Direct Numerical Simulations of Wave-Current Boundary Layers Over Bumpy walls

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Western Coastal Collaboratorium

At The University of Washington

Photo Source: Google Images

Stanford University

Motivation

Wind-Waves

Tidal Currents

"Bumpy" bottom

$$Re_w = \frac{U_b^2}{\omega\, \nu}$$

Wave Reynolds number

$$Re_* = \frac{u_* H}{\nu}$$

Flow Reynolds number

$$\bar{k}_s = f(\psi_r(x_3))$$

Mean roughness height

Goal

$$\overline{\tau(t)} = f(Re_w, Re_*, \bar{k}_s, \dots)$$

$$C_d = f(Re_w, Re_*, \bar{k}_s, \dots)$$

SUNTANS, SWASH, DELFT-3D, etc.

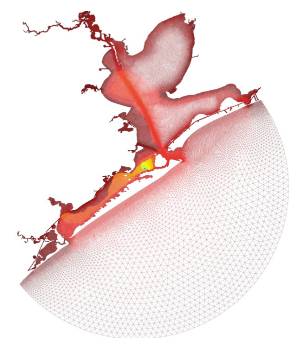


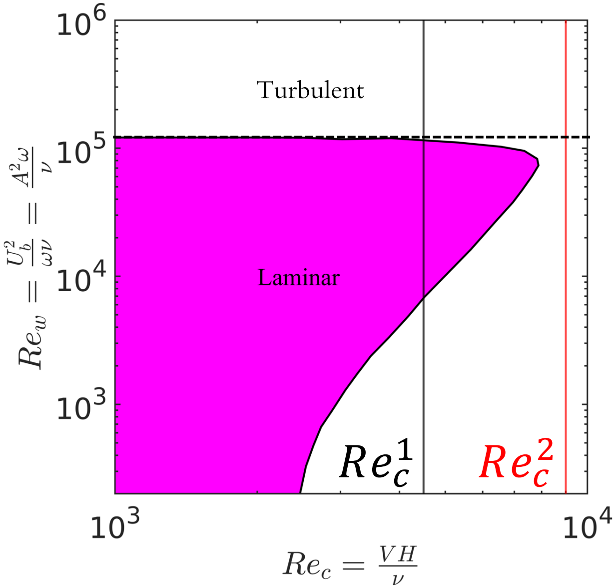
Photo Source

1. https://sites.google.com/site/thebrockeninglory/home?authuser=0
2. https://i.ytimg.com/vi/_FfK4HVrCfY/maxresdefault.jpg
3. Egan et al. (2019)

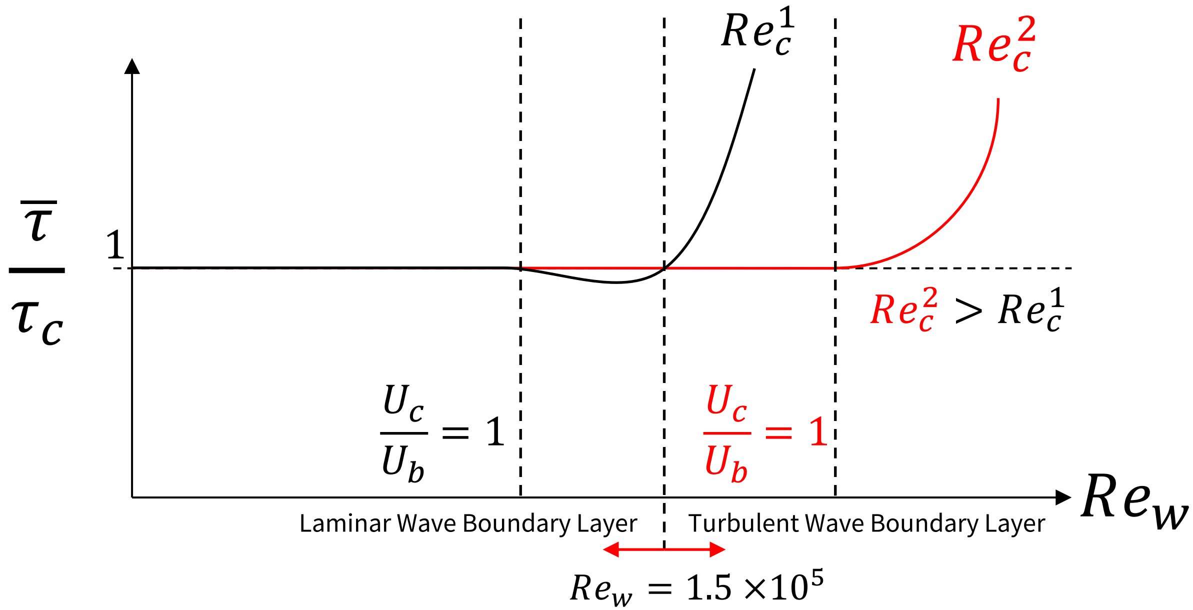
Photo Source: https://i.ytimg.com/vi/_FfK4HVrCfY/maxresdefault.jpg

What do we know already?

Wave-Current boundary layer over ***flat walls*** well understood (Lodahl et al. 1998; Scotti & Piomelli 2001; Manna et al. 2012, 2015; Nelson & Fringer 2018)



Source: Lodahl et al. (1998)



What about "bumpy" walls?

- Most studies are experimental
- Grant & Madsen (1979) analytical theory
- Only exception is the work by Bhaganagar (2008) – 1st order statistics

Problem Setup

Staggered, second-order accurate, finite-difference method (Orlandi 2000, Moin & Verzicco 2016)
IBM implemented over the fluid solver developed by Lozano-Duran & Bae (2016,2019)

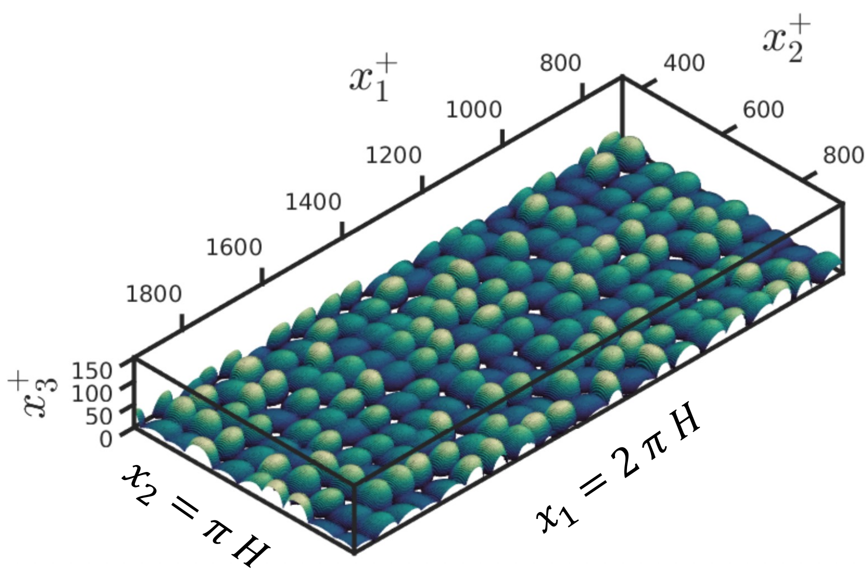
$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_o}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + U_b \omega \cos(\omega t)\, \delta_{i,1} + \Pi_c \delta_{i,1} + F_{IBM} \quad \& \quad \frac{\partial u_i}{\partial x_i} = 0$$

Waves ***Current*** ***Roughness***

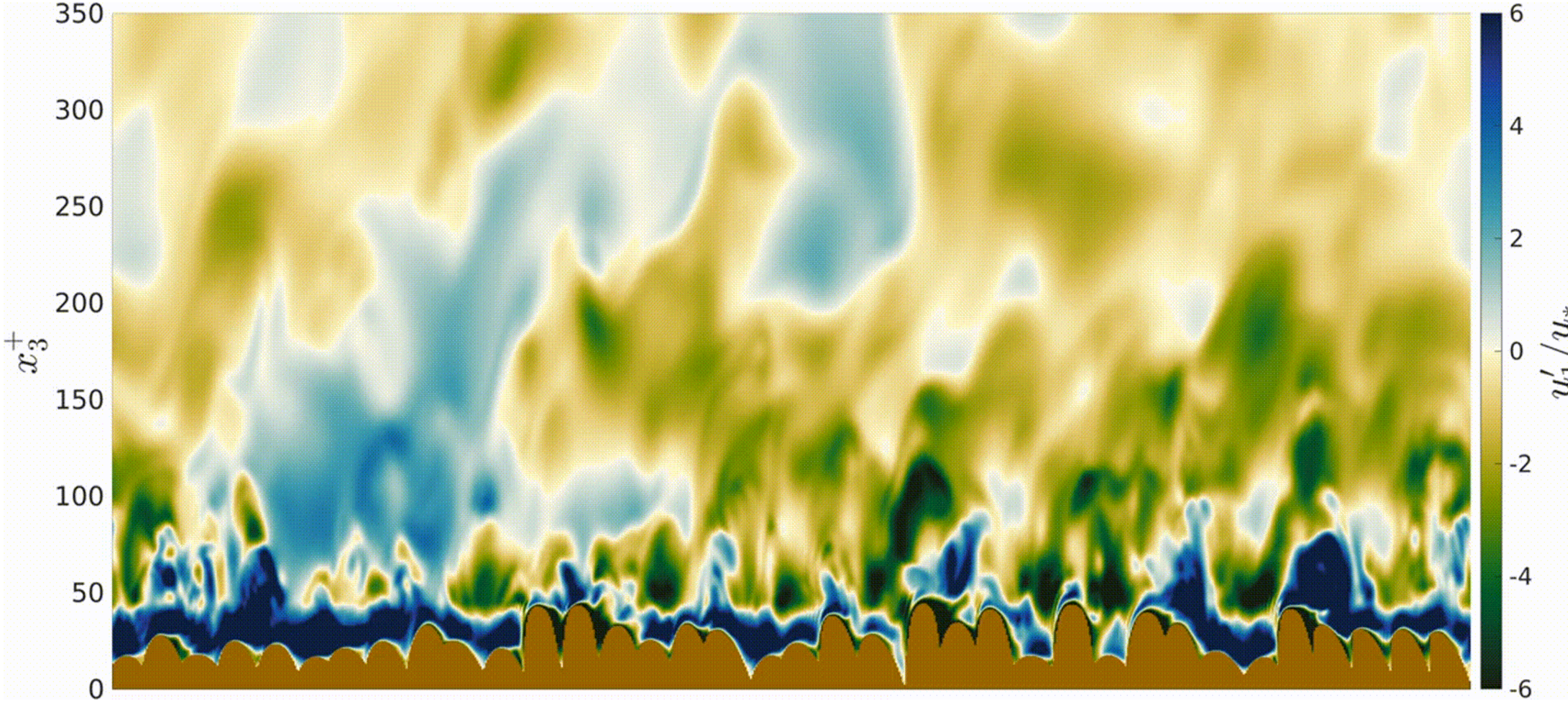
$$u_3(x_3 = H) = 0, \& \; \frac{\partial u_i}{\partial x_3}(x_3 = H) = 0 \quad \forall i \in \{1,2\}$$

Non-dimensional wall coordinates

$$x_3^+ = \frac{x_3 u_*}{\nu}$$



Channel depth is 0.1 m = 10 cm

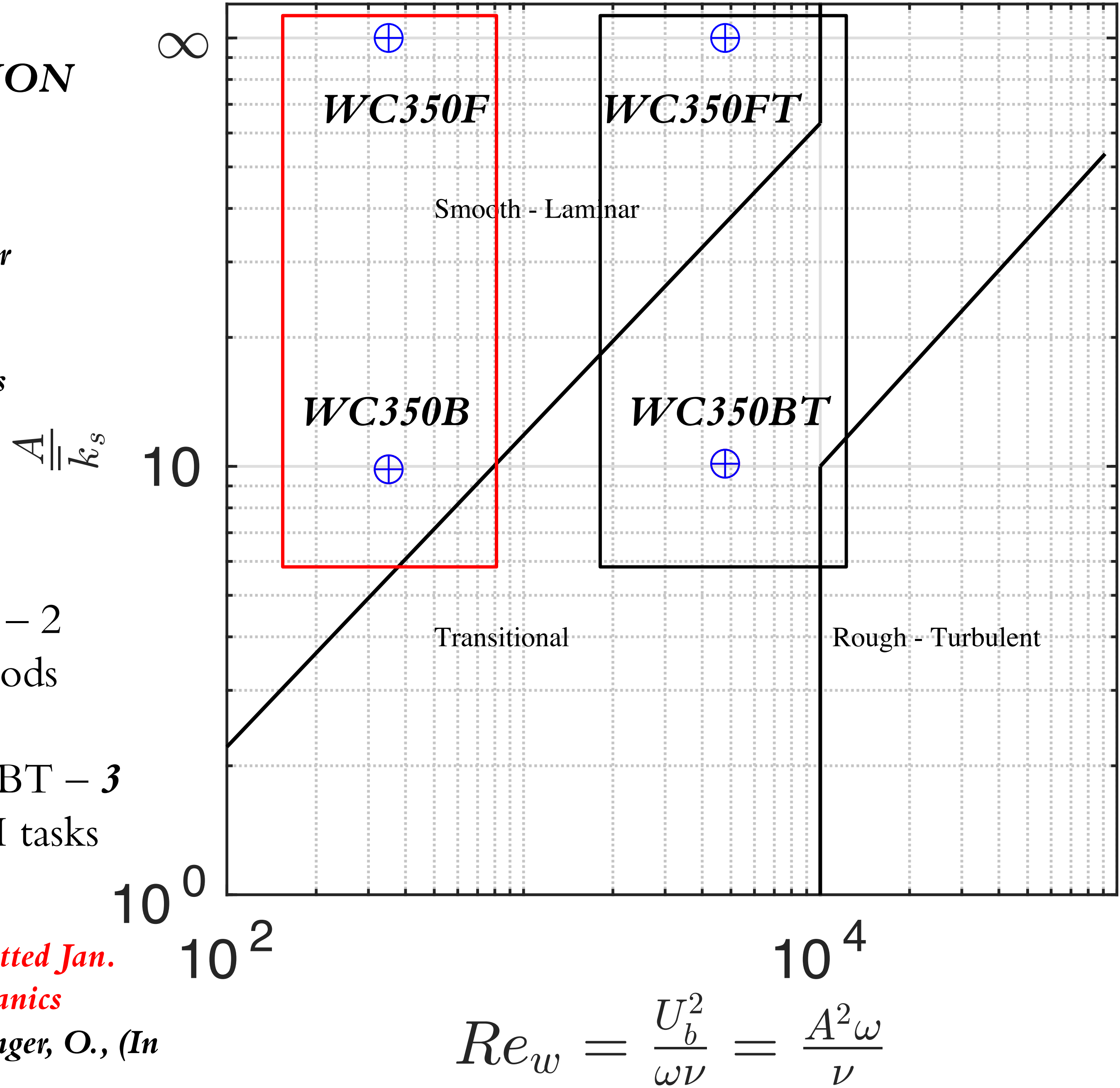


NAMING CONVENTION

W – Waves
C – Currents
350 – Friction Reynolds Number
F – Flat Walls
B – Bumpy Walls
T – Transitional wave conditions

$$A = \frac{U_b}{\omega}$$

- WC350F & WC350B – 2 days for 200 wave periods using 64 MPI tasks
- WC350FT & WC350BT – ***3 months*** using 256 MPI tasks



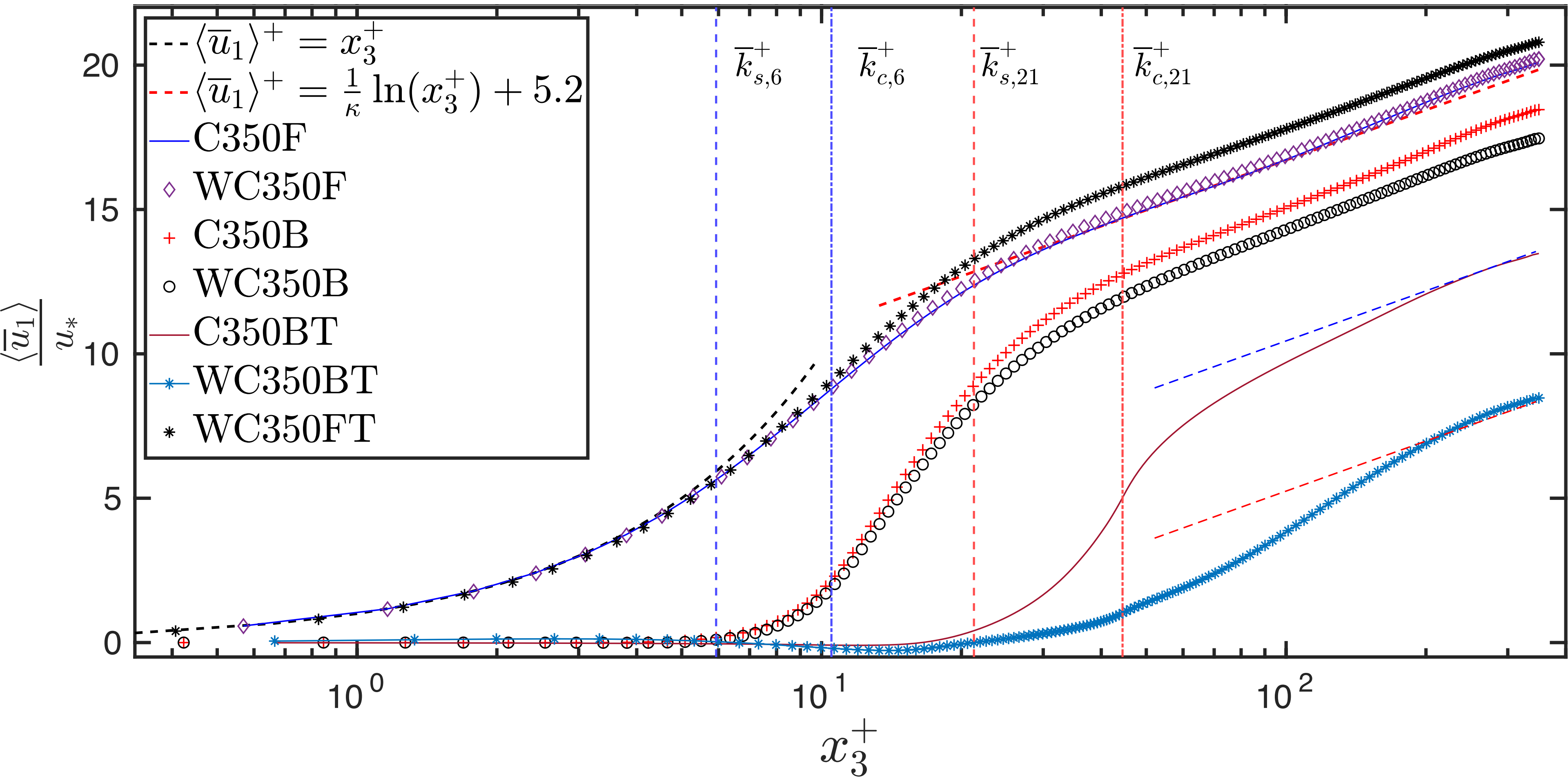
- *Patil, A., Fringer, O., (Submitted Jan. 2022), Journal of Fluid Mechanics*
- ***Patil, A., Monismith, S., Fringer, O., (In Prep)***

Time- and Planform-averaged Velocity Profile

Log-law (Raupach et al. 1991)

$$\frac{\langle \bar{u}_1 \rangle}{u_*} = \frac{1}{\kappa} \ln\left(\frac{x_3 - \bar{k}_s}{z_0}\right)$$

$$z_0 = \begin{cases} \dfrac{\bar{k}_s}{\alpha_k} & \ldots\ \bar{k}_s > 0 \\ \dfrac{\nu}{9u_*} & \ldots\ \bar{k}_s = 0 \end{cases}$$



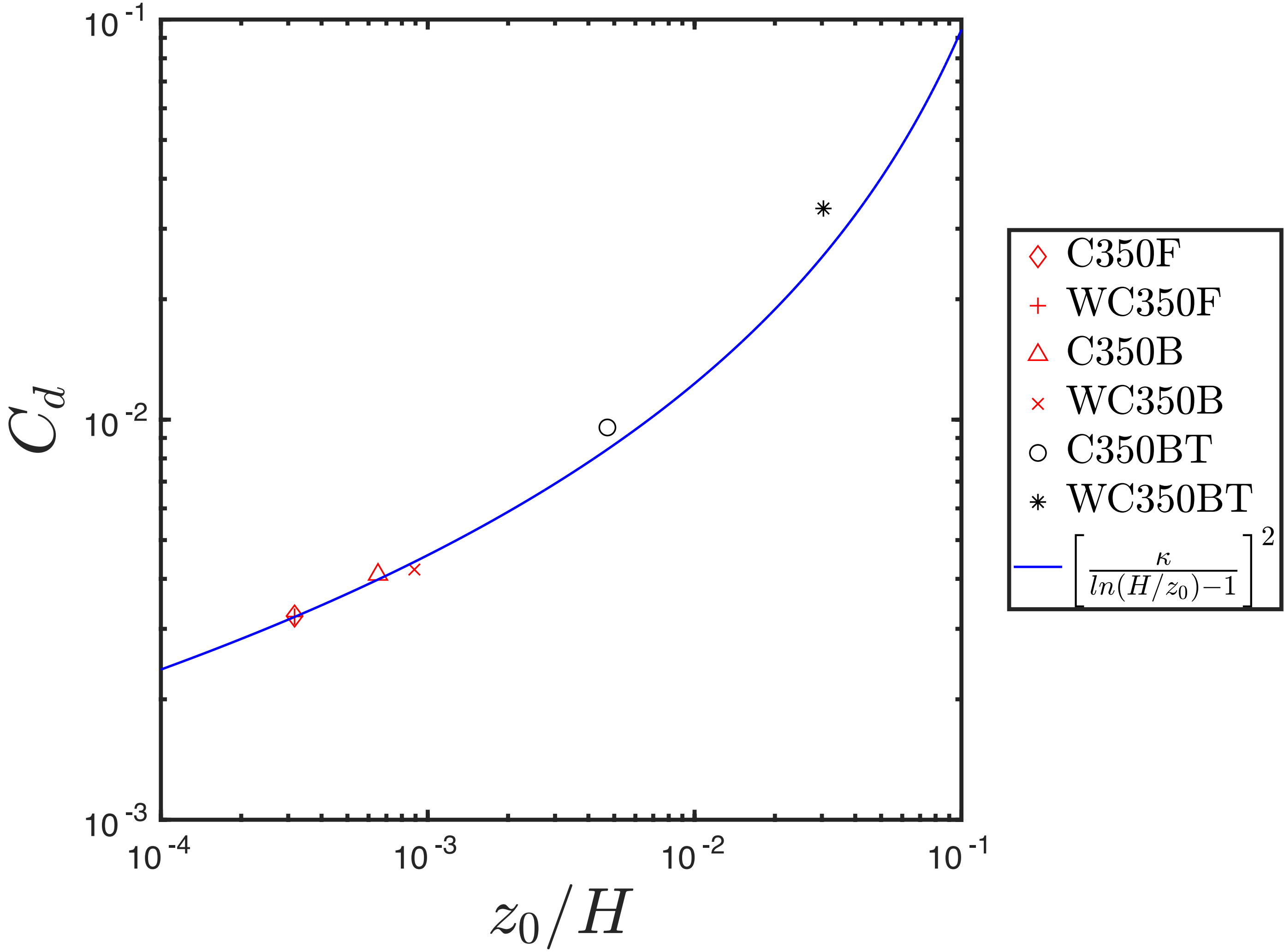
Drag Coefficient

Exact Definition

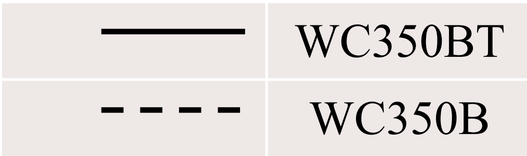
$$C_d^* = \frac{u_*^2}{\langle \bar{u}_1 \rangle_v^2}$$

Assuming log-law holds

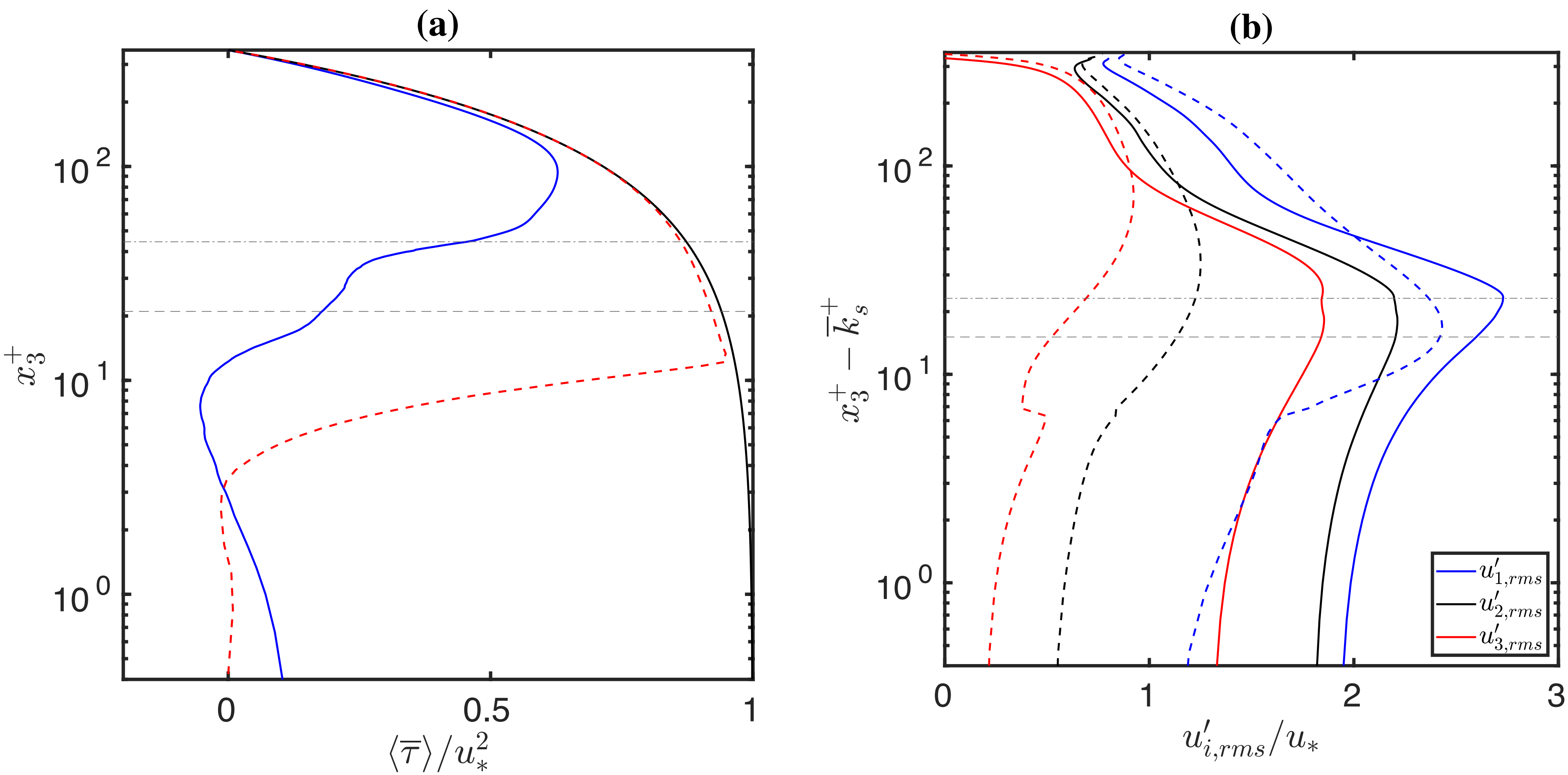
$$C_d = \left[\frac{\kappa}{\ln\left(\frac{H}{z_0}\right) - 1} \right]^2$$



Time-averaged Stress & RMS velocity



$$0 = \Pi_c - \frac{\partial \langle \bar{\tau} \rangle}{\partial x_3}$$



Key Points

- Wave-Current BL's (Flat walls) – No change – Current dominated, hydraulically smooth $\left(\frac{\bar{k}_s}{\delta_w} < 4\right)$
- Wave-Current BL's (Bumpy walls) –Drag coefficient increases (3*% to 11%) – Current dominated, hydraulically smooth
- One-way coupled flow (Scotti & Piomelli 2001; Manna et al. 2012, 2015; Nelson & Fringer 2018)
- ***Grant & Madsen (1979) theory holds despite the various assumptions that demonstrably do not hold***
- Enhanced dissipation with simultaneous decreased mean shear production of TKE
- Pressure-Strain rate correlations important

THANK YOU!

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XSEDE Project: CTS190063