



**TRANSIENT EVOLUTION OF LANGMUIR TURBULENCE
IN OCEAN BOUNDARY LAYERS DRIVEN BY
HURRICANE WINDS AND WAVES**

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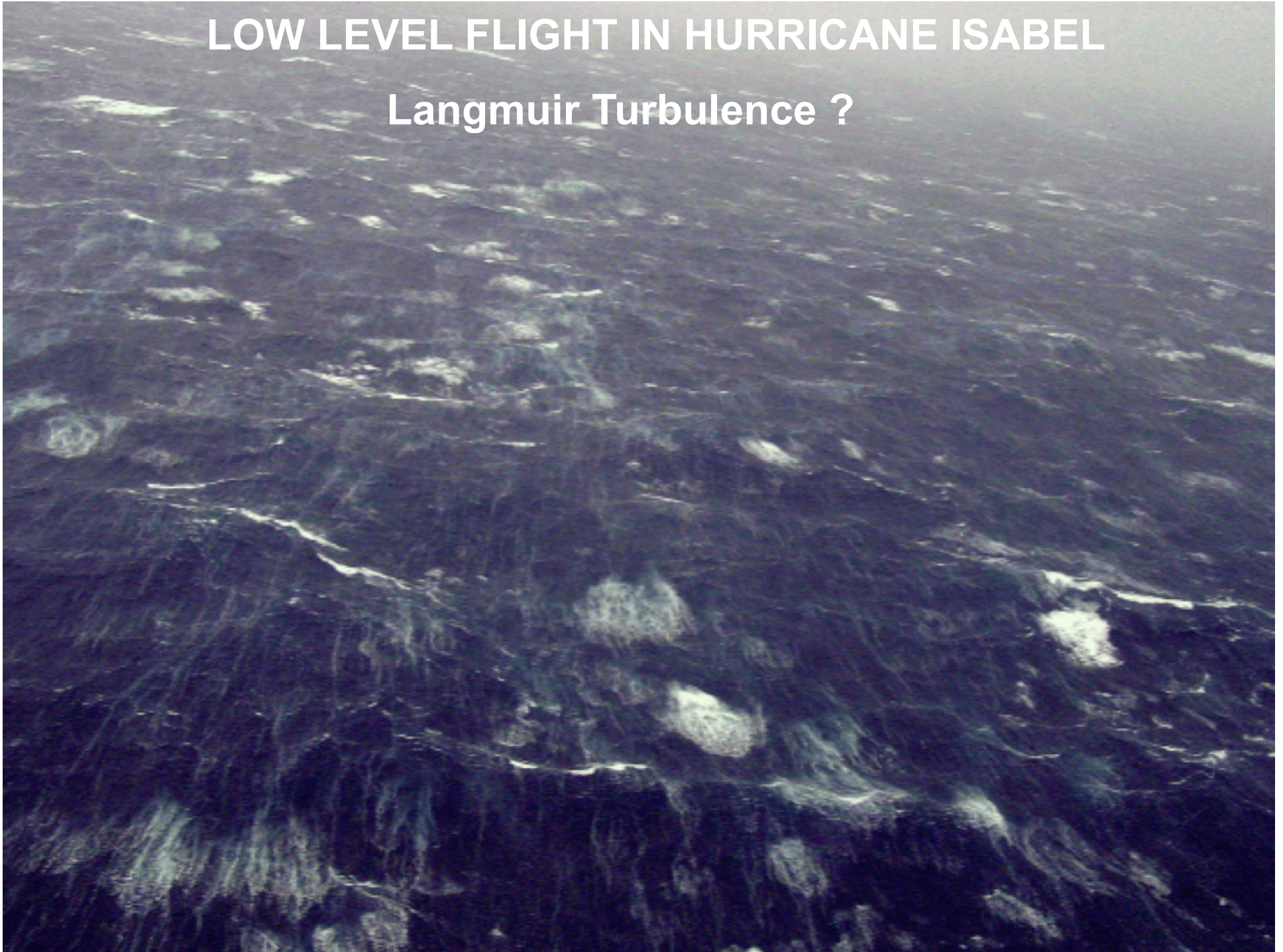
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Support from ONR, NCAR is sponsored by NSF

LOW LEVEL FLIGHT IN HURRICANE ISABEL

Langmuir Turbulence ?



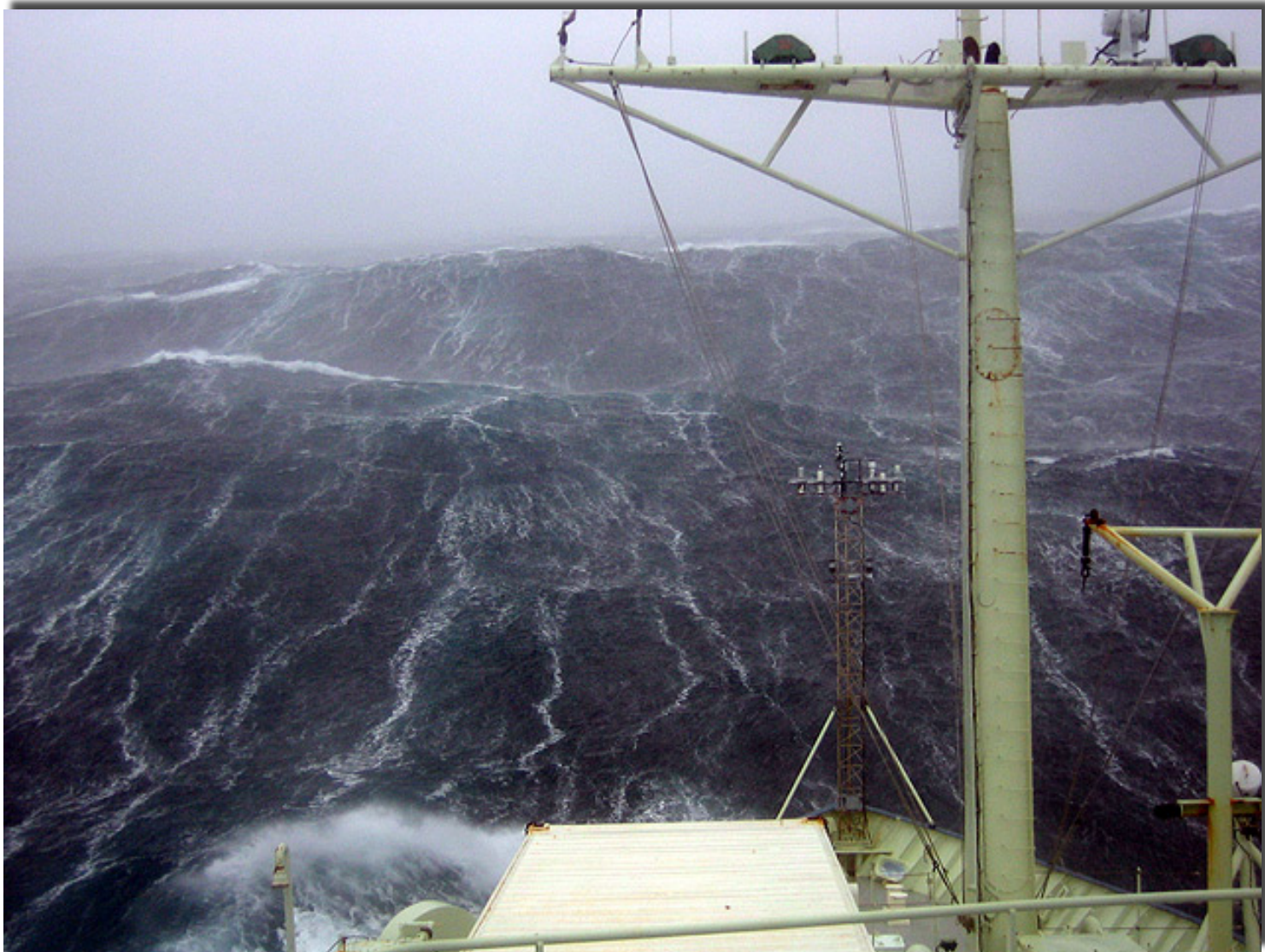
OCEAN BOUNDARY LAYERS (OBLs) DRIVEN BY WINDS AND WAVES

- The classical view of the OBL is as a shear driven layer that obeys law-of-the-wall scaling with negligible wave influences
- Coupling of the atmospheric and oceanic boundary layers is through air-sea fluxes which pass through the surface wave field
- Surface wave field
 - Supports wind stress (form drag)
 - Breaks intermittently, supplies intermittent pulses of momentum and energy, generates spray and bubbles
 - Generates phase-averaged wave-current interactions
- Do waves play a role in air-sea coupling and do they alter the classical picture of how the OBL works?
- Do climate models need to account for surface waves?

Langmuir circulations in Monterey Bay courtesy Luc Lenain SIO



LANGMUIR CIRCULATIONS IN HIGH WINDS?



Photograph from the research vessel *Knorr* in winds ranging from 60 to 100 knots and 30-40 foot tall waves on an expedition to the Irminger Sea in October 2007. (Photo by Kjetil Vage, Woods Hole Oceanographic Institution)

LANGMUIR TURBULENCE

Langmuir turbulence \Rightarrow the OBL regime where phase-averaged wave-current interactions are comparable to or greater than shear/buoyancy generated turbulence

Characteristics of Langmuir turbulence:

- Non-local vertical transport of momentum and scalars
- Near surface intensification of spanwise and vertical velocity variances
- Coherent structures
 - streamwise oriented Langmuir cells
 - downwelling jets induced by the CL2 instability and breaker vorticity

McWilliams *et al.*(1997) argue that the high-Reynolds number parameter measuring the competition between shear instability and vortex force is the turbulent Langmuir number:

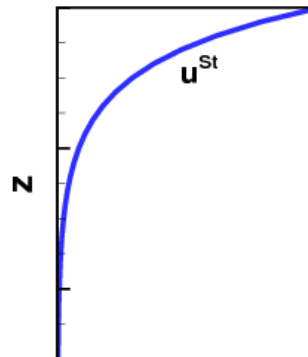
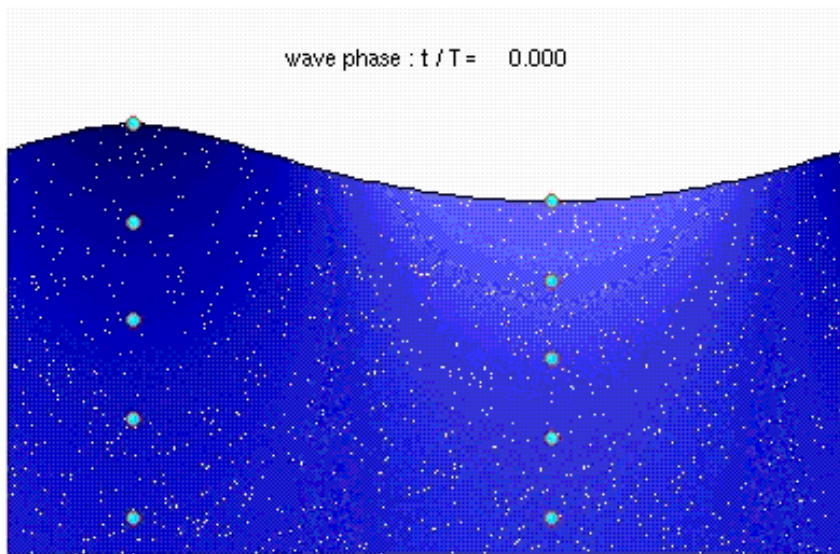
$$La_t = \sqrt{\frac{u_*}{|\mathbf{u}_s|}}$$

Friction velocity

Stokes drift velocity

PHASE-AVERAGED WAVE-CURRENT ASYMPTOTICS

- Assumptions for multiple-time scale analysis, *e.g.*, Craik & Leibovich (1976), McWilliams *et al.*(1997), McWilliams *et al.*(2004)
 - $\mathbf{v} = \epsilon \mathbf{u}^w + \epsilon^2 \mathbf{u} + \dots$ with $\epsilon = ak$ the waveslope
 - Wave orbital speeds are larger than the currents
 - Wave period is short compared to the time scale for current development
- Critical result momentum equations are augmented by a “vortex force”
 $\mathbf{u}_s \times \boldsymbol{\omega}$ ←
- \mathbf{u}_s is the Stokes drift of the wavefield
- $\boldsymbol{\omega}$ is the resolved vorticity



Stokes drift for a pure wave motion is the average Lagrangian velocity following a fluid particle

LES MODEL WITH WAVE EFFECTS

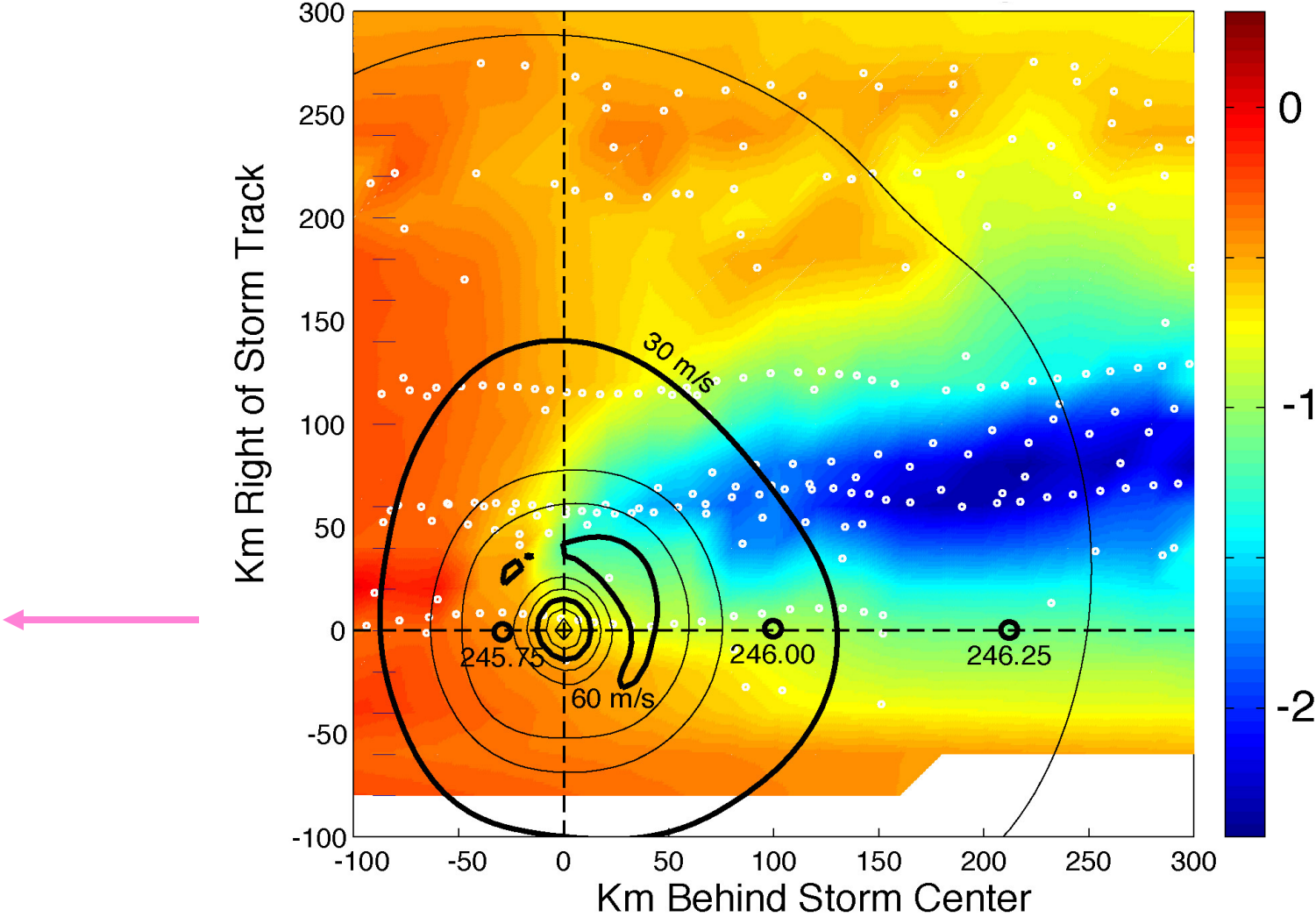
- Phase-averaged wave-current interactions \Rightarrow depend on Stokes drift \mathbf{u}_s
 - Vortex force
 - Coriolis-Stokes term
 - Scalar advection by Stokes drift
 - Stokes production
- Discrete stochastic wave breaking model replaces uniform stress τ_o
 - Compact momentum \mathbf{A} and energy W impulses
 - PDF of breaking matches the atmospheric inputs with a dependence on wave age and wind speed

$$\frac{\partial \mathbf{u}}{\partial t} = \dots \mathbf{u}_s \times (f\hat{\mathbf{z}} + \boldsymbol{\omega}) + \sum_{i=1}^n \mathbf{A}^{(i)}$$

$$\frac{\partial c}{\partial t} = \dots \mathbf{u}_s \cdot \nabla c$$

$$\frac{\partial e}{\partial t} = \dots \mathbf{u}_s \cdot \nabla e - \tau_{ij} \frac{\partial u_{i,s}}{\partial x_j} + \sum_{i=1}^n W^{(i)}$$

CBLAST HURRICANE FRANCES SST CHANGE “COLD WAKE”



Courtesy Eric D'Asaro (U. Wash.)

OBLs DRIVEN BY HURRICANE WINDS AND WAVES

OBJECTIVE:

- Determine the role (if any) of surface waves on ocean mixing under high winds
- Coupling between time varying wind and wave fields and inertial currents
- Evolution of the boundary layer in the cold wake

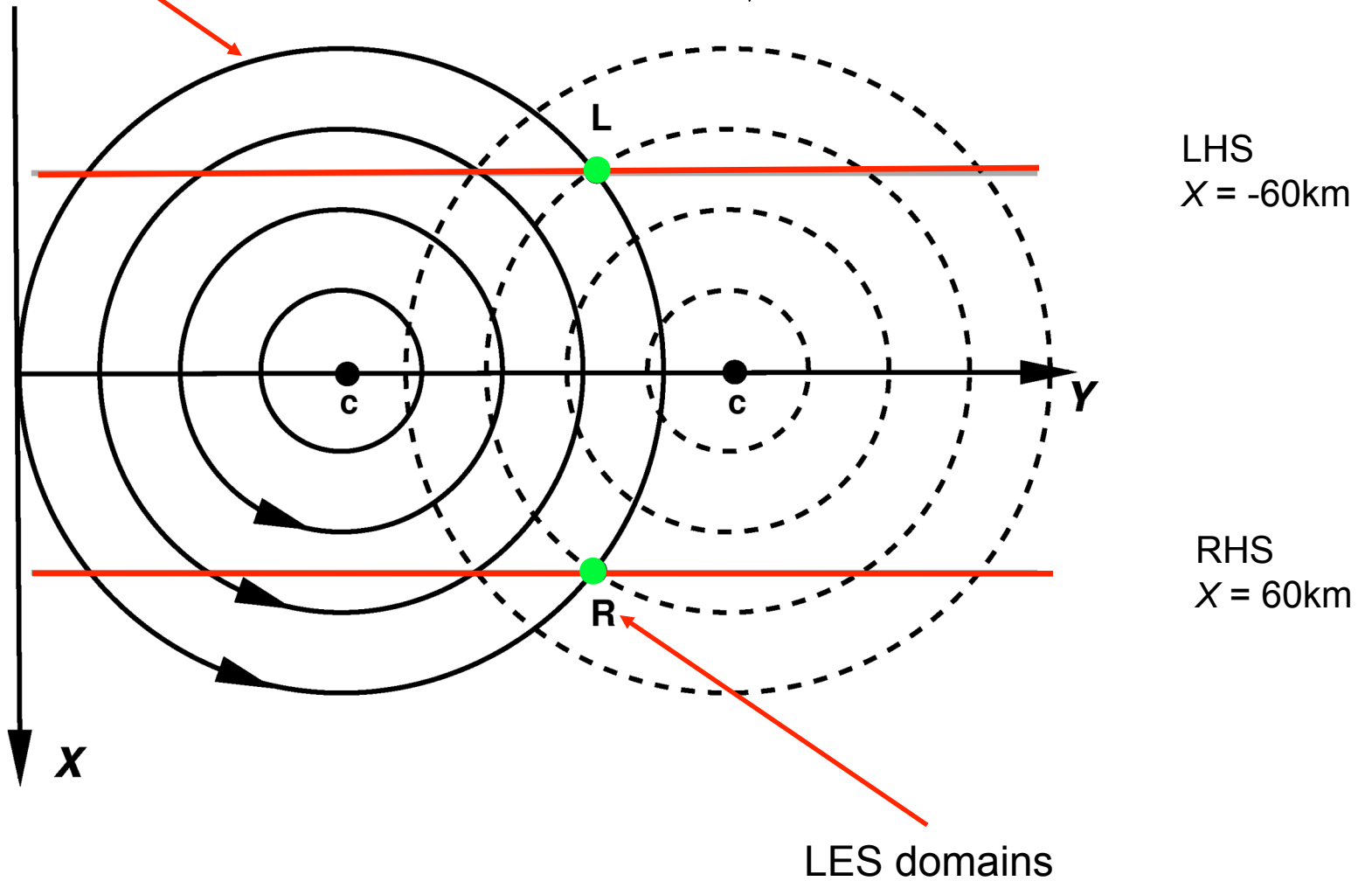
APPROACH:

- Turbulence resolving LES of the OBL with wave effects *360,000 core-hrs*
 - Fine mesh $1024^2 \times 256$ gridpoints
 - $(X_L, Y_L, Z_L) = (1500, 1500, -240)$ m
 - $(\Delta x, \Delta y, \Delta z) = (1.46, 1.46, [0.5 - 1.58])$ m
 - Time integration ~ 70 hours, $\Delta t = (0.4, 3.6)$ s
- Idealized Hurricane Frances winds
- Wavefields from Wavewatch III simulations
 - Integration of 2D wave spectrum \Rightarrow Stokes drift vector $\mathbf{u}_{st}(x, y, z, t)$

COUPLING LARGE SCALE WINDS AND WAVES TO LES

Hurricane
Frances winds

$$V_h = 5.5 \text{ m/s} \longrightarrow$$



2D WAVE HEIGHT SPECTRUM FROM WAVEWATCH III

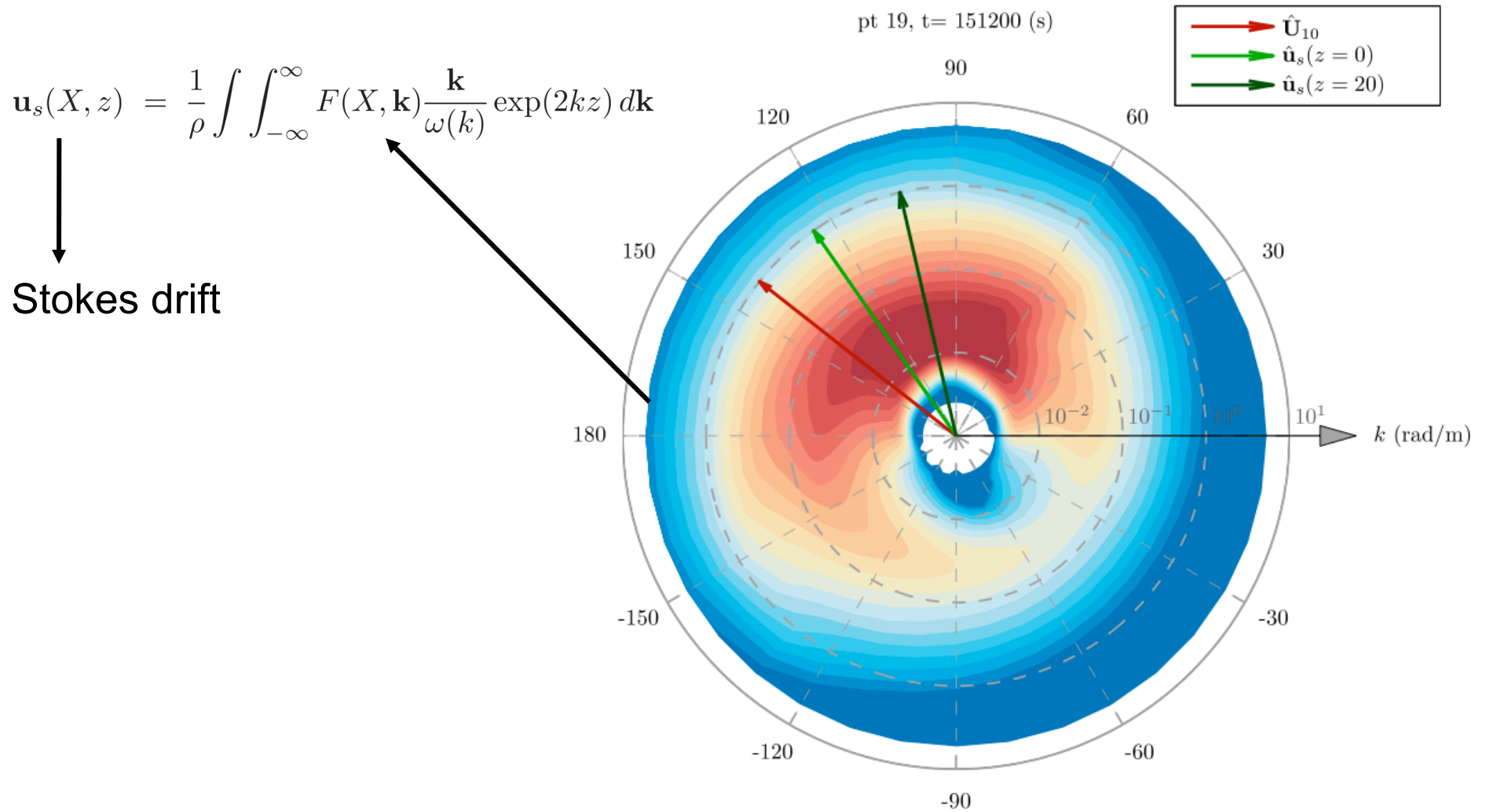
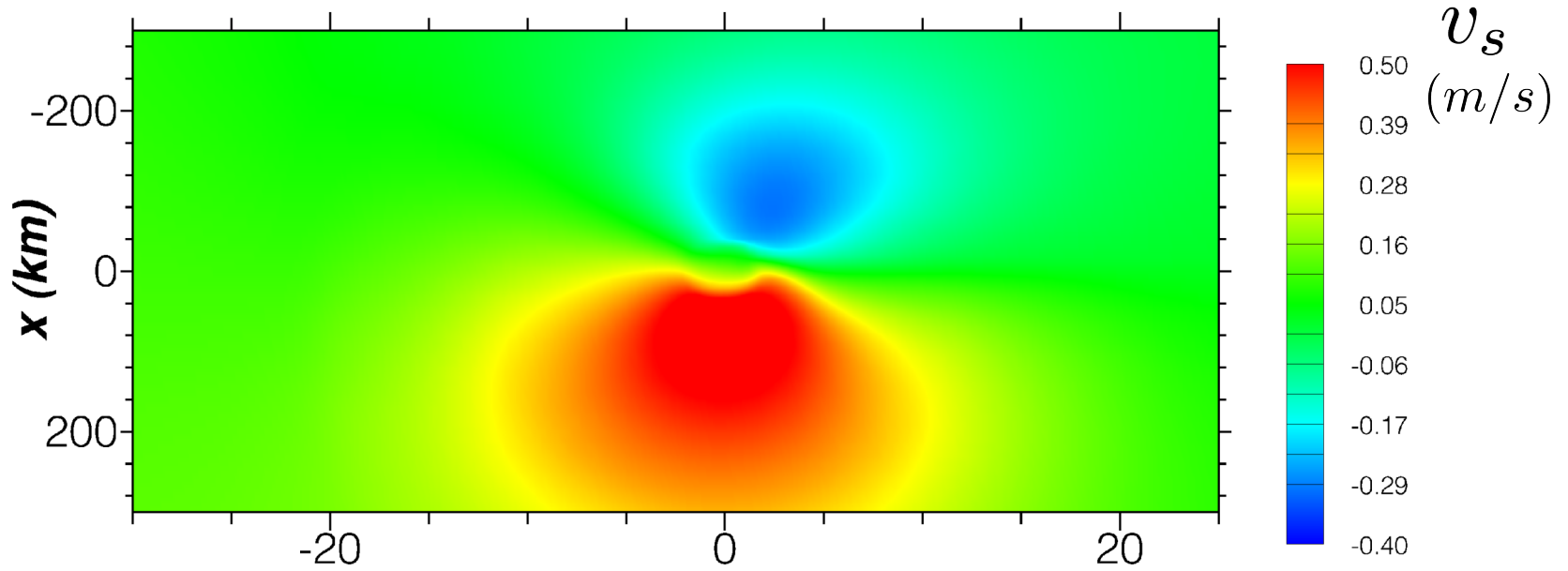
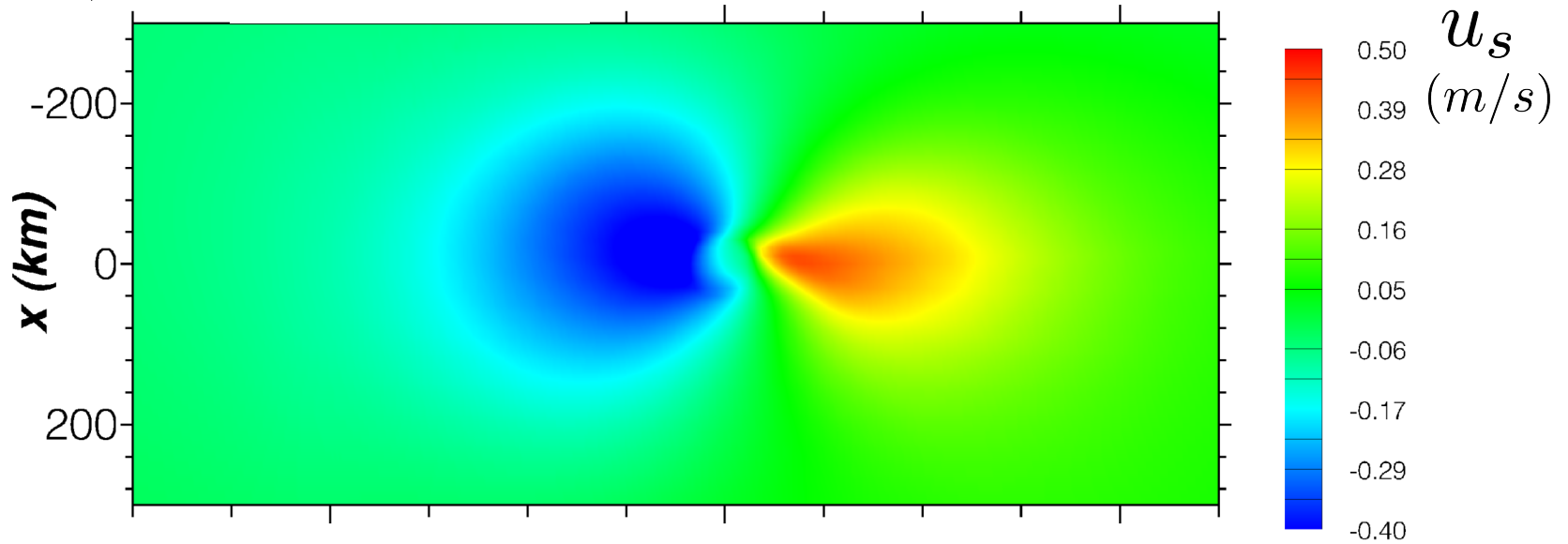
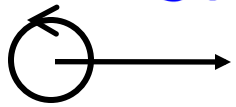


Figure 1: Sample directional wavenumber spectrum at point 19 near the time when the wind are strongest. The unit wind vector is shown in red. The unit stokes drift vectors at $z = 0$ and $z = 20$ m are shown the light and dark green lines, respectively.

STOKES DRIFT VELOCITY AT WATER SURFACE



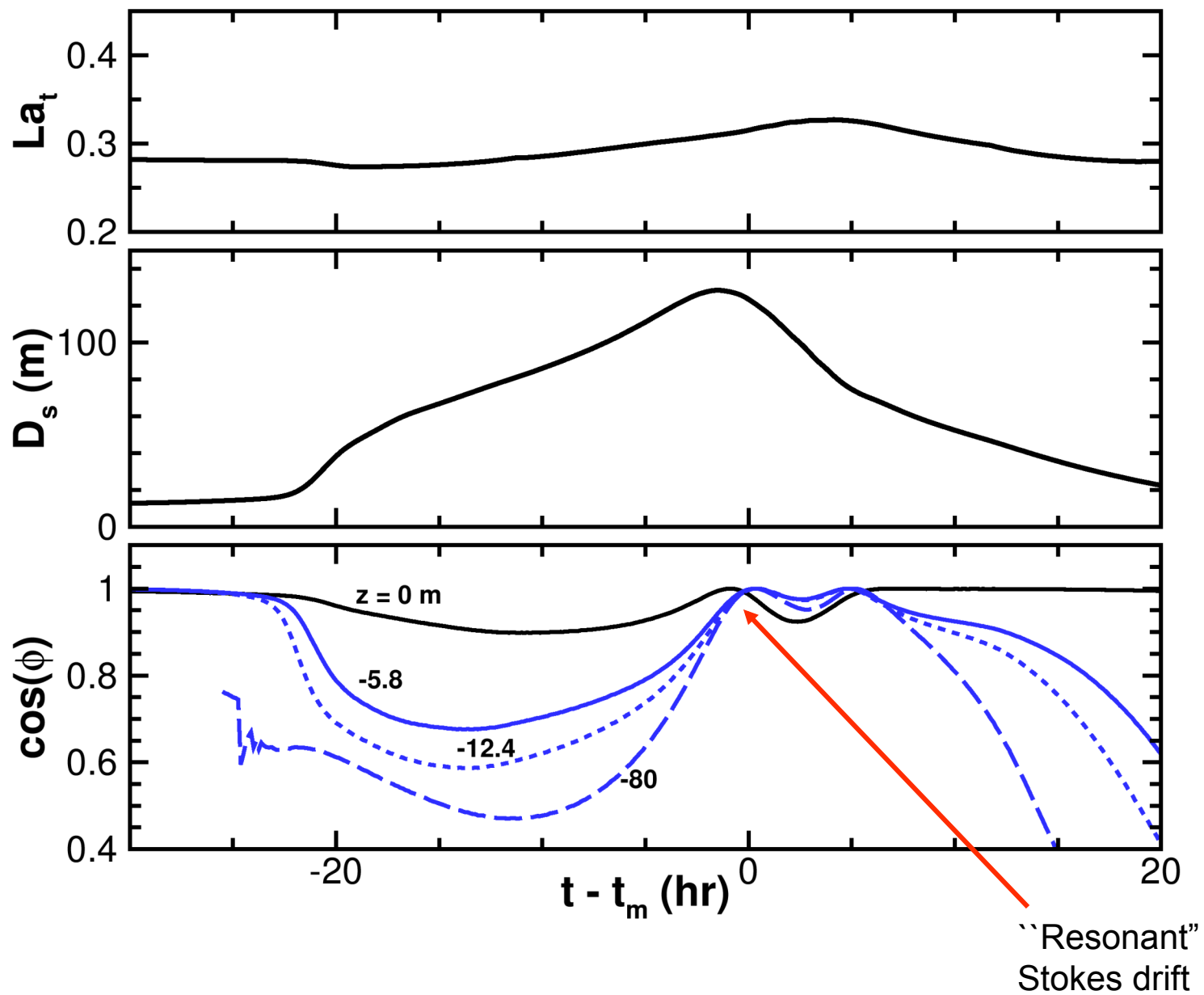
← Pre-storm $t - t_m$ (hr) Post-storm wake →

WIND-WAVE PARAMETERS IMPACTING LANGMUIR TURBULENCE IN A HURRICANE DRIVEN OBL

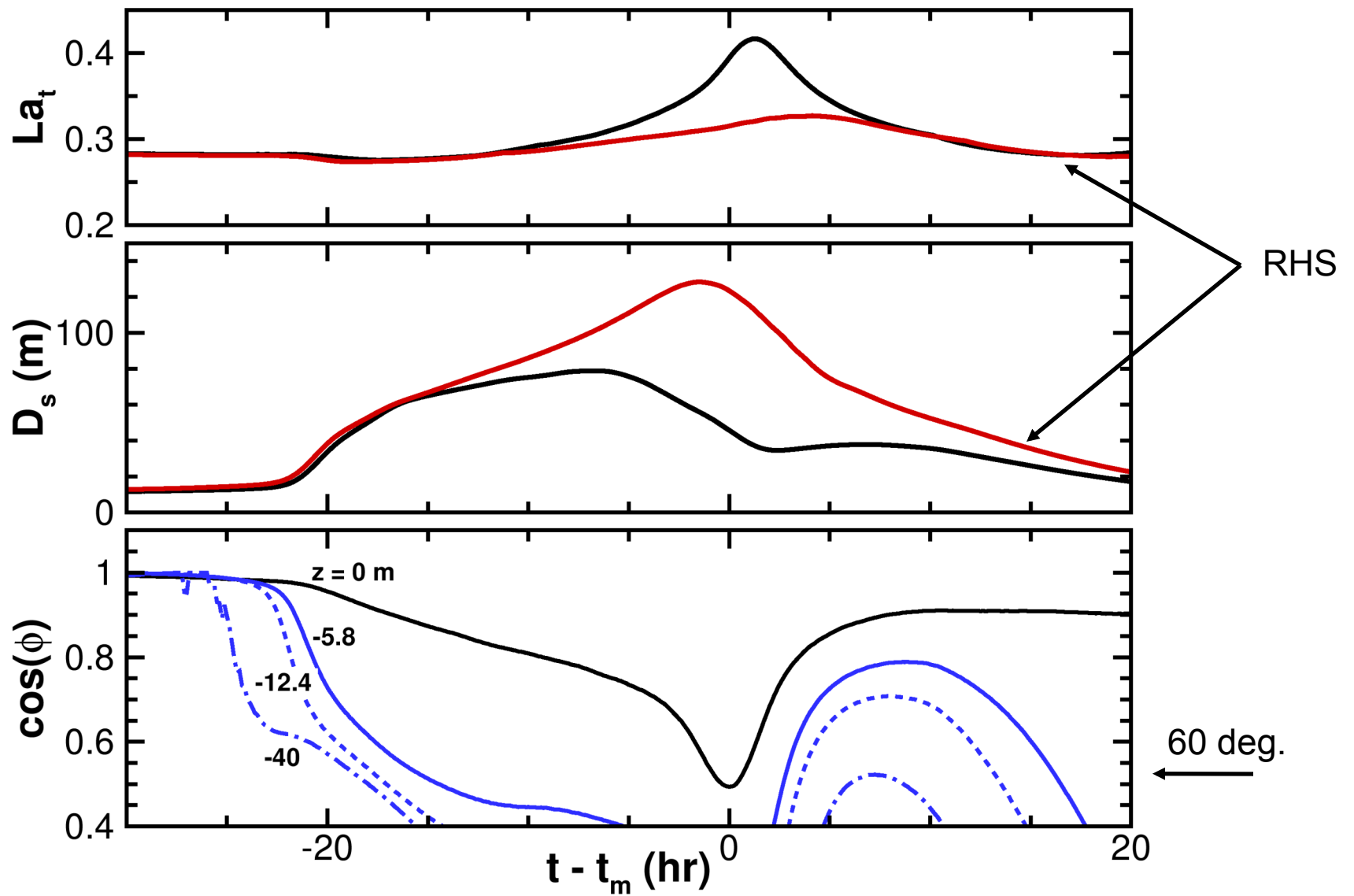
Surface turbulent Langmuir number (McWilliams *et al.*, 1997):

$$La_t = \sqrt{\frac{u_*(X, t)}{|\mathbf{u}_s(X, z = 0, t)|}}$$

La_t , DEPTH SCALE D_s , WIND-STOKES ALIGNMENT, RHS

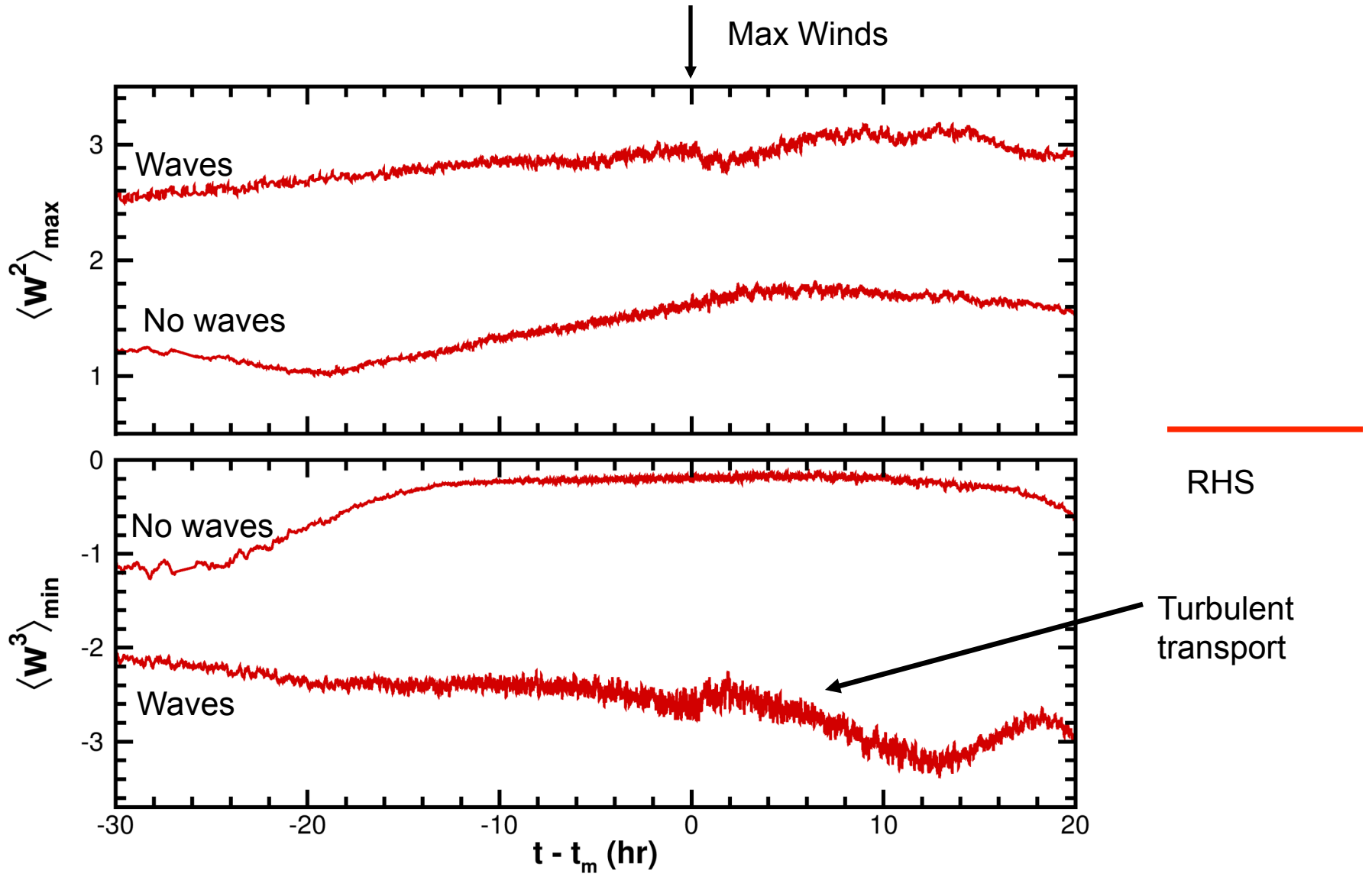
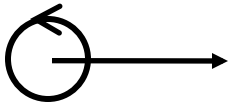


La_t , DEPTH SCALE D_s , WIND-STOKES ALIGNMENT, LHS

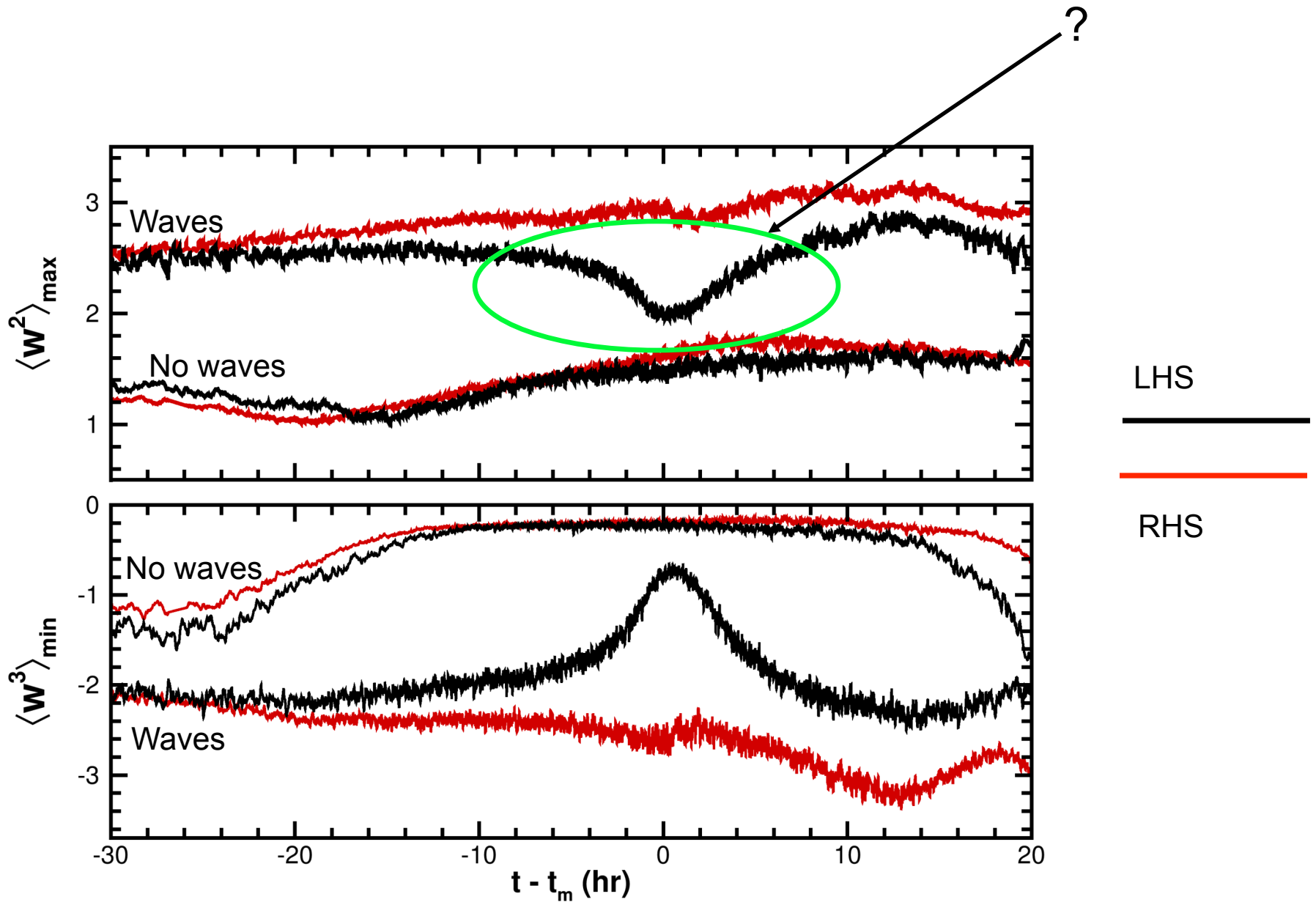


***Identification of Langmuir
turbulence in LES solutions***

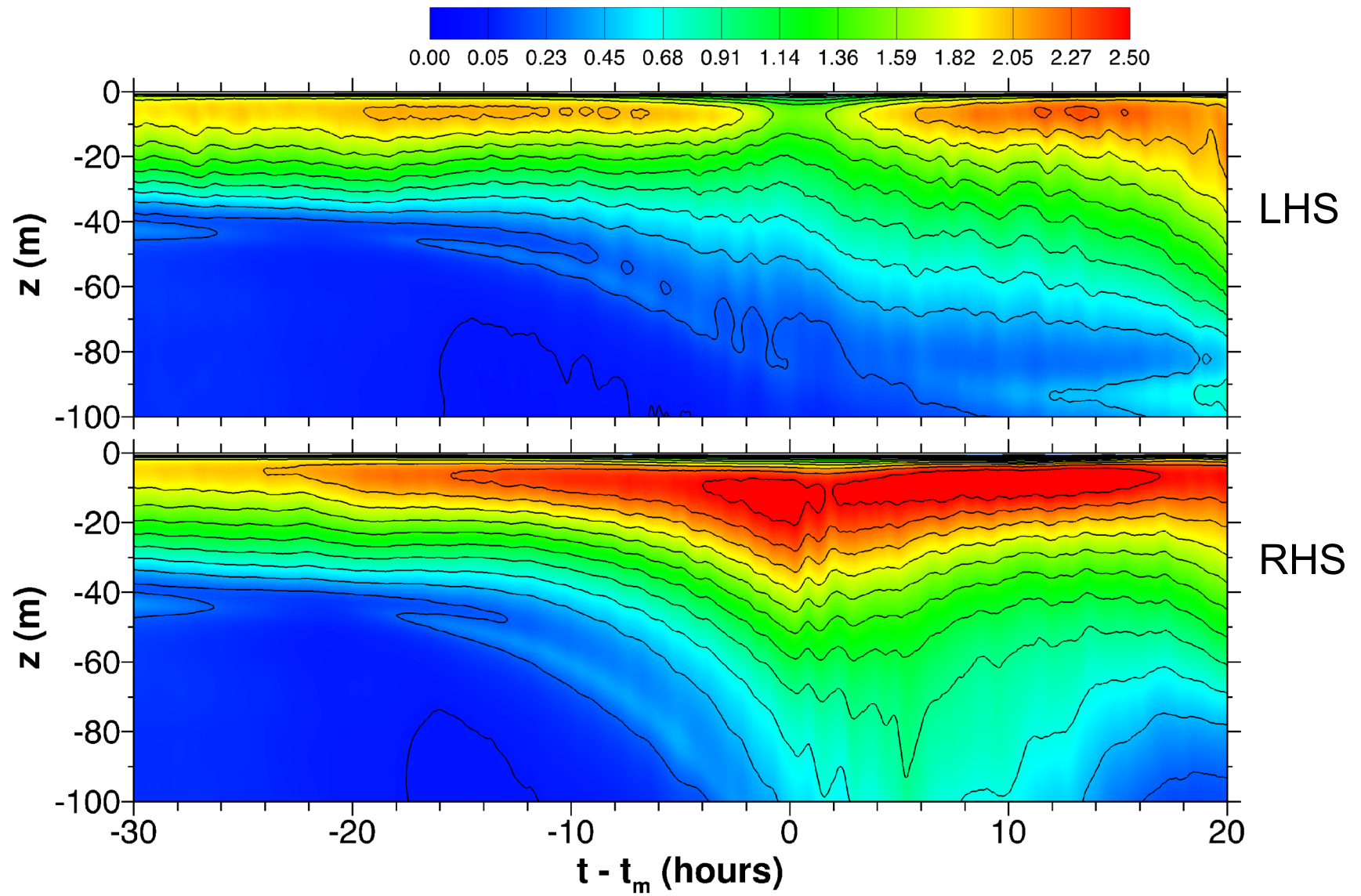
VERTICAL VELOCITY MOMENTS



VERTICAL VELOCITY MOMENTS



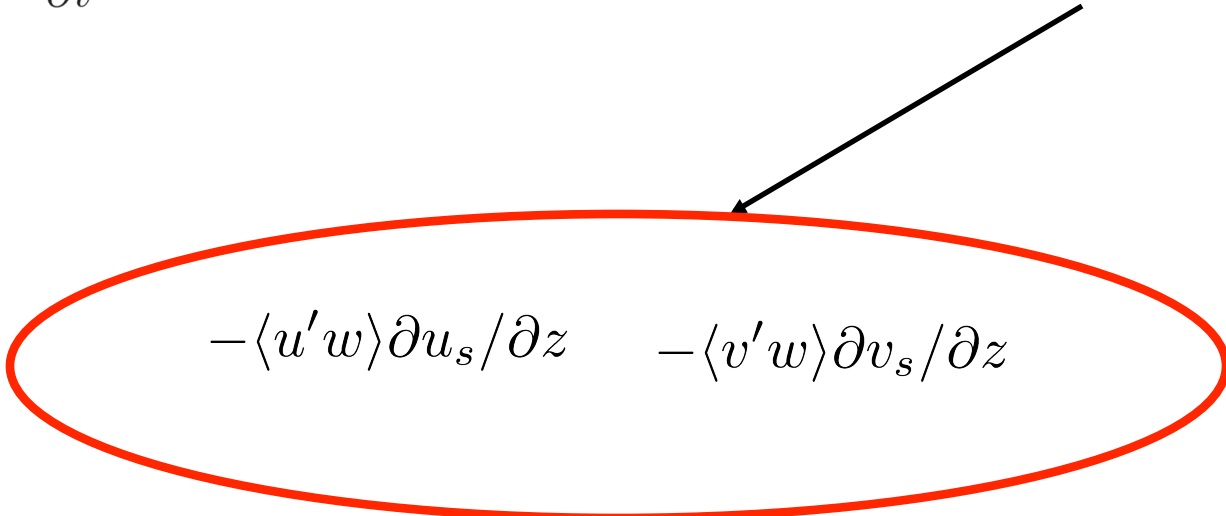
VERTICAL VELOCITY VARIANCE $\langle w^2 \rangle / u_*^2$ WITH WAVES



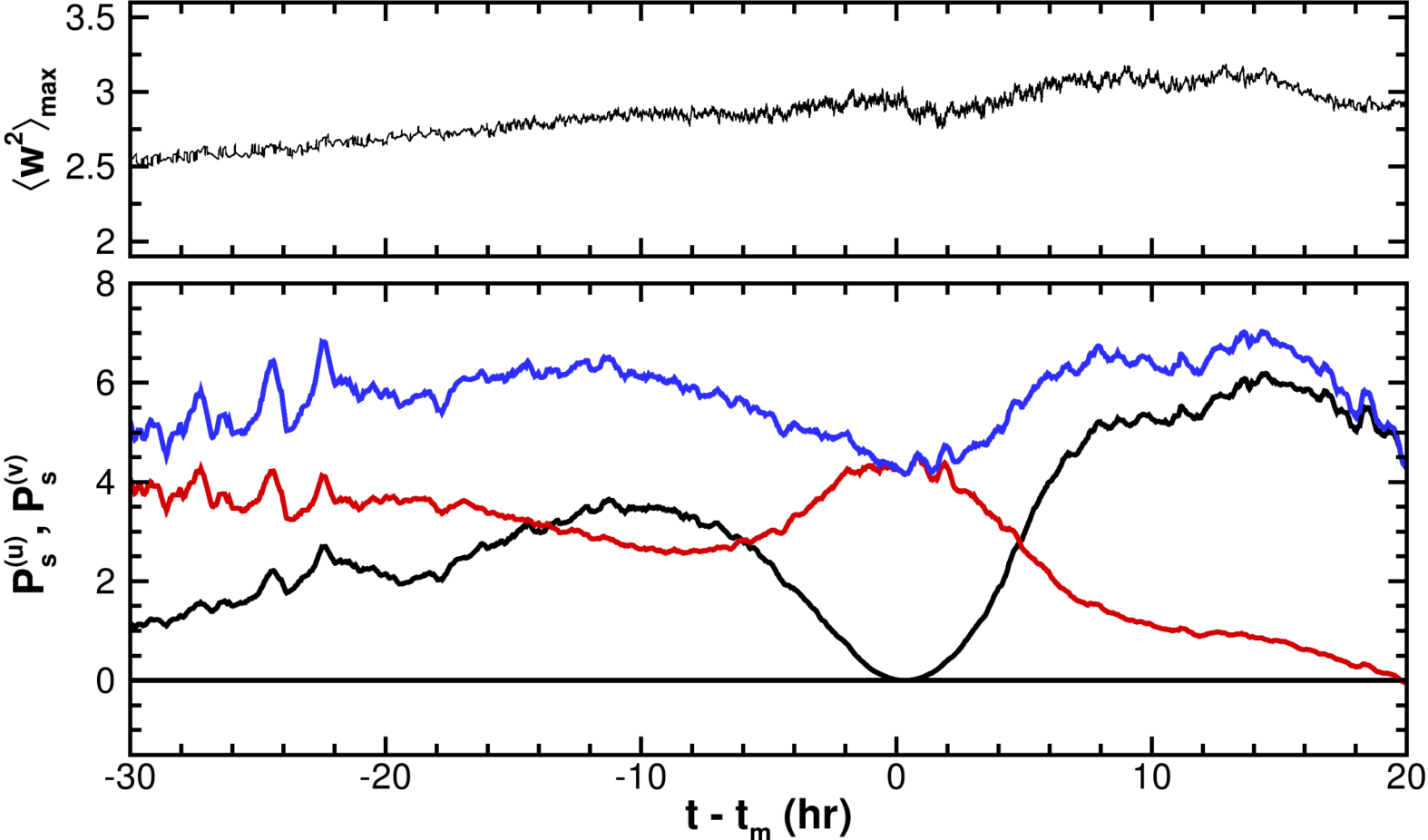
STOKES PRODUCTION IN W-VARIANCE BUDGET

$$\left\langle w \frac{\partial w}{\partial t} = w \left[-u_j \frac{\partial w}{\partial x_j} - \frac{\partial \pi}{\partial z} + \frac{g}{\theta_o} \theta' + (u_s \omega_y - v_s \omega_x) + SGS \right] \right\rangle$$

$$\frac{1}{2} \frac{\partial \langle w^2 \rangle}{\partial t} = \textit{Trans} + \textit{Press strain} + \textit{Buoy} + \textit{Stokes prod} - \textit{Diss}$$

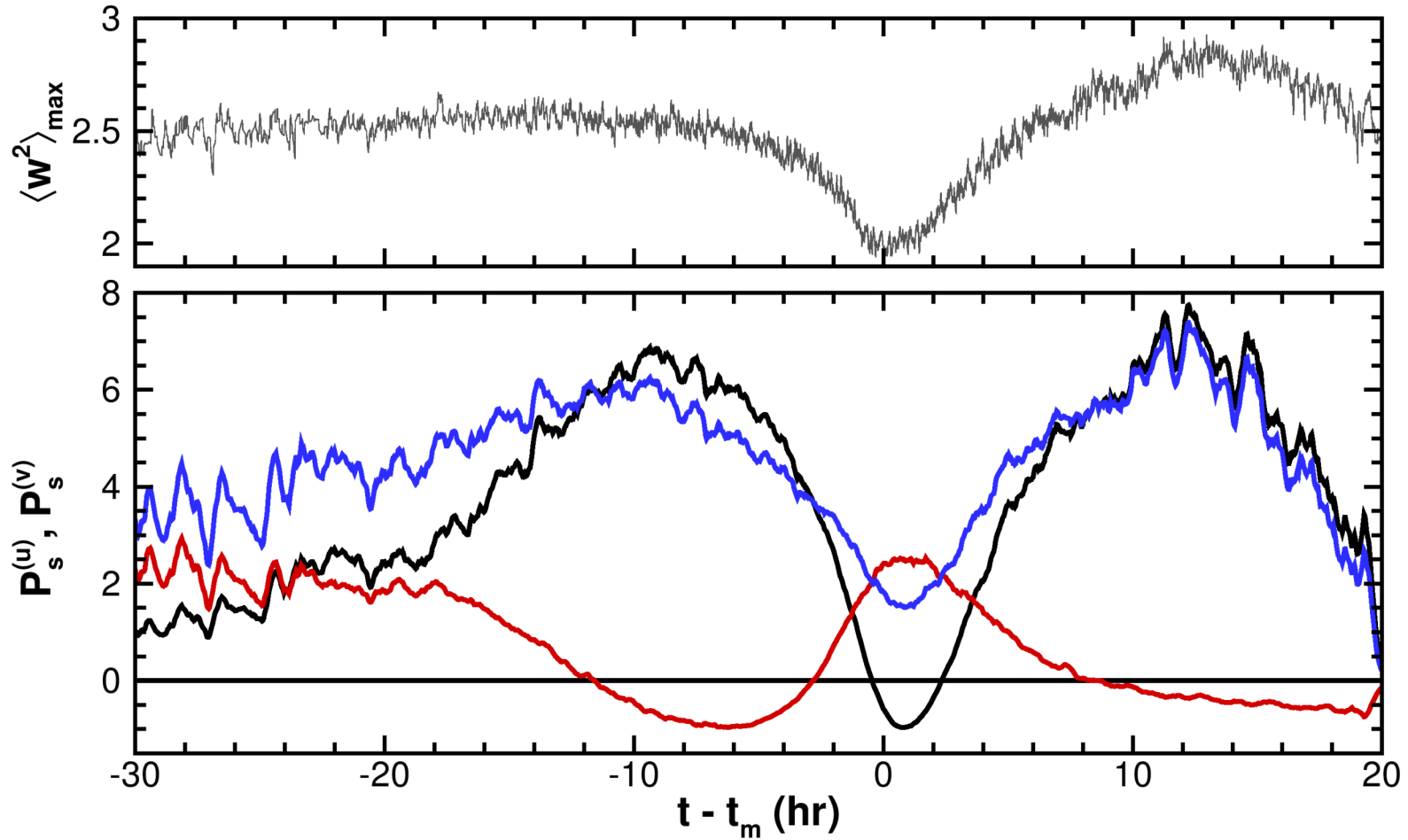

$$-\langle u'w \rangle \partial u_s / \partial z \quad -\langle v'w \rangle \partial v_s / \partial z$$

STOKES PRODUCTION IN W-VARIANCE BUDGET, RHS



$$\underbrace{-\langle u'w \rangle \partial u_s / \partial z}_{\text{black}} \quad \underbrace{-\langle v'w \rangle \partial v_s / \partial z}_{\text{red}} \quad = \quad \underbrace{total}_{\text{blue}}$$

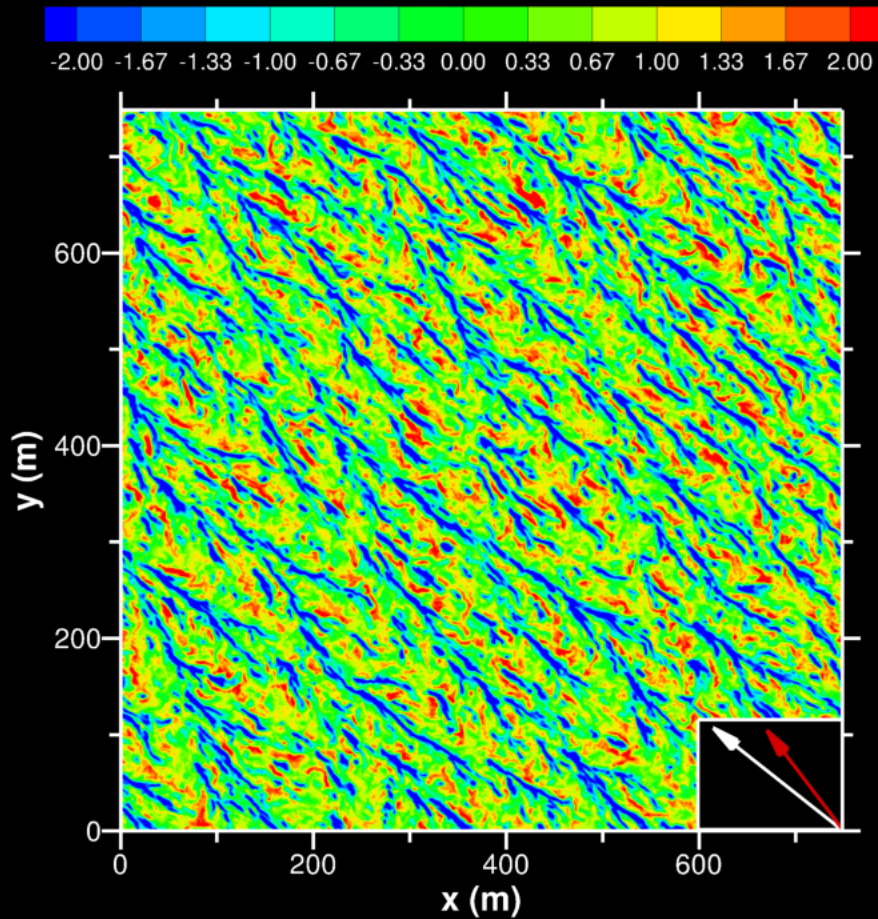
STOKES PRODUCTION IN W-VARIANCE BUDGET, LHS



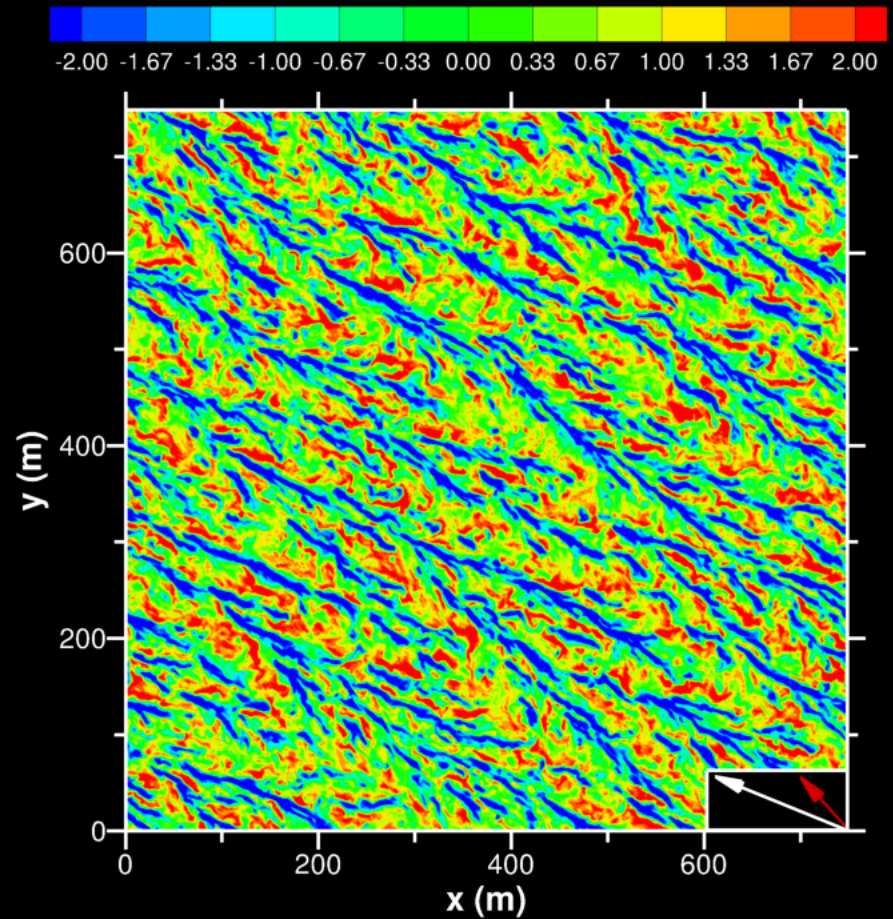
$$\underbrace{-\langle u'w \rangle \partial u_s / \partial z}_{\text{black}} \quad \underbrace{-\langle v'w \rangle \partial v_s / \partial z}_{\text{red}} \quad = \quad \underbrace{total}_{\text{blue}}$$

Coherent structures

ROTATION OF LANGMUIR CELLS WITH TURNING WINDS AND WAVES, VERTICAL VELOCITY w/u_*



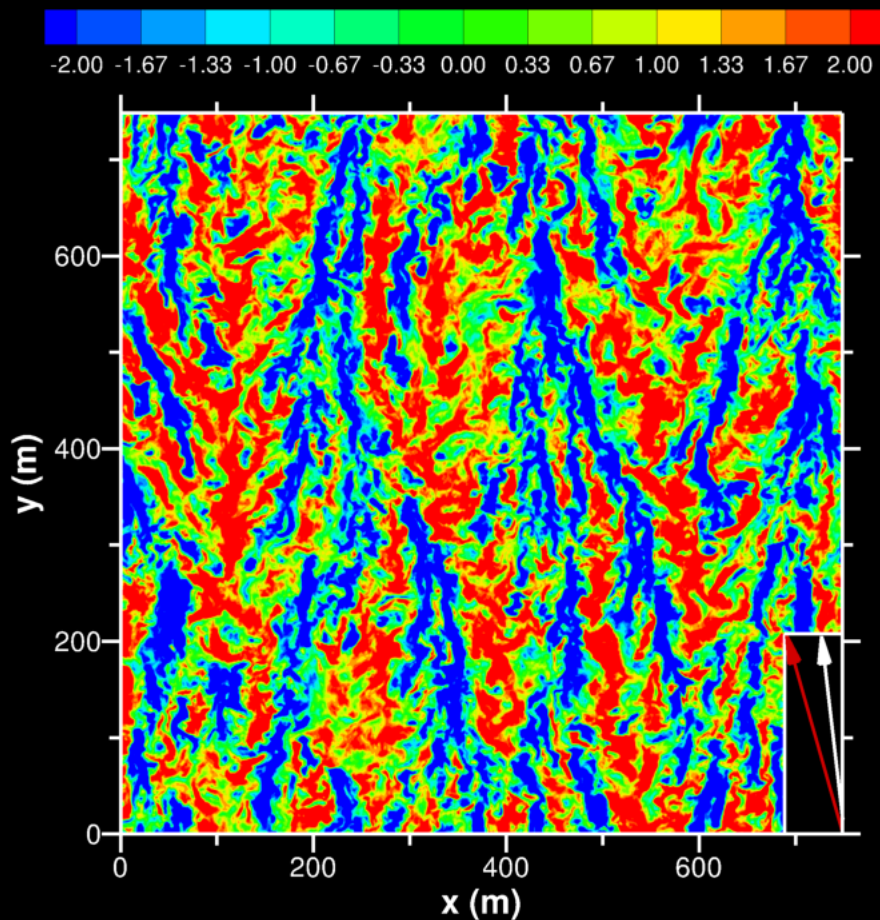
$t - t_m = -20$ hr



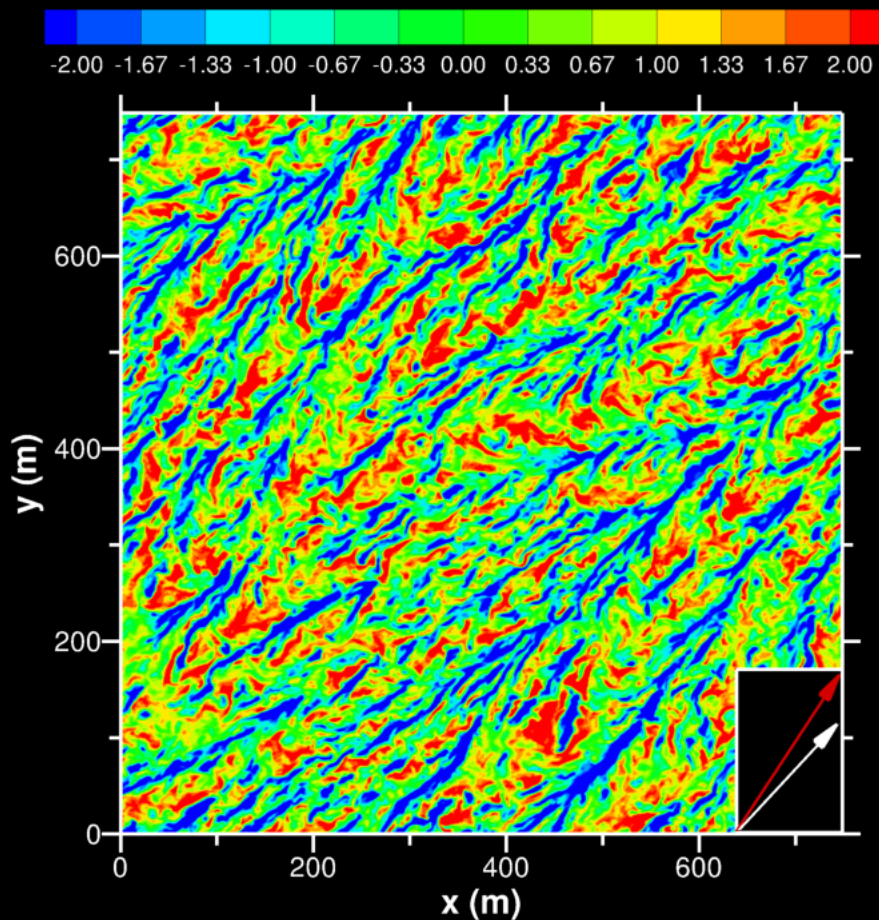
$t - t_m = -10$ hr

\rightarrow U u_{st} \rightarrow

ROTATION OF LANGMUIR CELLS WITH TURNING WINDS AND WAVES, VERTICAL VELOCITY w/u_*



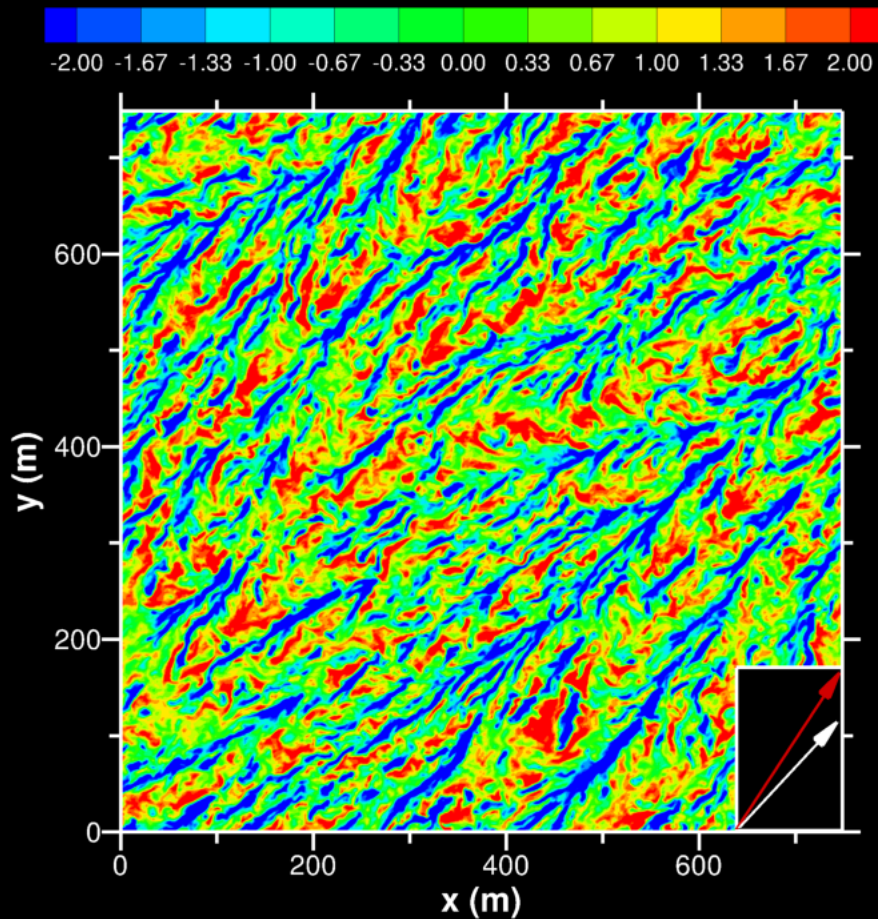
$t - t_m = 0$ hr



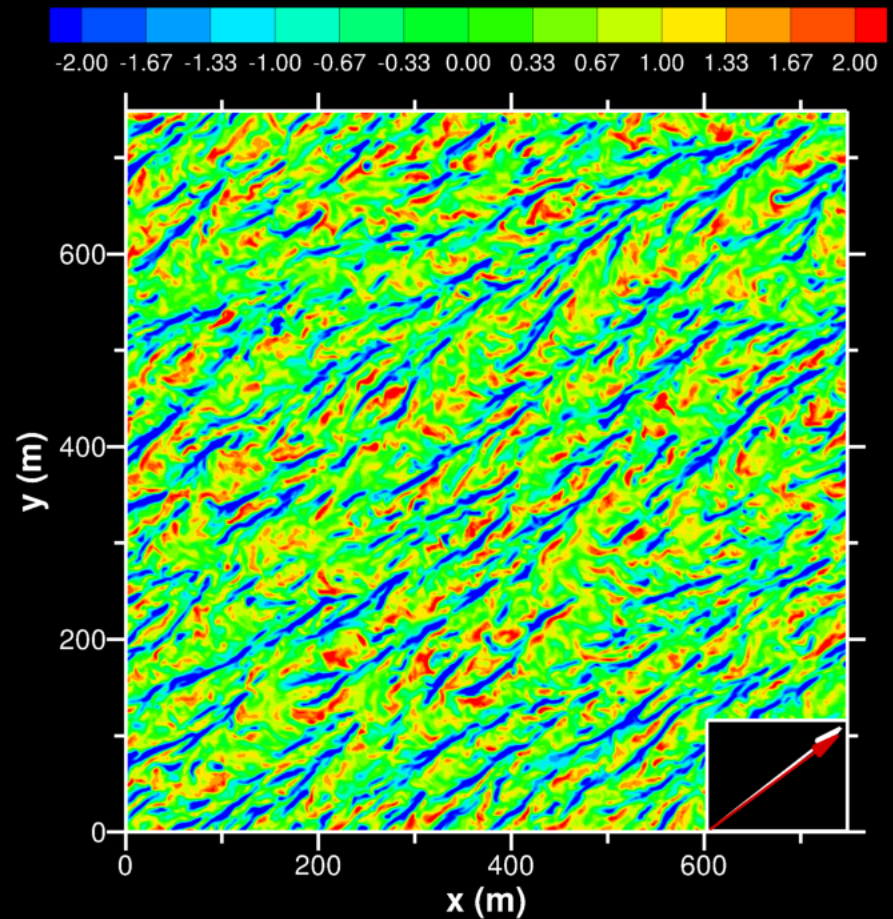
$t - t_m = 5$ hr



ROTATION OF LANGMUIR CELLS WITH TURNING WINDS AND WAVES, VERTICAL VELOCITY w/u_*



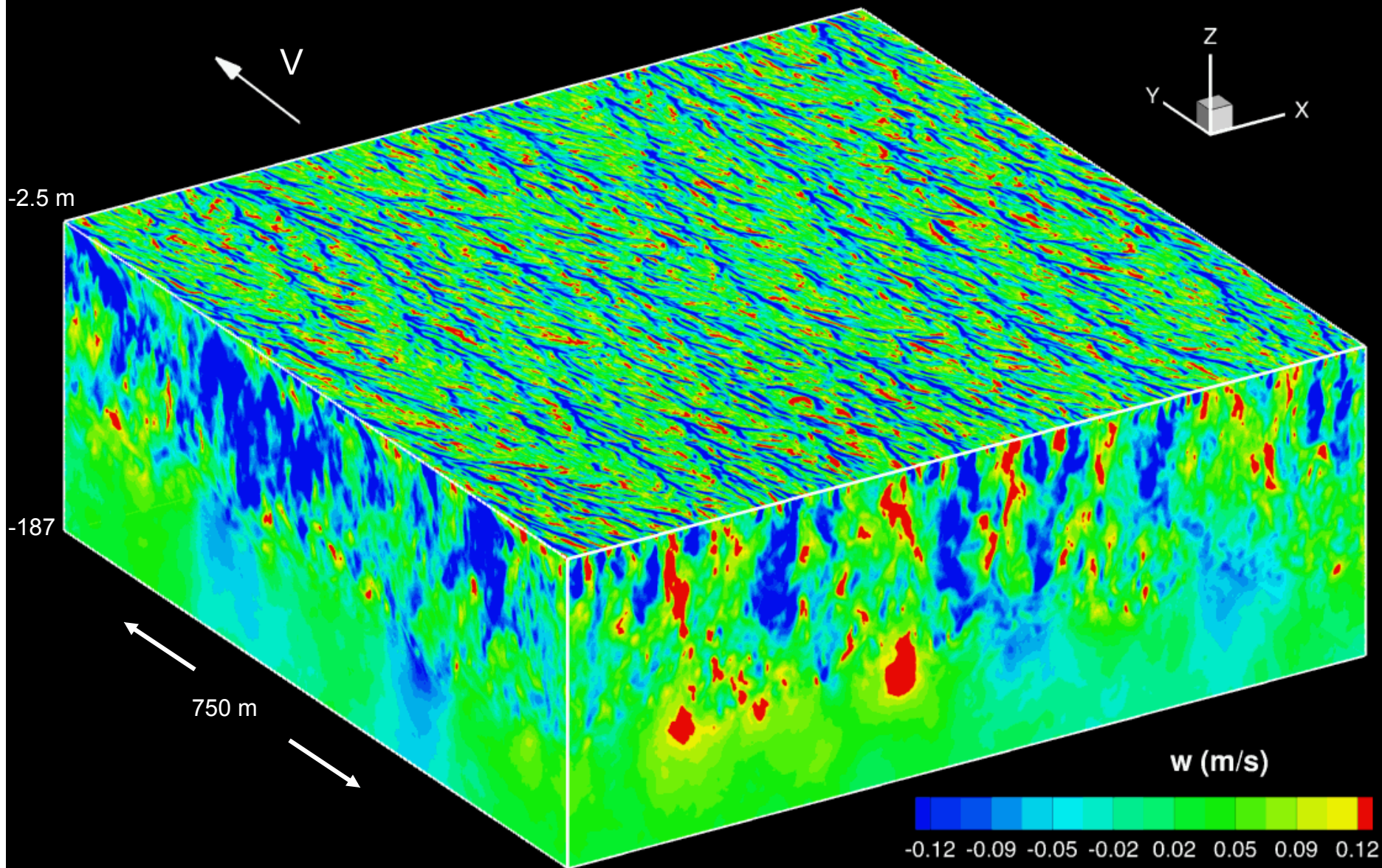
$t - t_m = 5$ hr



$t - t_m = 10$ hr

\rightarrow U u_{st} \rightarrow

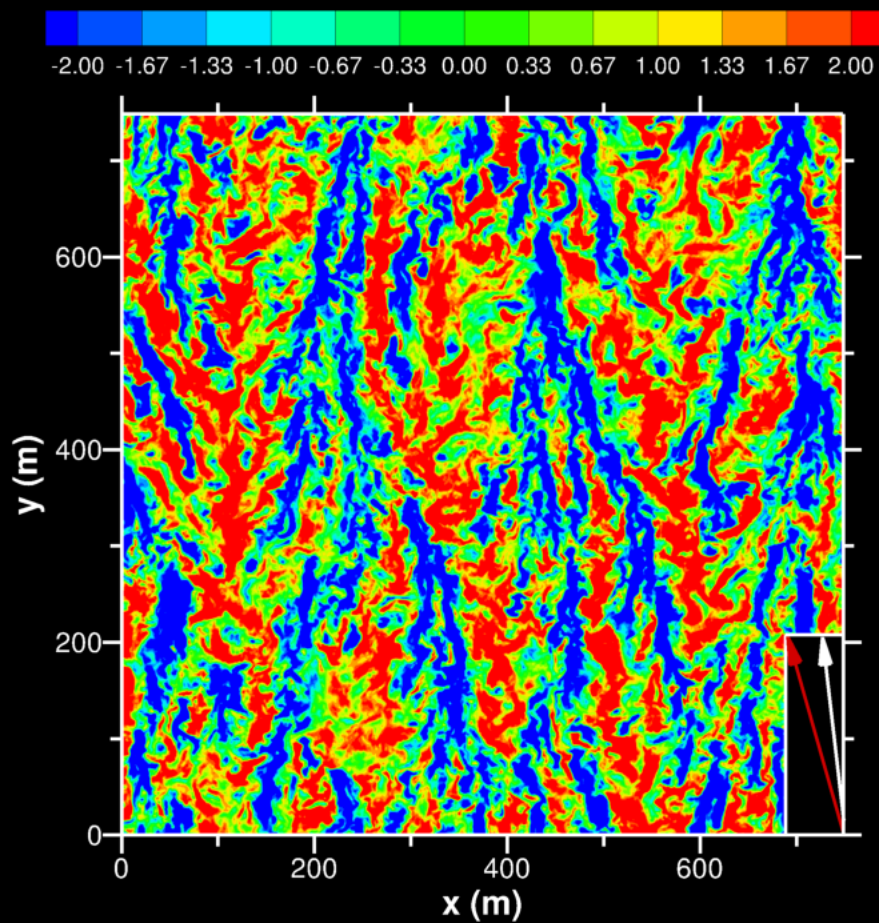
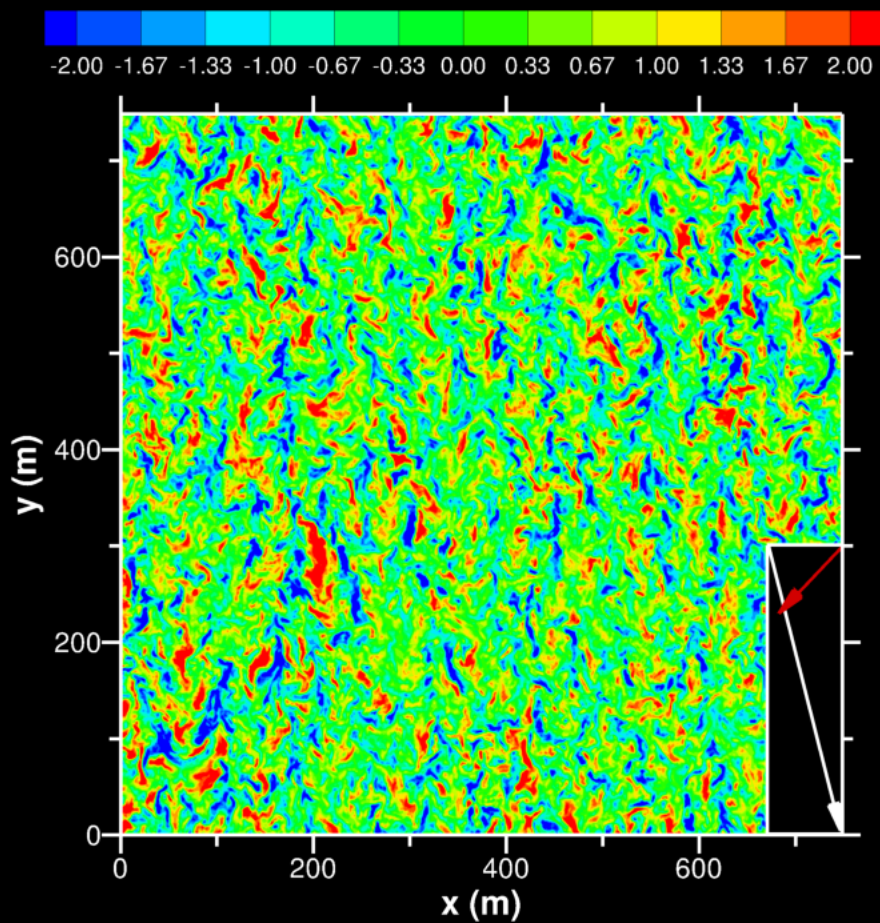
VERTICAL VELOCITY ON RHS



ROTATION OF LANGMUIR CELLS WITH TURNING WINDS AND WAVES, VERTICAL VELOCITY w/u_*

$$La_t = 0.41, D_s = 46 \text{ m}$$

$$La_t = 0.33, D_s = 123 \text{ m}$$



LHS



RHS

CONDITIONALLY AVERAGED FLOW FIELDS

OBJECTIVE:

- Determine the “average” coherent structure, a turbulent Langmuir cell

TECHNIQUE:

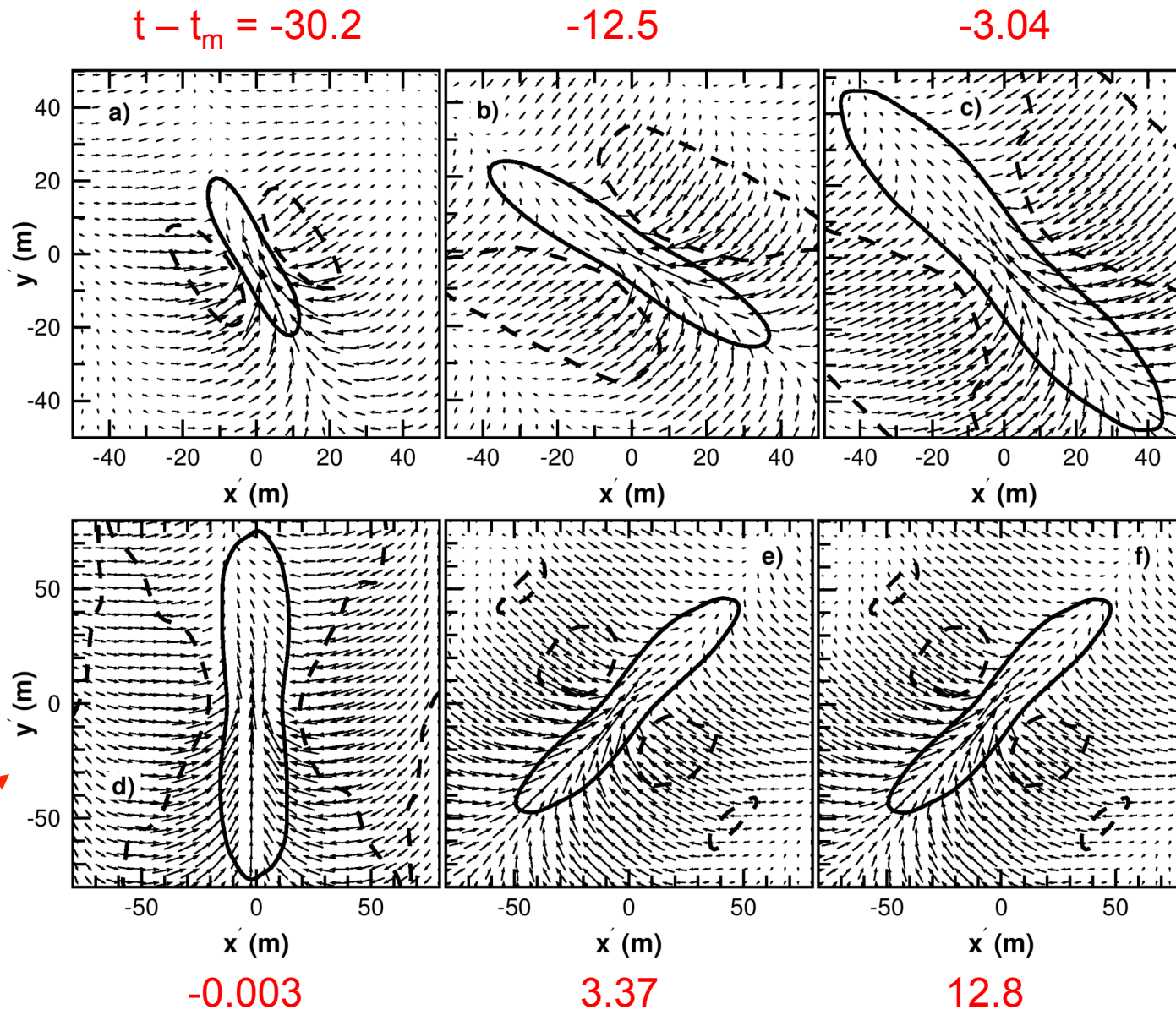
- Linear stochastic estimation (LSE) developed by Adrian *et al.*(1989)
- The average horizontal velocity field $\mathbf{u}'_{\perp} = (u', v', 0)$ is the conditional average

$$\langle \mathbf{u}'_{\perp}(\mathbf{x}') | w(\mathbf{x}) \rangle \approx \frac{\langle \bar{w}(\mathbf{x}) \mathbf{u}'_{\perp}(\mathbf{x}') \rangle}{\langle \bar{w}(\mathbf{x}) \bar{w}(\mathbf{x}) \rangle} \bar{w}(\mathbf{x})$$

- LSE utilizes two-point correlations

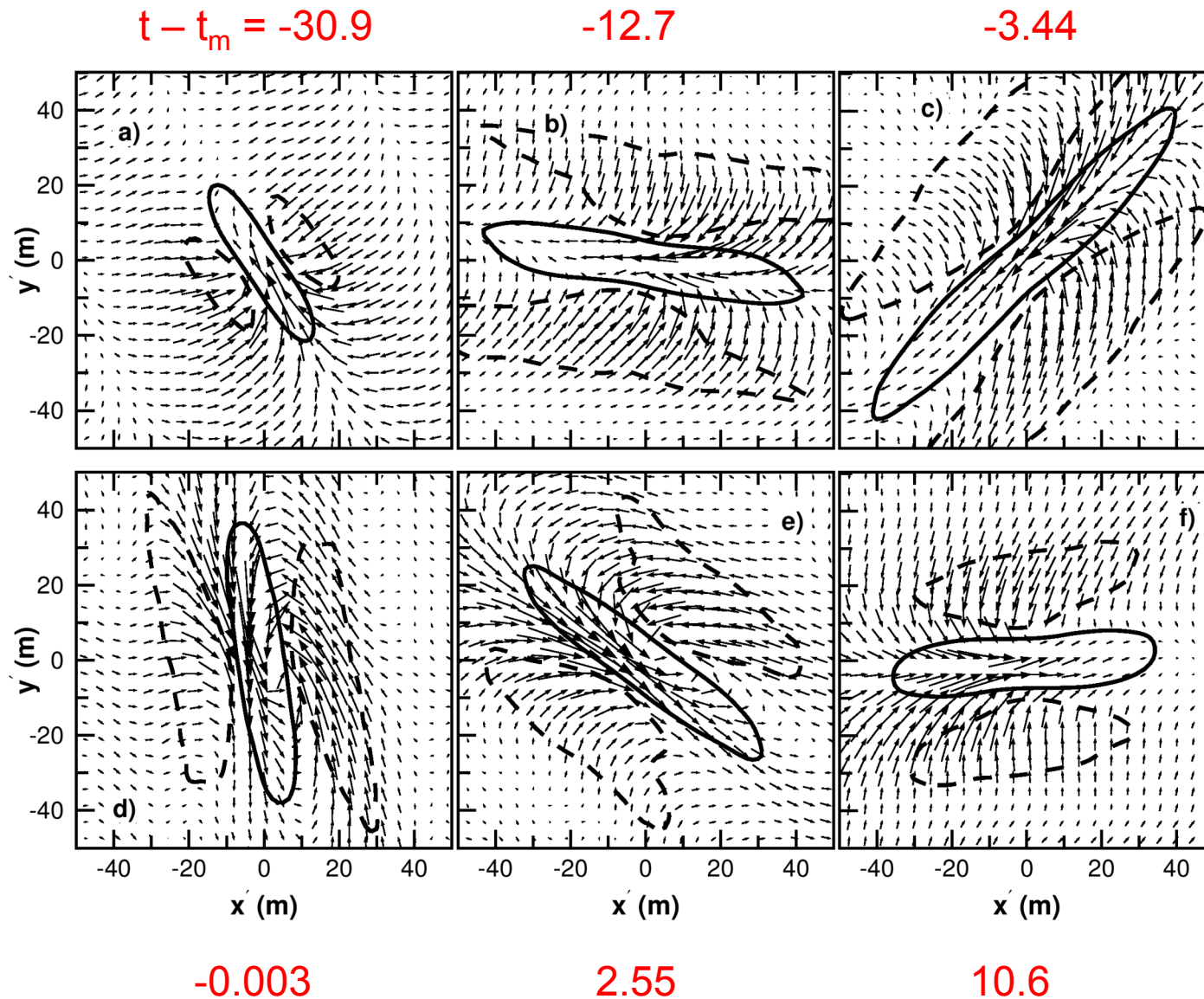
$$R_{wu}(x', y', z) = \frac{\langle \bar{w}(x, y, z_{max}) u'(x', y', z) \rangle}{\sigma_w(z_{max}) \sigma_u(z)}$$

CONDITIONALLY AVERAGED LANGMUIR CELL, RHS



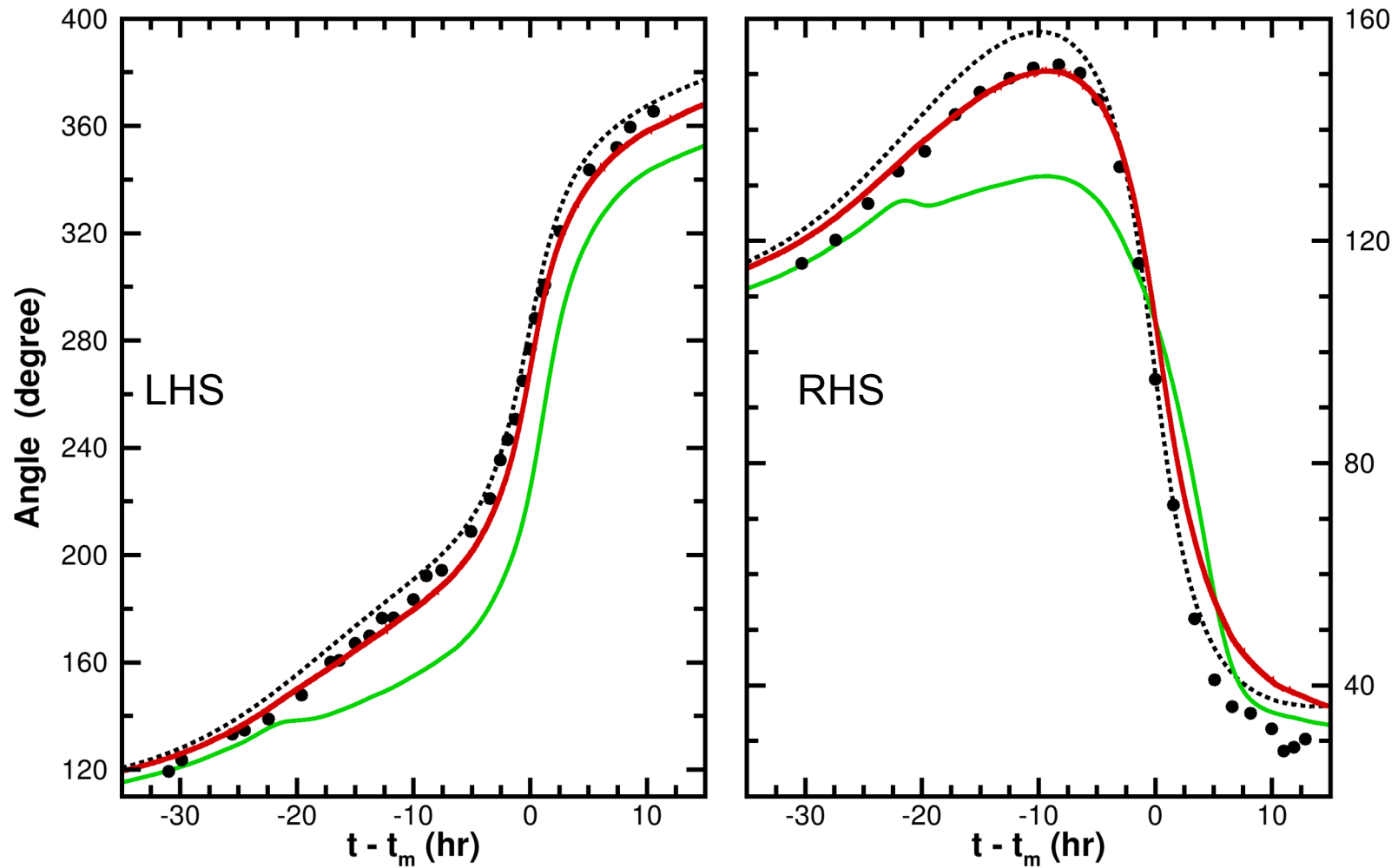
Note scale change!

CONDITIONALLY AVERAGED LANGMUIR CELL, LHS



Van Roekel, *etal*, 2012 (mis-aligned winds and waves)

LANGMUIR CELL ALIGNMENT



Wind dir

Stokes dir

$L_s = \partial(\mathbf{u} + \mathbf{u}_s)/\partial z$

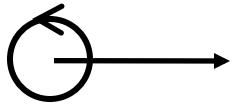
• *LES*



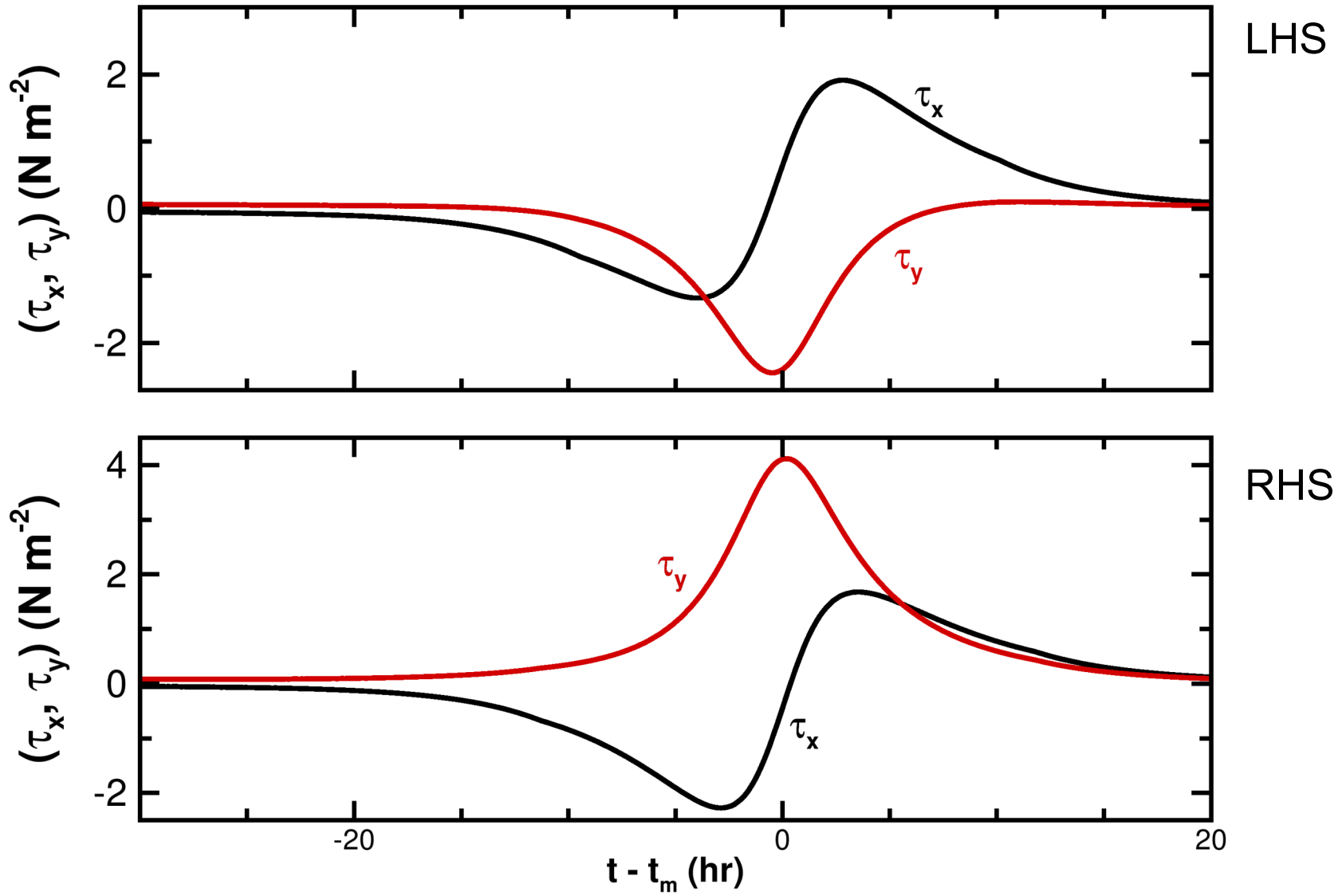
Does Langmuir Turbulence (LT) matter for turbulent transport in the hurricane OBL?

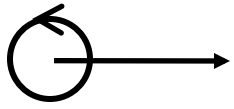
No --- “LT is simply mixing an already well mixed layer ...”

Yes --- “LT is how the mixed layer got mixed in the first place ...”

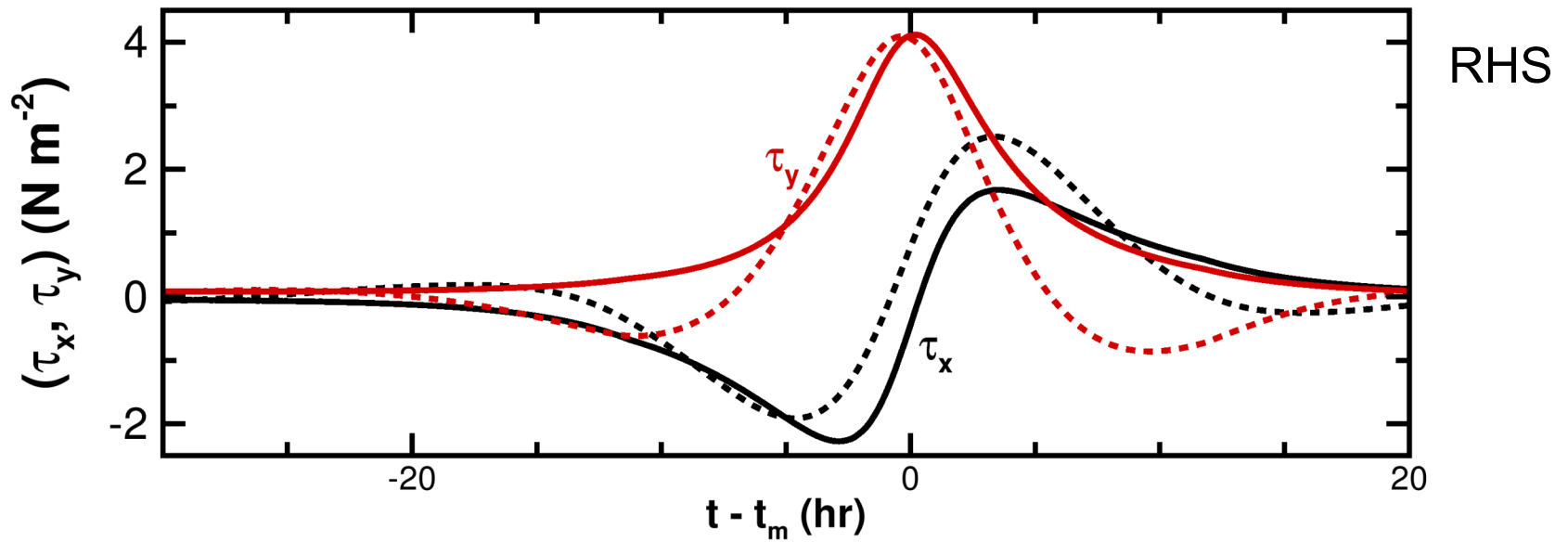
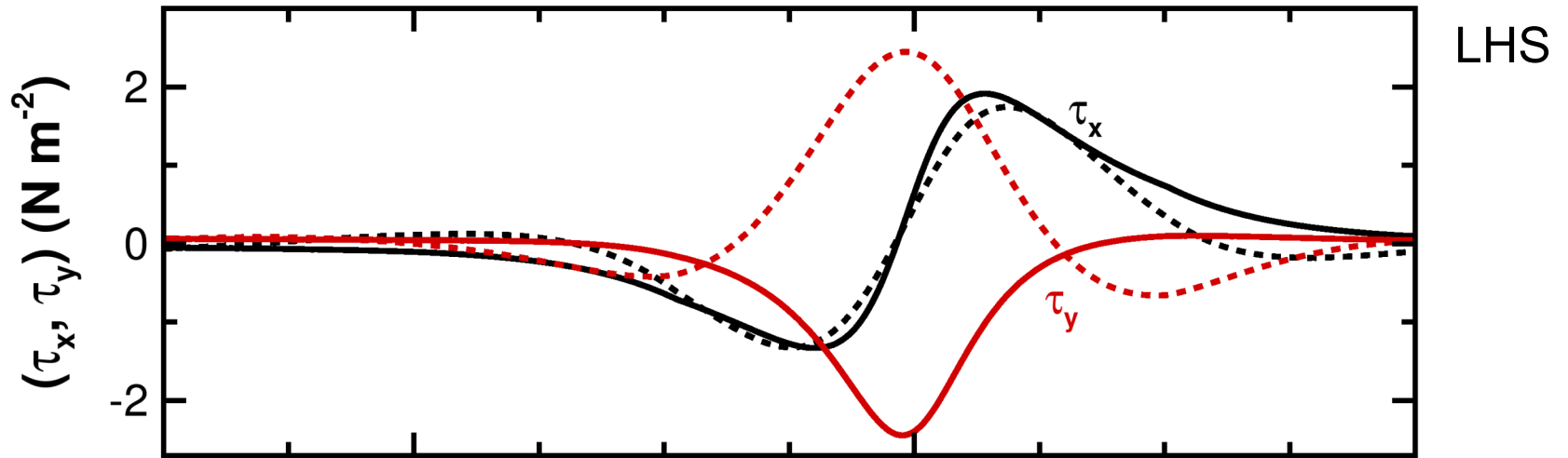


WIND STRESS COMPONENTS (τ_x, τ_y)





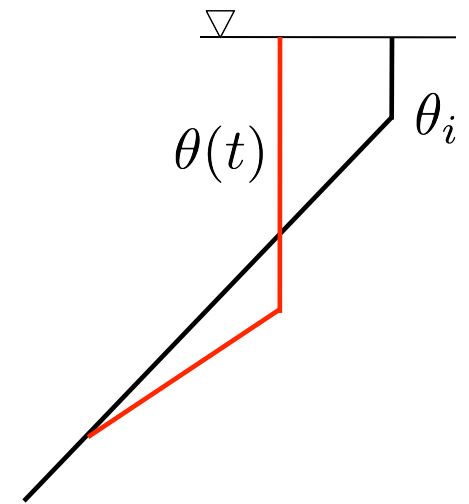
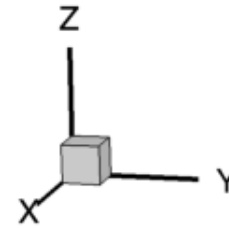
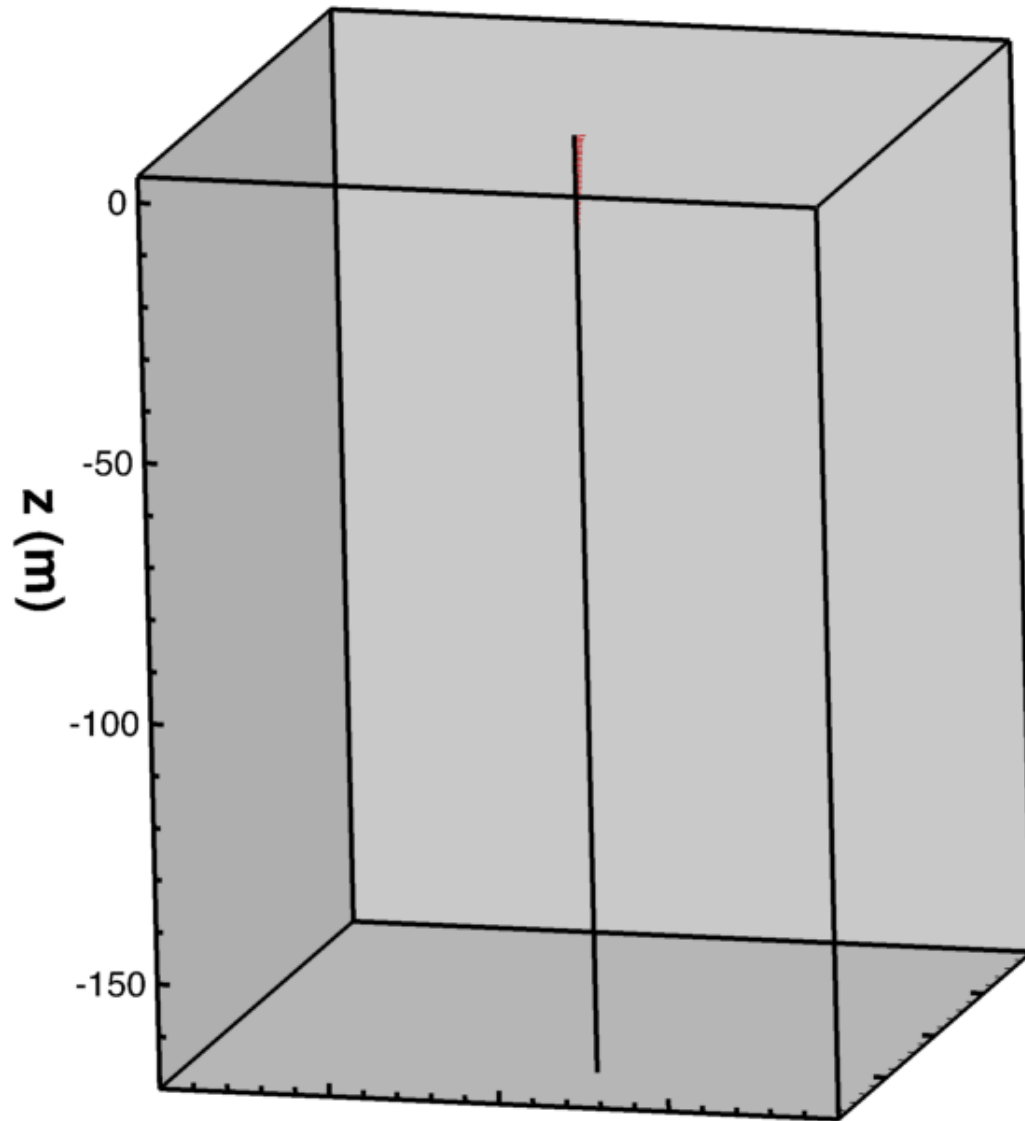
WIND STRESS COMPONENTS (τ_x, τ_y)



inertial stress $\tau_{in} = |\tau|e^{-ift}$ dotted lines

HORIZONTAL CURRENTS WITH VORTEX FORCE ON RHS

Time = -44.5 hr

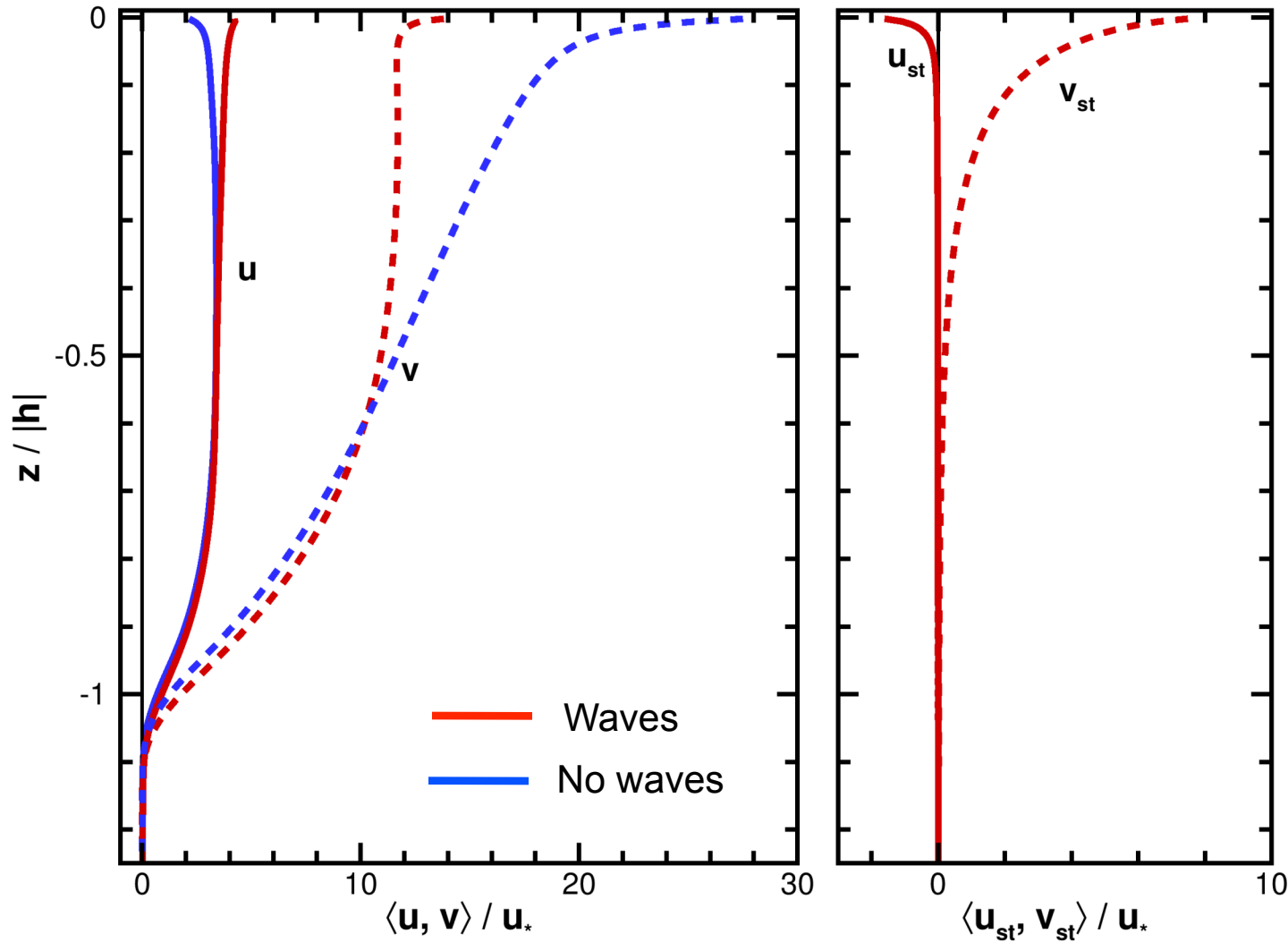


CURRENTS AND STOKES DRIFT AT TIME OF MAXIMUM WINDS

RHS

$$La_t = 0.33$$

$$D_s = 123m$$



Stokes-Coriolis term

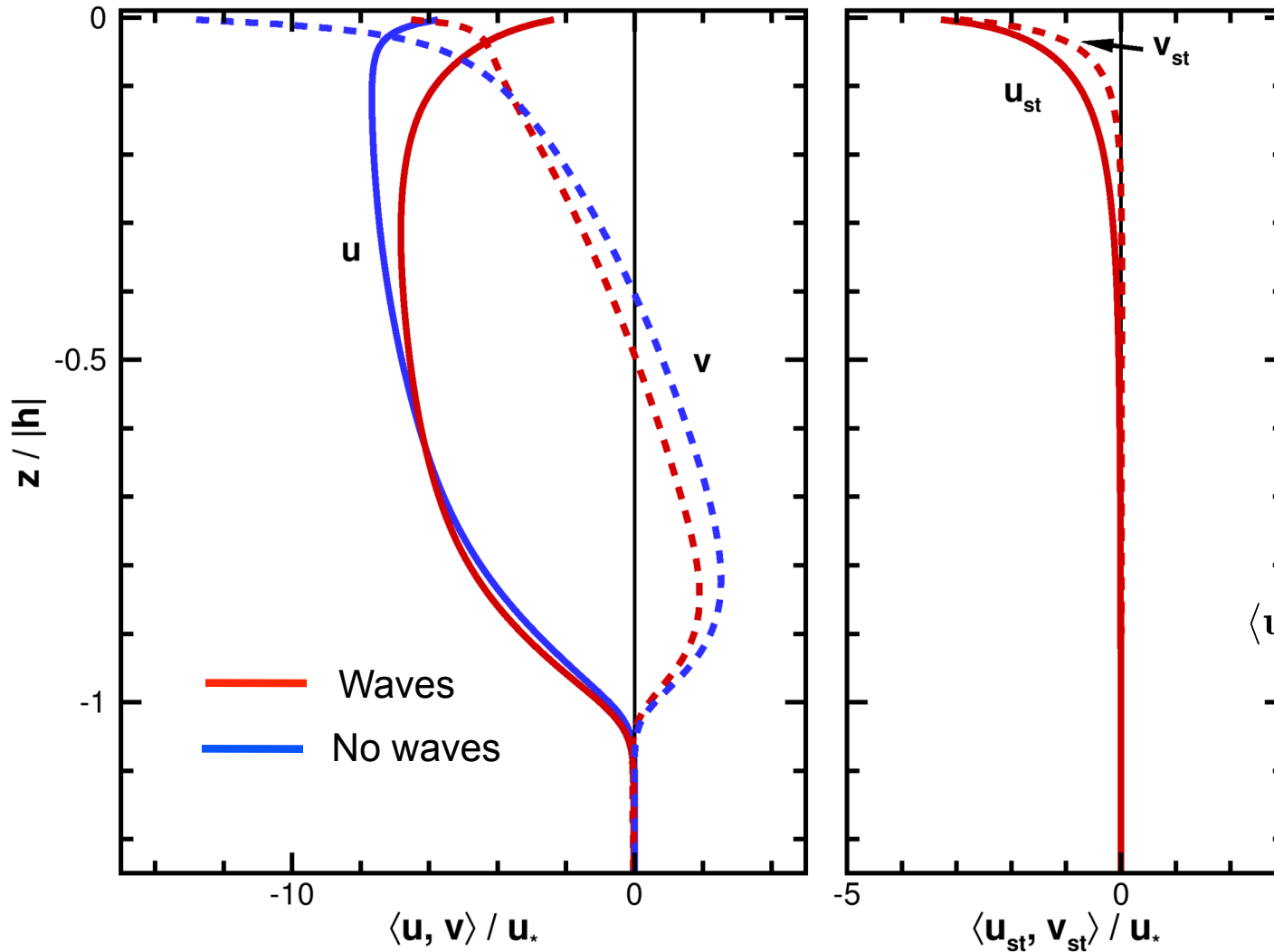
$$\mathbf{u}_s \times f \hat{\mathbf{z}}$$

CURRENTS AND STOKES DRIFT AT TIME OF MAXIMUM WINDS

LHS

$$La_t = 0.41$$

$$D_s = 46m$$



$$\frac{\partial u_s}{\partial z} < 0$$

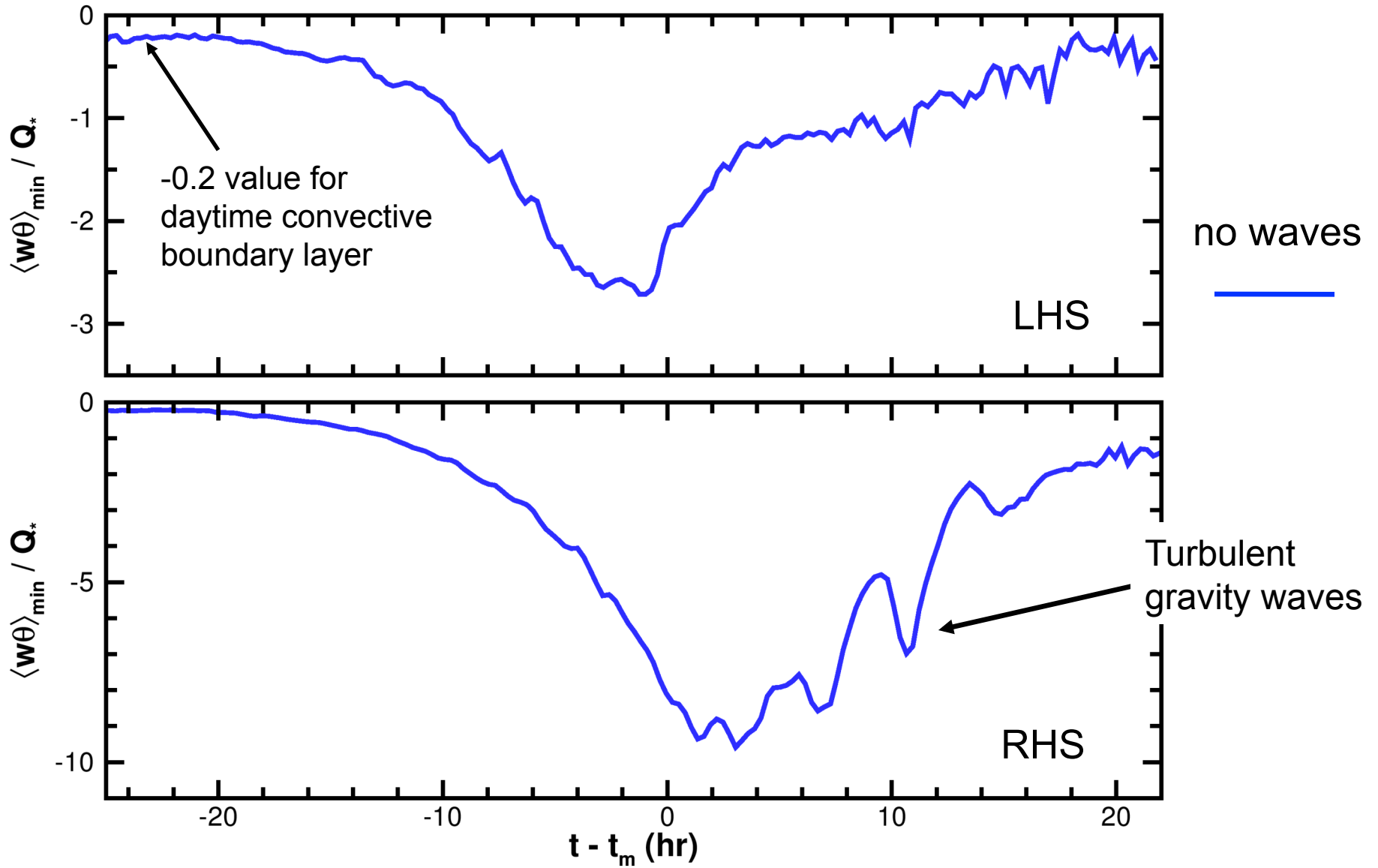
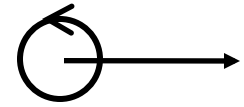
$$\frac{\partial u}{\partial z} > 0$$

!

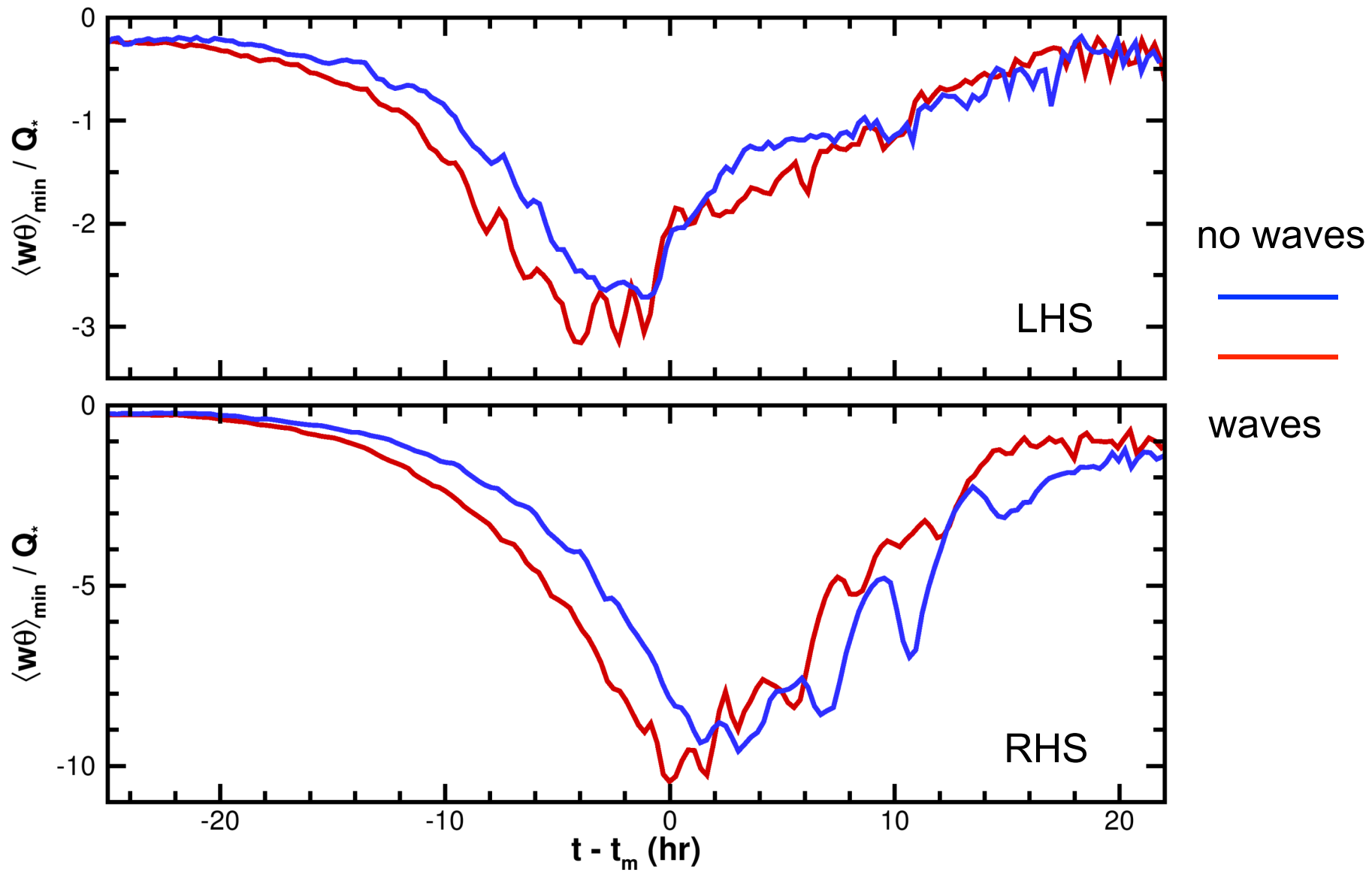
$$\langle \mathbf{u}'w \rangle \cdot \left(\frac{\partial \langle \mathbf{u} \rangle}{\partial z} + \frac{\partial \mathbf{u}_s}{\partial z} \right)$$

***Impacts of Langmuir Turbulence
on entrainment, mixed layer
temperature and SST***

NORMALIZED ENTRAINMENT FLUX

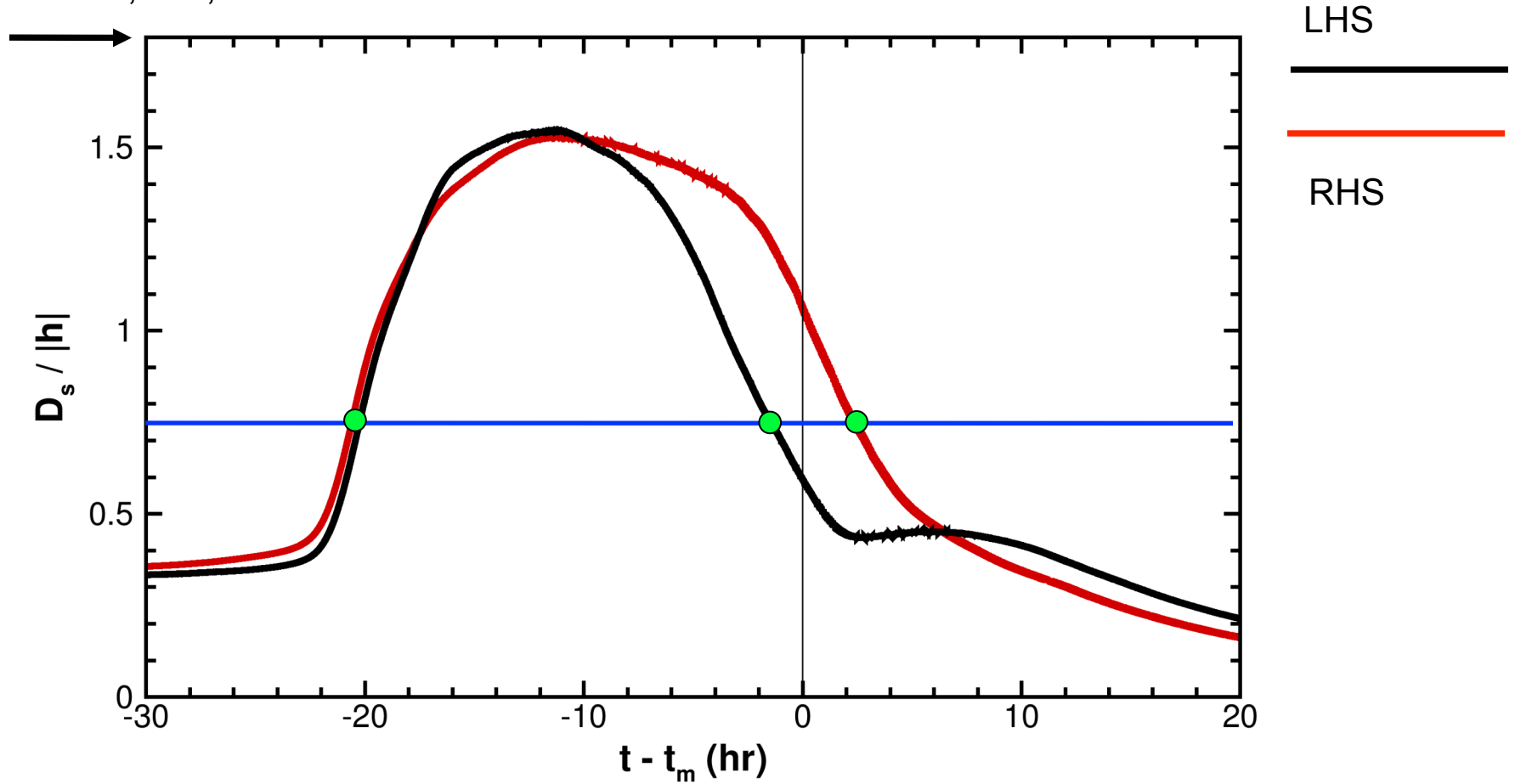


NORMALIZED ENTRAINMENT FLUX



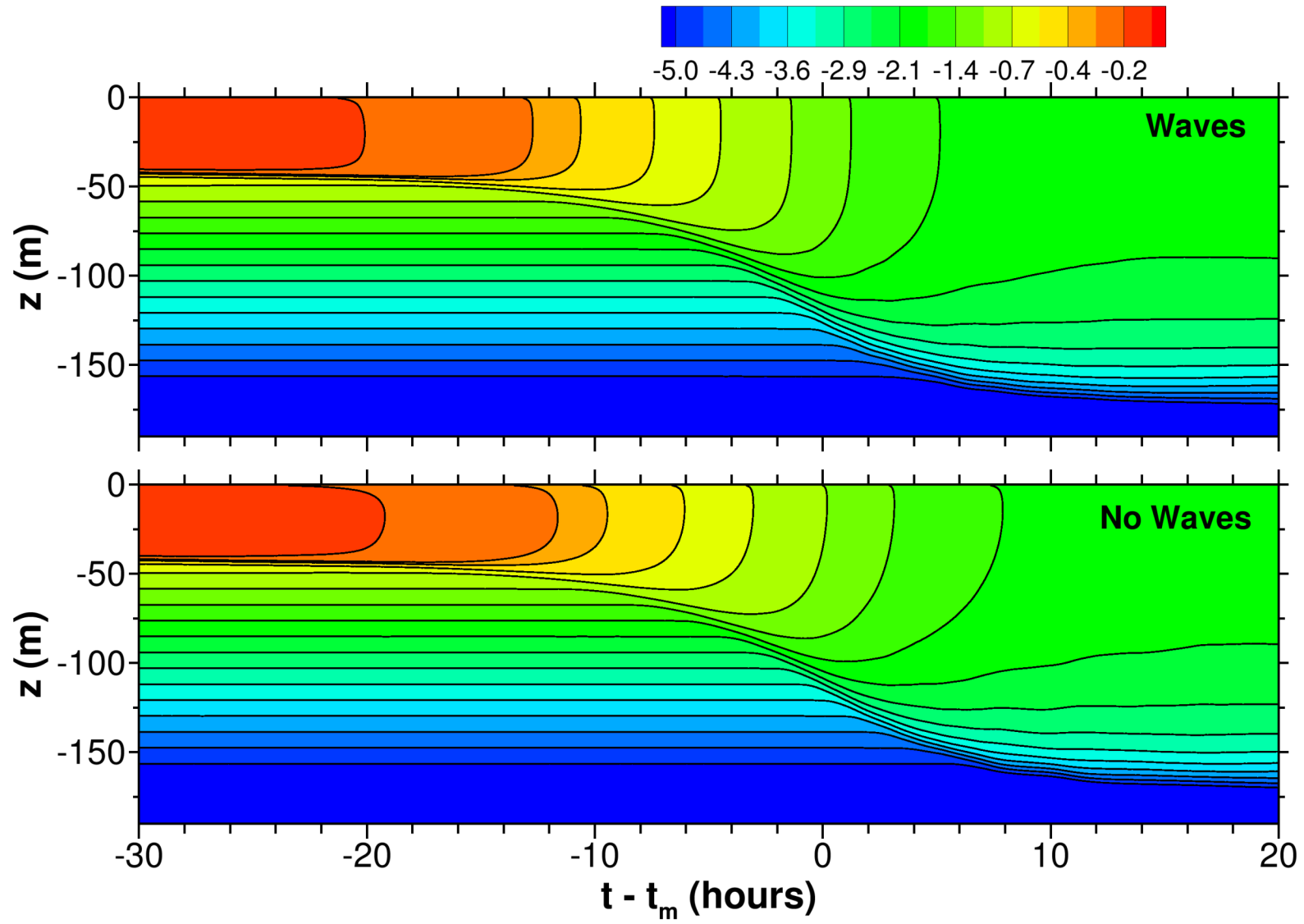
RATIO OF STOKES DEPTH AND OBL DEPTH $D_s/|h|$

McWilliams, *etal*, 1997

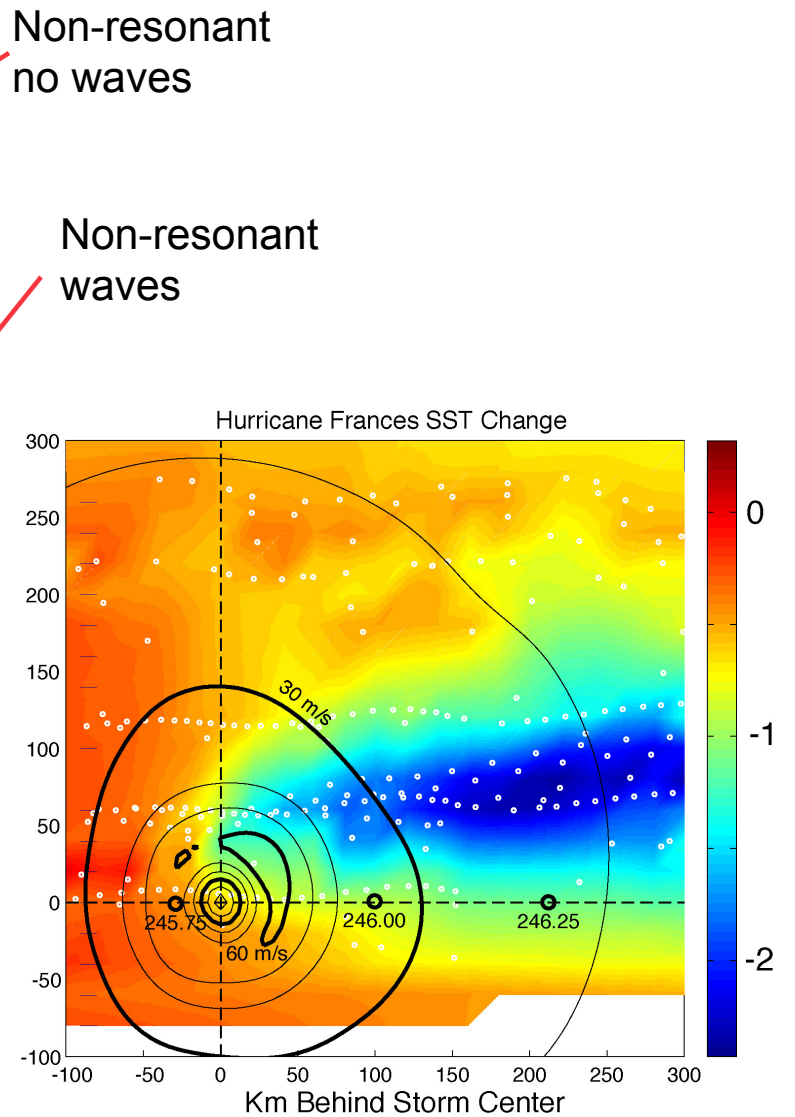
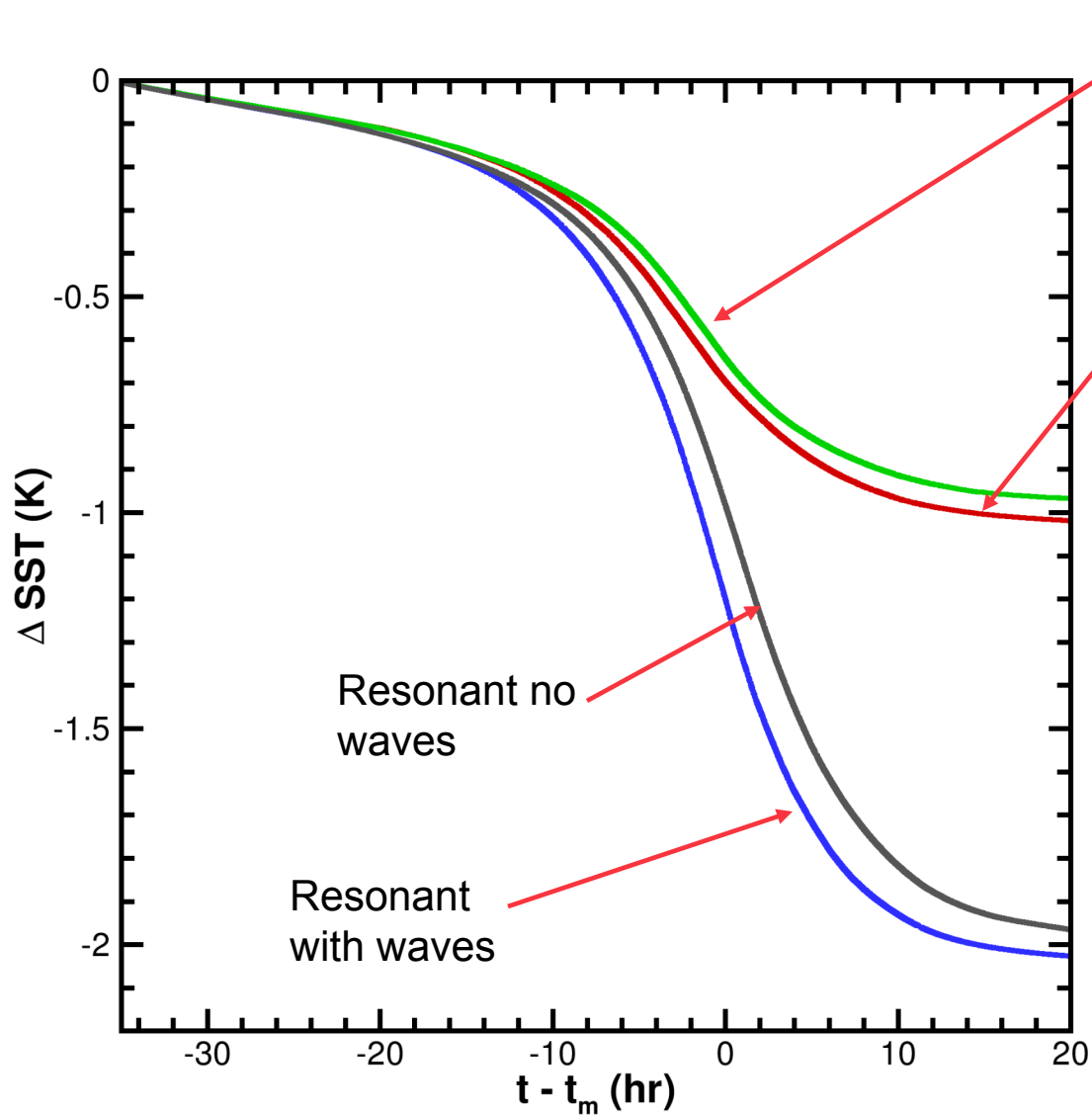


$D_s/|h| > 0.75$ Langmuir turbulence impacts entrainment

MEAN TEMPERATURE CHANGE $\langle \theta \rangle - \theta_i$ ON RHS



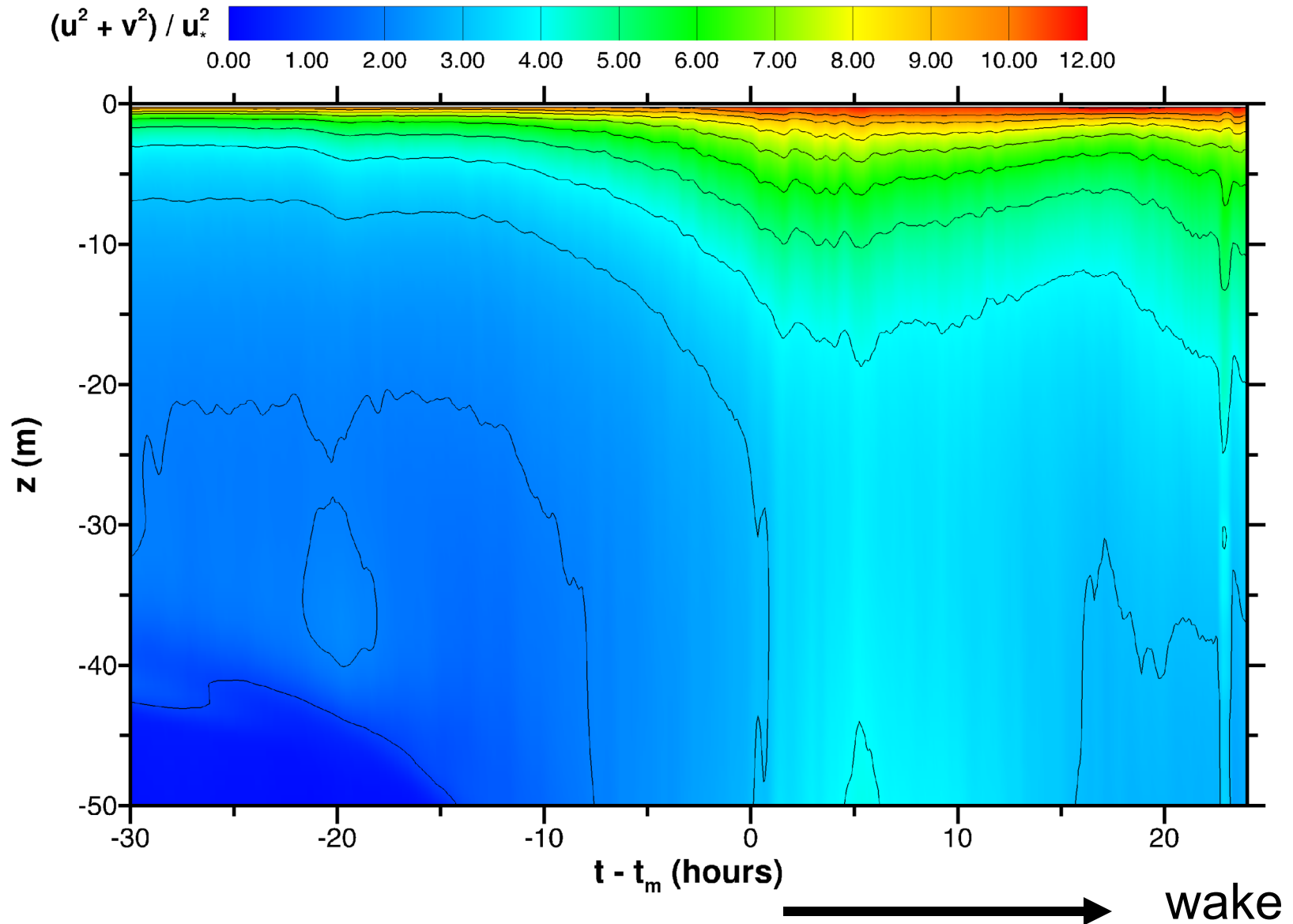
SST CHANGE ON RESONANT AND NON-RESONANT SIDES OF STORM



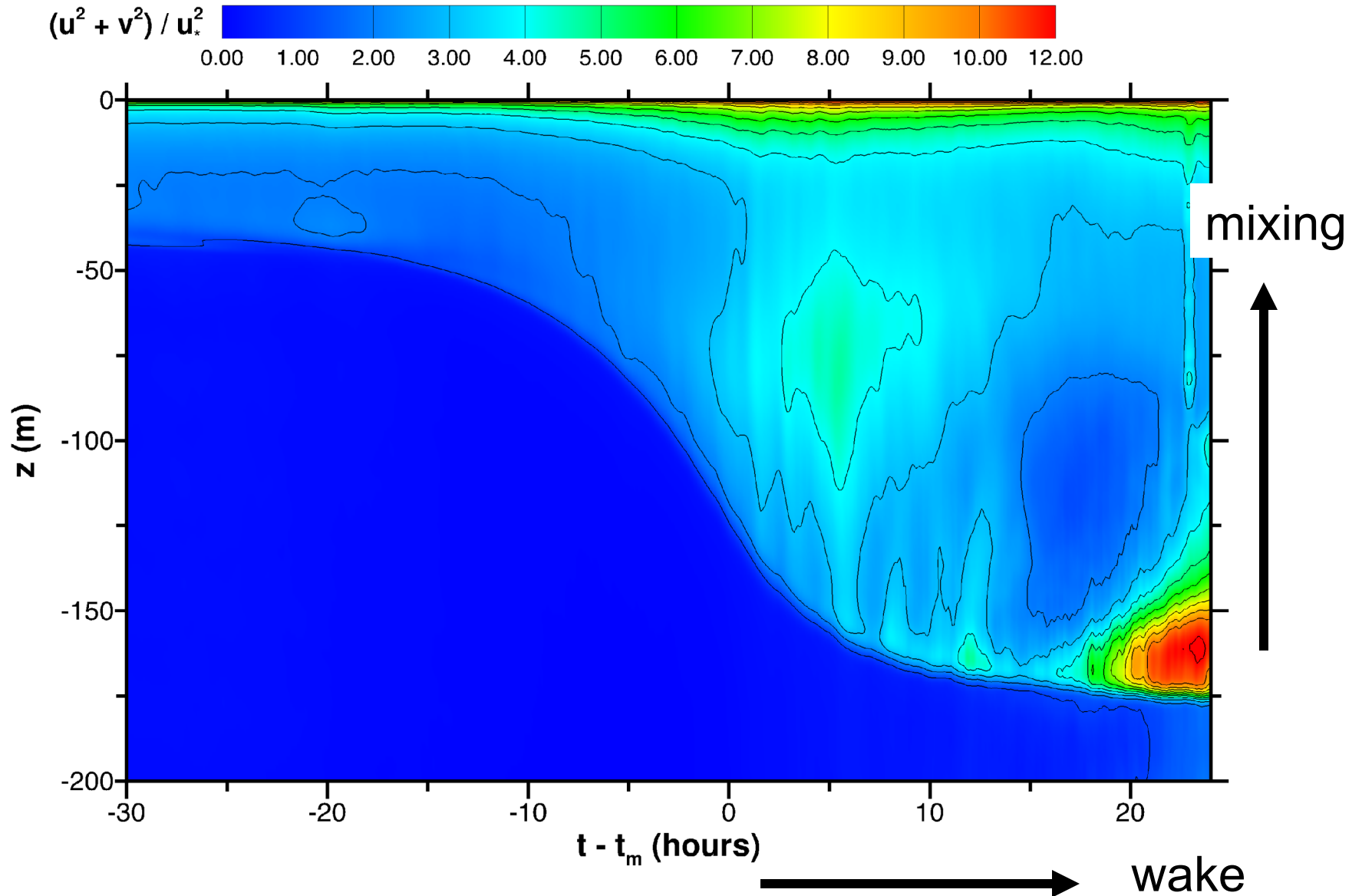
Hurricane wakes

- **Stratified rotating decaying turbulence**
- **Upside down boundary layers?**

WAKE DYNAMICS: HORIZONTAL VARIANCES



WAKE DYNAMICS: HORIZONTAL VARIANCES



SUMMARY

- Wave-current interactions are a key OBL process
- OBLS driven by realistic hurricane winds and waves show:
 - Stokes drift velocity is asymmetrical about storm track
 - Vertical velocity variance *nearly* scales with u_*^2
 - RHS of storm generates near “resonant” Stokes velocity and Langmuir cells are $\mathcal{O}(100\text{s m})$ in horizontal scale and depth filling
 - LHS of storm Stokes drift velocity can be counter-gradient to the momentum fluxes
 - Cells align with the mean Lagrangian shear
 - Entrainment at the thermocline is mainly do to shear instability resulting from inertial resonance
 - Wave effects increase the entrainment flux by $\sim 20\%$ and lower the SST by ~ 0.25 K
 - Wave effects are most pronounced in the OBL deepening phase where $D_s/|h| > 0.75$
- Building a 1D column model of the OBL with wave effects remains a challenge