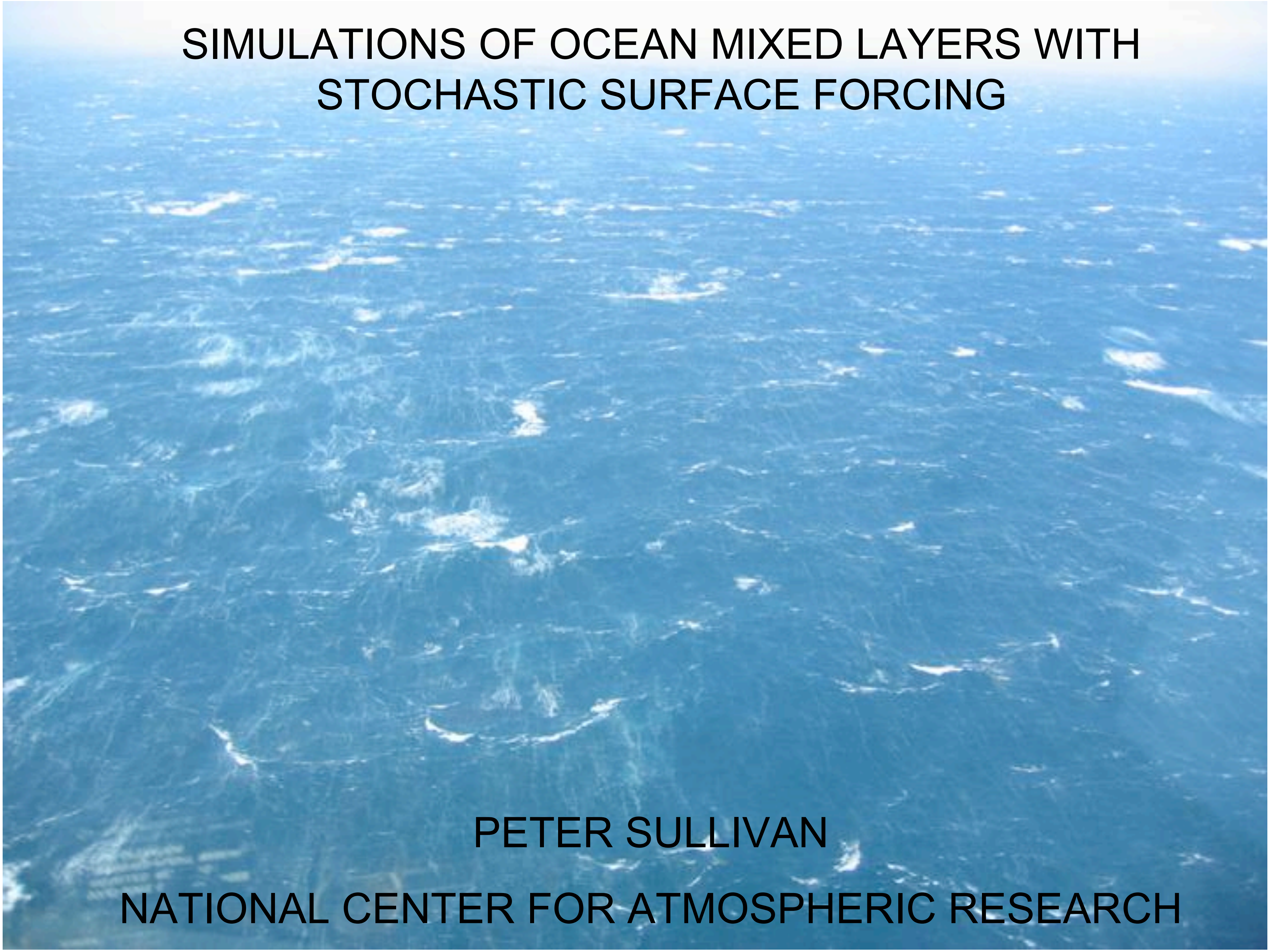

SIMULATIONS OF OCEAN MIXED LAYERS WITH STOCHASTIC SURFACE FORCING

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Collaborators:

James McWilliams (UCLA)

Ken Melville (SIO)

WINDS TO WAVES TO CURRENTS

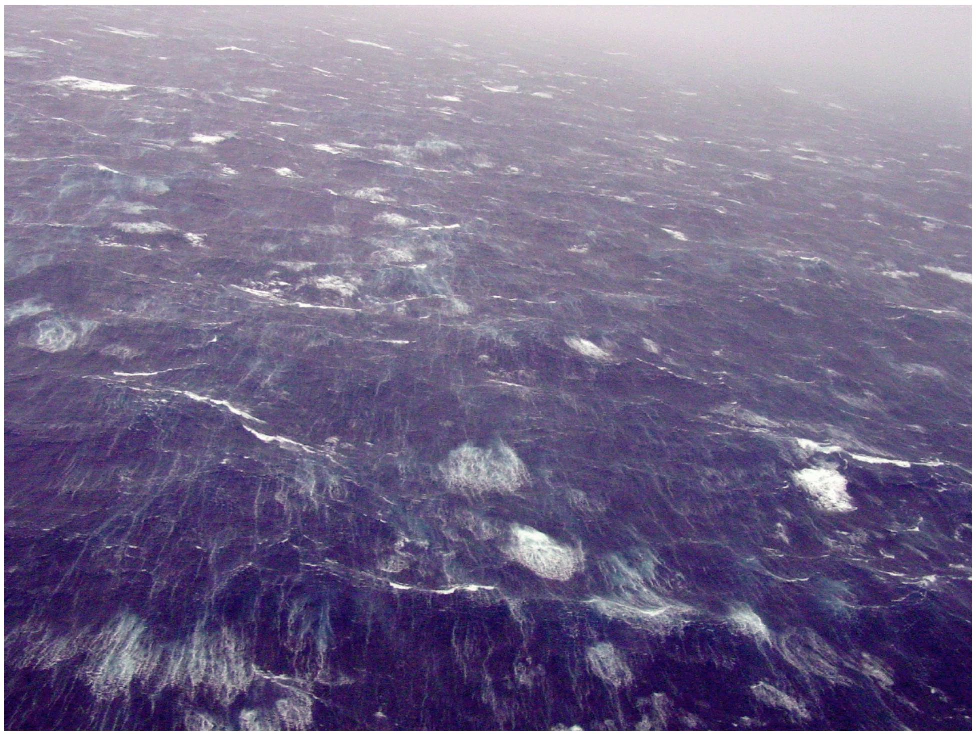
``… At wind speeds above about 8m/s, momentum is believed to be transferred between air and water principally through waves and not by viscous drag on the surface.

… Momentum and kinetic energy is delivered to the underlying water through the intermediary of waves amplified and dissipated locally…"

Mark Donelan (1998)

HIGH WIND SURFACE DYNAMICS
WAVE BREAKING AND LANGMUIR CIRCULATIONS

Intermittent fluxes of momentum and energy



Hurricane Isabel CBLAST Photo courtesy M. Montgomery (CSU)

Wave-averaged effects

Great Salt Lake Photo courtesy S. Monismith (Stanford)

DISCRETE EVENT WAVE BREAKING MODEL

Breaker properties:

- Events are 3D, compact, impulses $A_b(\mathbf{x}, \mathbf{t})$
- Stochastic surface sites with random orientation θ
- Breaker phase speed c is drawn from the measured p.d.f. $p(c) = e^{-0.64c}/c^2$
- Breakers are limited to $c < c_p$ the peak in the wave spectrum
- Breaker production rate $\dot{N}(U_{10})$ matches mean wind stress $\langle\tau\rangle$
- Small scale breaker work $W = k_w A_b c$ matches mean atmospheric energy flux $\langle E_f\rangle$

Momentum conservation:

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

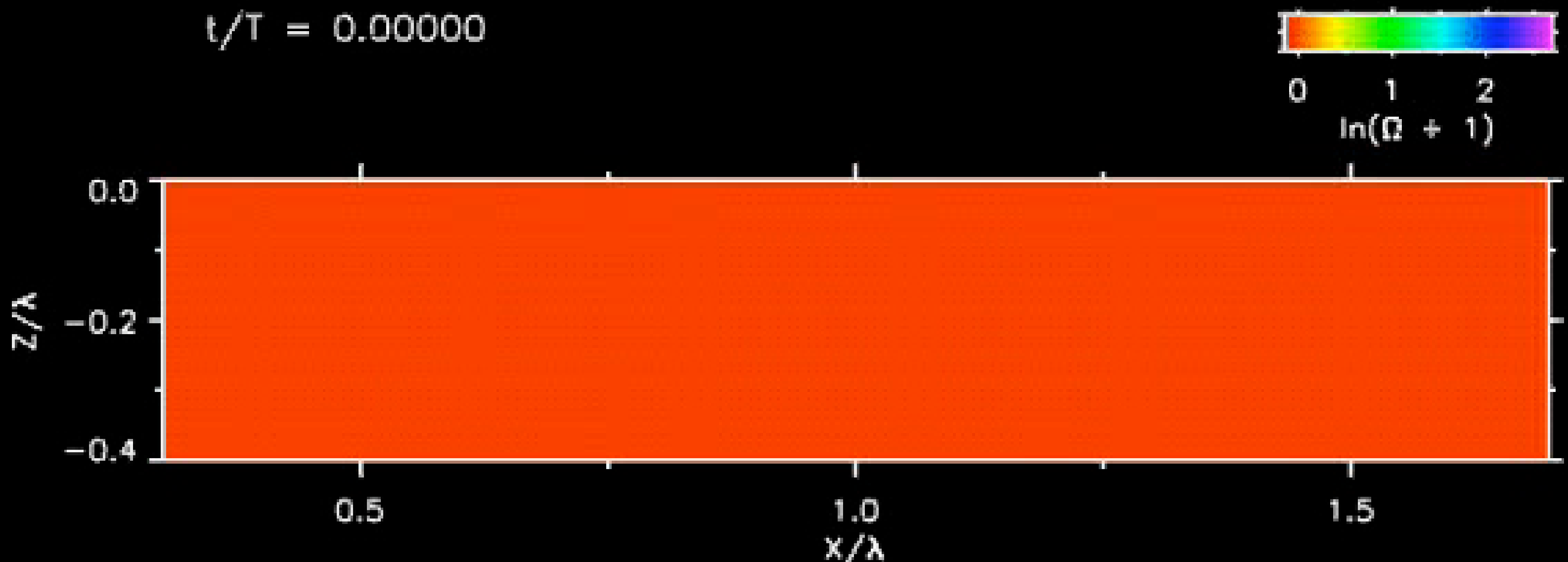
Breaker momentum:

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

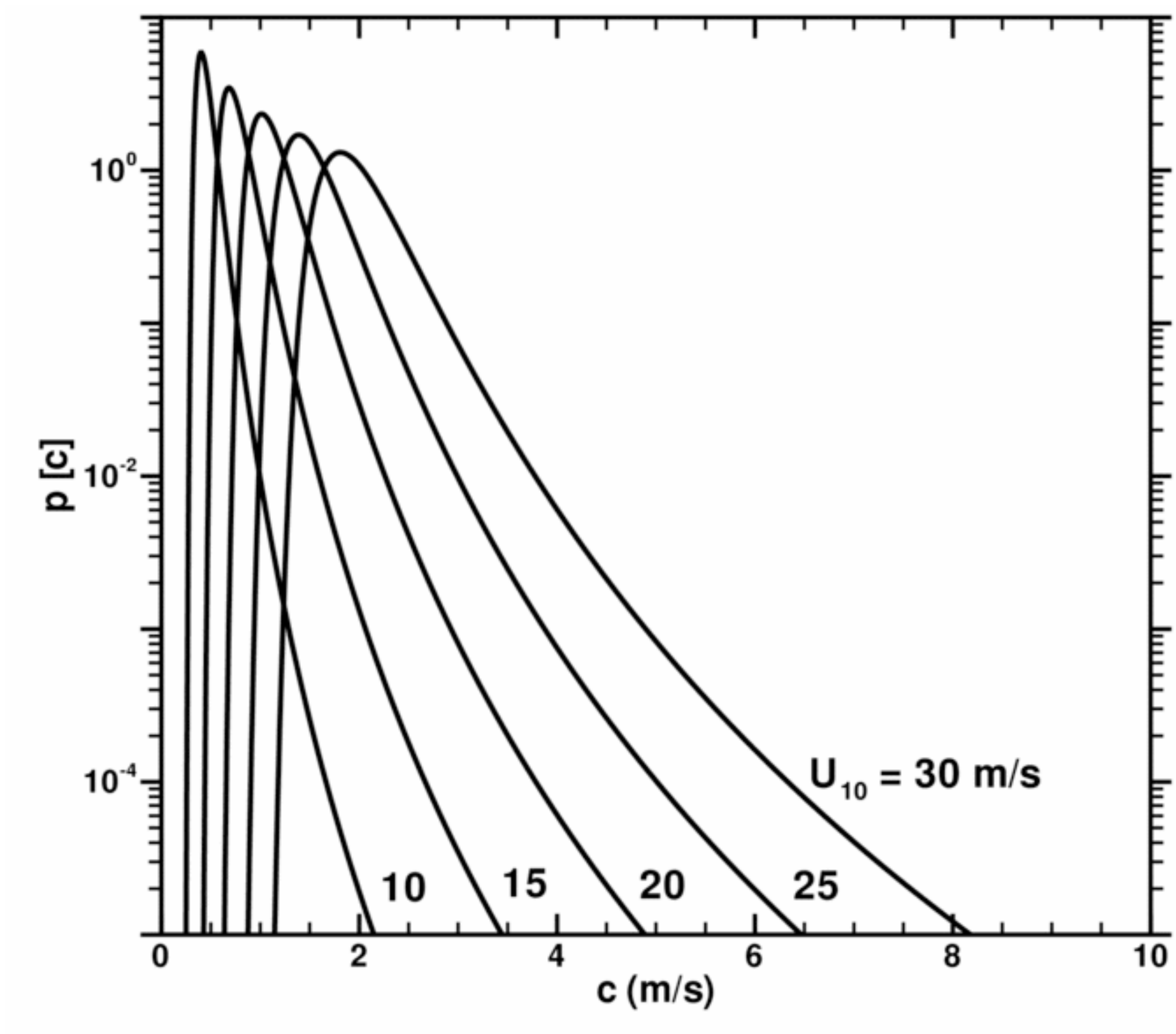
BREAKER MODEL

- Developed from laboratory measurements (Melville *et al.*, JFM 2002) and evaluated in DNS (Sullivan *et al.*, JFM, 2004)

- Impulse A_b is described by dimensionless shape functions based on Froude scaling
  $A_b(x, y, z, t) = k_b \frac{g}{2\pi} \mathcal{T}(\alpha)\, \mathcal{X}(\beta)\, \mathcal{Y}(\delta)\, \mathcal{Z}(\gamma)$



PDF OF BREAKING FOR VARYING WIND SPEED



CRAIK-LEIBOVICH EQUATIONS WITH WAVE-CURRENT INTERACTIONS

ASSUMPTIONS FOR MULTIPLE-TIME-SCALE ANALYSIS

- Surface waves produce a drift in the wind direction
- Wave orbital speeds are much larger than the currents produced by frictional stresses
- Wave period is short compared to the time scale for the development of the currents

Craik-Leibovich (1976), Leibovich (1983), McWilliams & Restrepo (1999), McWilliams *et al.*(2004)

LES EQUATIONS WITH WAVE EFFEECTS

Momentum

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

SGS e

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

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

Density

(..) - Stokes terms

(..) - Breaker terms

LES EXPERIMENTS

Problem Design

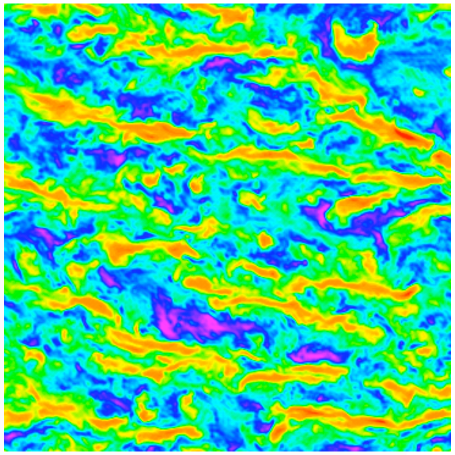
- $U_{10} \geq 10$ m/s
- $Q_* \approx [5 \cdot 10^{-7}]$ K-m/s
- $z_i = -35$ m
- Fully developed wave field with f^{-4} tail Donelan spectrum

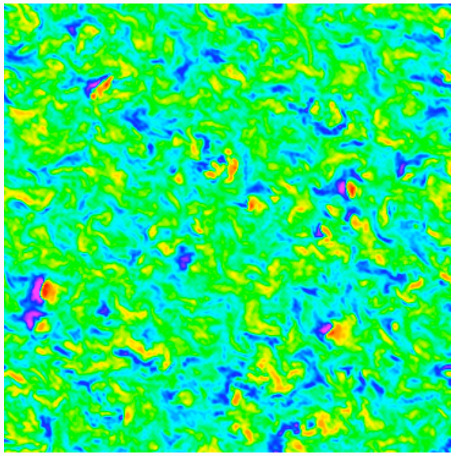
Parameter Variations

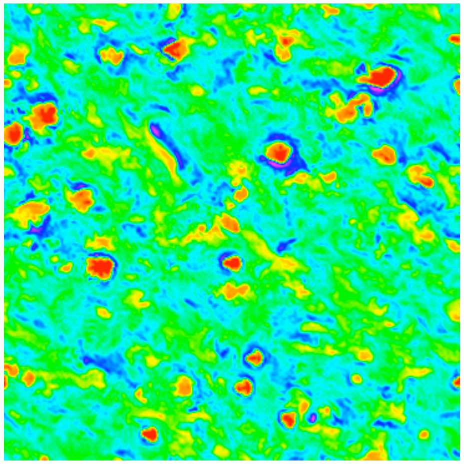
- Uniform surface stress no wave effects
- Uniform surface stress with Stokes drift
- 100% intermittent stress from breakers
- Mixed run with breakers + Stokes drift

Discretization

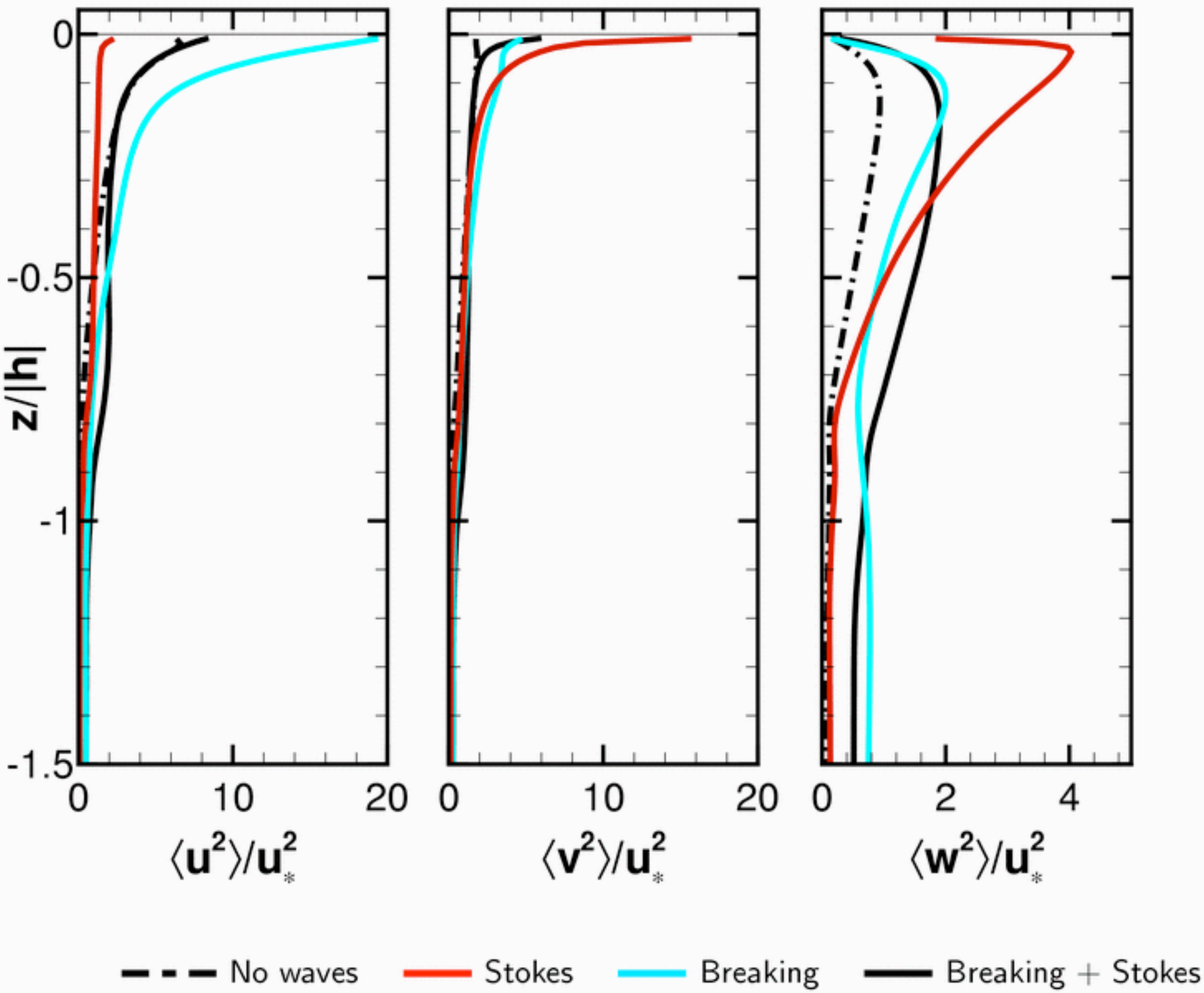
- $X_L = Y_L = 300m$, $Z_L = -110m$
- $N_x = N_y = 300$, $N_z = 128$
- $\Delta_x = \Delta_y = 1.0m$, $\Delta_z \approx [0.37 - 1.6]m$
- $\Delta t \approx [0.5 - 1.0]$ s
- $N_{steps} > 50,000$



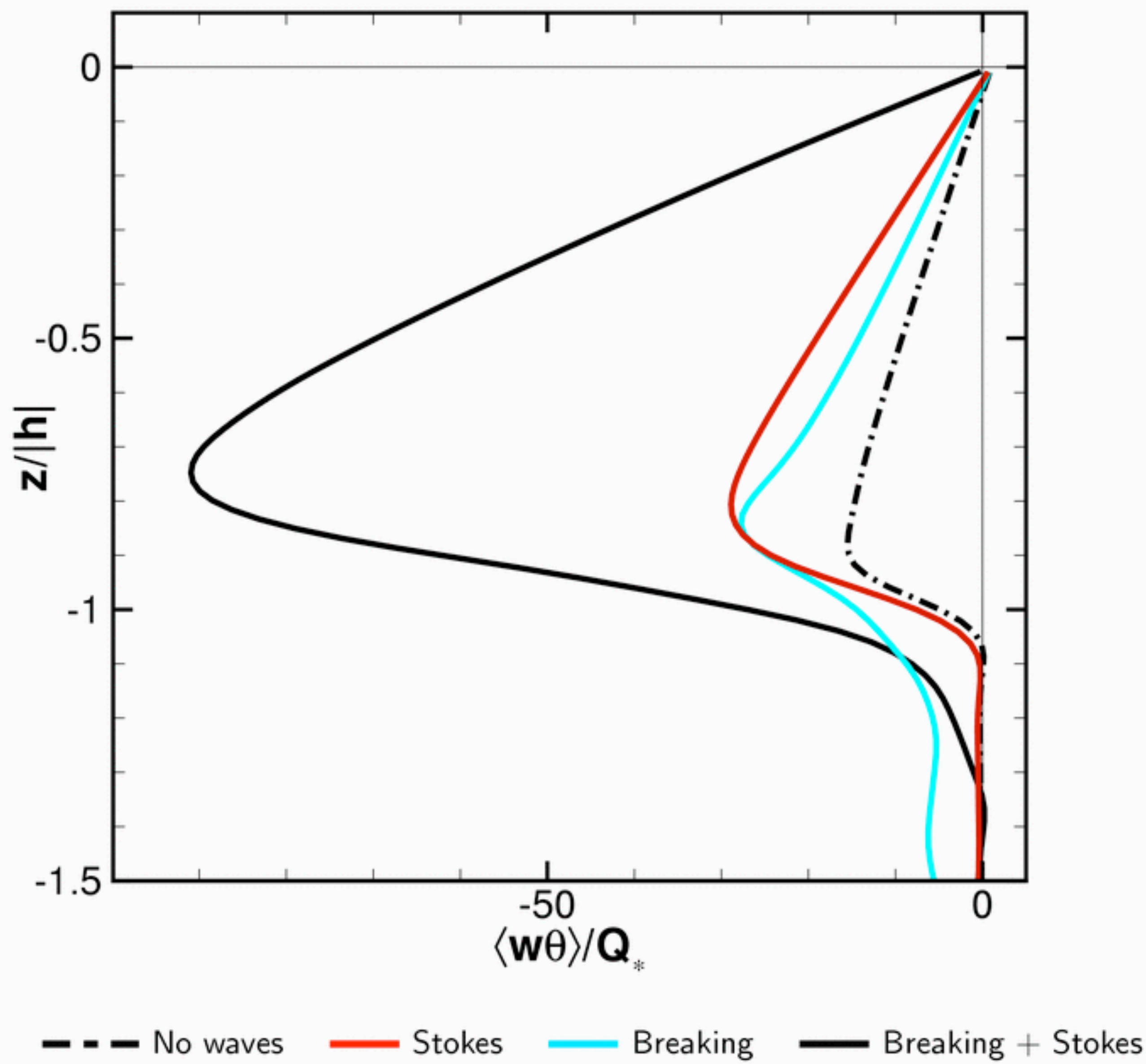




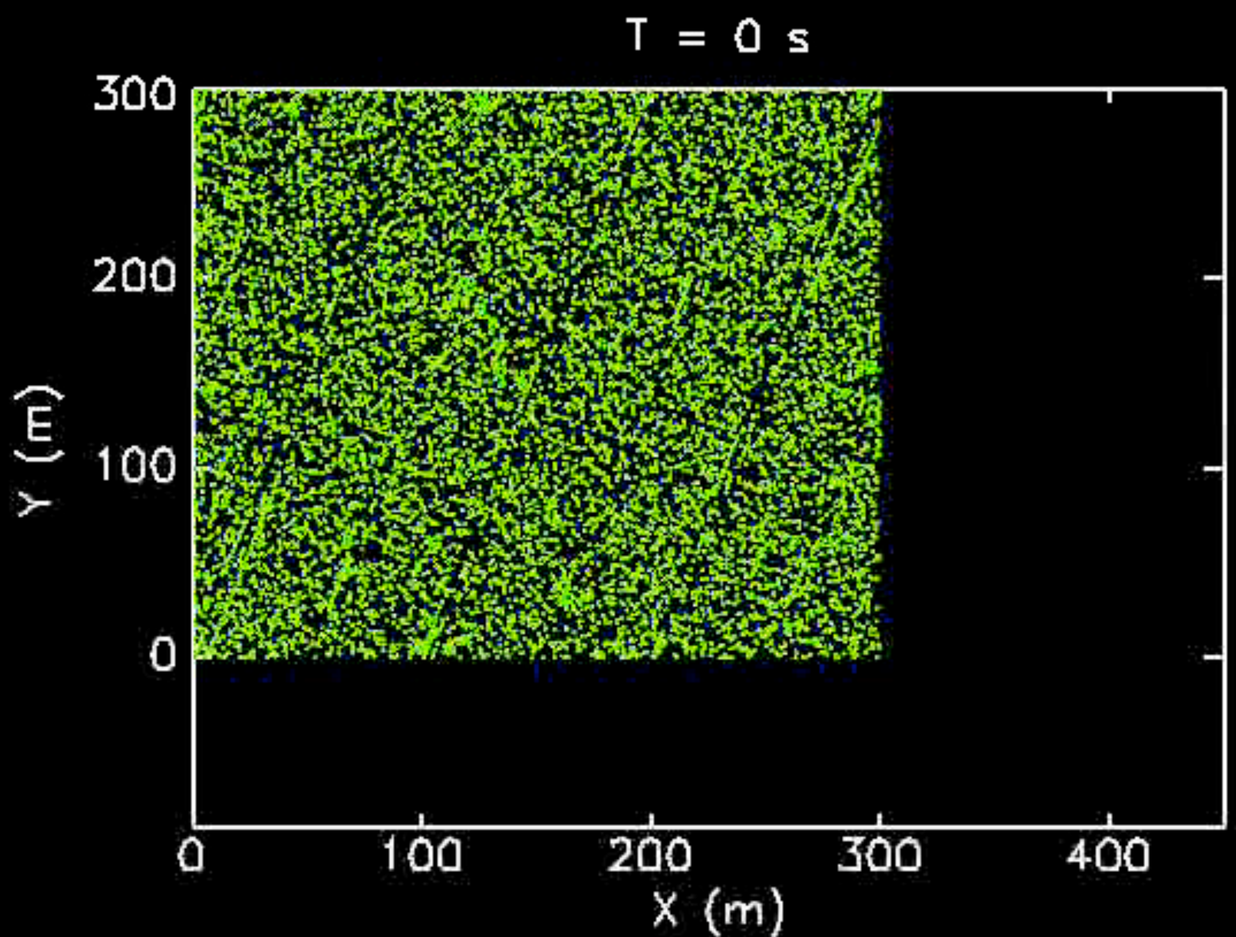
VARIANCE PROFILES



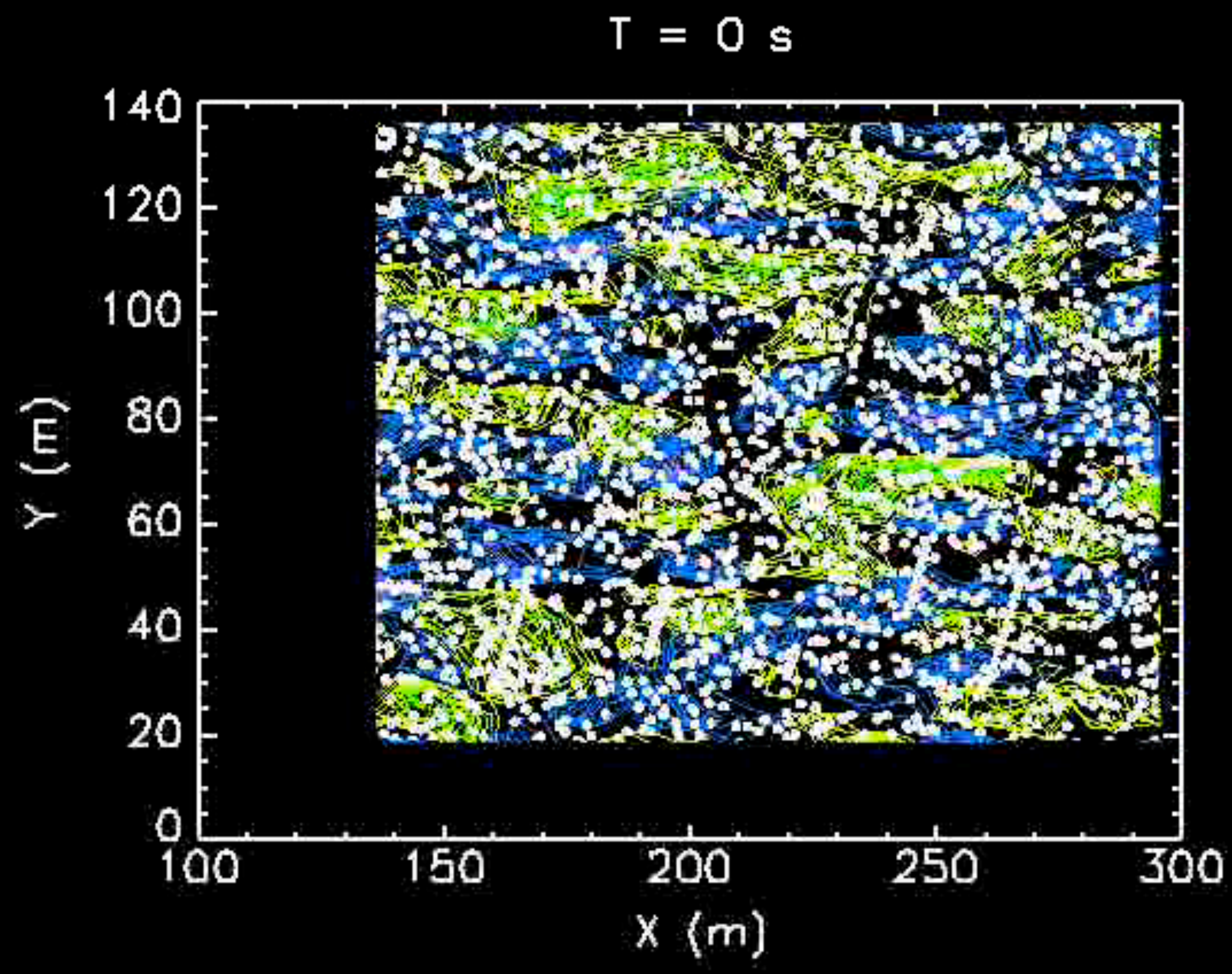
VERTICAL SCALAR FLUX $\langle W\Theta \rangle$



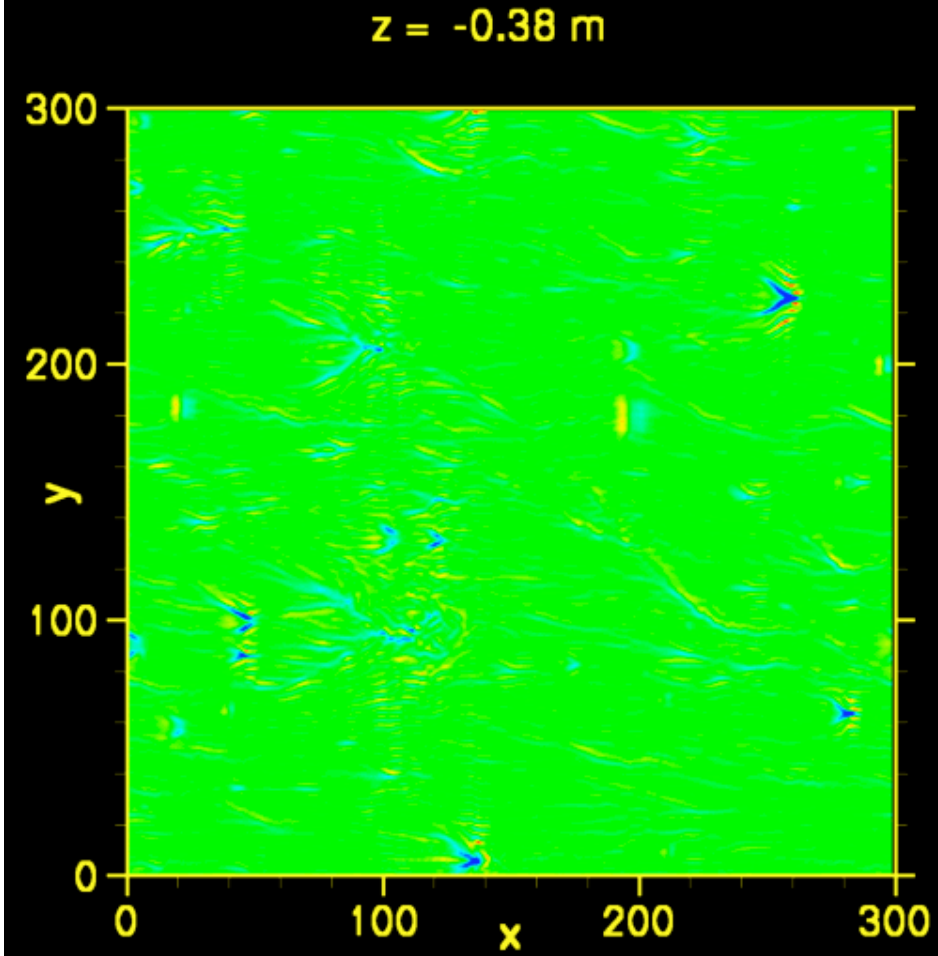
LES OF OCEAN PBL WITH WAVE EFFECTS
PARTICLE PATHS

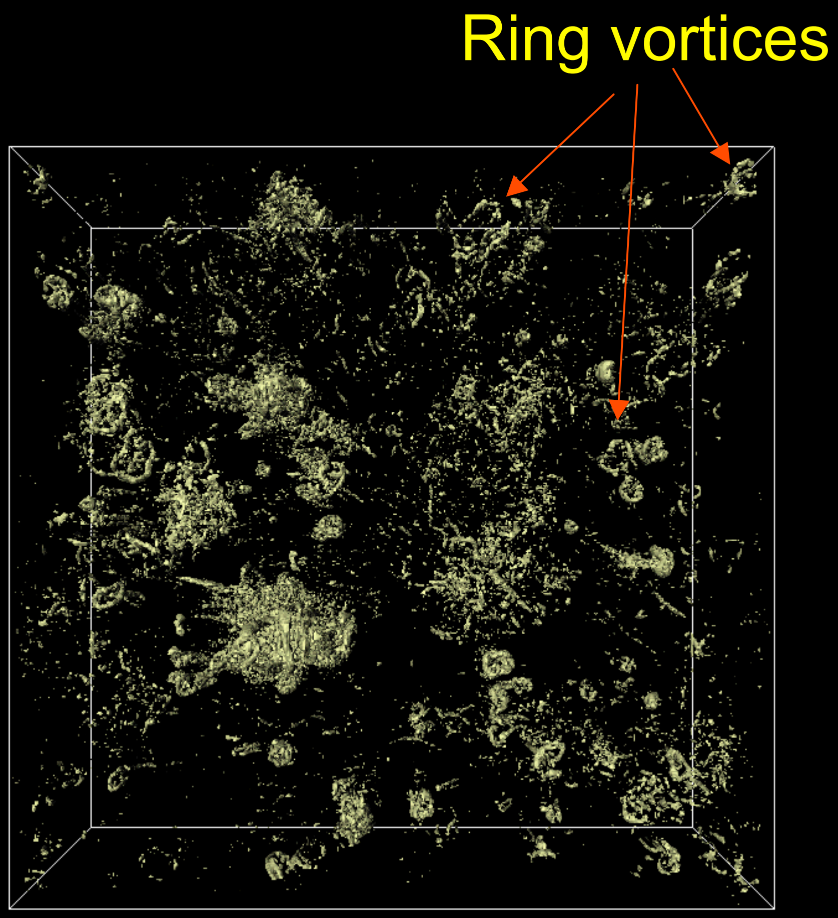


PARTICLE PATHS OVERLAYING VORTICITY CONTOURS



STOCHASTIC LES WITH WAVE BREAKING:
W VISUALIZATION IN Z PLANES AND 3D STRUCTURES





CONCLUSIONS/SUMMARY

We have developed an LES OBL model for high winds:

- Primary input is the U_{10} wind this fixes
  the wave field and the fluxes of momentum and energy supplied to the OBL
- Discrete stochastic wave breaking model
- Model of wave-current interaction from asymptotic analysis

High-wind LES show that:

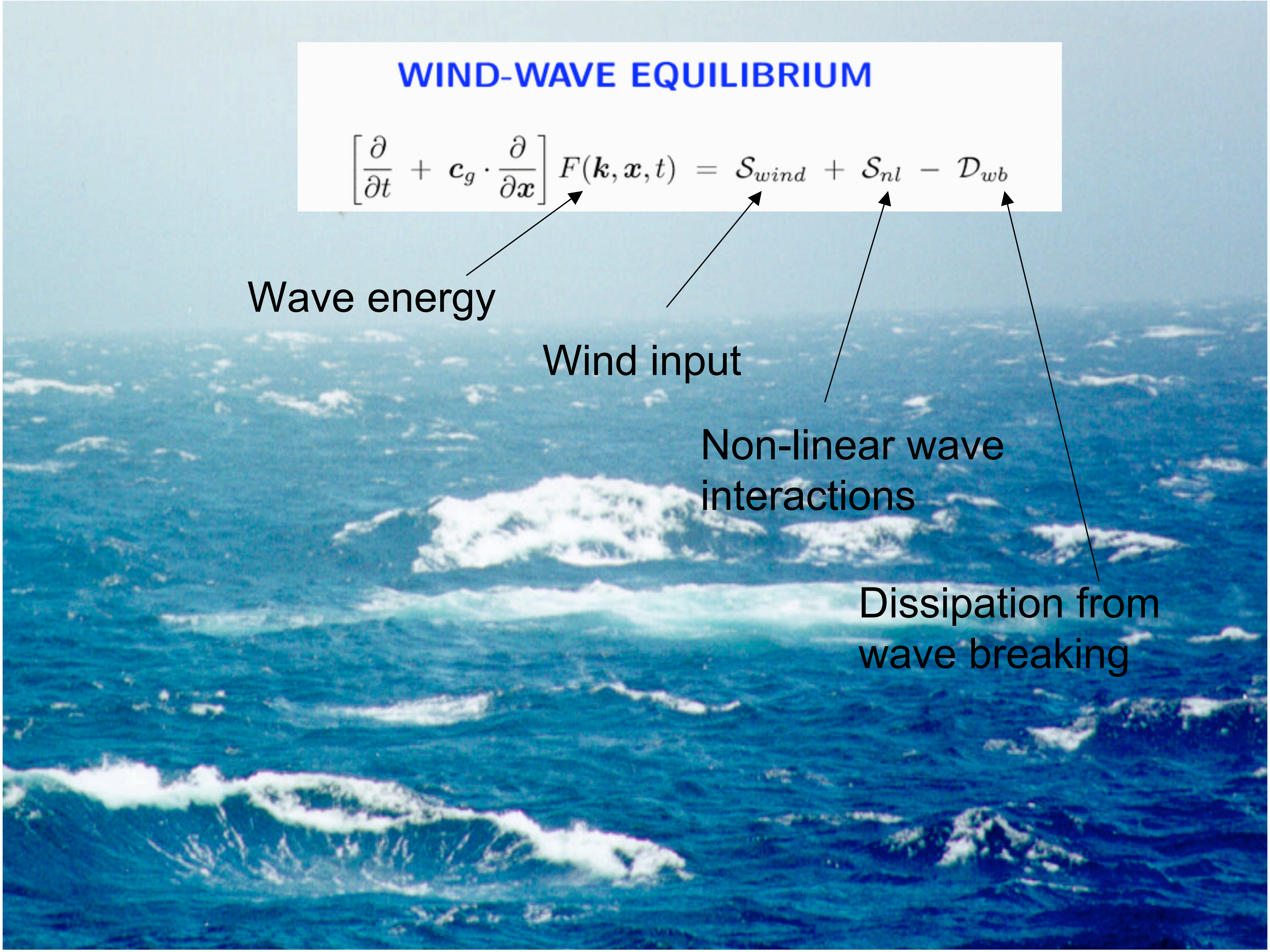
- Effects of breaking and Stokes drift are NOT additive
- Breaking and Langmuir circulations act synergistically
- Potent coherent structures are induced by breaking waves in
  the presence of LC convergence
- These "new" turbulent structures promote global mixing
- Inclusion of a realistic wave spectrum greatly enhances
  near surface production/dissipation of TKE compared to prior LES

Observational needs:

- Breaker pdf[c], or $\Lambda(c)dc$ average length of breaking crests
- Stokes drift in high winds
- Vertical velocity skewness
- Evolution of the OBL with time dependent forcing

WIND-WAVE EQUILIBRIUM

$$\left[\frac{\partial}{\partial t} + \boldsymbol{c}_g \cdot \frac{\partial}{\partial \boldsymbol{x}}\right] F(\boldsymbol{k}, \boldsymbol{x}, t) = \mathcal{S}_{wind} + \mathcal{S}_{nl} - \mathcal{D}_{wb}$$

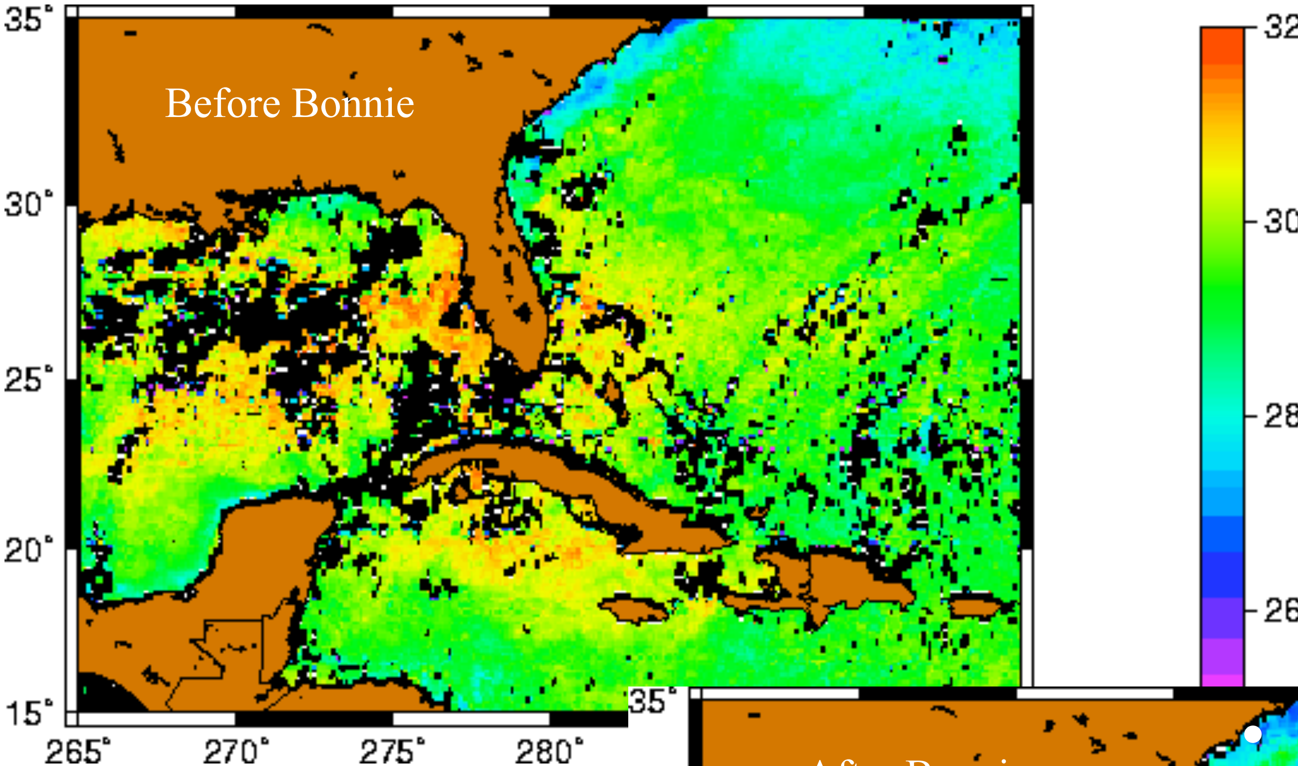


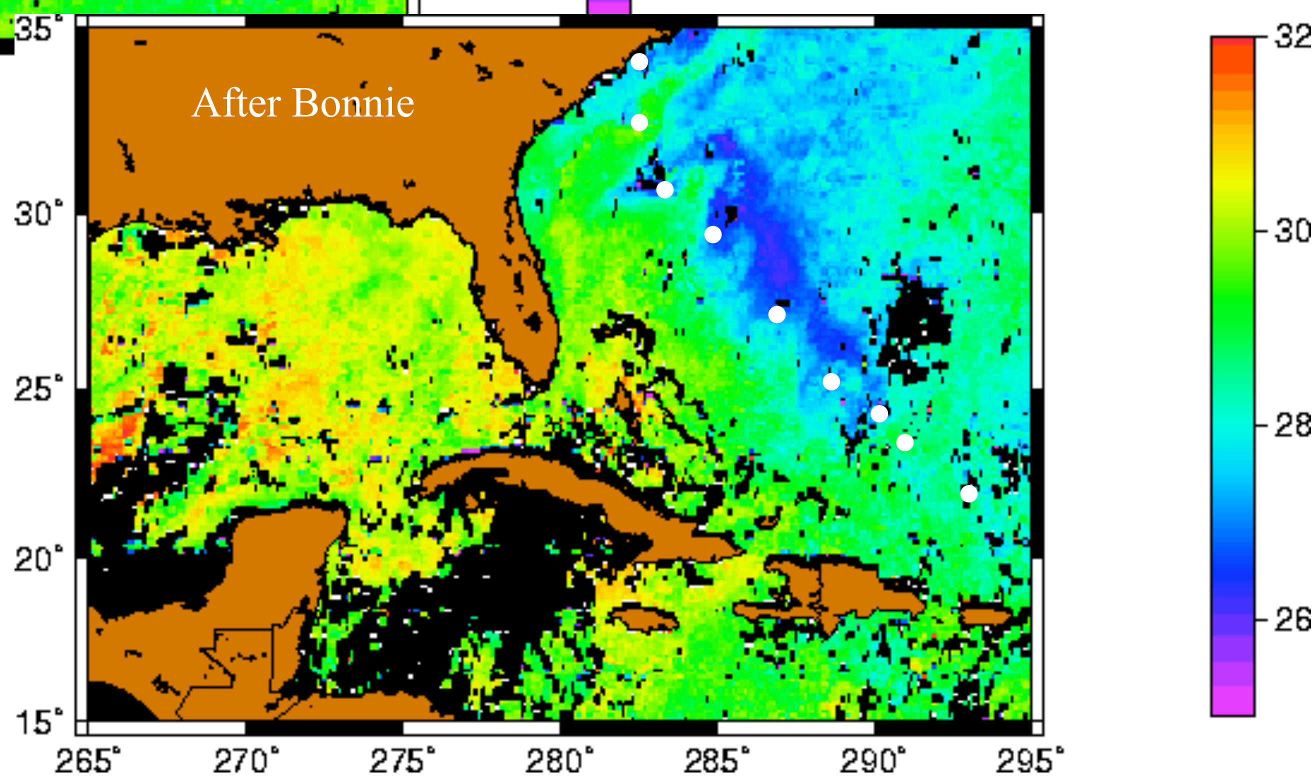
CONCLUSIONS

Waves leave a strong imprint on the atmosphere and ocean

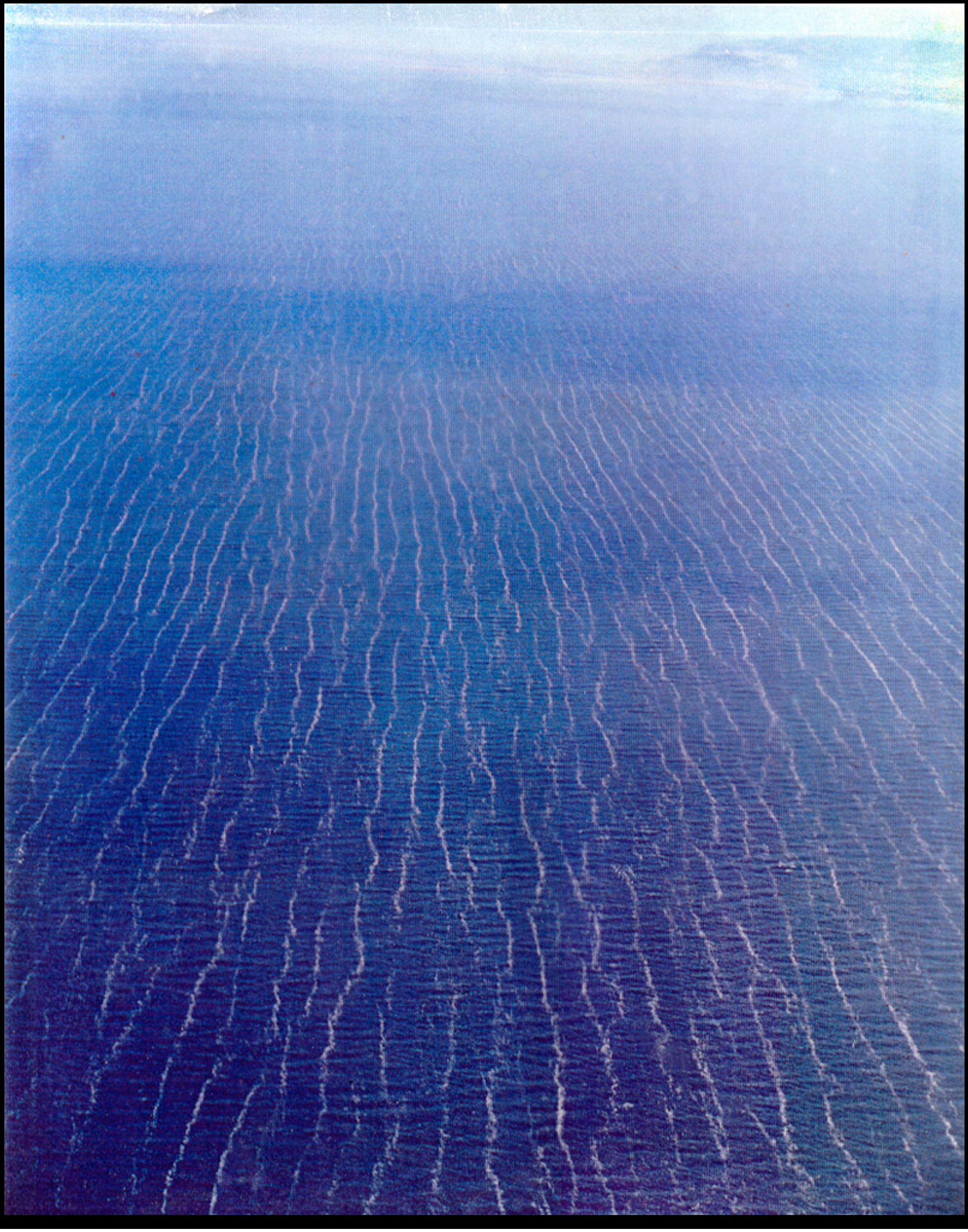
- Waves interact with the turbulence and the flux carrying structures
- Form drag is a strong function of wave age c/u_*
- Impact of swell depends on stratification
- Monin-Obukhov surface layer scaling does not hold with wind following fast running waves
- Swell represents *reverse* atmosphere-ocean coupling
- Impact of swell should be apparent in aircraft measurements
- LES (with a wavy boundary) replicates and aides the interpretation of observational data about the marine surface layer
- CL asymptotics provide a framework for including wave effects
- High wind LES of the ocean mixed layer with surface waves needs to be pursued

SST Variations & Ocean Mixing





Shuyi Chen, RSMAS



LANGMUIR CIRCULATIONS

GREAT SALT LAKE

COURTESY S. MONISMITH

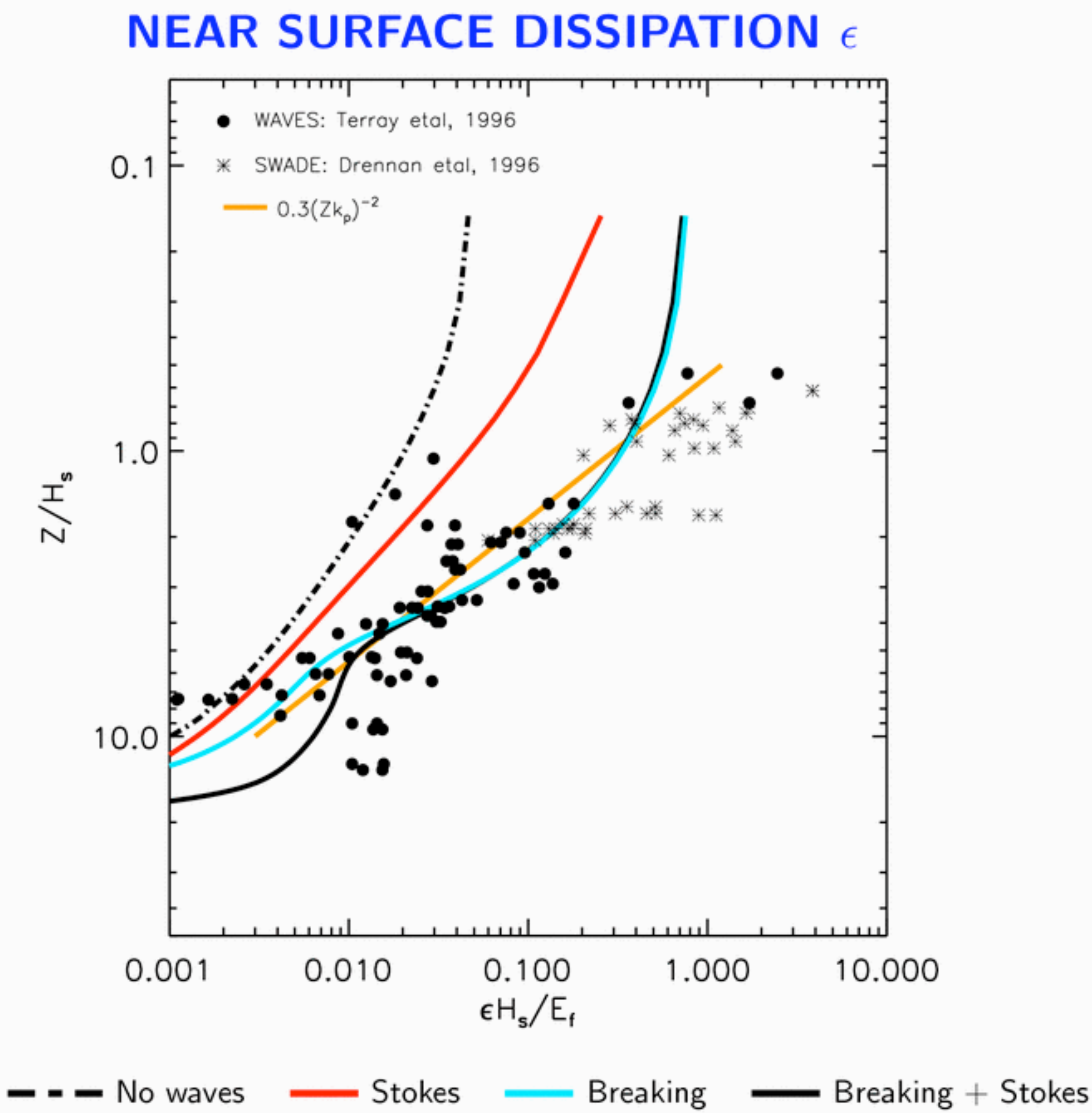
SURFACE GRAVITY WAVES AND MARINE SURFACE LAYERS

ATMOSPHERE

- Low winds and fast waves, non-equilibrium wind and wave fields

OCEAN

- Langmuir circulations, conservative wave-current interactions from Stokes drift, and stochastic breakers



NEAR SURFACE DISSIPATION ϵ
WAVES: Terray etal, 1996
SWADE: Drennan etal, 1996
0.3(Zk_p)^-2
0.1
1.0
10.0
Z/H_s
0.001
0.010
0.100
1.000
10.000
ϵH_s/E_f
No waves
Stokes
Breaking
Breaking + Stokes