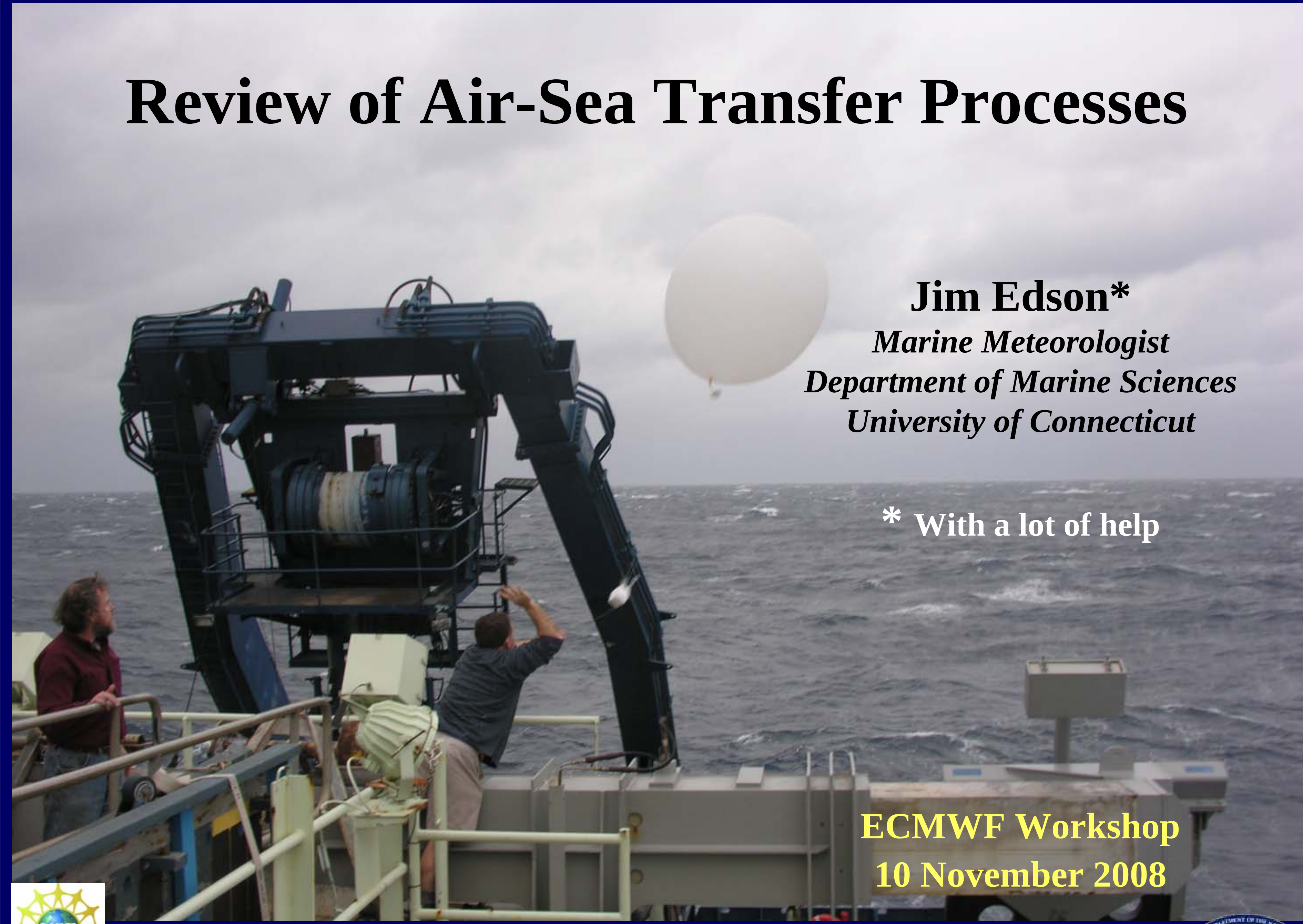


Review of Air-Sea Transfer Processes

Jim Edson*

Marine Meteorologist

Department of Marine Sciences

University of Connecticut

*** With a lot of help**

ECMWF Workshop

10 November 2008

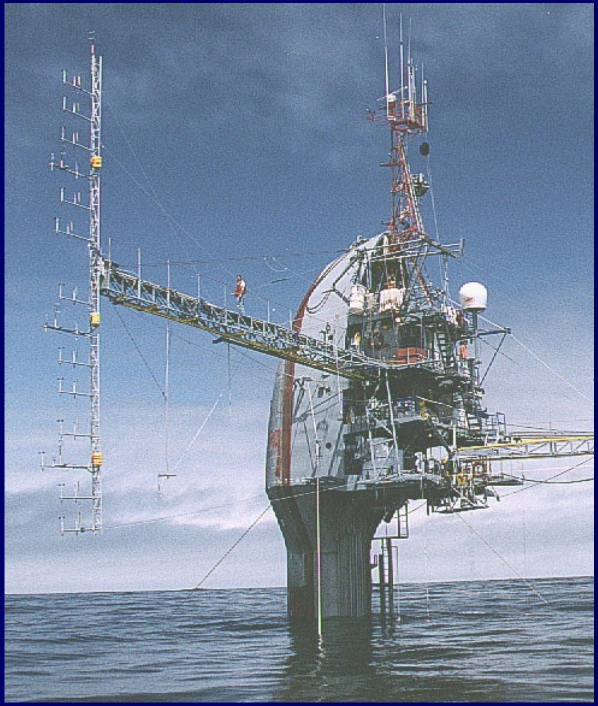
Research supported by grants from the Office of Naval Research and the National Science Foundation

Outline

- Introduction
- Momentum Exchange
  - FLIP - Wind event
  - CBLAST - Coastal ocean time series
  - CLIMODE – Open ocean time series
  - Momentum exchange in the “mean”
  - Other wave effects?
- Energy Exchange
- Summary

MBL/CBLAST Objectives

- When and where is Monin-Obukhov Similarity theory valid over the ocean?
- When, where and why does it fail?



Monin-Obukhov Similarity

$$\frac{\kappa z}{u_*^3}\left[\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta_v}\overline{w\theta_v} - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}\right]$$

$$\phi_\varepsilon(z/L) = \phi_m(z/L) - z/L - \phi_{te}(z/L) - \phi_{tp}(z/L)$$

- MOS states that various turbulent statistics are universal function of z/L after normalization by the appropriate scaling parameters.
- For example, the dimensionless shear

$$\frac{\kappa z}{u_*}\frac{\partial U}{\partial z} = \phi_m(z/L)$$

  is predicted to be a universal functions of z/L.
- This hypothesis has been substantiated by a number of studies in the atmospheric boundary layer over land.
- Although the overland results have been used for years over the ocean, we are finally testing this hypothesis in the marine boundary layer.

MOMENTUM EXCHANGE & DRAG COEFFICIENTS

Monin-Obukhov Similarity

$$\frac{\kappa z}{u_*^3}\left[\varepsilon = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta_v}\overline{w\theta_v} - \frac{\partial \overline{we}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}\right]$$

$$\phi_\varepsilon(z/L) = \phi_m(z/L) - z/L - \phi_{te}(z/L) - \phi_{tp}(z/L)$$

$$\phi_m(z/L) = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$$

Rearrange

$$-\overline{uw} = u_*^2 = \frac{u_* \kappa z}{\phi_m(z/L)}\frac{\partial U}{\partial z} = K_m \frac{\partial U}{\partial z}$$

Integrate

$$\Delta U = \frac{u_*}{\kappa}[\ln(z/z_0) - \psi_m(z/L)]$$

Rearrange

$$u_* = \kappa/[\ln(z/z_0) - \psi_m(z/L)]\Delta U$$

Semi-empirical Basis
for Bulk Formulae

$$u_* = C_D^{1/2}\Delta U$$

Drag Coefficient Formulas

- Semi-empirical

$$C_D(z/z_0, z/L) = \frac{-\overline{uw}}{\Delta U^2} = \left(\frac{\kappa}{\ln(z/z_o) - \psi_m(z/L)} \right)^2$$

$$C_{DN}(z/z_0) = \left(\frac{\kappa}{\ln(z/z_o)} \right)^2 = \frac{-\overline{uw}}{\Delta U_N^2}$$

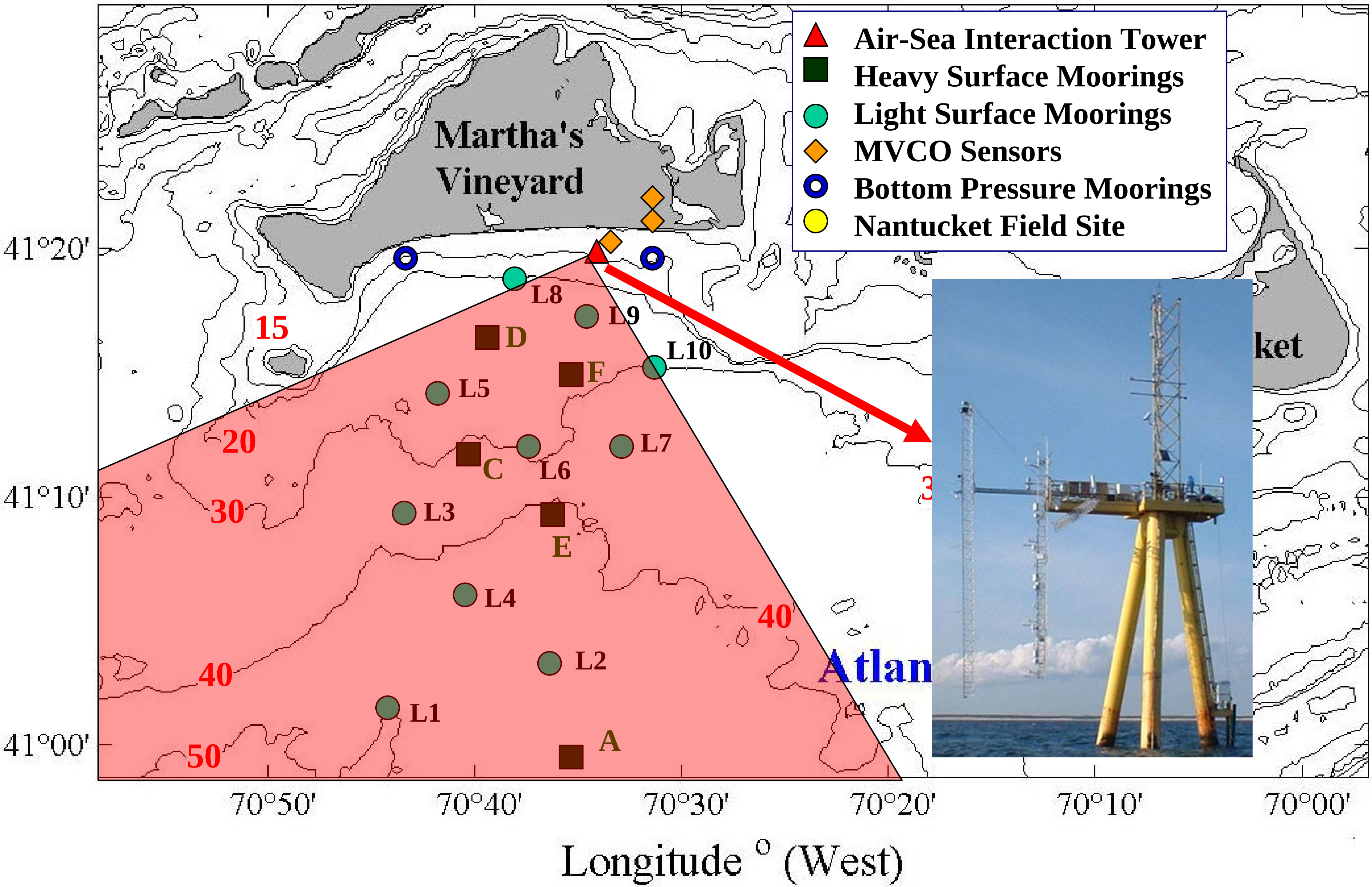
TOGA-COARE 3.0

- "Empirical"

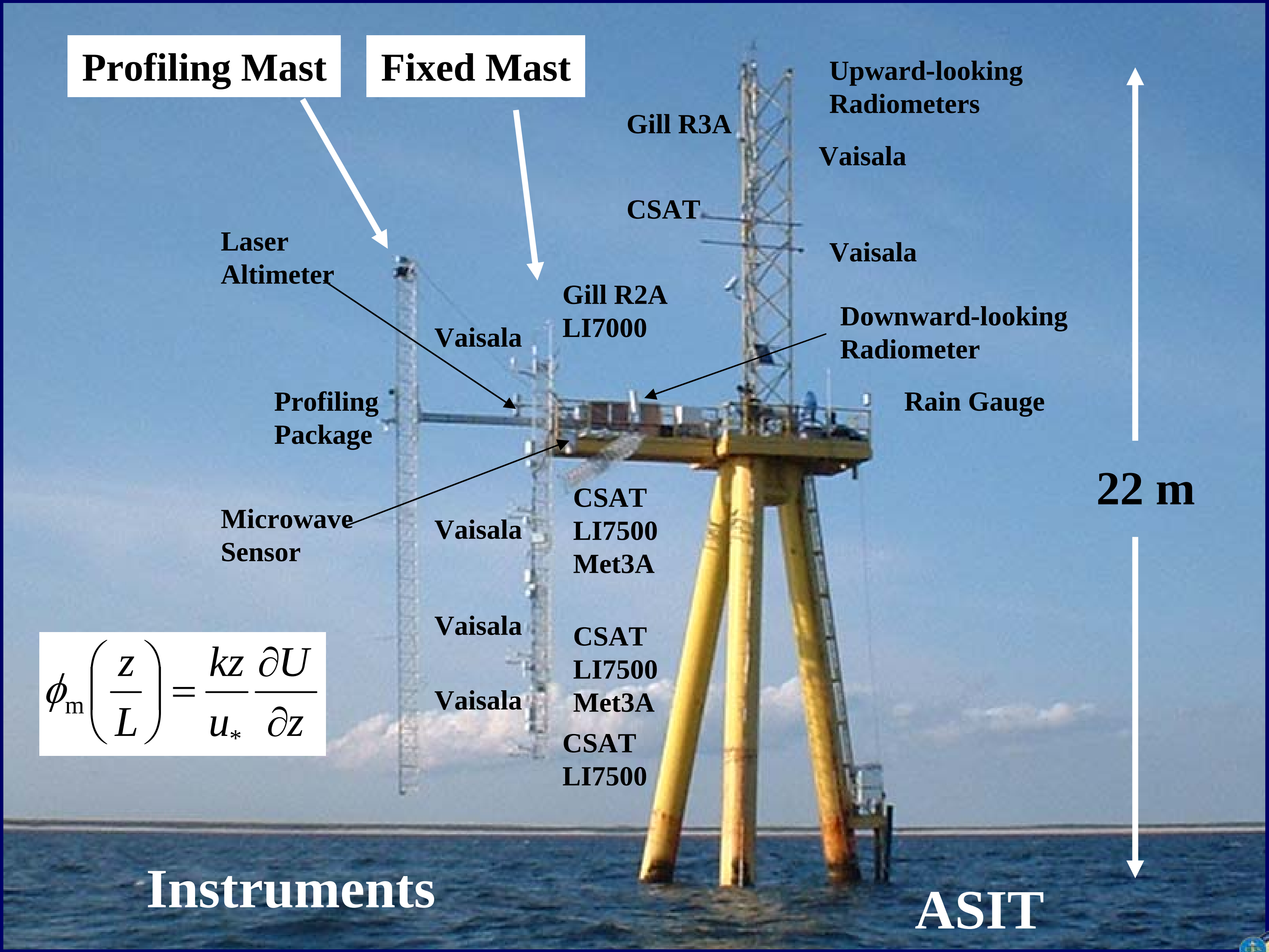
$$10^3 C_{DN}(U_{10N}) = \begin{cases} 1.2 & 4 \le U_{10N} \le 11\,\mathrm{ms}^{-1} \\ 0.49 + 0.065\,U_{10N} & 11 \le U_{10N} \le 25\,\mathrm{ms}^{-1} \end{cases}$$

Large & Pond (1981)

CBLAST 2003 Offshore Array



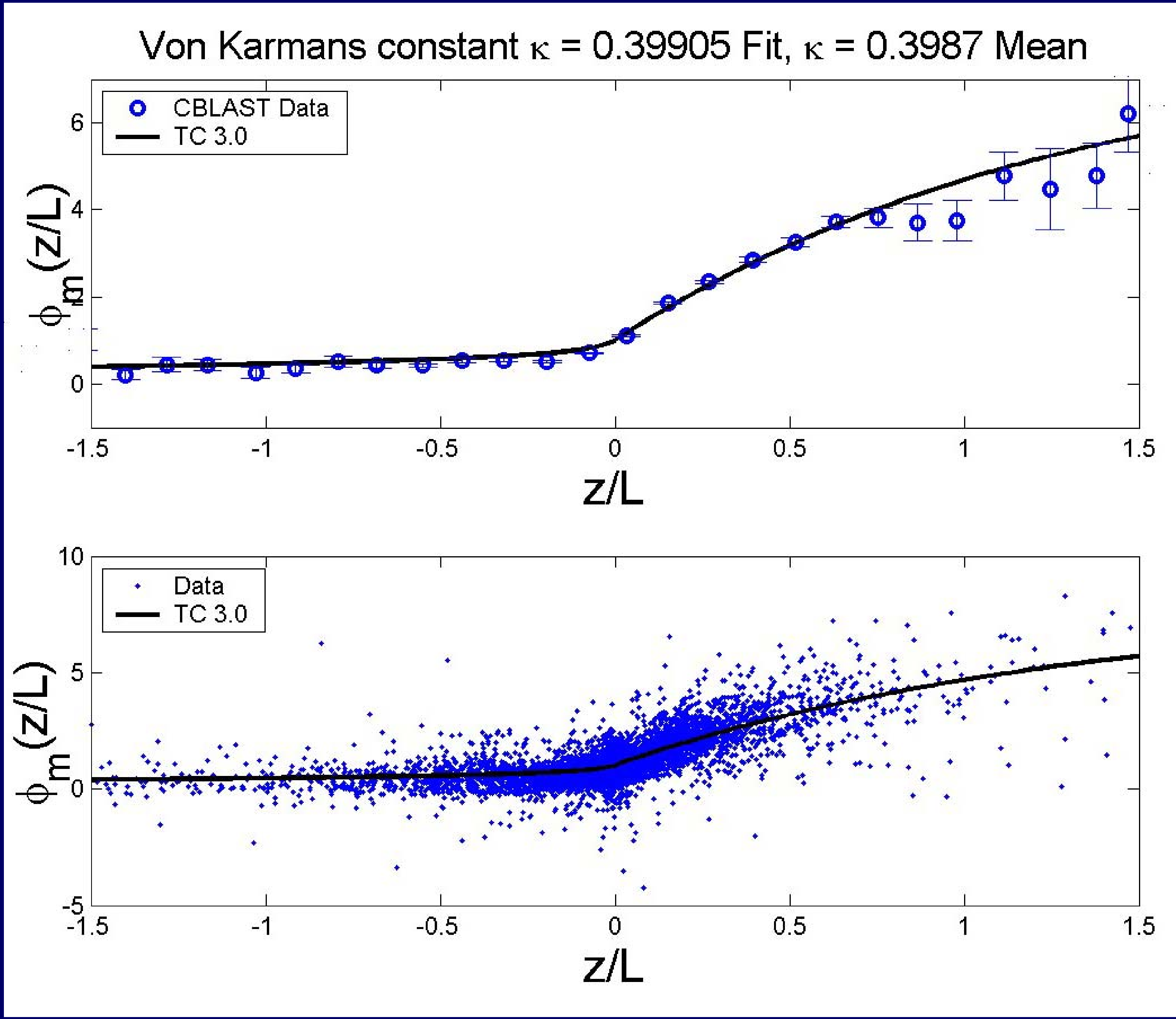
ASIT Flux-Profile Measurements



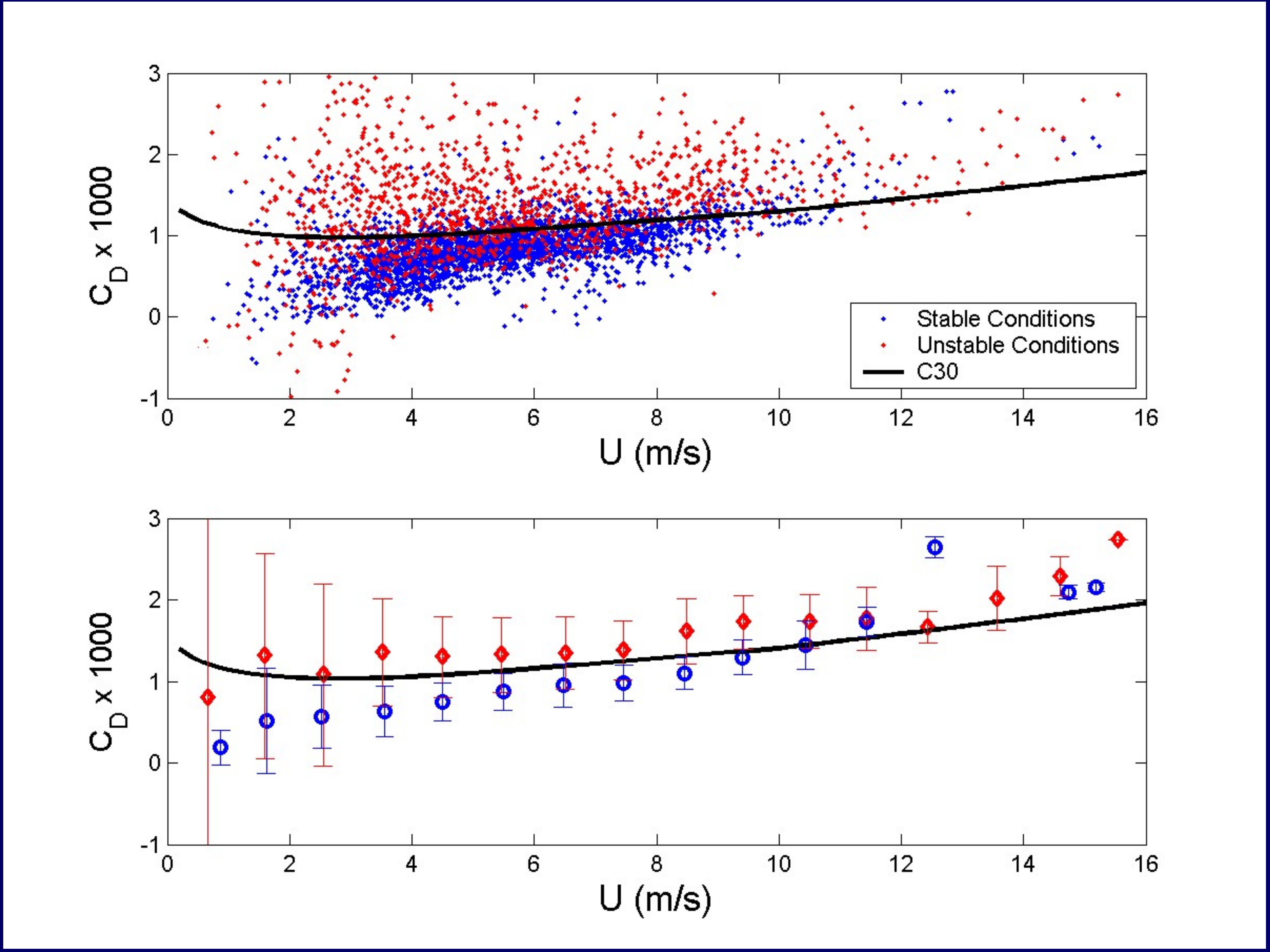
Dimensionless Shear

Kansas-like
(TOGA-COARE)
in the Mean

$$\phi_m\left(\frac{z}{L}\right) = \frac{kz}{u_*}\frac{\partial U}{\partial z}$$



Stability Correction: $C_D(z/z_0, z/L) = \frac{-\overline{uw}}{\Delta U^2} = \left(\frac{\kappa}{\ln(z/z_o) - \psi_m(z/L)} \right)^2$



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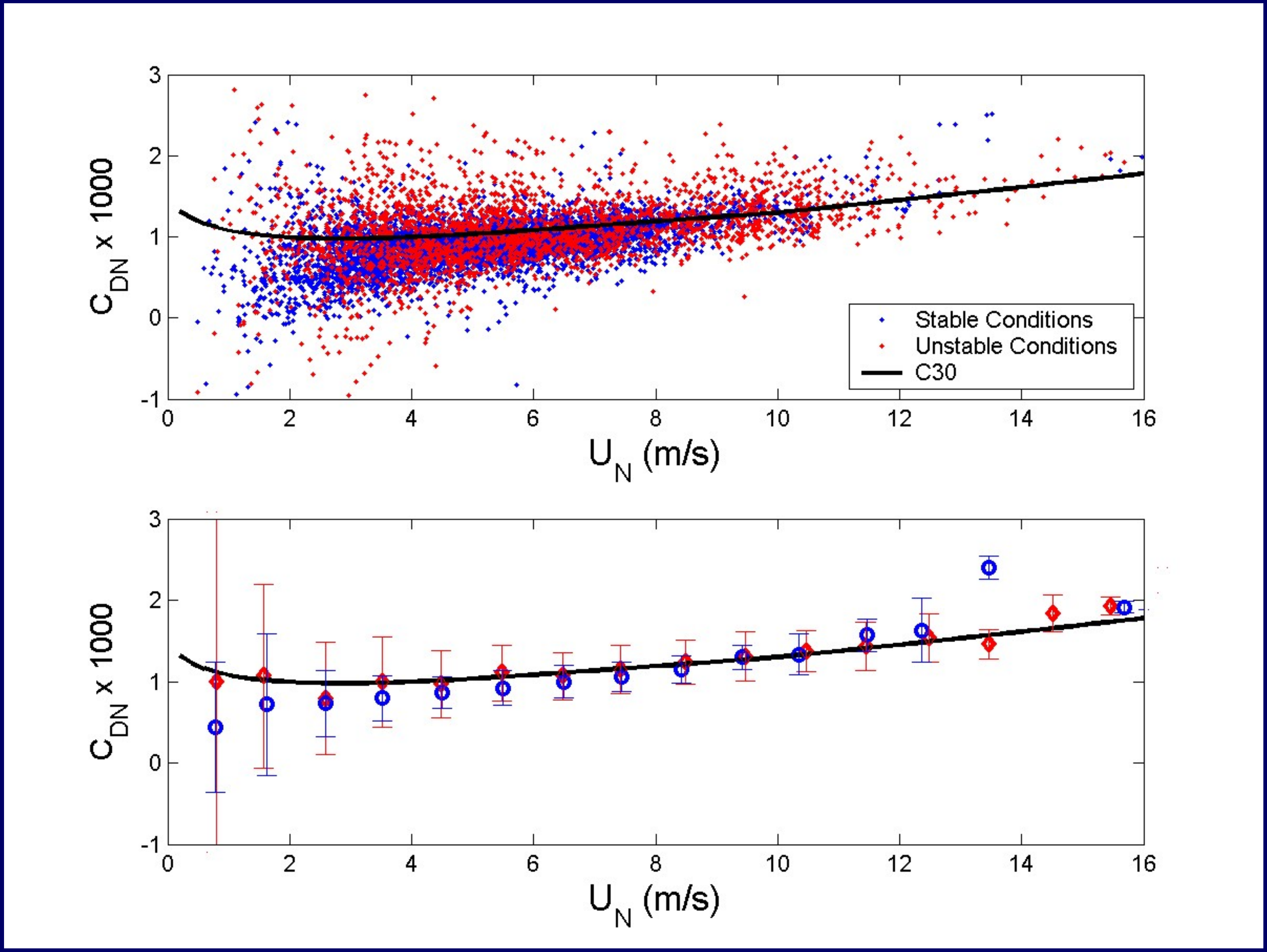


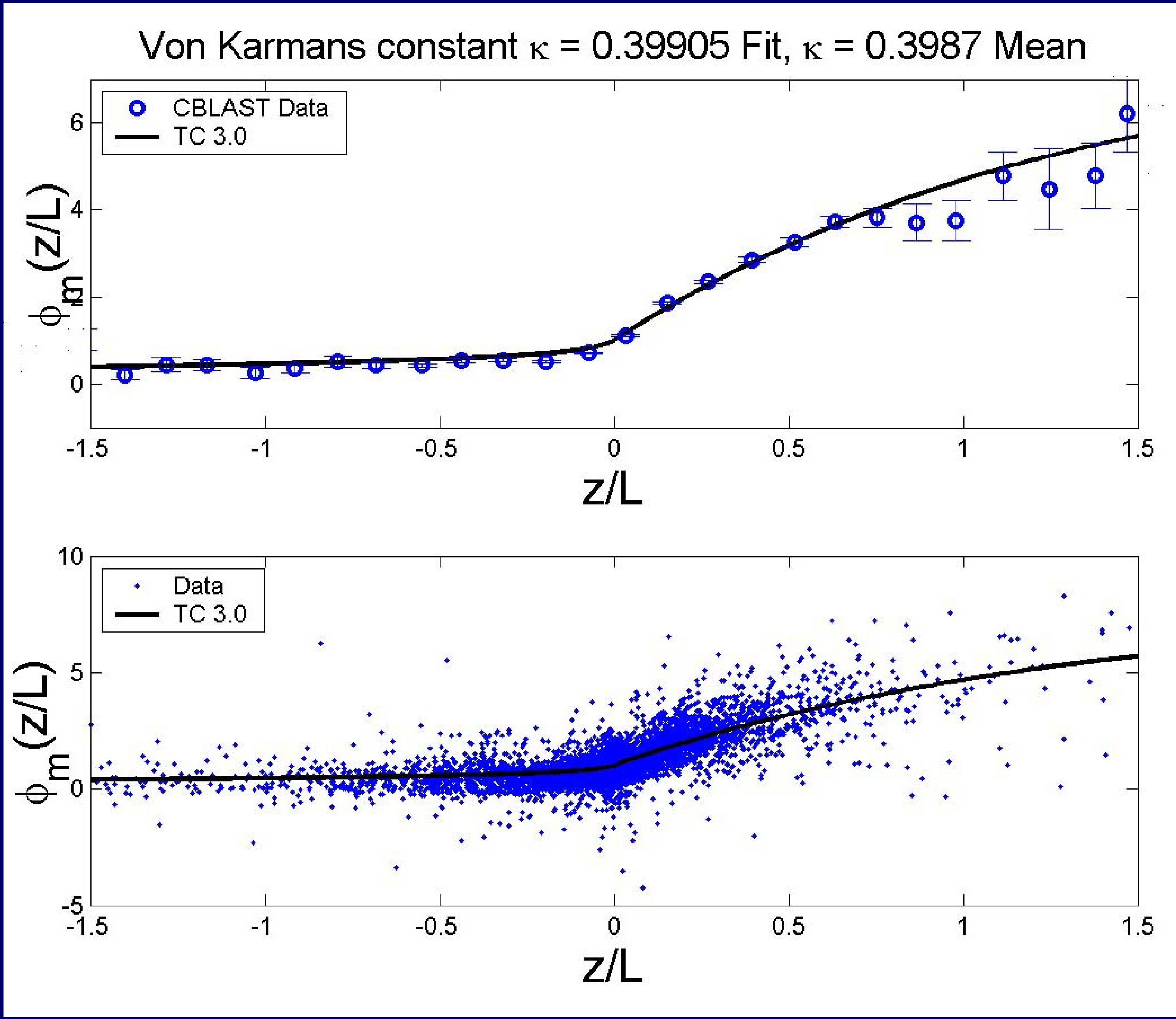
Dimensionless Shear

Kansas-like (TOGA-COARE) in the Mean

$$\phi_m\left(\frac{z}{L}\right) = \frac{kz}{u_*}\frac{\partial U}{\partial z}$$

Is this really the best fit?

Can we quantity any of the variability about the mean?



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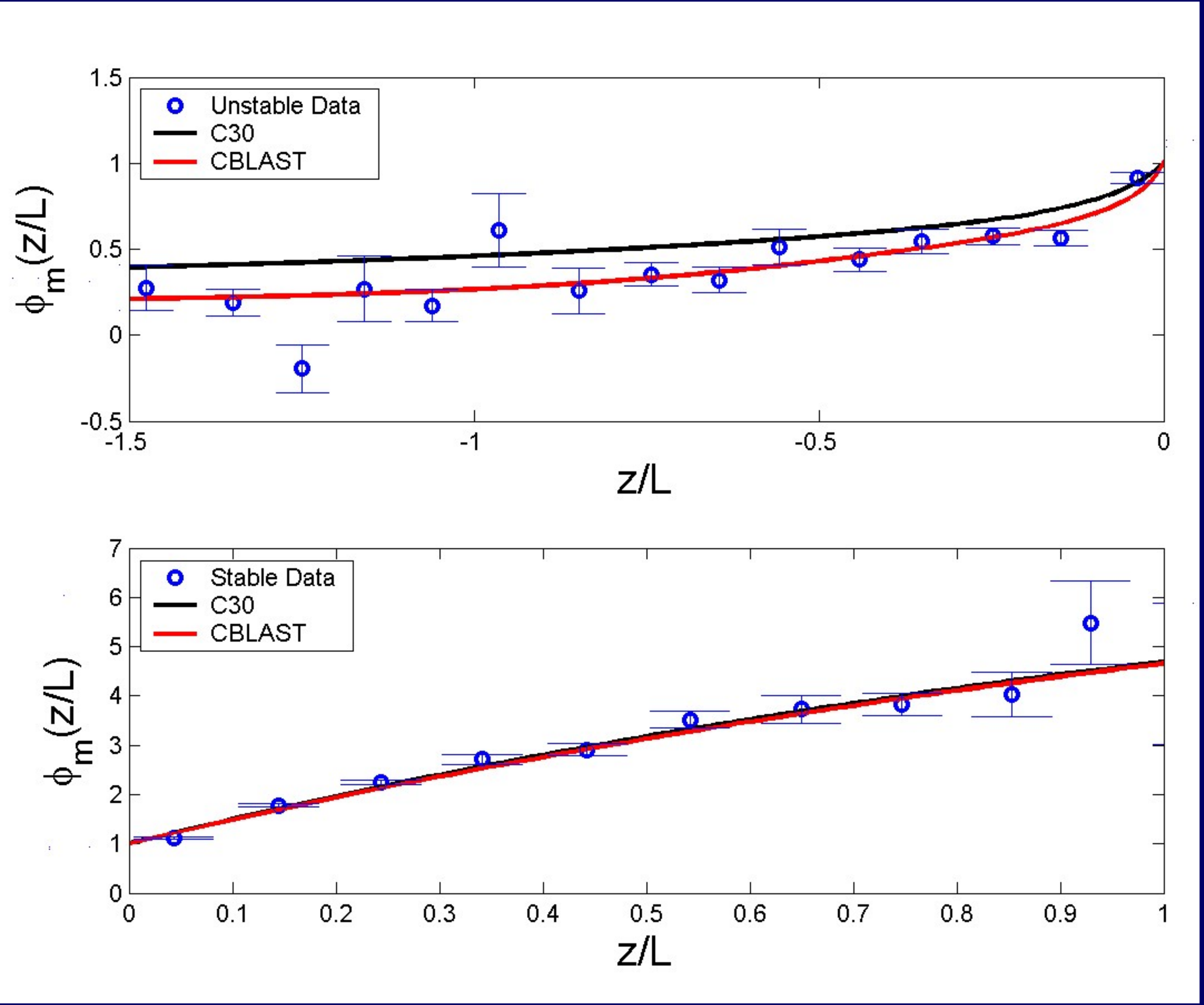
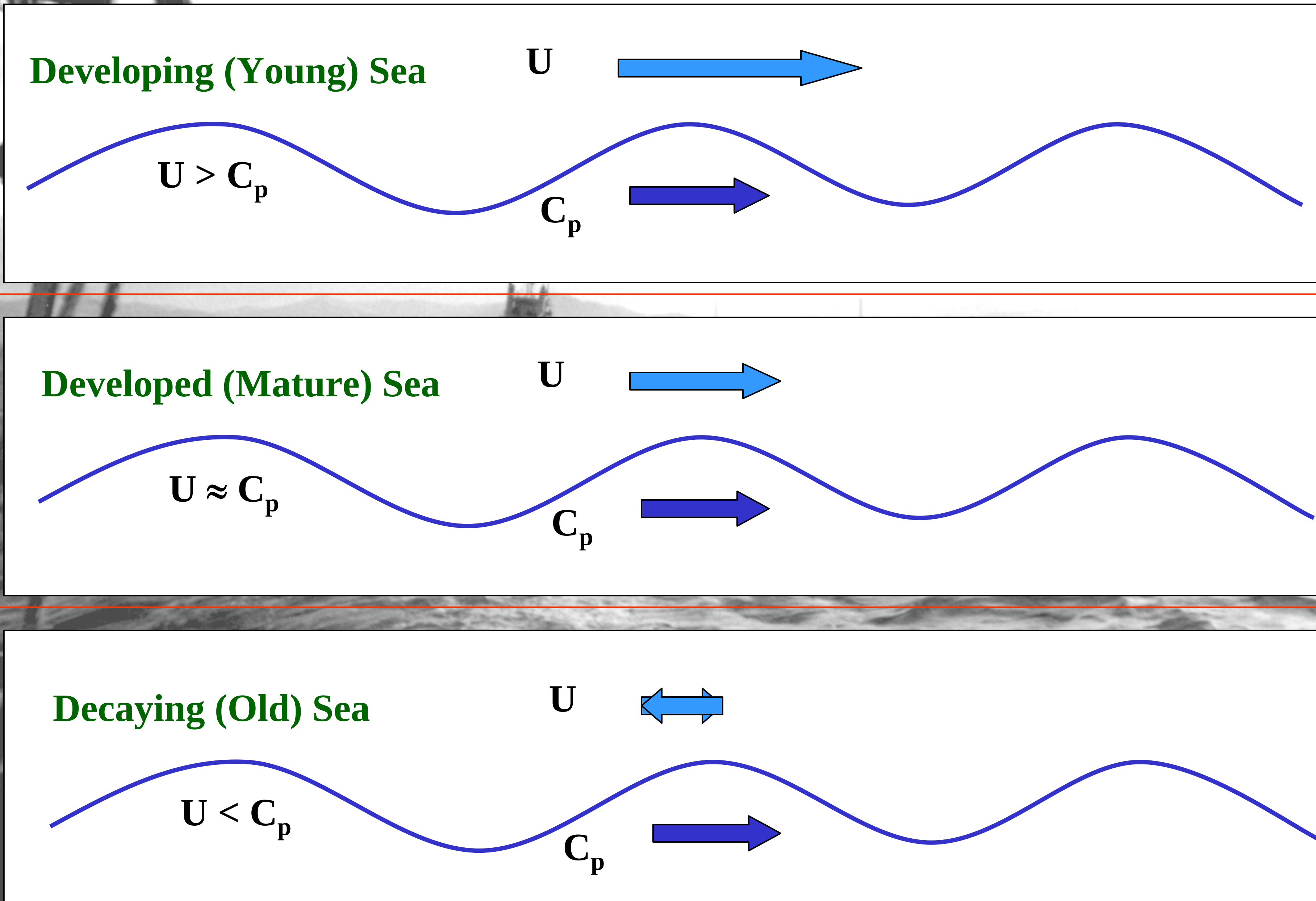


Wave Age


Developing (Young) Sea
U
U > Cp
Cp
Developed (Mature) Sea
U
U ≈ Cp
Cp
Decaying (Old) Sea
U
U < Cp
Cp

Dimensionless Shear

Kansas-like (TOGA-COARE) in the Mean

$$\phi_m\left(\frac{z}{L}\right) = \frac{kz}{u_*}\frac{\partial U}{\partial z}$$

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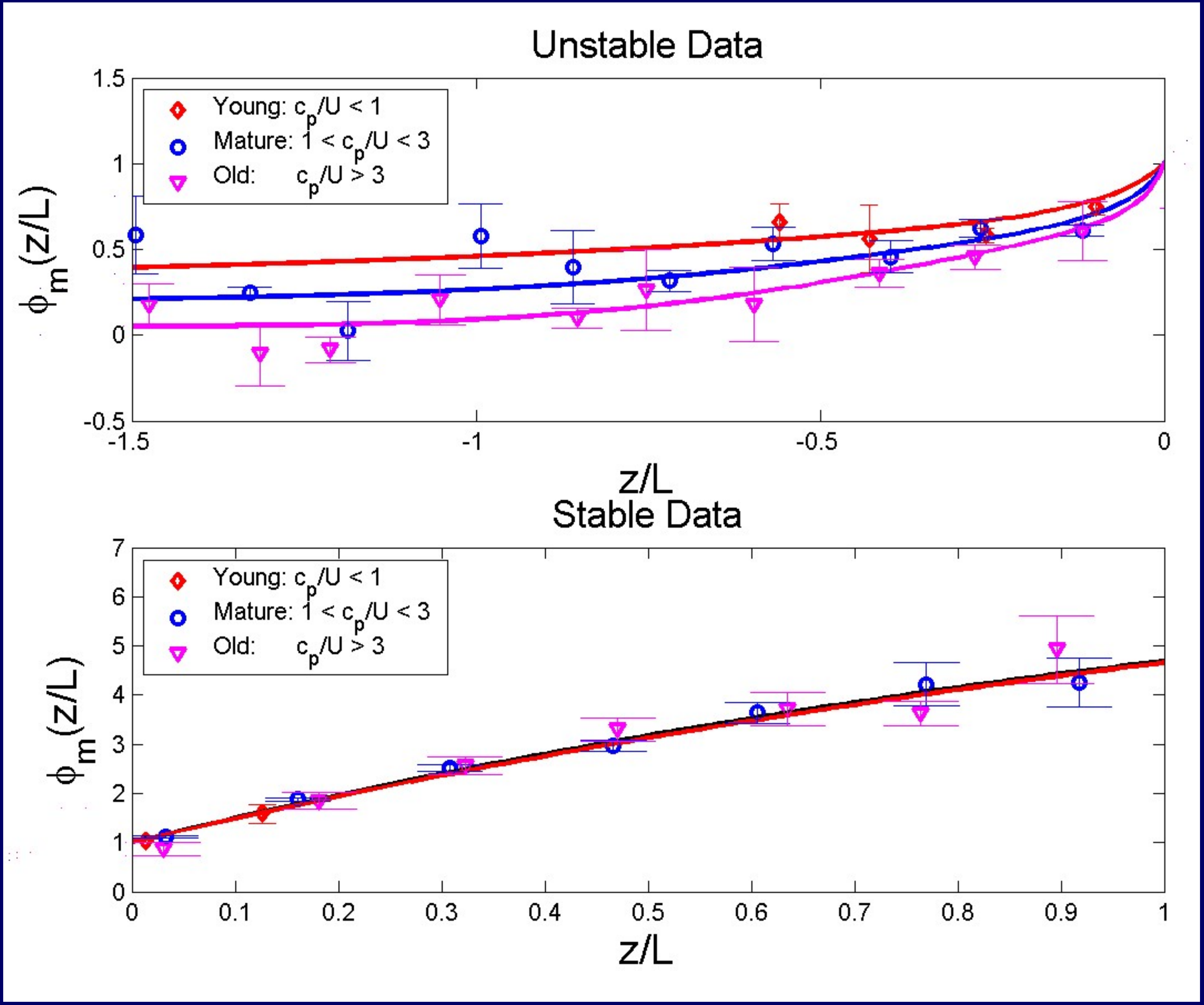

Dimensionless Shear

Kansas-like (TOGA-COARE) in the Mean

$$\phi_{\mathrm{m}}\left(\frac{z}{L}\right) = \frac{kz}{u_*}\frac{\partial U}{\partial z}$$

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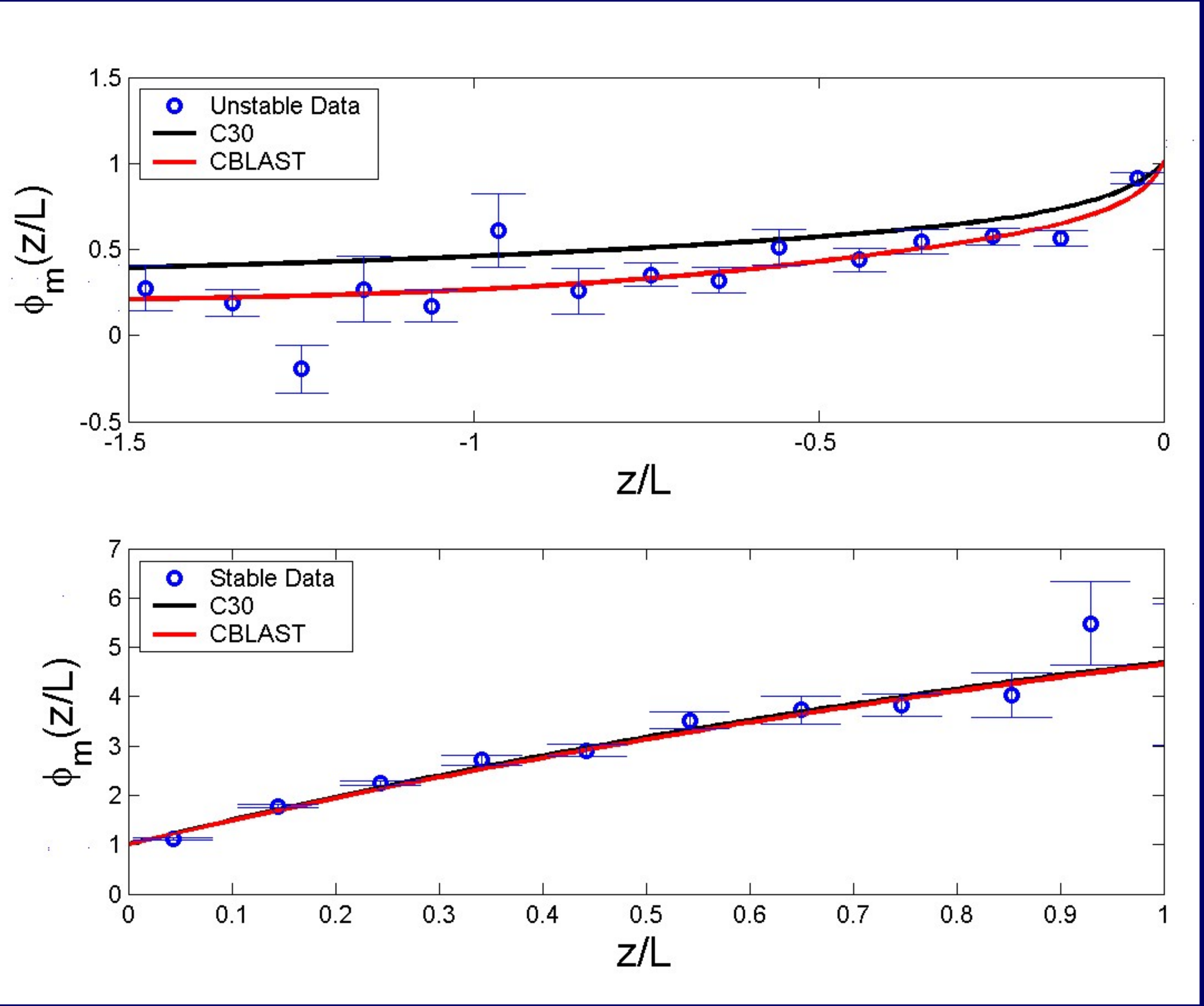

Drag Coefficient Formulas

- Semi-empirical

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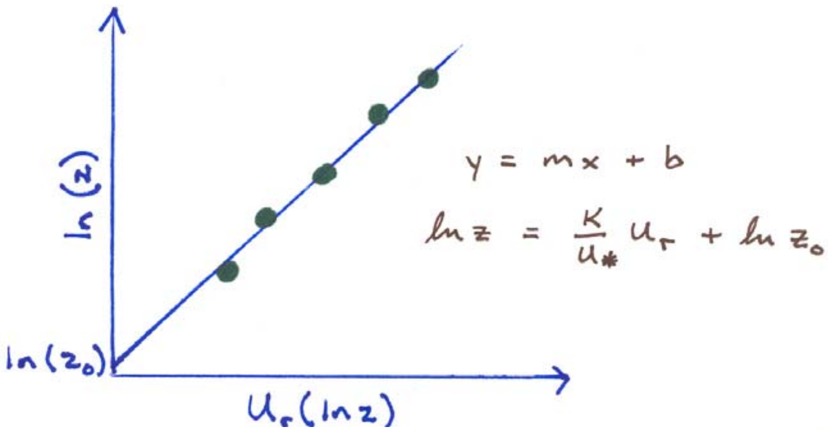
$$10^3 C_{DN}(U_{10N}) = \begin{cases} 1.2 & 4 \le U_{10N} \le 11\,\mathrm{ms^{-1}} \\ 0.49 + 0.065\,U_{10N} & 11 \le U_{10N} \le 25\,\mathrm{ms^{-1}} \end{cases}$$

Large & Pond (1981)

The Roughness Length



Coastal & Open Ocean

TABLE 6.2. RELATION OF z_0 TO VARIOUS TERRAIN TYPES (ESDU, 1974)

$z_0(m)$ (logarithmic scale from 10^{-5} to 5)

z_0 (m)			
2	Centers of cities with very tall buildings		Very hilly or mountainous areas
1	Centers of large towns, cities		Forests
5	Centers of small towns		
4	Outskirts of towns		Fairly level wooded country
2	Many trees, hedges, few buildings		
10^{-1}	Many hedges	Farmland	
6	Few trees, summer time	Farmland	Long grass (≈ 60 cm), crops
3	Isolated trees	Farmland	Airports (runway area)
2	Uncut grass	Fairly level grass plains	
10^{-2}	Few trees, winter time	Fairly level grass plains	
7	Cut grass (≈ 3 cm)	Fairly level grass plains	
2	Natural snow surface (farmland)		
10^{-3}	Off-sea wind in coastal areas	Large expanses of water	
6		Large expanses of water	Desert (flat)
3		Large expanses of water	
10^{-4}	Calm open sea	Large expanses of water	Snow-covered flat or rolling ground
2	Ice, mud flats		
10^{-5}			

Surface Momentum Exchange & Waves

- **Above the Wave Boundary Layer – MO Similarity expected to hold.**

$$\rho\overline{uw} = \rho\overline{u'w'}$$

- **Within the Wave Boundary Layer – MO Similarity begins to break down.**

$$\rho\overline{uw} = \rho\overline{u'w'} + \rho\overline{\tilde{u}\tilde{w}}$$

- **At the surface**

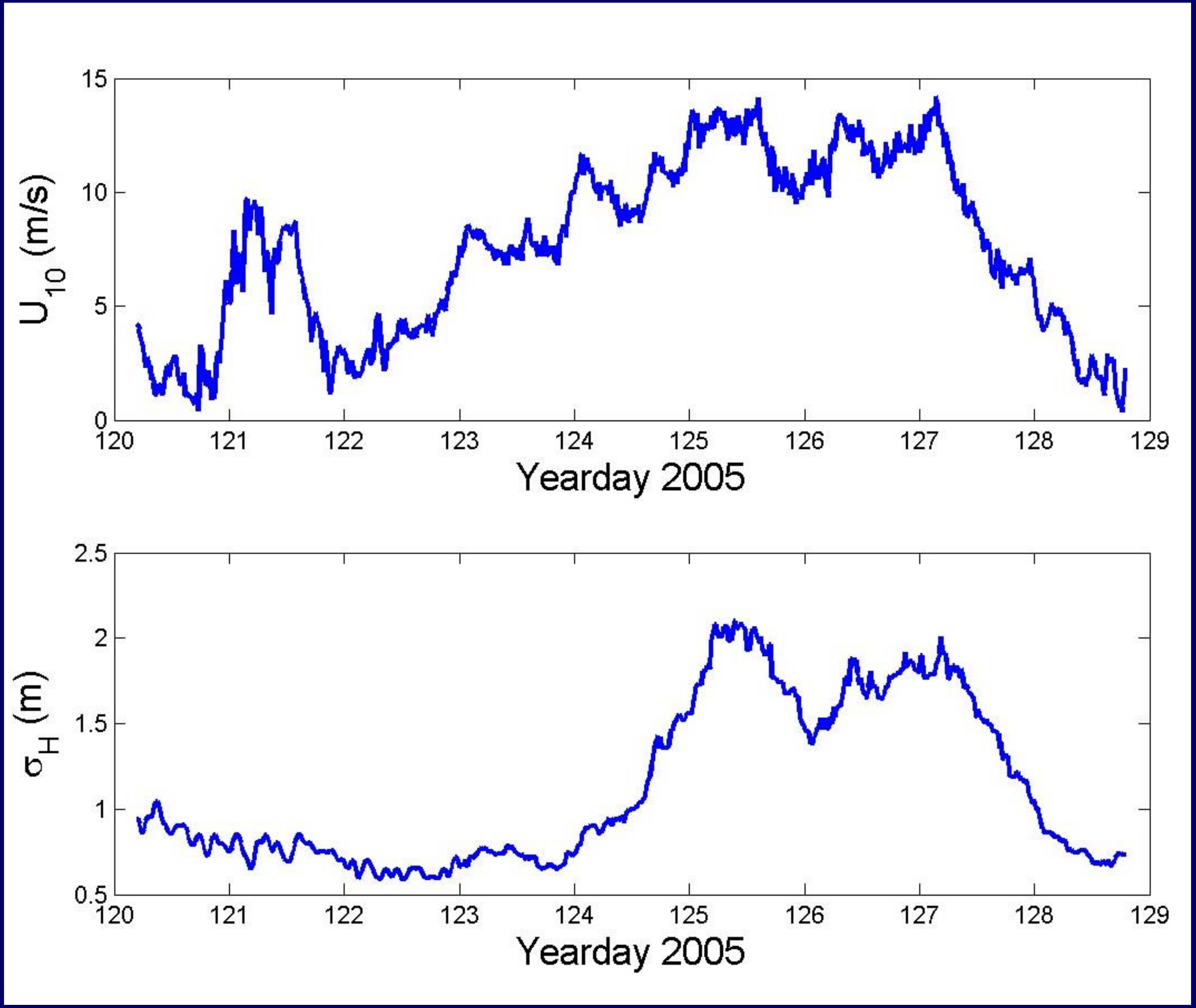
$$\rho\overline{uw} = \nu\frac{dU}{dz} + \rho\overline{\tilde{u}\tilde{w}} = \underbrace{\nu\frac{dU}{dz}}_{\text{Viscous Stress}} + \underbrace{\overline{p_0\frac{\partial\eta}{\partial x}}}_{\text{Form Drag}}$$

- **COARE parameterizes this through the roughness length:**

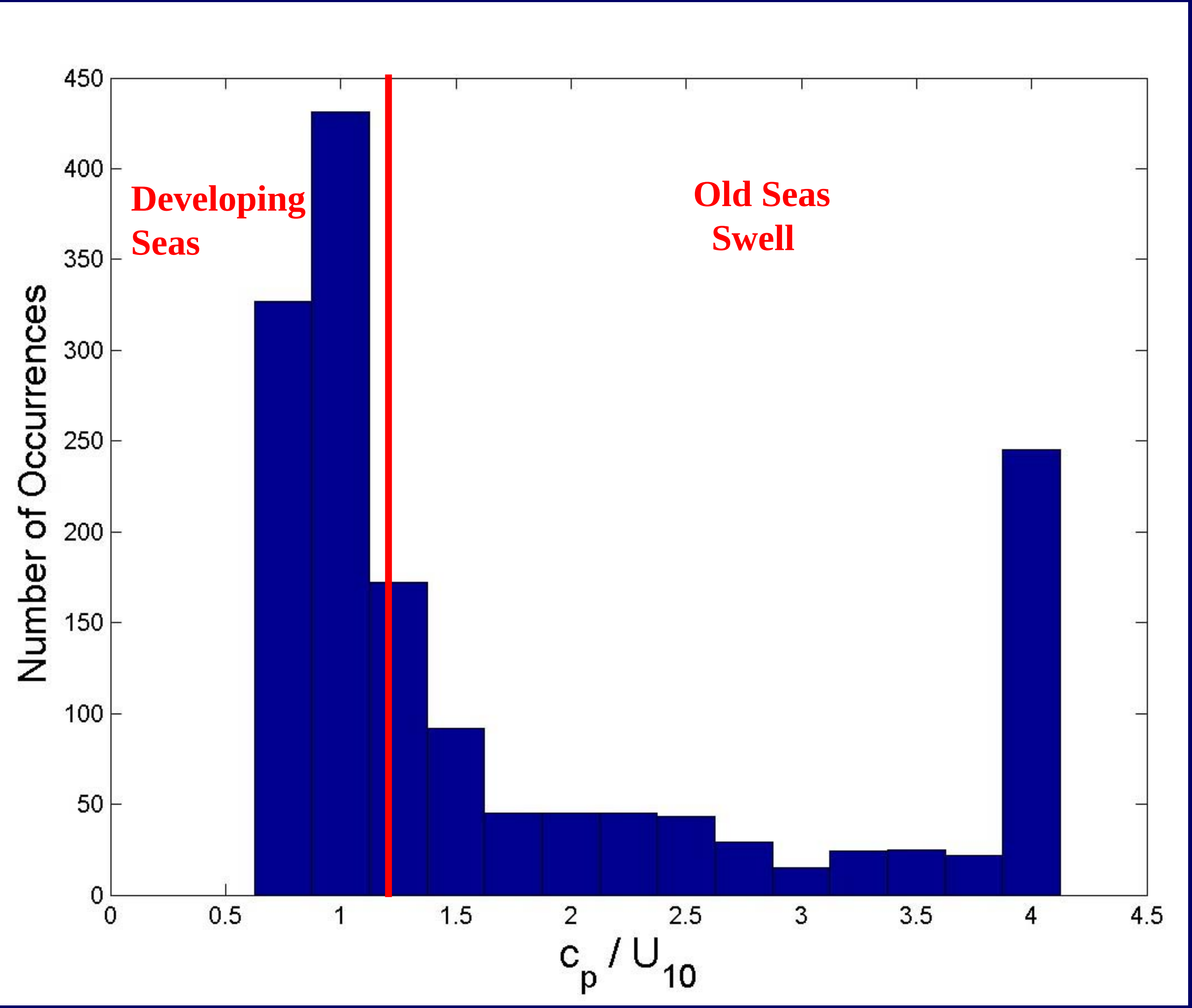
$$z_0 = \alpha\frac{\nu}{u_*} + \boxed{\beta}\frac{u_*^2}{g}$$

Charnock Parameter

MBL/FLIP Wind Event

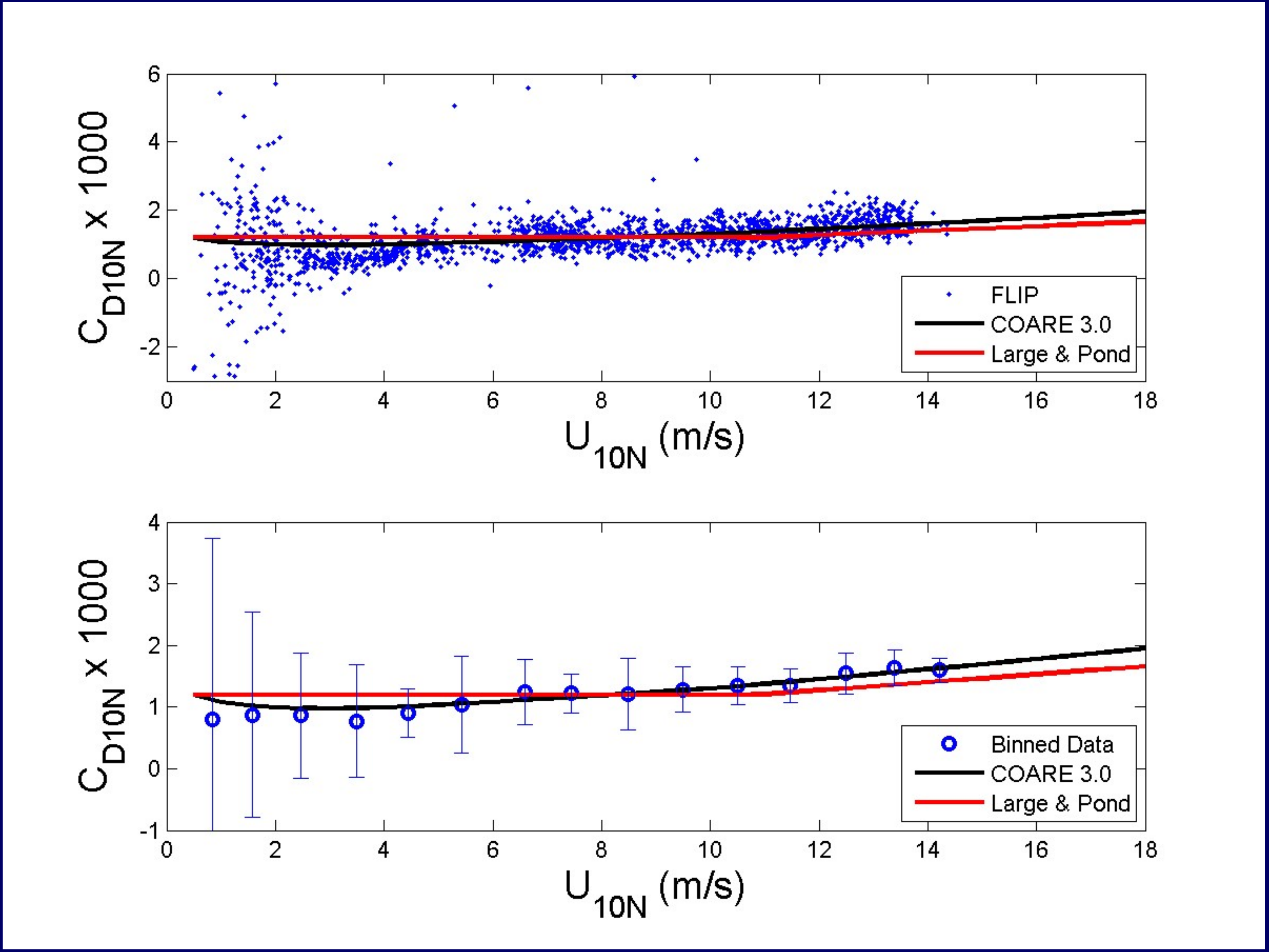


MBL/FLIP Wave Ages

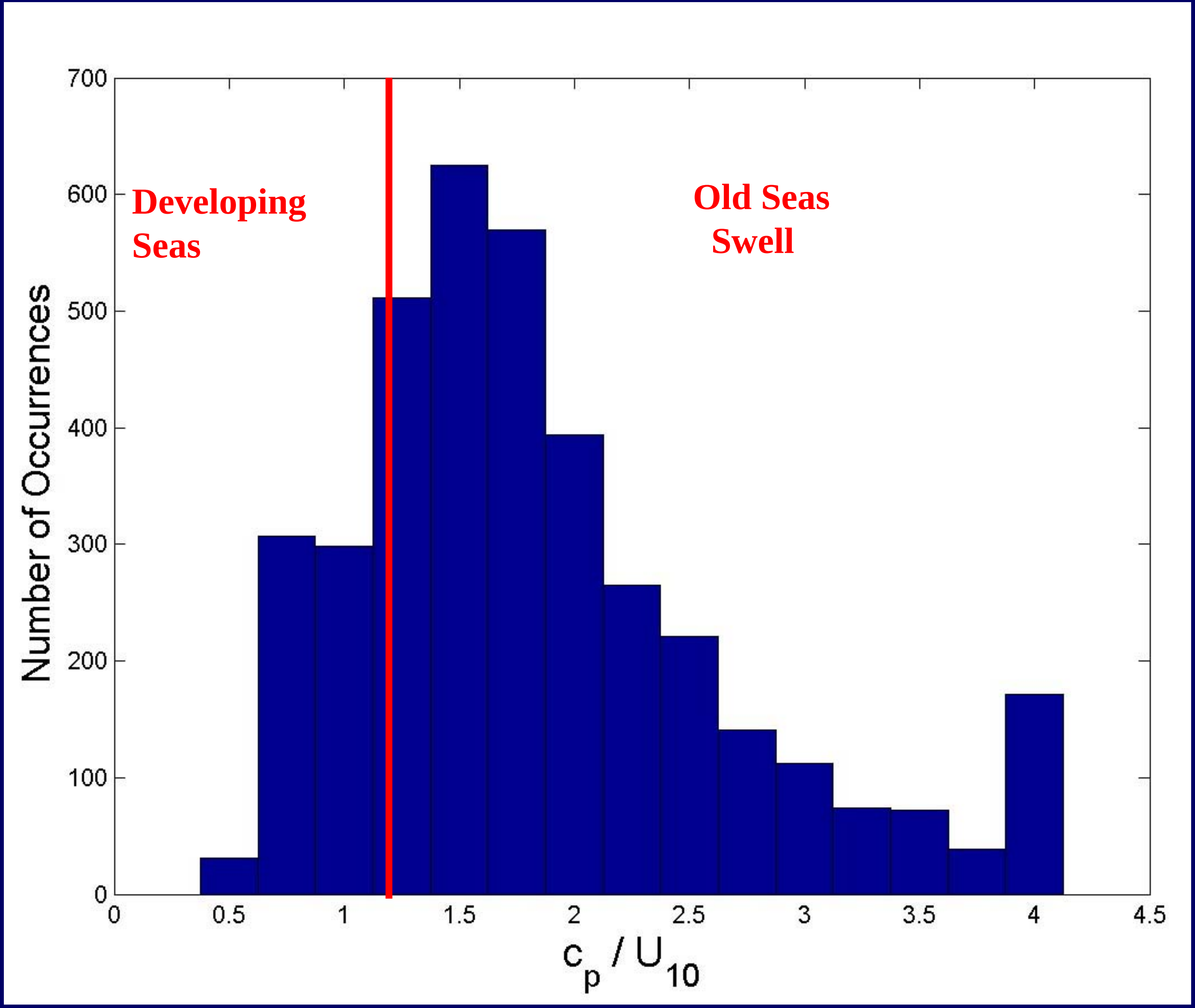


Fully Developed Sea : $c_p / U_{10} \approx 1.2$

FLIP Drag Coefficients



CBLAST/OHATS Wave Ages



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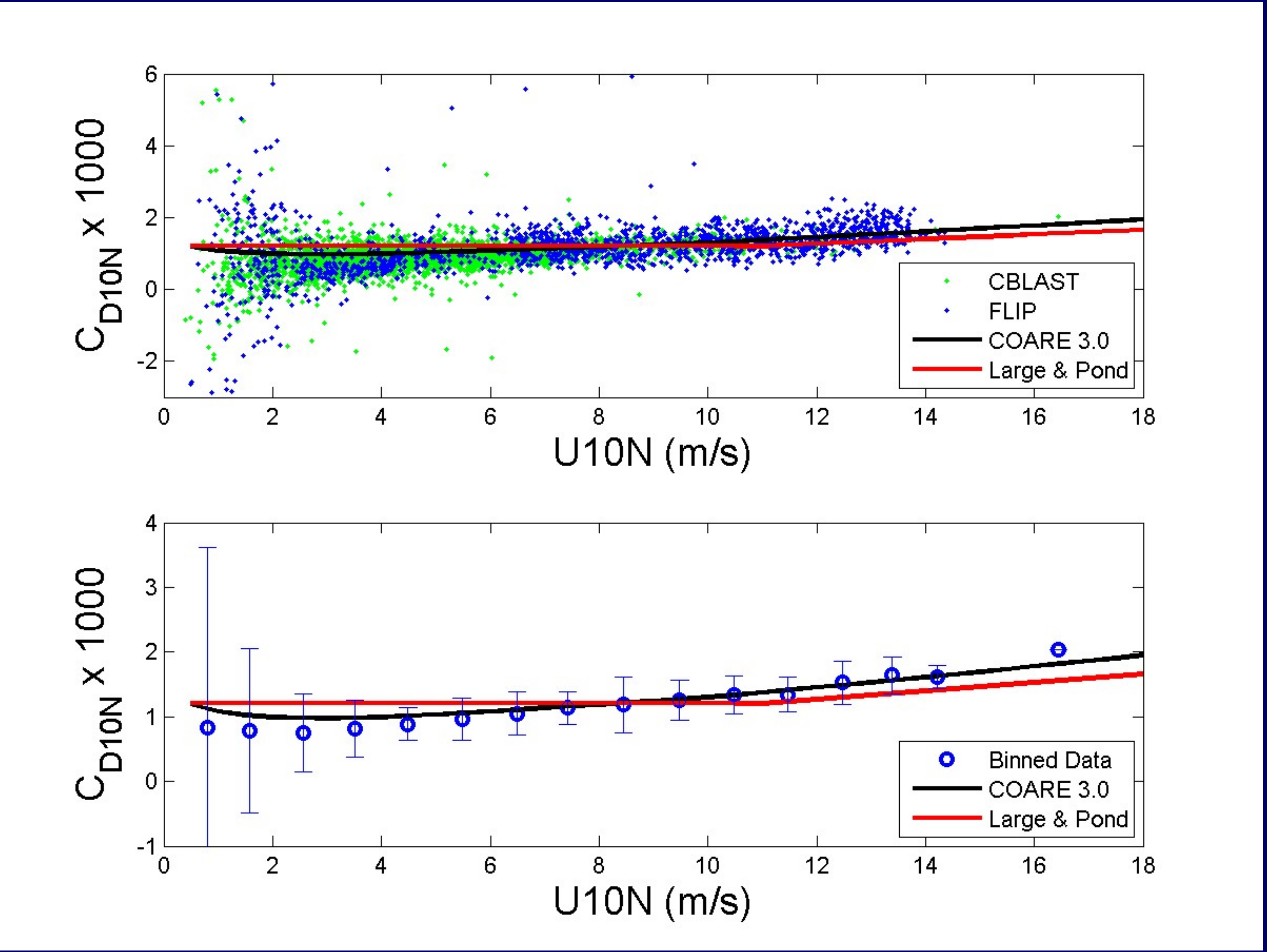
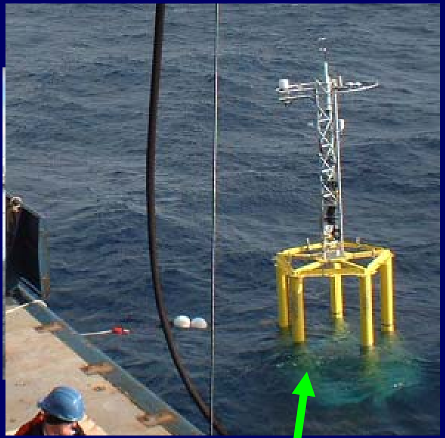
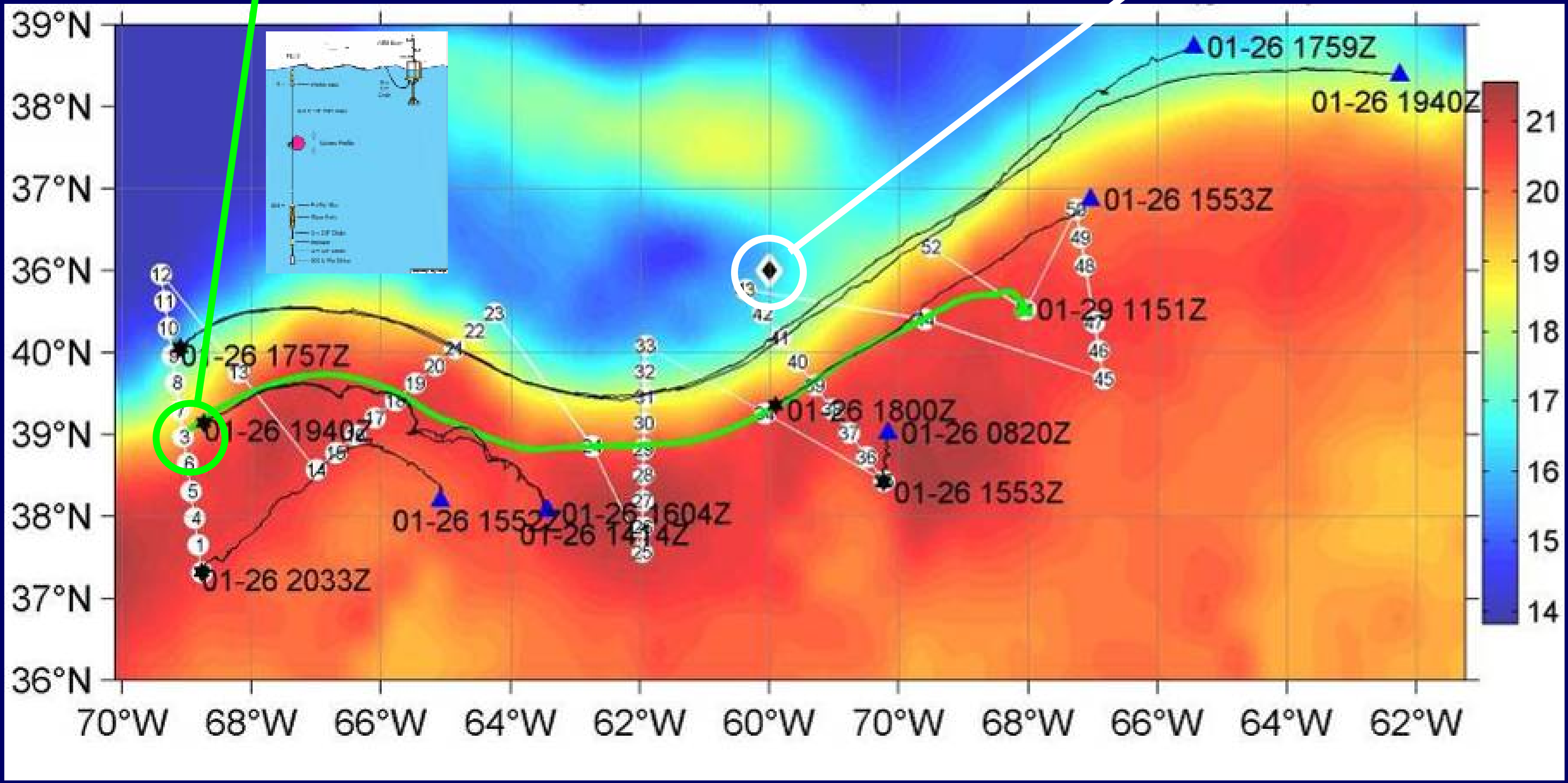
FLIP/CBLAST Drag Coefficients



CLIMODE Platforms

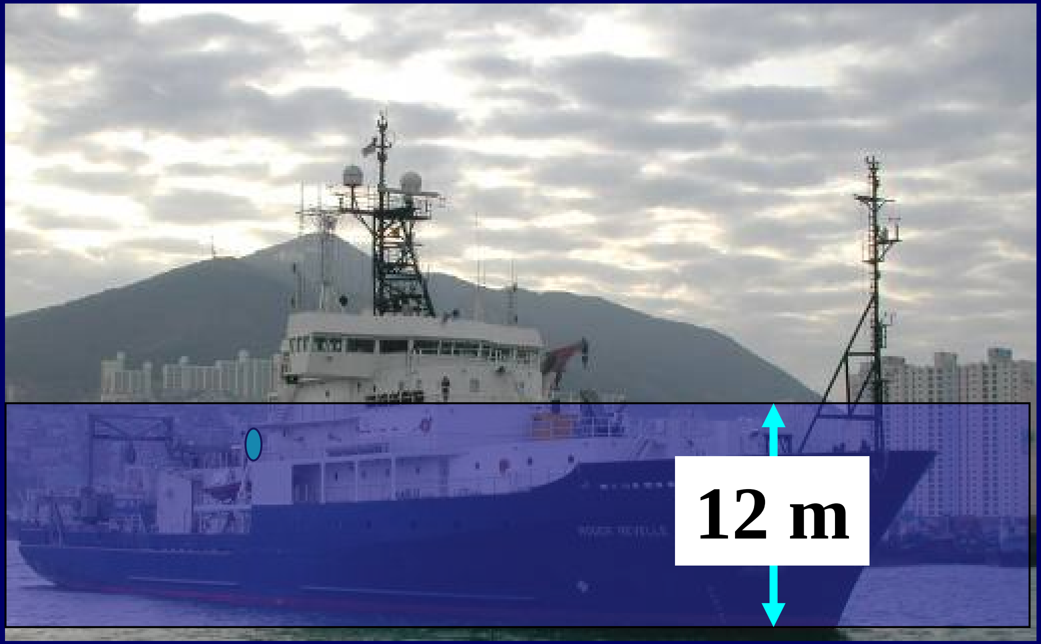




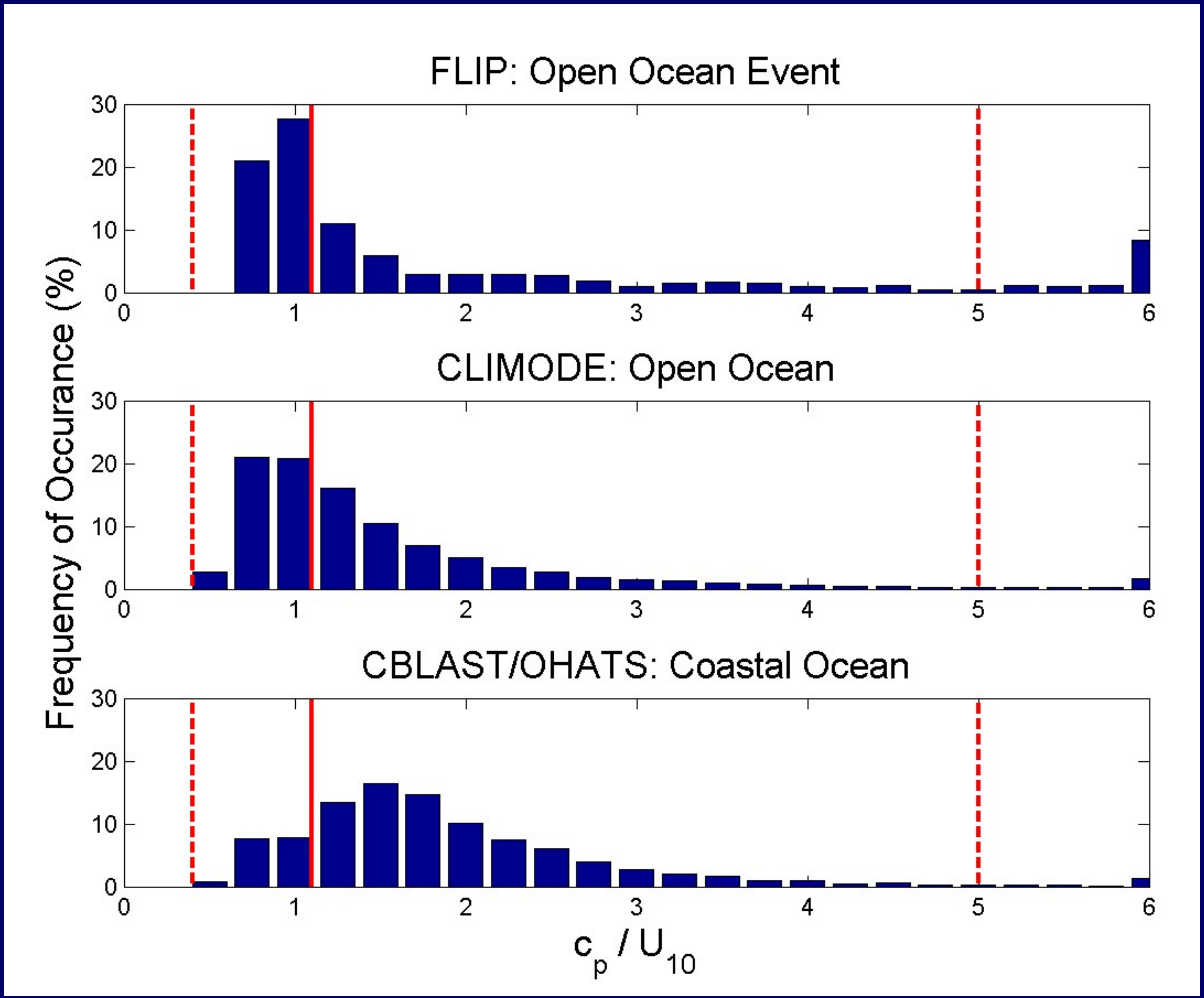
Extreme Conditions

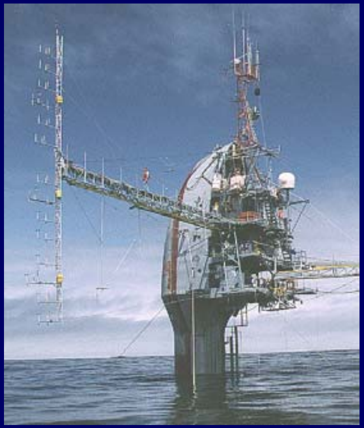
Maximum wind speeds exceeded 30 m/s in near hurricane conditions.

ASIS destroyed by rough wave



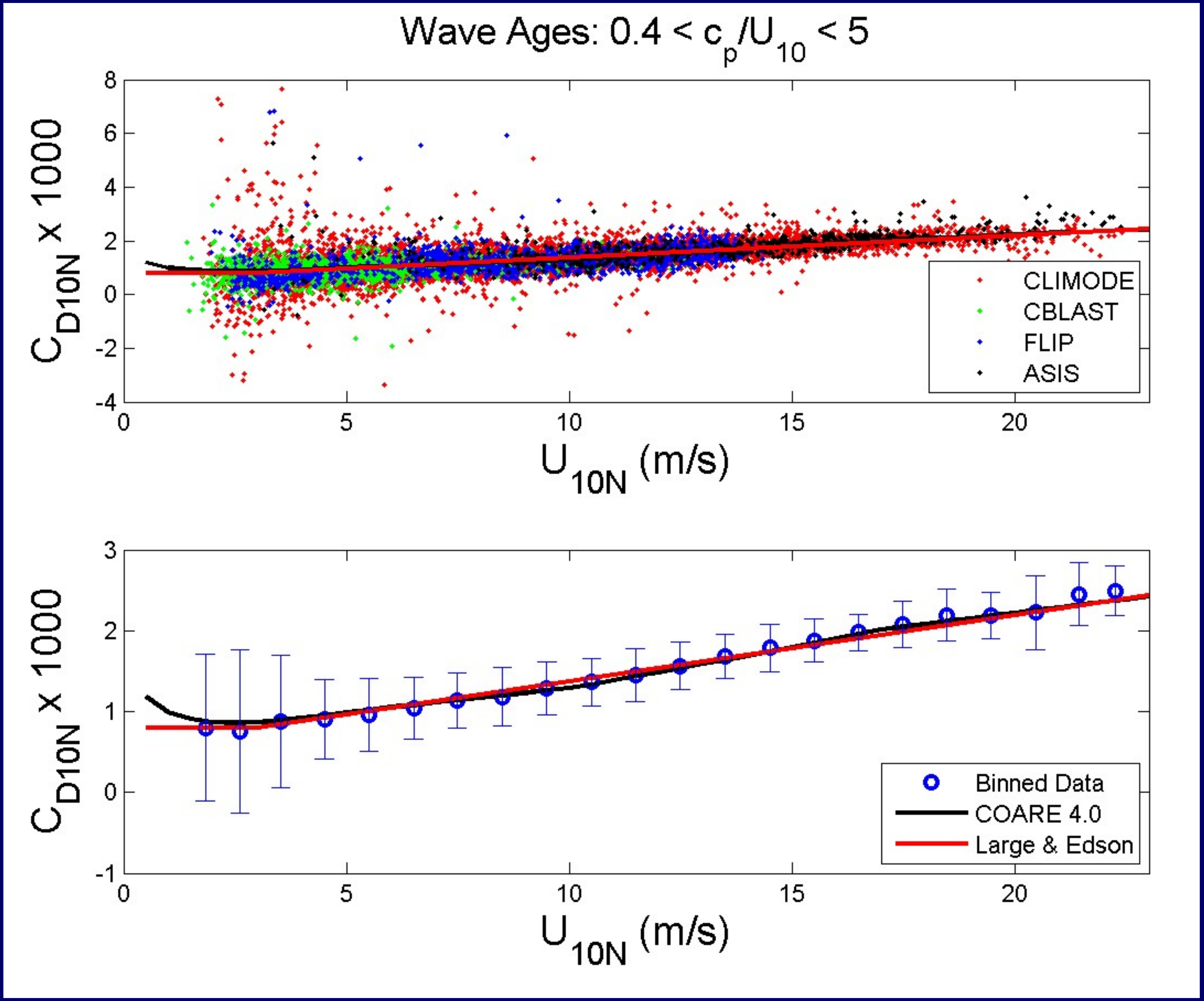
MBL/CBLAST/CLIMODE Wave Ages

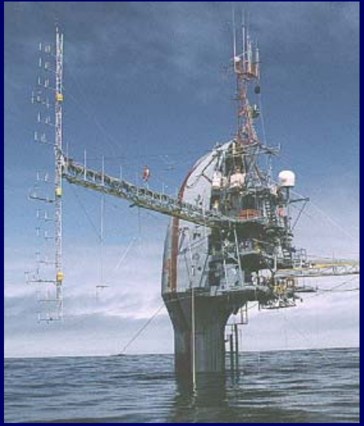




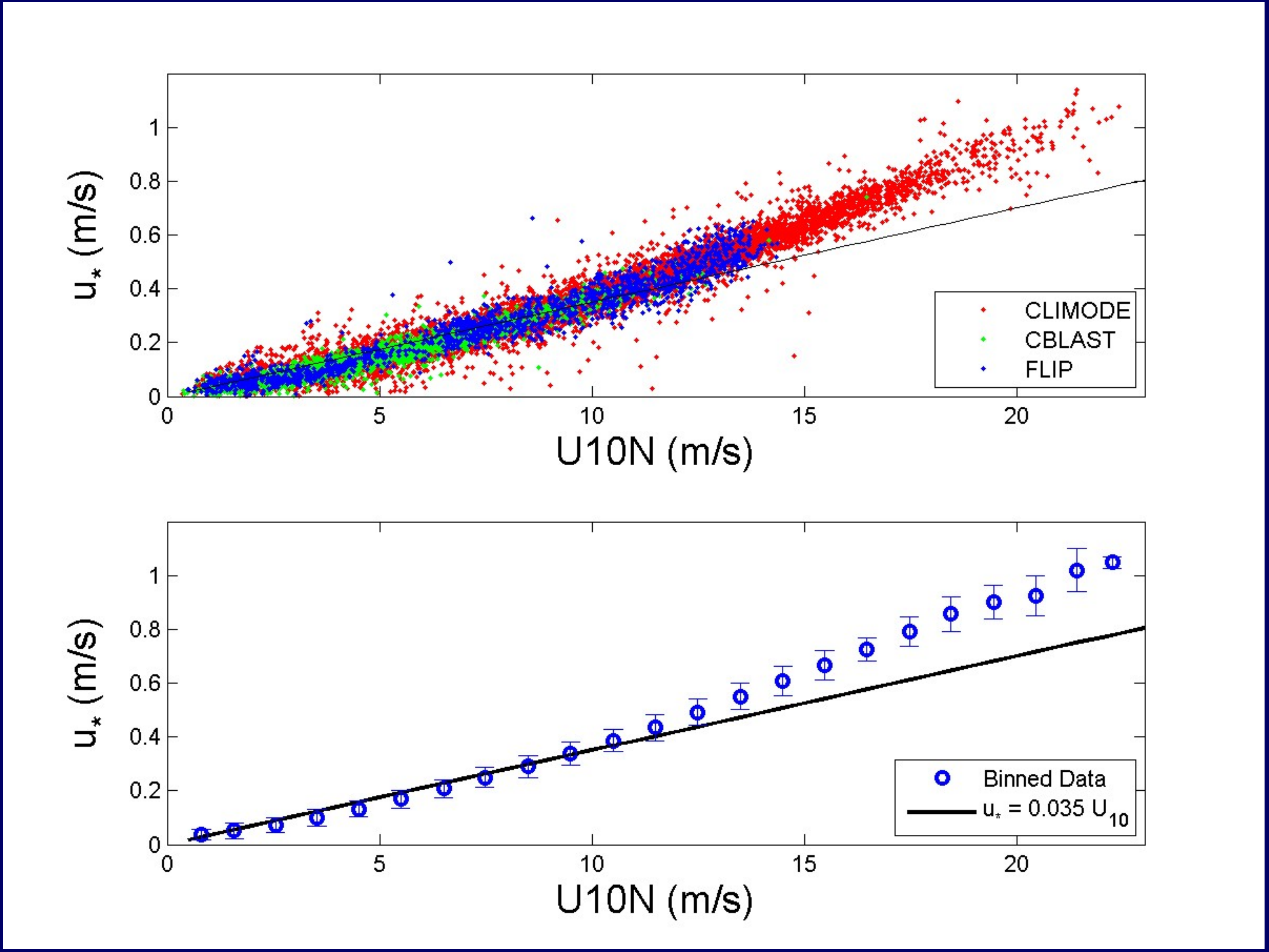
Fully Developed Sea: $c_p / U_{10} \approx 1.2$

MBL/CBLAST/CLIMODE Drag Coefficients





Wave Age Dependent Drag



Wave Age Dependent Drag

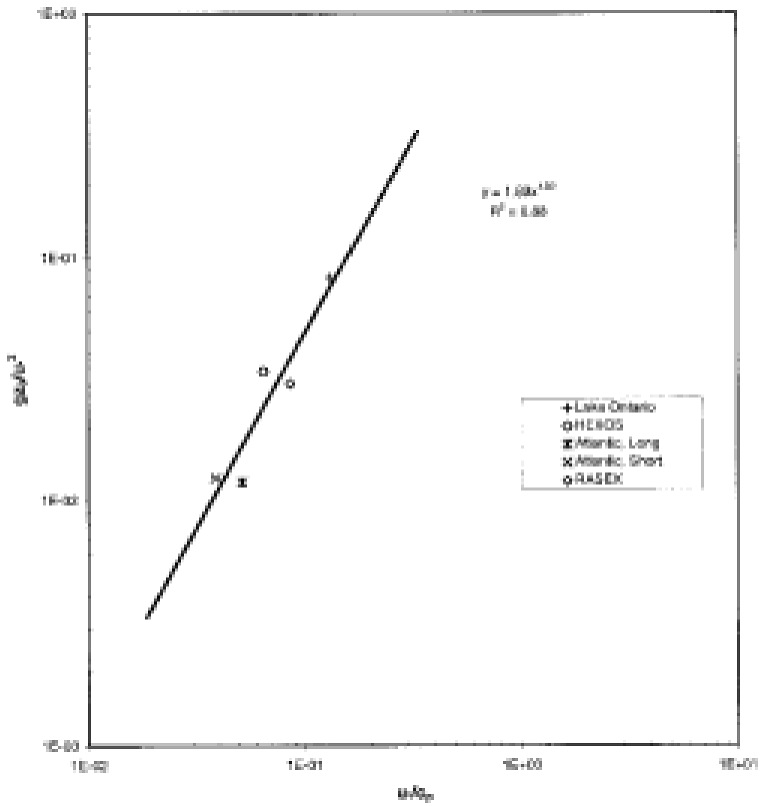


FIG. 5. Scatterplot of the mean Charnock parameter from different datasets and inverse wave age. The full line is the least squares best fit line.

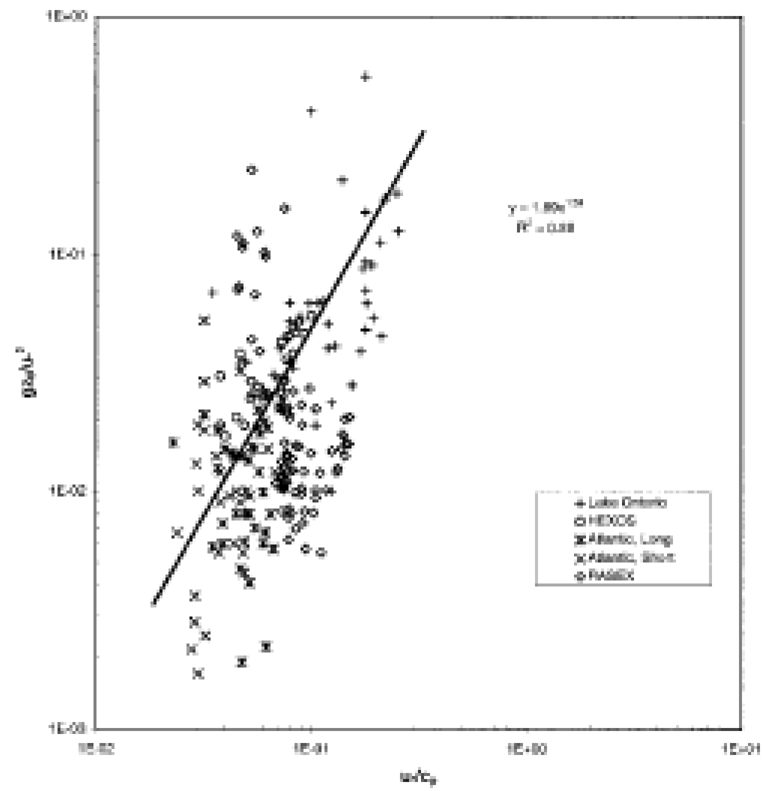
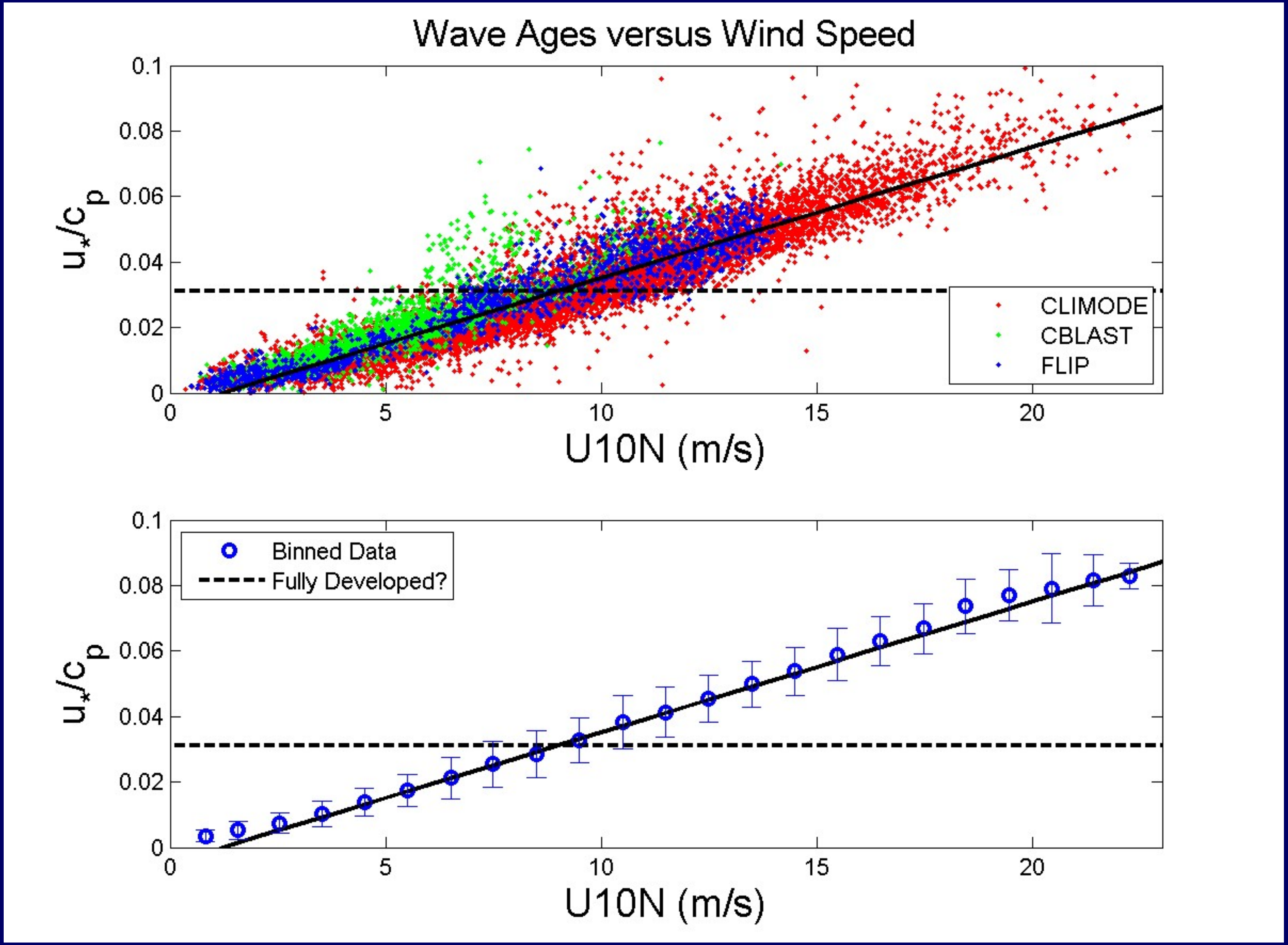


FIG. 6. Scatterplot of the Charnock parameter from different datasets and inverse wave age. The full line is the least squares best fit line from Fig. 4.4.

Johnson, et al., 1999: On the dependence of sea surface roughness on wind waves, J. Phys. Oceanog., 1702-1716.

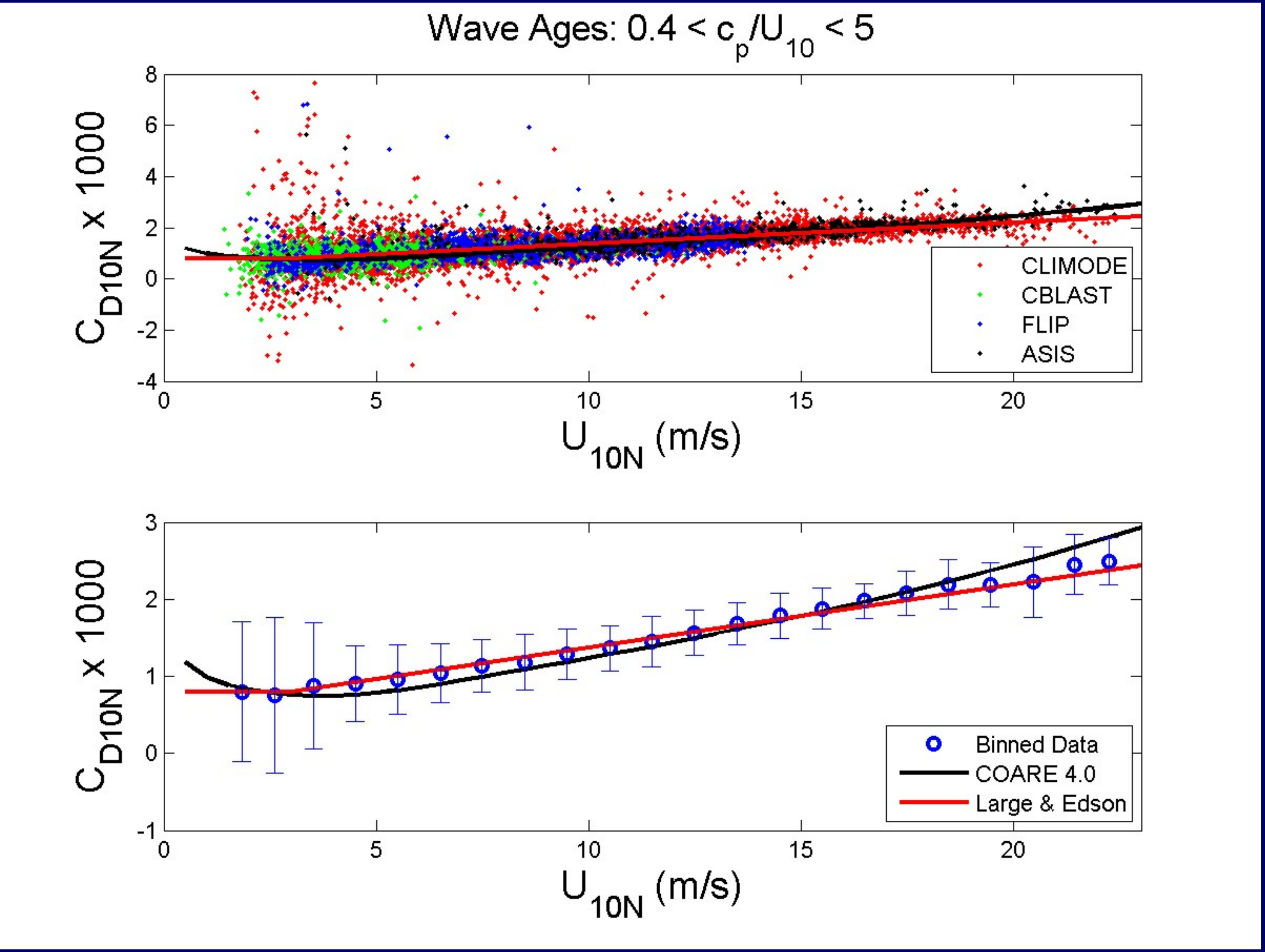
$$\beta = 1.89(c_p / u_*)^{-1.59}$$

Wave Age Dependent Drag



$$u_* / c_p = 0.004U_{10} - 0.005$$

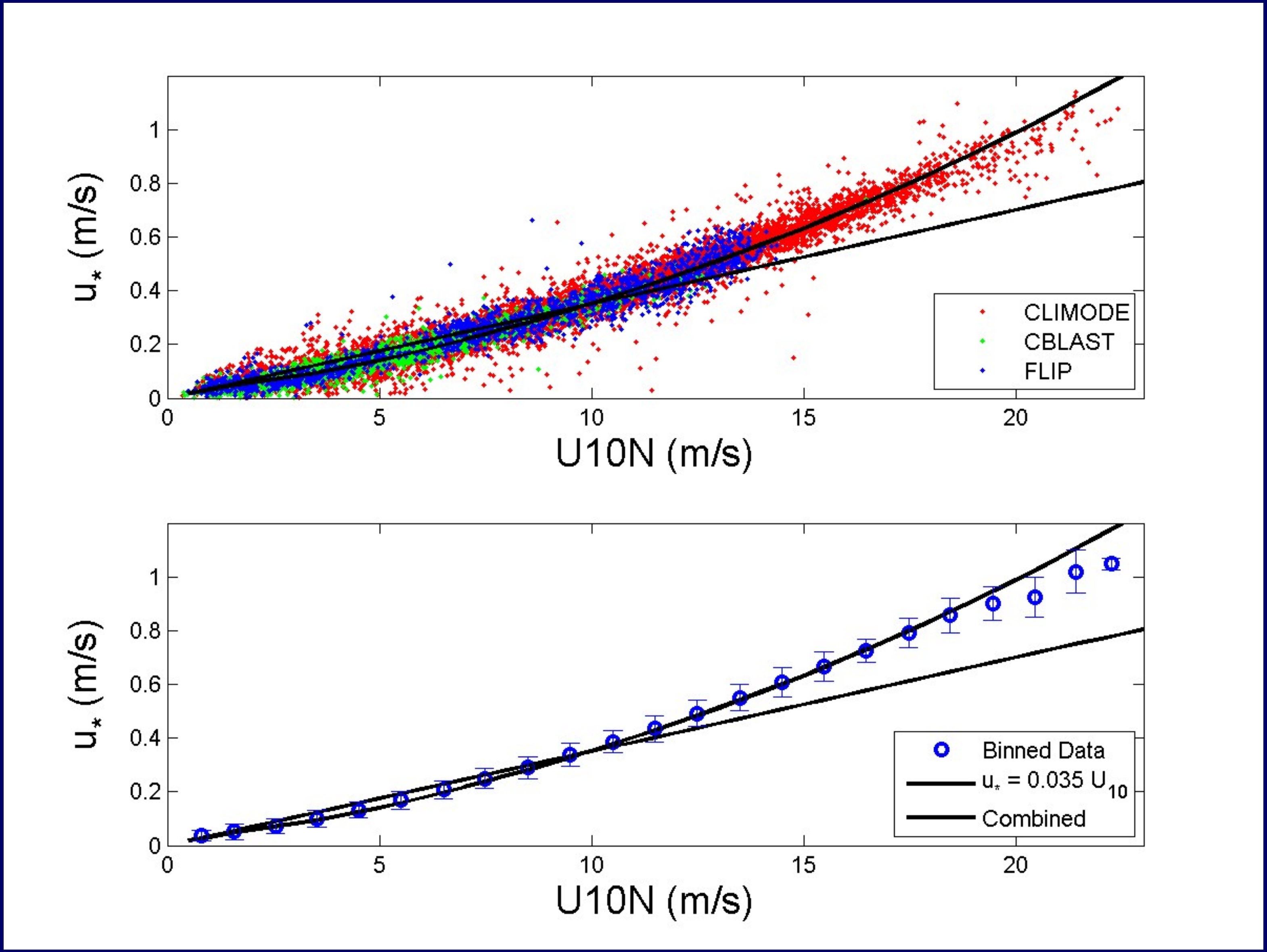
Wave Age Dependent Drag



$$u_* / c_p = 0.004 U_{10} - 0.005$$

$$\beta = 1.89 (c_p / u_*)^{-1.59}$$

Wave Age Dependent Drag



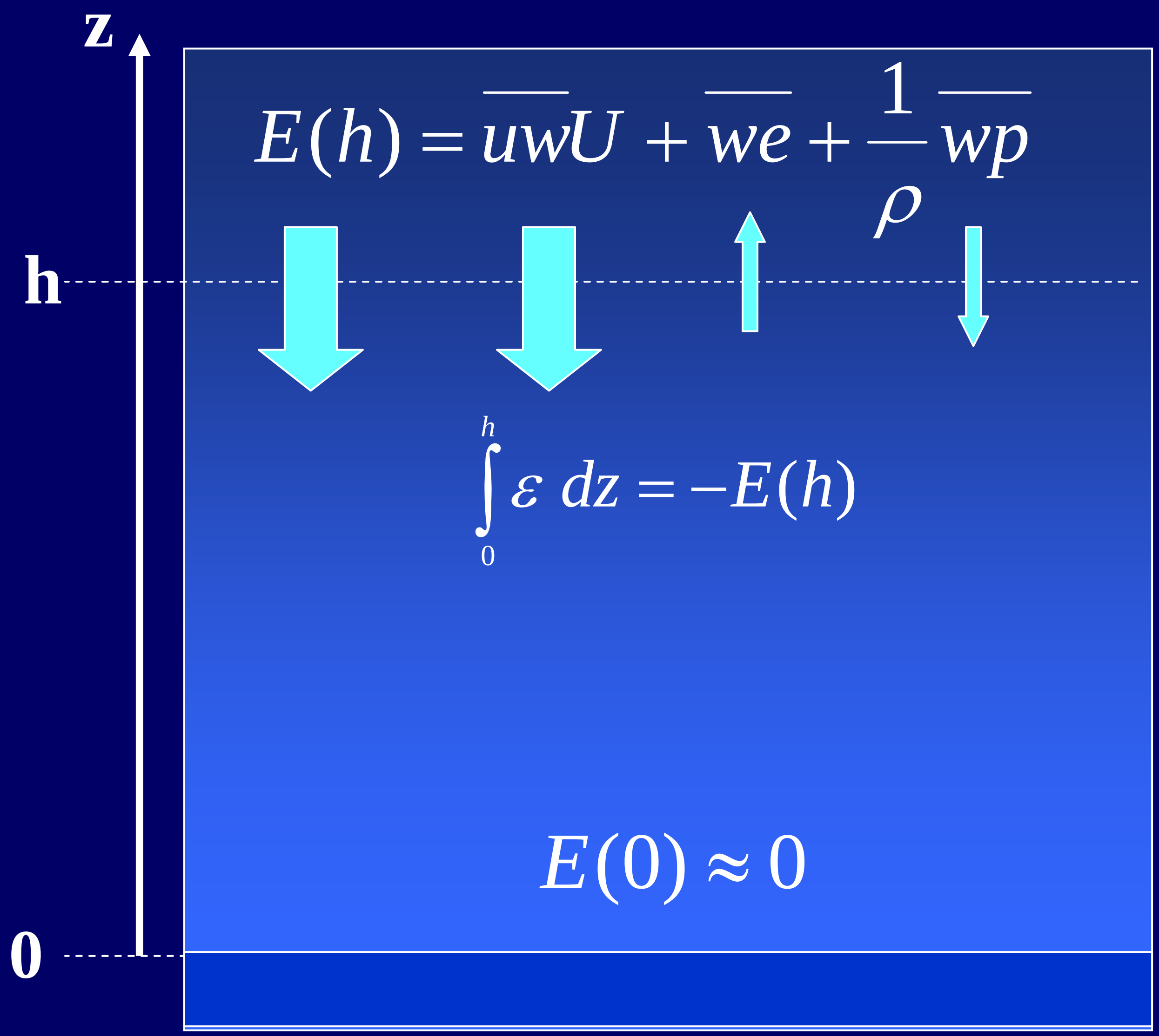
Summary I

- The form of dimensionless wind shear is very similar to Businger-Dyer like formulations developed over land.
  - The largest differences are seen over swell.
- A wind speed dependent drag coefficient give good results over a wind range of sea-states/wave-ages.
  - This requires a wind speed dependent Charnock variable
  - Numerous investigations have shown that the Charnock variable is dependent on wave-age.
  - However, these findings can be reconciled since observed wave ages over the coastal and open ocean are clearly associated with wind ranges.
- We have collected a nice set of data for model validations and parameterization studies over a wide range of conditions.
- The presenter likes to collaborate!

ENERGY EXCHANGE & WAVE GROWTH

Energy Flux Into the Marine Surface Layer

(Neutral & Horizontally Homogeneous)



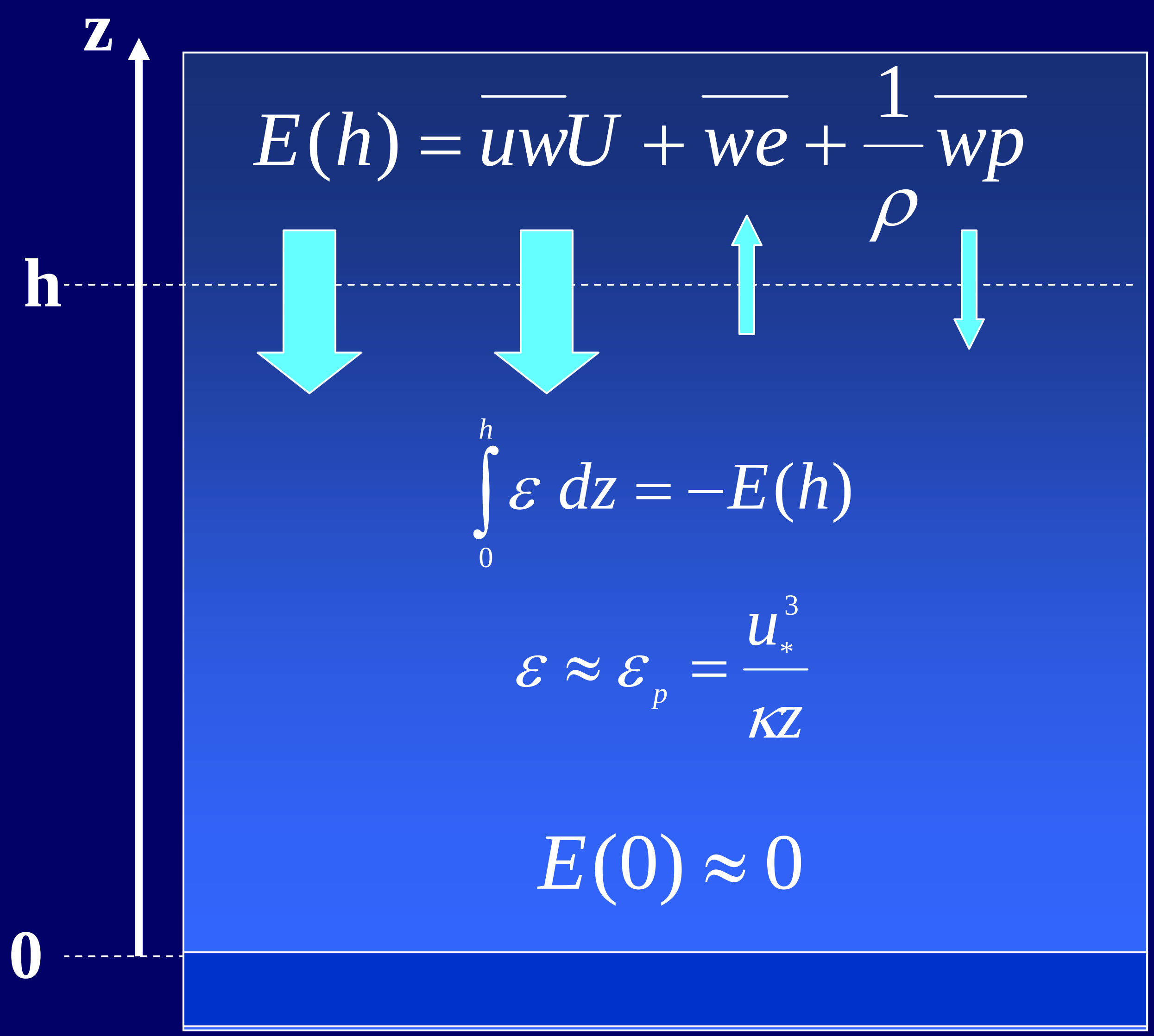
$$E(h) = \overline{uw}U + \overline{we} + \frac{1}{\rho}\overline{wp}$$

$$\int_0^h \varepsilon \, dz = -E(h)$$

$$E(0) \approx 0$$

Energy Flux Into the Marine Surface Layer

If there is no energy out the bottom, then the law-of-the-wall is expected.



$$E(h) = \overline{uwU} + \overline{we} + \frac{1}{\rho}\overline{wp}$$

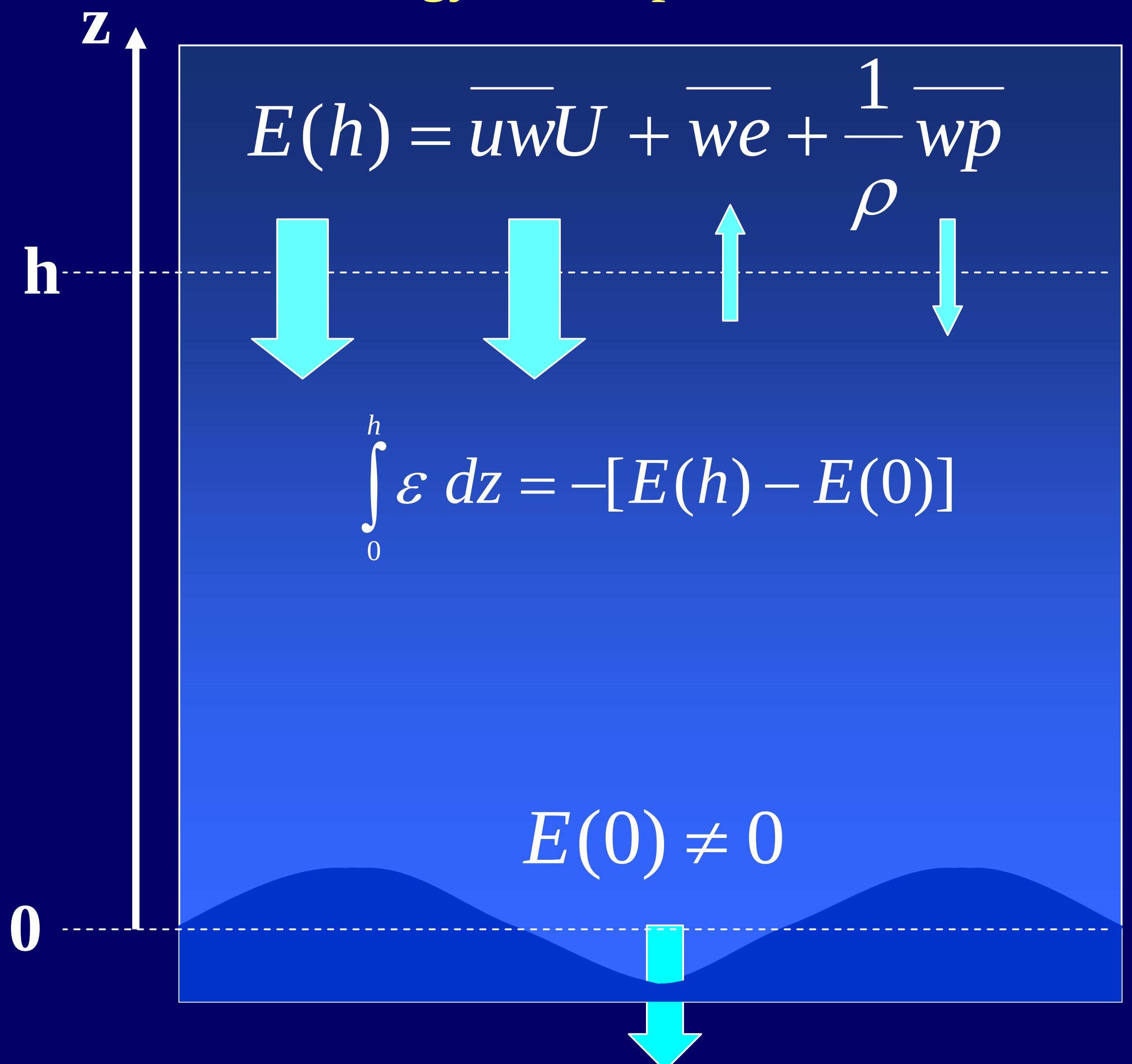
$$\int_0^h \varepsilon \, dz = -E(h)$$

$$\varepsilon \approx \varepsilon_p = \frac{u_*^3}{\kappa z}$$

$$E(0) \approx 0$$

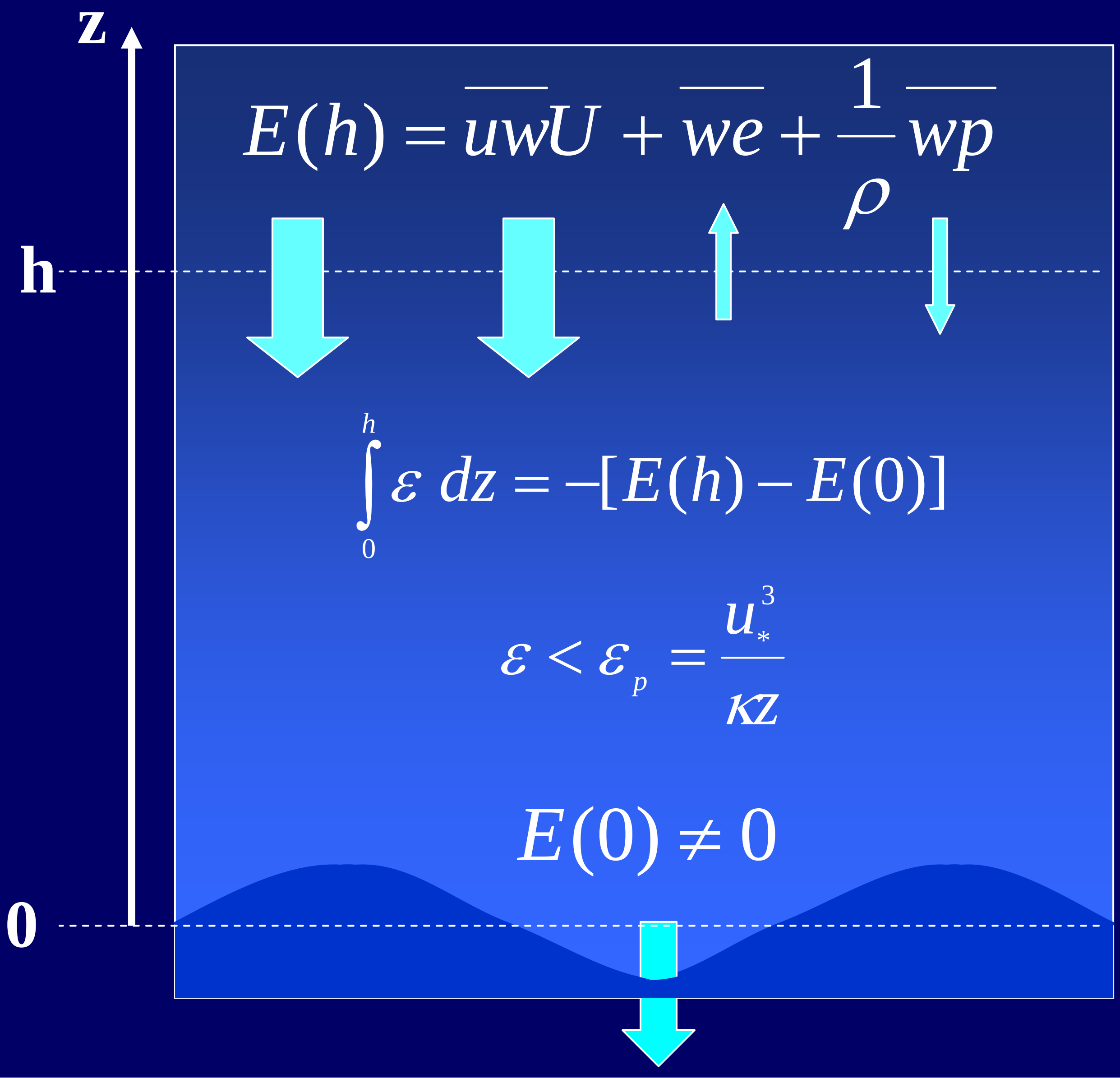
Energy Flux Into the Marine Surface Layer

However, if some of the energy is transported to the ocean then less energy is dissipated & ...



Energy Flux Into the Marine Surface Layer

The measured dissipation should be less than predicted by the law-of-the-wall.



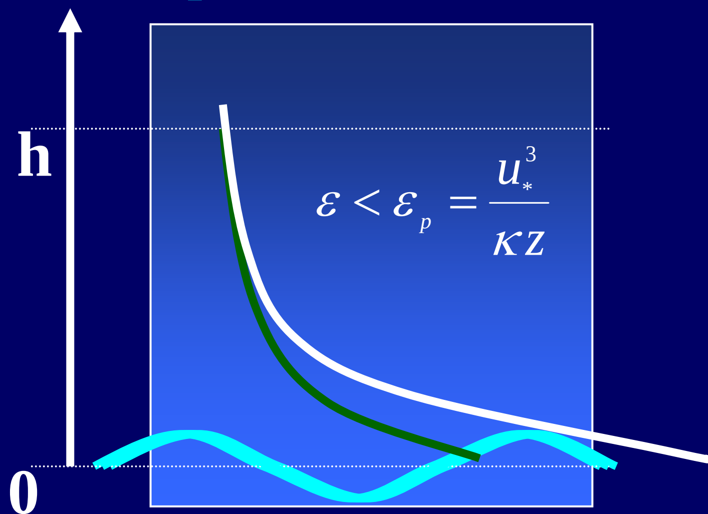
$$E(h) = \overline{uw}U + \overline{we} + \frac{1}{\rho}\overline{wp}$$

$$\int_0^h \varepsilon \, dz = -[E(h) - E(0)]$$

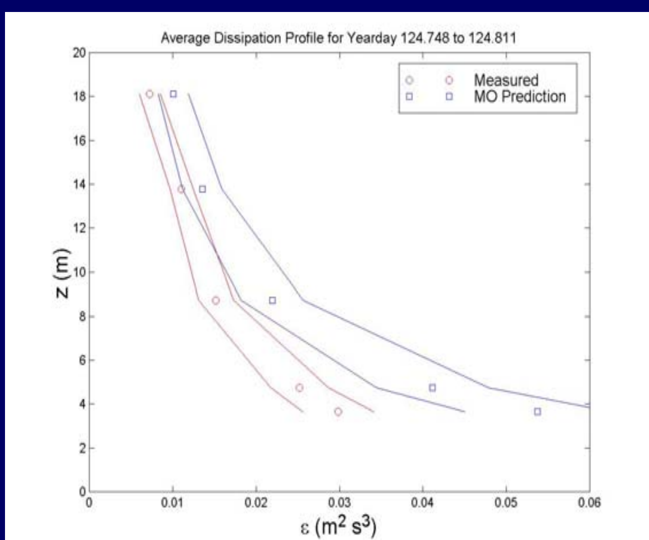
$$\varepsilon < \varepsilon_p = \frac{u_*^3}{\kappa z}$$

$$E(0) \neq 0$$

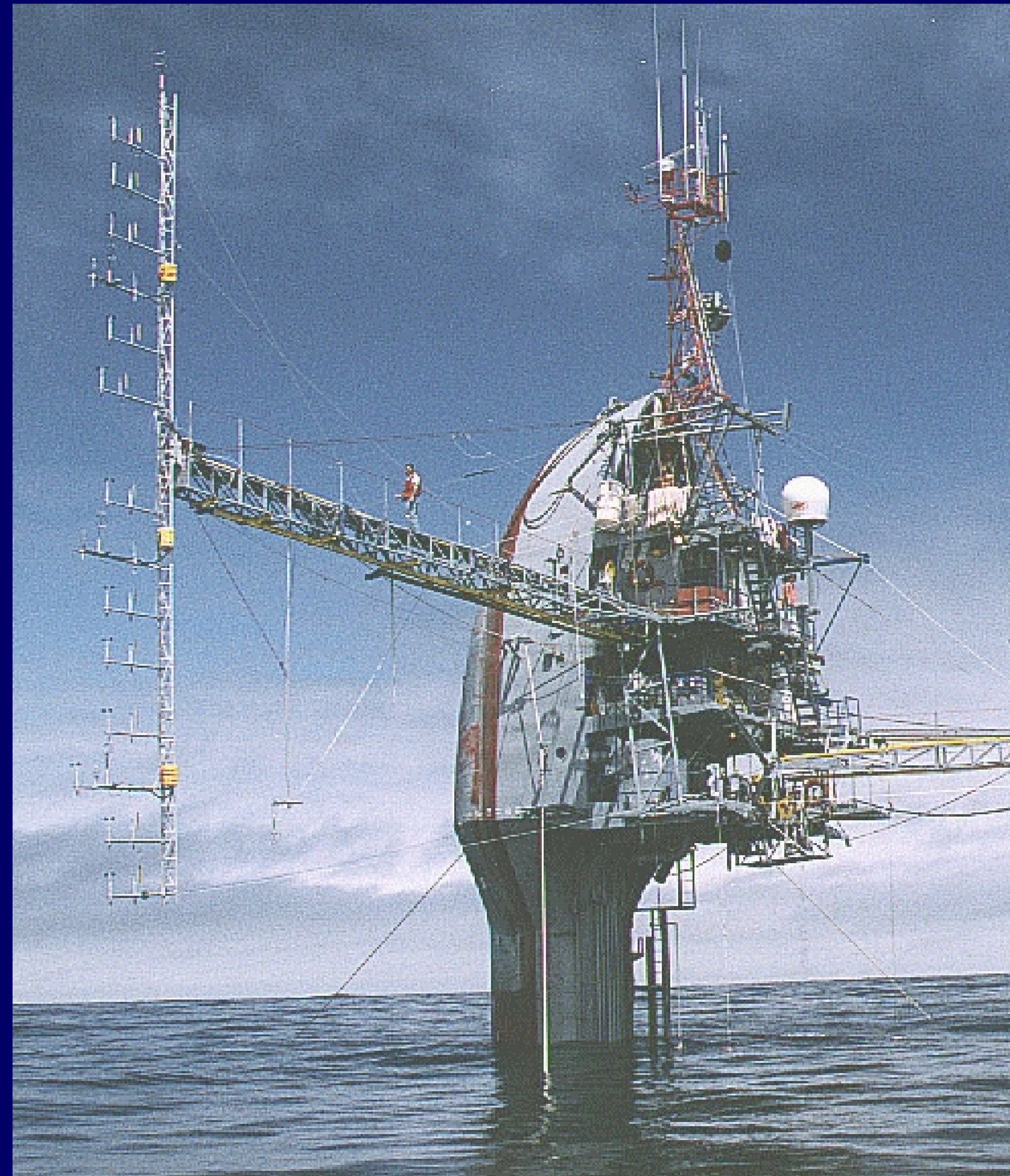
Measured dissipation should be less than predicted.



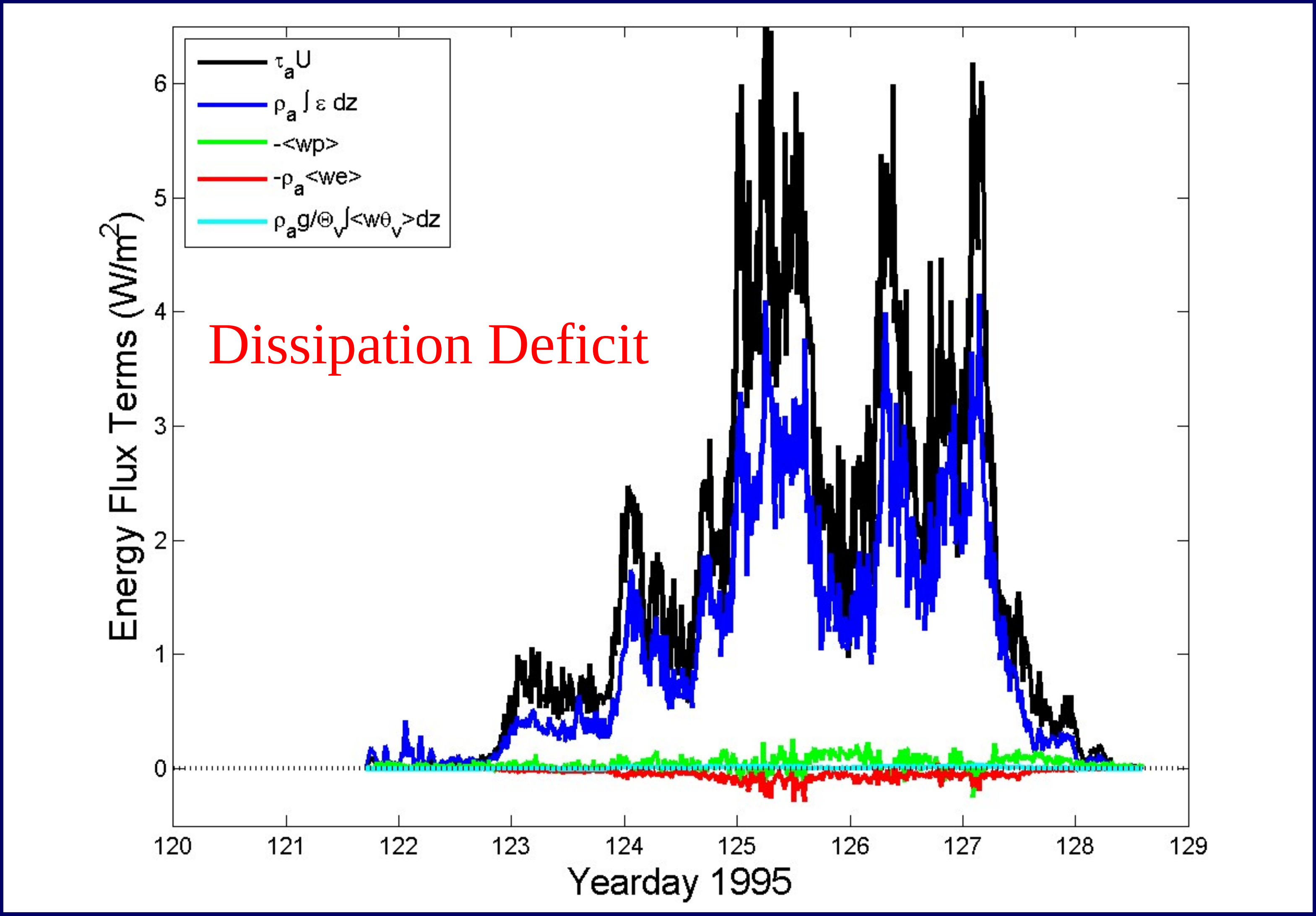
FLIP results



confirm this

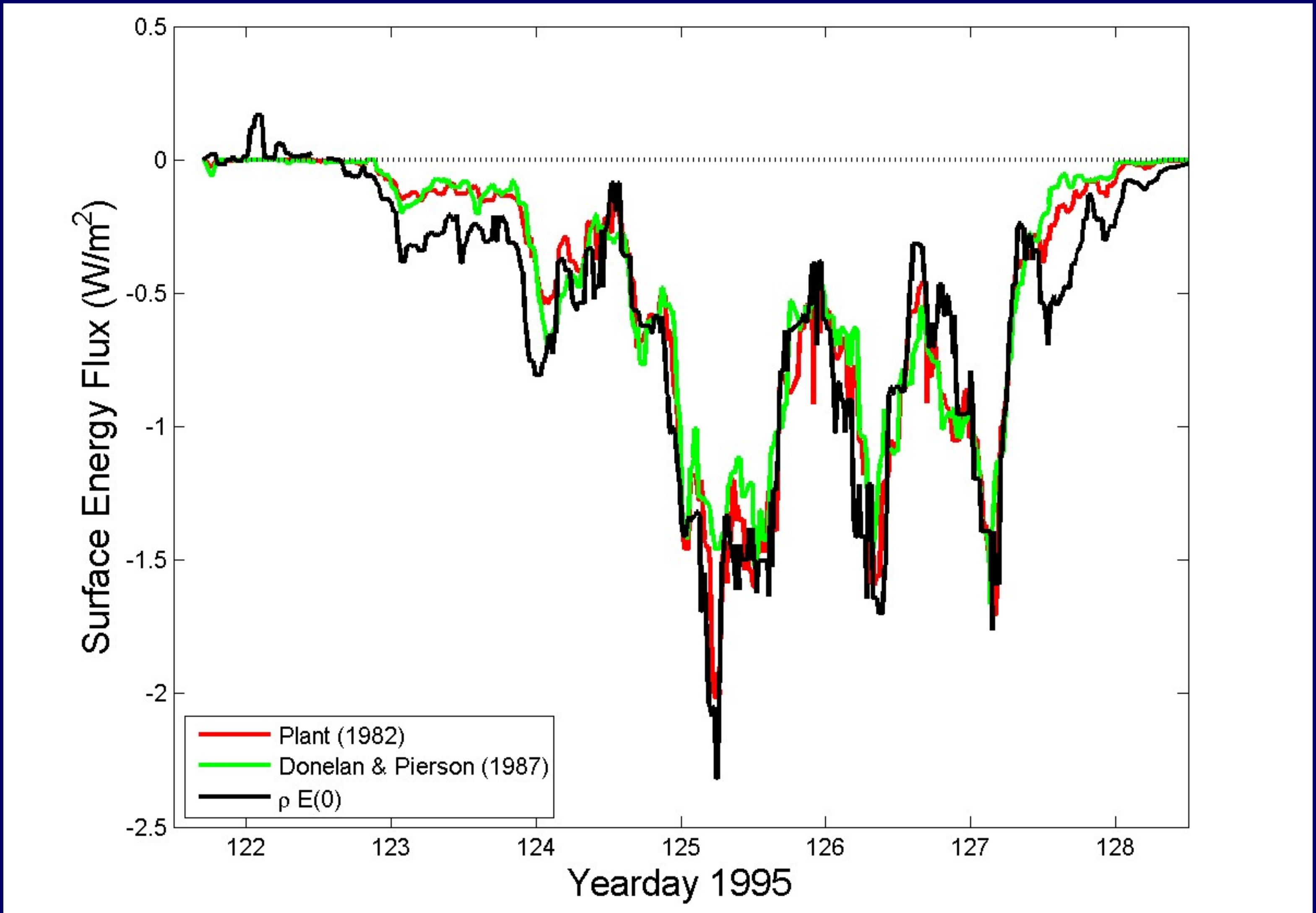


Energy Flux Into the Marine Surface Layer



$$E(0) = \rho_a \int_0^h \varepsilon\, dz - \tau_a U + \rho_a \overline{we} + \overline{wp} - \frac{\rho g}{\Theta_v} \int_0^h \overline{w\theta_v}\, dz$$

Energy Flux Into the Marine Surface Layer



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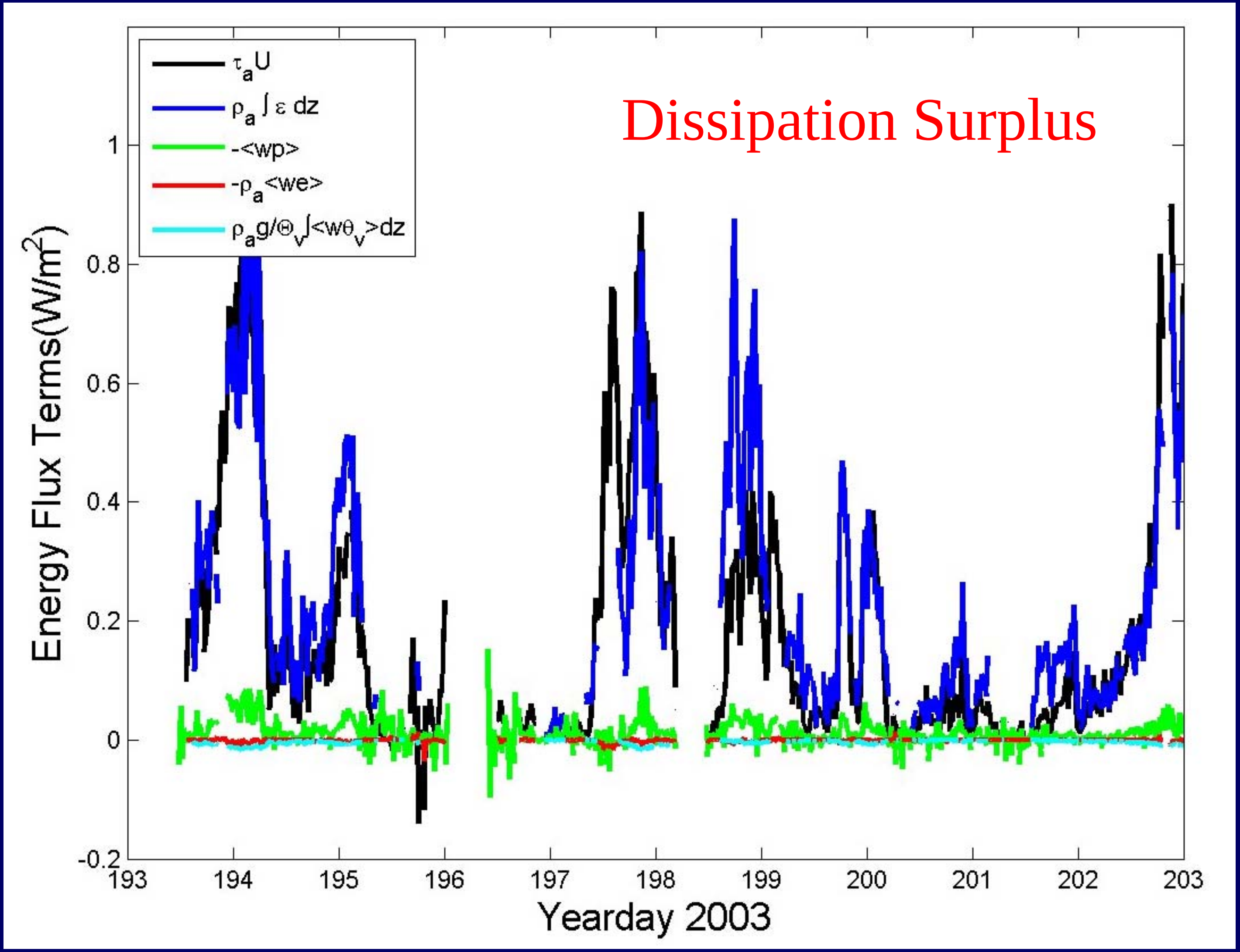
Energy Flux Into the Marine Surface Layer



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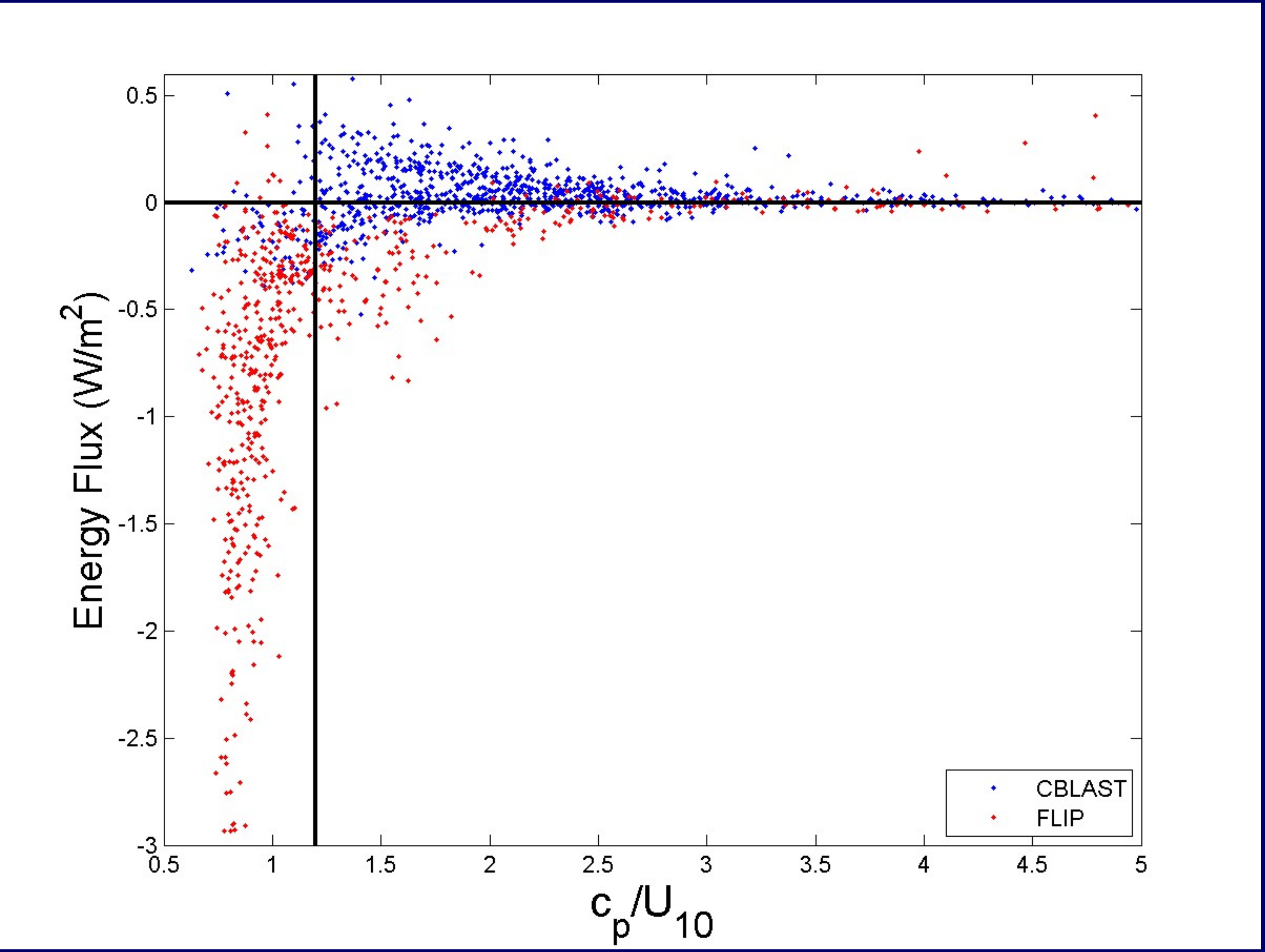
Energy Flux Into the Marine Surface Layer



$$E(0) = \rho_a \int_0^h \varepsilon \, dz - \tau_a U + \rho_a \overline{we} + \overline{wp} - \frac{\rho g}{\Theta_v} \int_0^h \overline{w\theta_v} \, dz$$

The reduced/enhanced dissipation is caused by:

$$\varepsilon = \boxed{-\overline{uw}\frac{\partial U}{\partial z}} - \frac{g}{\Theta_v}\overline{w\theta_v} - \boxed{\frac{\partial \overline{we}}{\partial z}} - \boxed{\frac{1}{\rho}\frac{\partial \overline{wp}}{\partial z}}$$

- Wave-induced modulation of the shear production term.
  - Momentum Flux → $\rho uw(0) = p(0)\,\partial\eta/\partial x$
- Energy transport
- Wave induced modulation of the energy transport terms.
  - Energy Flux → $wp(0) = p(0)\partial\eta/\partial t$

Summary II

- Our investigations of energy transport in the MABL indicate a dissipation deficit over growing seas and a dissipation surplus over swell.
  - This corresponds to the expected energy input to the waves in growing seas and an energy output to the atmosphere over swell.
  - As demonstrated earlier, the mechanical production (and wind profiles) is not substantially affected by waves except over swell.
  - As such, there is often an imbalance between dissipation and production over the ocean.
  - The balance is primarily accounted for via the pressure transport term.
- This would appear to have important implications for closure in numerical models.

$$-\overline{uw} = K_m \frac{\partial U}{\partial z} \quad \Rightarrow \quad K_m = \frac{\kappa z u_*}{\phi_m} \qquad K_m = C_\mu \frac{k^2}{\varepsilon}$$