HIGH RESOLUTION SIMULATIONS OF OCEAN BOUNDARY LAYERS WITH STOCHASTIC WAVE BREAKING

Peter P. Sullivan

Mesoscale & Microscale Meteorology
National Center for Atmospheric Research

Contributions: Jim McWilliams (UCLA), Ken Melville (SIO)
Edward Patton (NCAR)

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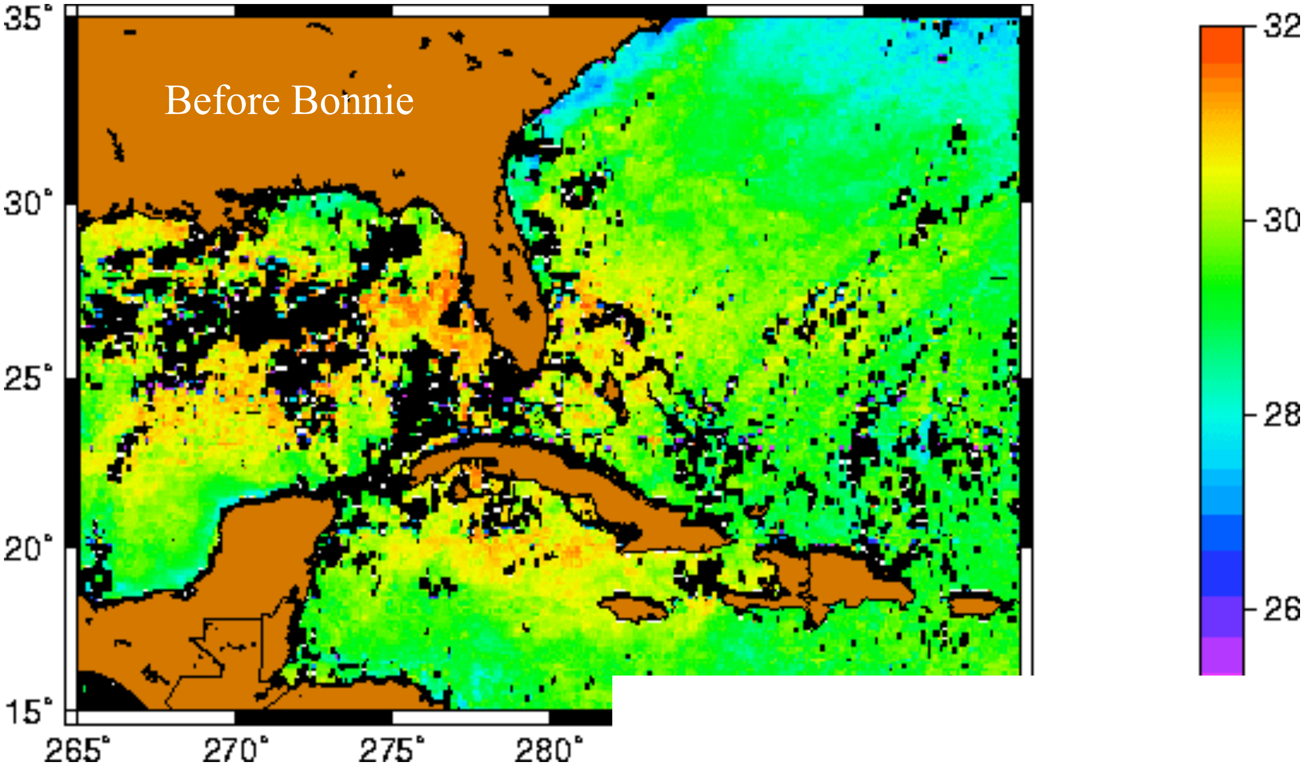
BACKGROUND/MOTIVATION

- The ocean boundary layer (OBL) plays an important role in geophysical flows despite its limited vertical extent $h \leq \mathcal{O}(100m)$

- Climate prediction, weather forecasts, air-sea coupling, biology, ...

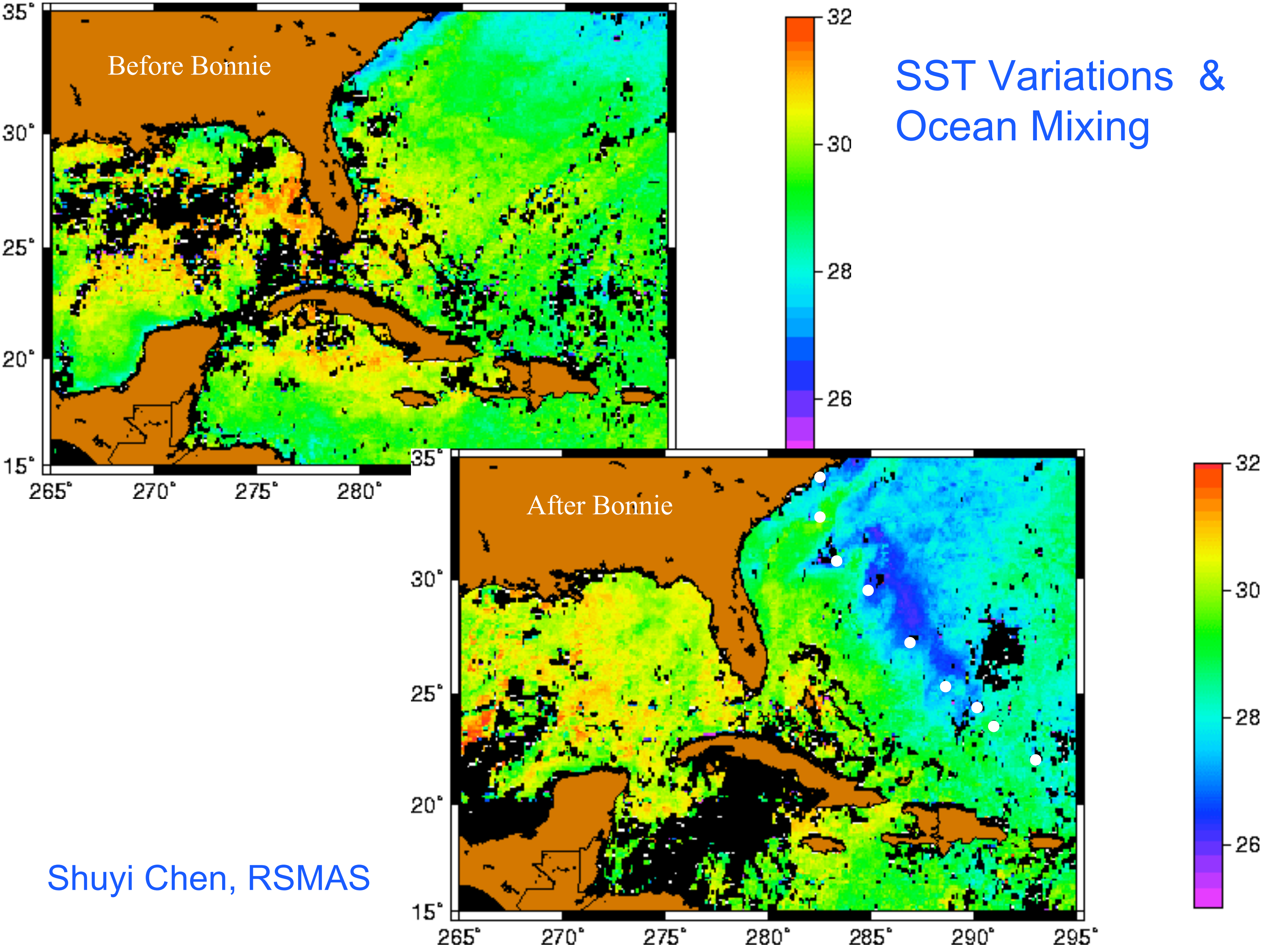
- Upper ocean mixing is especially critical for hurricane evolution



SST Variations & Ocean Mixing

Shuyi Chen, RSMAS

SST Variations & Ocean Mixing



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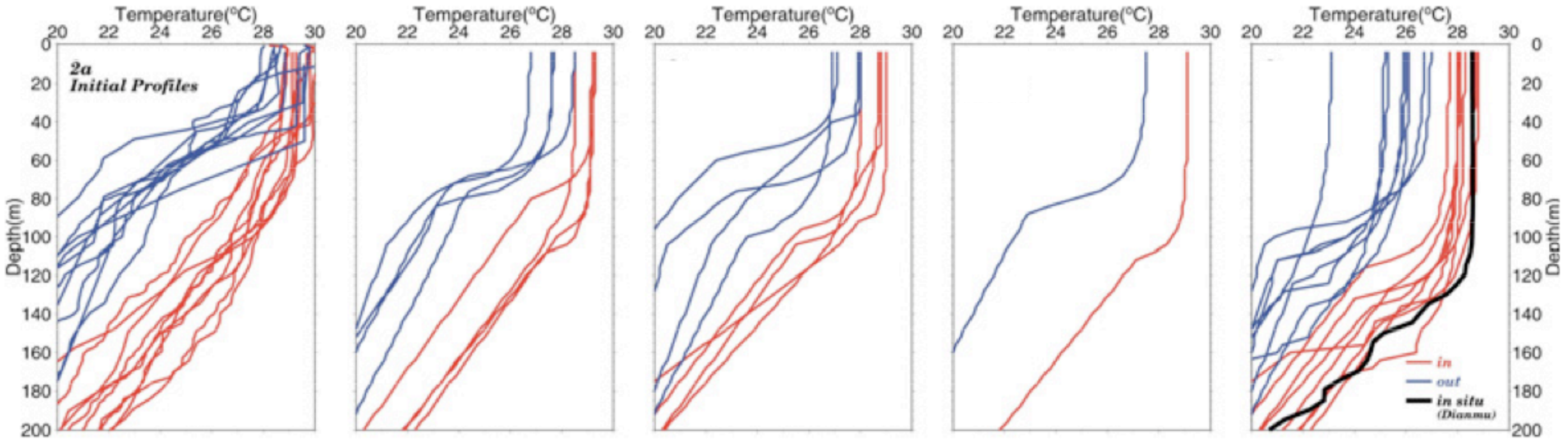
IMPACT OF OCEAN MIXED LAYER TEMPERATURE ON HURRICANE EVOLUTION IN WESTERN PACIFIC



CATEGORY 1-2 2-3 3-4 4-5

Depends on SST, mixed layer depth *h*, entrainment of cool water

LIN *ETAL*, 2005, 27th Conference on Hurricanes and Tropical Meteorology

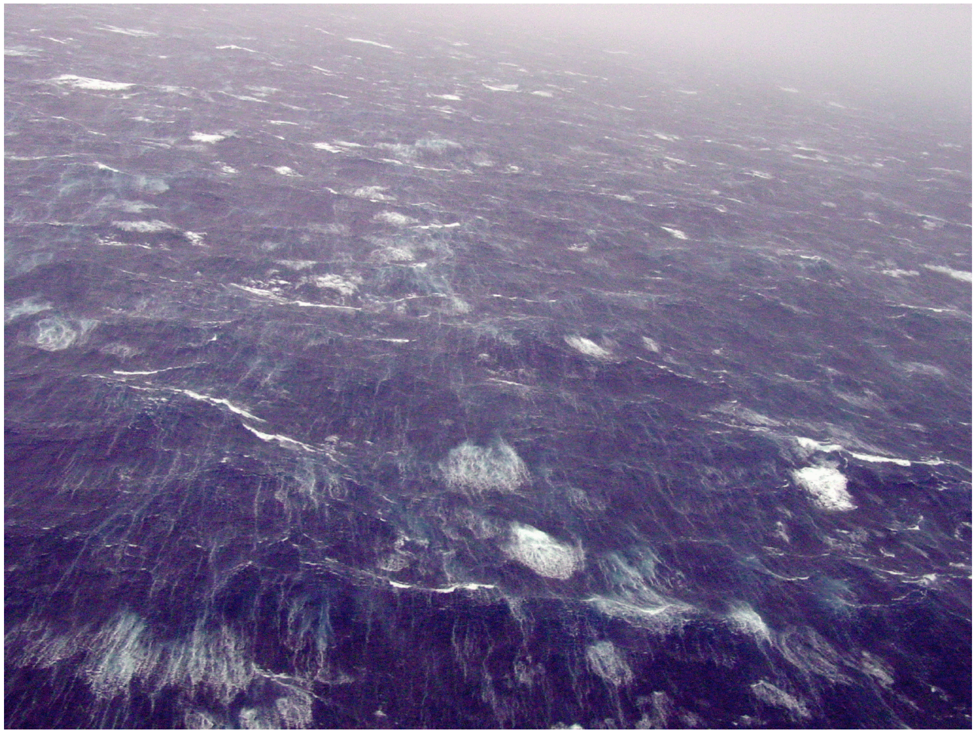
MODELING THE UPPER OCEAN BOUNDARY LAYER

- Traditional view: OBL is the upside down atmospheric boundary layer driven by constant wind stress $\boldsymbol{\tau}$
- What's the role (if any) for surface waves?
  - Near surface injection of momentum and energy by breaking waves $l \leq \mathcal{O}(0.1\,h)$
  - Langmuir circulations resulting from phase averaged wave-current interactions, *viz.*, Craik-Leibovich (CL2) instabilities $l \sim \mathcal{O}(h)$

HIGH WIND SURFACE DYNAMICS

WAVE BREAKING AND LANGMUIR CIRCULATIONS

Intermittent fluxes of momentum and energy



Hurricane Isabel CBLAST Photo courtesy P. Black (Miami)

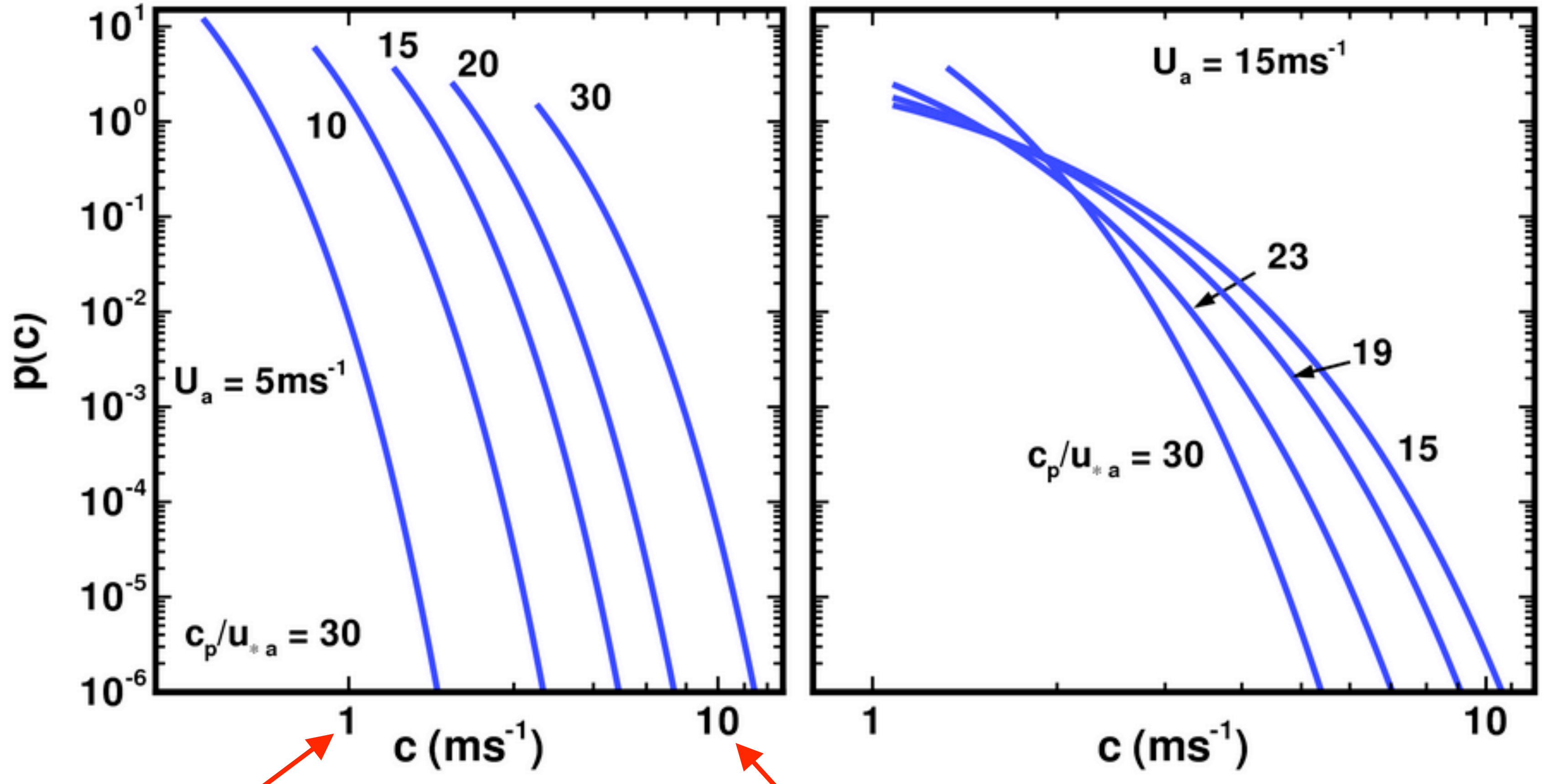
Wave-averaged effects

Great Salt Lake Photo courtesy S. Monismith (Stanford)

MODELING OF WAVE IMPACTS ON CURRENTS

- **Craik-Leibovich asymptotics**
  - Wave orbital speeds are large compared to the currents
  - Surface waves produce a Stokes drift $\mathbf{u}^{St}(z)$
  - Momentum equations are augmented by a phase-averaged "vortex force" $\boxed{\mathbf{u}^{St} \times \boldsymbol{\omega}}$
- **Discrete event wave breaking model**
  - Compact 3D impulses replace uniform surface stress $\langle \boldsymbol{\tau} \rangle$
  - Breakers are drawn from a PDF $p(c) \sim f(U_a, C_p/u_*)$
  - Breakers are located at random surface sites
  - Breaker production rate $\dot{N}$ matches long-time large-area *average* atmospheric wind stress and energy flux

BREAKER PDF FOR VARYING WINDS AND WAVE AGE



$\lambda = 0.64\ m$

$\lambda = 64\ m$

LES OCEAN MODEL WITH WAVE EFFECTS

Momentum

$$\frac{\partial \overline{u}_i}{\partial t} = -\frac{\partial}{\partial x_j}(\overline{u}_j \overline{u}_i + \tau_{ij}) - \delta_{i3}\frac{g\overline{\rho}}{\rho_o} - \frac{\partial \pi}{\partial x_i} - \epsilon_{ijk} f_j (\overline{u}_k + u_k^{St}) + \boxed{\epsilon_{ijk} u_j^{St} \overline{\omega}_k} + \boxed{\sum_m \overline{A}_i^m}$$

``Vortex Force”

Stochastic impulses

SGS TKE

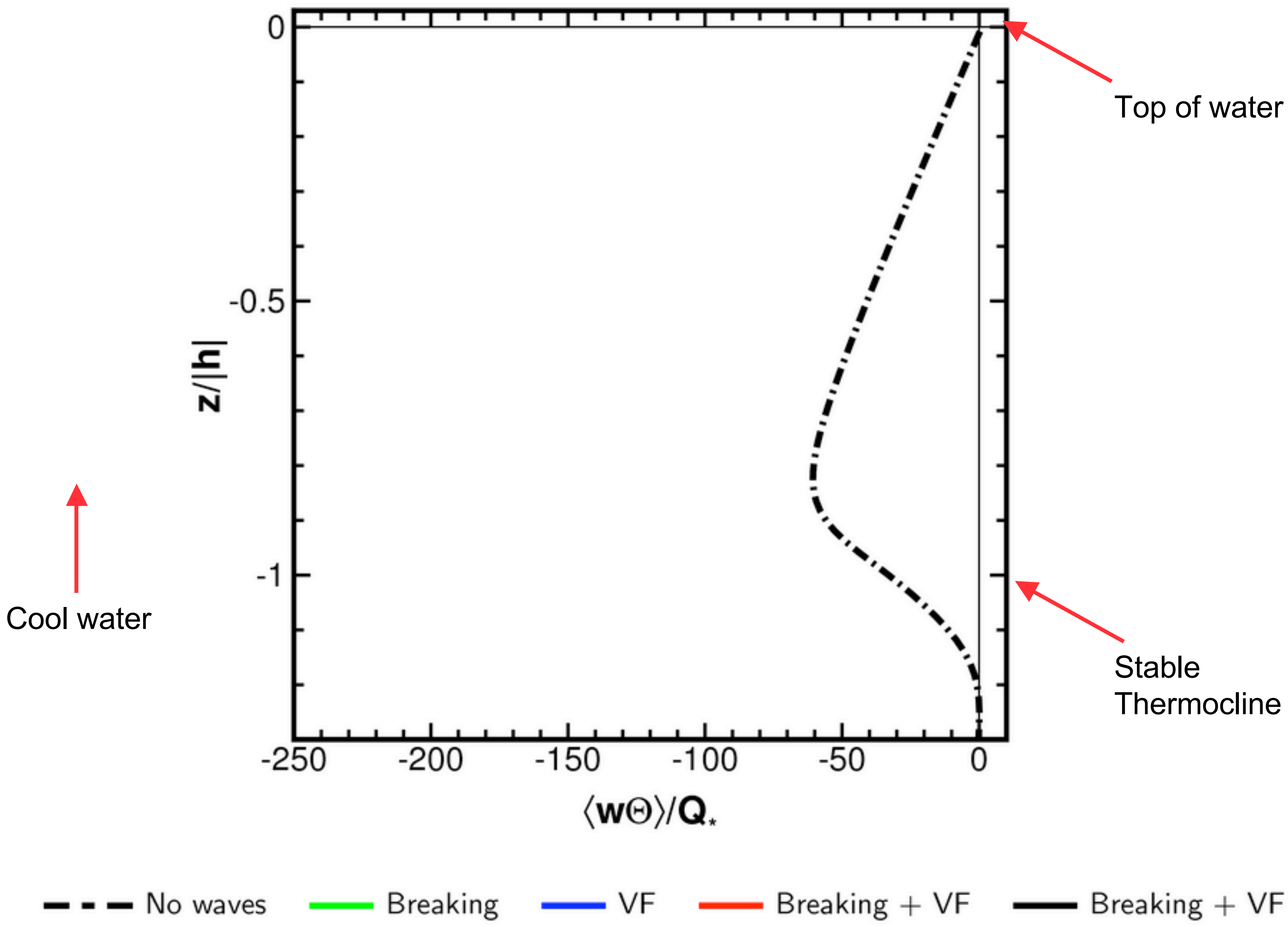
$$\frac{\partial e}{\partial t} = \ldots - u_j^{St} \frac{\partial e}{\partial x_j} - \tau_{ij} \frac{\partial u_i^{St}}{\partial x_j} + \boxed{\sum_m W^m}$$

Breaker work

Density

$$\frac{\partial \overline{\rho}}{\partial t} = -\frac{\partial}{\partial x_j}(\overline{u}_j \overline{\rho} + \tau_{j\rho}) - u_j^{St} \frac{\partial \overline{\rho}}{\partial x_j}$$

VERTICAL SCALAR FLUX WITH WAVE EFFECTS

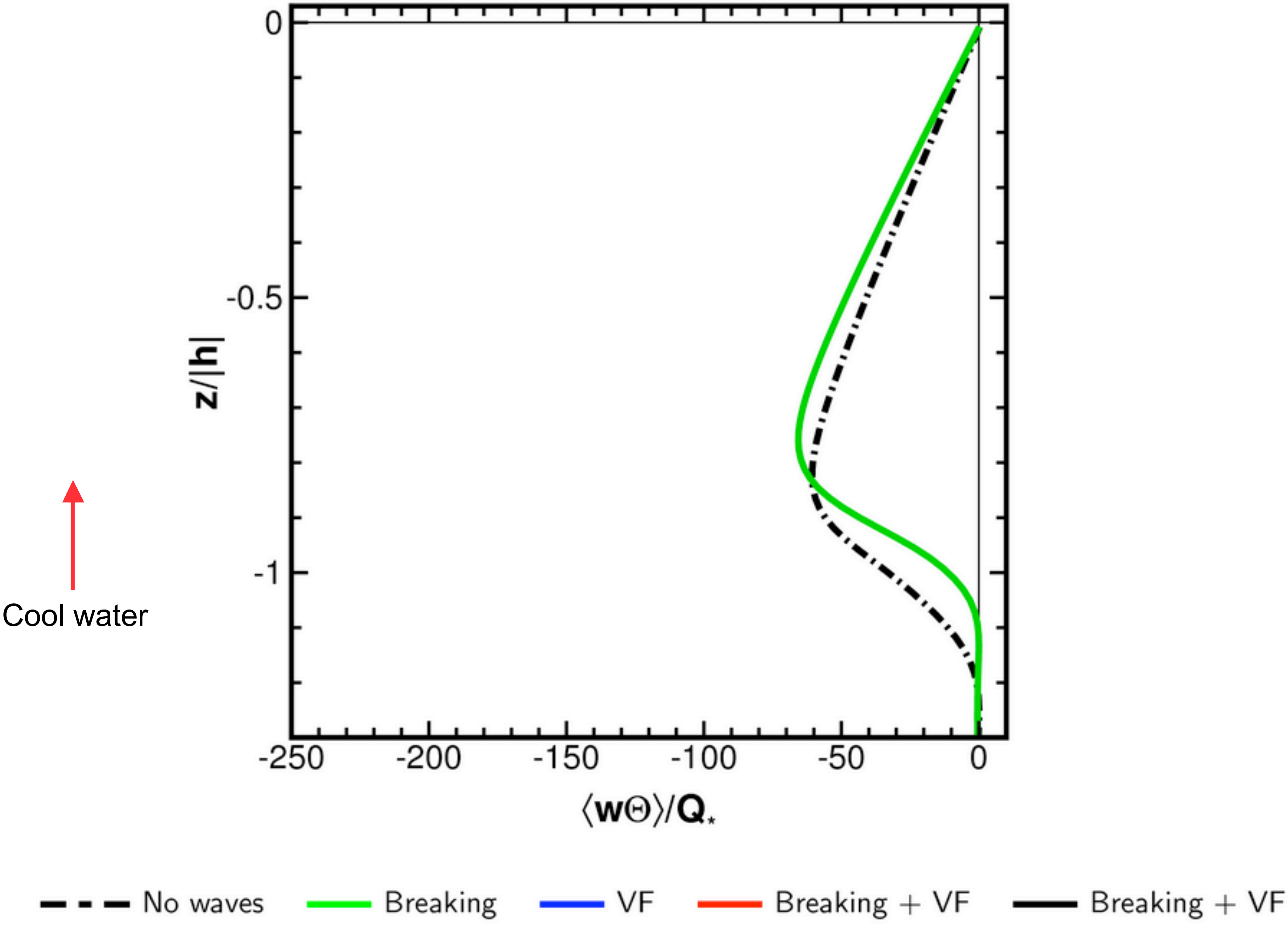


Top of water

Stable Thermocline

Cool water

VERTICAL SCALAR FLUX WITH WAVE EFFECTS



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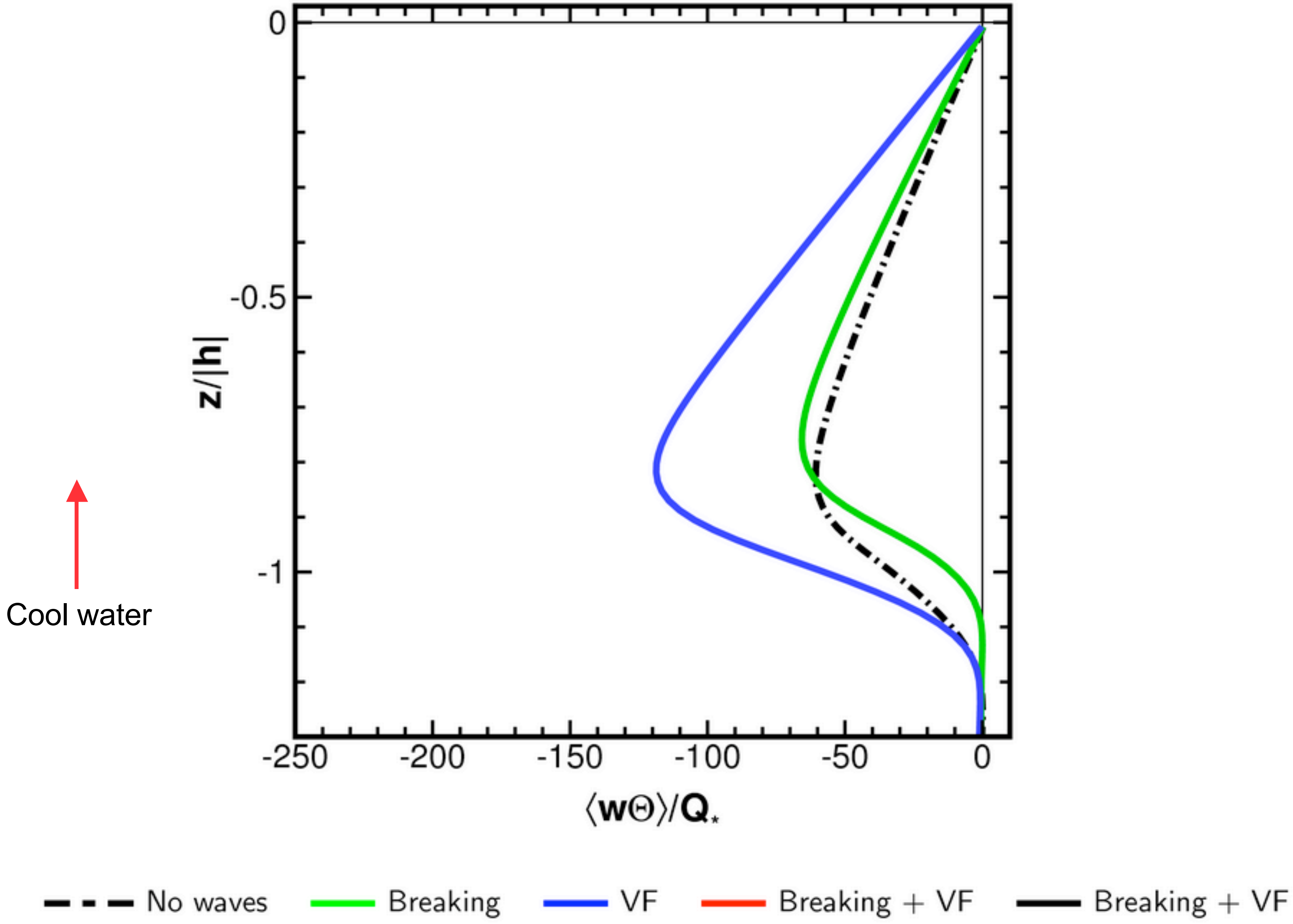
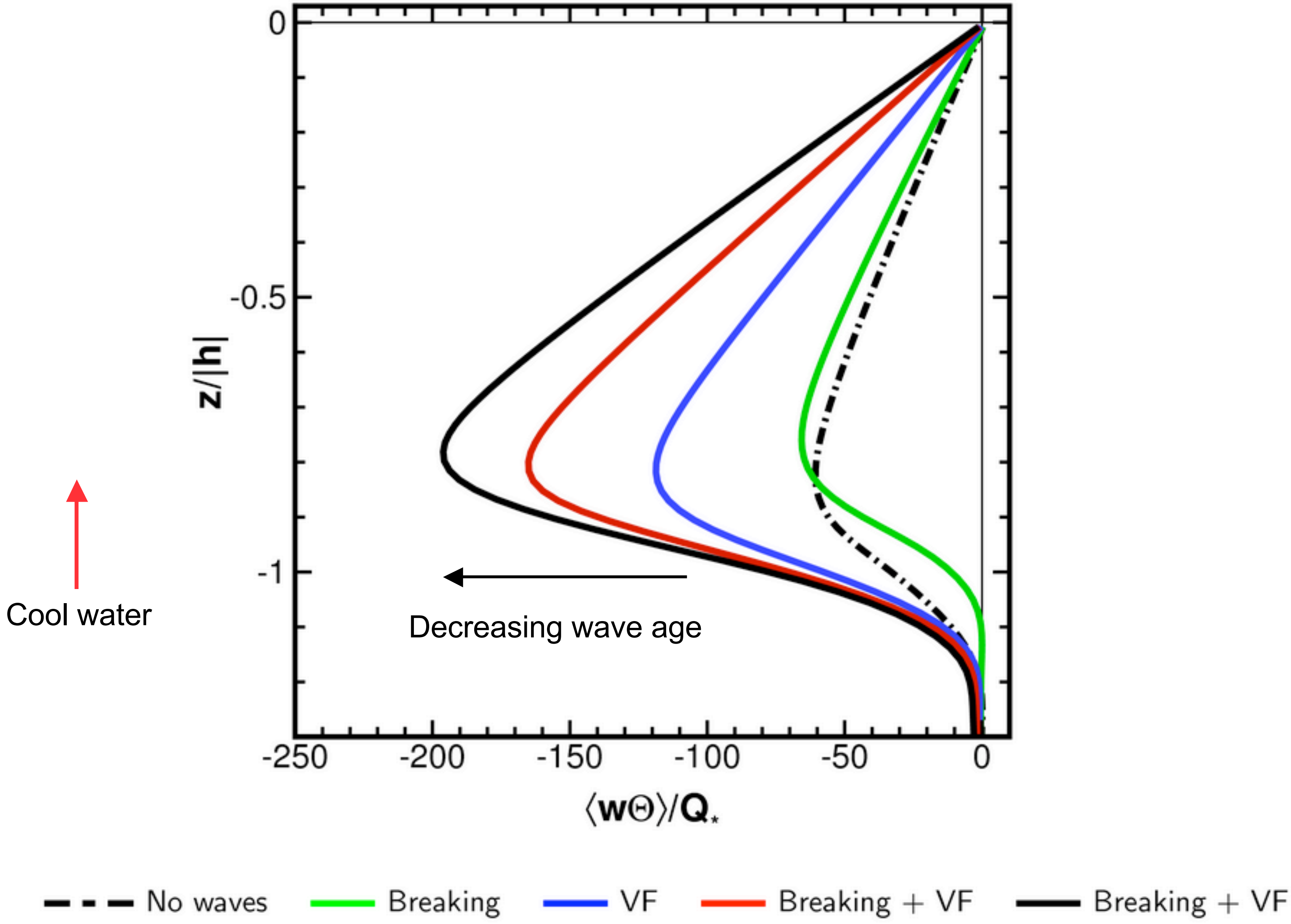


Cool water

VERTICAL SCALAR FLUX WITH WAVE EFFECTS

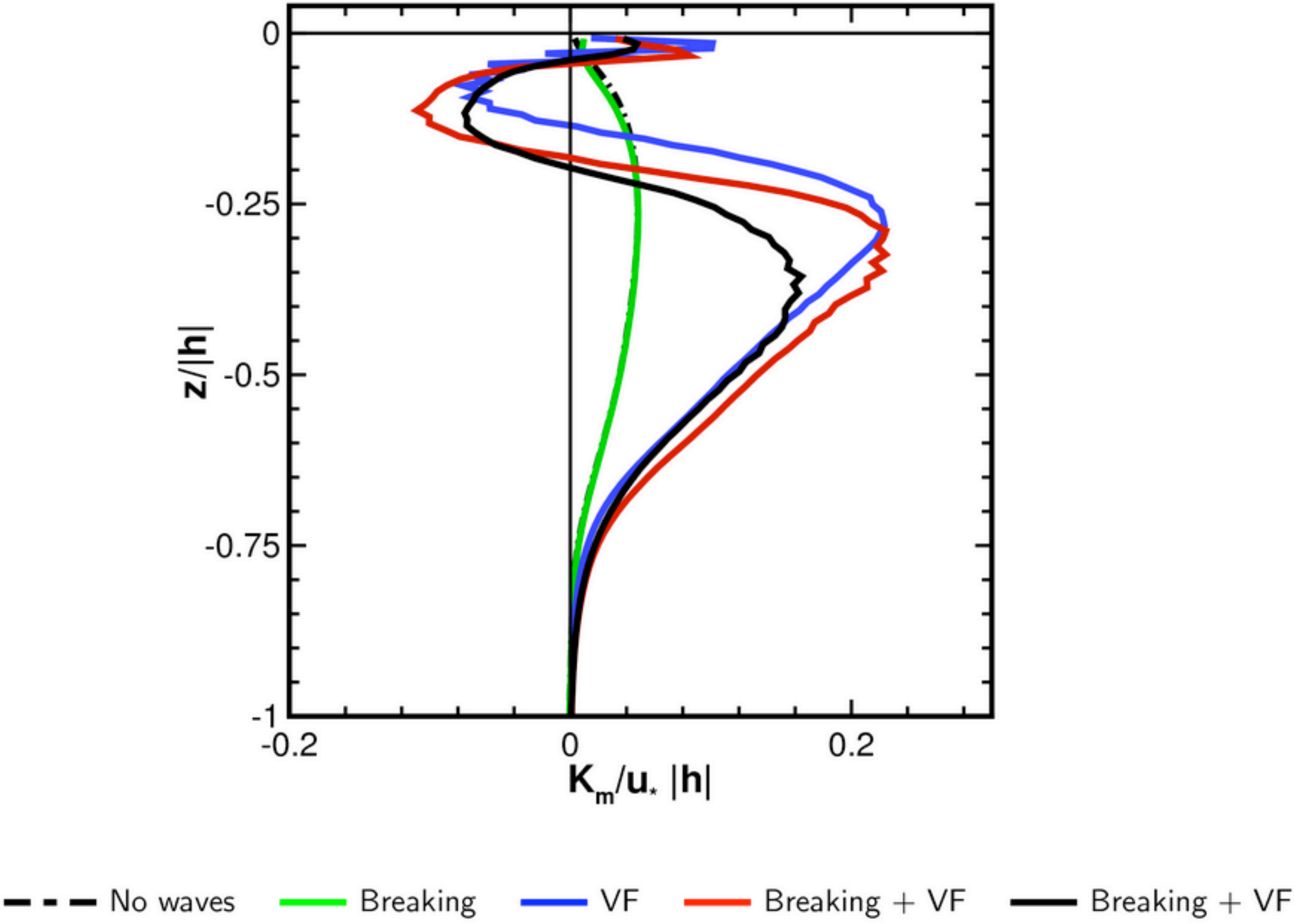


Cool water

Decreasing wave age

EDDY DIFFUSIVITY FOR MOMENTUM

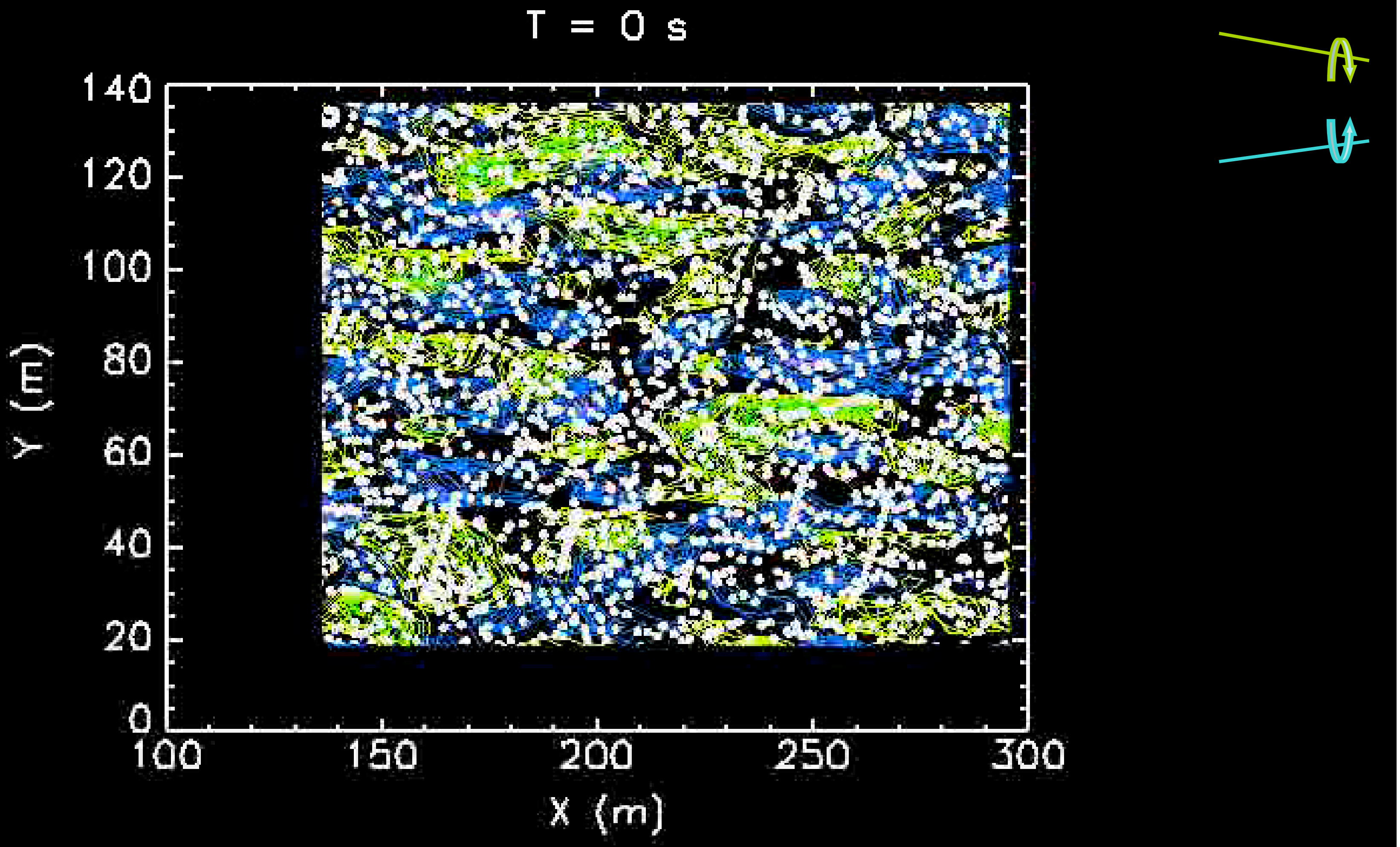
$$\langle u'w' \rangle = -K_m \partial \langle u \rangle / \partial z$$



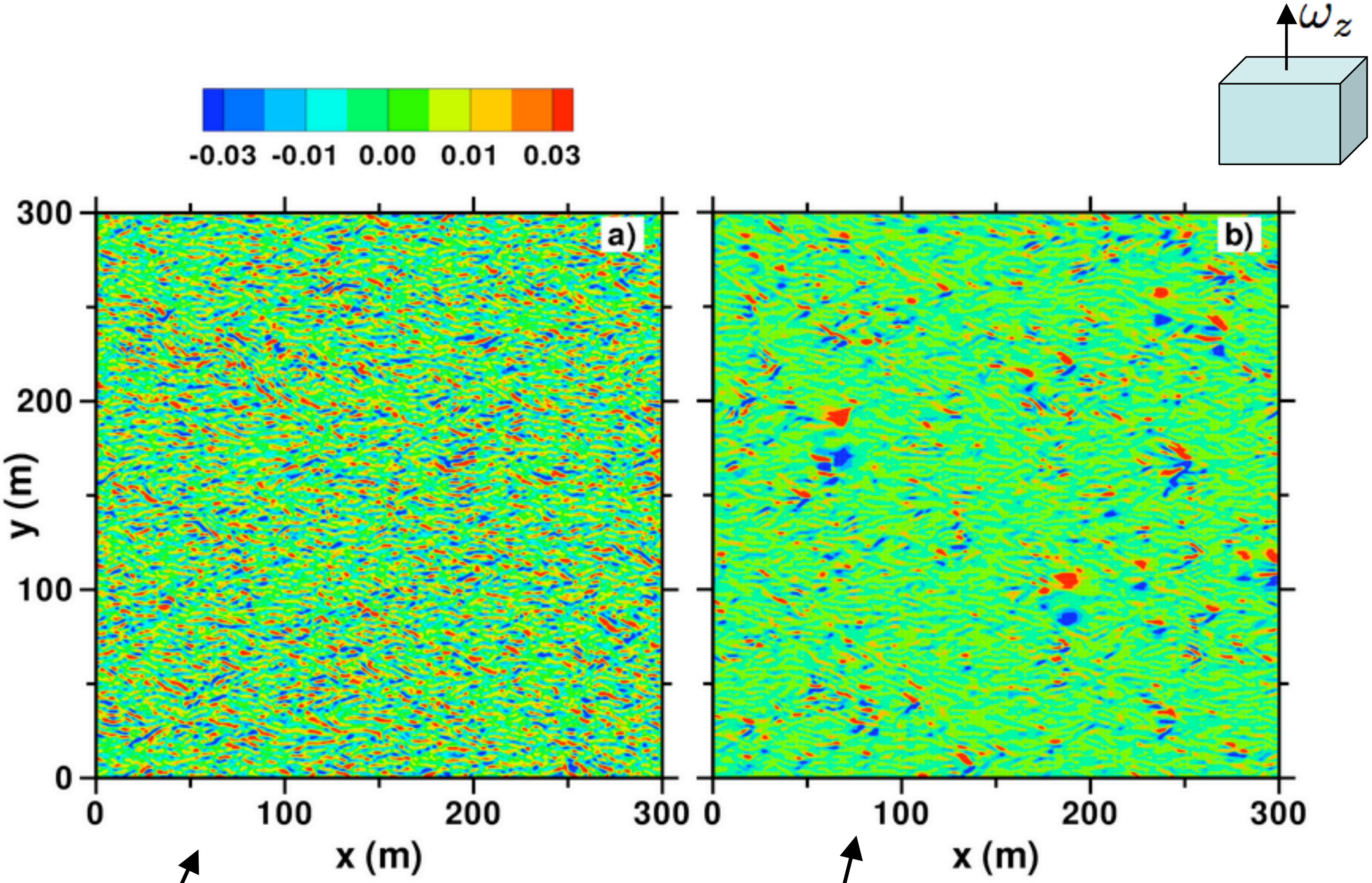
SURFACE WAVES AND OCEAN MIXING

- LES results with explicit wave effects show surface waves modulate OBL currents, scalar transport, and promote non-local mixing
- How did this happen?
- Depth filling coherent structures emerge from the interactions between waves, currents, and turbulence
    - Primary agent is wave-current interactions
    - Combination of wave-current interactions and breaking generates the largest response, but depends on wave age c_p/u_{*a}

PARTICLE PATHS OVERLAYING VORTICITY CONTOURS
UNIFORM STRESS (no breaking) U_{10} = 5m/s



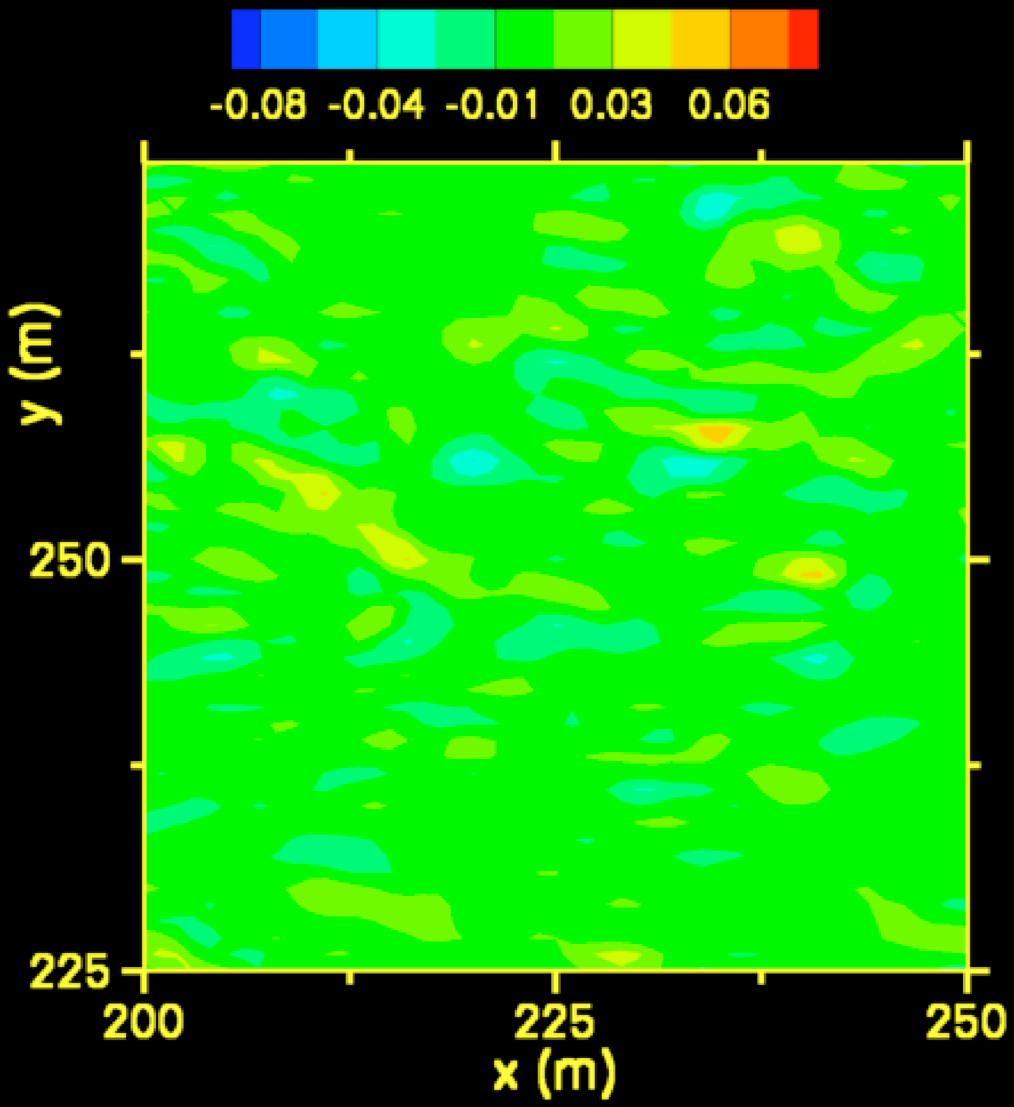
VERTICAL VORTICITY ω_z NEAR WATER SURFACE

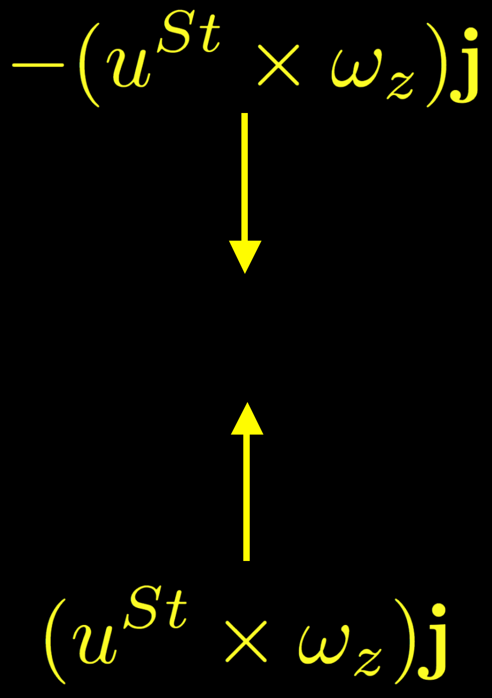


Uniform stress + vortex force

Breaking + vortex force

X-Y SURFACE PATTERNS OF VERTICAL VORTICITY, z = -1m, WINDS = 15m/s

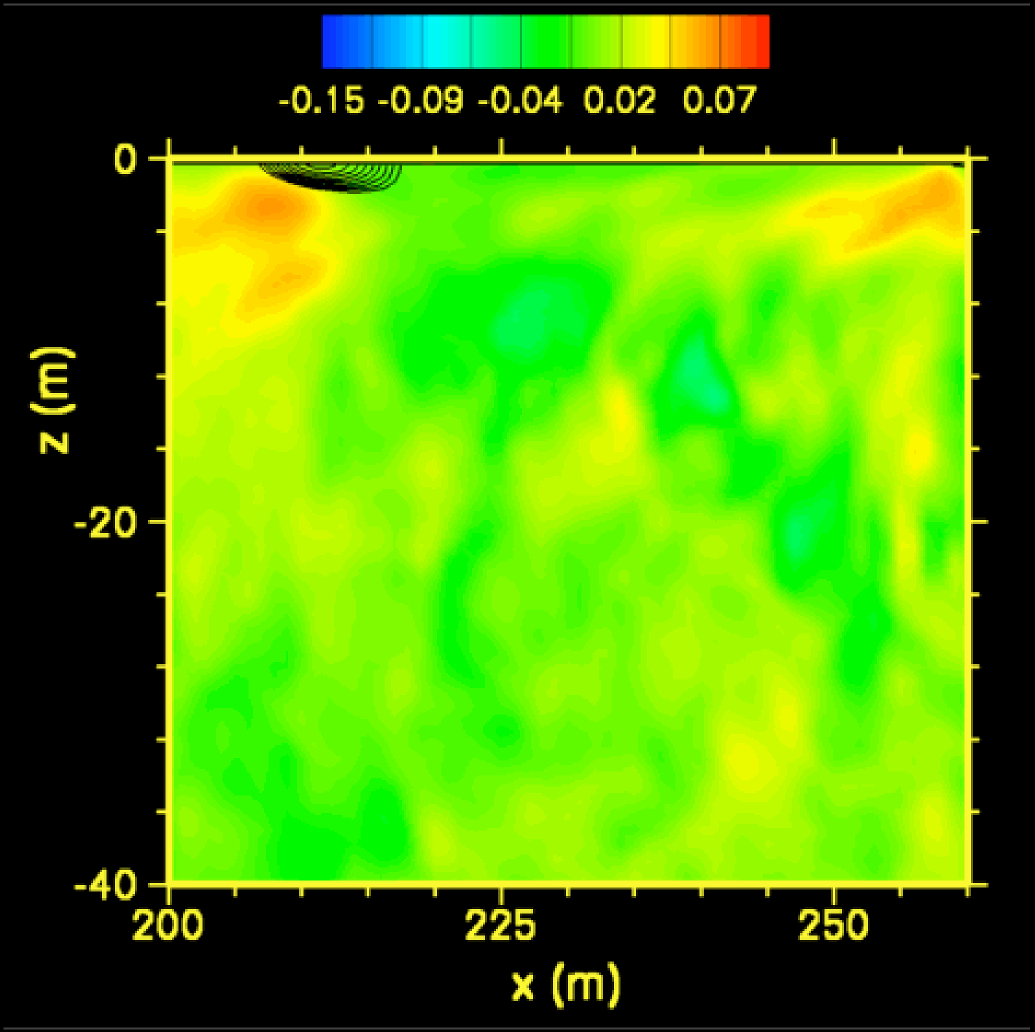




$$-(u^{St} \times \omega_z)\mathbf{j}$$

$$(u^{St} \times \omega_z)\mathbf{j}$$

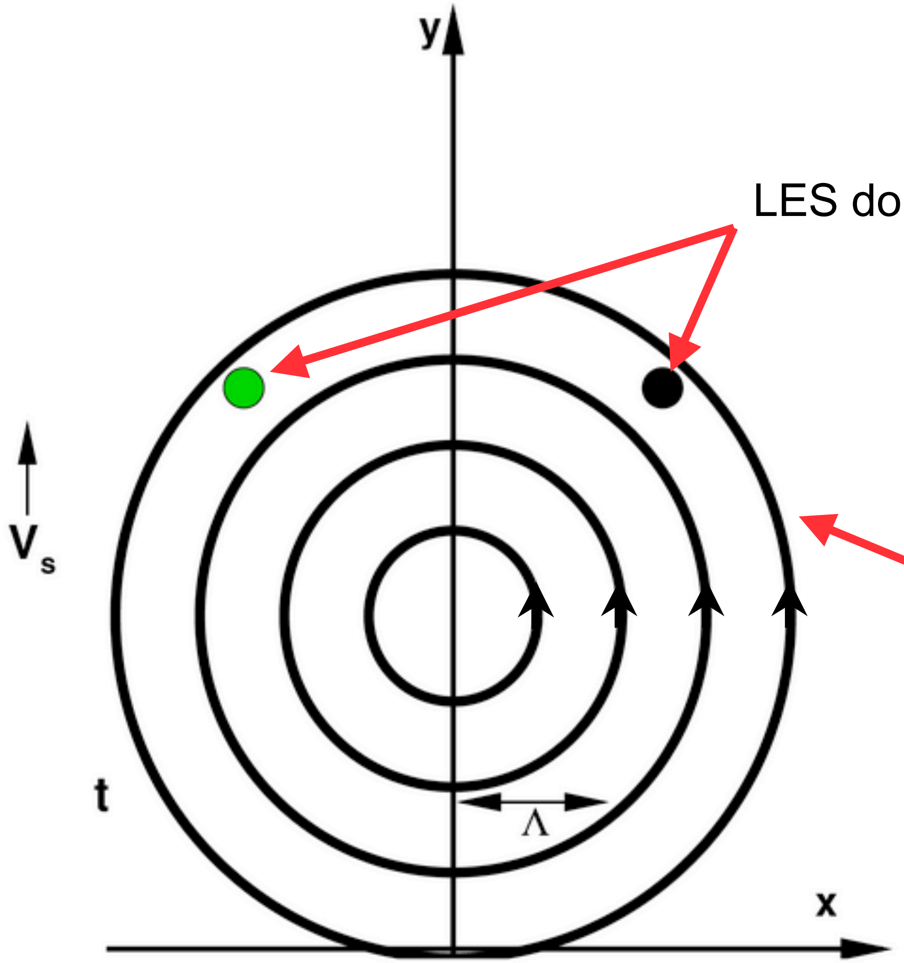
X-Z PATTERN OF VERTICAL VELOCITY W AND U-CURRENT



U_A=15m/s

``WHAT IF …. “

HURRICANE PASSAGE OVER LES DOMAINS
INERTIAL RESPONSE

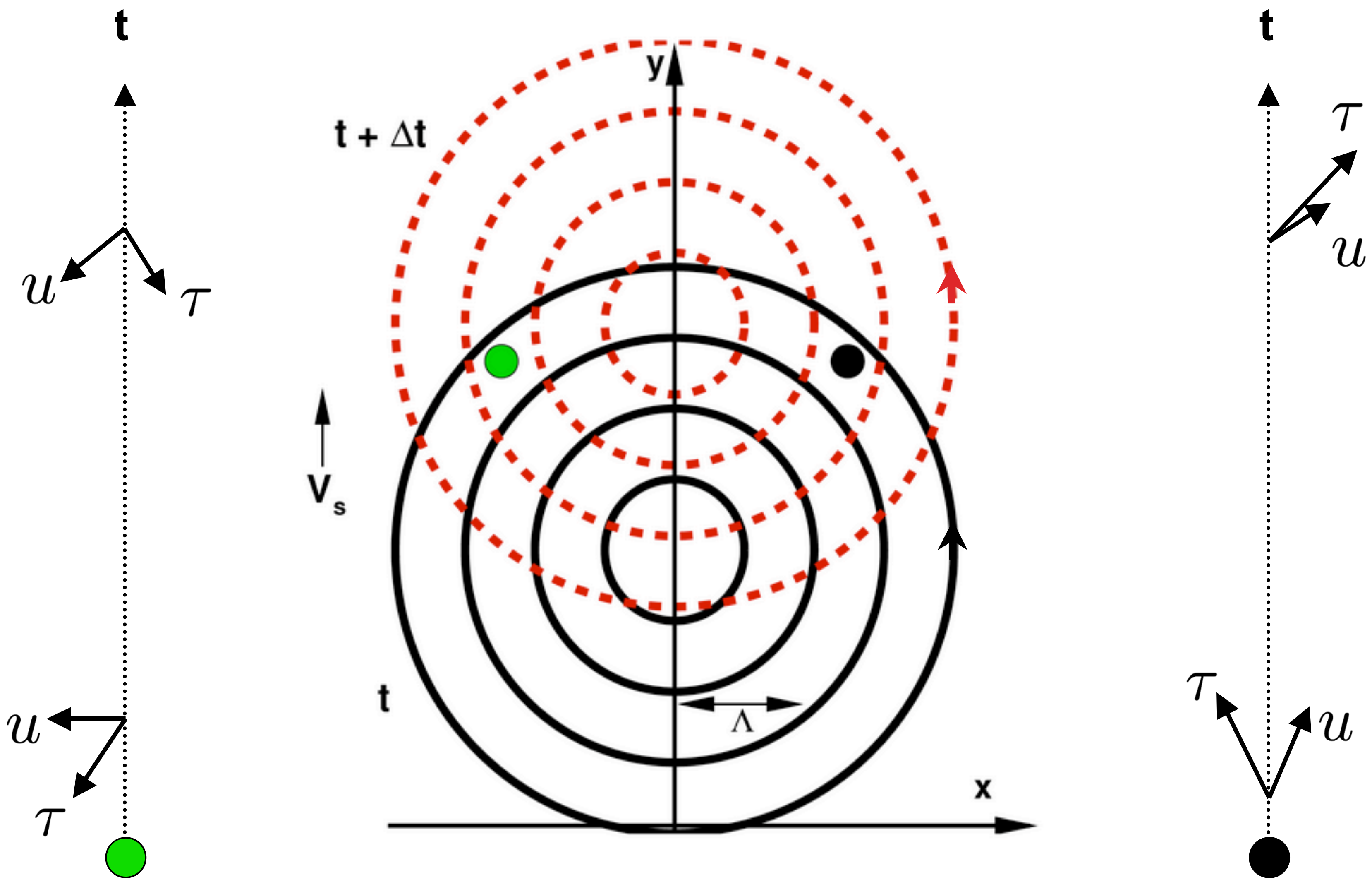


LES domains $\mathcal{O}(1\ km)$

Hurricane``Vortex”

$$V_s \sim \mathcal{O}(5m/s) \qquad \Lambda \sim \mathcal{O}(50km)$$

HURRICANE PASSAGE OVER LES DOMAINS
INERTIAL RESPONSE



COUPLING WAVES AND INERTIAL RESPONSE IN A HIGH WIND DRIVEN OBL

Wind speed $U_a = 30$ ms^{-1}

- Smallest breaker modeled $t_b = 1$ s
- Wave-current interactions $t_{St} = 20$ s
- Large eddy turnover time $t_t = 2900$ s
- Inertial period $t_i = 62,800$ s

LES domain and time step

- $\triangle t \sim 0.5$ s
- $\triangle x \sim 1.0$ m
- $(N_x, N_y, N_z) \sim (1000, 1000, 256)$
- Number of time steps $N_s \sim [400,000 \sim 500,000]$ steps

Vary translation speed V_s and LES domain locations

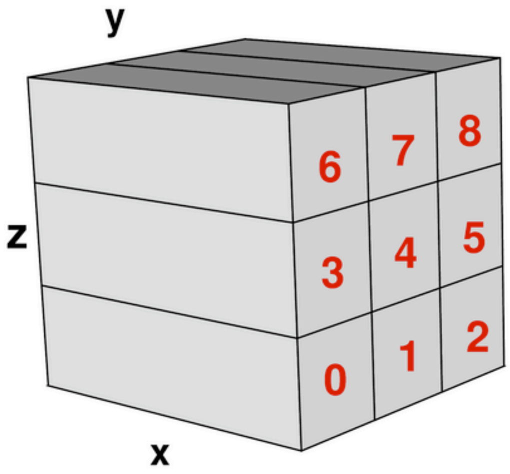
GOAL: IMPACT ON SST AND MIXED LAYER COOLING

``MORE PARALLELISM …“

MASSIVELY PARALLEL ALGORITHM FOR BOUSSINESQ BOUNDARY LAYERS

Algorithm Constraints:

- Utilize 2-D domain decomposition
- Employ a mixed pseudospectral finite-difference scheme
- Incompressible flow must solve $\nabla^2 p = s$



Highlights:

- Employ *local* MPI matrix transposes to evaluate derivatives and solve for the pressure:
  $f(x,\, y_s\!:\!y_e,\, z_s\!:\!z_e) \;\Leftrightarrow\; f^T(y, x_s\!:\!x_e, z_s\!:\!z_e)$
  $\hat{s}(k_y, k_{xs}\!:\!k_{xe}, z_s\!:\!z_e) \;\Leftrightarrow\; \hat{s}^T(z, k_{xs}\!:\!k_{xe}, k_{ys}\!:\!k_{ye})$
- No ALLTOALLV global communication,
  use SENDRECV
- Use MPI I/O, single large direct-access like file

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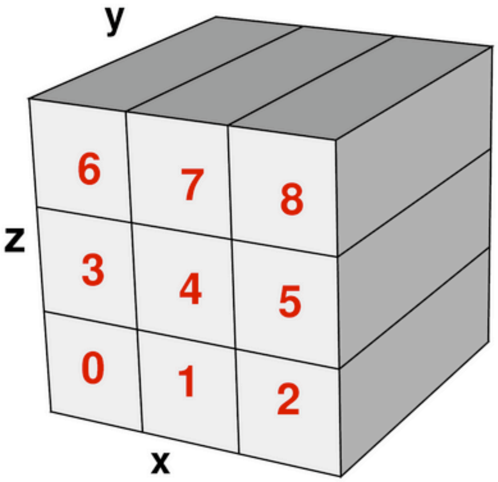

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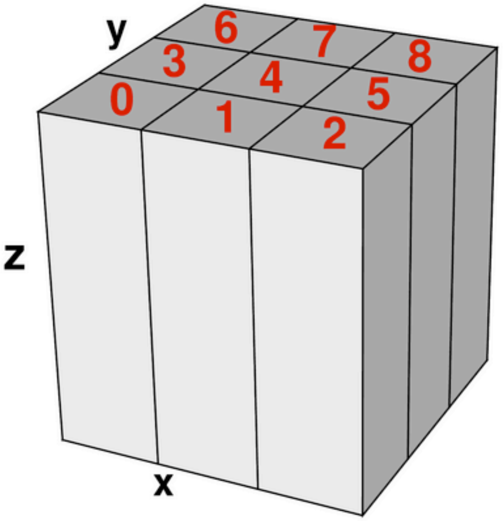

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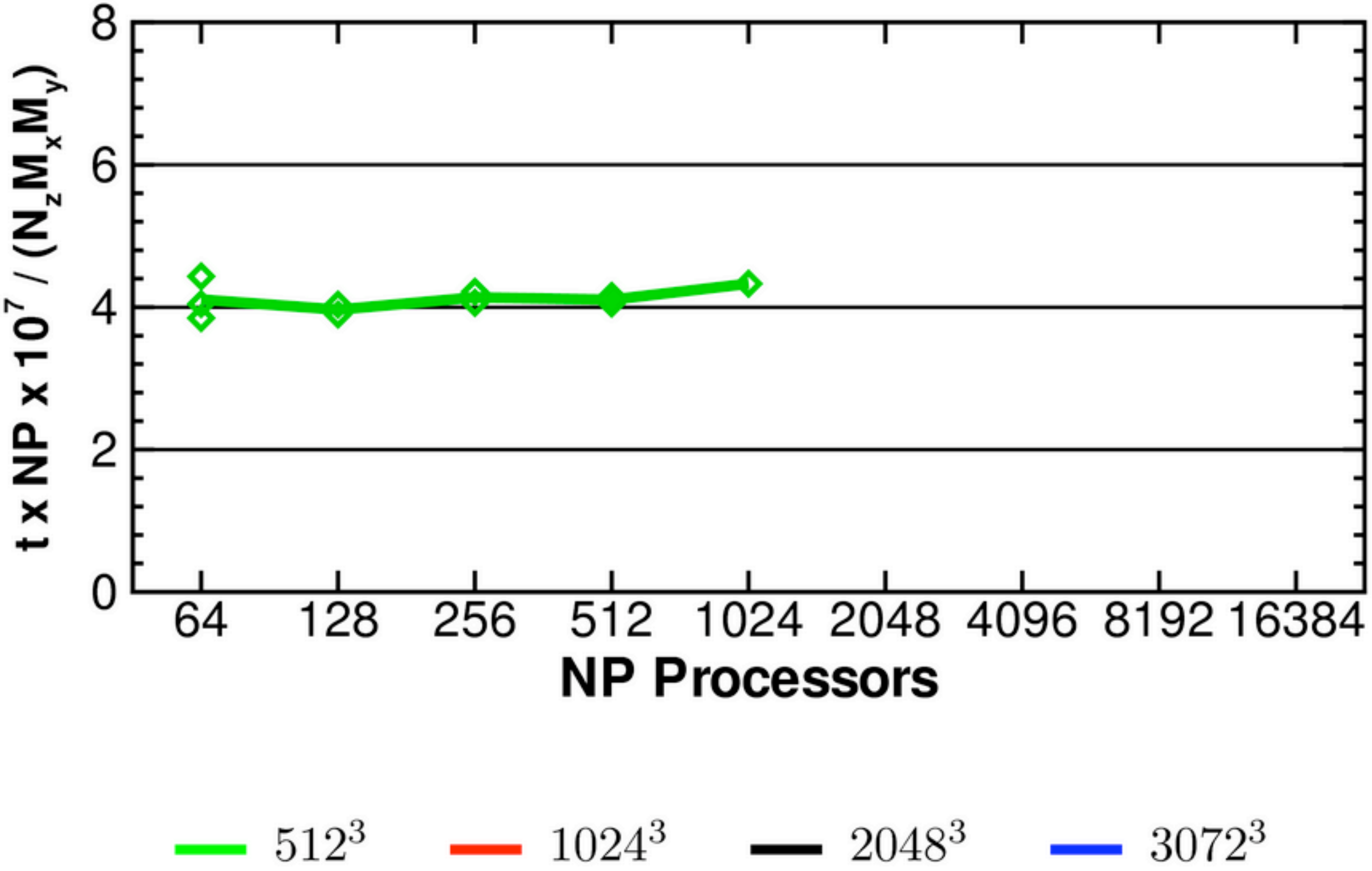
SCALING OF PARALLEL PSEUDOSPECTRAL ALGORITHM WITH 2-D DOMAIN DECOMPOSITION

Cray XT4, NERSC
E. Patton, NCAR



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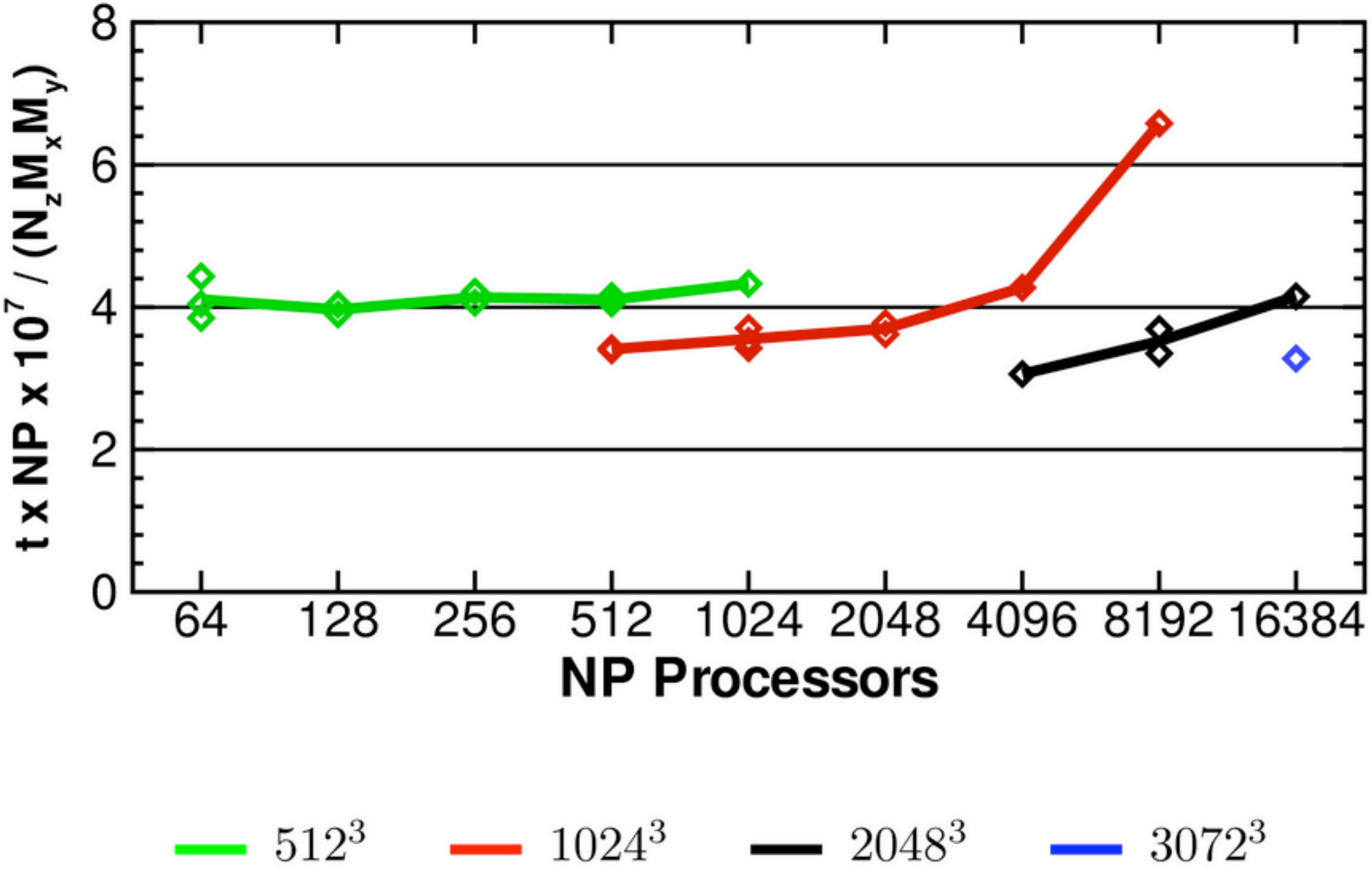
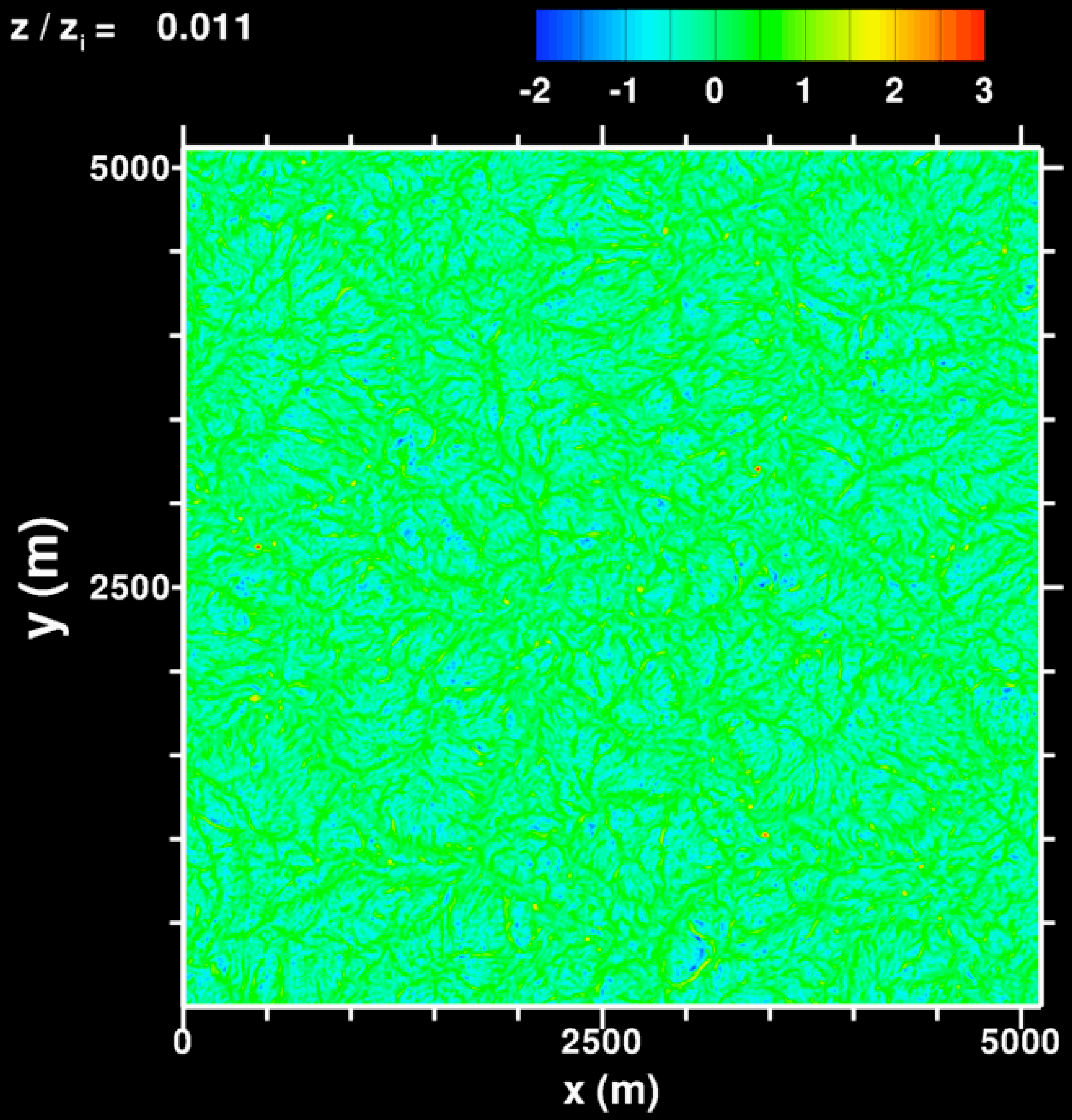


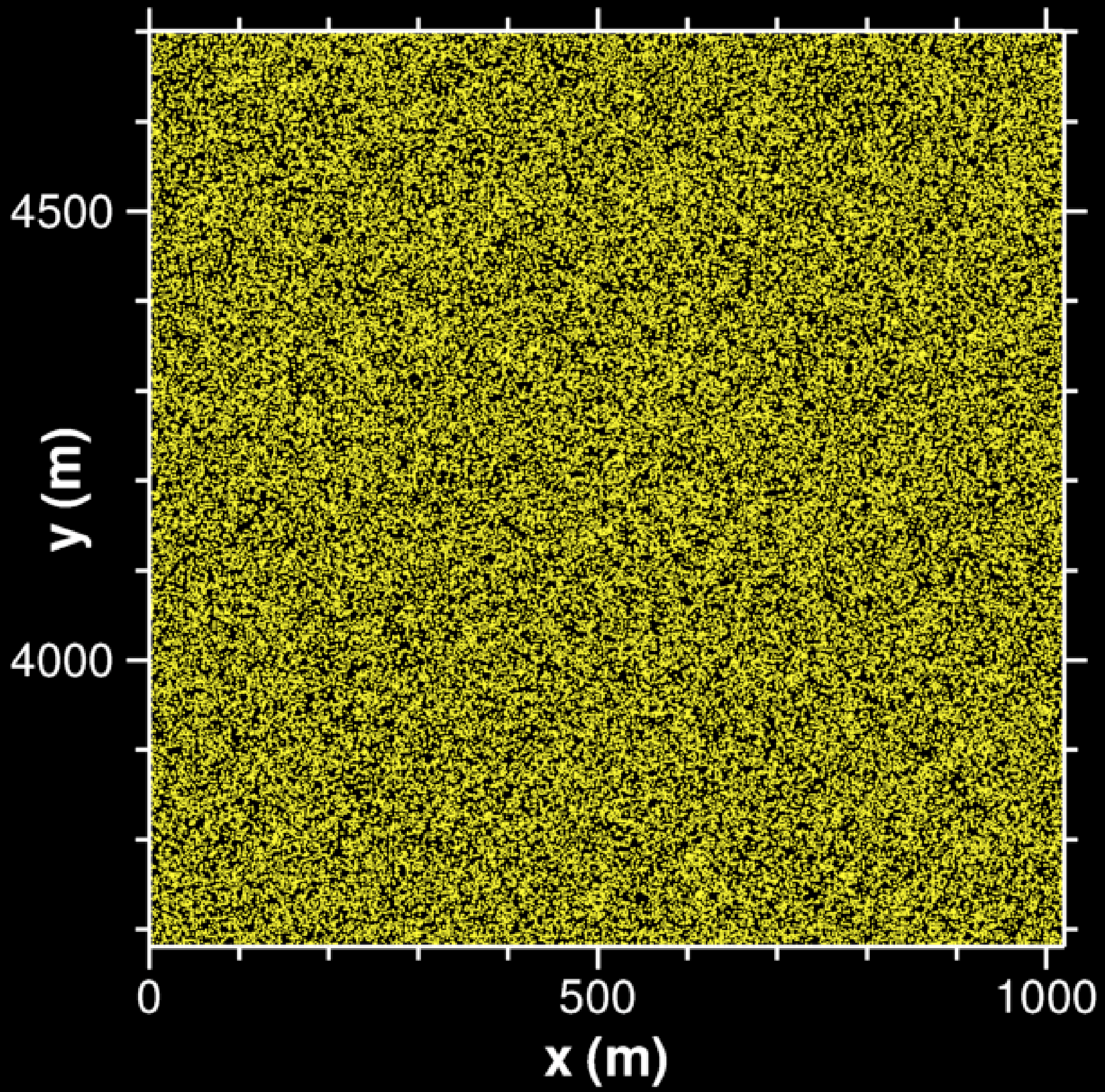
FREE CONVECTION 512^3 W-FIELD

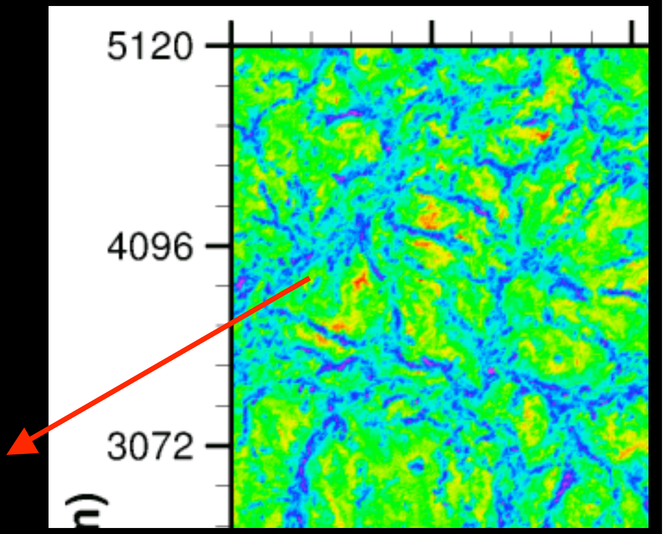


$$\triangle x = \triangle y = 10\ m$$

$$\triangle z = 4\ m$$

PARTICLE TRACING IN X-Y PLANE **1024^3** SIMULATION

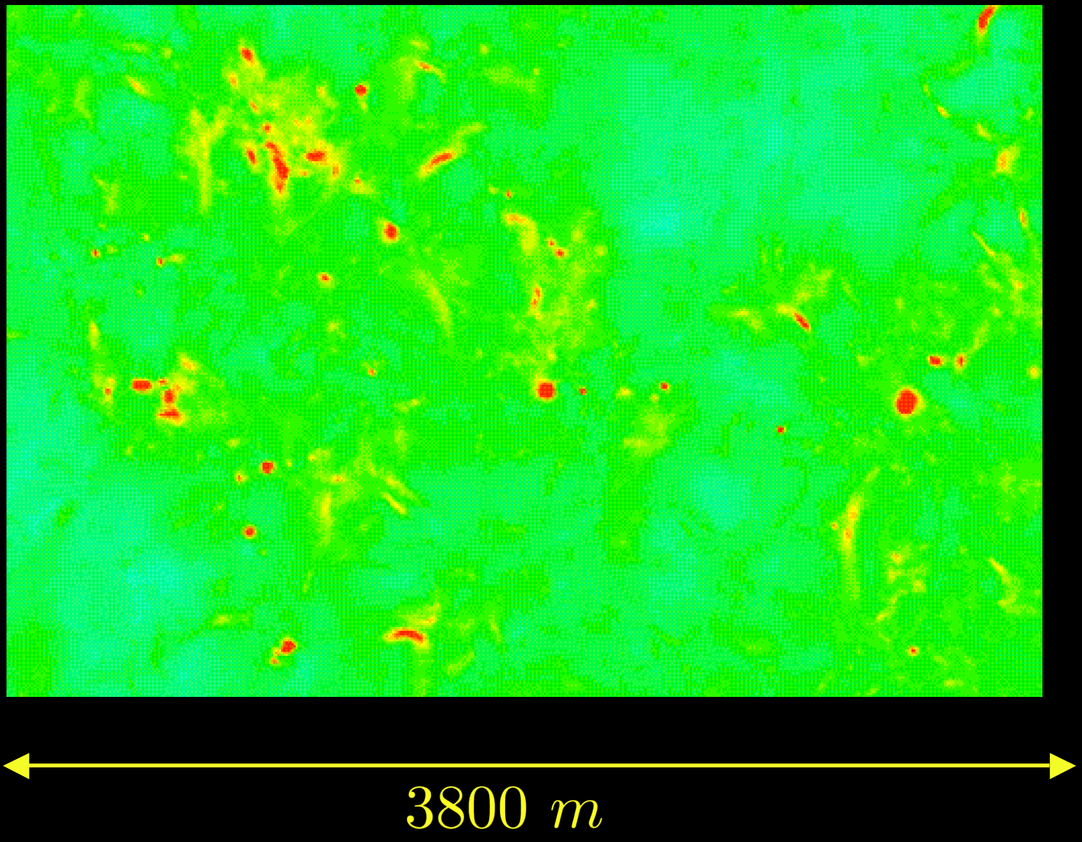




17 Turnover times

4096 CPUs

TEMPORAL EVOLUTION OF VORTICES IDENTIFIED BY LOW (NEGATIVE) PRESSURE



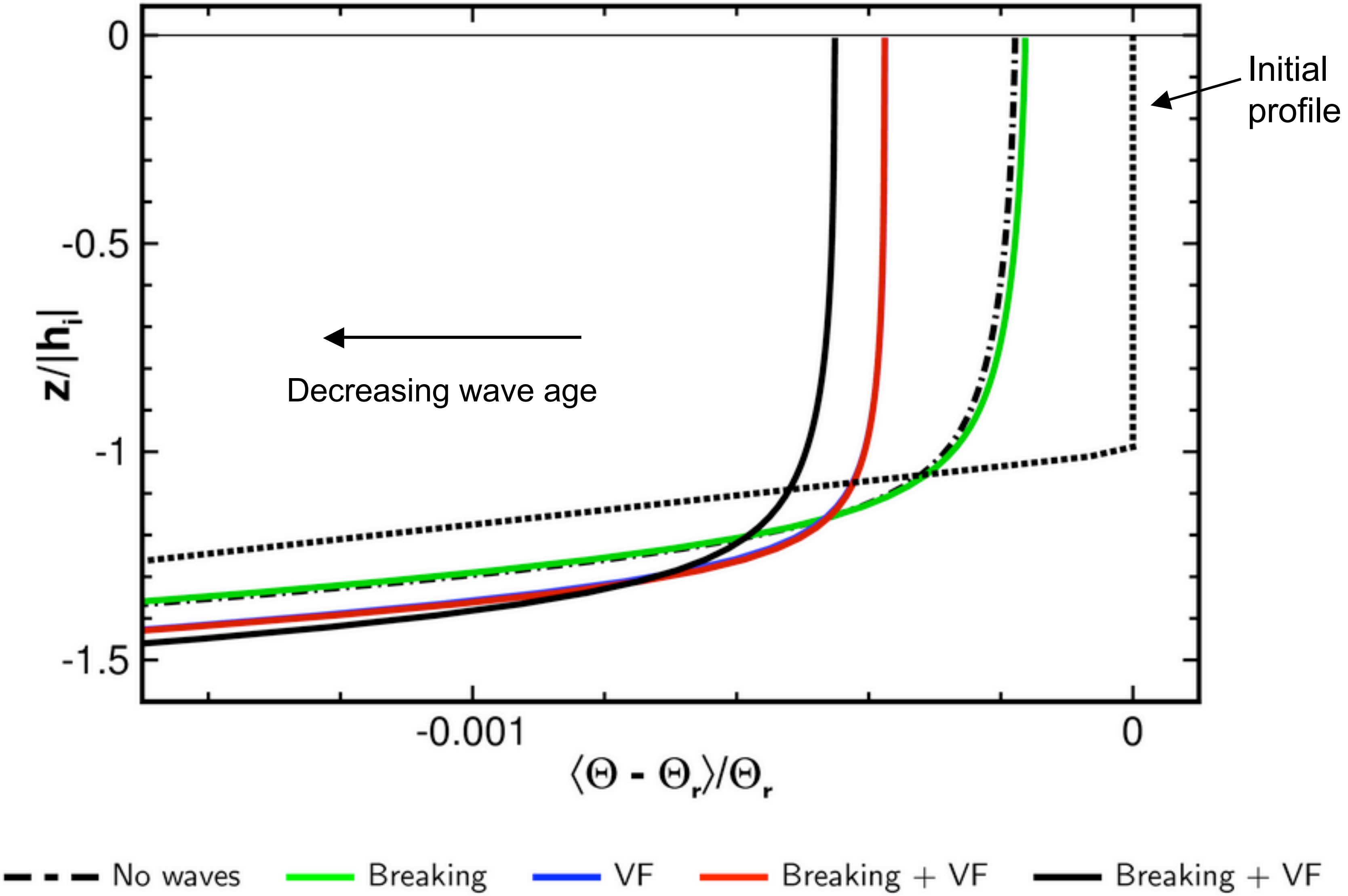
$z = 24\ m$

Dust devil image courtesy NASA

SUMMARY

- Simulations of turbulent atmospheric and oceanic boundary layers are prime candidates for petascale computing
  - Highly parallel algorithm for Boussinesq boundary layers
  - Boundary layer domains with fine resolution
  - Small mesoscale domains with well resolved turbulence
- Coupling of complex surface layer dynamics with PBL turbulence
- Stable (nocturnal) PBLs
- Canopy turbulence, scalar mixing, land surface heterogeneity
- Turbulent dispersion with stratification
- Boundary layer clouds & chemistry
- $\cdots$
- Adequacy of the SGS parameterization, $\Delta_f \sim \mathcal{O}(\Lambda) \Longleftrightarrow$ **OBSERVATIONS**

VARIATION OF MIXED LAYER TEMPERATURE



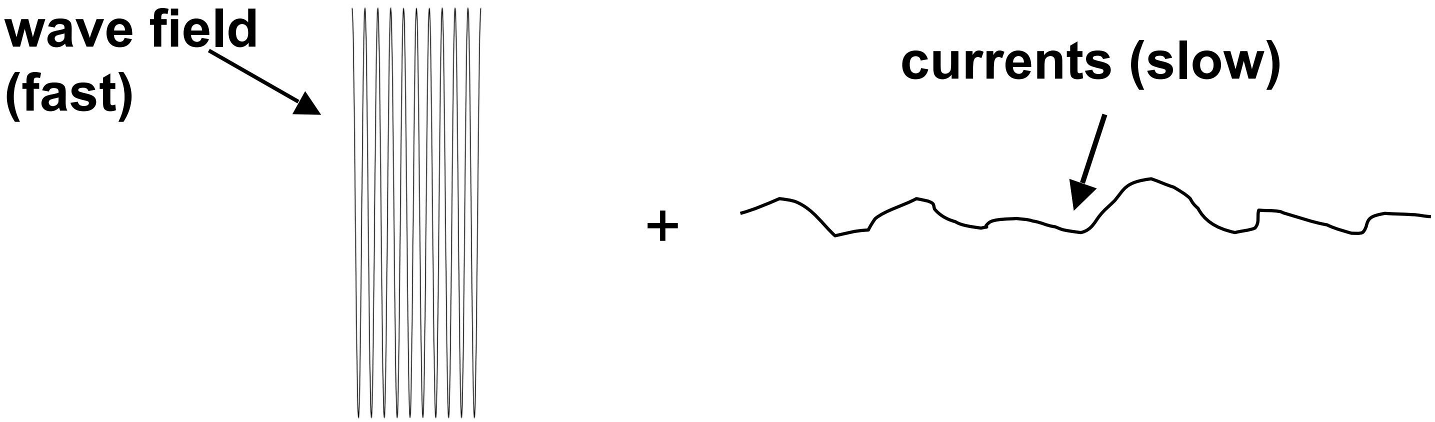
SURFACE WAVES AND OCEAN MIXING

- LES results with explicit wave effects show surface waves modulate OBL currents, scalar transport, and promote non-local mixing
- How did this happen?

CRAIK-LEIBOVICH ASYMPTOTICS

- Assumptions for multiple-time scale analysis
  - Surface waves produce a drift in the wind direction
  - Wave orbital speeds are larger than the currents
  - Wave period is short compared to the time scale for current development

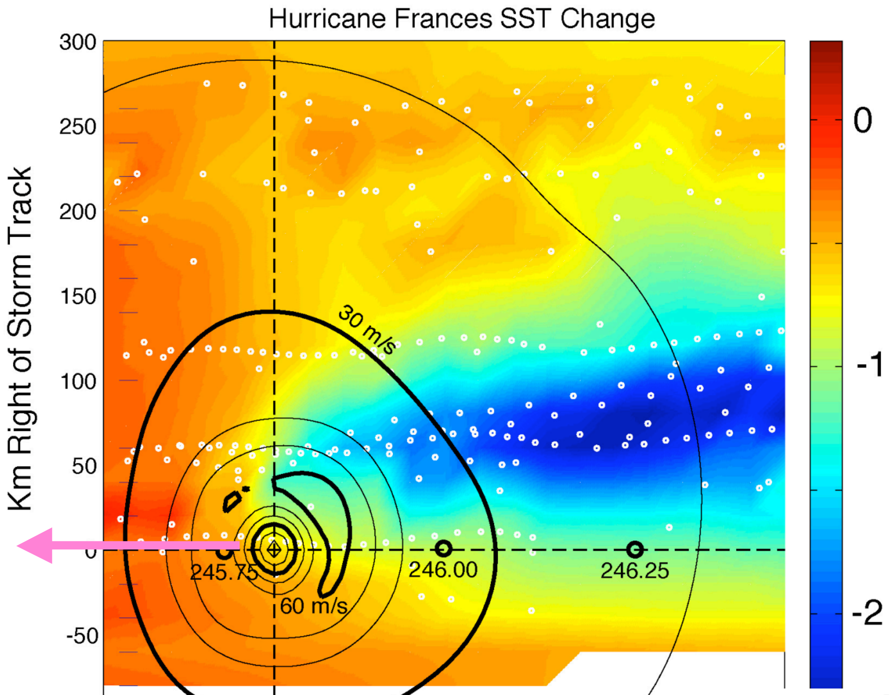
- Critical result momentum equations are augmented by a “vortex force” $\mathbf{u}^{St} \times \boldsymbol{\omega}$
  - $\mathbf{u}^{St}$ is the Stokes drift of the wavefield
  - $\boldsymbol{\omega}$ is the resolved vorticity



wave field (fast)

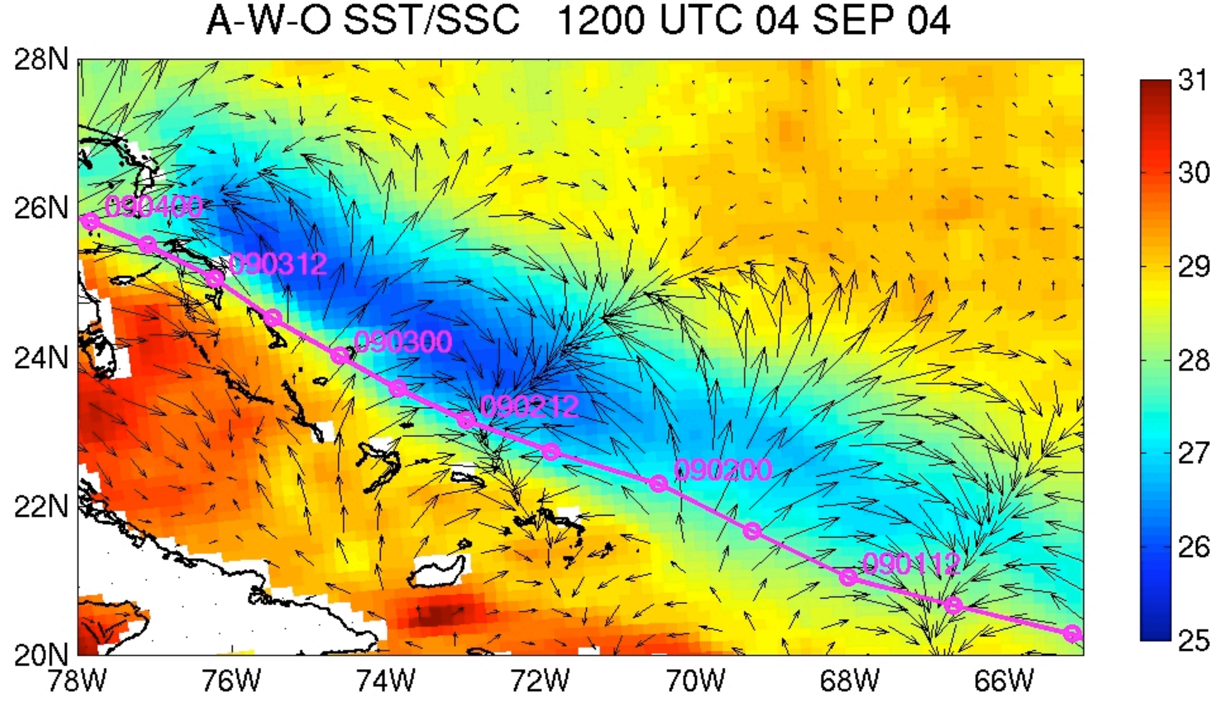
+

currents (slow)

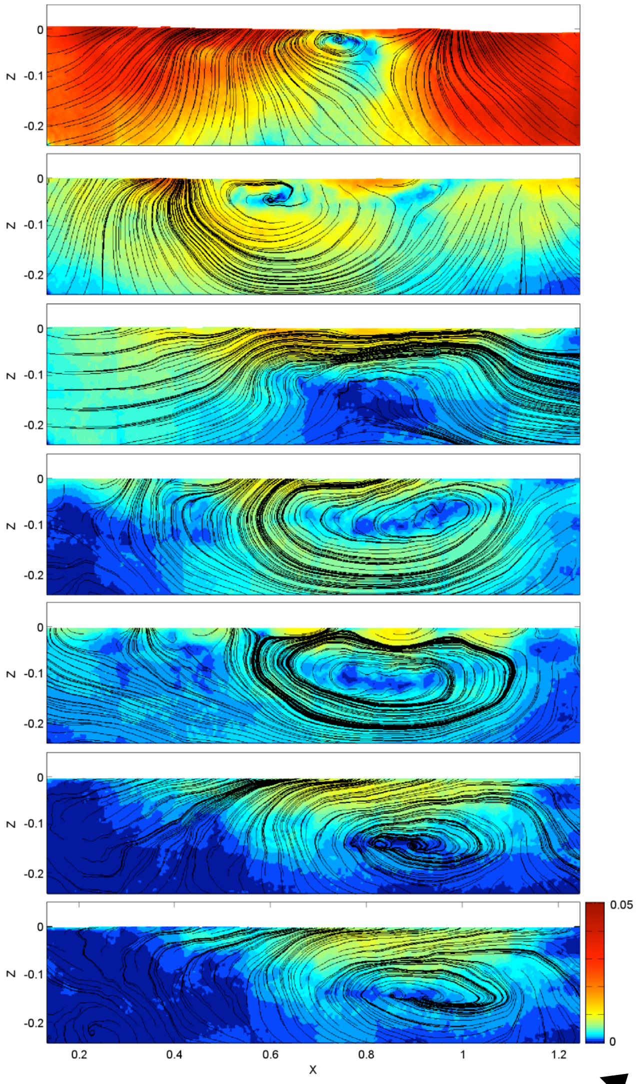


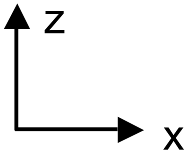
CBLAST observed SST

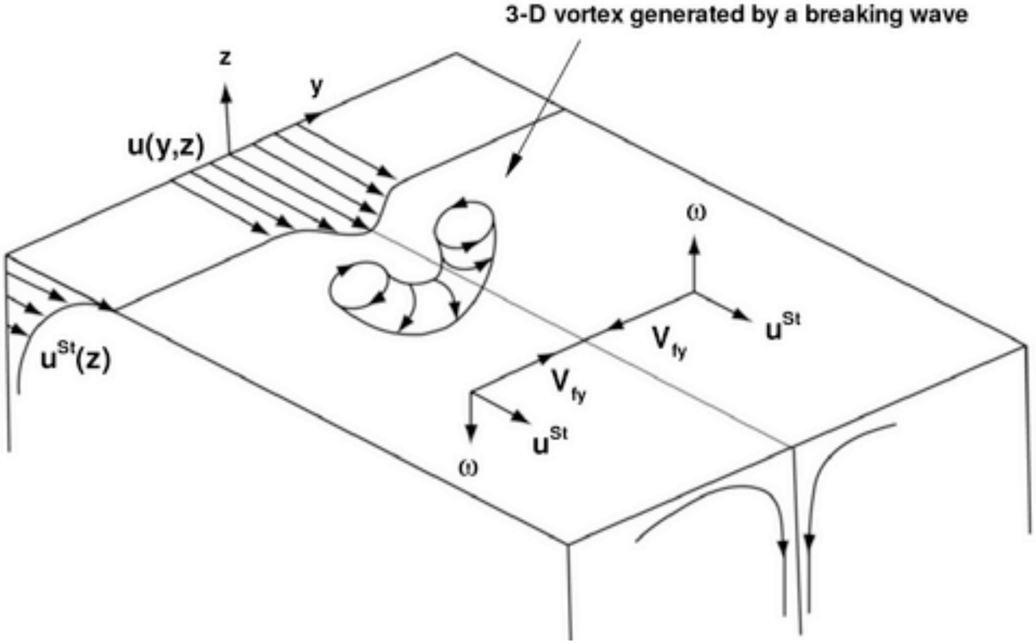
Coupled model SST



COUPLING OF CL2 INSTABILITY AND AN ISOLATED BREAKER







2-D laboratory breaker, Melville, Veron & White

DISCRETE EVENT WAVE BREAKING MODEL

Breaker properties:

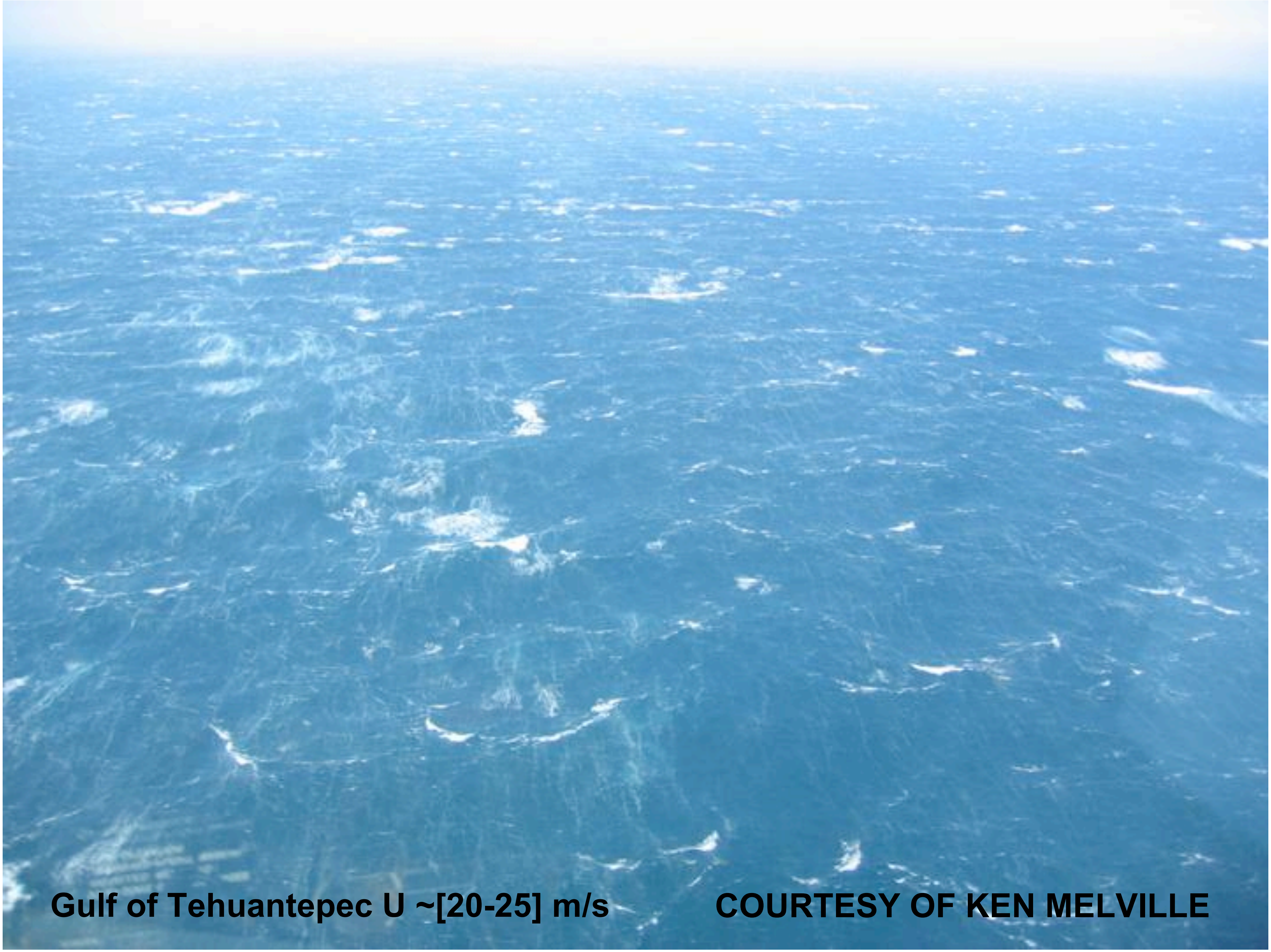
- Events are 3D, compact, impulses $A_b(\mathbf{x}, \mathbf{t})$
- Stochastic surface sites
- Breaker phase speed c is drawn from a PDF $p(c) \sim e^{-\beta\, c/u_{*a}}$
- Breaker production rate $\dot{N}(U_a)$ matches mean wind stress and energy flux

Momentum conservation:

$$\underbrace{\rho_a C_D U_{10}^2 Area}_{Air} \quad = \quad \underbrace{\dot{N} \int_0^c p(c) M(c) dc}_{Water}$$

Breaker momentum:

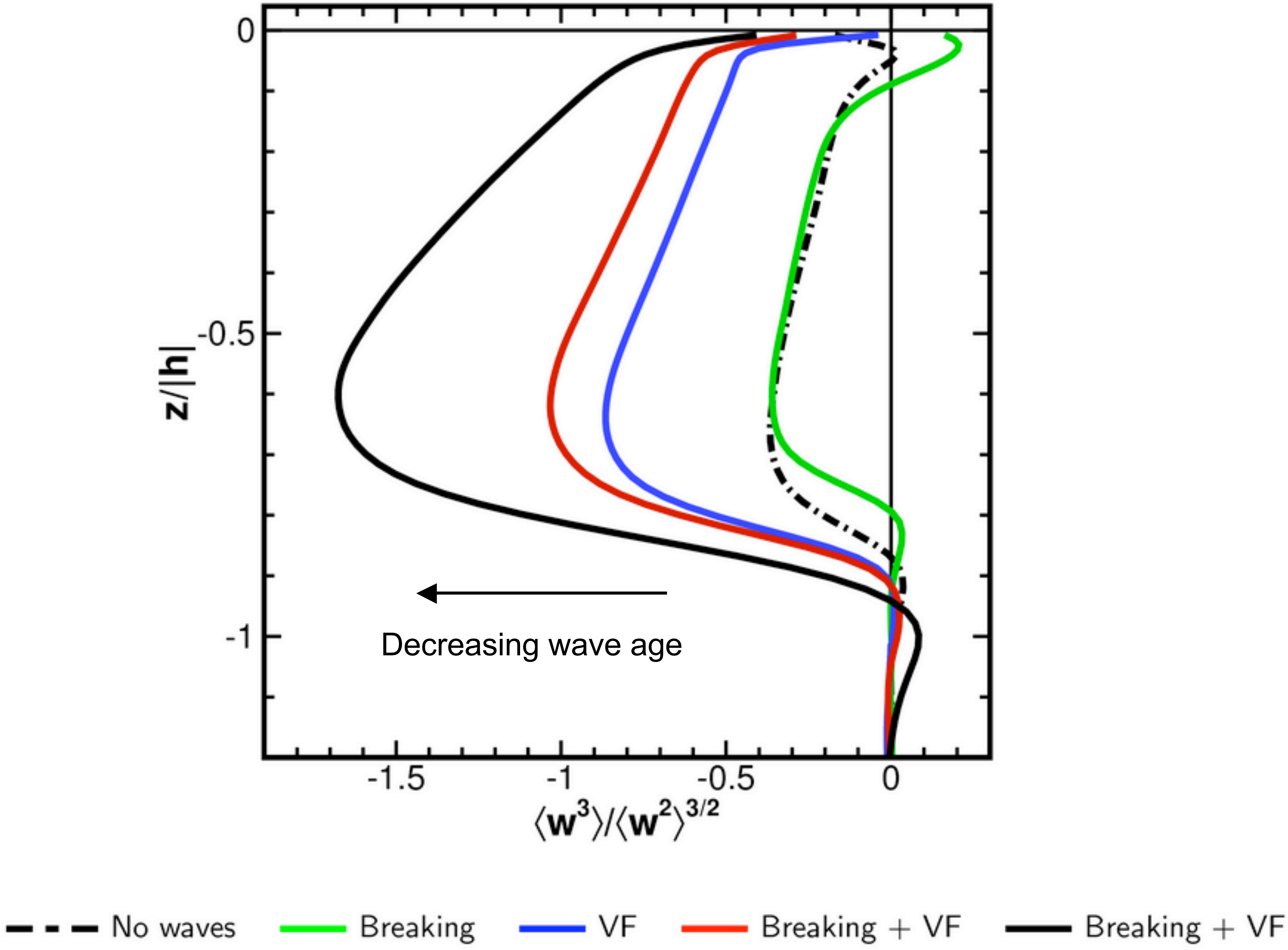
$$M(c) = \rho_w \int_0^{T(c)} dt \int_{-\infty}^{0} dz \int_{-\infty}^{\infty} dy \int_0^{\infty} dx A_b(\mathbf{x}, c)$$



Gulf of Tehuantepec U ~[20-25] m/s

COURTESY OF KEN MELVILLE

VERTICAL VELOCITY SKEWNESS WITH WAVE EFFECTS



COUPLING WAVES AND INERTIAL RESPONSE IN A HIGH WIND DRIVEN OBL

Wind speed $U_a = 30$ ms^{-1}

- Smallest breaker modeled $c_b \sim 2$m/s $\rightarrow t_b = 1$ s
- Wave-current interactions $C_p \sim 1.2 U_a = 36$ m/s $\rightarrow t_{St} = 20$ s
- Large eddy turnover time $(h, u_*) \sim (100m, 0.034m/s) \rightarrow t_t = 2900$ s
- Inertial period $2\pi/f \rightarrow t_i = 62,800$ s

LES domain and time step

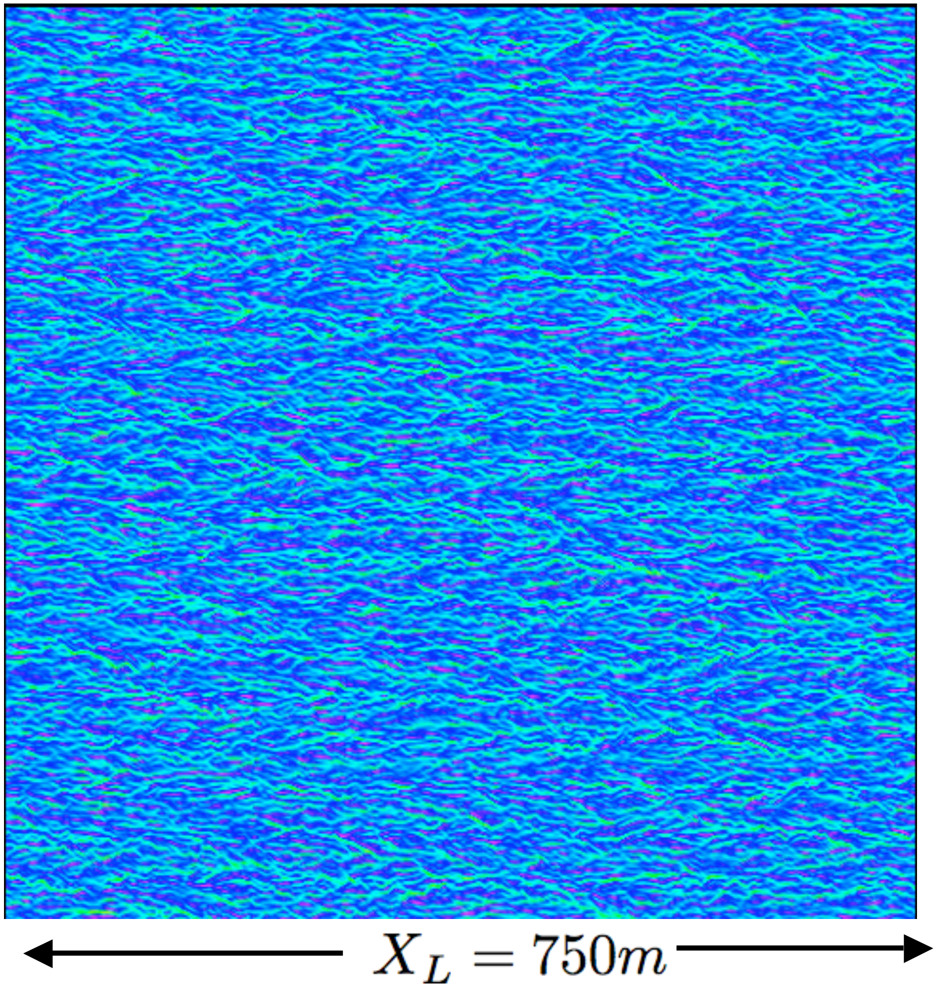
- $\triangle t \sim 0.5$ s
- $\triangle x \sim 1.0$ m
- $(N_x, N_y, N_z) \sim (1000, 1000, 256)$
- Number of time steps $N_s \sim [400,000 \sim 500,000]$ steps

Vary translation speed V_s and LES domain locations

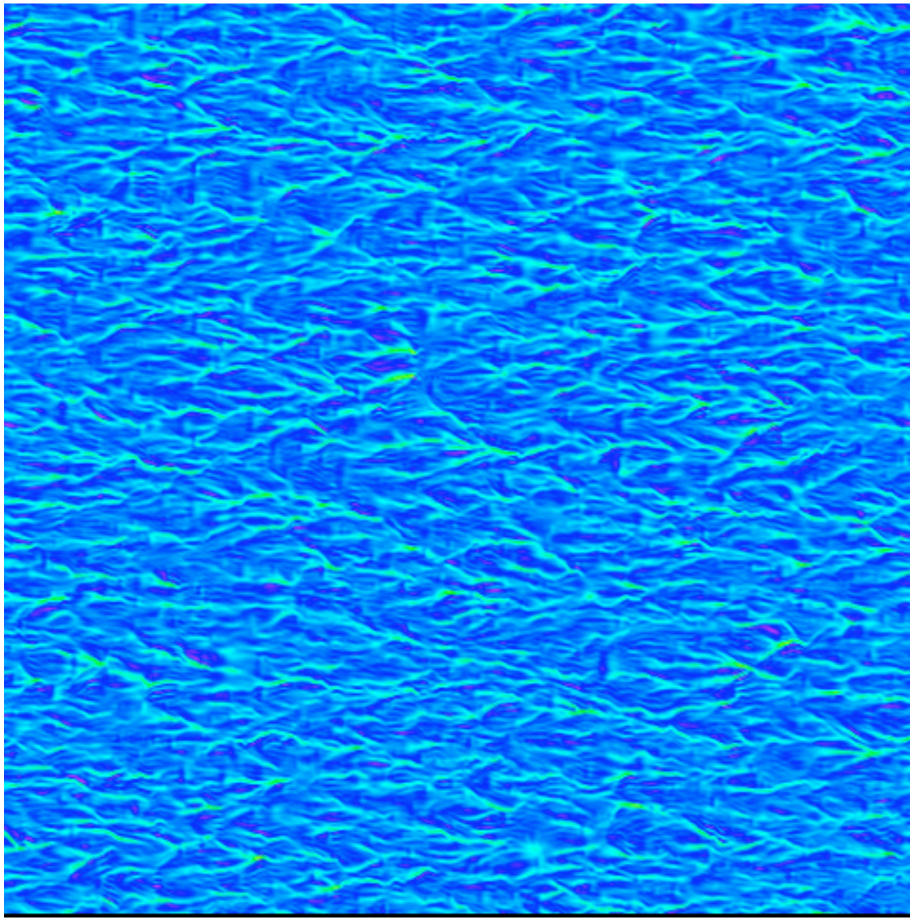
GOAL: IMPACT ON SST AND MIXED LAYER COOLING

X-Y SURFACE PATTERNS OF VERTICAL VELOCITY, z = -1m, WINDS = 30m/s

UNIFORM STRESS PLUS VORTEX FORCE



VORTEX FORCE PLUS WAVE BREAKING



OBL LES EXPERIMENTS WITH WAVE EFFECTS

Problem Design

- Moderate to high winds, $U_a = [15 - 30]$ m/s
- Fetch limited wave height spectrum, Donelan (1985)

Parameter Variations

- Uniform surface stress $\boldsymbol{\tau}$ no wave effects
- Uniform surface stress with vortex force no breaking
- Stochastic breaking no vortex force
- Mixed runs with breaking + vortex force for varying wave age

Algorithm

- Mixed pseudospectral finite-difference scheme
- Runge Kutta time stepping
- FFTPACK routines
- Custom transpose routines for pressure solver
- Parallelization
  - MPI decomposition in z-direction (limiting)
  - OMP threads in $x - y$ planes (complicated)

SCALING OF PARALLEL PSEUDOSPECTRAL ALGORITHM WITH 2-D DOMAIN DECOMPOSITION

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