Air-sea momentum exchange: influence of waves on drag coefficients

Edson et al. (2013), Donelan & Dobson (2001), and many more

Surface Waves Reading Group 03/05/2020

Presented by Alli Ho

Guiding questions

How is momentum transferred between the ocean and the atmosphere?

How do we describe the roughness of the ocean surface?

How does this interaction change with

- High winds
- Low winds
- Wave breaking
- Sheltering
- BL separation
- Following swell or counter swell

How do we parametrize this in global models - a significant BC in many coupled models - in a way that is **accurate** but **efficient**? What is ‘good enough’?

How does our estimation of this interaction affect circulation models, climate models, wave models, air-sea gas transfer, remote sensing, etc.?

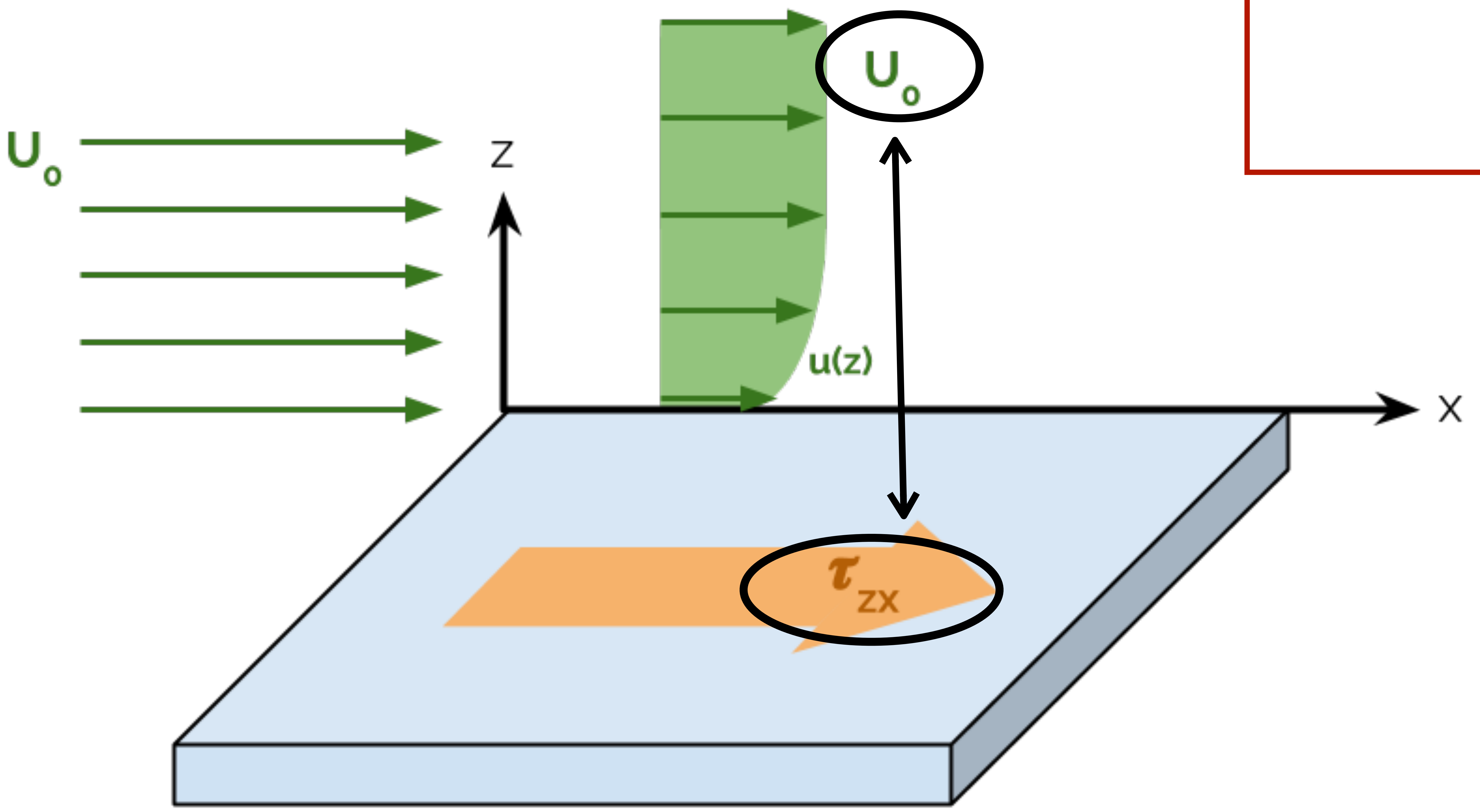
What measurements are most useful?

Momentum flux and drag at a boundary layer

Wind stress is a key parameter for oceanic and atmospheric modeling, forecasting, and hydrodynamic studies.

$$\tau = \rho\overline{u'w'} = u_*^2 \rightarrow \rho C_D |\vec{U}_{10}| \vec{U}_{10}$$

$$C_D = \frac{u_*^2}{U_{10}^2}$$



Surface stress : $\tau = \rho\overline{u'w'}$

The drag coefficient C_D relates the surface stress to the wind speed at a height z above the ocean surface.

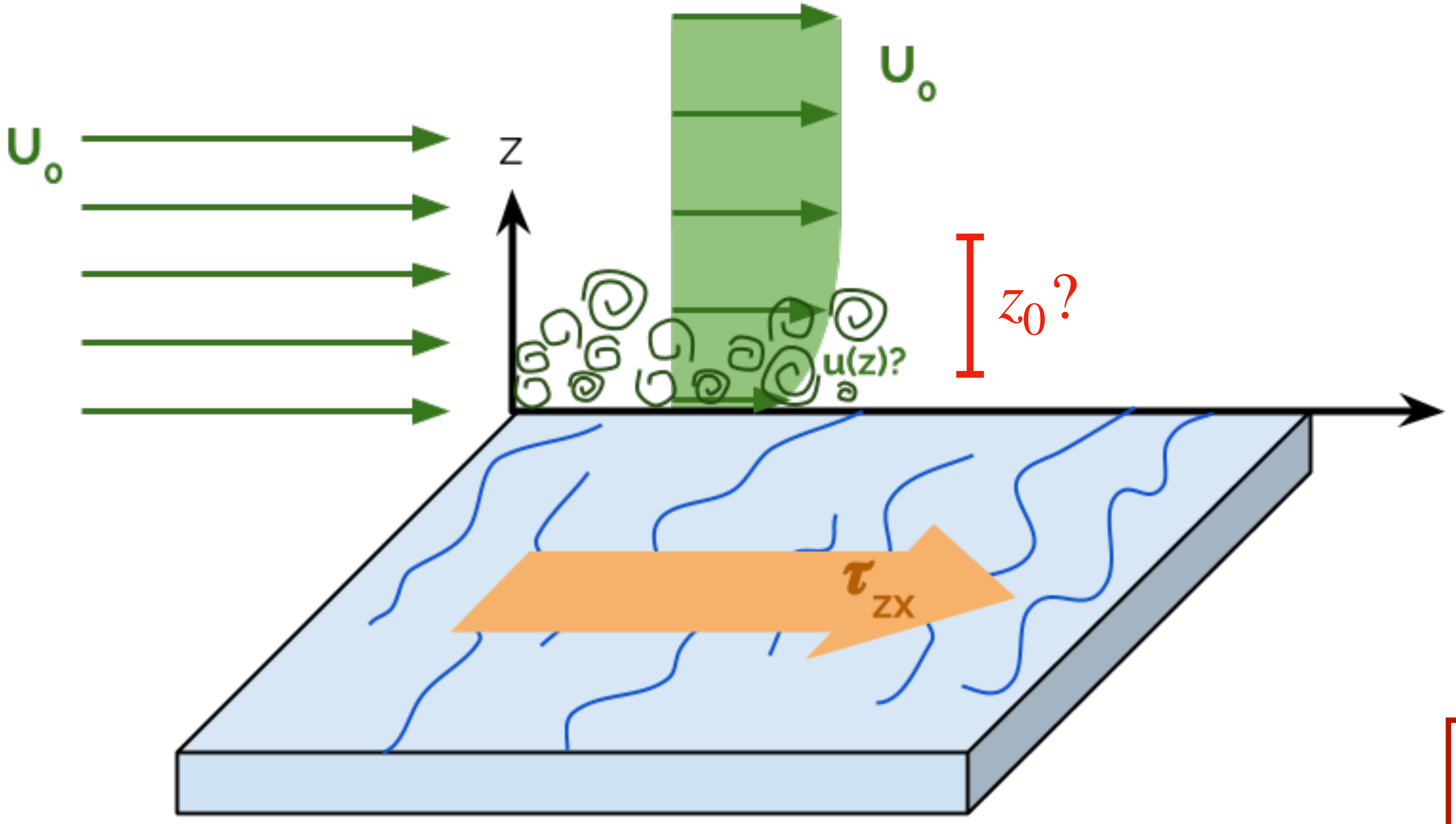
$$\tau = \tau(\rho, U) = \rho C_D U_z^2 = u_*^2$$

We calculate the drag coefficient via,

$$C_D = \frac{\overline{u'w'}^2}{U_z^2} = \frac{u_*^2}{U_z^2}$$

Momentum flux and drag at a boundary layer

Dimensional argument asserts that τ should be proportional to density and the speed of the external flow.
What does this assume?



Law of the wall (Von Karman, 1930 & Prandtl, 1932) parameterizes turbulent fluxes close to the surface by introducing a roughness length, z_0. Above this height, the flow returns to match the speed of the fluid. The steady state solution for the wind speed profile over a boundary layer is,

$$\vec{\tau} = \nu_t \frac{\partial \vec{u}}{\partial z} = (\kappa z)^2 \frac{\partial \vec{u}}{\partial z} \left| \frac{\partial \vec{u}}{\partial z} \right|$$

$$\sqrt{\tau} = \kappa z \frac{\partial \vec{u}}{\partial z} = u_*$$

$$\int_{z_0}^{z} dU = \frac{u_*}{\kappa} \int_{z_0}^{z} \frac{1}{z} dz$$

$$U(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right)$$

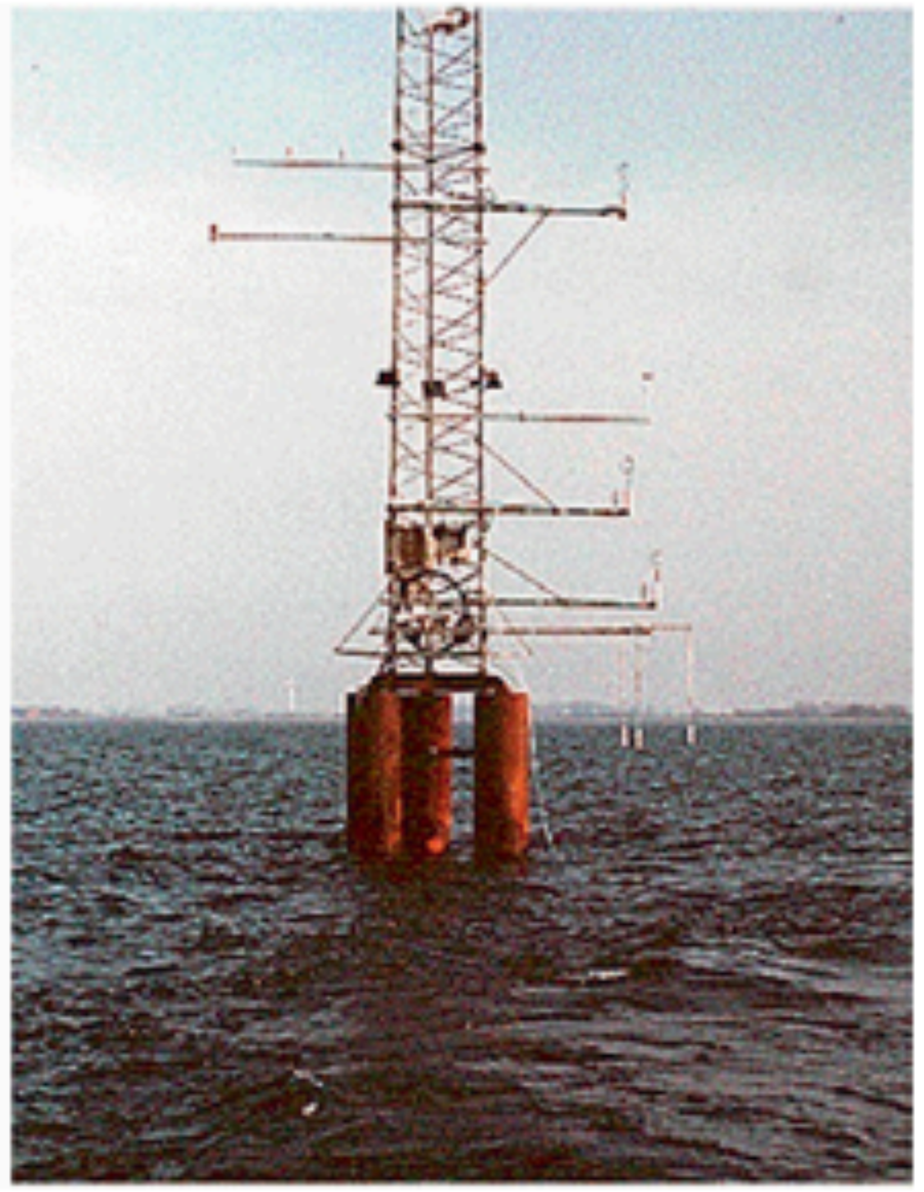
Charnock (1955) proposed a parameterization for the roughness length based on dimensional analysis,

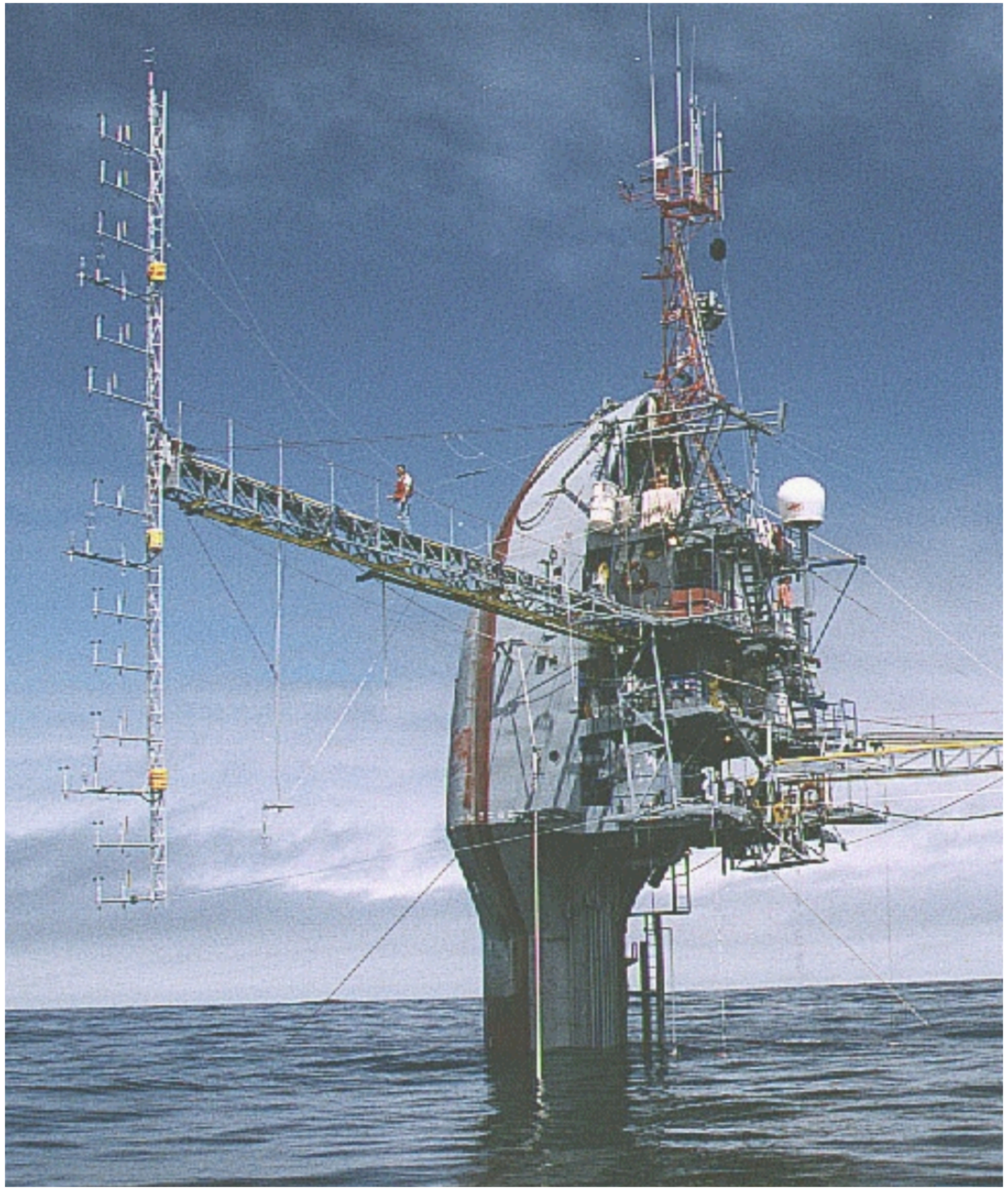
$$\boxed{z_0 = \alpha_{CH} \frac{u_*^2}{g} \text{ for } C_D = \kappa^2 ln^{-2}\left(\frac{z}{z_0}\right)}$$

Measurement

Direct measurement of τ requires sampling turbulent fluctuations of the horizontal downwind u and crosswind v components of the velocity and correlating them with the vertical component w. In stationary and homogenous conditions, τ is assumed to be constant within the surface flux layer and above the viscous sublayer and is calculated from.

$$\hat{\tau} = -\rho(\overline{u'w'}\hat{i} + \overline{v'w'}\hat{j})$$





Measurement

Wu (1968)

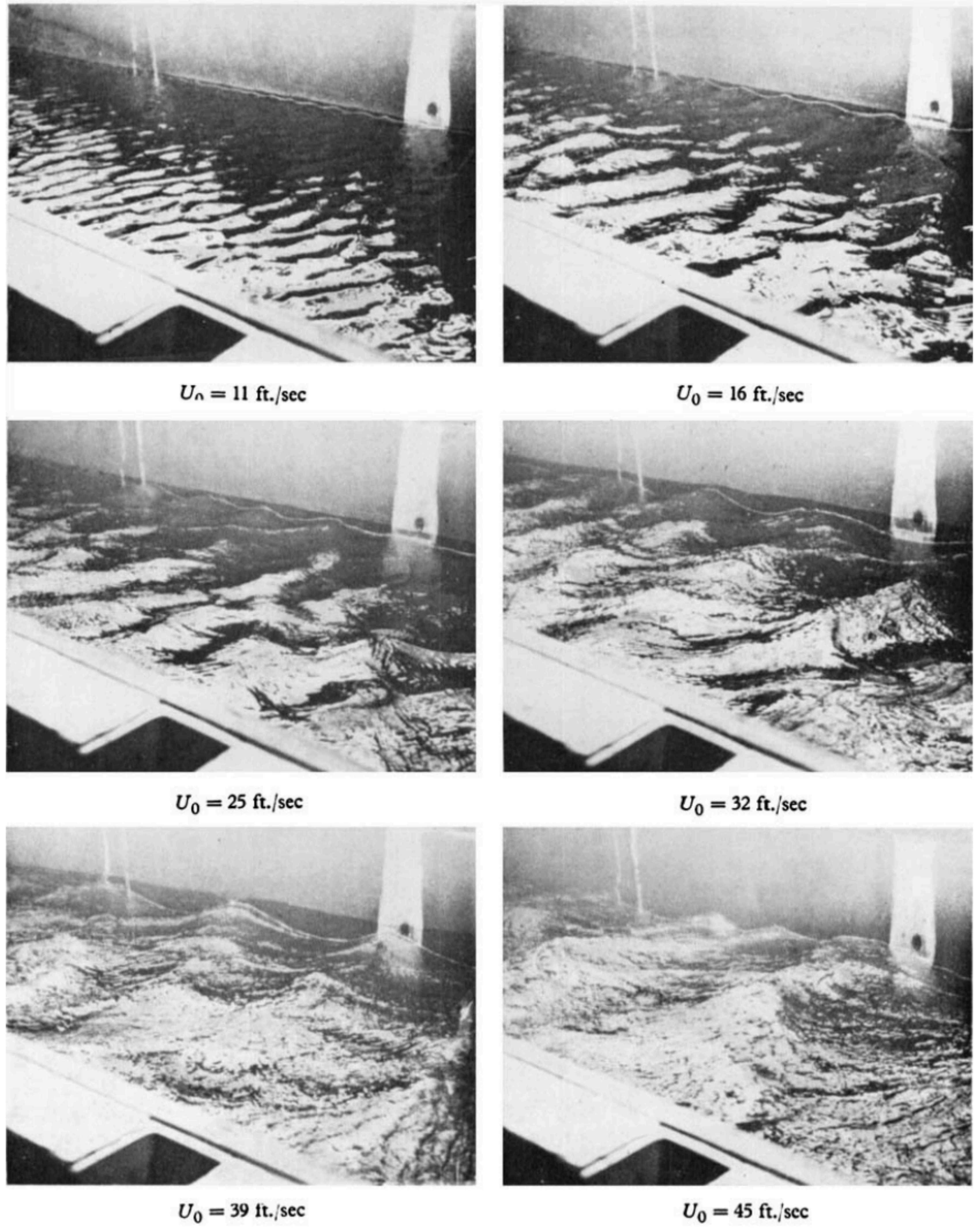


FIGURE 1. Sample pictures of wind waves generated in present tank.

Buckley & Veron (2019)

M.P. Buckley, F. Veron / European Journal of Mechanics / B Fluids 73 (2019) 132–143

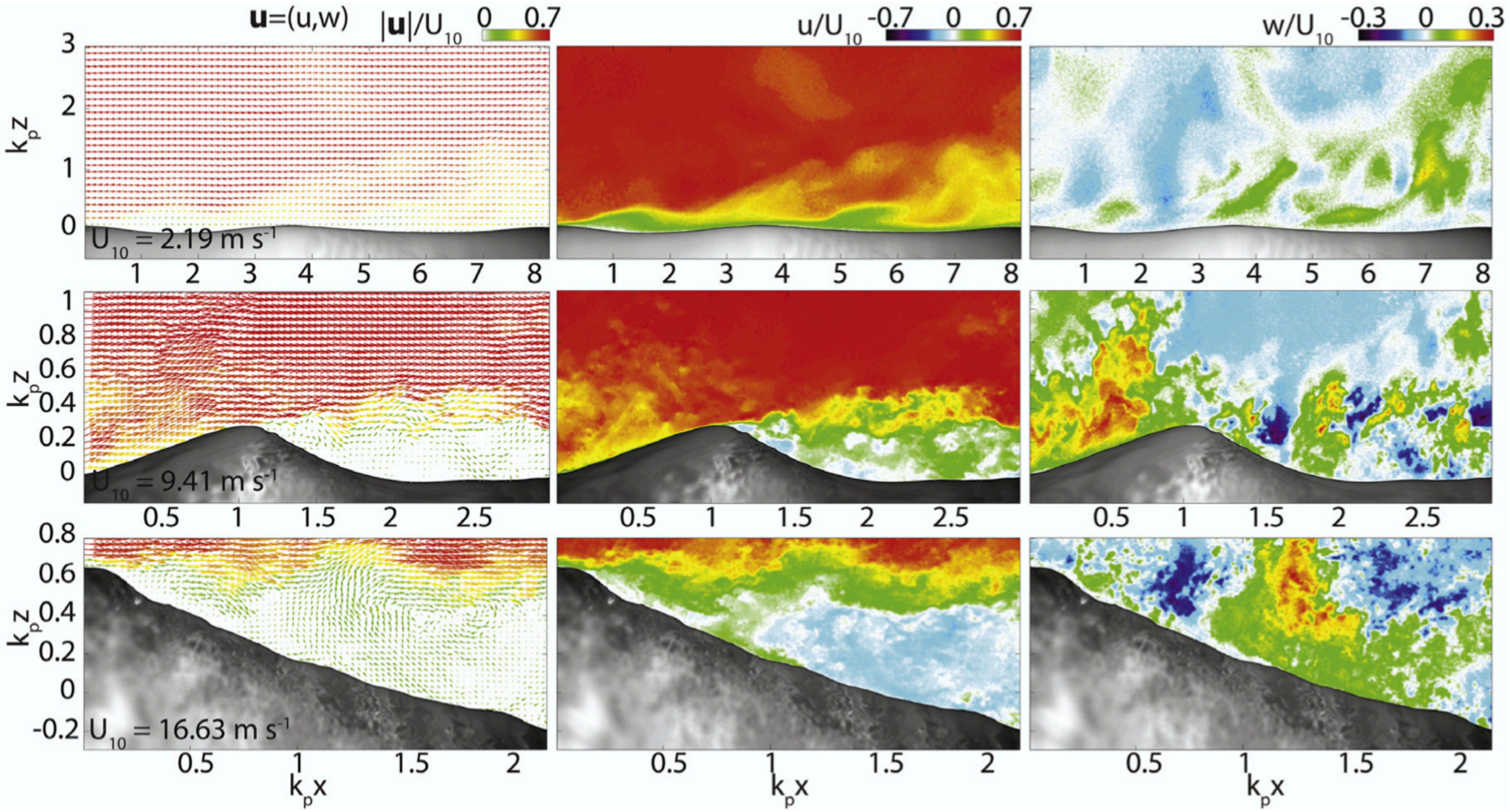


Fig. 2. Instantaneous velocity fields obtained with the PIV system for U_{10} of 2.19, 9.41, and 16.63 m s^{-1}; the wind speed is indicated in the first panel of each row. The first column of panels shows instantaneous velocity vector fields. For clarity, less than 10% of measured vectors are shown. The second and third columns show the horizontal u and vertical w components of the velocity vector $\mathbf{u}$ respectively. Velocities are normalized by the 10-m wind speed U_{10}, and plotted above the surface image collected by the LIF camera. The vertical and horizontal axes are non-dimensionalized by the wavenumber of the peak surface wave.

Parameterizations

A brief history

Wind-speed dependent [U_{10N}]

Wave age dependent [u_*/c_p]

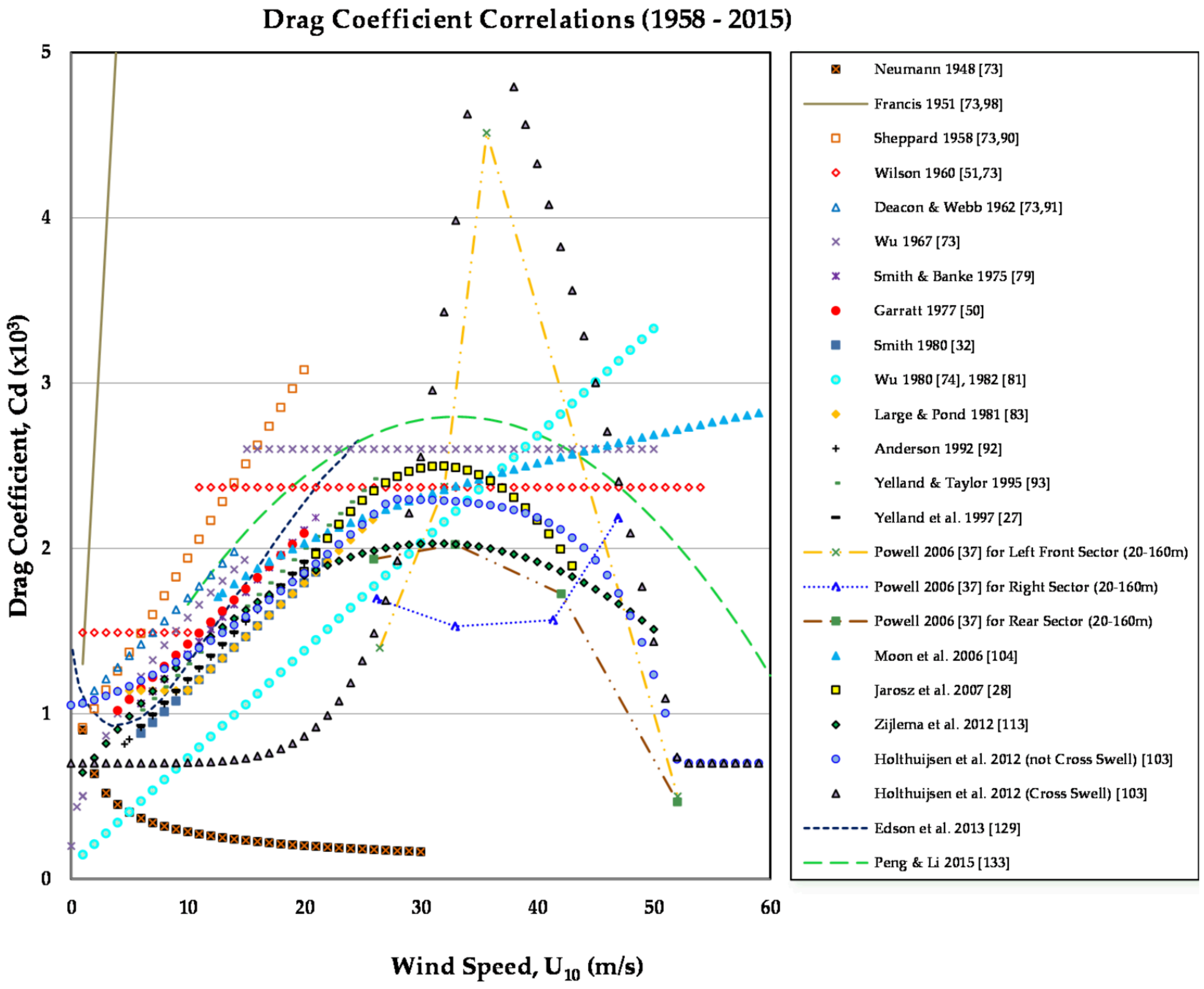
Sea-state dependent [$H_s k$]

Bryant & Akbar (2016)

Compiled a pretty comprehensive list of drag coefficient parameterizations and saved me a lot of work. Features include:

- saturation of drag coefficient (waves can't grow infinitely?)
- sometimes an increase at very low winds
- decrease again at very high winds
- some things based on swell

Why is there no agreement?



Parameterizations

A brief history

Wind-speed dependent [U_{10N}]

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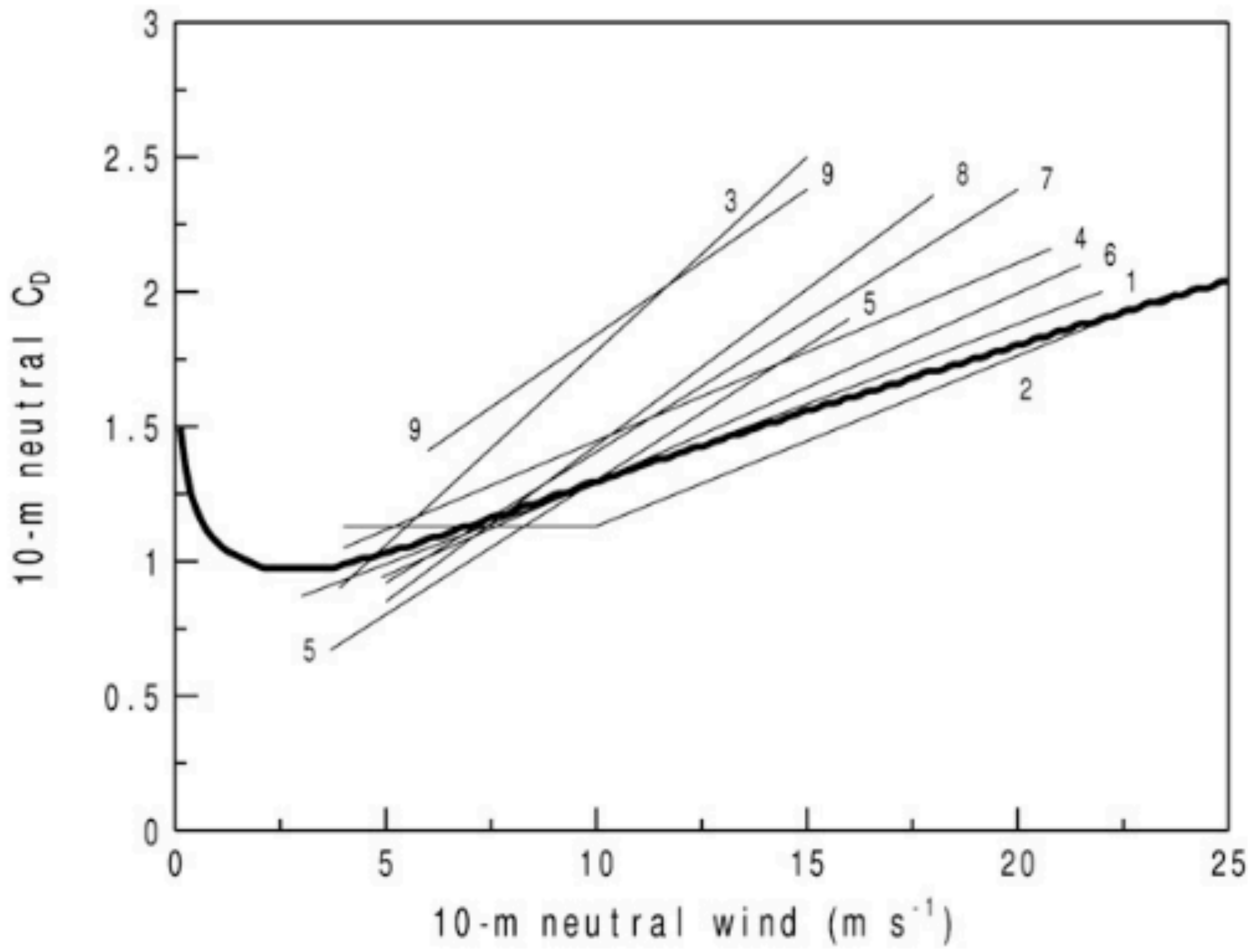
FIG. 1. Published drag coefficient wind speed relationships: 1) Smith (1980), 2) Large and Pond (1981), 3) Donelan (1982), 4) Garratt (1977), 5) Sheppard et al. (1972), 6) Smith and Banke (1975), 7) Geernaert et al. (1986), 8) Smith et al. (1992), 9) Smith et al. (1992) "very young waves." The heavy curve is the Charnock plus smooth flow relationship with $\alpha = 0.011$. The drag coefficient has been multiplied by 10^3 to make it of order one.

Why did all these relationships differ so much? Unique conditions (waves, fetch, swell, gustiness) in each measurement used to fit the relationship? Measurement technique?

Vickers et al. (2012)

Example of all drag coefficient vs wind speed relationships



Parameterizations

Now a few examples:

$$C_D = \kappa^2 ln^{-2}\left(\frac{z}{z_0}\right),$$
where $z_0 = z_0^{smooth} + z_0^{rough}$
and $z_0^{rough} = \alpha_{CH}\frac{u_*^2}{g}$

A brief history

Wind-speed dependent [U_{10N}]

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Sea-state dependent [$H_s k$]

Large & Pond (1981)

$$10^3 C_D = \begin{cases} 1.14 & 4 < U_{10} \leq 10\text{ms}^{-1} \\ 0.48 + 0.065u_{10} & 10 < U_{10} \leq 26\text{ms}^{-1} \end{cases}$$

COARE 2.5

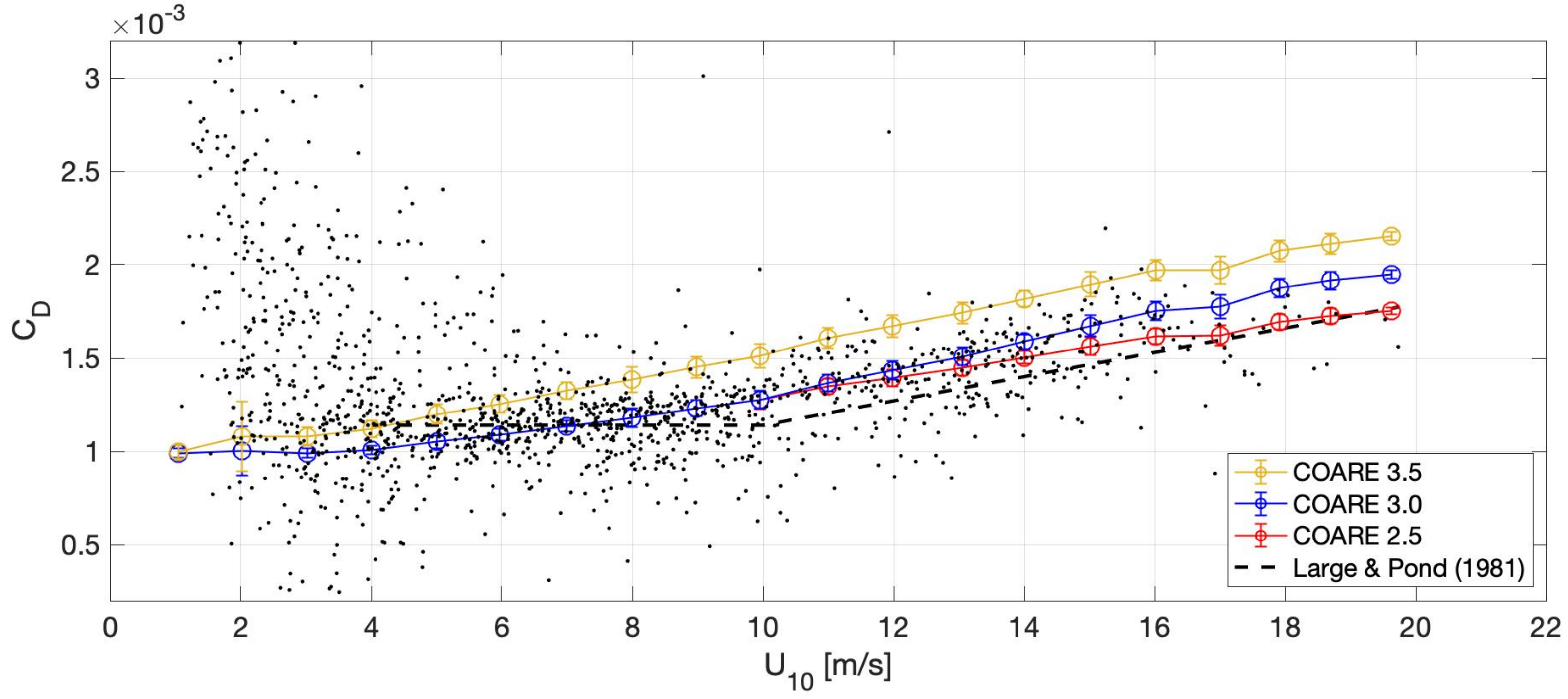
$$z_0 = \frac{\alpha u_*^2}{g} + \frac{0.11\nu}{u_*}, \text{ where } \alpha = 0.011$$

Fairall et al. (2003) - COARE 3.0

$$\alpha = \begin{cases} 0.011 & U_{10n} < 10\text{ms}^{-1} \\ 0.011 + 0.000875U_{10n} & 10 < U_{10n} \leq 18\text{ms}^{-1} \\ 0.018 & U_{10n} > 18\text{ms}^{-1} \end{cases}$$

Edson et al. (2013) - COARE 3.5

$$\alpha = 0.017U_{10n} - 0.005 \text{ if } 7 < U_{10n} \leq 18\text{ms}^{-1}$$



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Wind-speed dependent [U_{10N}]

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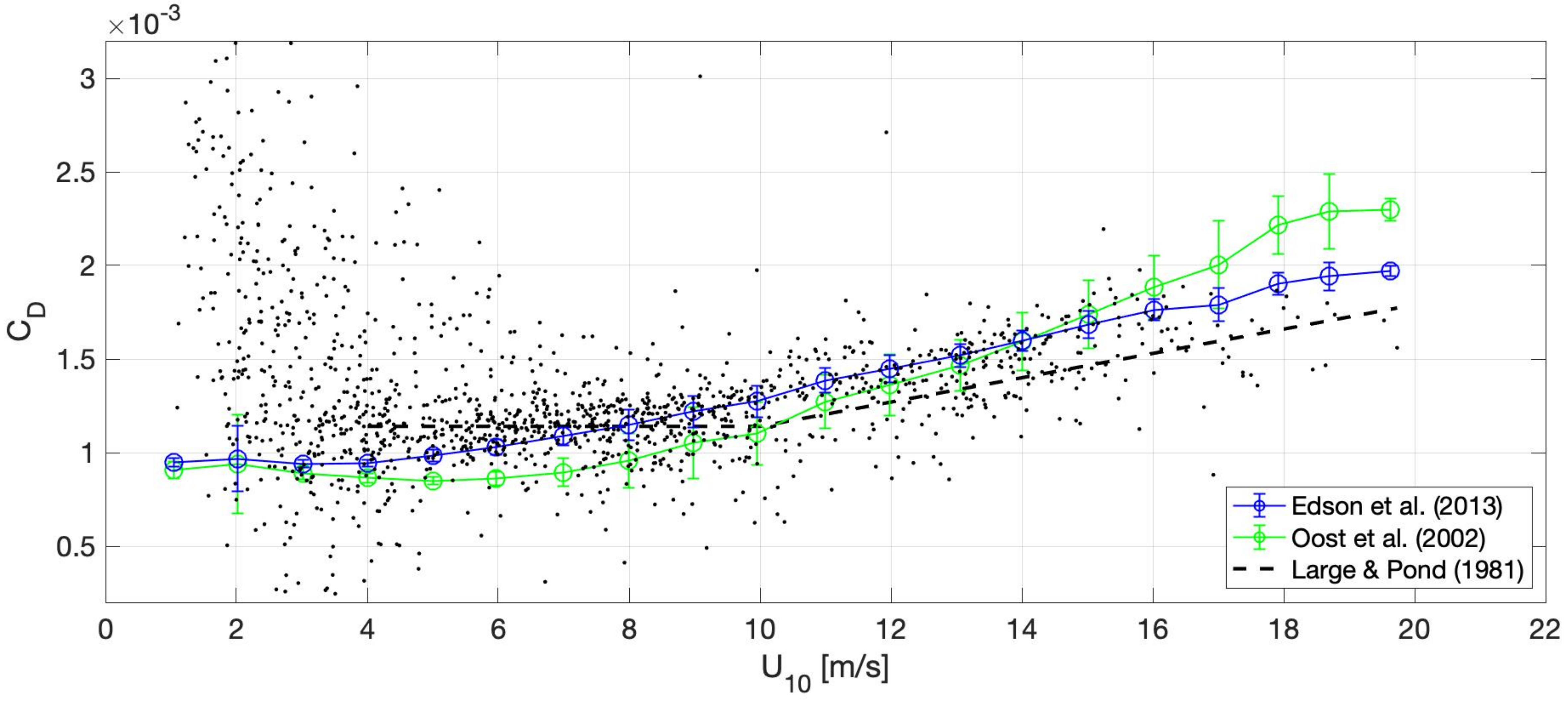
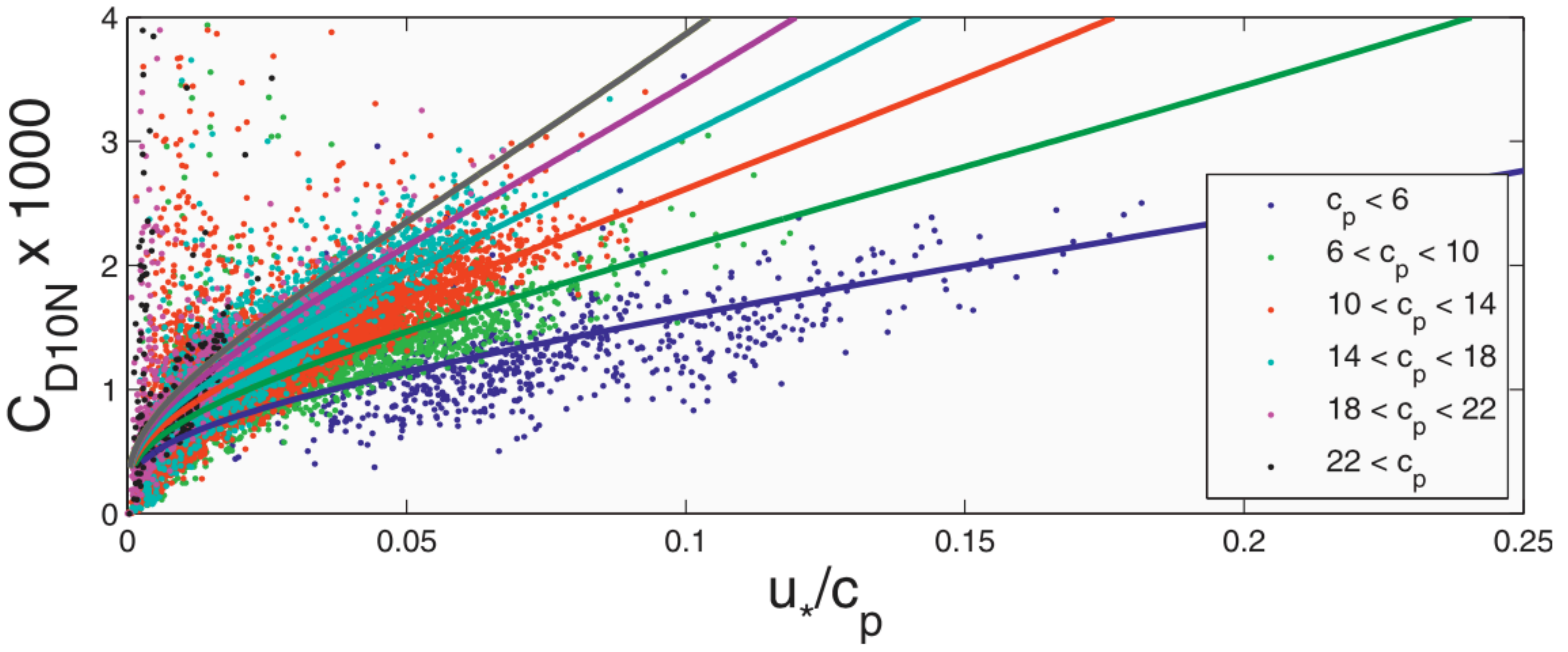
Oost et al. (2002)

$$\alpha = 50(C_p/u_*)^{-2.5}$$

Edson et al. (2013) - COARE 3.5

$\alpha = A\left(\frac{u_*}{c}\right)^B$, for $A = 0.114$ and $B = 0.622$





Parameterizations

$C_D = \kappa^2 ln^{-2}\left(\frac{z}{z_0}\right)$,
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A brief history

Wind-speed dependent [U_{10N}]

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Now a few examples:

Taylor & Yelland (2001)

$z_0 = 1200h_s(h_s/L_p)^{4.5}$, for significant wave height h_s and peak wavelength L_p

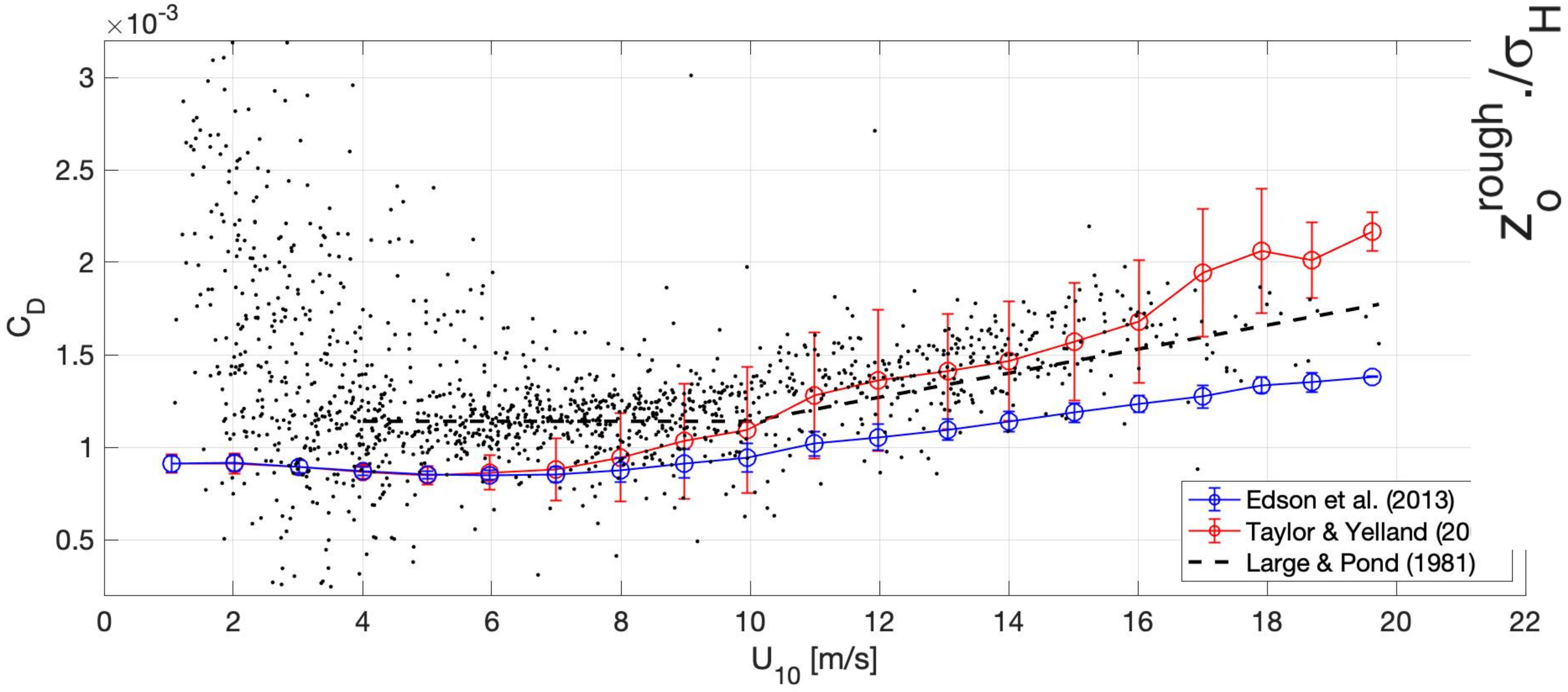
- Option in COARE 3.0

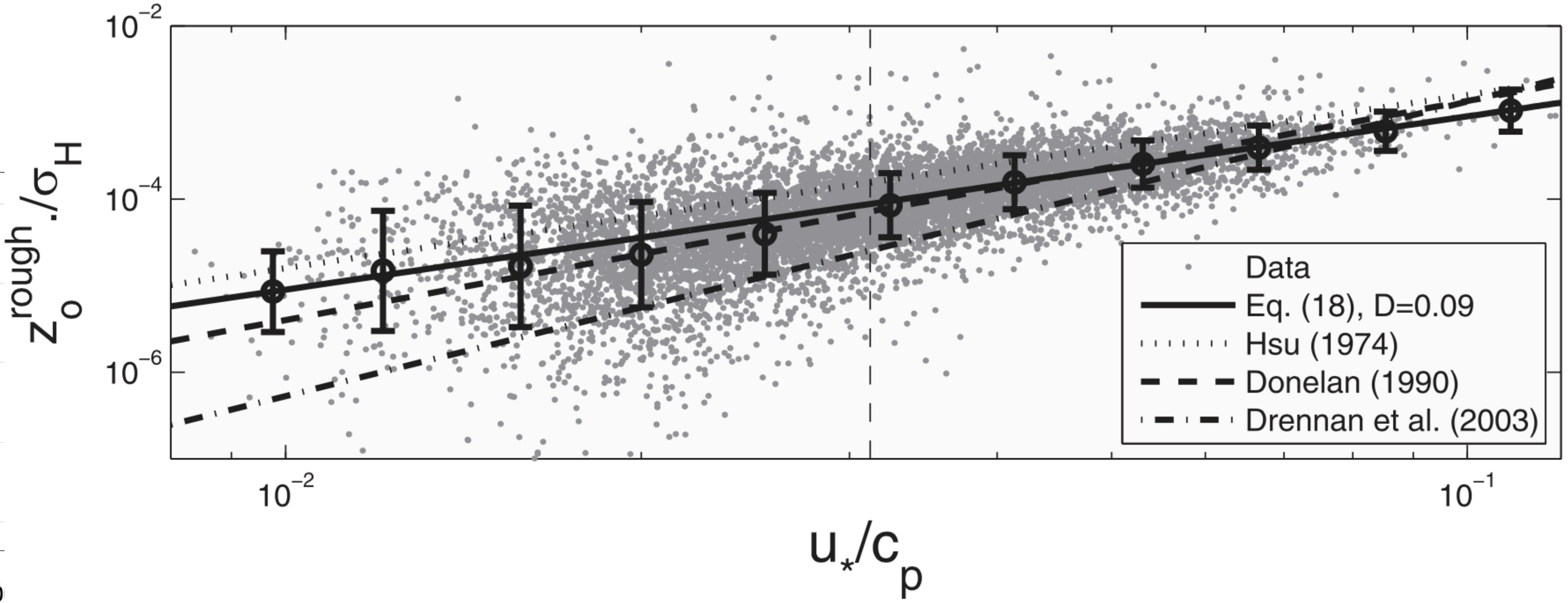
  $z_{0TY} = 1200h_s(h_s/L_p)^{4.5} + 0.11\nu/u_*$

Edson et al. (2013) - COARE 3.5

$$\frac{gz_0^{rough}}{u_*^2} = D\sigma_H k_p,$$ for significant wave height σ_H and peak wavelength k_p,

where $D = 0.09$





Parameterizations

Now a few examples:

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<u>WW3 ST3+, Janssen 1991</u>

Include a wave-modulated stress component of the roughness length,

$$
\begin{aligned}
U_{10} &= \frac{u_\star}{\kappa}\log\left(\frac{z_u}{z_1}\right) \\
z_1 &= \alpha_0 \frac{\tau}{\sqrt{1-\tau_w/\tau}},
\end{aligned}
$$

$$
\tau_w = \left| \int_0^{k_{\max}} \int_0^{2\pi} \frac{S_{in}(k',\theta)}{C} (\cos\theta, \sin\theta)\, \mathrm{d}k' \mathrm{d}\theta + \tau_{\mathrm{hf}}(u_\star, \alpha)(\cos\theta_u, \sin\theta_u) \right|,
$$

Parameterizations

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Something else

Edson et al. (2013)

"The COARE 3.5 wind speed–dependent formulation is shown to provide better agreement with the DC stress measurements without any wave information. Furthermore, it is nearly identical to the function representing the globally averaged drag coefficient from a wave age–based model run at the ECMWF."

$C_D = \kappa^2 ln^{-2}\left(\frac{z}{z_0}\right)$,

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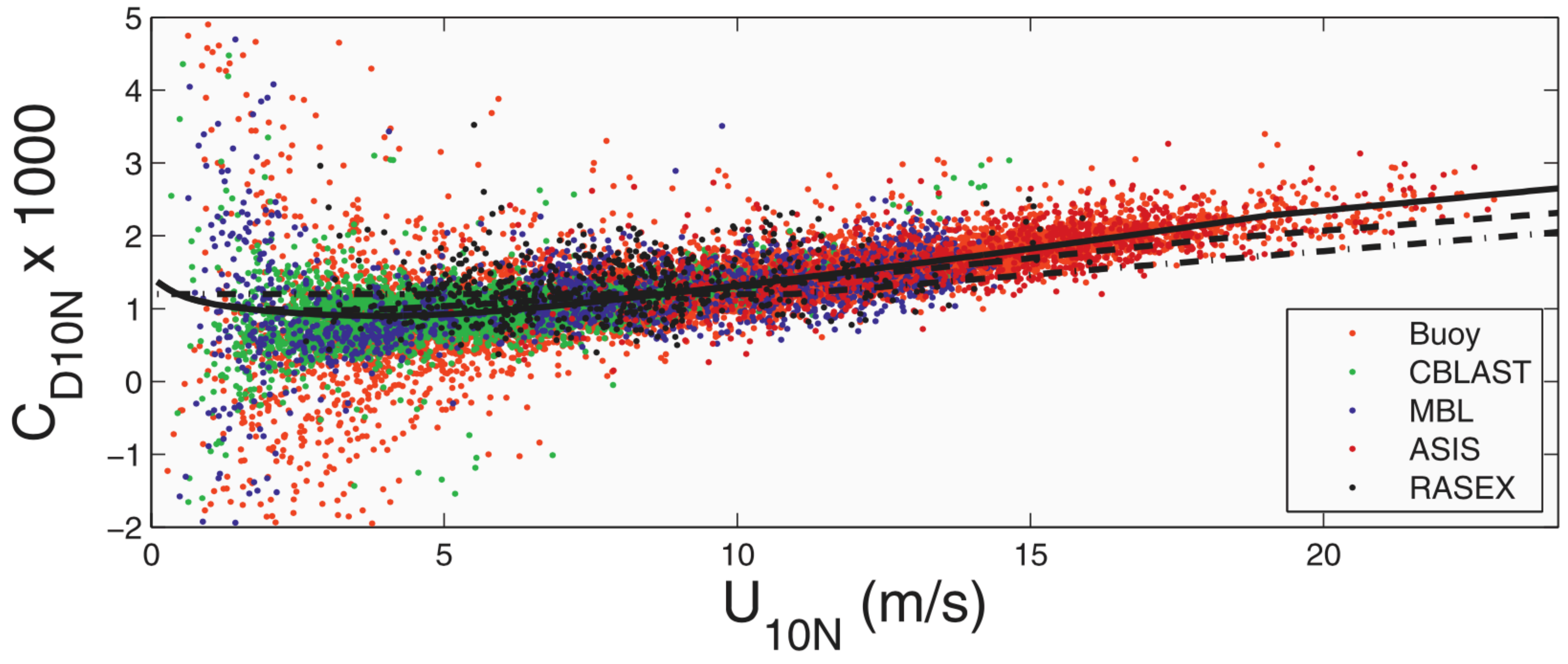
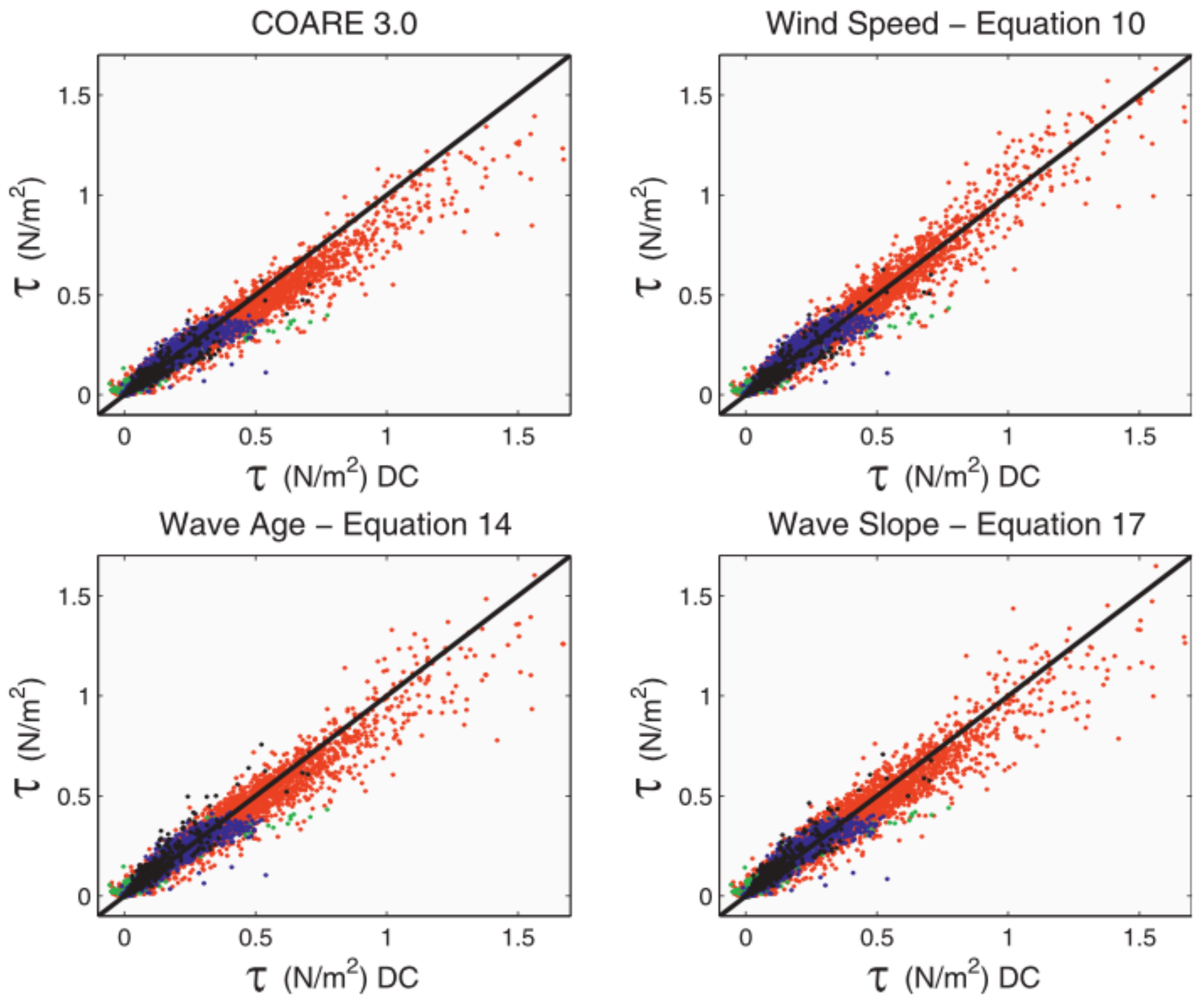
What relationship do we emphasize when we choose wave age dependence? Hs?





Parameterizations

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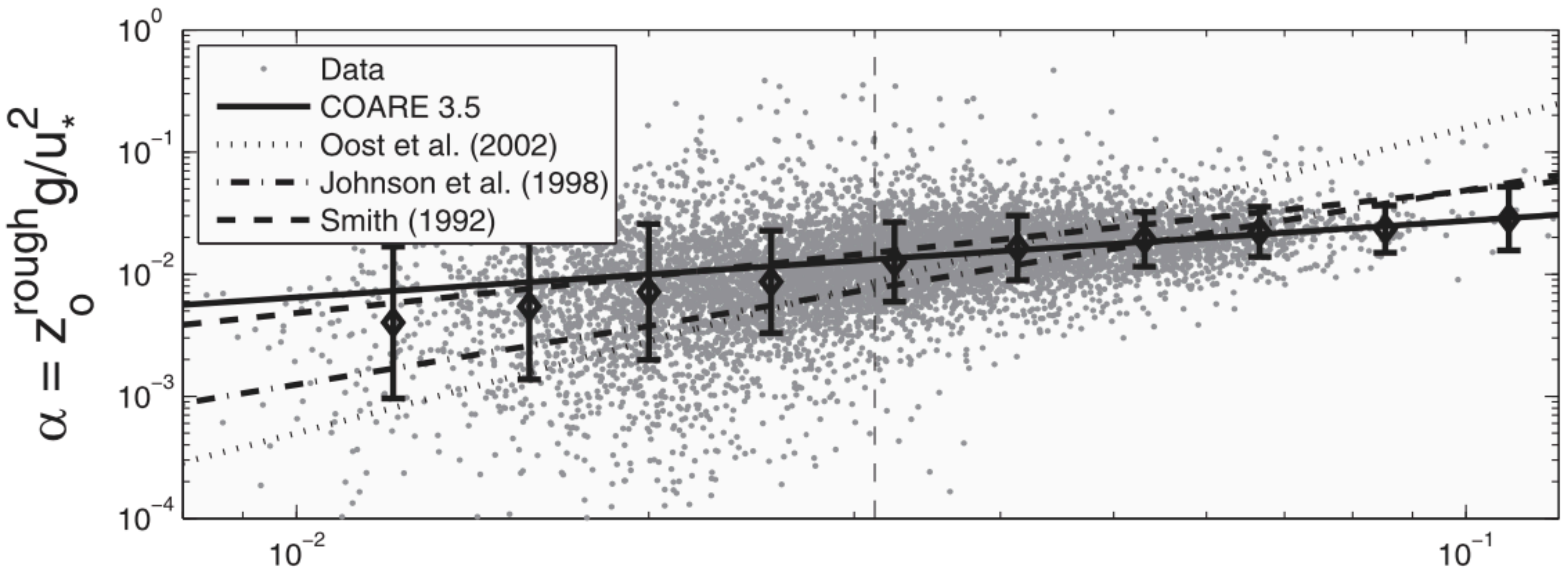
Back to a brief history

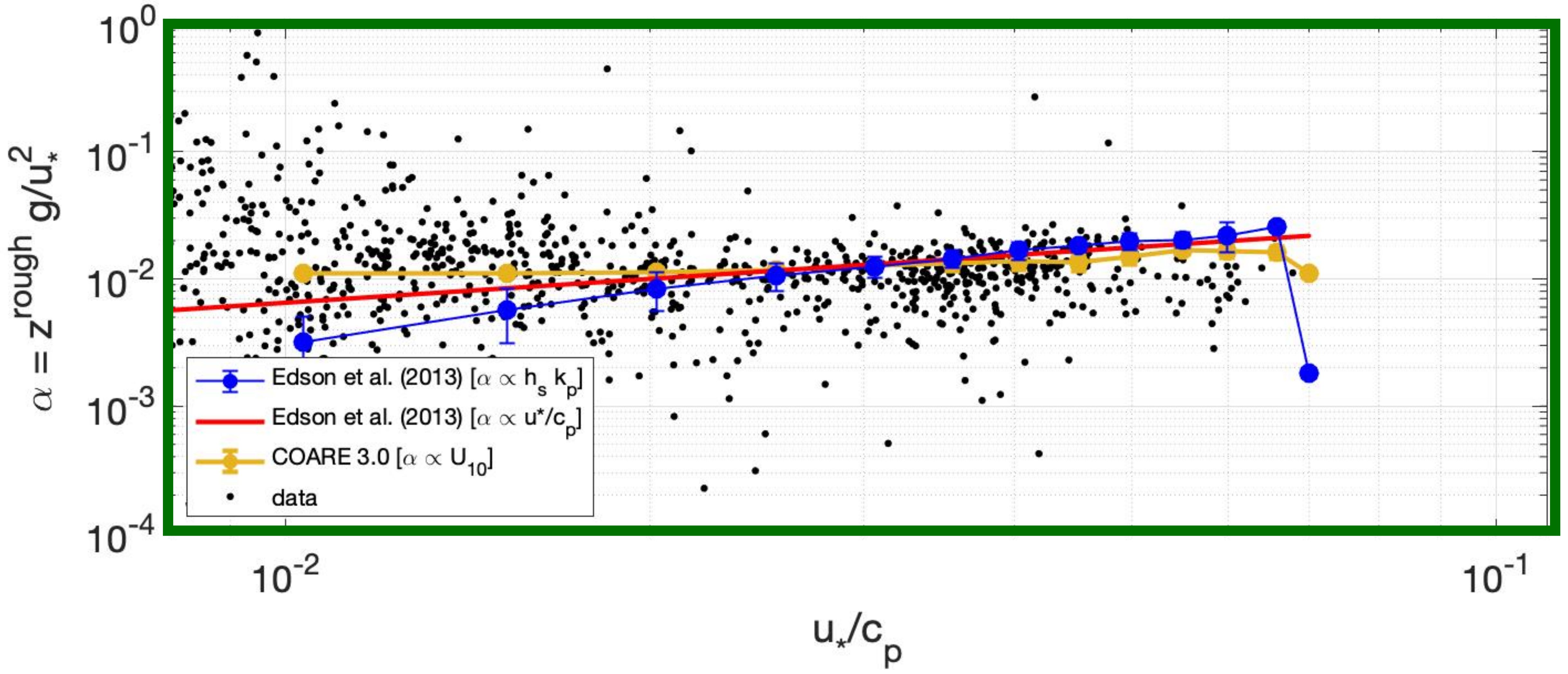
Wind-speed dependent [U_{10N}]

Wave age dependent [u_*/c_p]

Sea-state dependent [$H_s k$]

COARE 3.5 works ~well for data within the wave age range $c_p/U_{10} < 2.5$





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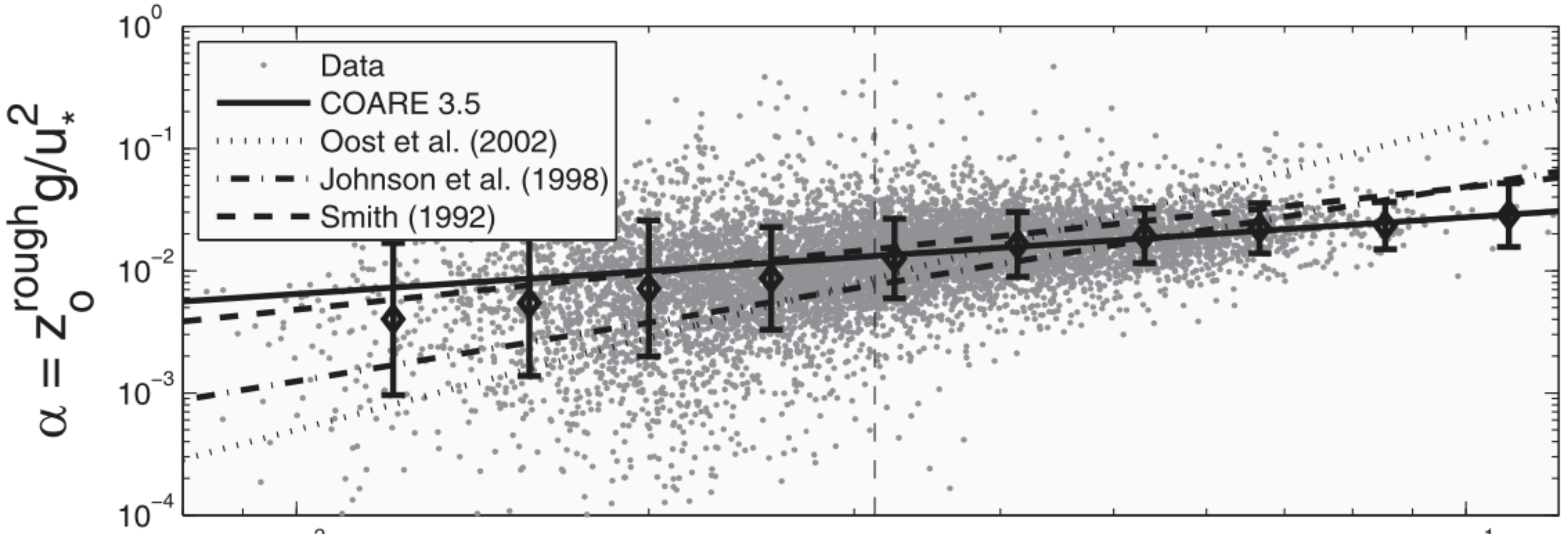
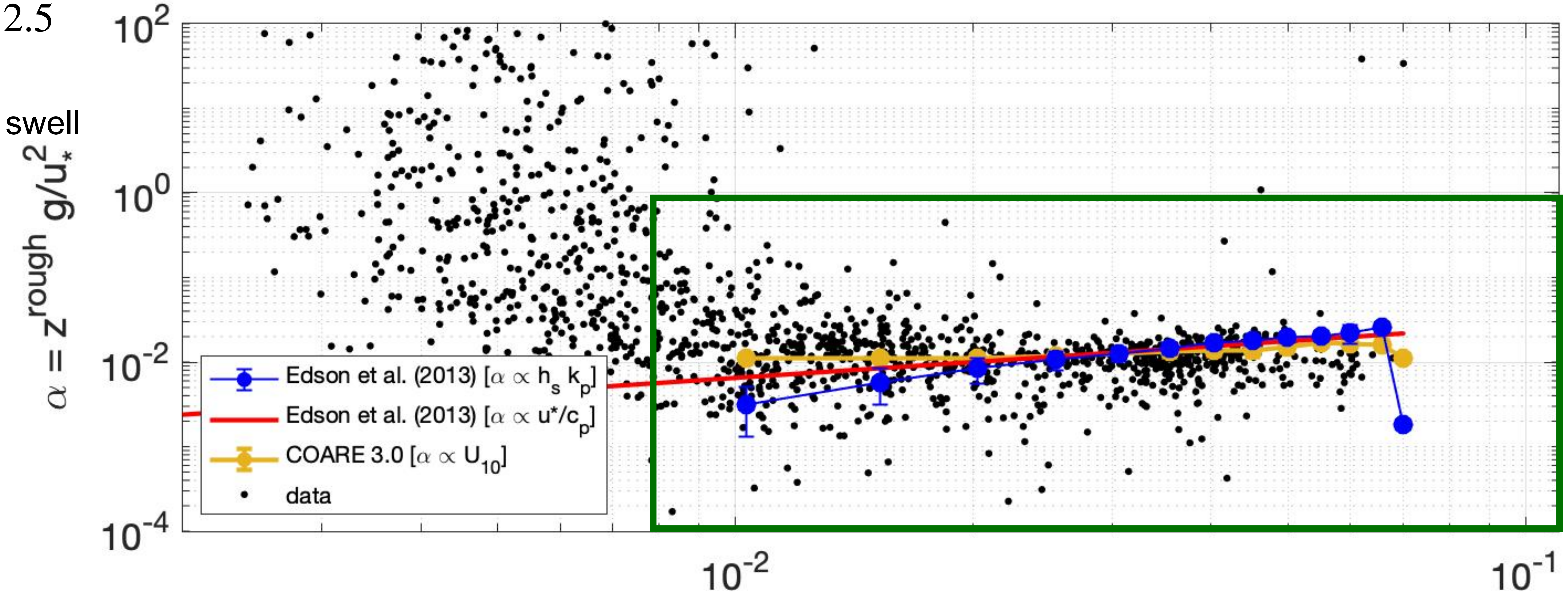


COARE 3.5 works ~well for data within the wave age range $c_p/U_{10} < 2.5$

Significant spread in low-wind, swell dominated regime

(A regime not captured in this paper's dataset)



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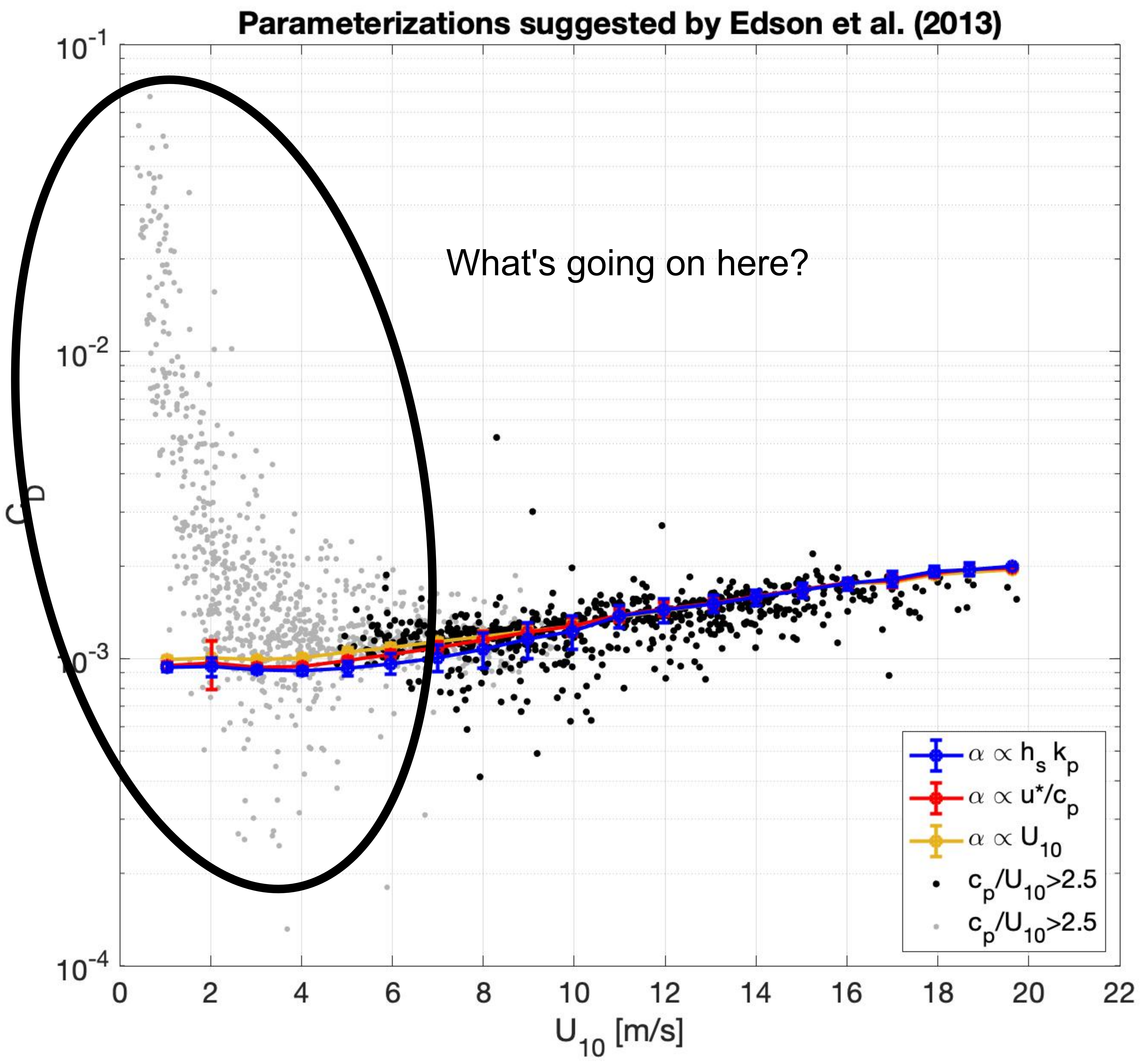
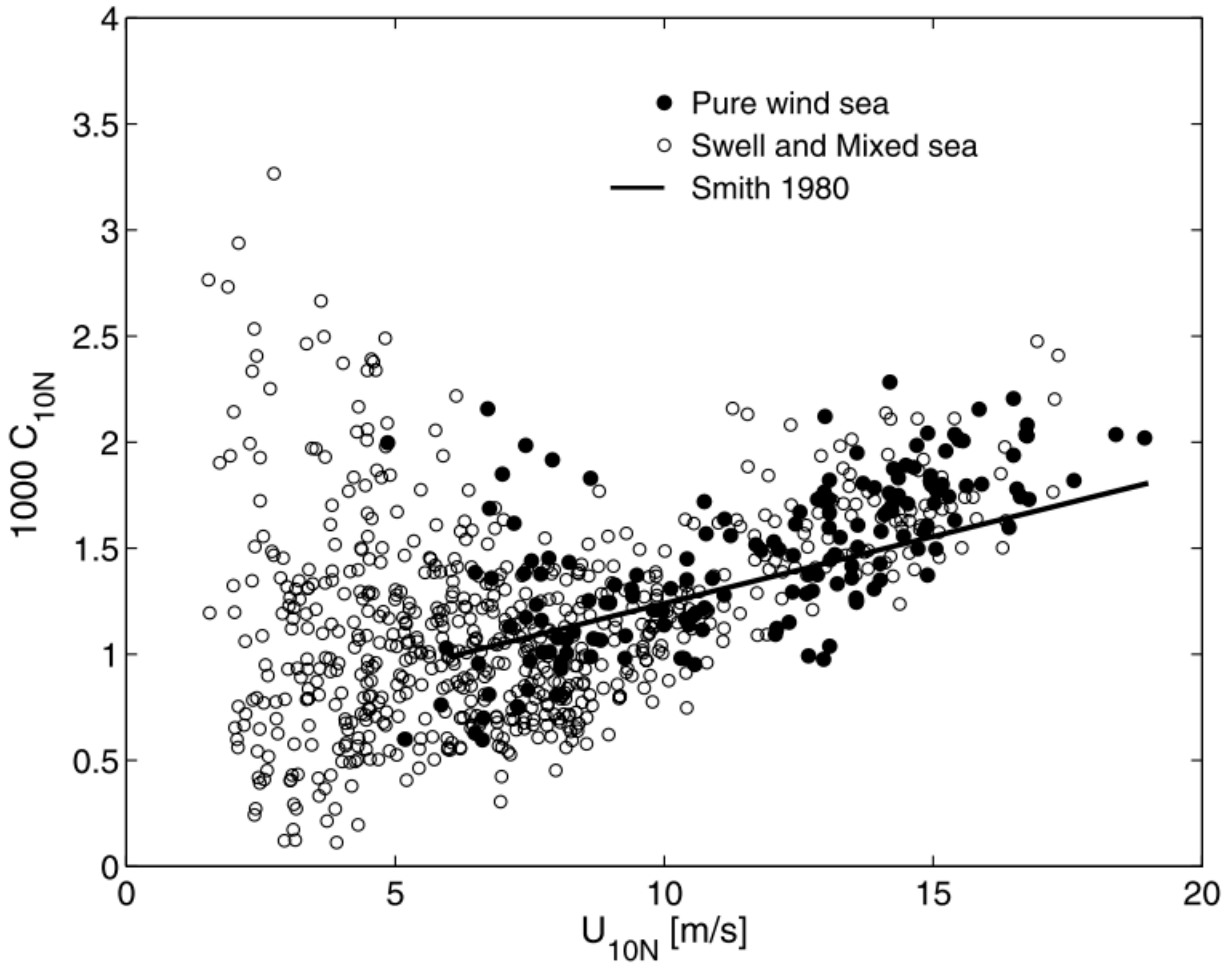


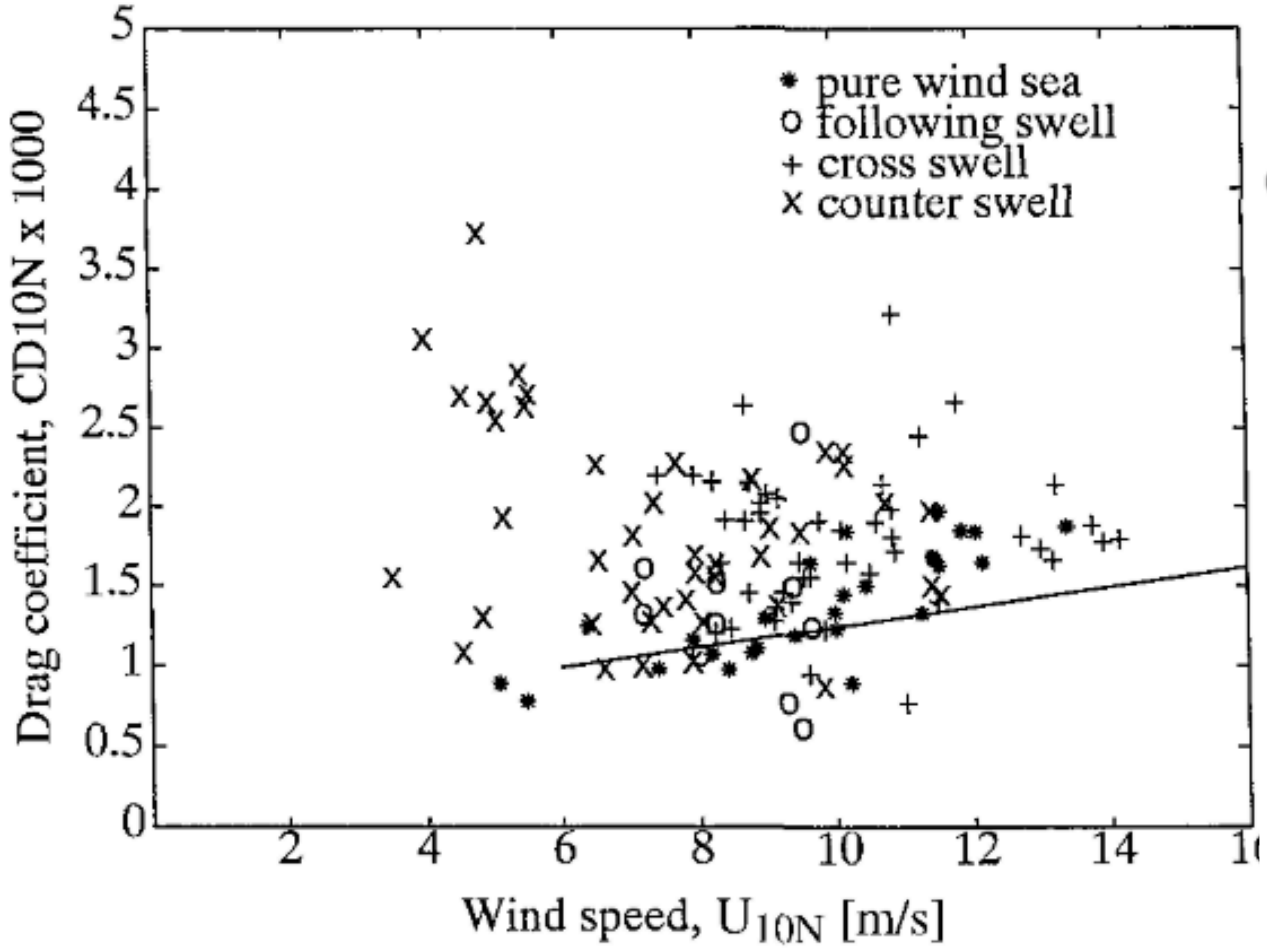
Influence from swell

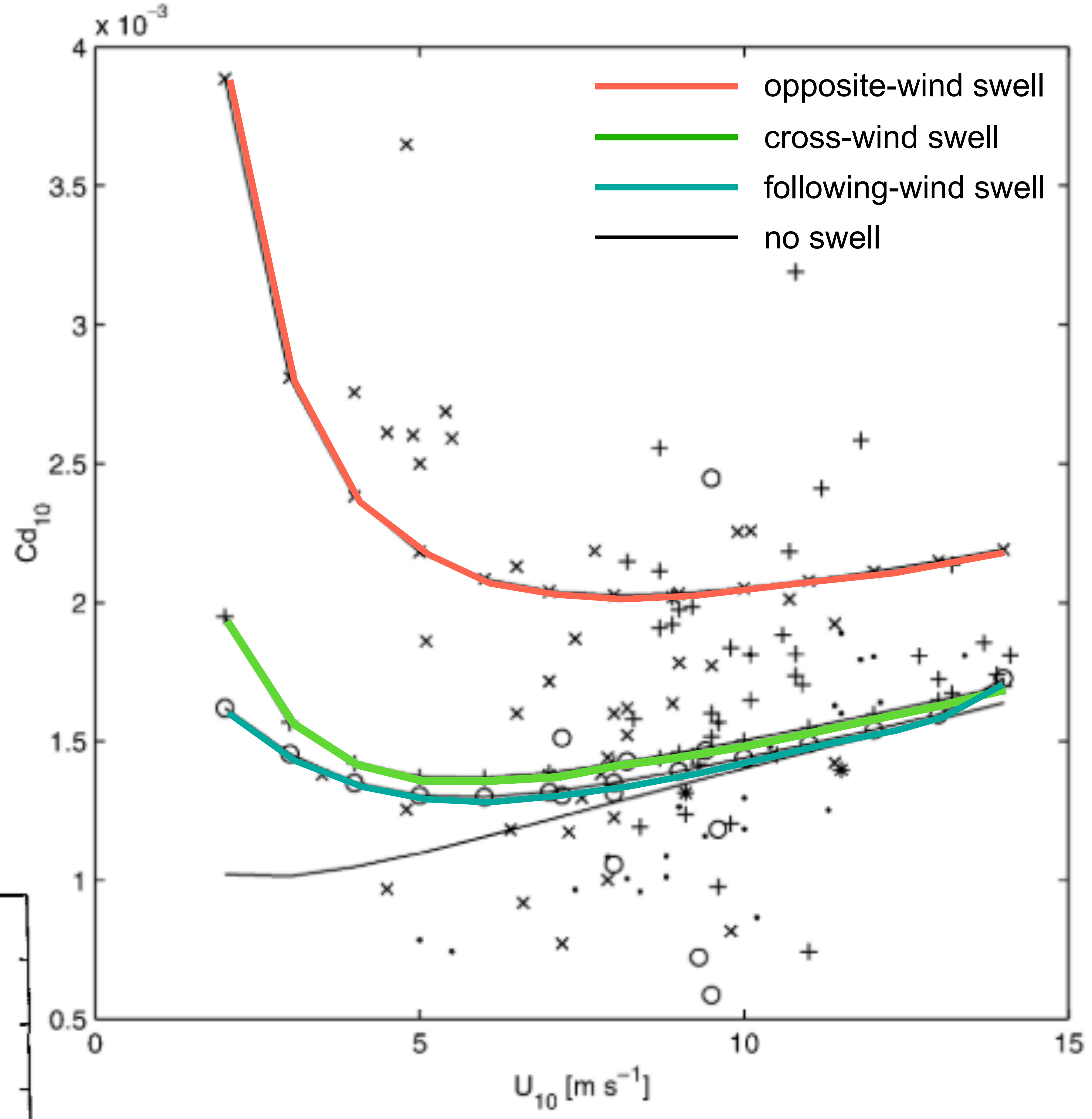
beyond bulk parameterization

Drennan et al. (2003)
Differentiating pure wind sea from swell-dominated and mixed seas.



Donelan & Dobson (2001)
When swell is relatively steep and travels with the wind, the wind waves are suppressed and the drag is lower than in swell-free cases. When swell is relatively steep and travels against the wind, the wind waves are again suppressed, but now the momentum transfer (the drag) to the swell is large enough to enhance the drag coefficient. For cross-wind swells and low-slope swells the effect on the drag coefficient appears to be small.

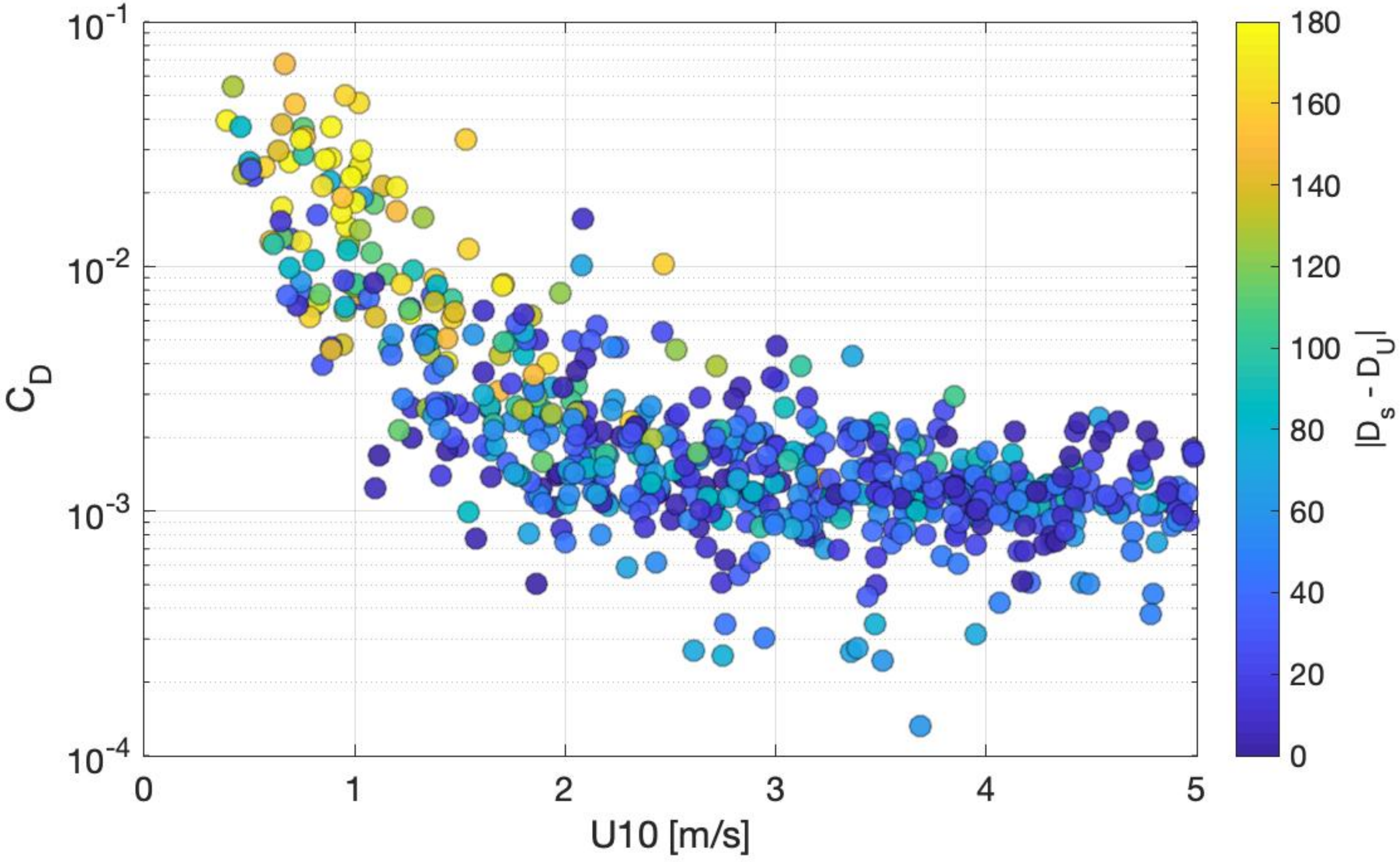




Kudryavstev & Makin (2004)
Two-layer boundary layer model shows influence of swell direction on drag. Following-wind swell accelerates the flow, which for a very low wind results in a swell-driven wind. Opposite-wind swell decelerates the airflow, which for a steep swell could cause the reverse airflow.

Influence from swell

beyond bulk parameterization



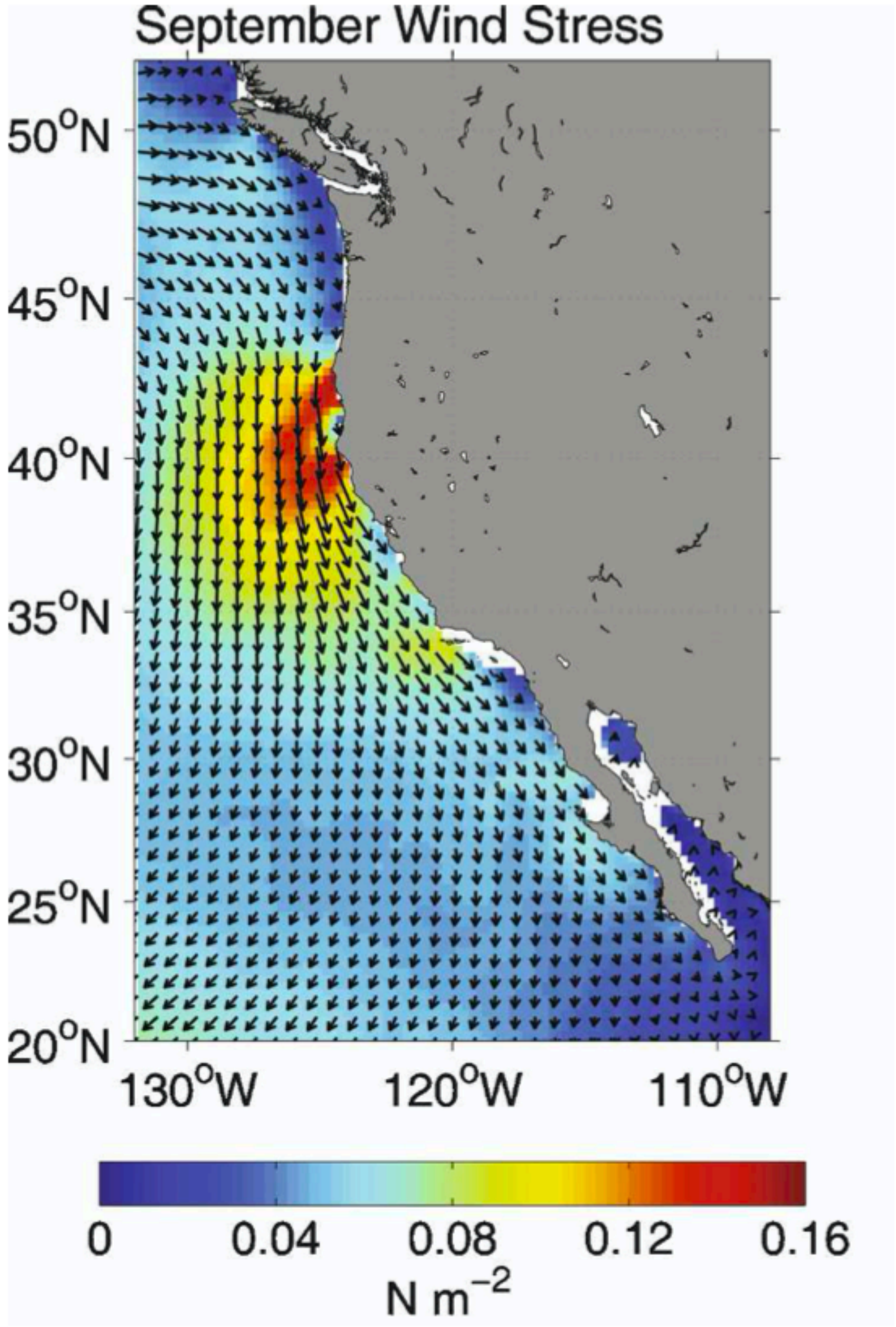
Should long period swell be accounted for in these bulk parameterizations?

Use in models and reanalysis

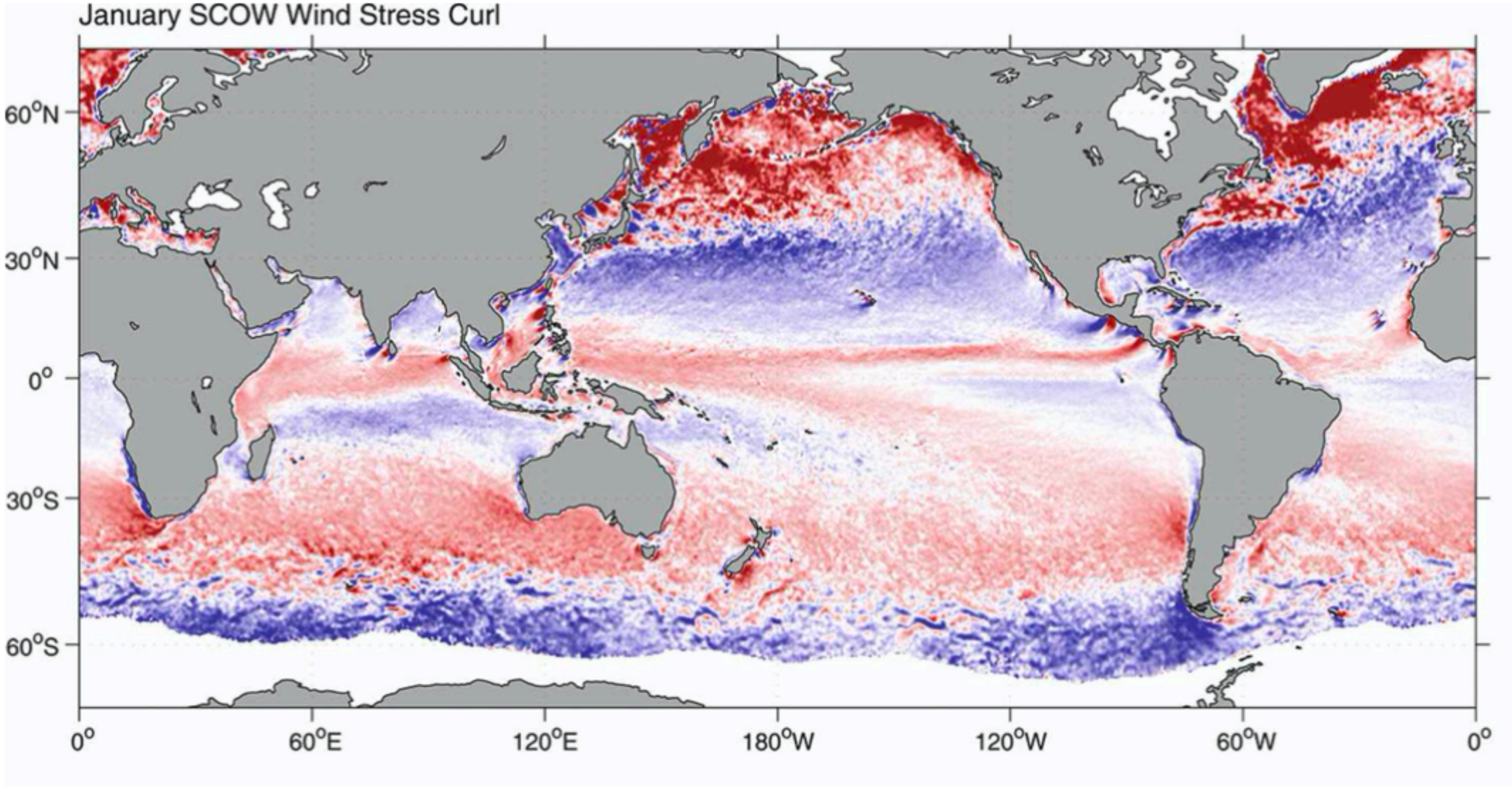
What's used in circulation models? Coupled models?

What's used in atmospheric reanalysis products?

What about remote sensing?



Risen & Chelton (2008) - scatterometer climatology



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How do we describe the roughness of the ocean surface?

How does this interaction change with

- High winds
- Low winds
- Wave breaking
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- BL separation
- Following swell or counter swell

How do we parametrize this in global models - a significant BC in many coupled models - in a way that is **accurate** but **efficient** *(good enough)*? $C_D(u_*, U_{10}, z, H_s, u_*/c_p, k_p)$ … $C_D(\tau, U(z), z, S(f, \theta))$

How does our estimation of this interaction affect circulation models, climate models, wave models, air-sea gas transfer, remote sensing, etc.?

What measurements are most useful?