TEMPERATURE FRONTS AND FLUXES IN STABLE BOUNDARY LAYERS

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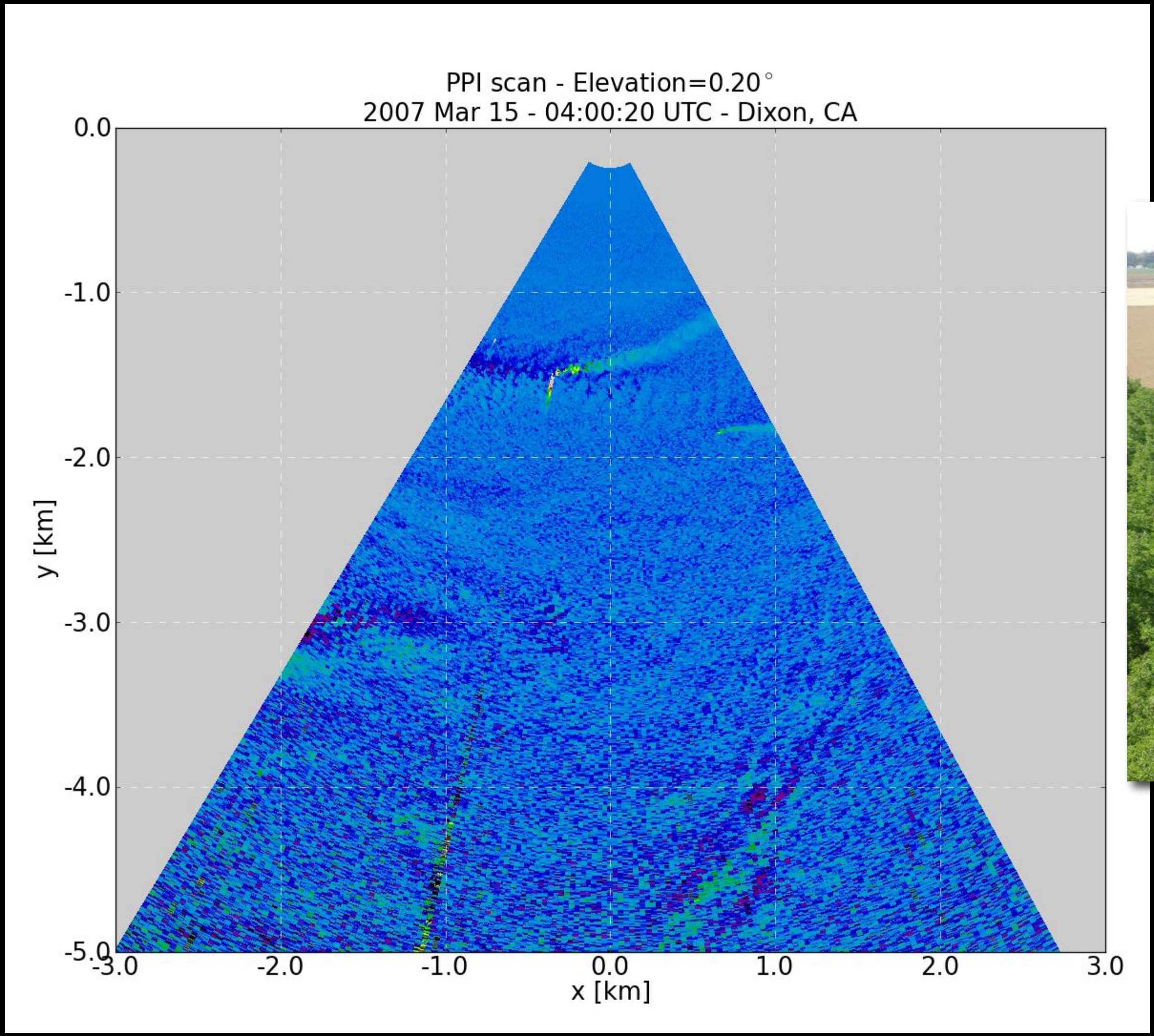
TURBULENCE+WAVES IN THE VERY STABLE ATMOSPHERIC SURFACE LAYER: 8 pm to 4 am



Canopy Horizontal Array Turbulence Study Patton et al (BAMS, 2011)

Photo/Publication credit Shane Mayor (AFM, 2017)

MOTIVATION

- Stratified stable boundary-layers (SBLs) are ubiquitous in the atmosphere and ocean

- Climate projections and weather forecasts are (very) sensitive to their SBL parameterization (Holtslag et al, 2013)

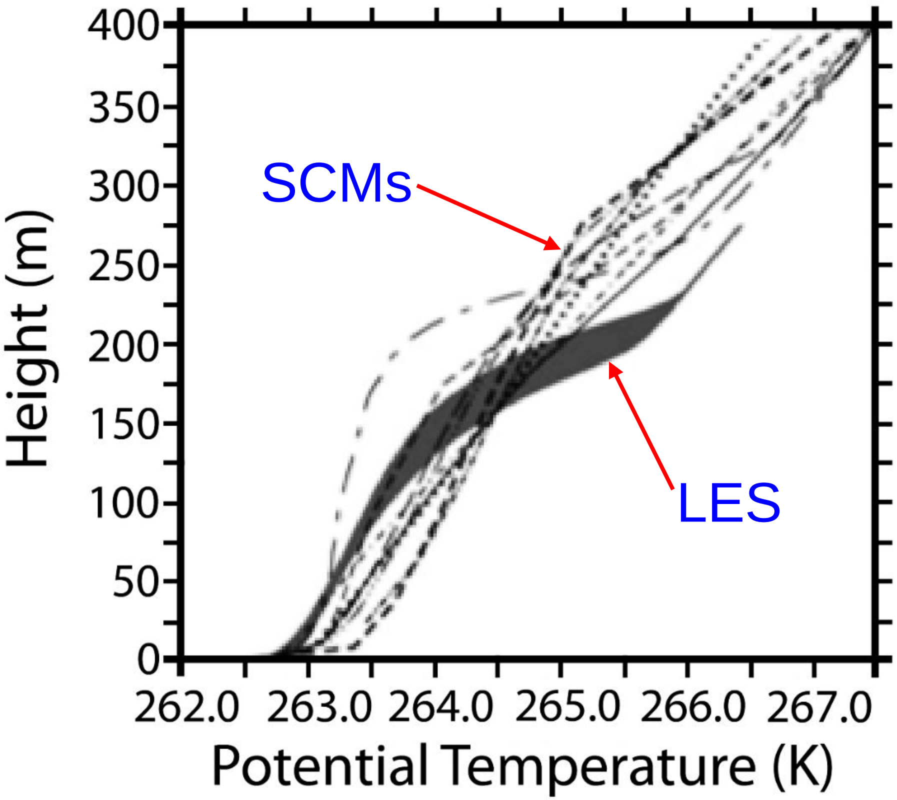
- Vertical layering from refractive index turbulence in SBLs impacts all forms of propagation, light beams, radio waves, sounds (Wyngaard et al, 2001)

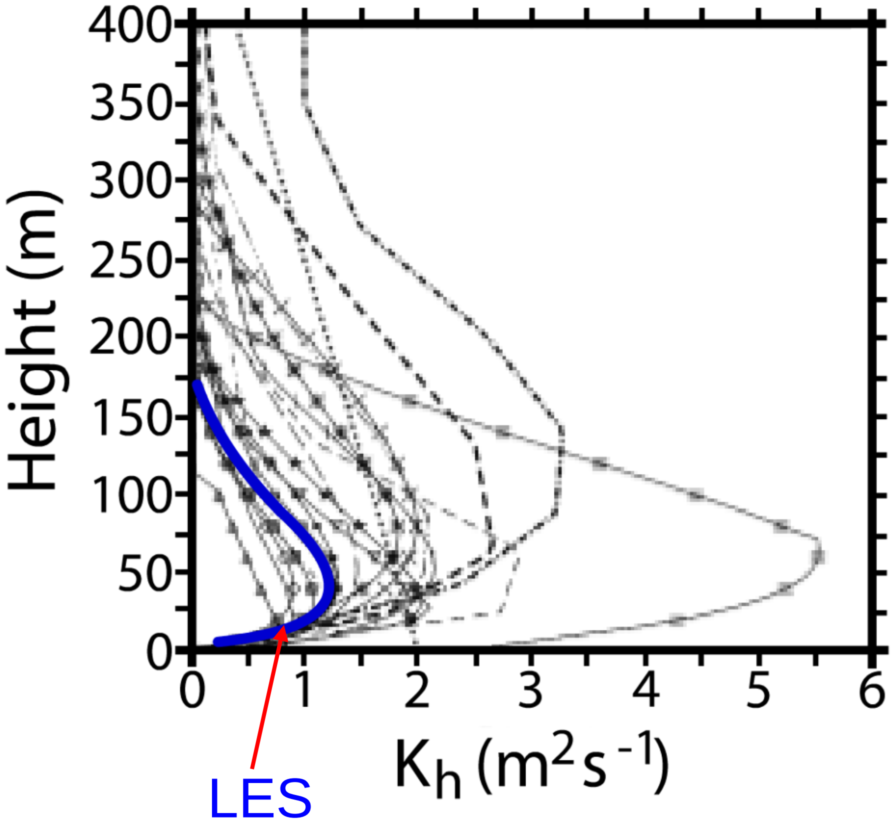
- Air quality (Weil, 2012)

- Nocturnal low level jets and stratified turbulence are often the design point for loads on wind turbines over the Great Plains (Kelley et al, 2004)

- …

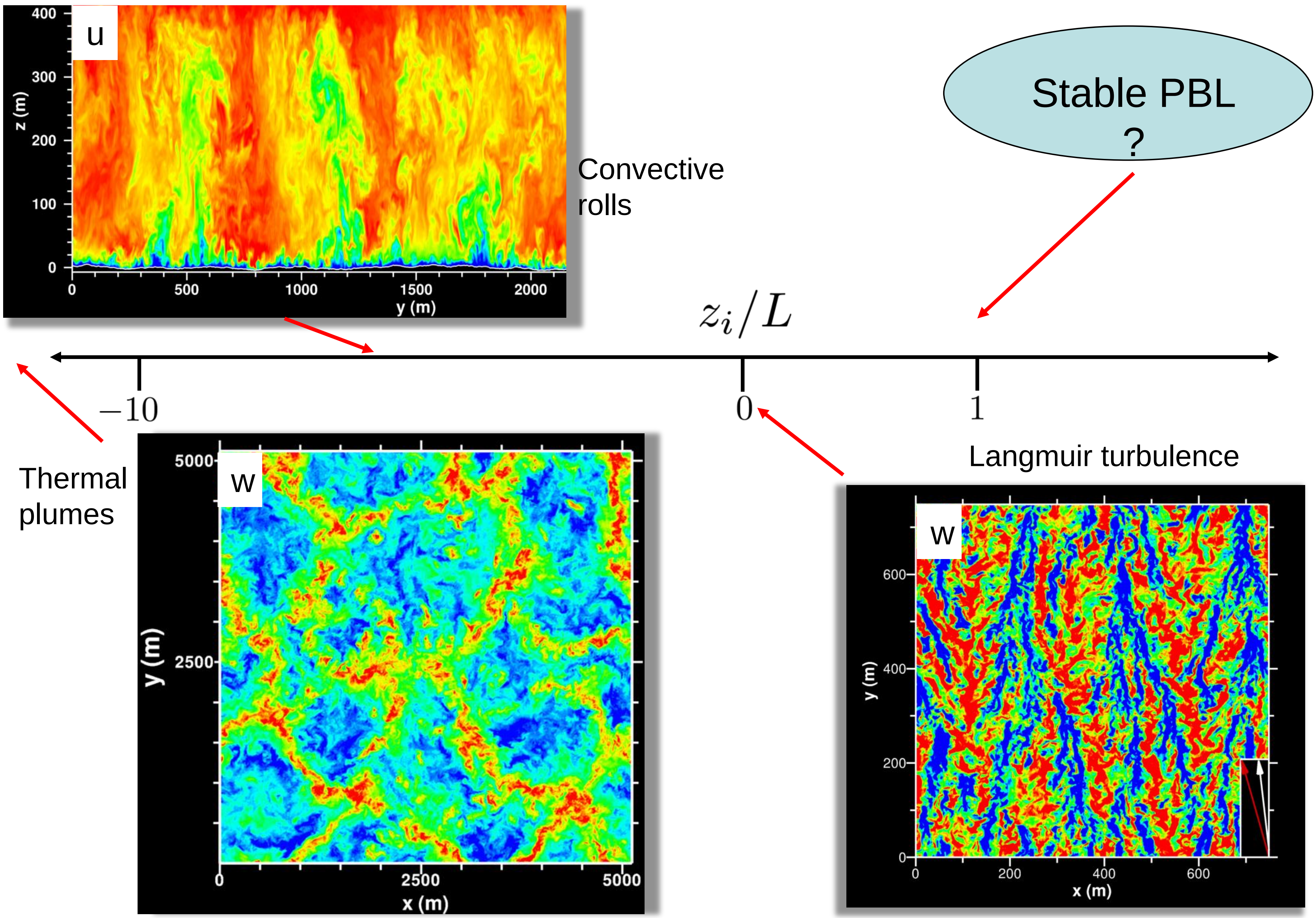
SBL MODELING:
Single-Column Models vs LES
Cuxtart et al (2006), Beare et al (2006)





Operational: 1st order closure,
Heat flux $\overline{w\theta} = -K_h(\partial\Theta/\partial z)$

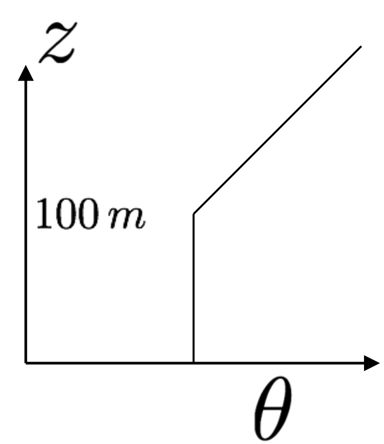
Coherent Structures in Geophysical Boundary Layers



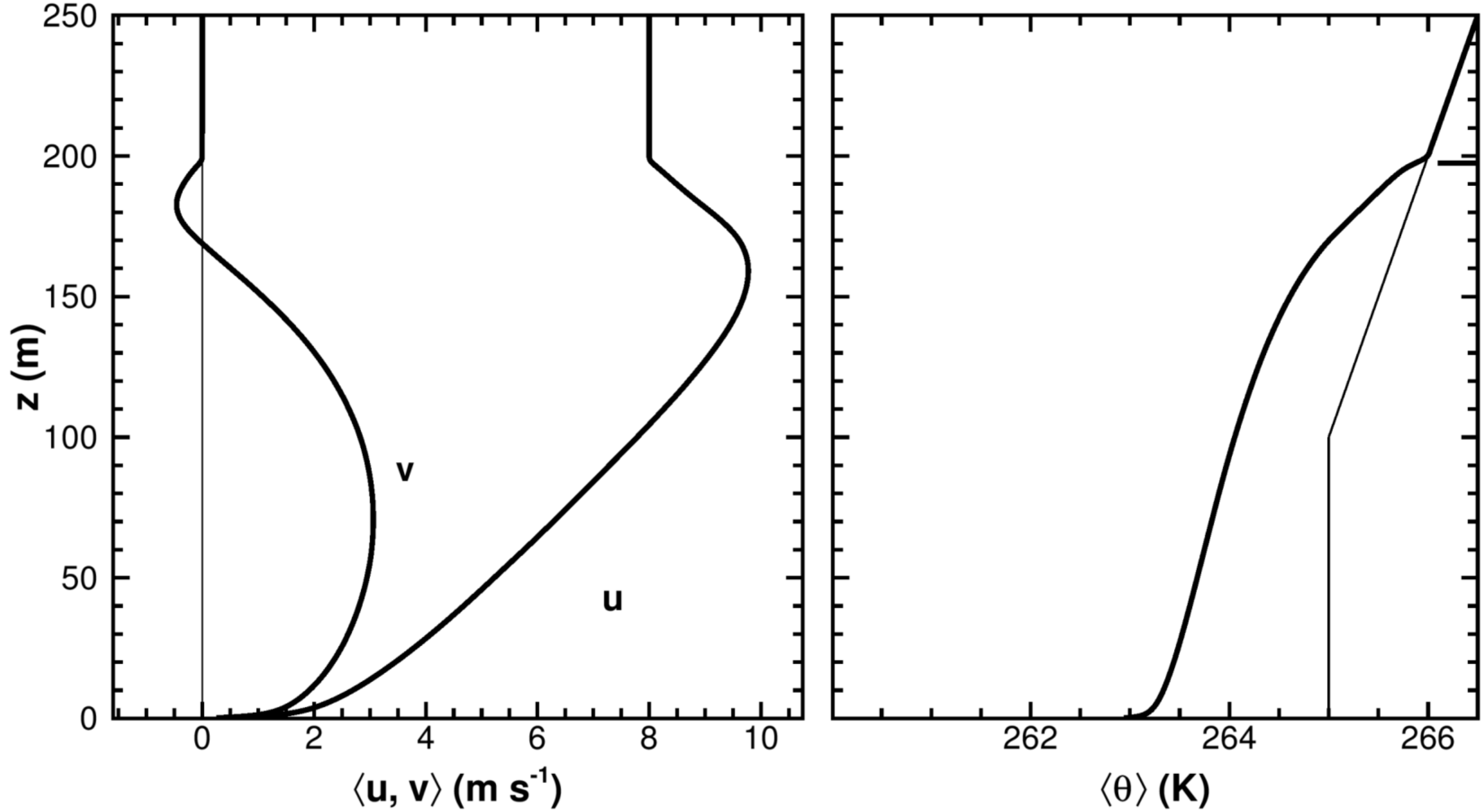
LARGE EDDY SIMULATION OF CANONICAL STABLE BOUNDARY LAYERS

- High latitude Arctic boundary layer
  - Homogeneous lower boundary temperature
- LES
  - $400 \times 400 \times 400$ m domain
  - Mesh $(200^3, 512^3, 1024^3)$
  - Spacing $\triangle = (2, 0.78, 0.39)$ m
  - 900,000 timesteps, 2.9×10^6 core hours
  - Geostrophic wind $\mathbf{U}_g = (8, 0)$ m s^{-1}
  - Stability $z_i/L = (0, 1.7, 2.4, 3.2, 6.0)$
  - Boundary layer depth $z_i \leq 200$ m
  - Gradient Richardson number $R_i = \frac{g}{\theta_o}\frac{\partial \theta}{\partial z} / \left(\frac{\partial \mathbf{u}_h}{\partial z}\right)^2 < 0.25$ (weakly stable)
  - Incompressible Bousinessq flow model, CFL limited timestep

Initial state



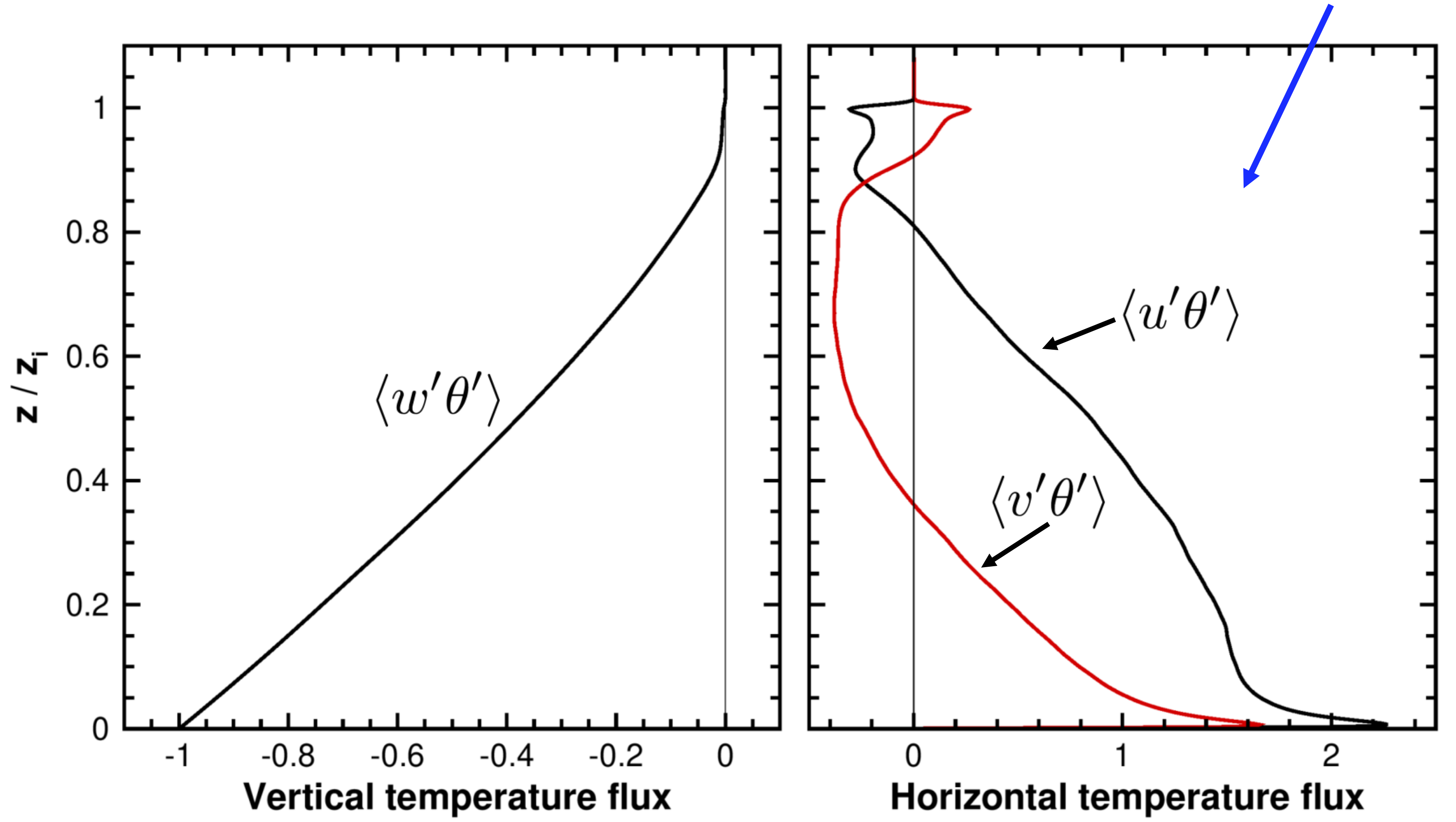
WIND AND TEMPERATURE PROFILES



$z_i/L = 1.7$ — 2.4 — 3.2 — 6.0

VERTICAL PROFILES OF SCALAR FLUXES: $z_i/L = 1.7$

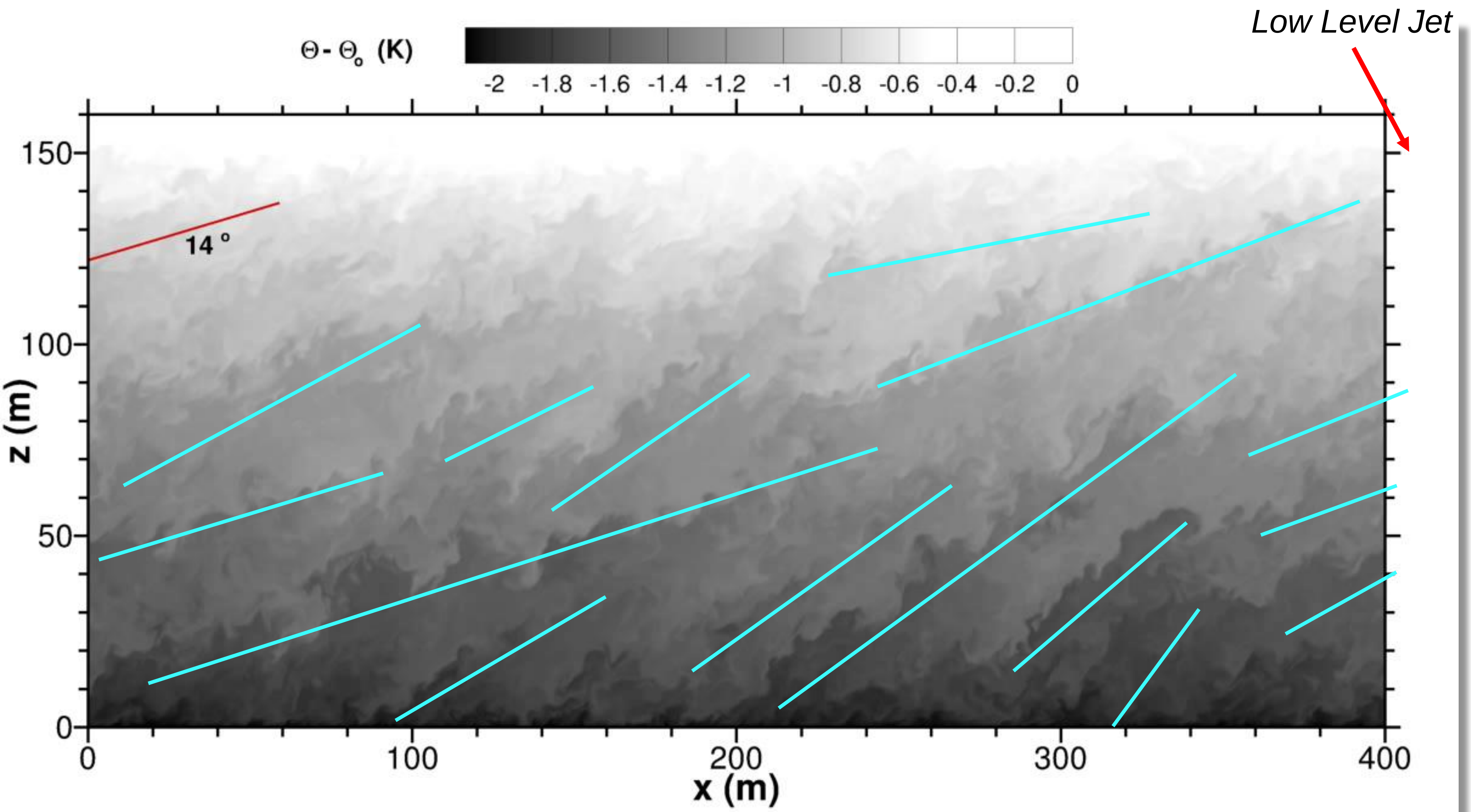
$$\frac{\partial}{\partial x}\langle\theta\rangle = \frac{\partial}{\partial y}\langle\theta\rangle = 0$$



Flow is horizontally homogeneous, what makes net horizontal scalar fluxes?

FLUCTUATIONS IN THE TEMPERATURE FIELD

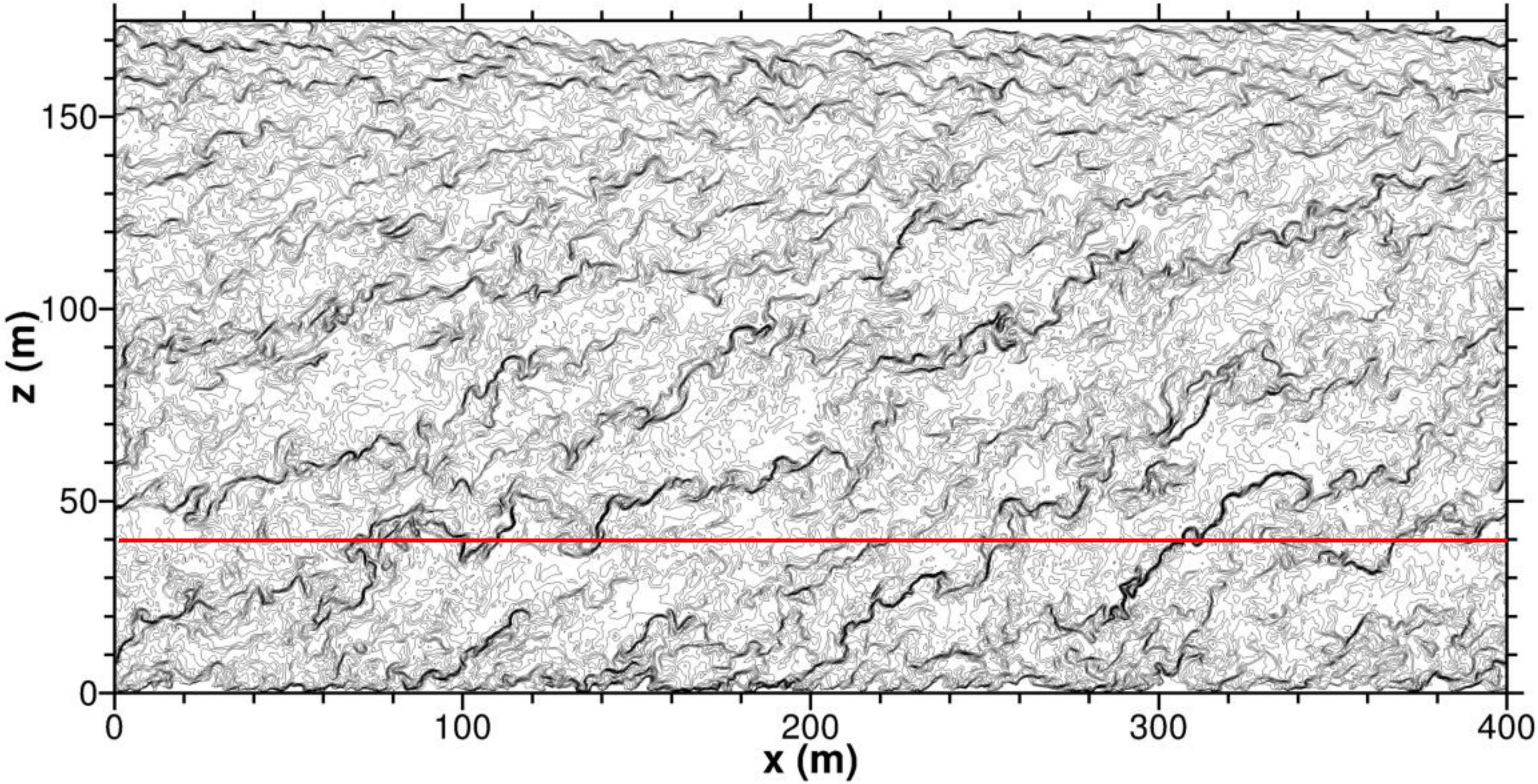
POTENTIAL TEMPERATURE CONTOURS IN AN XZ PLANE



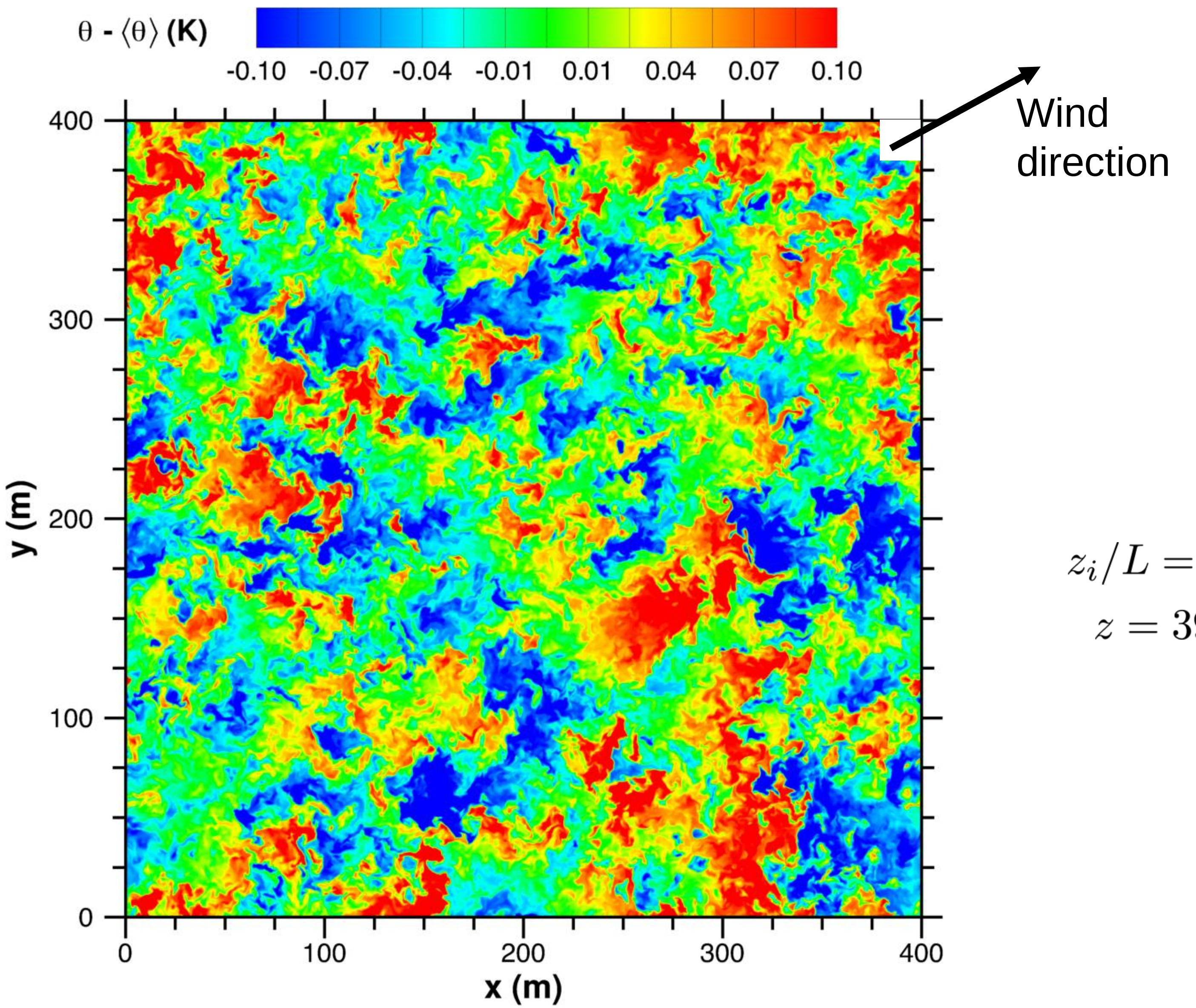
60 s of real time

$z_i / L = 1.7$

POTENTIAL TEMPERATURE CONTOURS IN AN XZ PLANE



TEMPERATURE FIELD IN X-Y PLANE



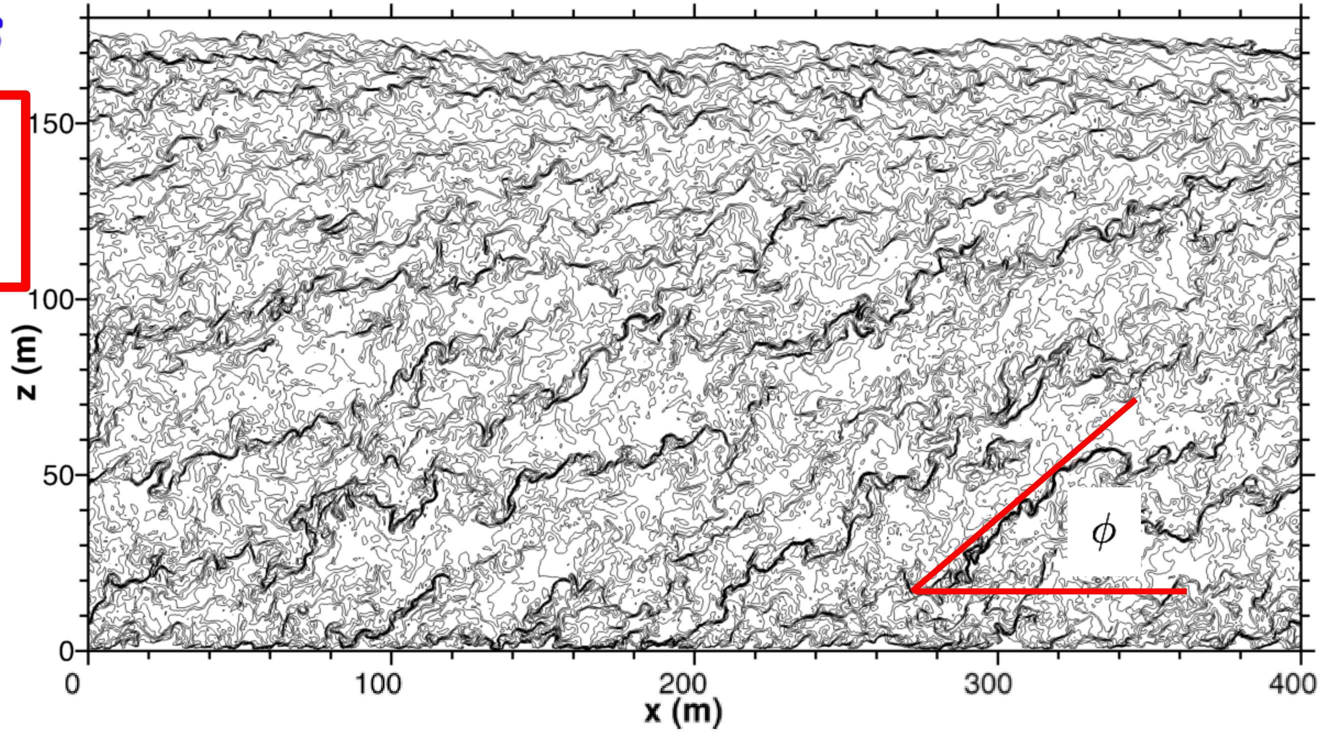
$z_i/L = 1.7$

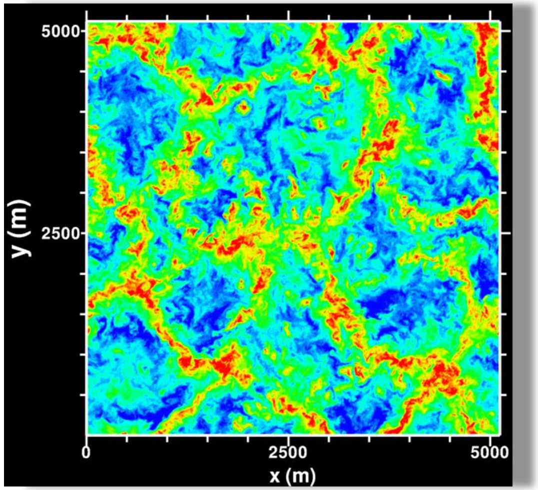
$z = 39\, m$

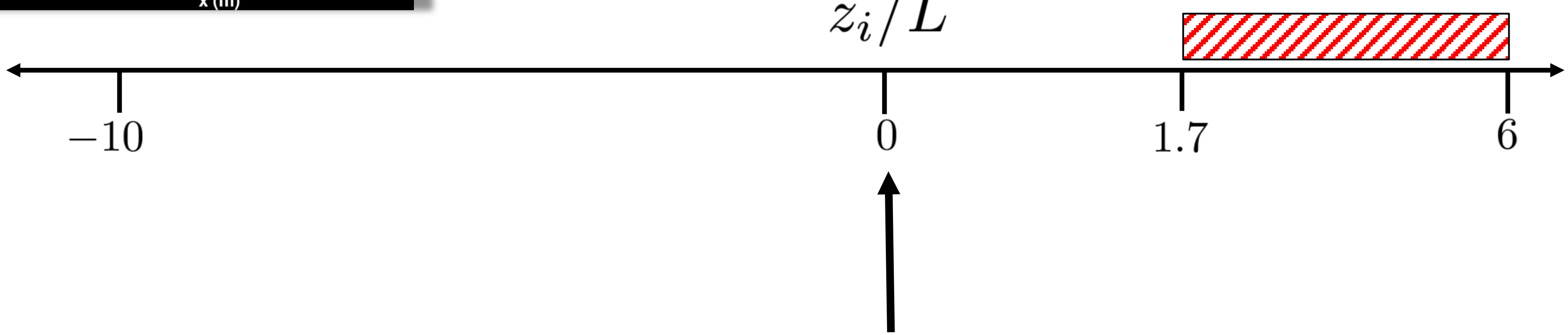
$\theta - Contours$

$$tan\,\phi \;=\; \frac{-\partial\theta'/\partial x}{\partial\langle\theta\rangle/\partial z + \partial\theta'/\partial z}$$

$$z_i/L = 1.7$$

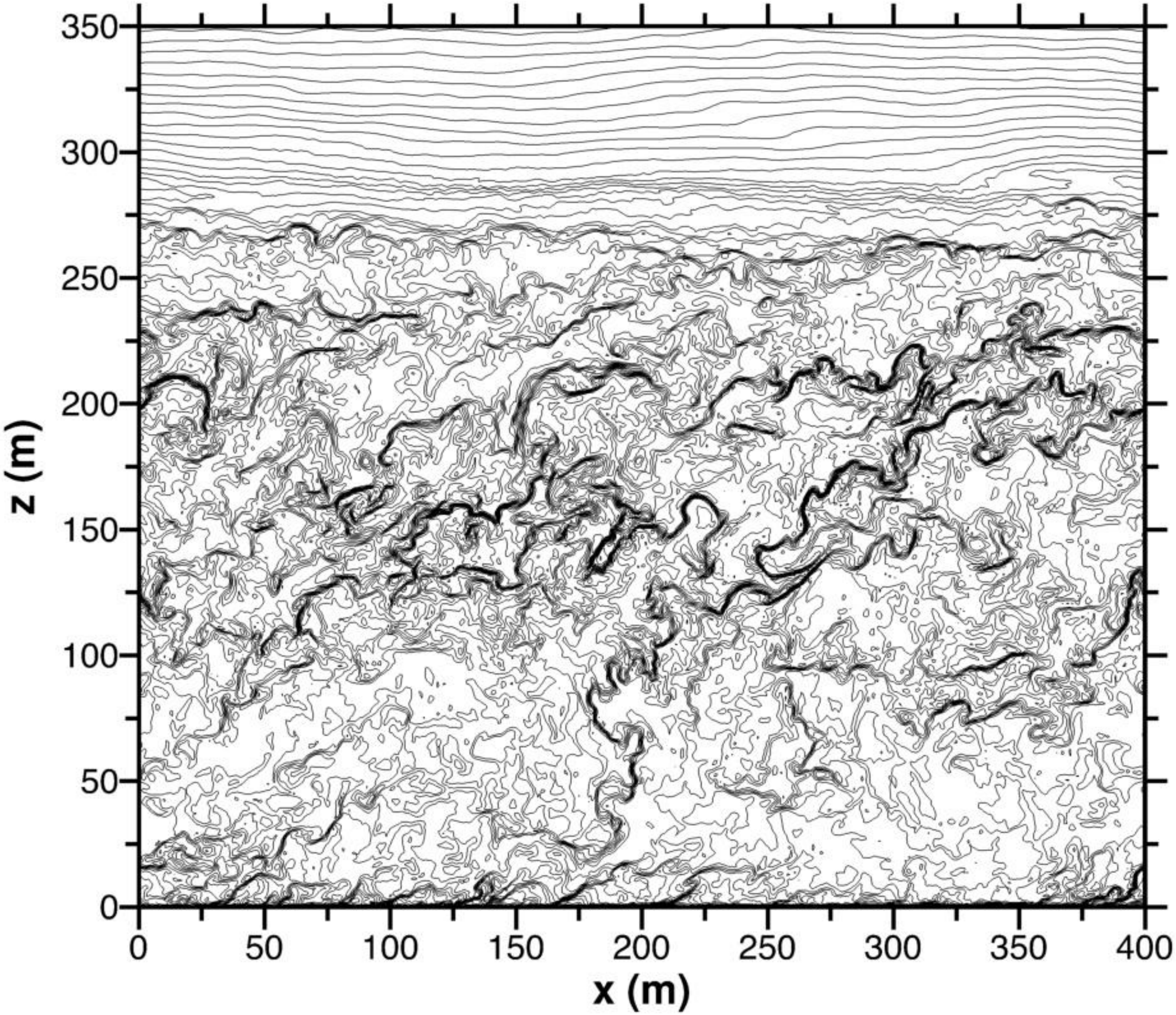


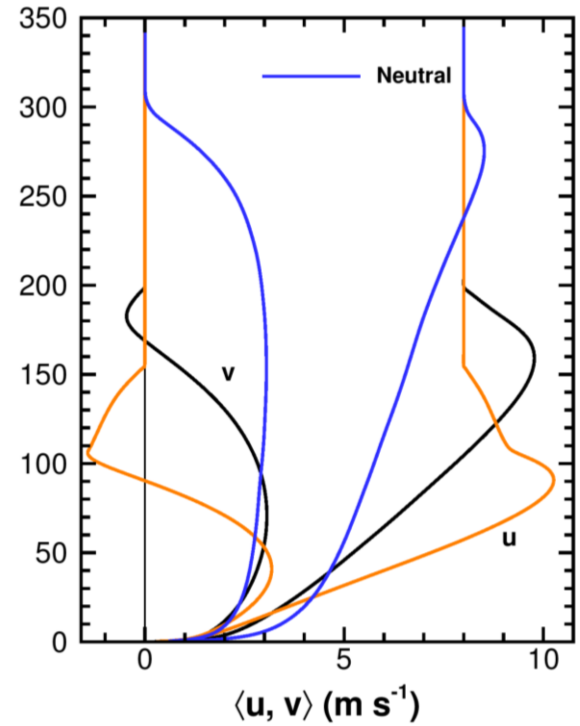




DECREASING STRATIFICATION ?

CONTOURS OF PASSIVE SCALAR C IN STABLY STRATIFIED NEUTRAL FLOW

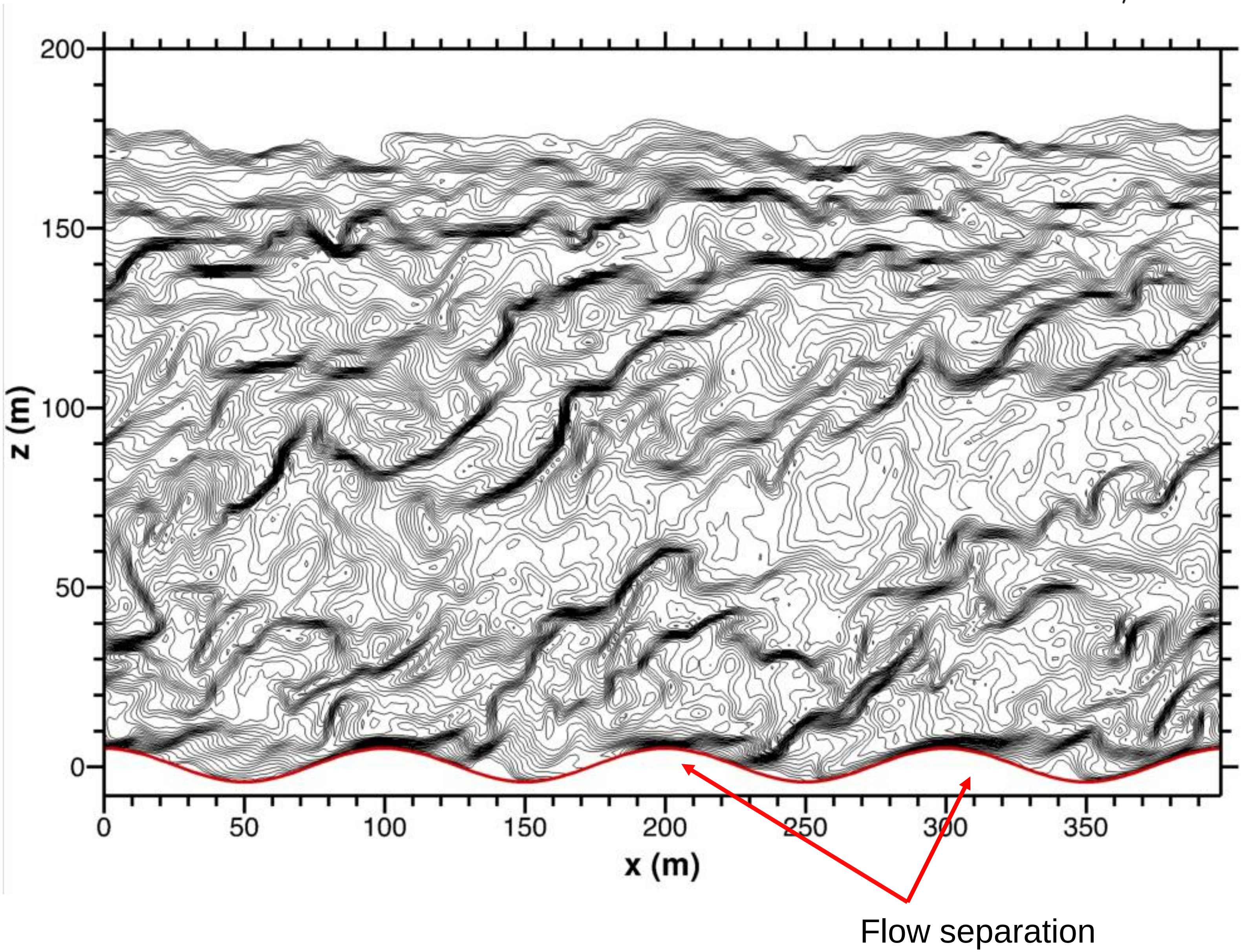




$z_i/L = 0$

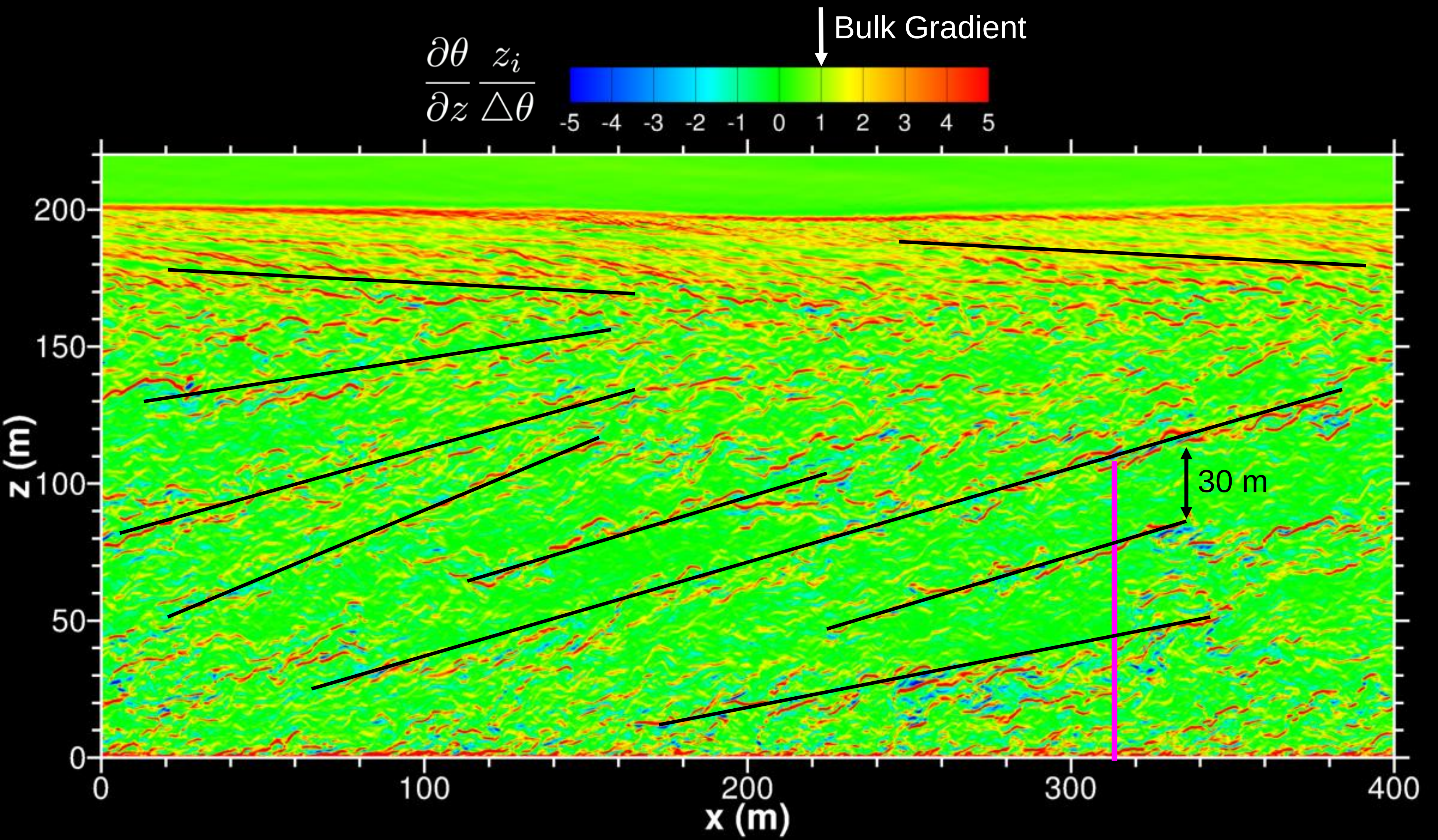
TEMPERATURE CONTOURS IN STABLY STRATIFIED FLOW OVER 2D BUMPS, ak = 0.3

$z_i/L = 1.7$

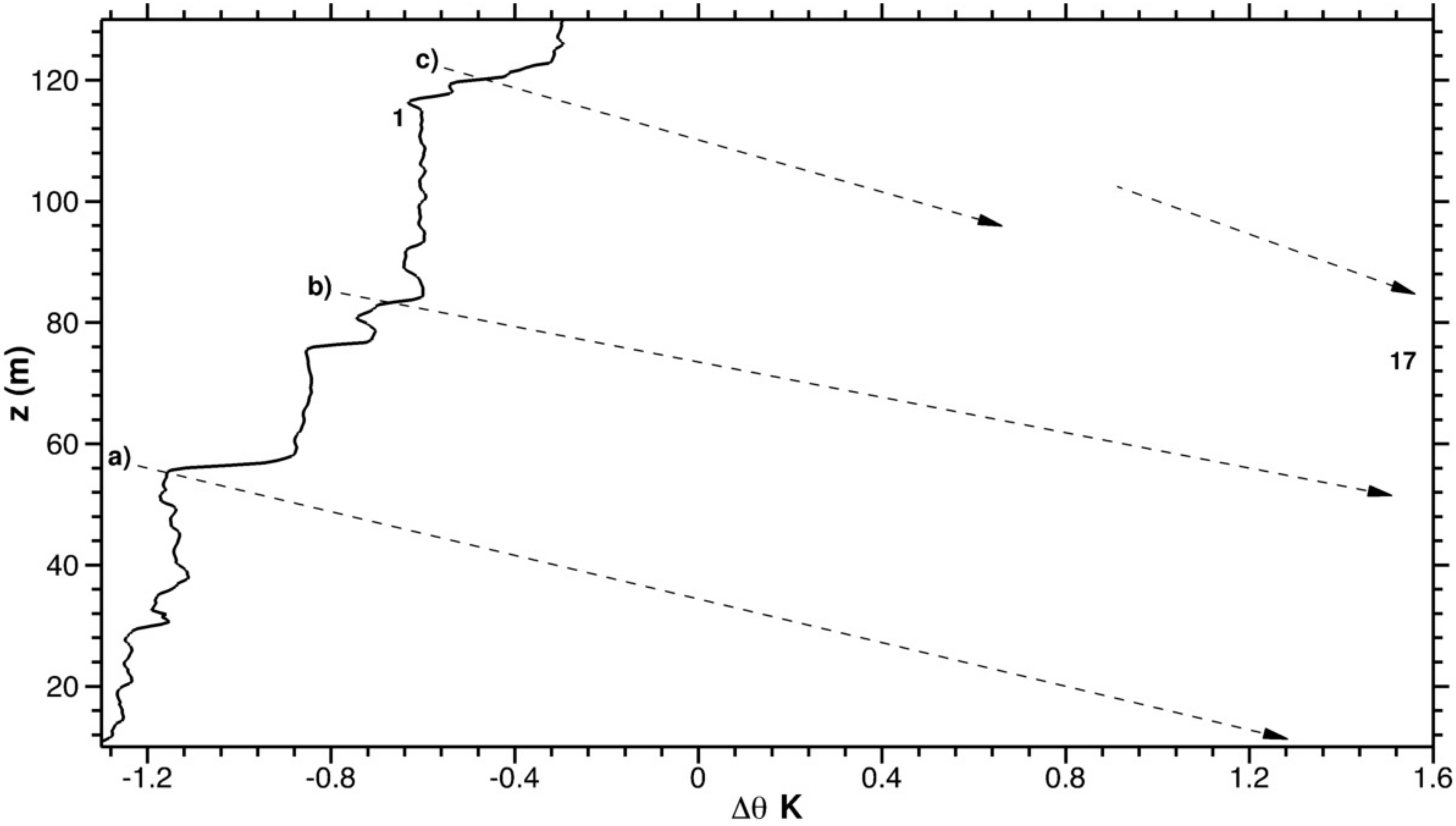


OBSERVATIONS OF TEMPERATURE PROFILES FROM A ``VIRTUAL” TOWER

CONTOURS OF VERTICAL TEMPERATURE GRADIENT



INSTANTANEOUS VERTICAL PROFILES OF TEMPERATURE



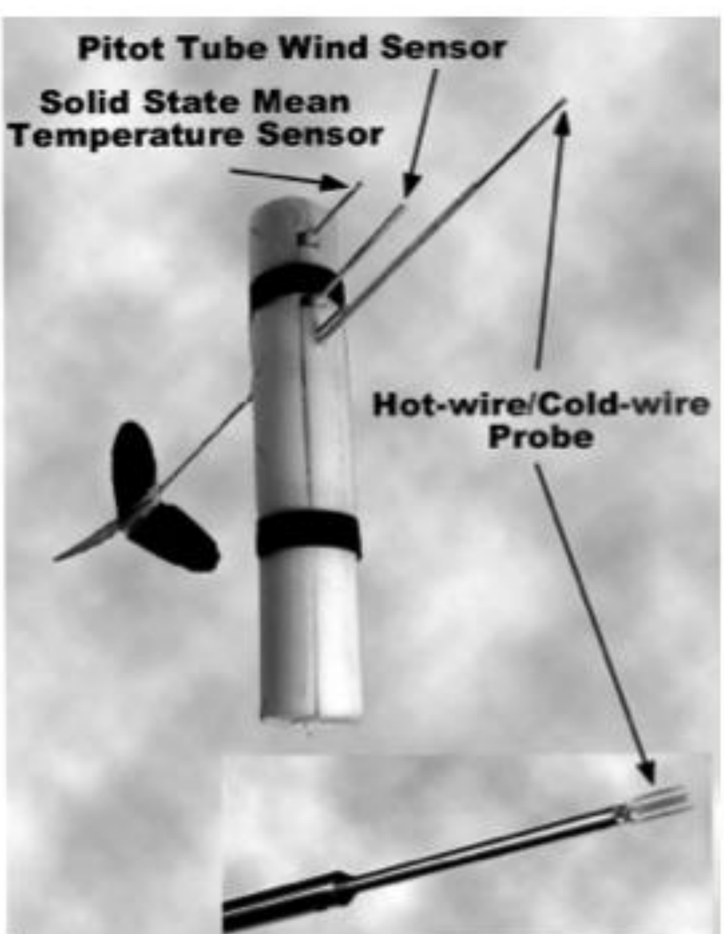
Extreme Gradients in the Nocturnal Boundary Layer: Structure, Evolution, and Potential Causes

Ben B. Balsley, Rod G. Frehlich, Michael L. Jensen, and Yannick Meillier

CIRES, University of Colorado, Boulder, Colorado

Andreas Muschinski

CIRES, University of Colorado, and NOAA/Environmental Technology Laboratory, Boulder, Colorado



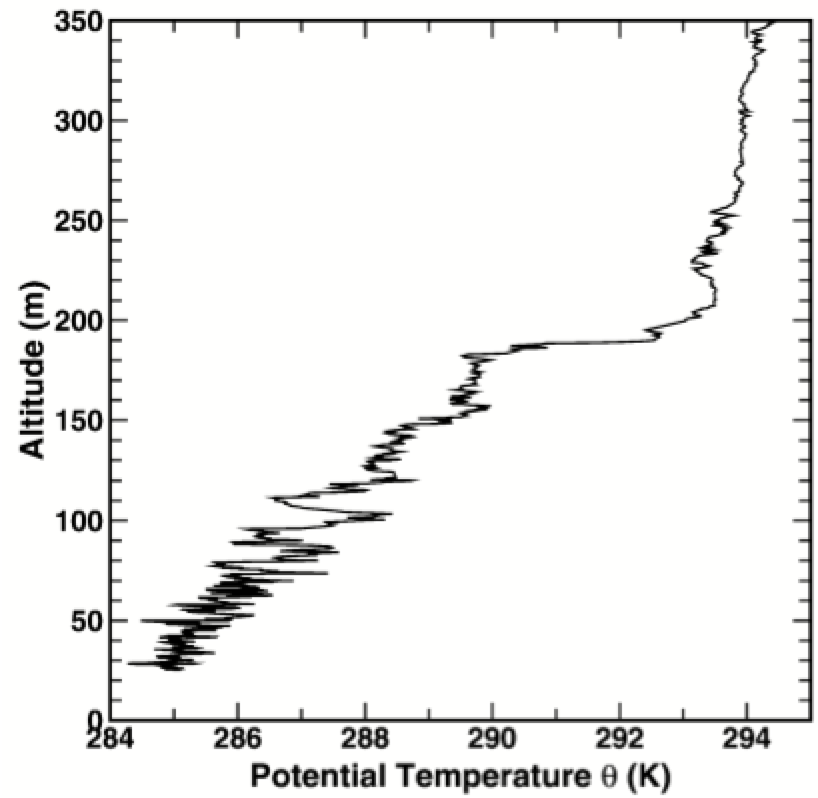
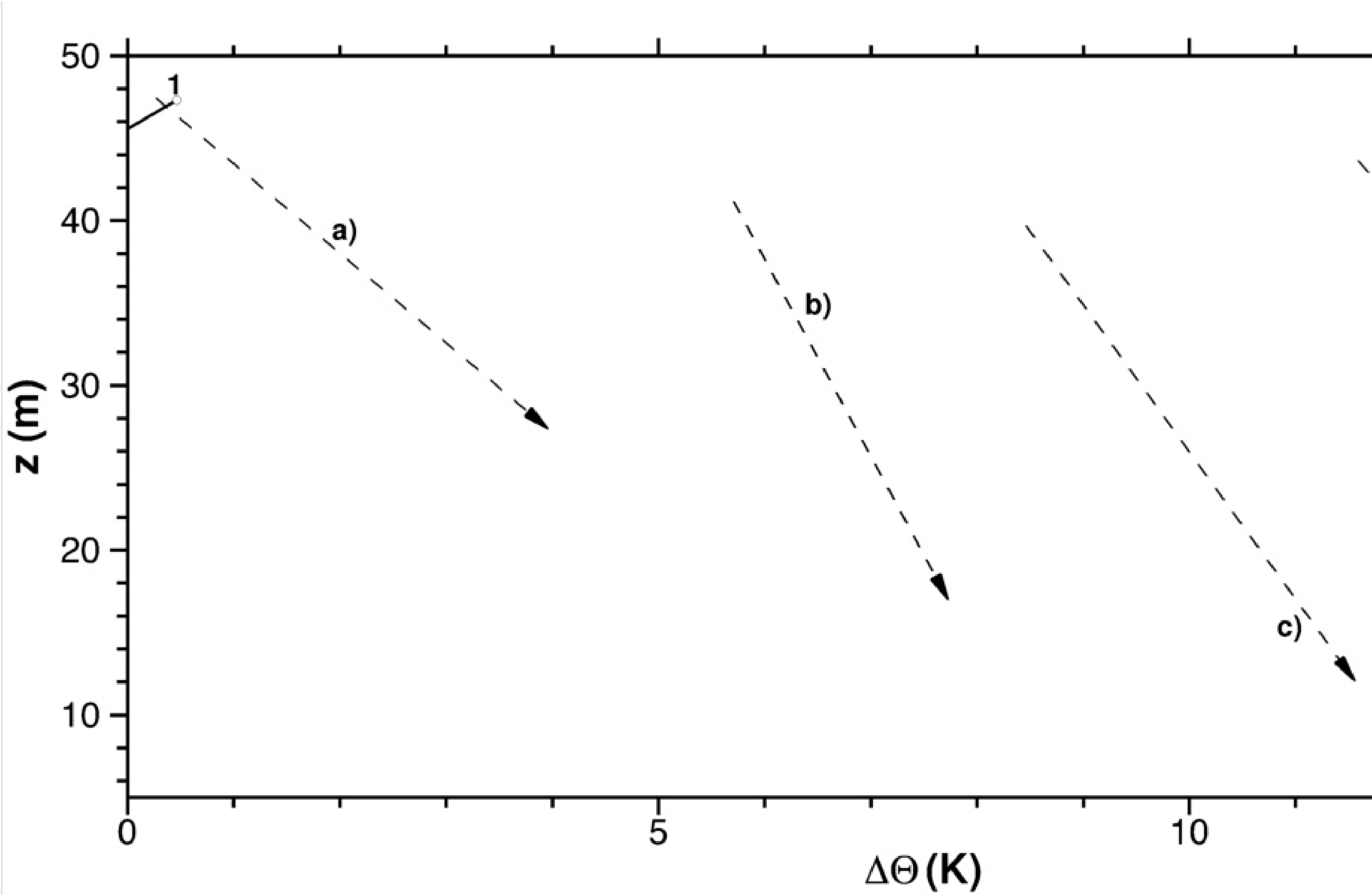


FIG. 9. Vertical profile of potential temperature obtained from 1-s values of the cold-wire temperature sensor and the pressure sensor on package 2 during the 0713–0731 UTC ascent.

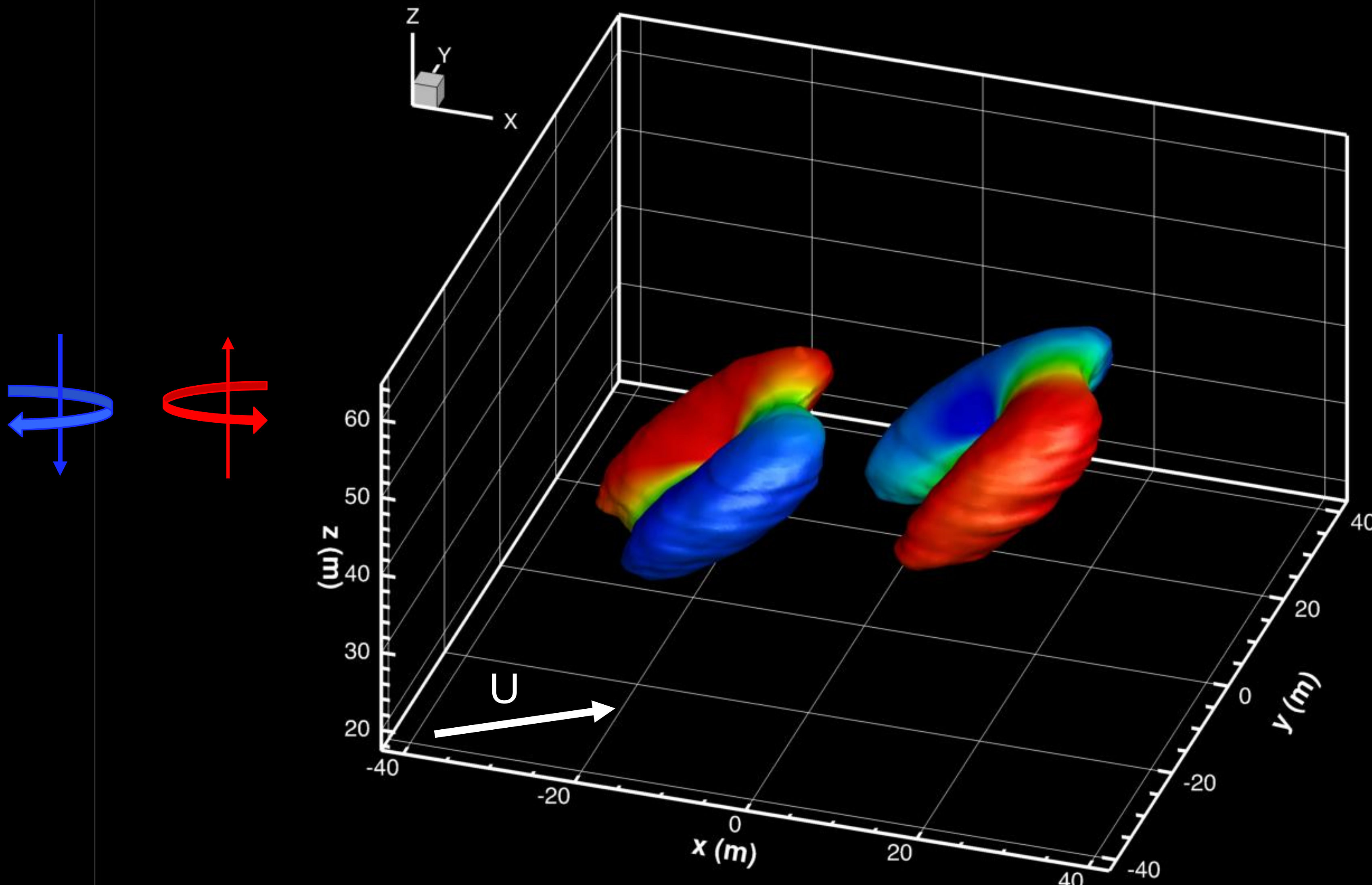
INSTANTANEOUS TEMPERATURE PROFILES OBSERVED FROM THE TALL TOWER IN CASES-99



92 seconds of data

DYNAMICS NEAR A SCALAR FRONT

3D ISOSURFACE OF SWIRL COLORED BY VERTICAL VORTICITY



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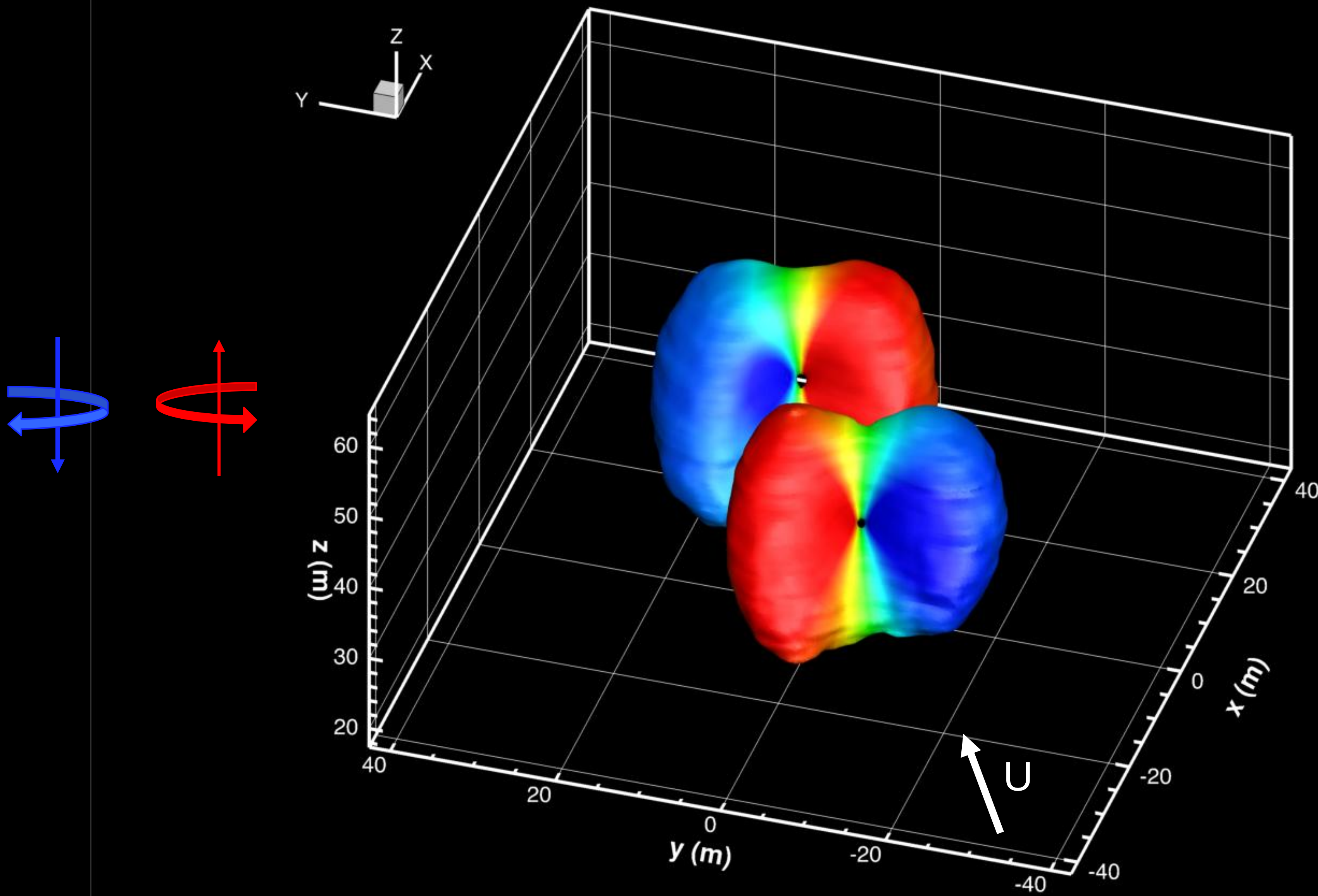
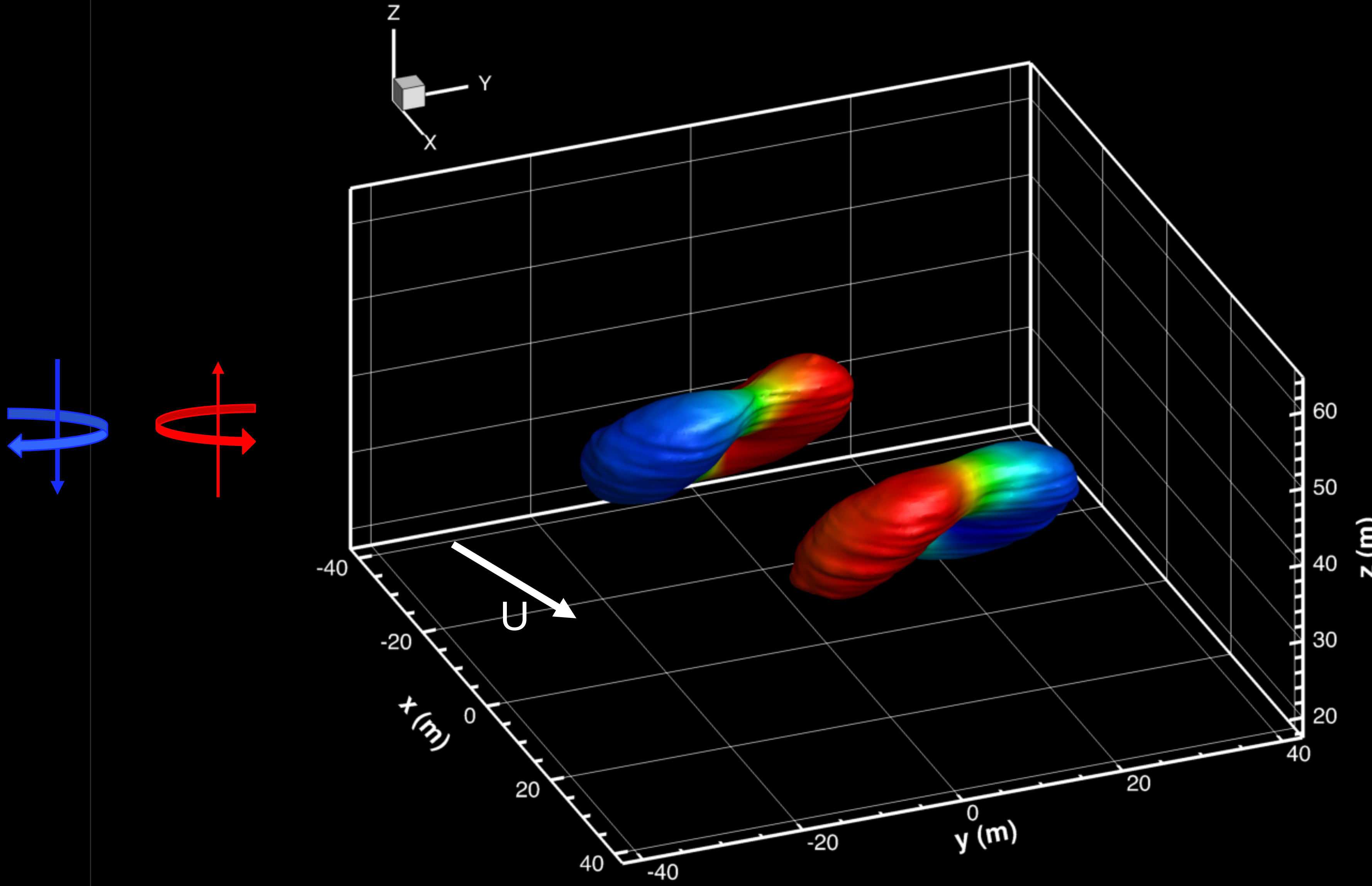


3D ISOSURFACE OF SWIRL COLORED BY VERTICAL VORTICITY



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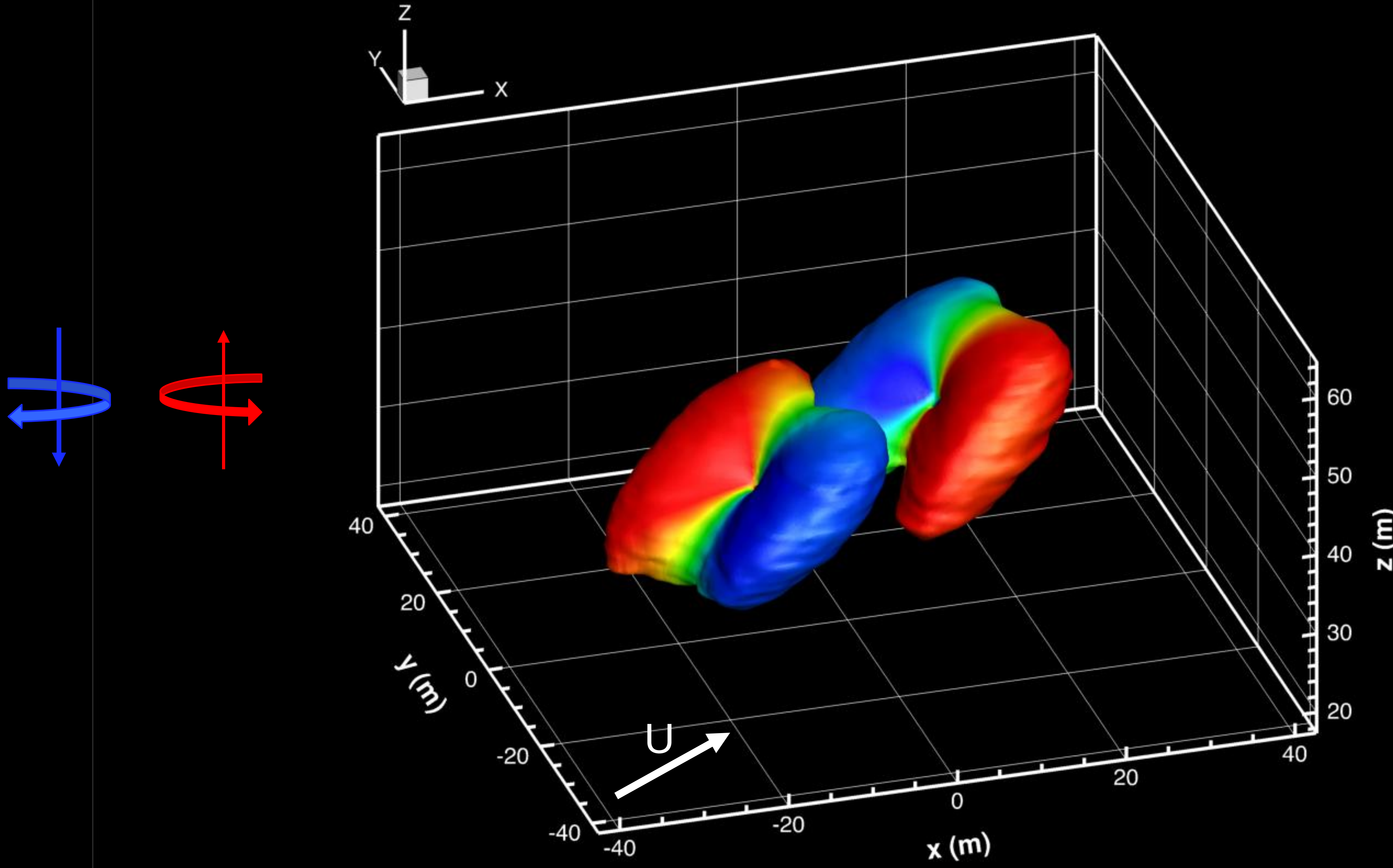
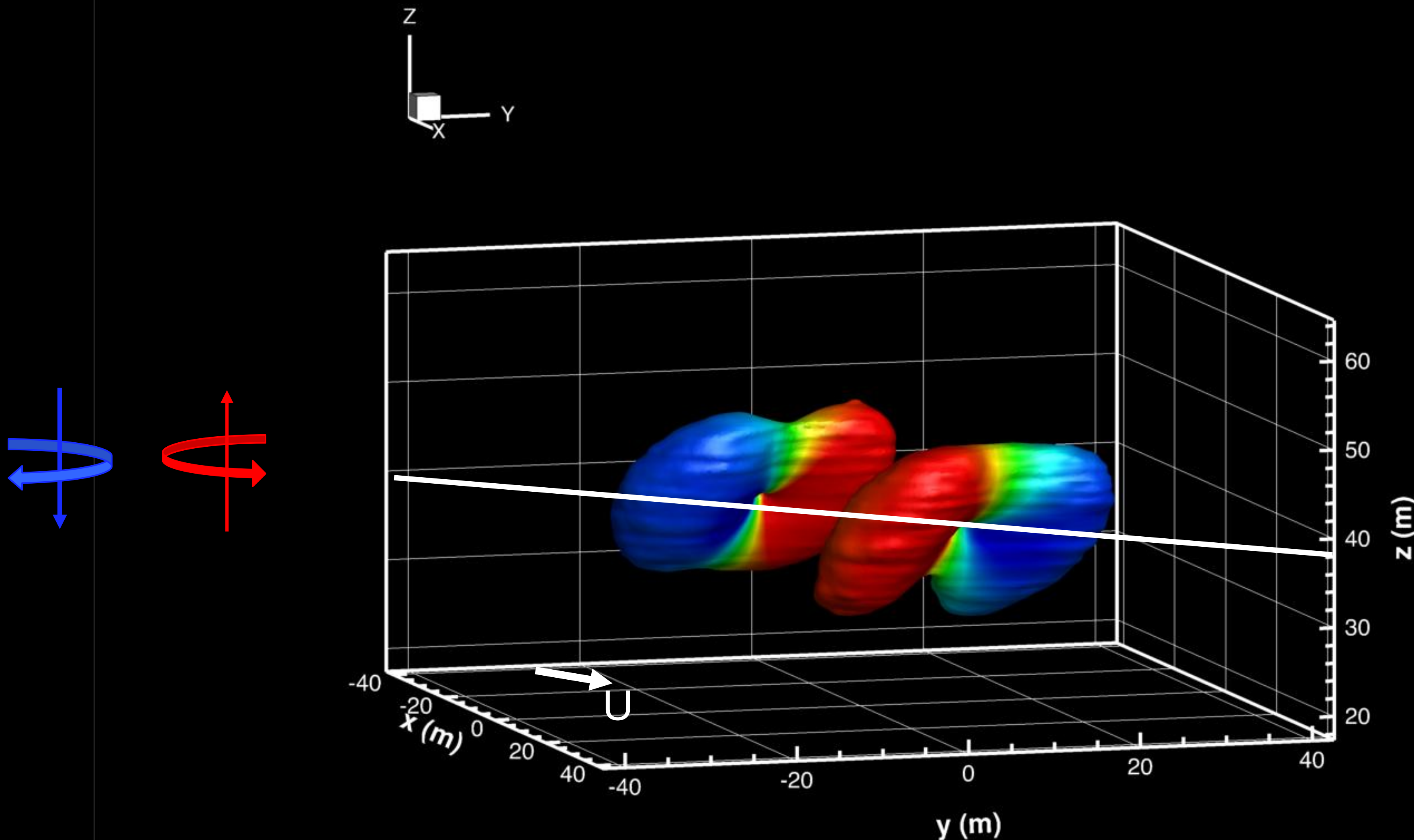
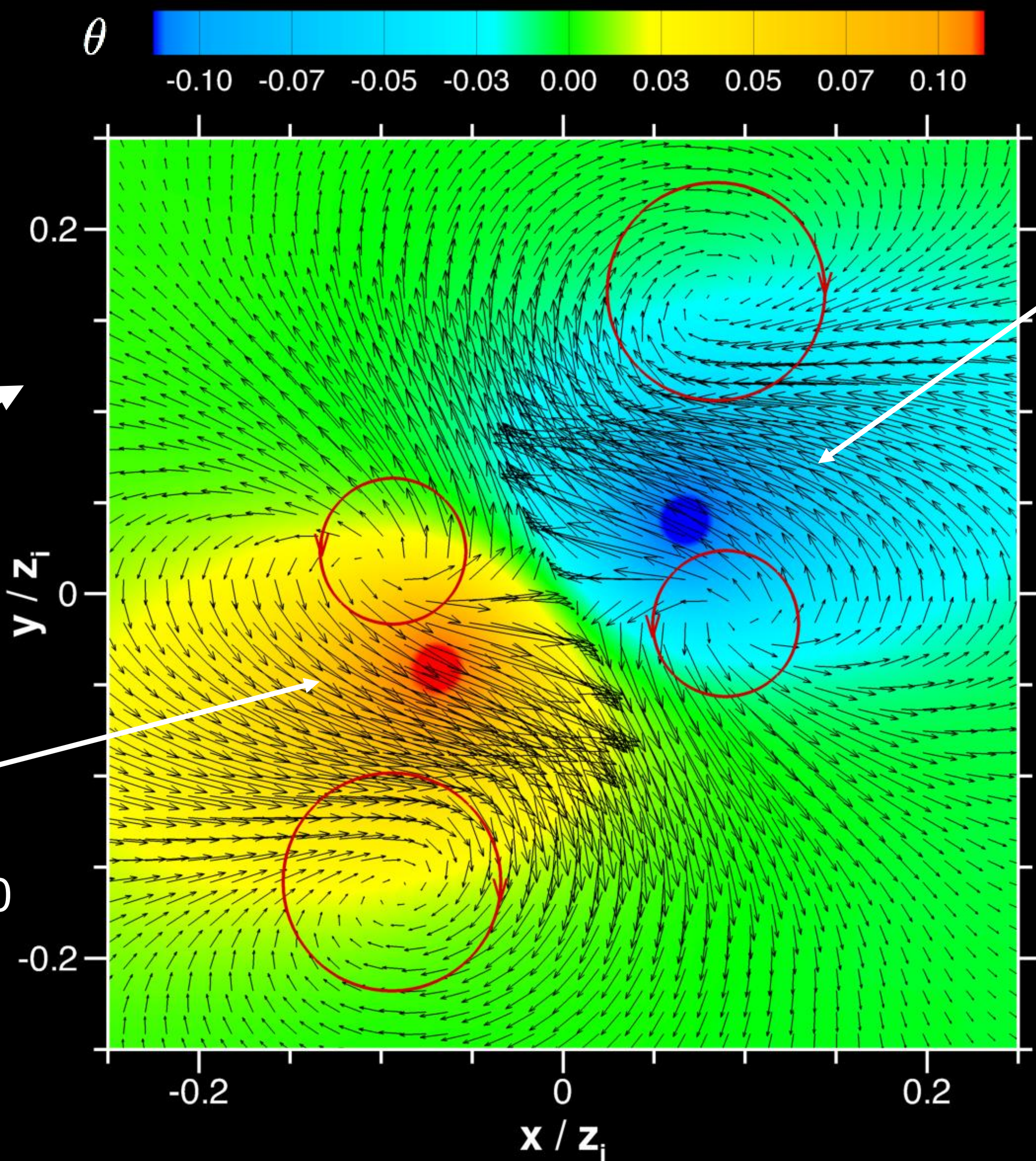


3D ISOSURFACE OF SWIRL COLORED BY VERTICAL VORTICITY



CONDITIONAL HORIZONTAL FLOW VECTORS OVERLAYING TEMPERATURE FIELD NEAR A FRONT $z/z_i = 0.2$

U



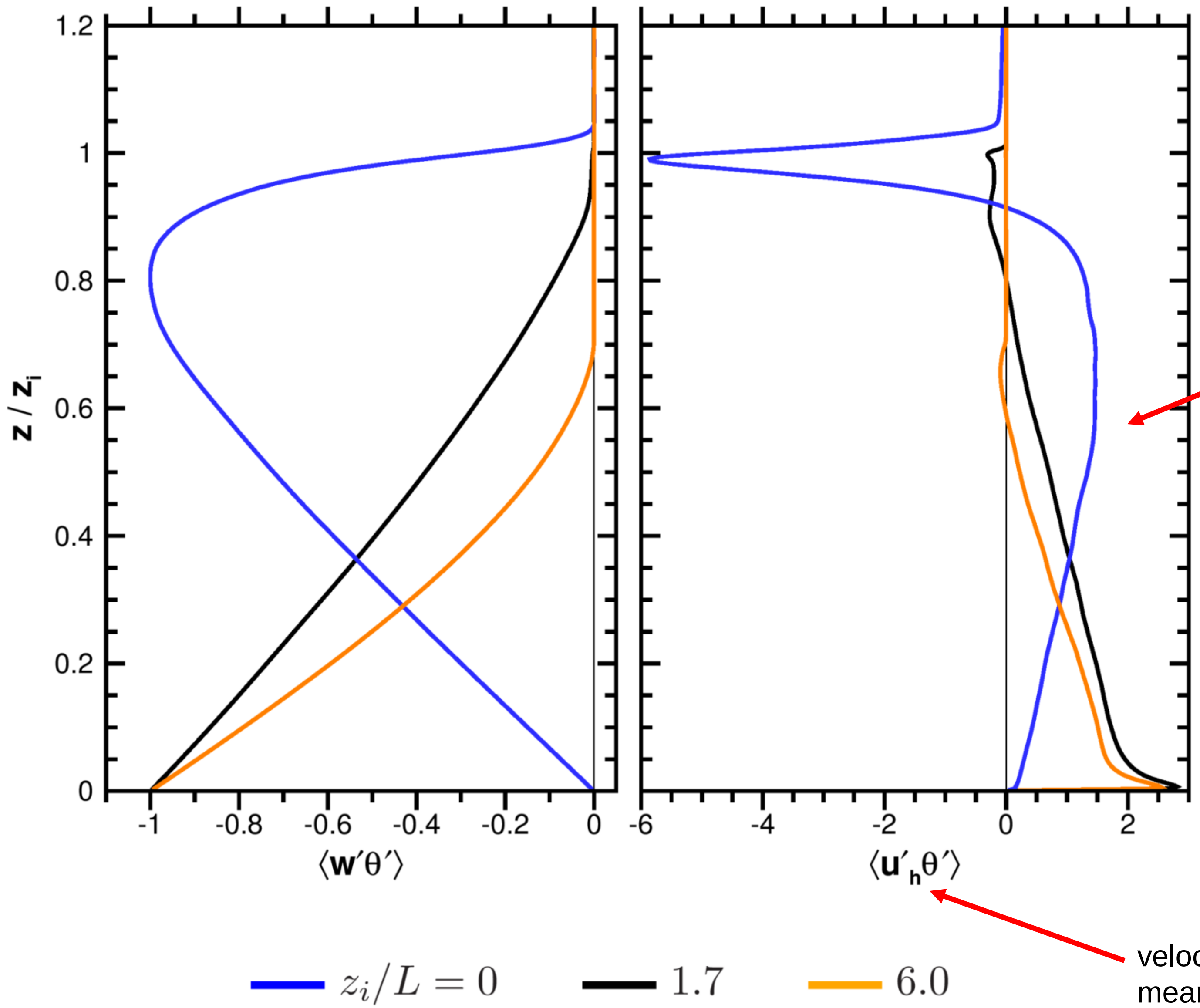
Q2 event

$u'<0$, $w'>0$, $\theta'<0$
$u'w' < 0$
$u'\theta' > 0$
$w'\theta' < 0$

Q4 event

$u'>0$, $w'<0$, $\theta'>0$
$u'w' < 0$
$u'\theta' > 0$
$w'\theta' < 0$

VERTICAL AND HORIZONTAL TEMPERATURE FLUXES IN STABLY STRATIFIED FLOW



Fronts!

velocity aligned with mean wind

Local Free Convection, Similarity, and the Budgets of Shear Stress and Heat Flux

J. C. Wyngaard, O. R. Coté and Y. Izumi

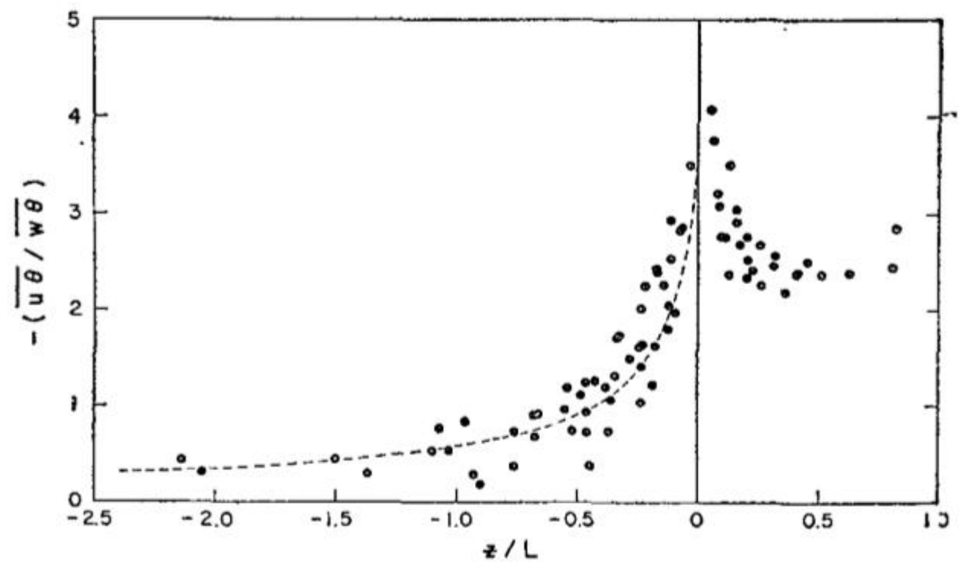


Fig. 4. Ratio of horizontal and vertical components of heat flux. The curve is the local free convection prediction.

The same procedure gives the vertical heat flux ($\overline{w\theta}$) budget

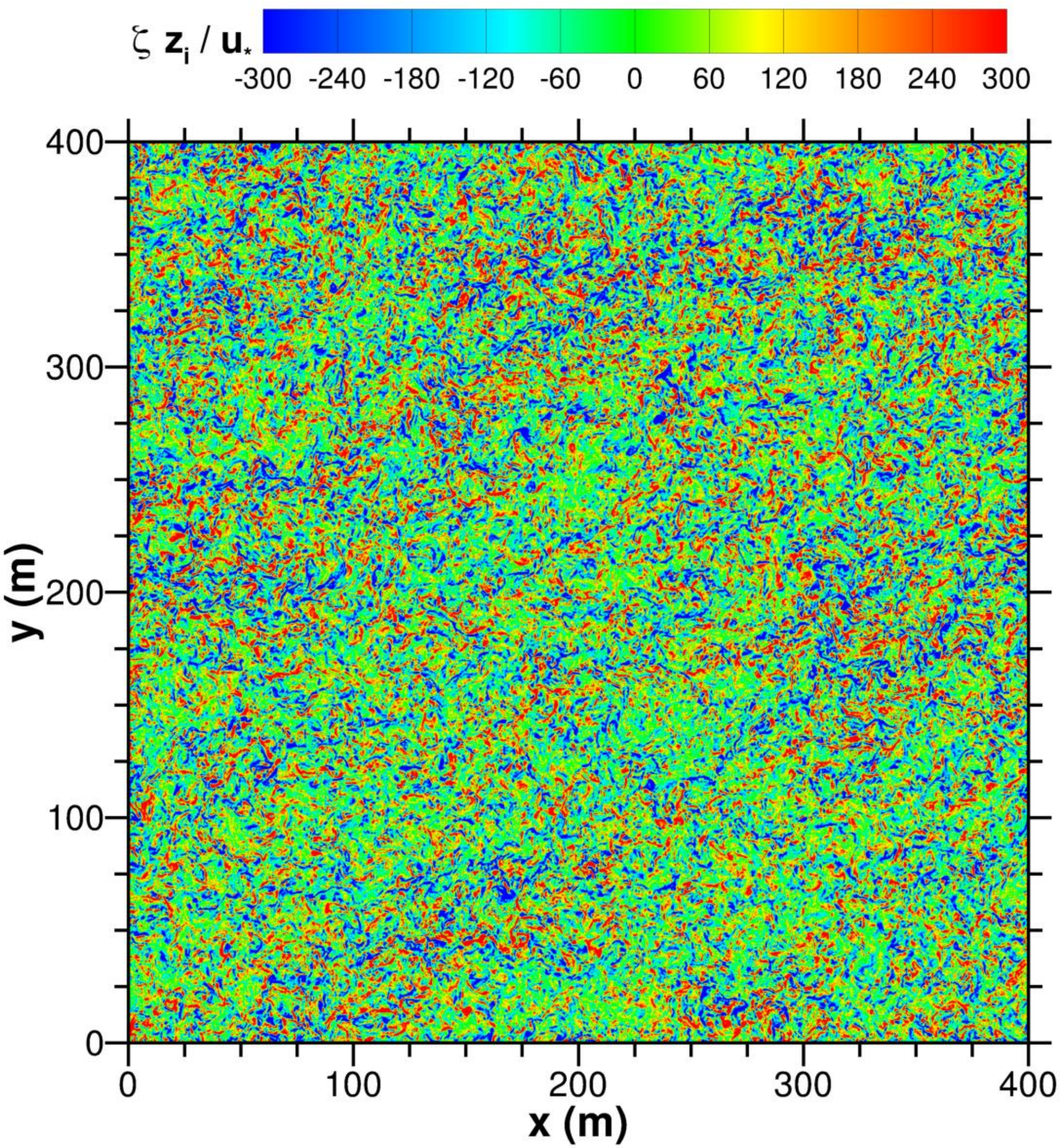
$$\frac{\partial\overline{w\theta}}{\partial t}+\overline{w^2}\frac{\partial\Theta}{\partial z}-\frac{g}{T}\overline{\theta^2}+\frac{\partial\overline{w^2\theta}}{\partial z}+\frac{1}{\rho}\overline{\theta\frac{\partial p}{\partial z}}=0, \qquad (13)$$

and the horizontal heat flux ($\overline{u\theta}$) budget

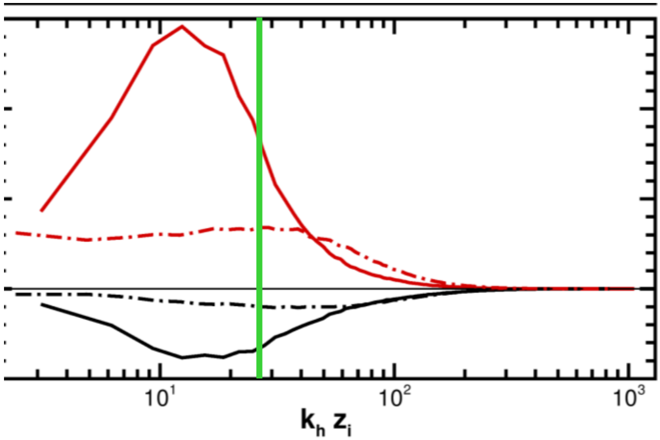
$$\frac{\partial\overline{u\theta}}{\partial t}+\overline{w\theta}\frac{\partial U}{\partial z}+\overline{uw}\frac{\partial\Theta}{\partial z}+\frac{\partial\overline{uw\theta}}{\partial z}+\frac{1}{\rho}\overline{\theta\frac{\partial p}{\partial x}}=0. \qquad (14)$$

$$\overline{w\theta} \sim \tau\overline{w^2}\frac{\partial\Theta}{\partial z}, \qquad \overline{u\theta} \sim \tau\overline{w\theta}\frac{\partial U}{\partial z}$$

EPILOGUE: VERTICAL VORTICITY



FILTERED
NEAR PEAK IN
ENERGY
SPECTRUM



SUMMARY

- LES of canonical SBL with 1024^3 mesh, $\triangle = 0.39\,\mathrm{m}$
- Organized coherent temperature fronts
  - Can span the entire depth of the SBL up to the low level jet
  - Tilted in the streamwise direction
  - Spatial scale $\downarrow$ as $z_i/L \uparrow$
- Between fronts scalars are vertically well mixed, or even unstable, staircase pattern
- Propagating fronts are sources of large-scale intermittency, and induce vertical and horizontal momentum and scalar fluxes
- Based on conditional sampling
  - Fronts are caused by upstream and downstream vortical structures
  - Scales are in the energy containing range
  - Robust for varying stratification $z_i/L = [0, 6]$
  - Interpretation similar to hairpin packets discussed by Adrian (2007)
- LES results are supported by observations in wind tunnels, upper ocean, and CASES-99