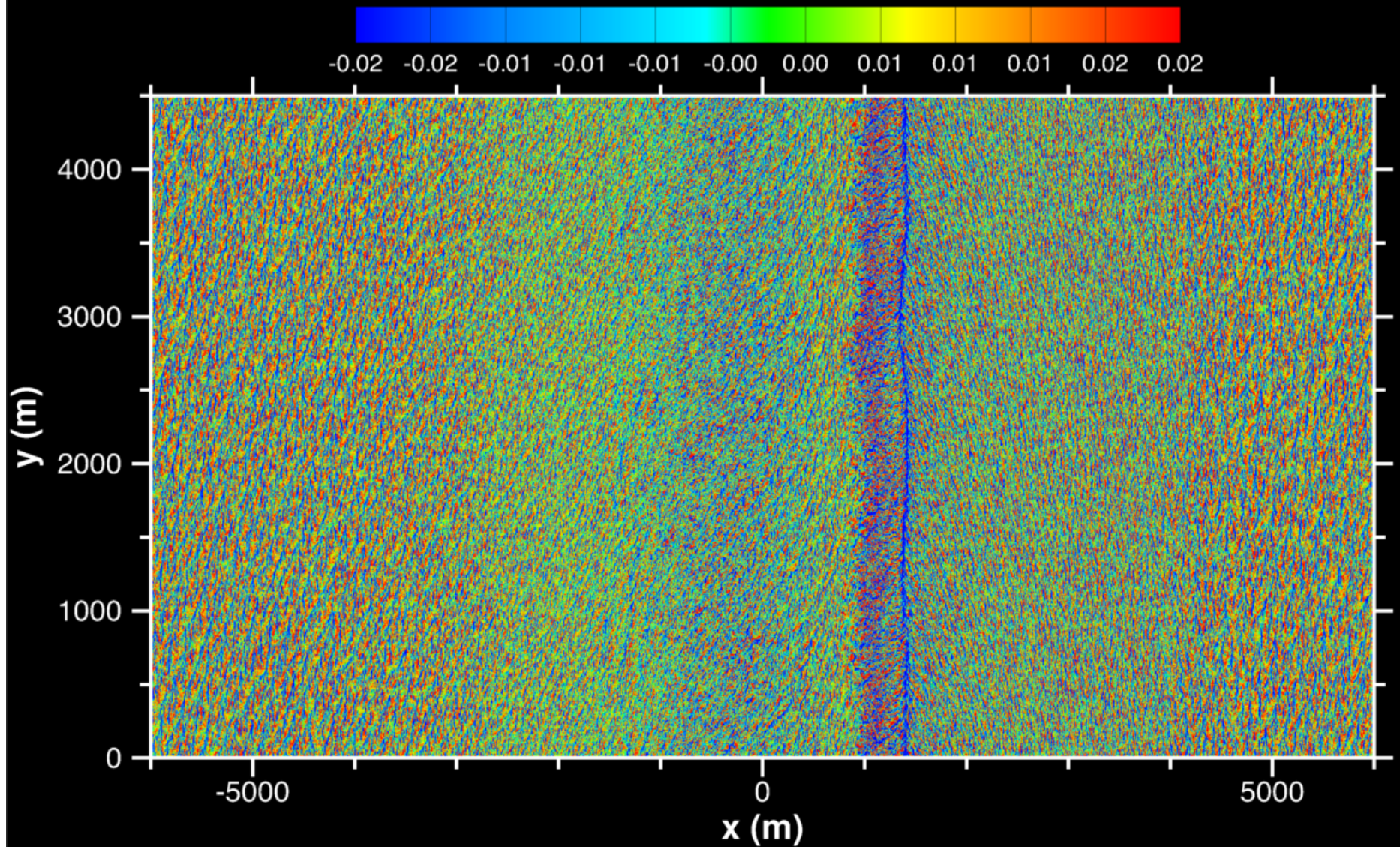


$$-\frac{\partial \langle u \rangle \langle u \rangle}{\partial x}$$

$$-\frac{\partial \langle u' u' \rangle}{\partial x}$$

$$-u_s \frac{\partial \langle u \rangle}{\partial x}$$

VERTICAL VELOCITY FOR NORTH WINDS AND WAVES



$z \sim -10 \text{ m}$

COLD FILAMENT FRONTOGENESIS (CFF)

WHY COLD FILAMENTS:

- Super exponential rate of intensification (McWilliams *et al.* 2009)
- Prevalence, *e.g.*, in the Gulf Stream

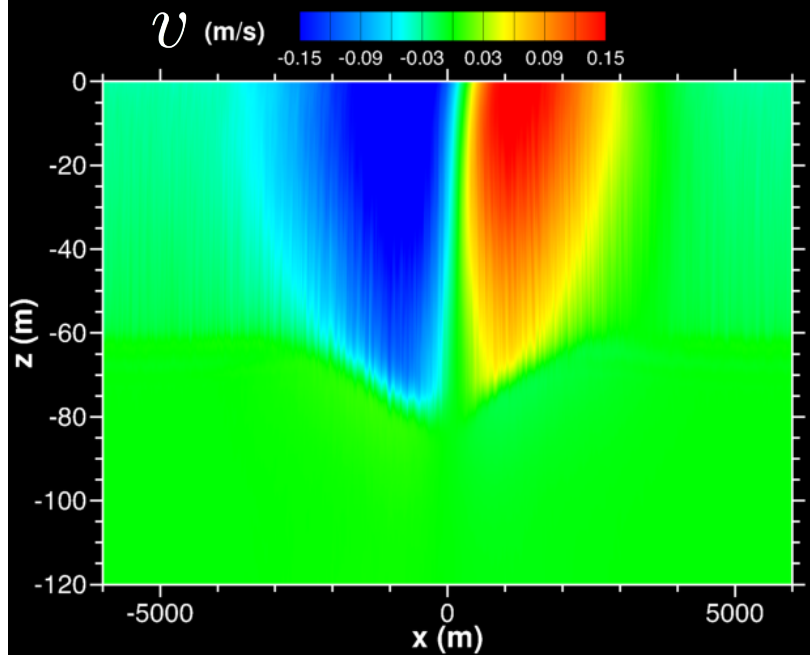
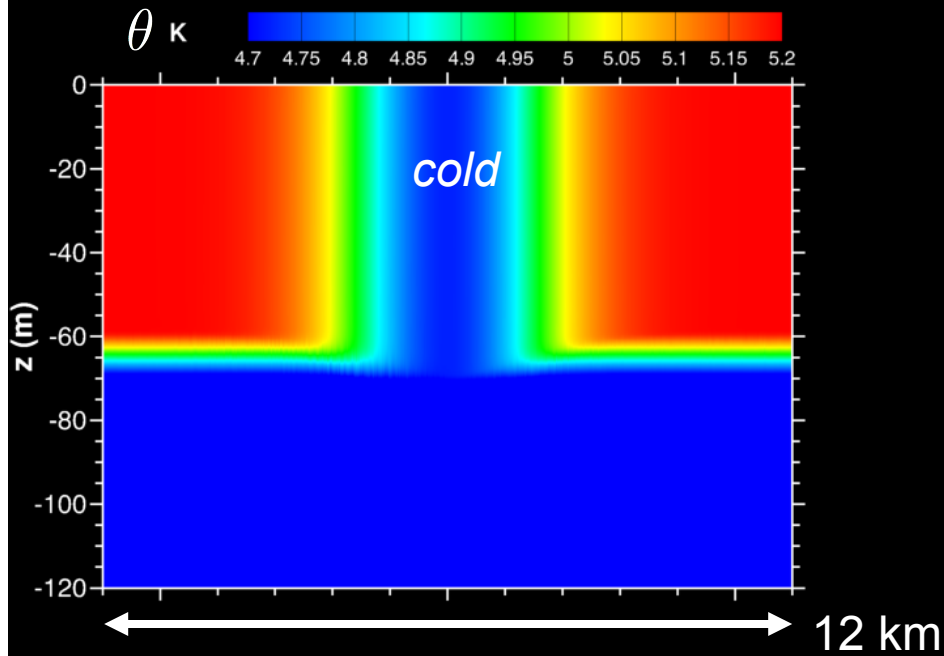
CFF MECHANICS:

- Lifecycle
- Arrest dynamics
- Role of OBL turbulence
- Role of winds
- Role of surface waves

APPROACH:

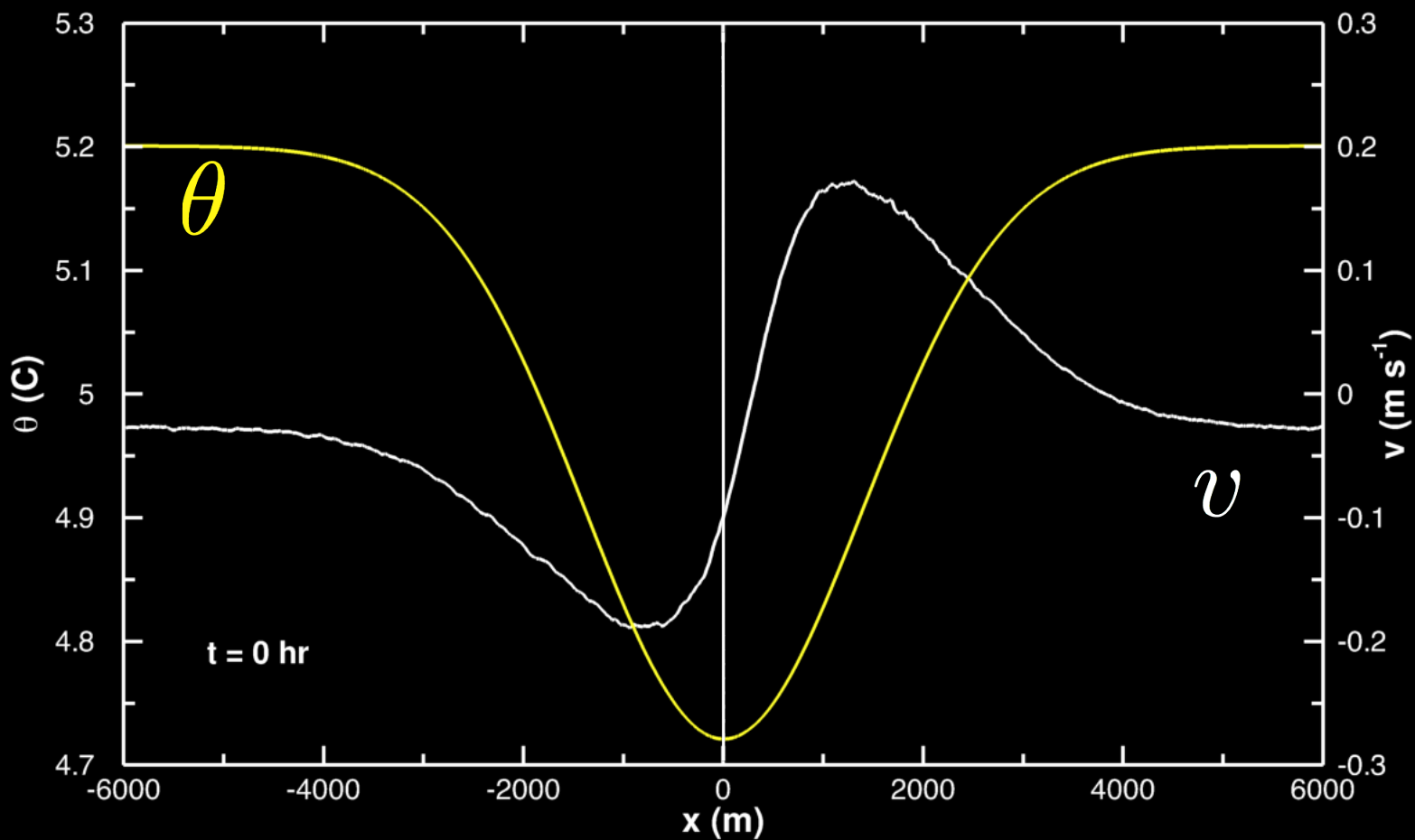
- Large domain Large Eddy Simulation (LES) with fine spatial meshes, simulations with $\mathcal{O}(10^9)$ gridpoints

TTW, CROSS FILAMENT FIELDS, Y-AVERAGE, AT T = 0 hrs



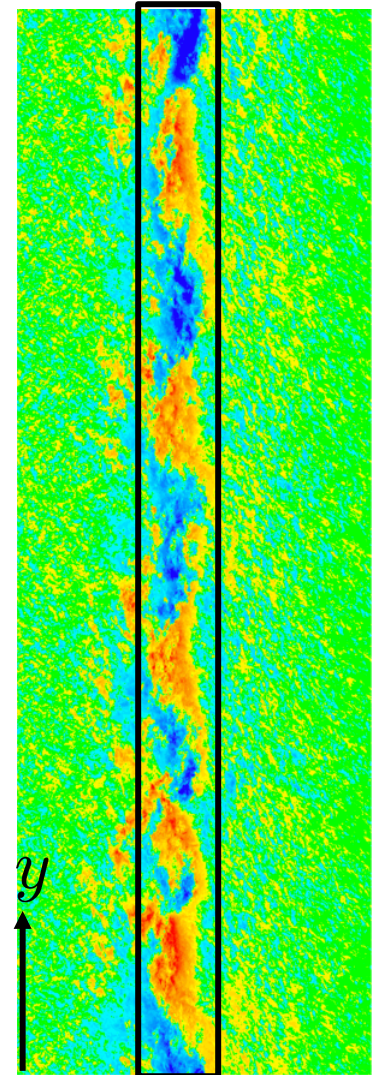
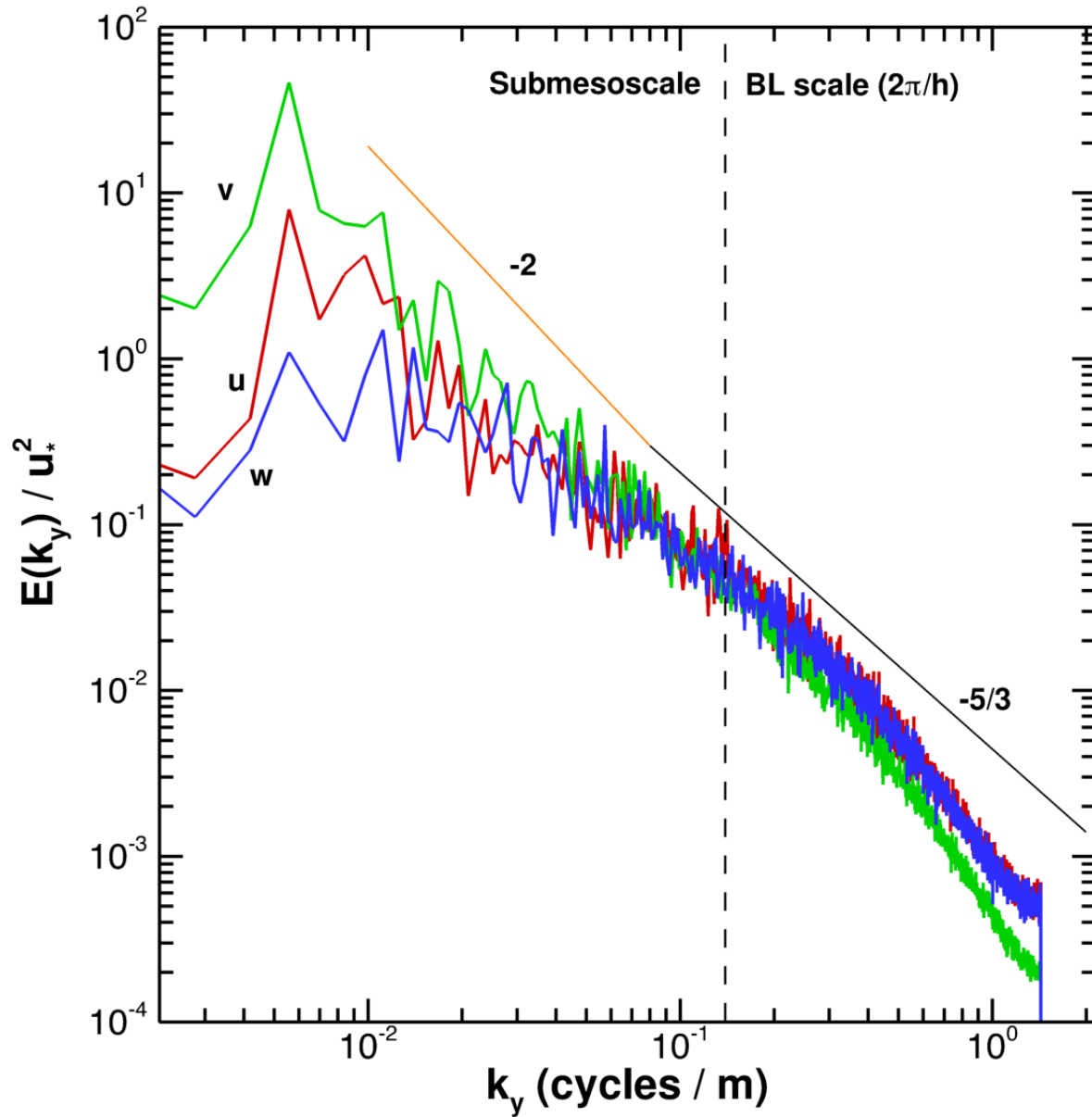
CROSS FILAMENT SURFACE TEMPERATURE AND SPANWISE CURRENT UNDER FRONTOGENESIS $0 < t < 12$ hrs

WINDS + WAVES \longrightarrow



POWER SPECTRA OF (U, V, W) FOR EAST WINDS + WAVES

T = 5.4 hr
z ~ -34 m



FLOW DECOMPOSITION: MEANS AND FLUXES

$$\langle f \rangle(x, z) = \int f(x, y, z) dy$$

$$u = \langle u \rangle + u'$$

$$v = \langle v \rangle + v'$$

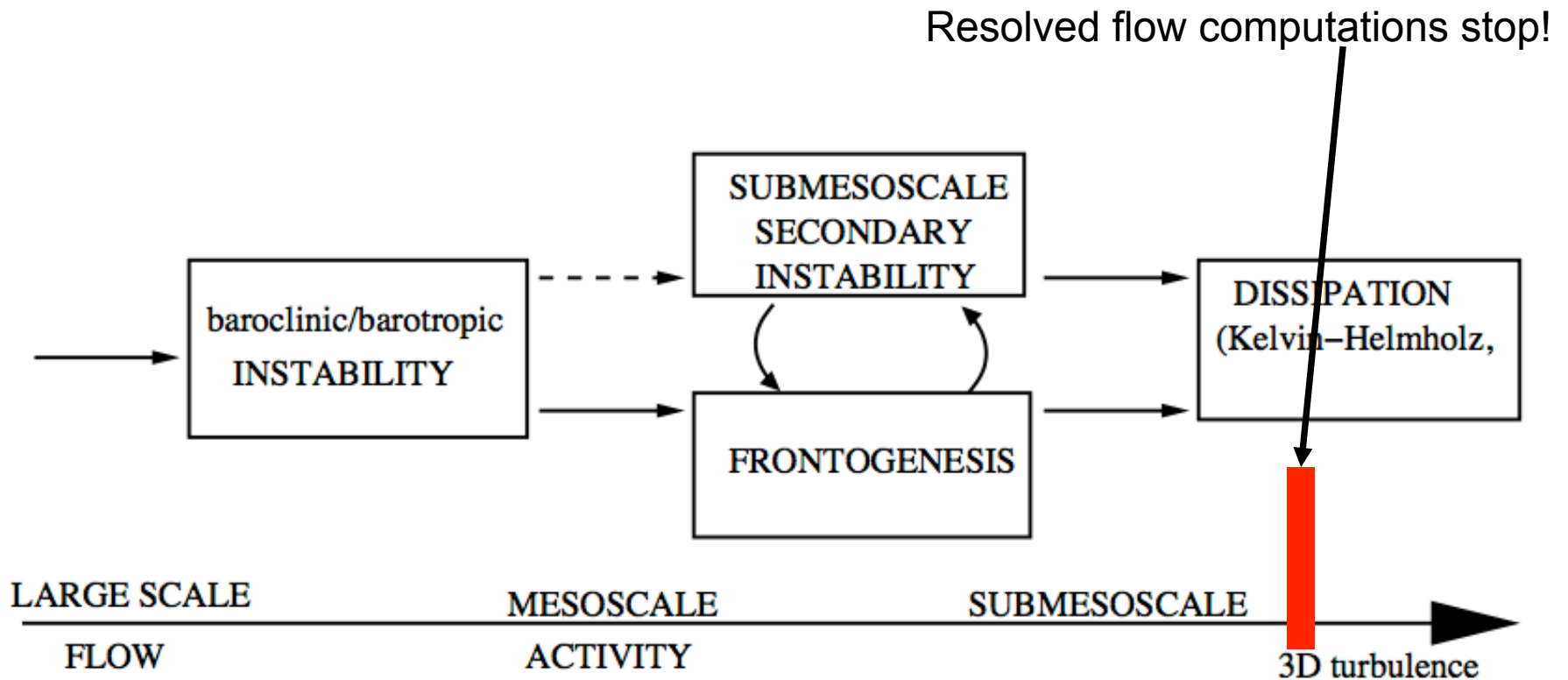
$$\frac{\partial \langle u \rangle}{\partial t} = -\frac{\partial}{\partial x} [\langle u \rangle \langle u \rangle + \langle u' u' \rangle] - \frac{\partial}{\partial z} [\langle u \rangle \langle w \rangle + \langle u' w' \rangle] \dots$$

$$\frac{\partial \langle v \rangle}{\partial t} = -\frac{\partial}{\partial x} [\langle u \rangle \langle v \rangle + \langle u' v' \rangle] - \frac{\partial}{\partial z} [\langle v \rangle \langle w \rangle + \langle v' w' \rangle] \dots$$

SUMMARY OF SUBMESOSCALE TURBULENCE

Courtesy Jim McWilliams (UCLA)

- Surface-intensified frontogenesis induced by mesoscale straining
- Frontal instabilities of several types
- Kinetic energy forward cascade towards turbulence dissipation
- ...



SAR Image of the Santa Barbara Channel

