Air-Sea Interaction Influenced by Swell Waves

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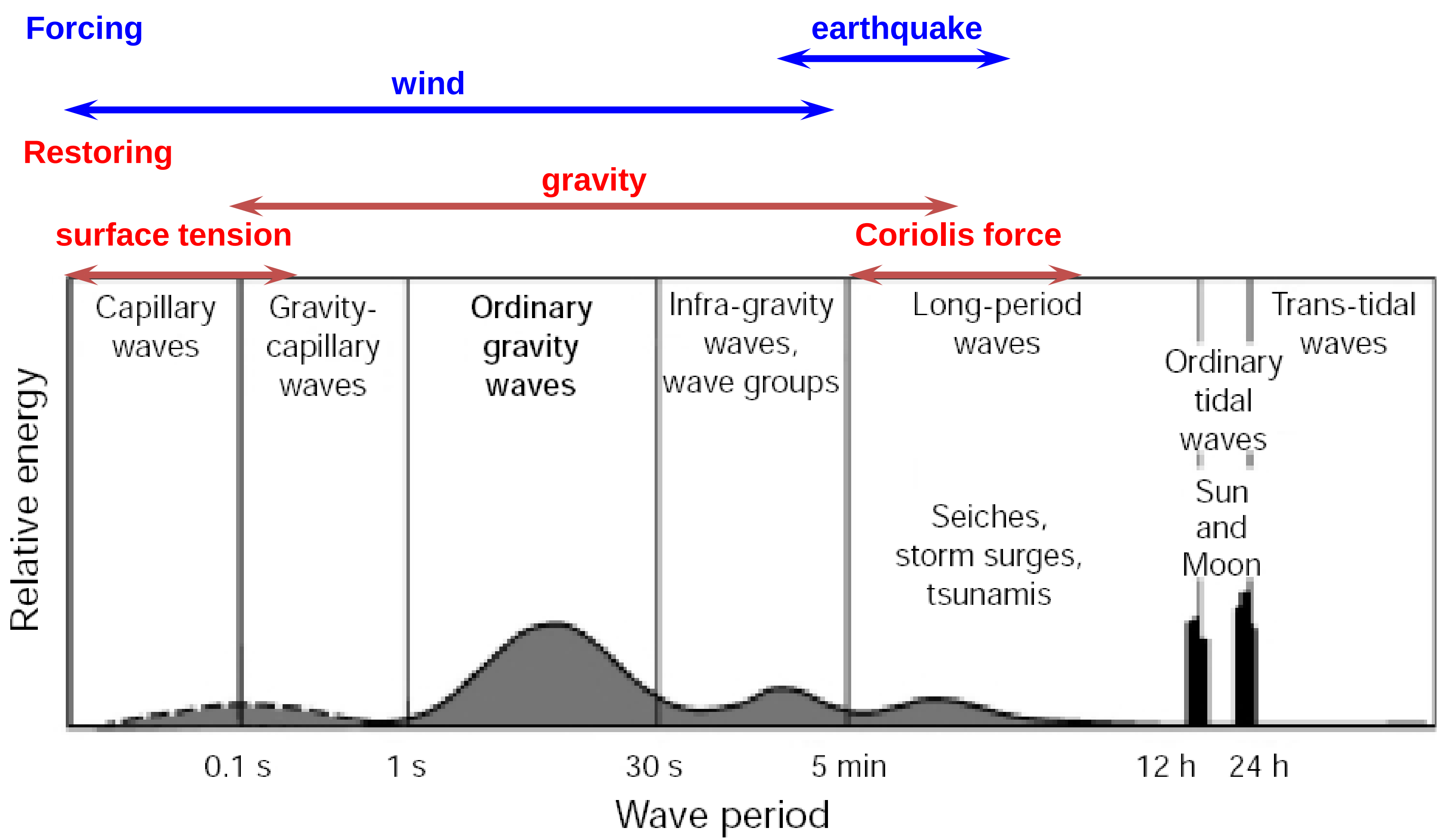
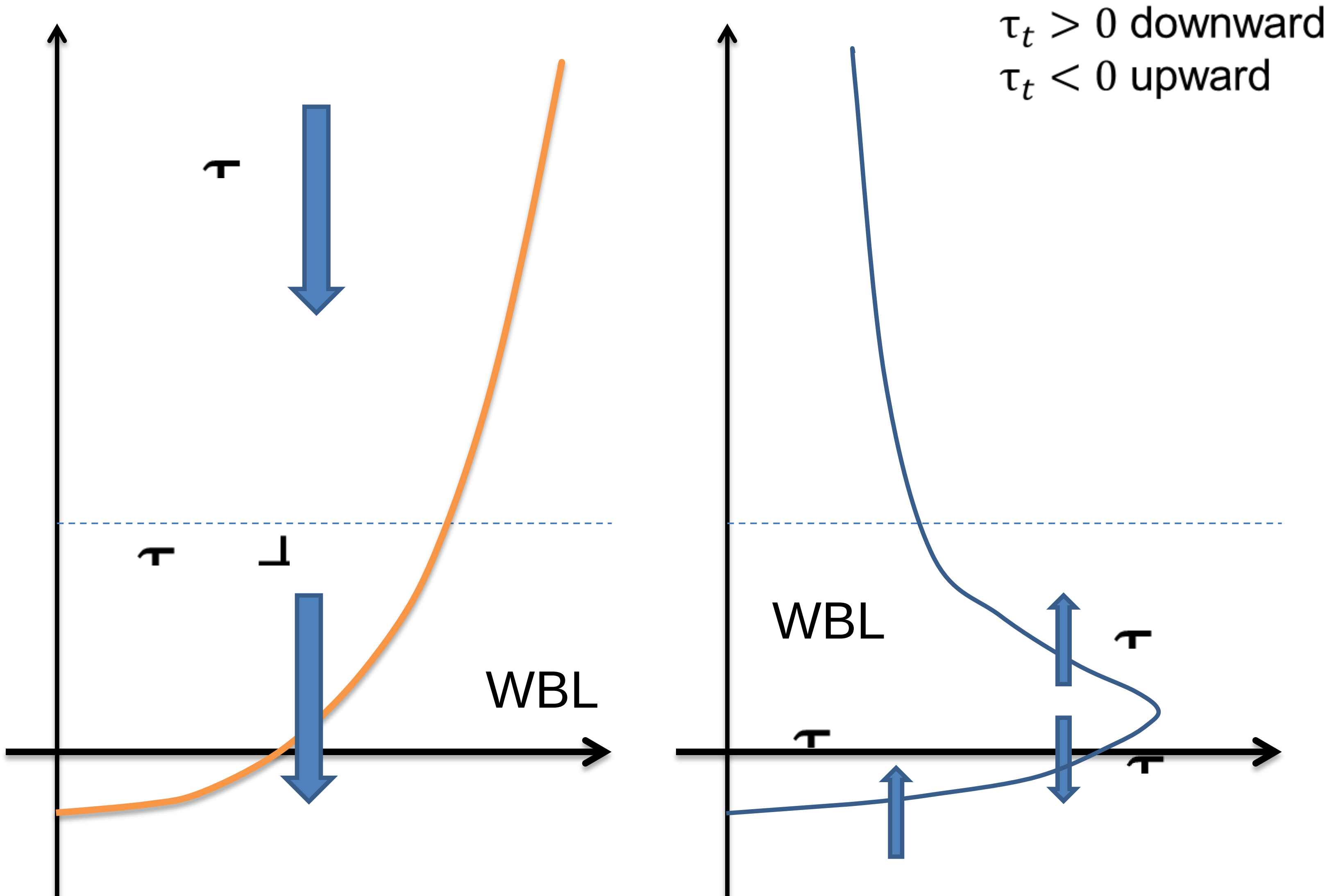
Wind and Wave energy distribution in period



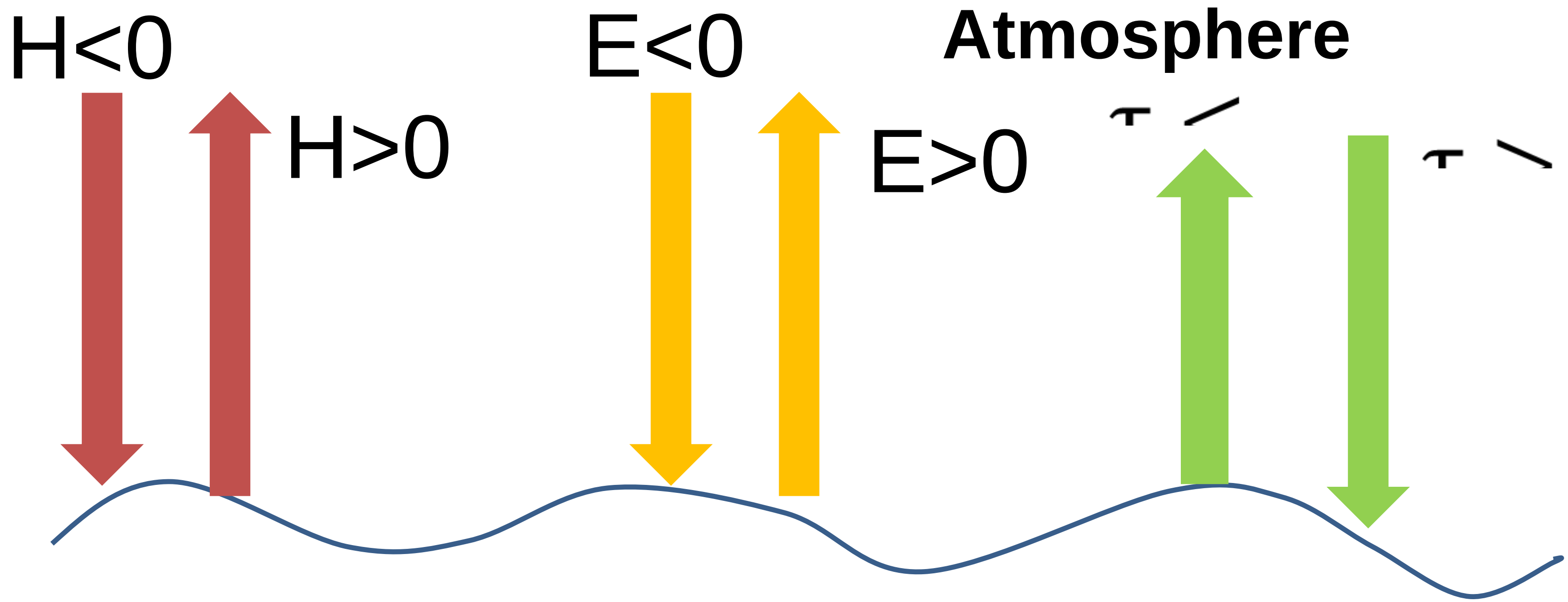
Outline

- **Wave processes in the Atmospheric Boundary Layer (ABL)**
- **Wave-current interaction**
- **Wave-turbulence interaction.**

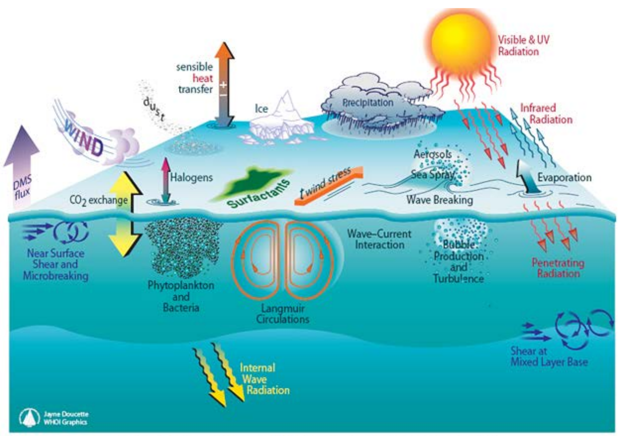
Wave Processes in ABL



The air-sea fluxes



Ocean



(Illustration by Jayne Doucette, Woods Hole Oceanographic Institution)

Analysis: Momentum

To account wave effects on momentum and energy equations, we decompose velocity and pressure in mean, wave, and turbulence components

$$\mathbf{u} = \bar{\mathbf{u}} + \tilde{\mathbf{u}} + \mathbf{u}',$$

$$p = \bar{p} + \tilde{p} + p'$$

Temporal scale for seperation

$$T \gg \tilde{t} \gg t'$$

Analysis: Momentum

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[K_m \frac{\partial \bar{u}}{\partial z} + \tau_{wx}\right],$$

$$\frac{\partial \bar{v}}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[K_m \frac{\partial \bar{v}}{\partial z} + \tau_{wy}\right],$$

wave-induced stress

Over the sea, the total wind stress can be made up as vector sum of shear stress, τ_s, and wave–induced stress, τ_w.

$$\tau = \tau_v + \tau_t + \tau_w.$$

Analysis: Momentum

Following Janssen 1991 , the wave–dependent total wind velocity is given by

$$U_{10}^{w}(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z+z_1}{z_0+z_1}\right) - \psi_m\right].$$

where z_1 is the wave stress contribution in the effective roughness ($z_e = z0 + z_1$).

The wave stress is expressed as

$$\tau_w = \rho_w \int_0^{2\pi}\int_0^{\infty} \sigma S_{in}(\sigma,\theta) d\sigma d\theta, \quad |\theta_{wind} - \theta| \leq \pi/2,$$

where θ_{wind} is the wind direction, θ and σ denote the direction and the angular frequency, respectively. The wind energy input source term is expressed as

$$S_{in}(\sigma,\theta) = \sigma\frac{\rho_a}{\rho_w}\left[\frac{1.2}{\kappa^2}\epsilon\ln^4(\epsilon)\right]\left(\frac{u_*\cos(\theta)}{c_p}\right)E(\sigma,\theta) = \beta_w E(\sigma,\theta),$$

with

$$\epsilon = \left(\frac{u_*\cos(\theta)}{c_p}\right)^2\left(\frac{g\kappa^2 z_e}{u_*^2}\right)\exp\left(\frac{\kappa c_p}{u_*\cos\theta}\right),$$

$$z_e = \frac{z_0}{\sqrt{1-c_0\tau_w/\tau}} \text{ and } z_0 = \frac{\beta_0 u_*}{g\sqrt{1-c_0\tau_w/\tau}},$$

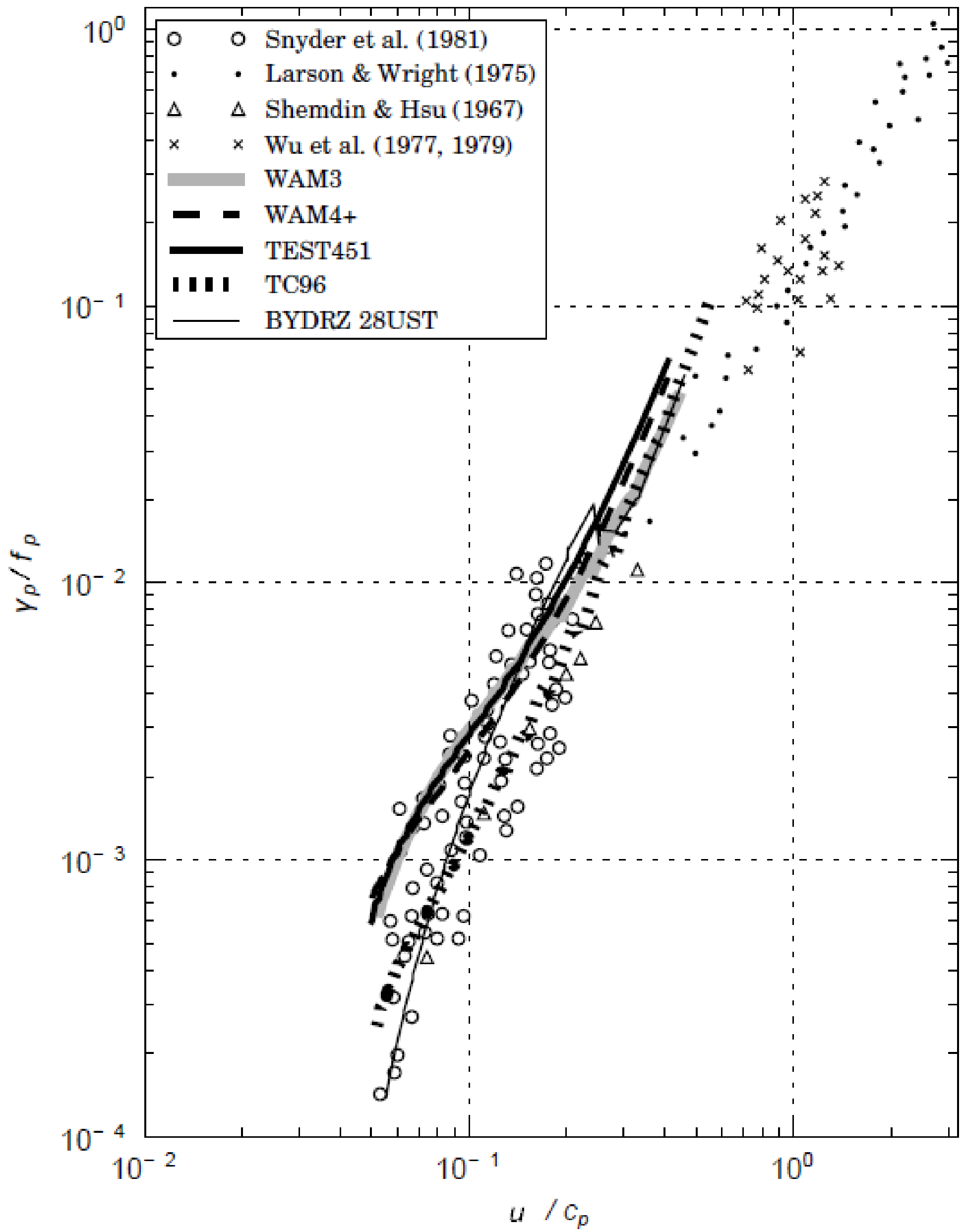
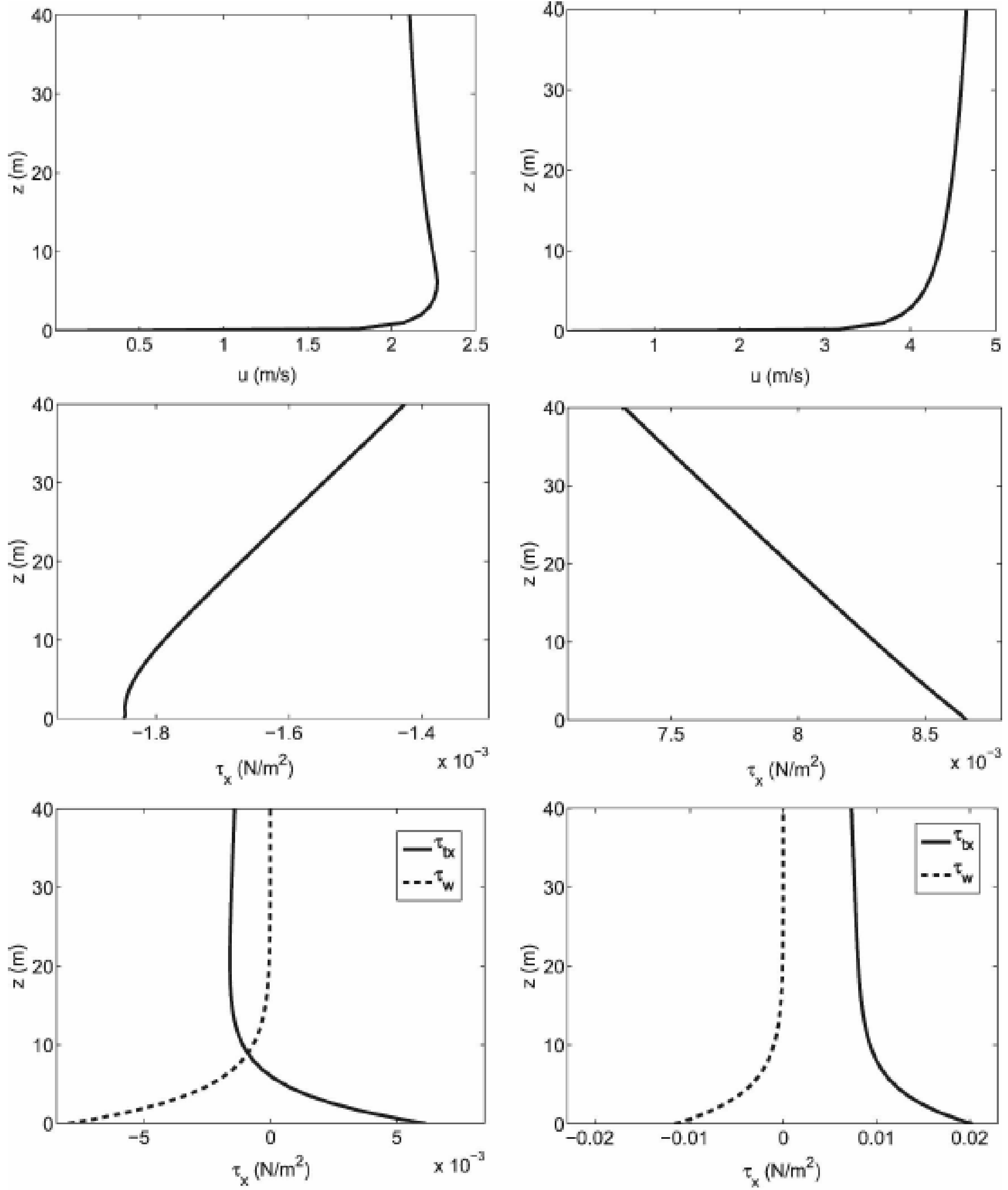


Fig. 1. (a) first picture.

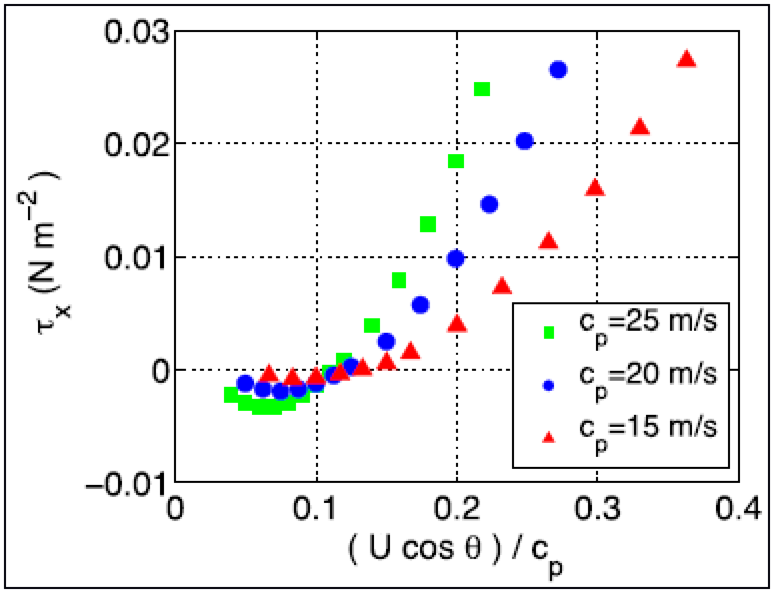
$$\tau_w = \tau_w(0) \exp^{-z/h_i},$$

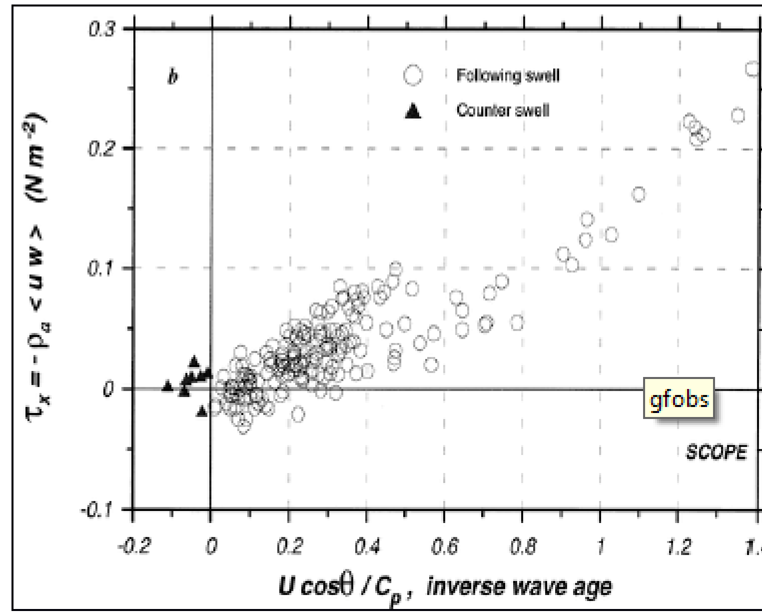


Belcheher et al 2008

Analysis: momentum flux

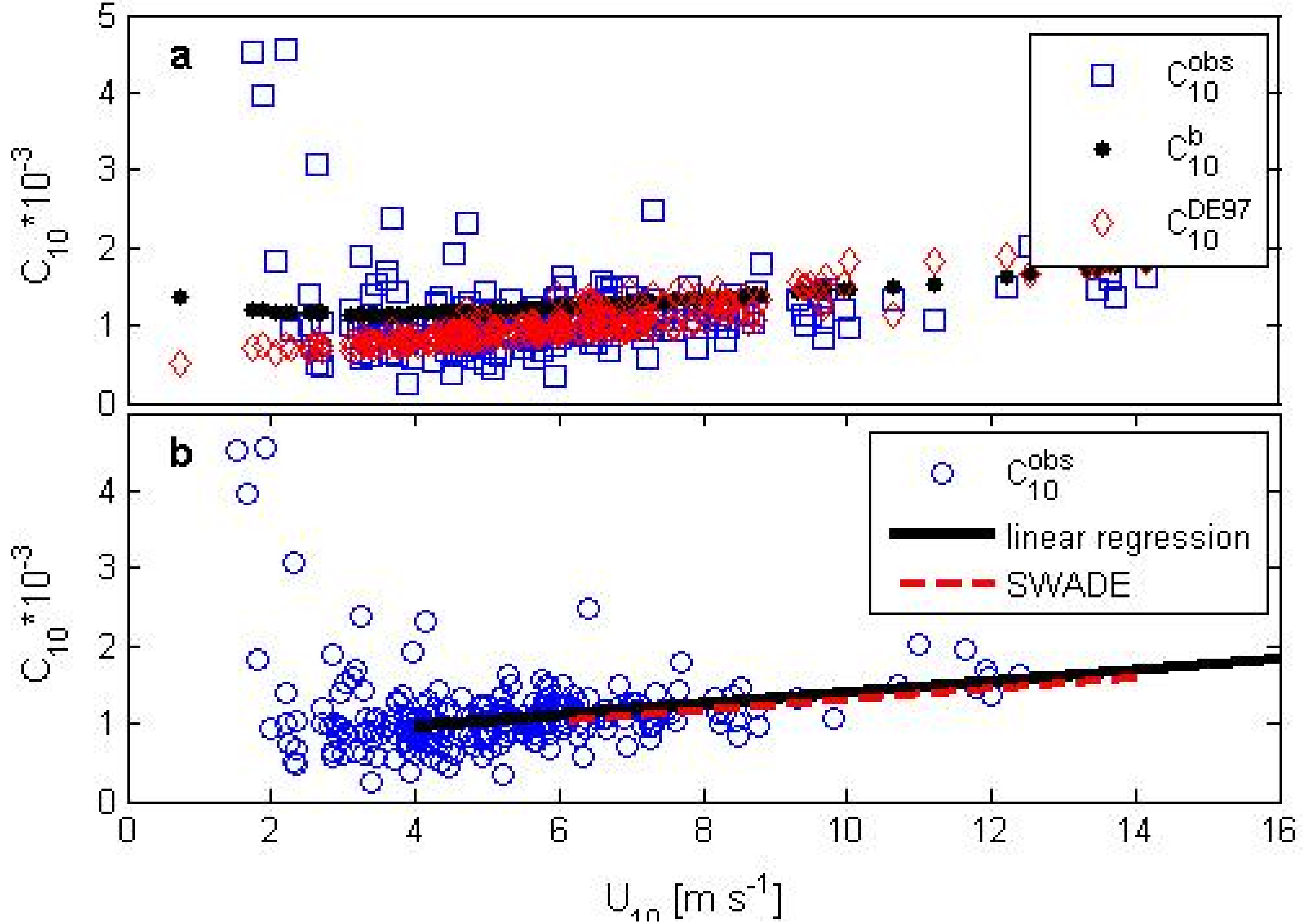
the direction change of total stress change within wave ages ragend Between 0-0.2.





Grachev & Friall 2001

Analysis: Drag Coeffiecent

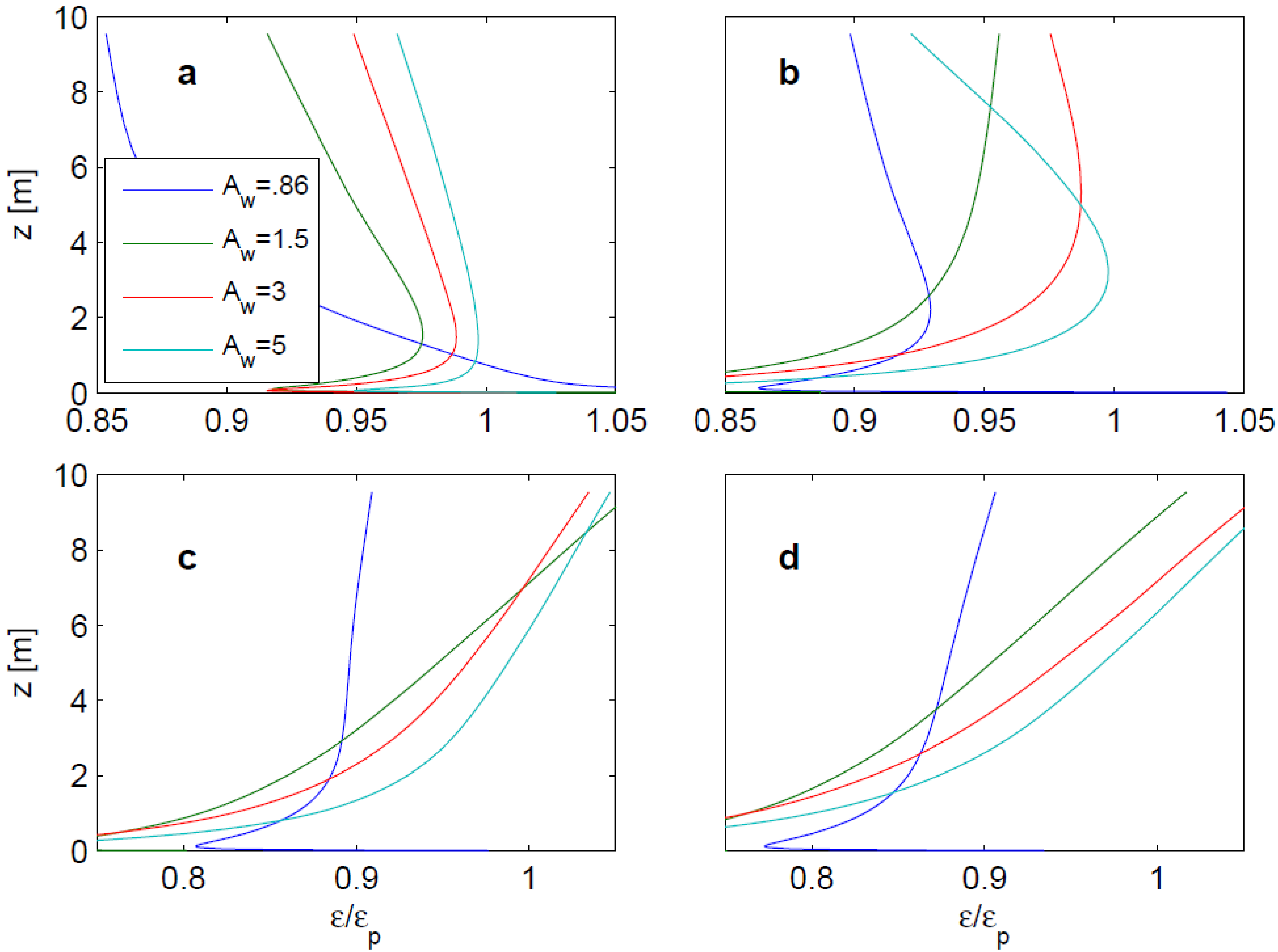


Bakhoday etal 2013

Analysis: TKE

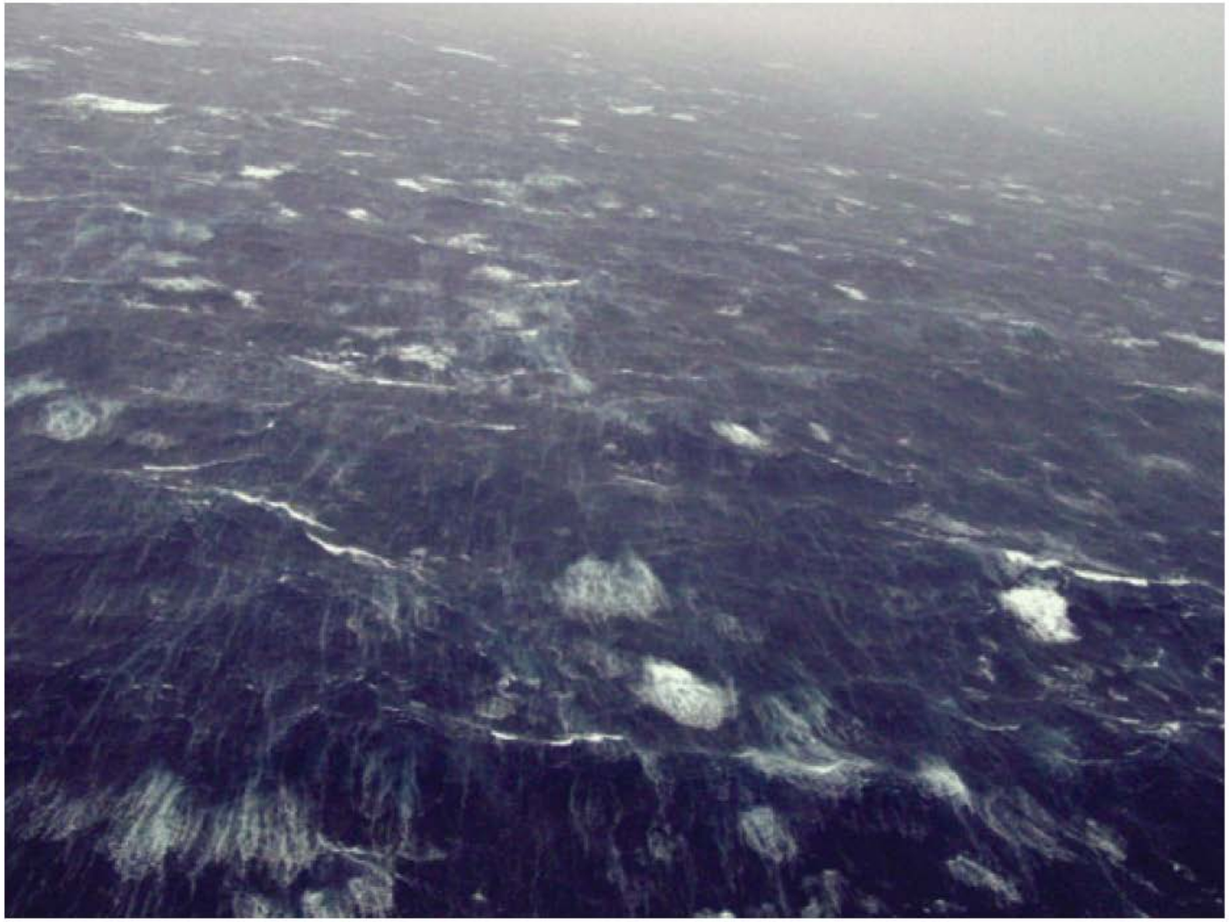
In the presence of gravity waves

$$\frac{\partial e}{\partial t} = -\overline{u'w'}\frac{\partial \bar{u}}{\partial z} \overbrace{-\overline{\tilde{u}\tilde{w}}\frac{\partial \bar{u}}{\partial z}}^{1} + \frac{\partial}{\partial z}\left[\frac{1}{\rho}\overline{w'p'} + \overline{e'w'}\right] \overbrace{-\frac{1}{\rho}\frac{\partial \overline{\tilde{w}\tilde{p}}}{\partial z}}^{2} - \varepsilon = 0,$$



Aw is inverse of wave age

Wave-ocean processes



Photograph of sea-surface and breaking waves in Hurricane Isabel taken from a low-level flight during the CBLAST field campaign (Black et al. 2007).

Wave parameters

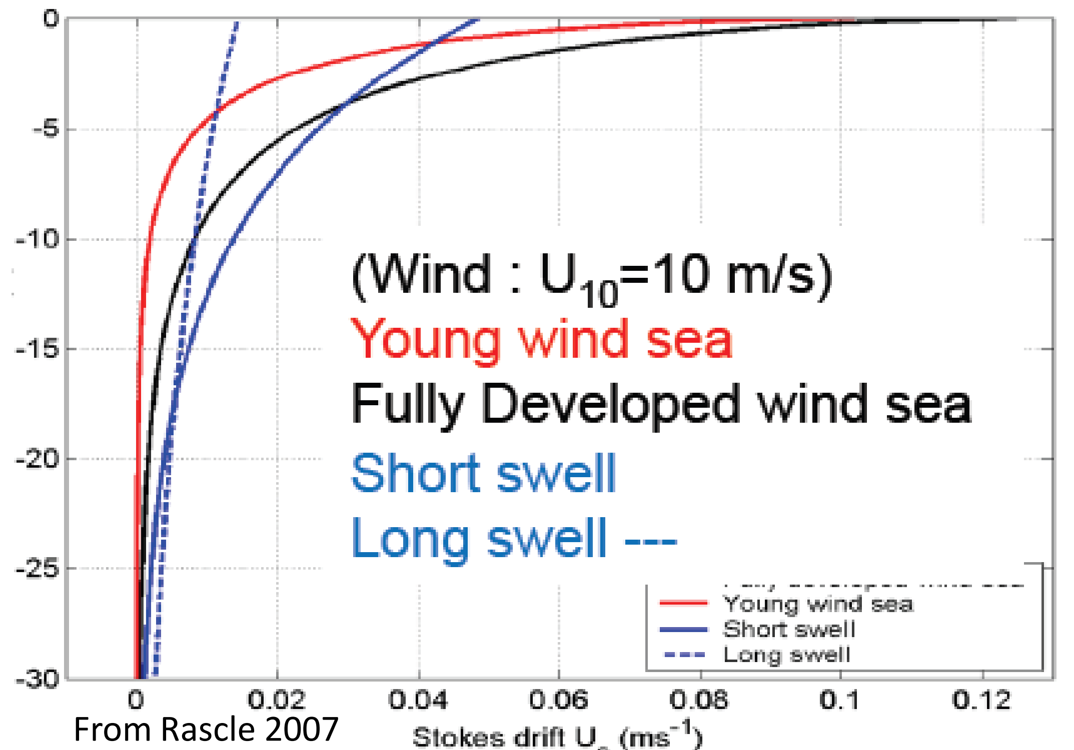
$$\mathbf{U}_s(z) = 4\pi \int_\theta \int_f f\,\mathbf{k}E(f,\theta)e^{-2k|z|}\, df\, d\theta,$$

$$\rho_w \nu_t \frac{\partial \mathbf{U}}{\partial z} = \vec{\tau}^{\,surf}_{mod},$$

$$\mathbf{F}_{ds} = -4\pi \int_f \int_\theta f S_{ds}(f,\theta)\hat{\mathbf{k}} k e^{-2k|z|}\, d\theta\, df,$$

where

$$\vec{\tau}^{\,surf}_{mod} = \tau_{tot} - 2\pi\rho_w \int_f \int_\theta \widehat{\mathbf{k}} f S_{in}(f,\theta)\, d\theta\, df.$$



From Rascle 2007

Wave Current Interaction

In the non–steady case, the (quasi) Eulerian mean currents are governed by the wave–modified momentum equations:

$$\frac{\partial \mathbf{u}}{\partial t} = -f_{cor}\hat{z} \times \mathbf{u} + \mathbf{F}_{CSF} - \frac{\partial}{\partial z}\underbrace{\overline{\mathbf{u}'w'}}_{1} - \frac{1}{\rho_0}\nabla p^*$$

$$+ \underbrace{\mathbf{u}_s \times (\nabla \times \mathbf{u})}_{2} + \mathbf{F}_{ds}(z),$$

Background Fig. From S. Monismith

From Bakhoday-Paskyabi & Fer a2013

Wave turbulence interactions

- By simplifying motion equations:

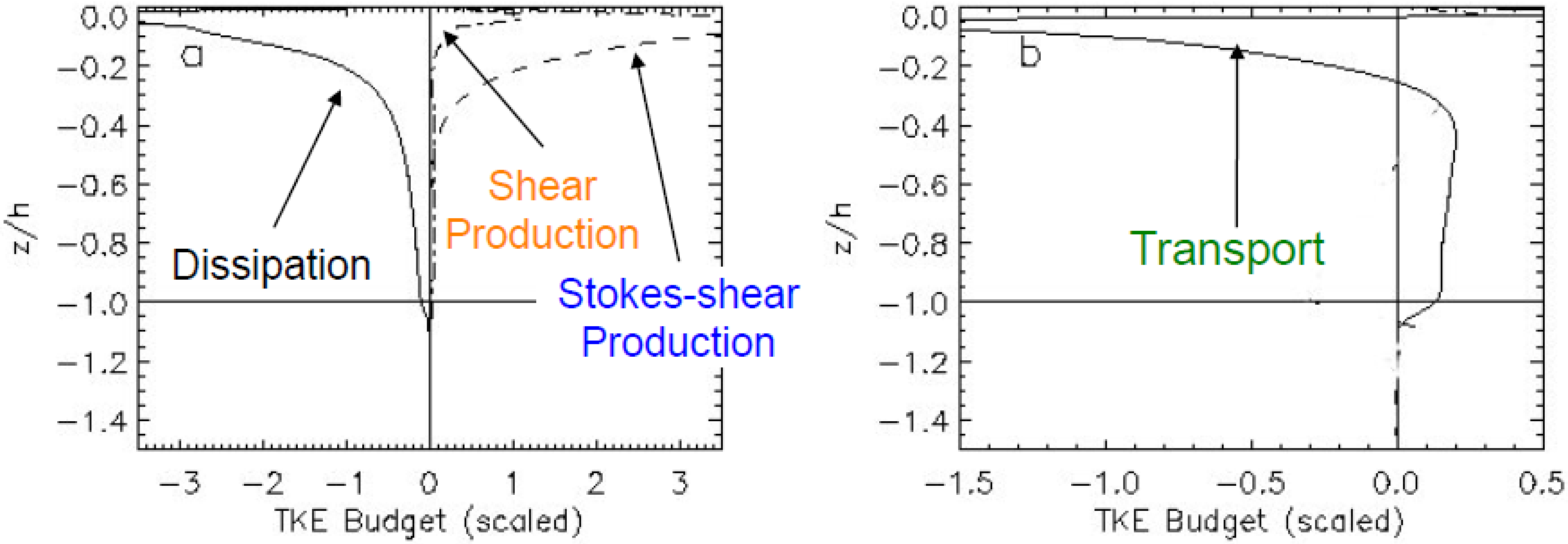
$$\frac{\partial u}{\partial t} = -\frac{\partial(\overline{u'w'})}{\partial z} + f_{cor}(v + v_s) + F_x,$$

$$\frac{\partial v}{\partial t} = -\frac{\partial(\overline{v'w'})}{\partial z} - f_{cor}(u + u_s) + F_y,$$

$$\frac{\partial e}{\partial t} = -\left(\overline{u'w'}\frac{\partial U}{\partial z} + \overline{v'w'}\frac{\partial V}{\partial z}\right) + \overline{b'w'} - \frac{\partial}{\partial z}\left(\overline{ew'} + \frac{1}{\rho_0}\overline{P'w'}\right) - \varepsilon.$$

From Bakhoday-Paskyabi & Fer b 2013

Wave turbulence interactions



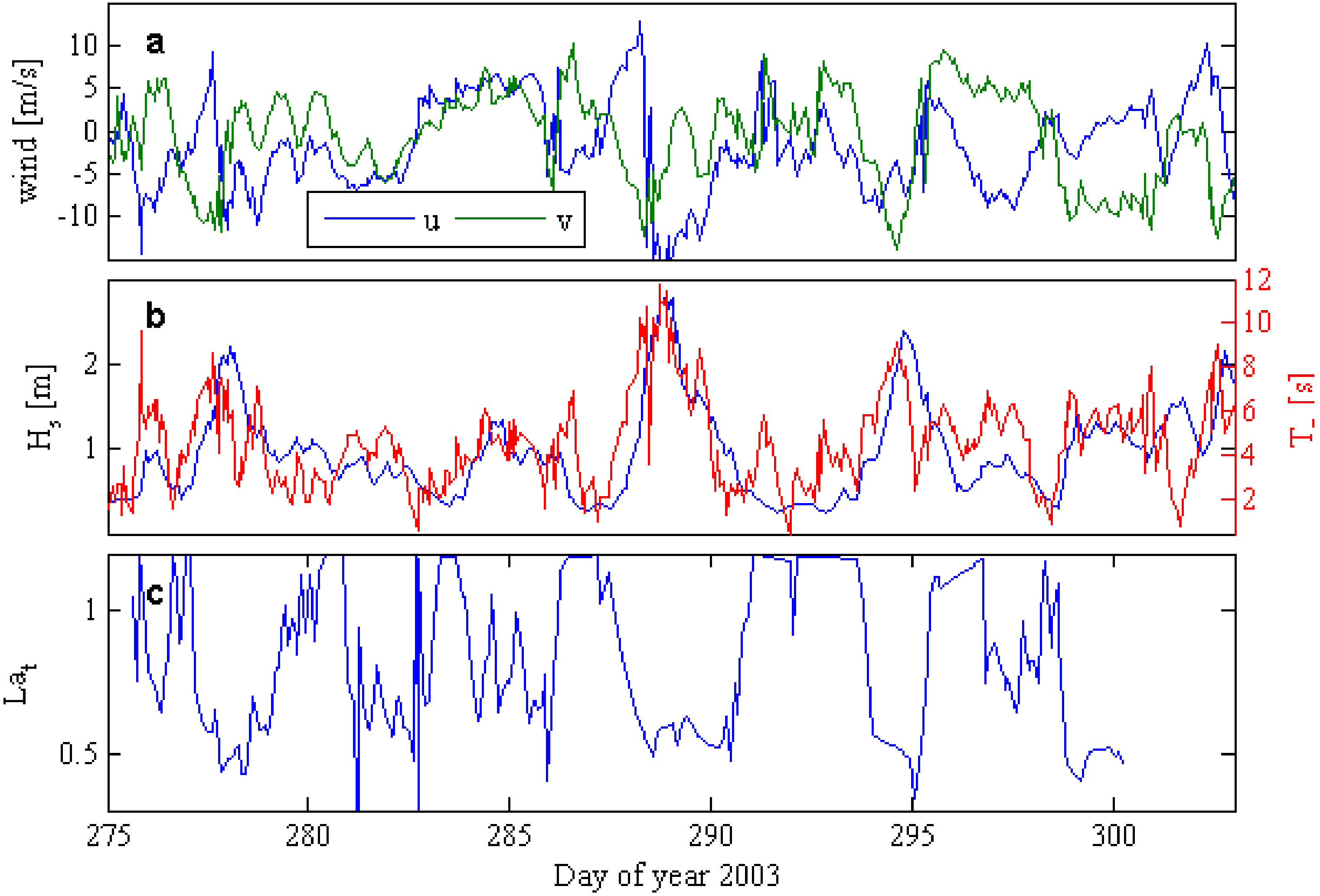
The k model

$$\overbrace{\frac{\partial k}{\partial t}}^{1} = \overbrace{\frac{\boldsymbol{\tau}}{\rho_0} \cdot \frac{\partial \mathbf{u}}{\partial z}}^{2} + \overbrace{\frac{\boldsymbol{\tau}}{\rho_0} \cdot \frac{\partial \mathbf{u}_s}{\partial z}}^{3} + \overbrace{\frac{g}{\rho_0}\overline{b'w'}}^{4} - \varepsilon + \overbrace{\frac{\partial}{\partial z}\left[\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial z}\right]}^{5} - \overbrace{\frac{\partial \mathbf{F}}{\partial z}}^{6},$$

Grant & Belcher (2009)

From Bakhoday-Paskyabi & A. Jenkins 2013

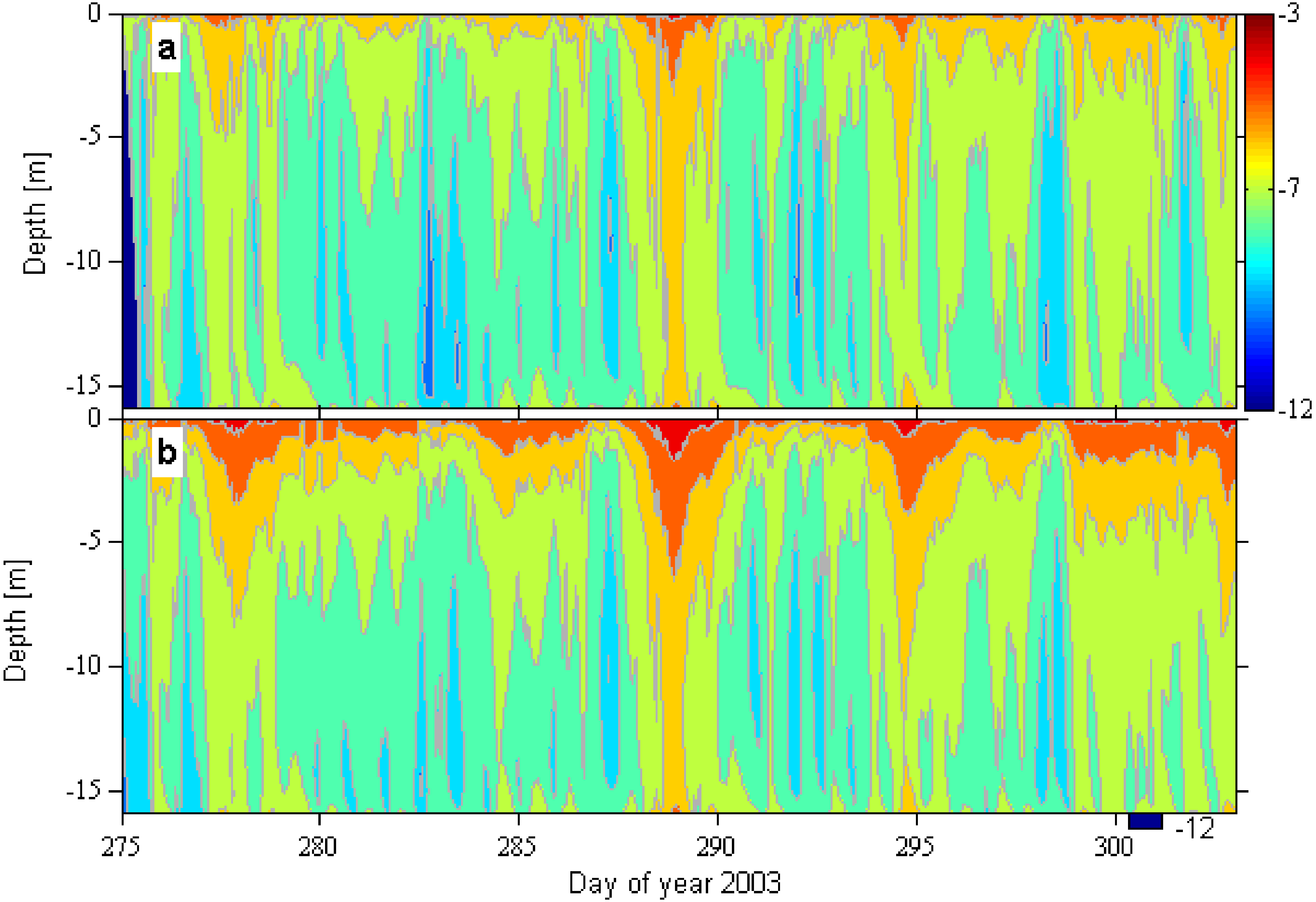
Comparisons with measurements



Data extracted from Kukula etal 2010

From Bakhoday-Paskyabi & A. Jenkins 2013

Comparisons with measurements



From Bakhoday-Paskyabi & Fer 2013

Comparisons with measurements

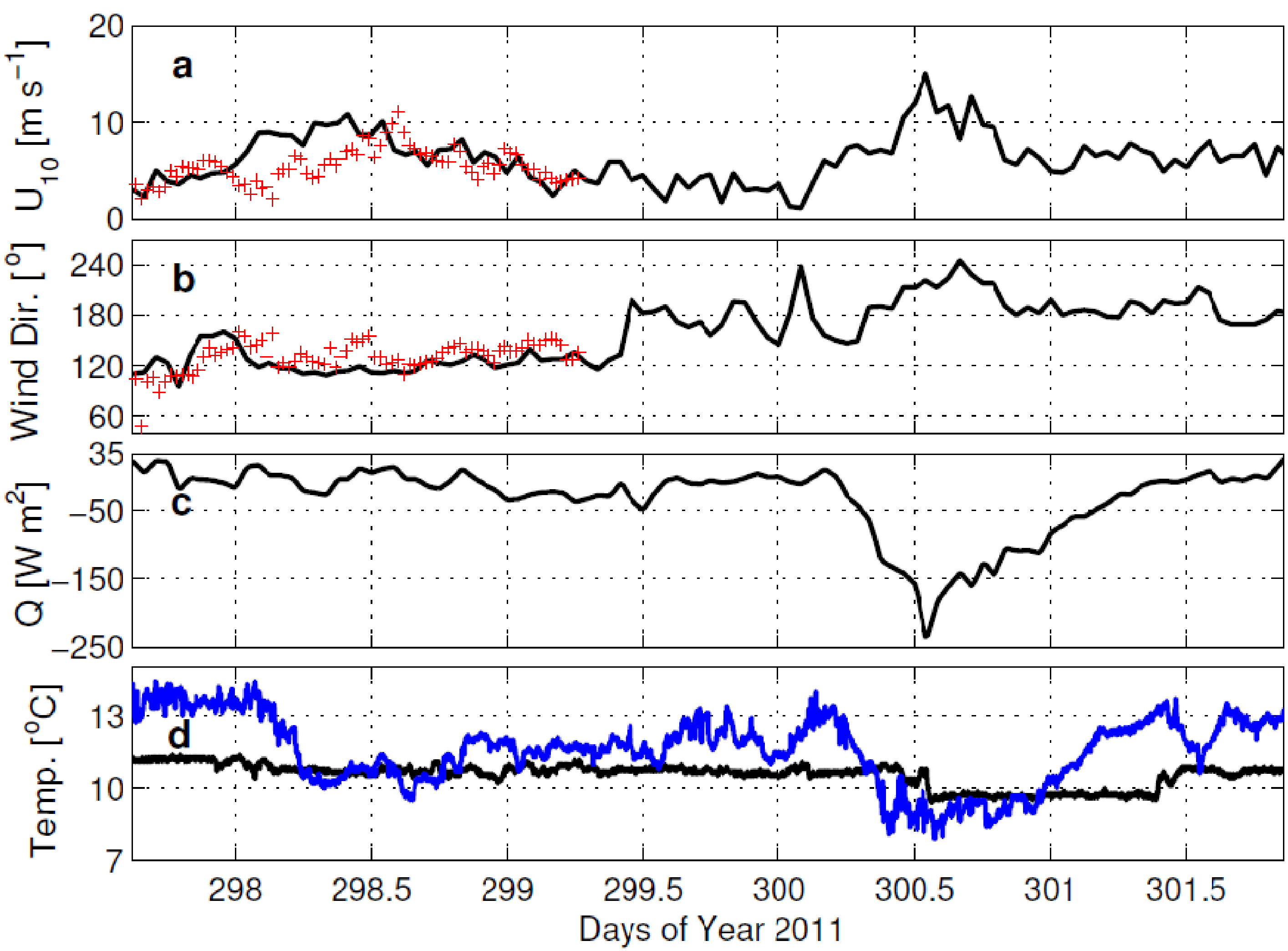


Fig. 2 Time series of (a) wind speed at 10 m height, U_{10}, from Vigra station (solid line), and from WS buoy (plus makers), (b) wind direction at 10 m height from Vigra station (solid line), and from WS buoy (plus markers), (c) total surface heat flux, and (d) water and air temperature at air–sea interface (black and blue solid lines, respectively) for the duration of the experiment on October 25 to 30 2011.

From Bakhoday-Paskyabi & Fer 2013

Comparisons with measurements

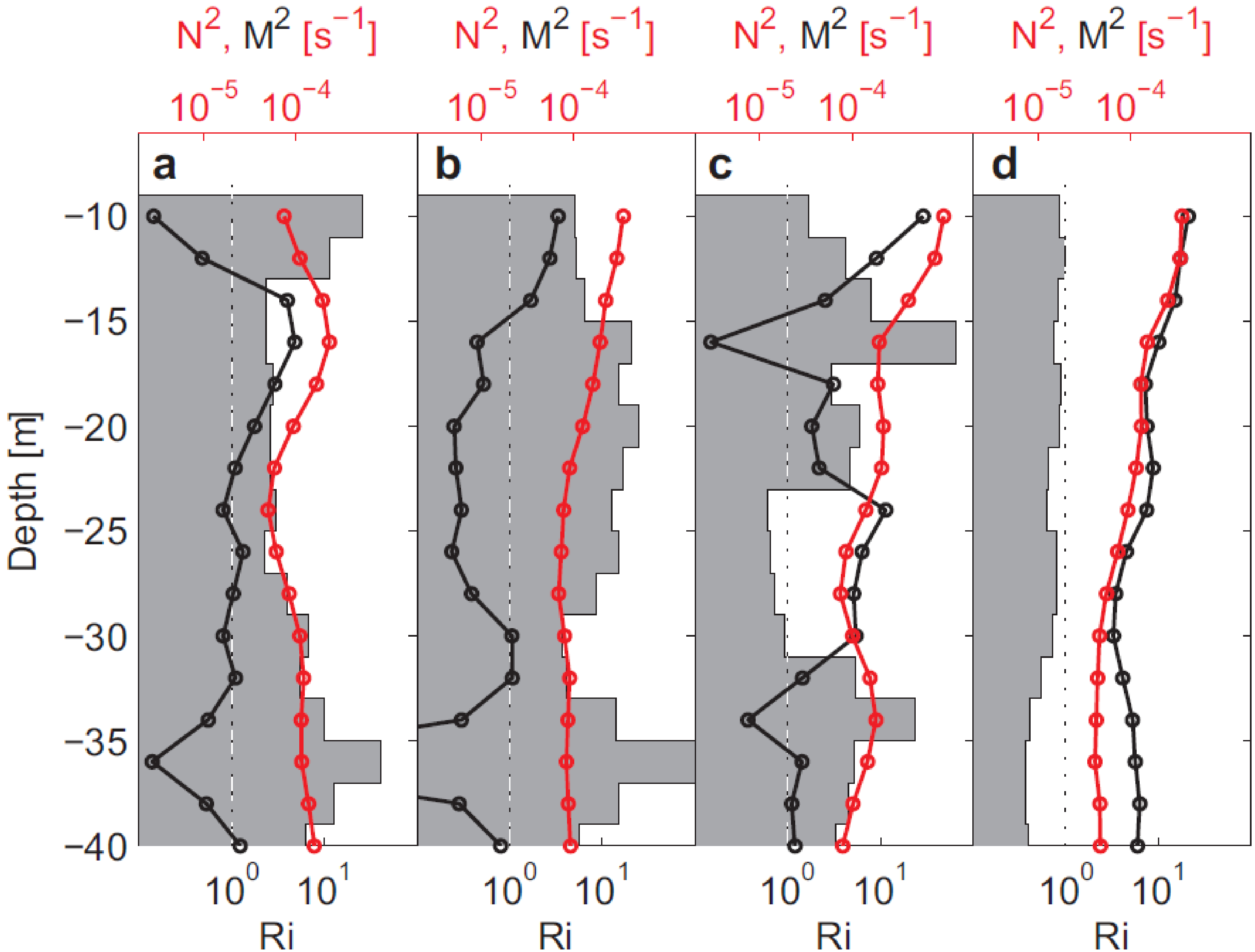
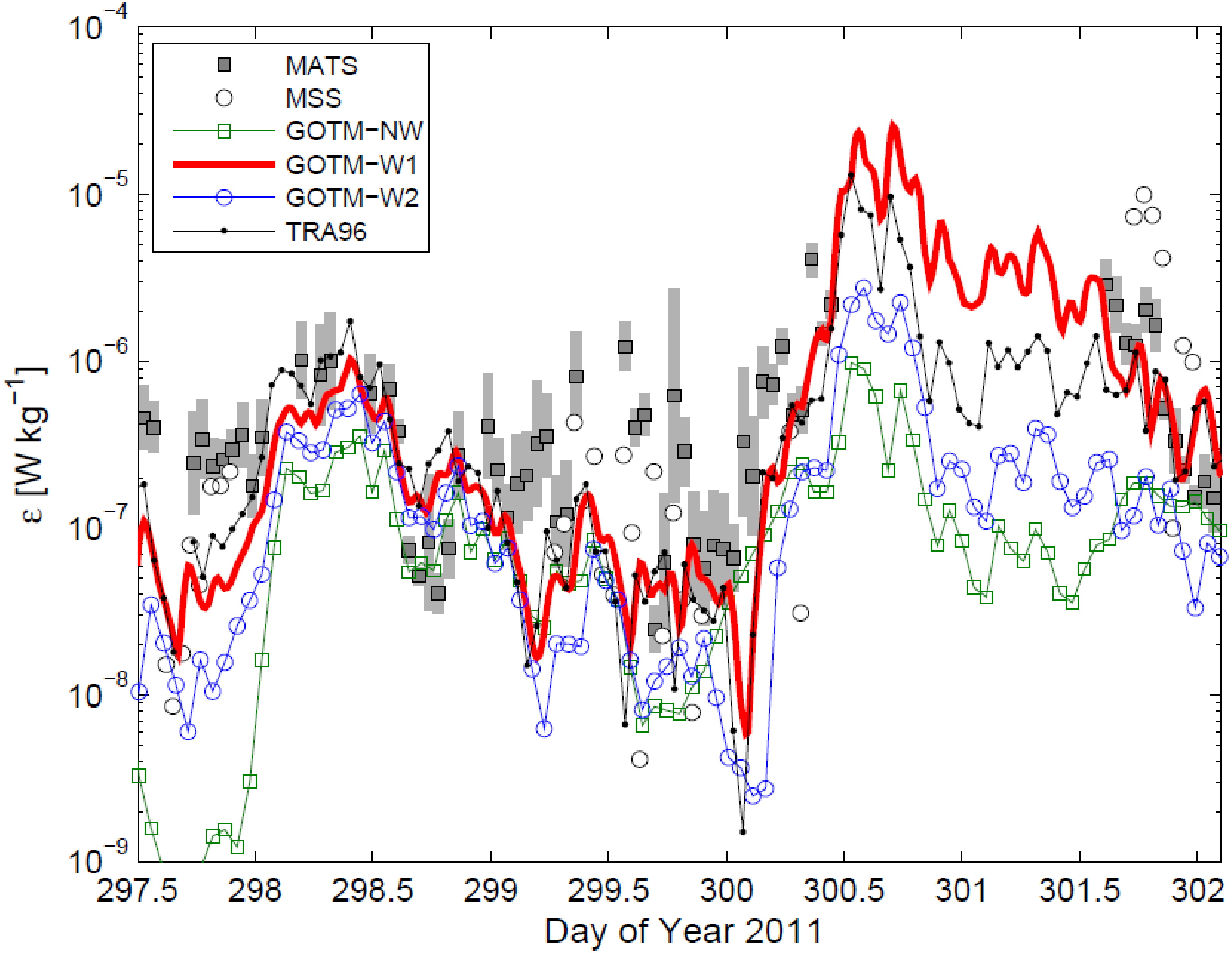


Fig. 11 Time averaged vertical profiles of squared shear M^2 (black solid lines), squared buoyancy N^2 (red solid lines), and $Ri = N^2/M^2$ (gray): (a) periods between 297.5 and 297.8, (b) between 299.4 and 299.9, (c) between 300.35 and 300.4, and (d) between 301.8 and 302.

From Bakhoday-Paskyabi & Fer 2013

Comparisons with measurements



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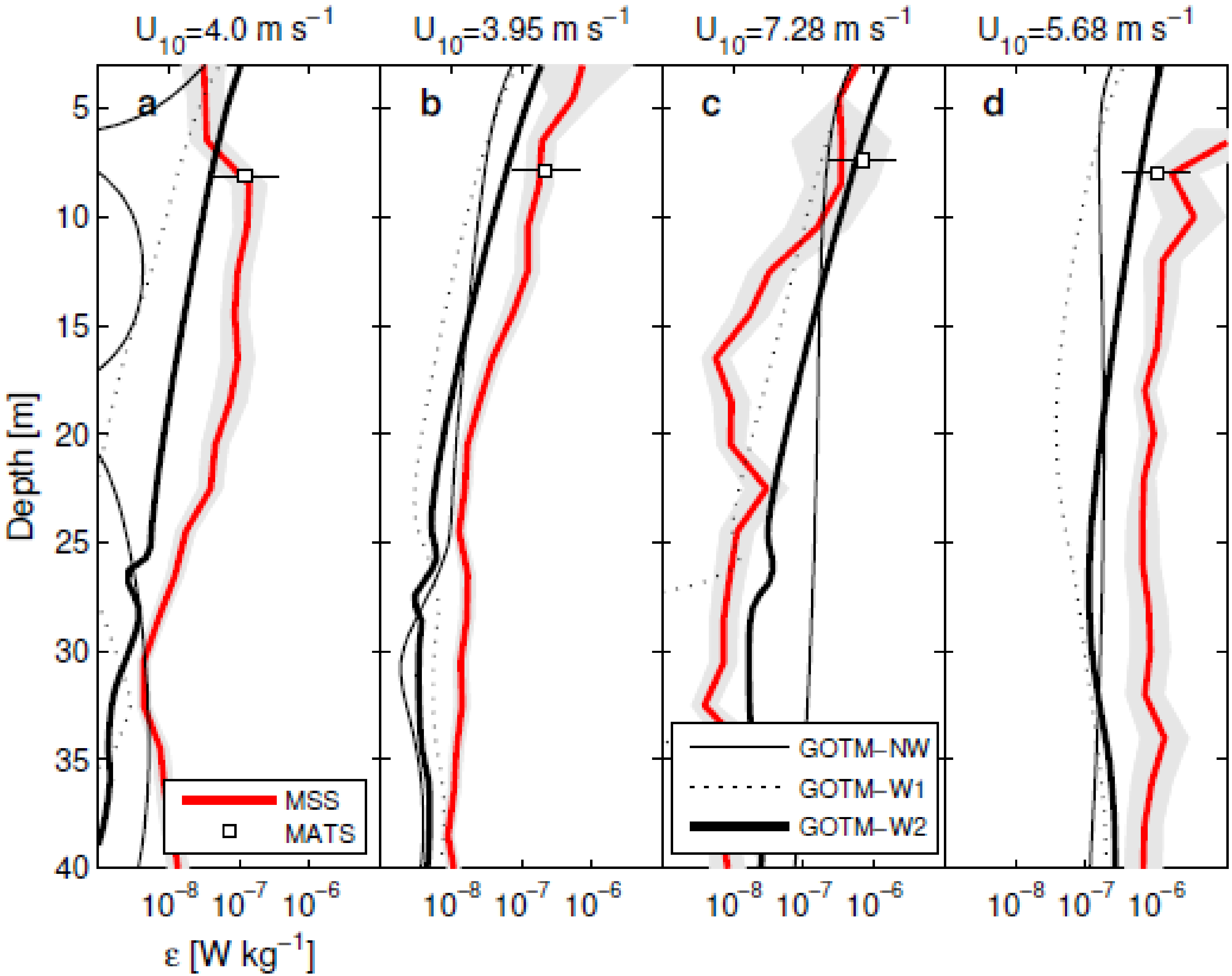
Comparisons with measurements



Conclusions:

1. Wave modified momentum and energy equations in both ABL and OBL,
2. Modified MY and k-epsilon models,
3. Wave induced momentum parameterization
4. Wave-current interaction,
5. Wave turbulence interaction (Wave-swell interaction)

Future works

1. Model-observation comparison with Marstein measured turbulence data acquired during November 2012 and 2013
2. Modification of 3D model,
3. Developing parameterizations using accessible data and theories.

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Grant, A. L. M. and Belcher, S. E. (2009)*Characteristics of Langmuir Turbulence in the Ocean Mixed Layer.* Journal of Physical Oceanography, 39 (8). pp. 1871-1887. ISSN 0022-3670 doi: 10.1175/2009JPO4119.1,

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