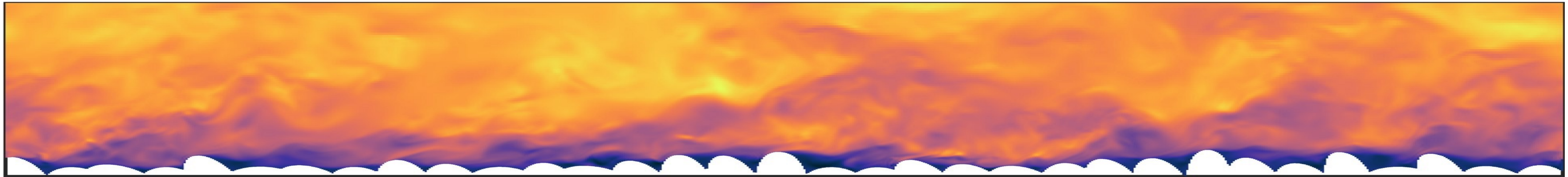
Understanding the Turbulence Dynamics in Environmental Flows with Complex Roughness

Akshay Patil (Post-Doctoral Researcher)

3DGeoinformation Research Group, Delft University of Technology, The Netherlands



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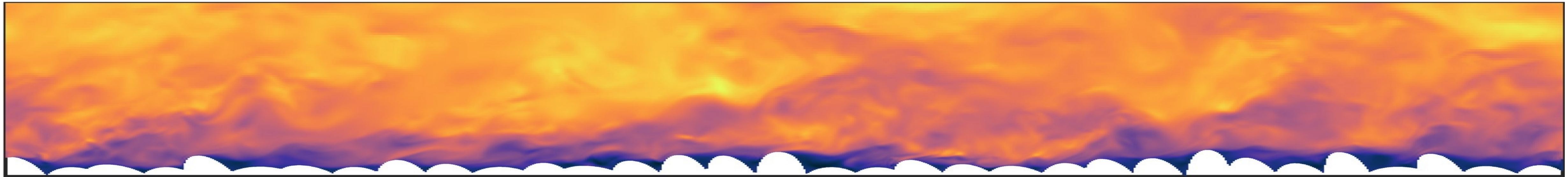
Post-Doc Advisor

Asst. Prof. Clara García-Sánchez



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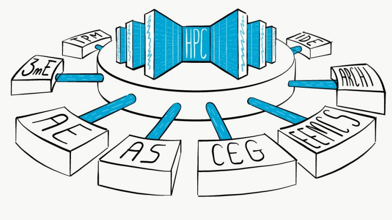
refmap

Funded by
the European Union

This Project has received funding from the European Union's HORIZON Research and Innovation Programme under Grant Agreement number 101096698



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SURF
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SRCC
Stanford University srcc.stanford.edu

EFML
The Bob and Norma Street Environmental Fluid Mechanics Laboratory

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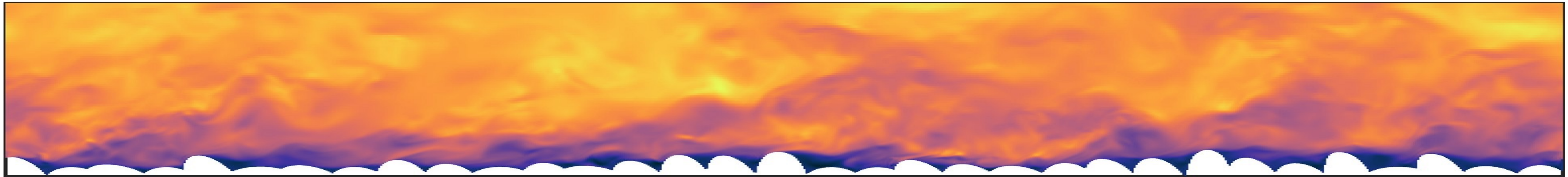

Agenda

- Motivation
- Coastal Ocean Boundary Layers
  - Connecting Roughness & Flow
  - Wave-Current-Roughness interactions
  - Wave-Coral boundary layers
- Urban Fluid Dynamics
  - Impact of Geometry

Painting by Gayle Reichelt

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EFML
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TU Delft 3Dgeoinfo

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B.E.
(2012-2016)

Break Year
(2016-2017)

MSc.
(2017-2019)

Ph.D.
(2019-2023)

Post-doc
(2023 - now)

University of Pune

Studio Musician
Sound Engineer

TUDelft Delft University of Technology

THE UNIVERSITY OF WESTERN AUSTRALIA

ARCADIS

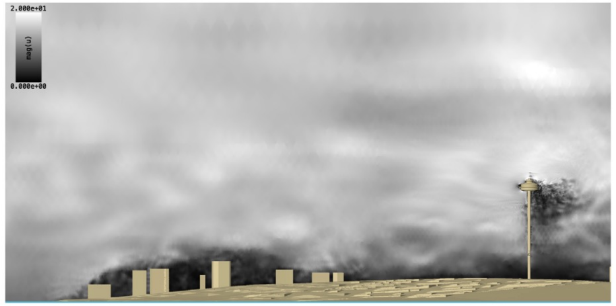
W

TUDelft 3Dgeoinfo

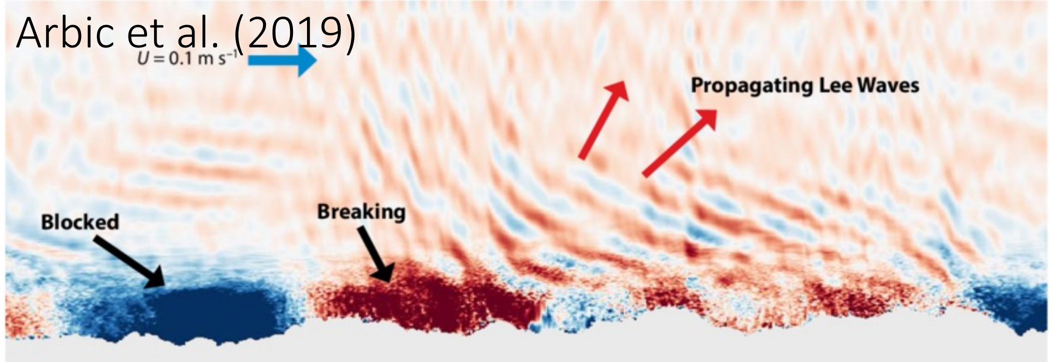
Motivation

- Wall bounded turbulent flows are all around us.

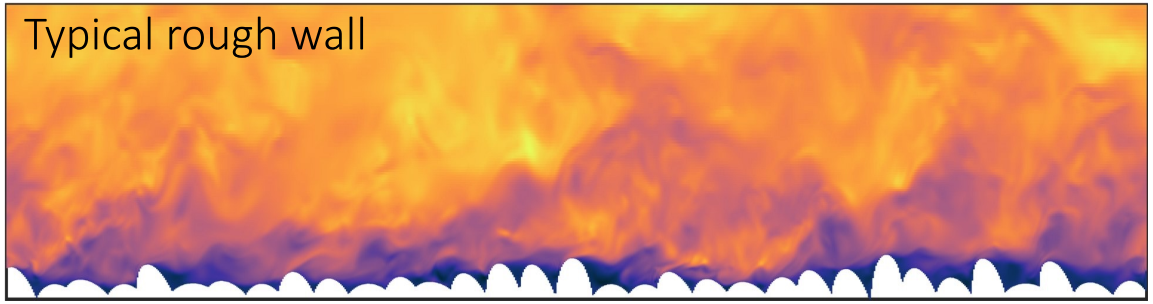
Wind carved rock



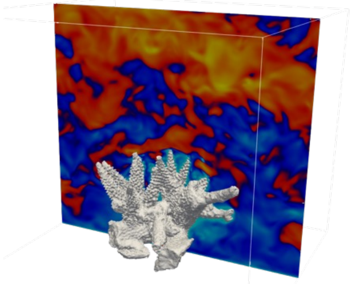
Hochschild & Gorle (2024)

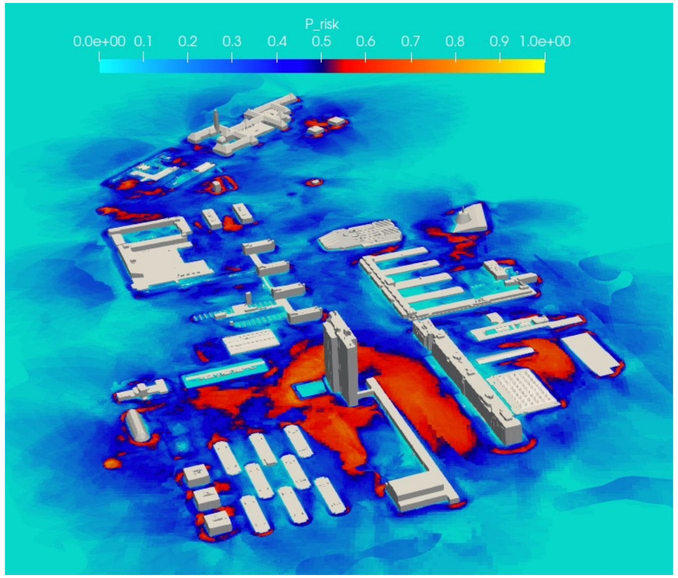


Arbic et al. (2019)



Typical rough wall





- Multi-scale (Flow and roughness itself)
- Complex interactions for unsteady systems
- Relevant across multiple disciplines

Coastal Ocean Boundary Layers

Connecting Roughness & Flow

Environmental Flows ?= Bumpy walls

$$\overline{U} = \frac{u_*}{\kappa} \ln\left(\frac{x_3 - k_s}{z_0}\right)$$

$$u_* = \sqrt{\tau/\rho_0} \qquad z_0$$

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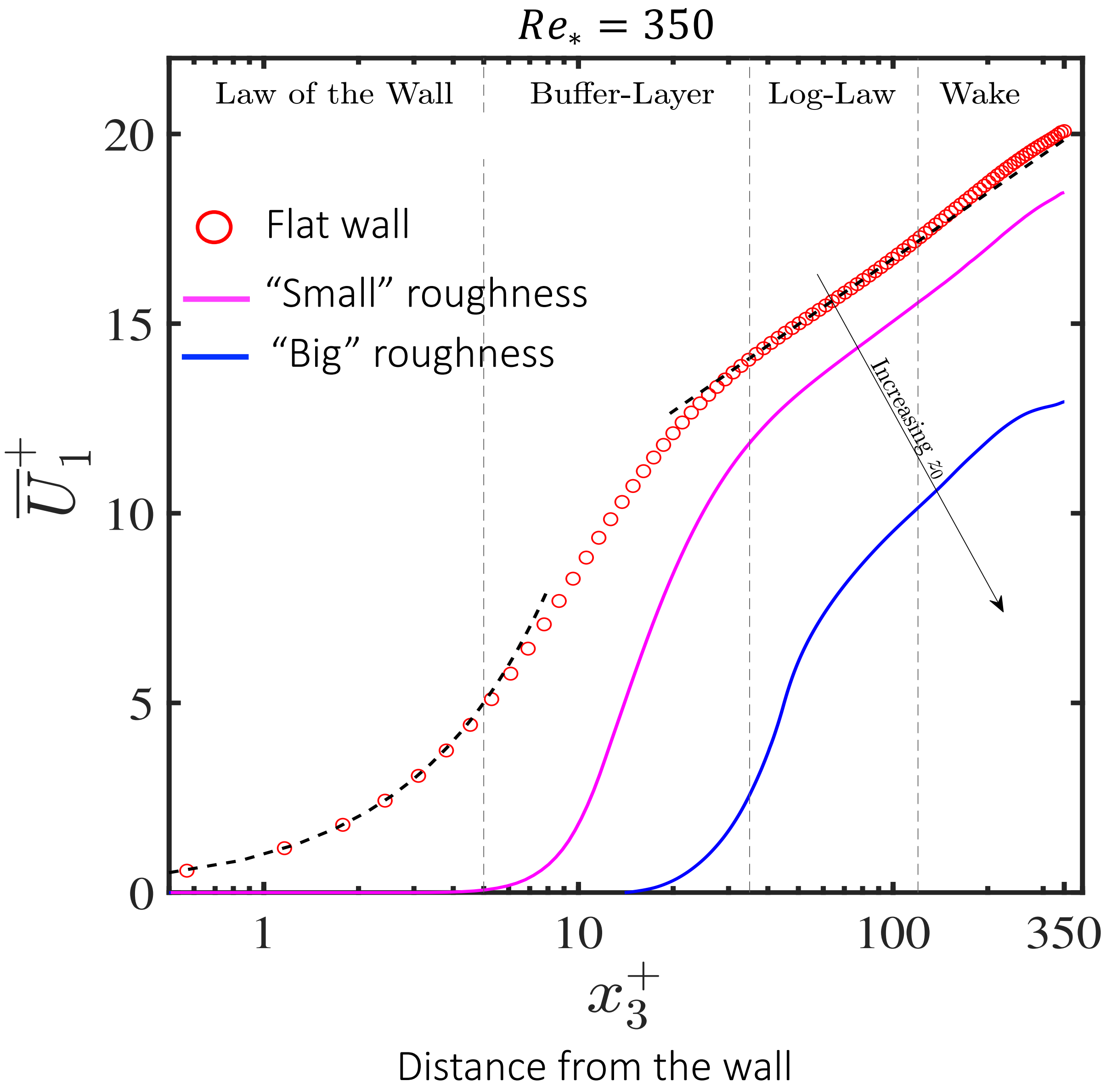

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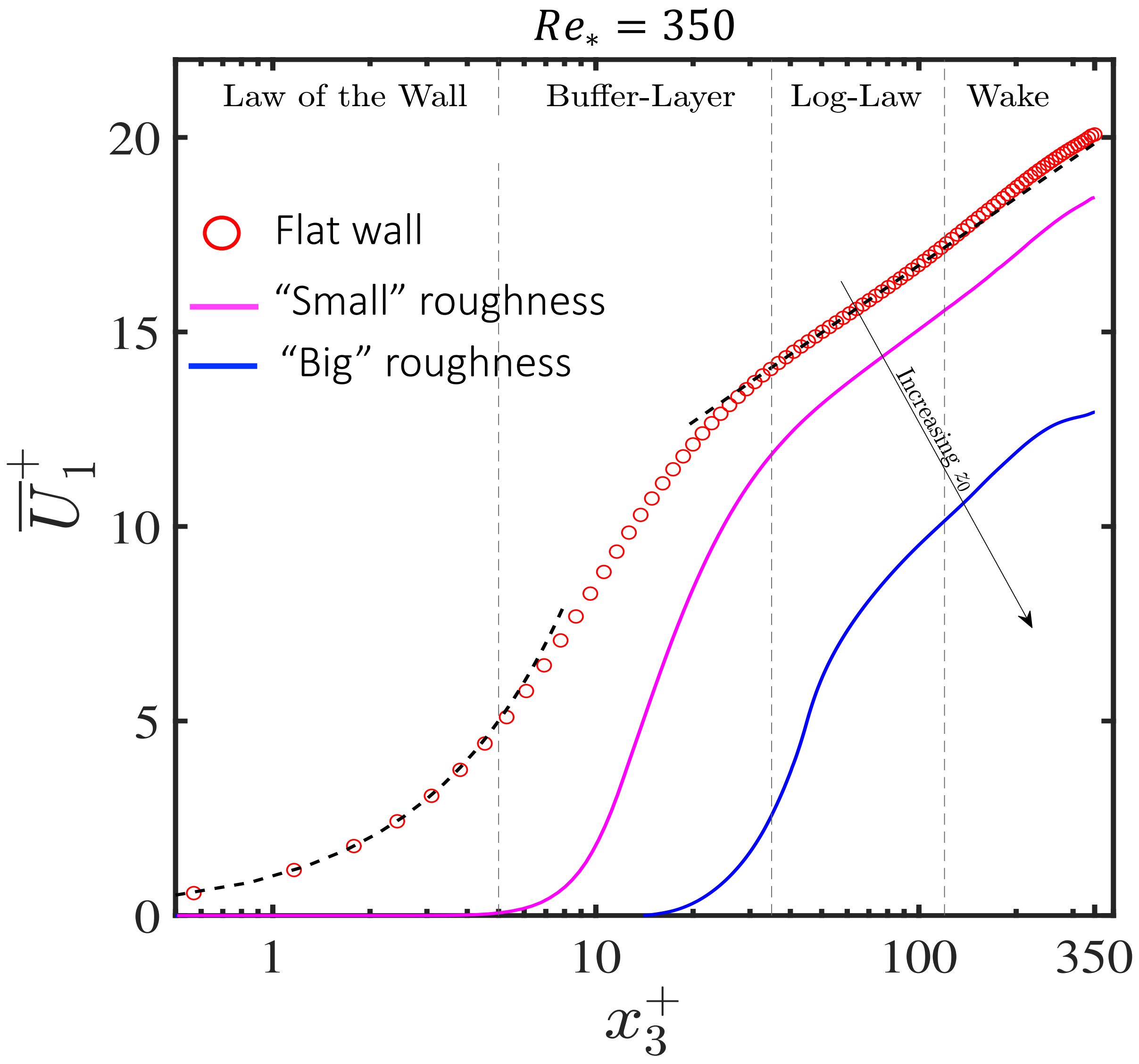
Not a trivial problem!

What sets the value for z_0?



Distance from the wall

Environmental Flows ?= Bumpy walls

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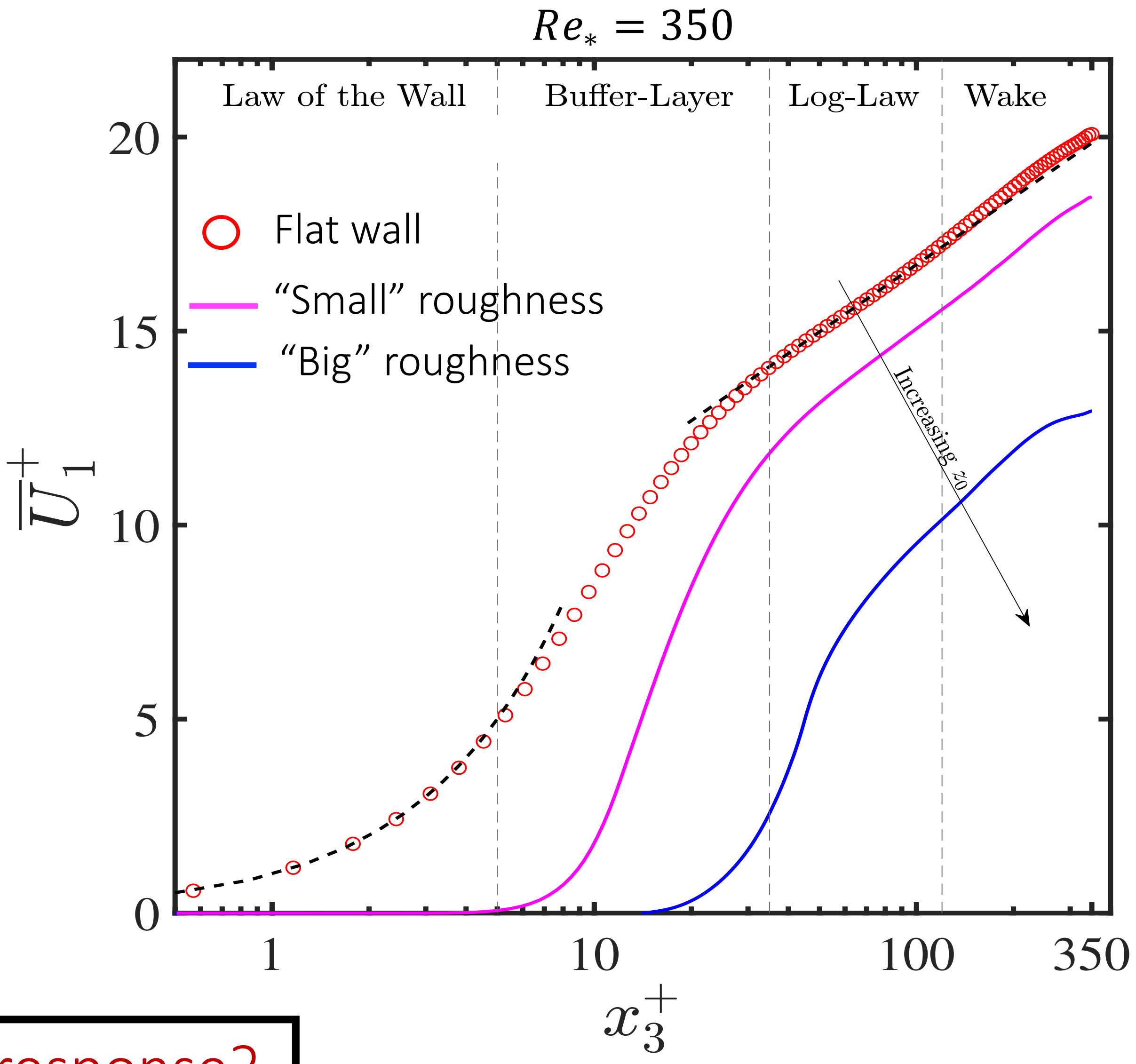
Not a trivial problem!

What sets the value for z_0?

$$z_0 = \frac{\bar{k}_s}{30}$$ [Nikuradse (1933)]

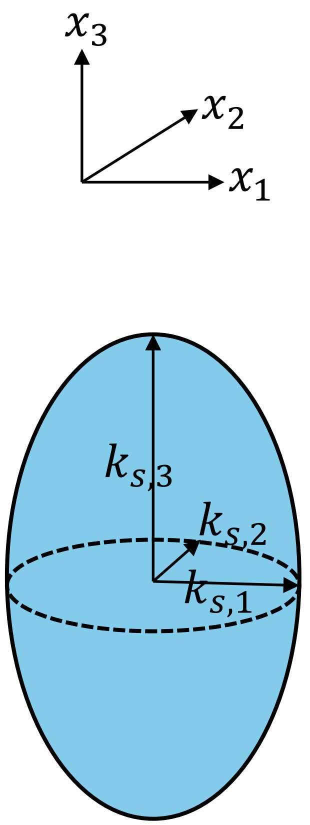
$$z_0 = g(k_{rms})$$ [Flack & Schultz (2011)]



Distance from the wall

How roughness characteristics dictate flow response?

Bottom Stress*	Velocity	Kinematic Viscosity	Channel Height	Streamwise Roughness Length	Spanwise Roughness Length	Vertical Roughness Length
τ	U	ν	H	$k_{s,1}$	$k_{s,2}$	$k_{s,3}$



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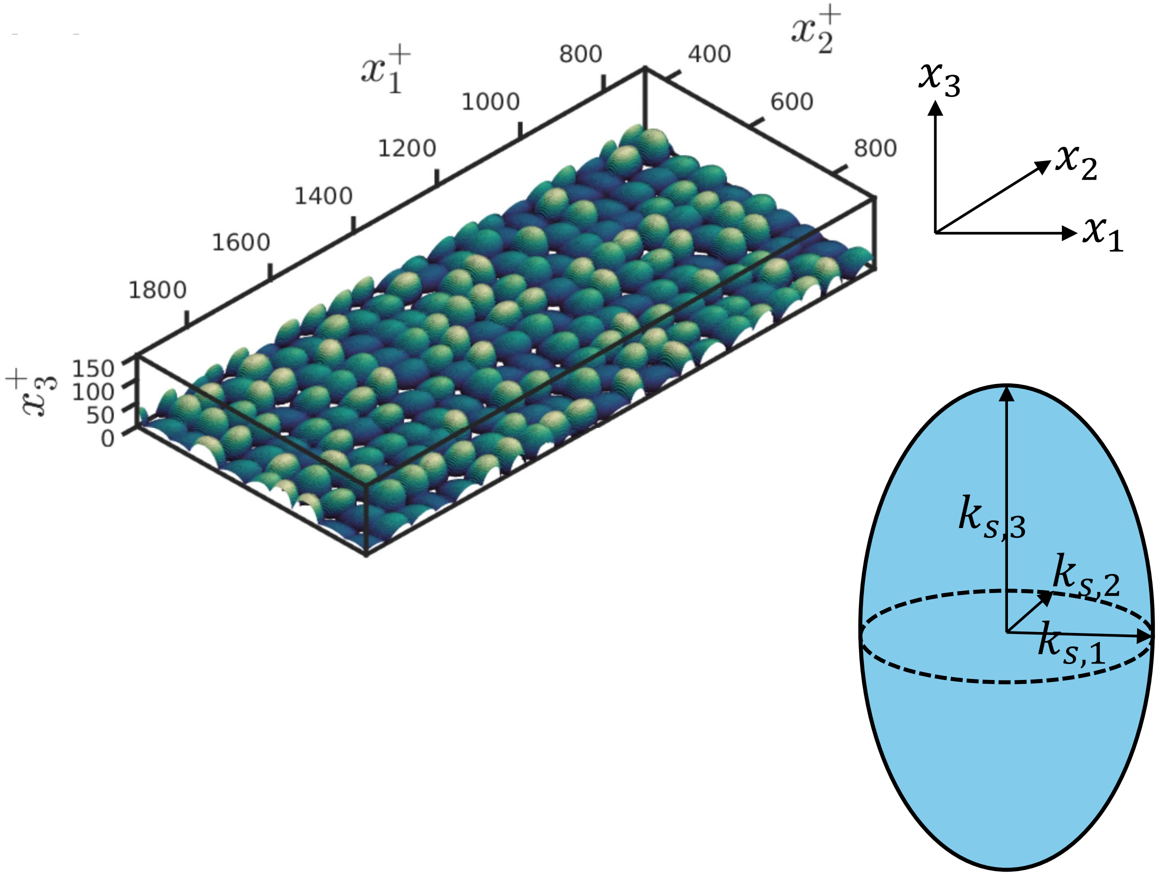

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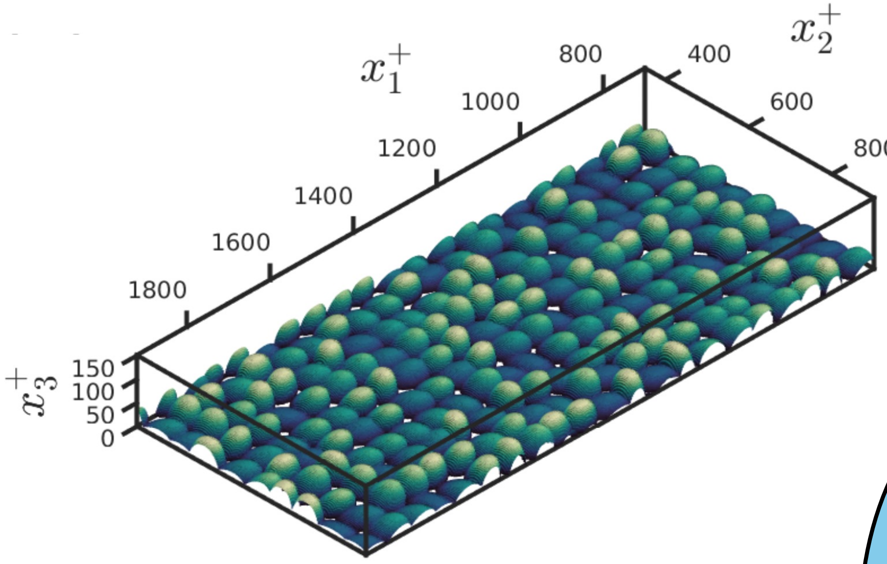

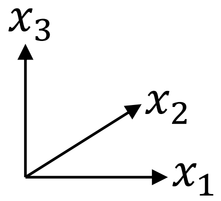

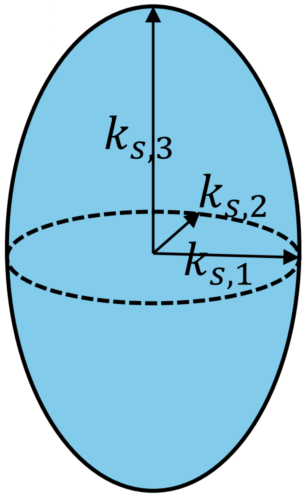

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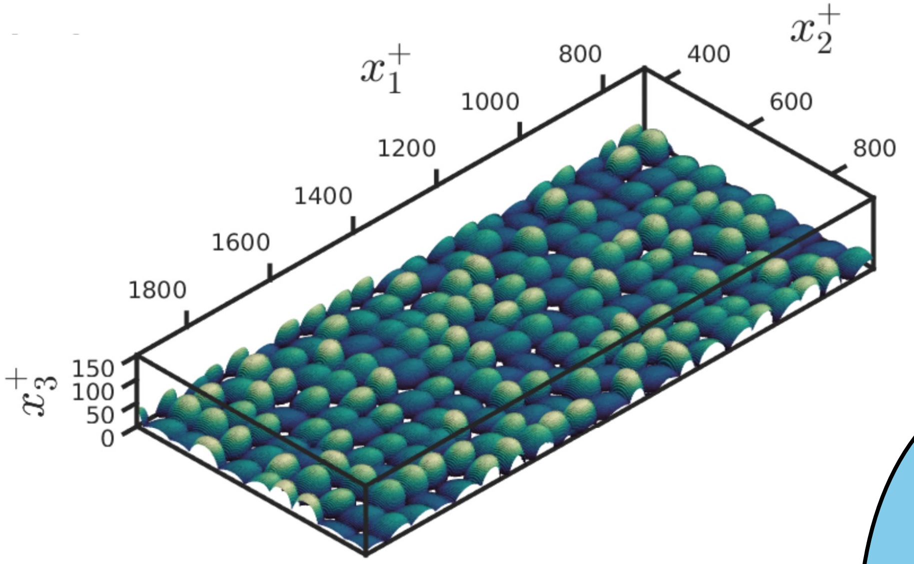
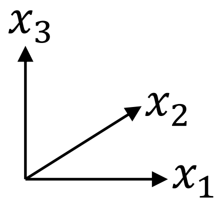
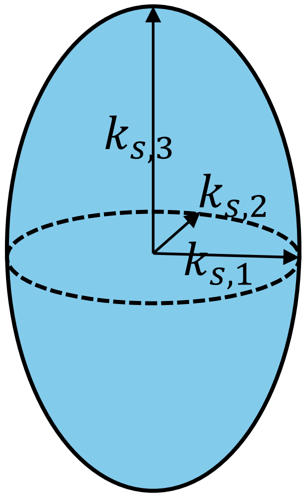
What is the effect of varying C_o and Re?







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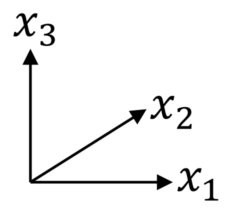

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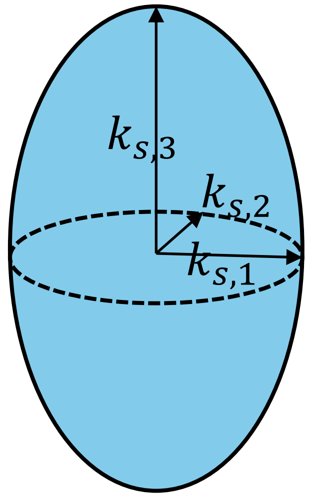

$$\partial_t u_i + \partial_j u_j u_i = -\frac{1}{\rho_0}\partial_i p + \nu \partial_j \partial_j u_i + \Pi_c \delta_{i1} + F_{IBM} \quad \& \quad \partial_i u_i = 0$$

Π_c - Driving pressure gradient F_{IBM} – Immersed Boundary Force (IBF)

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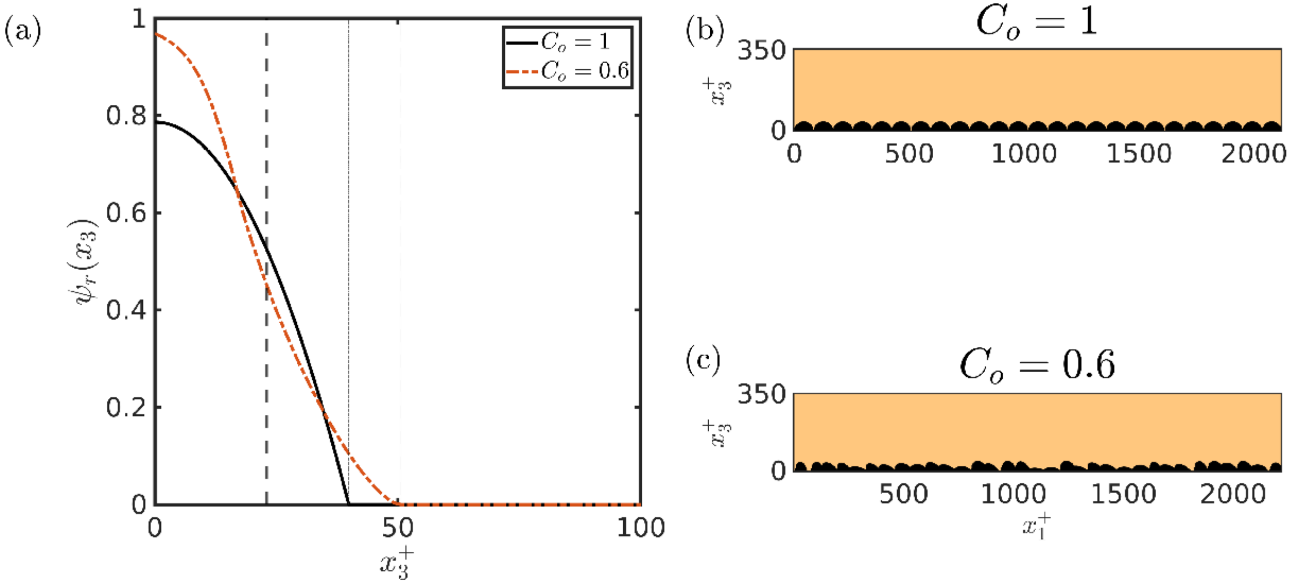

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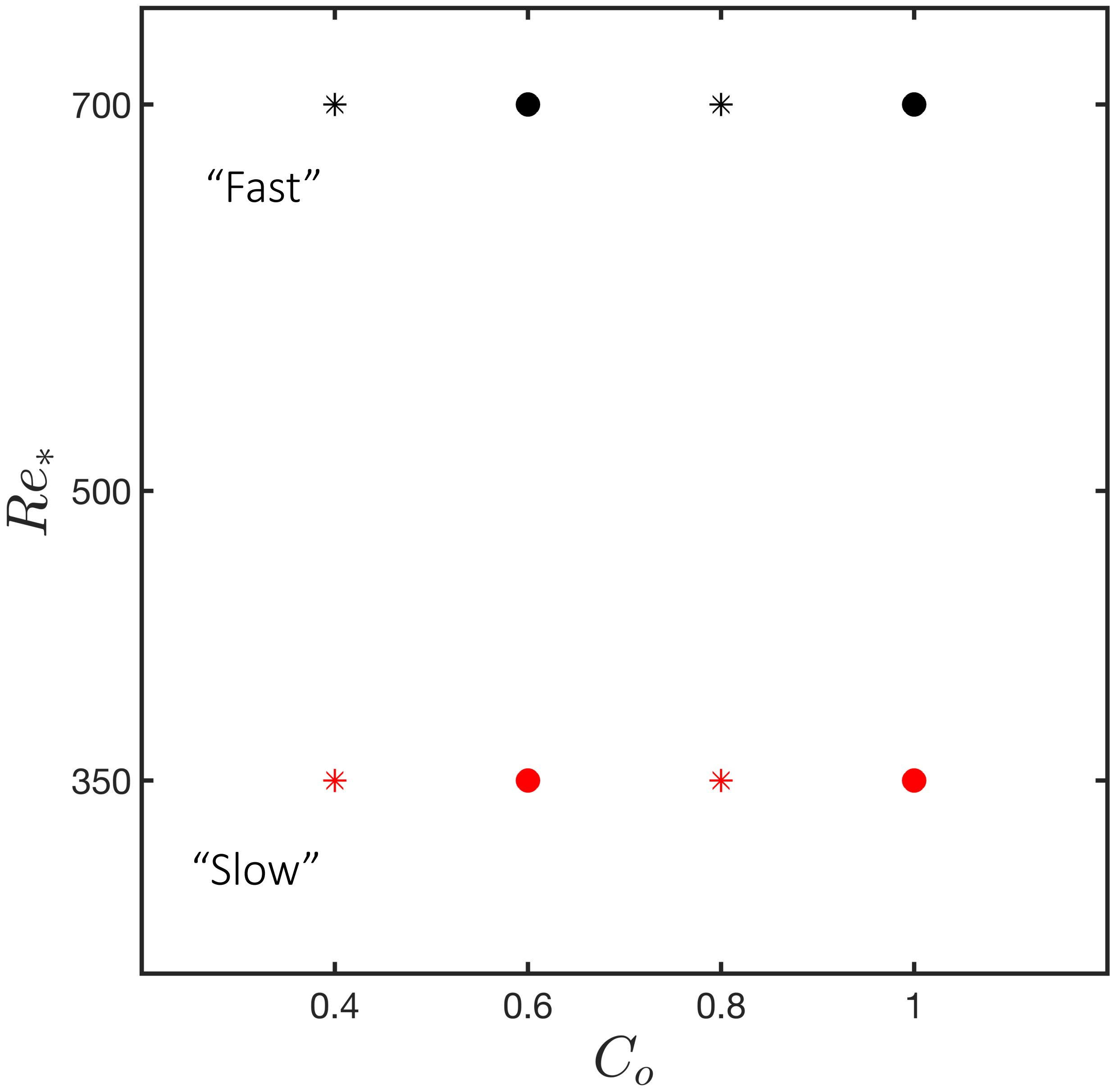
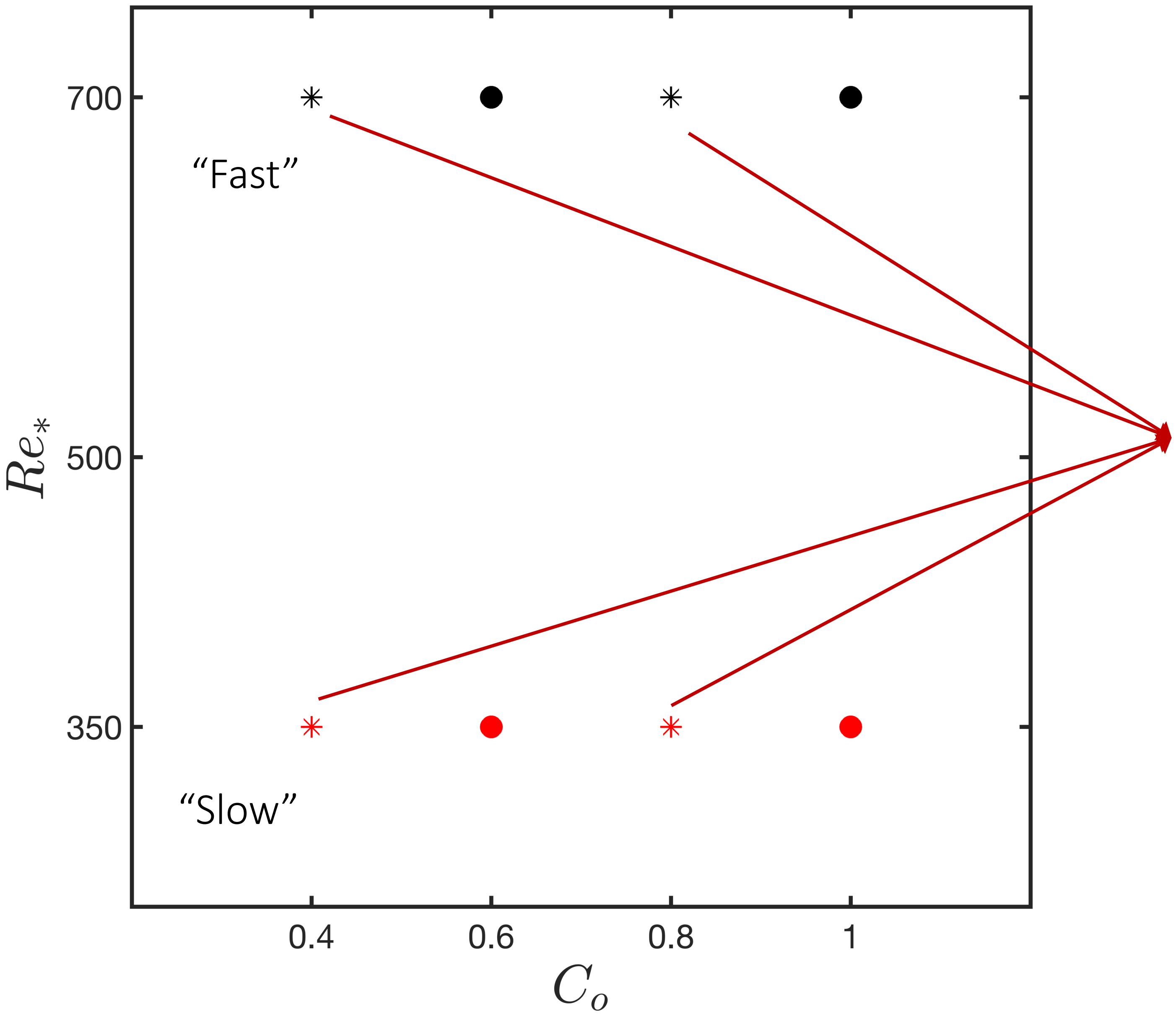
Π_c - Driving pressure gradient F_{IBM} – Immersed Boundary Force (IBF)

* Code without roughness developed by Adrian Lozano-Duran & Roughness – Scotti (2001)



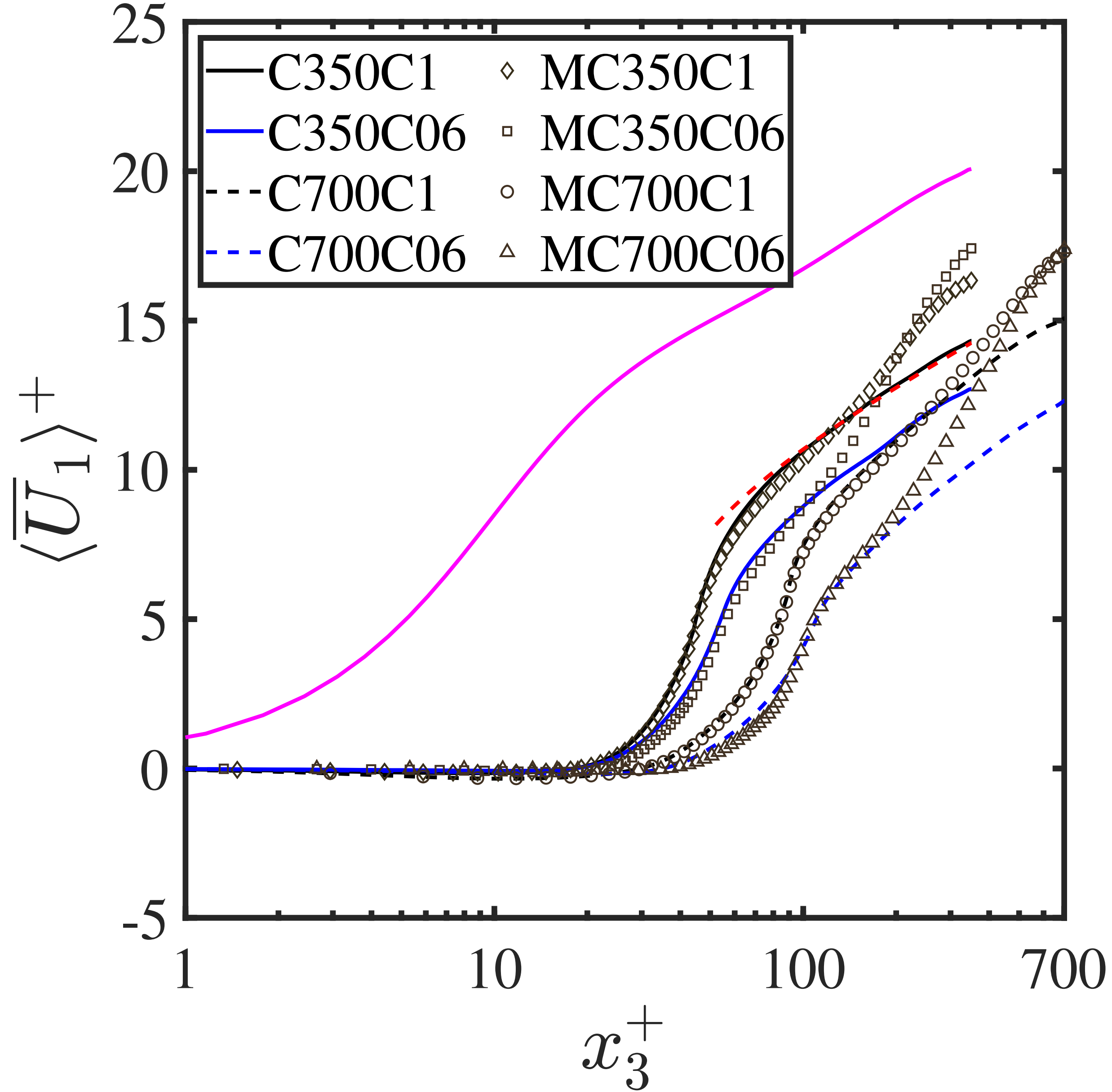
$$\frac{\mathrm{H}}{\overline{\mathrm{k}}_{\mathrm{s}}} = 15.04$$



$$\frac{H}{\overline{k}_s} = 15.04$$

Minimal Span Channels
Ly = 200 wall units

C <Reynolds Number> (M - Minimal Channel) C <Corey shape factor>



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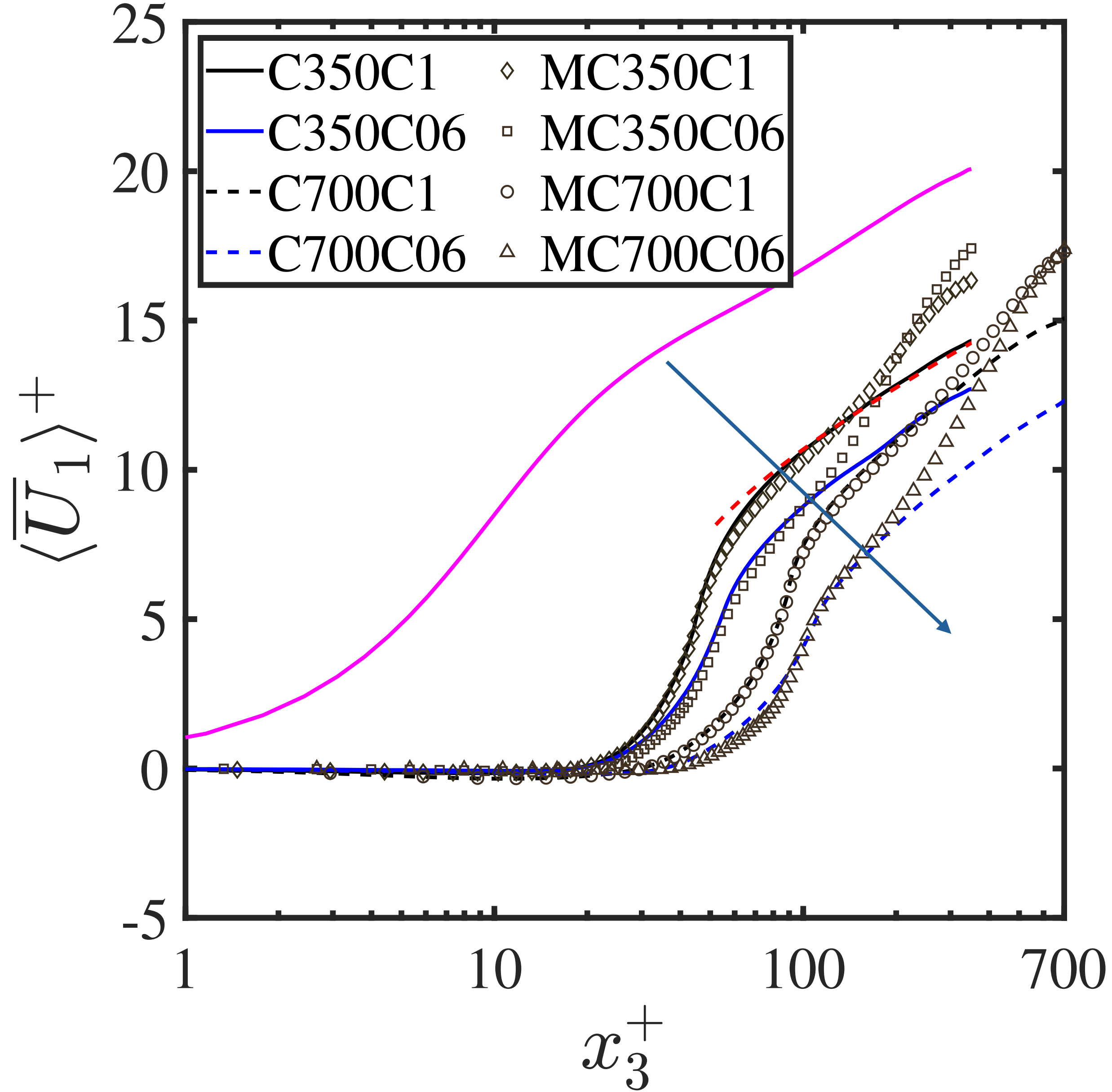

- Validates Nikuradse (1933) estimate for $z_0 \equiv \frac{\overline{k}_s}{30}$
- Increasing Re_* results is larger z_0
- Minimal span cases resolve $\langle \overline{U} \rangle$ until $x_3^+ \sim 160$

Smaller values of C_o lead to larger mean flow drag

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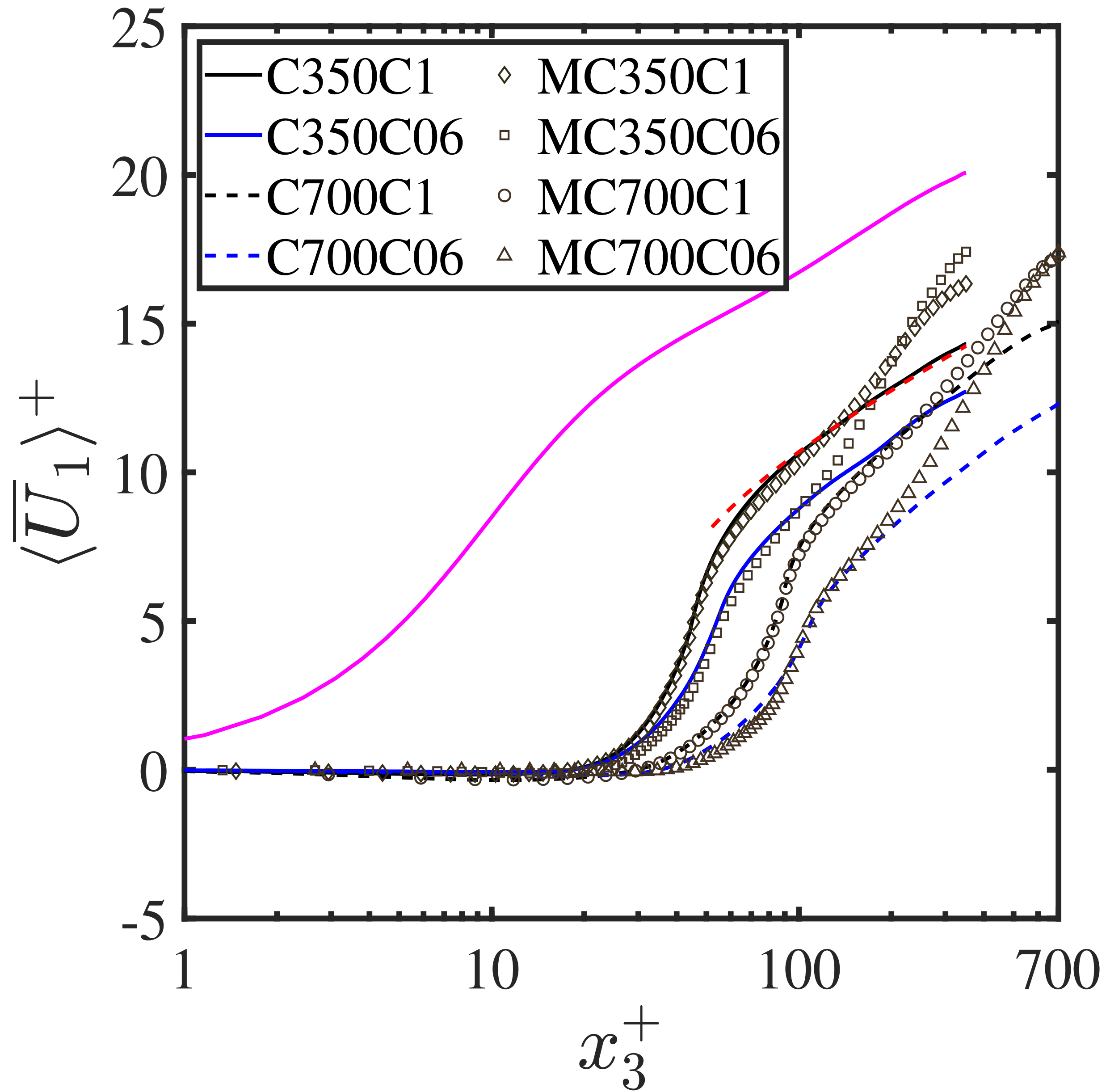

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Smaller values of C_o lead to larger mean flow drag

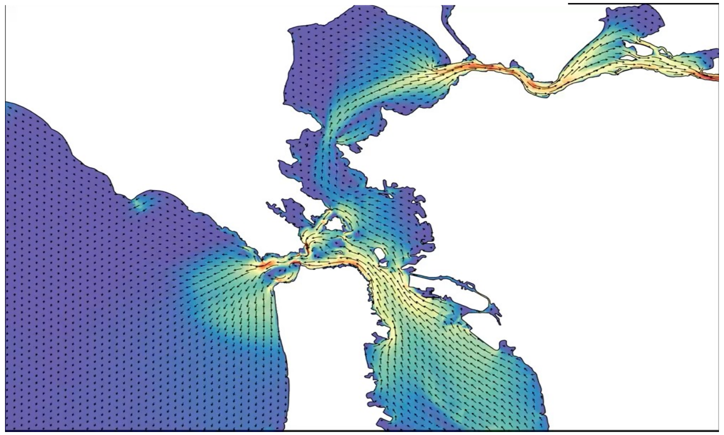
WHY?

- Relatively taller roughness elements
- Expect larger flow separation
- Larger form drag!

Patil & Fringer (2023) – Journal of Hydraulic Engineering

Wave-Current-Roughness interactions

Source: R. C. Holleman (Youtube)



Source: Egan et al. (2019)

Wave-Current-Roughness Interactions

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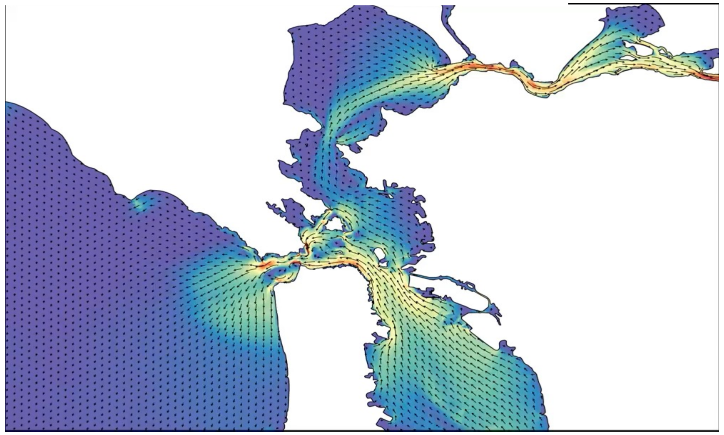

Source: Egan et al. (2019)

- Tidal Currents (~ hours)
- Oscillatory Wave Motion (~ seconds)
- Turbulence (< seconds)

Because we all love non-dimensional numbers!

Bottom Stress*	Current Velocity	Wave Orbital Velocity	Kinematic Viscosity	Wave Period	Roughness Height	Channel Height
τ	U_c	U_b	ν	T_w	$\bar{k}_s$	H

Because we all love non-dimensional numbers!

Bottom Stress*	Current Velocity	Wave Orbital Velocity	Kinematic Viscosity	Wave Period	Roughness Height	Channel Height
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$\frac{U_b}{U_c}$ - Flow Dominance

$\frac{U_c T_w}{\bar{k}_s}$ - Relative - Roughness

$\frac{U_c \bar{k}_s}{\nu}$ - Roughness Reynolds No.

$\frac{H}{\bar{k}_s}$ - Aspect Ratio

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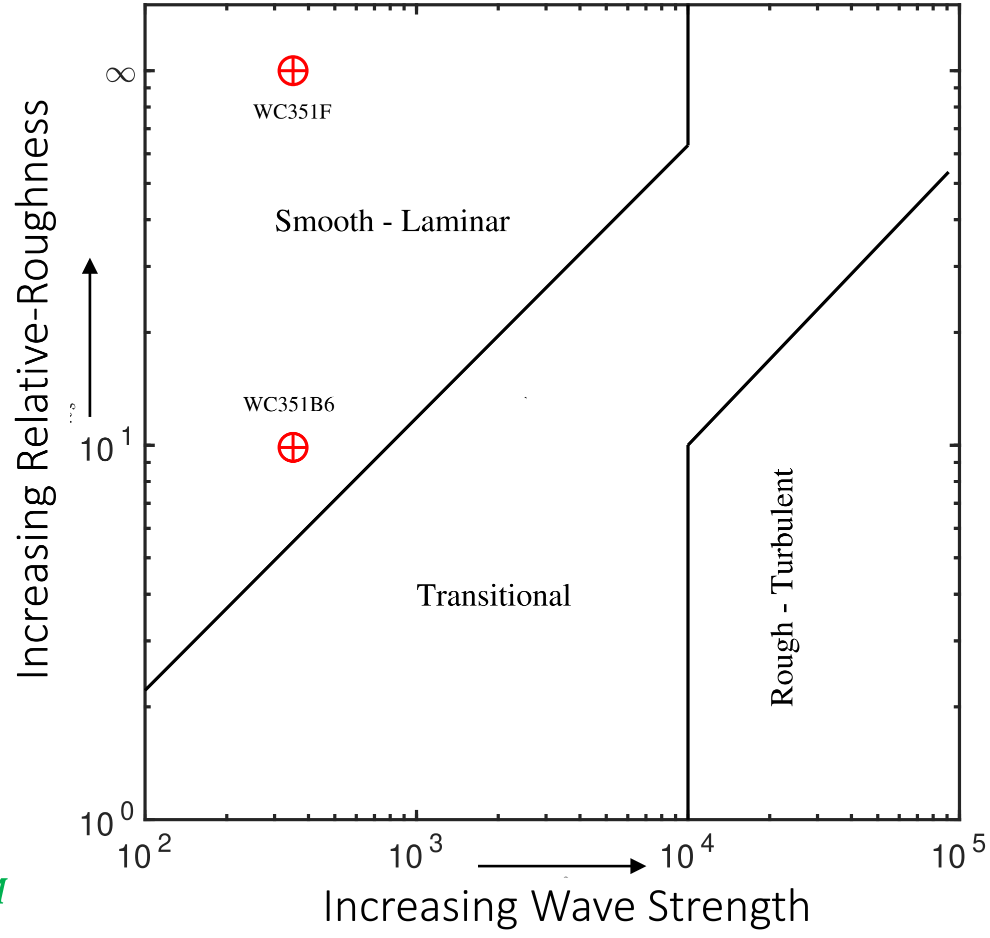
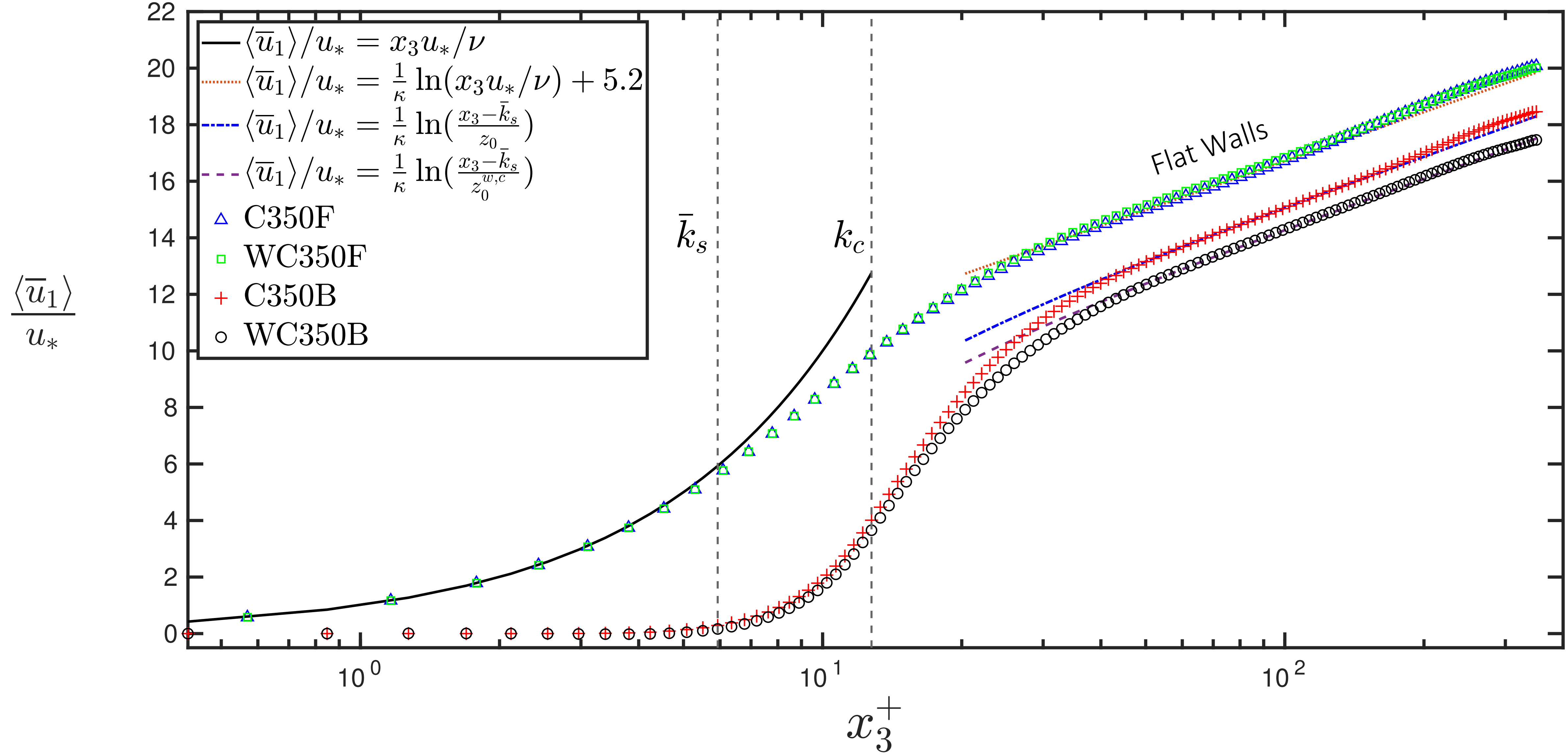
- Current dominated (Turbulent) $\left[\frac{U_b}{U_c} < 1\right]$
- Hydraulically smooth
- Laminar wave conditions



$$\partial_t u_i + \partial_j u_j u_i = -\frac{1}{\rho_0}\partial_i p + \nu \partial_j \partial_j u_i + \underbrace{\Pi_c \delta_{i1}}_{\text{Current}} + \underbrace{U_b \omega \cos(\omega t)}_{\text{Waves}} + \underbrace{F_{IBM}}_{\text{Roughness}}$$

Weak waves act to enhance the mean flow drag (or apparent roughness)



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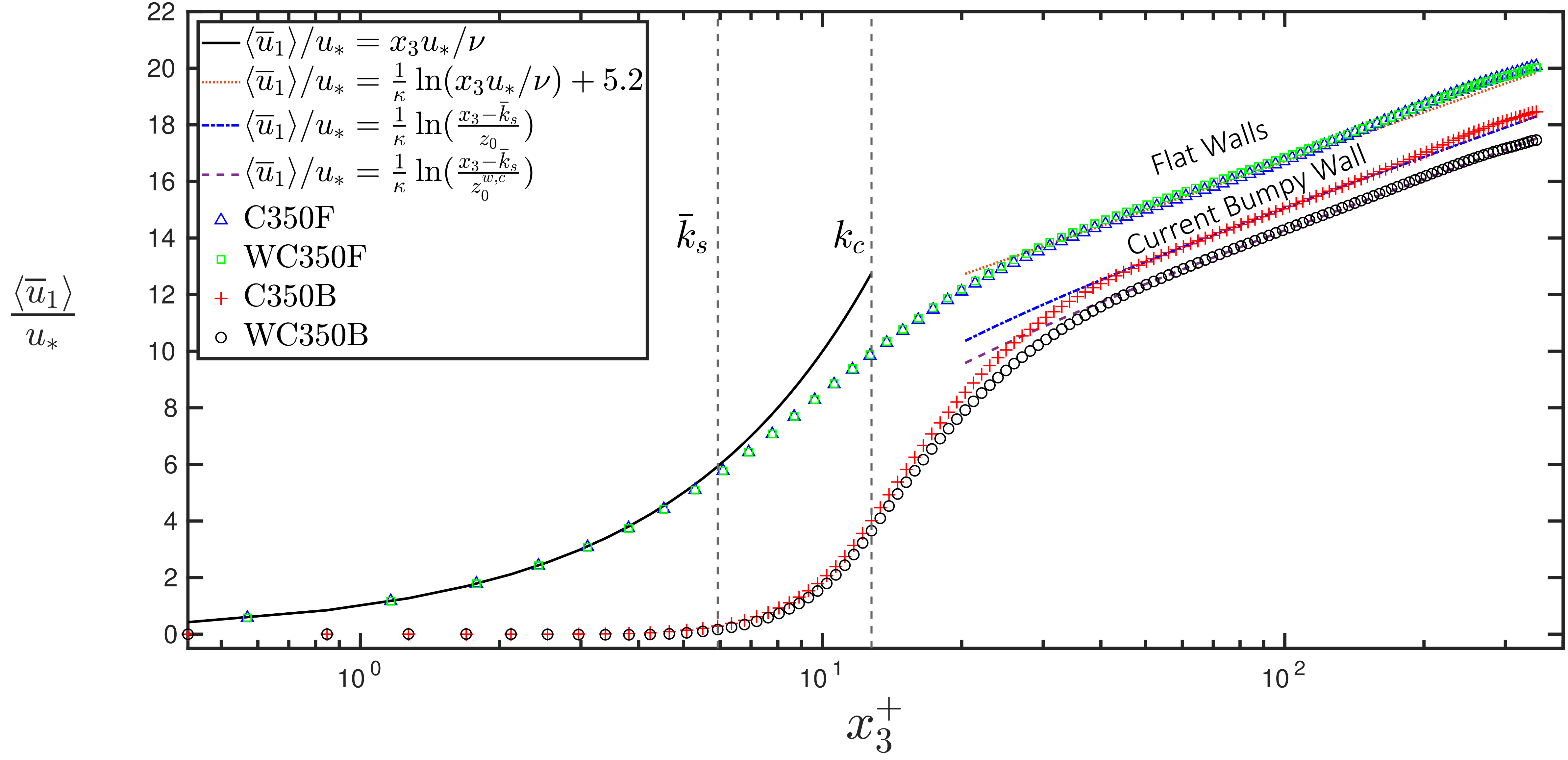

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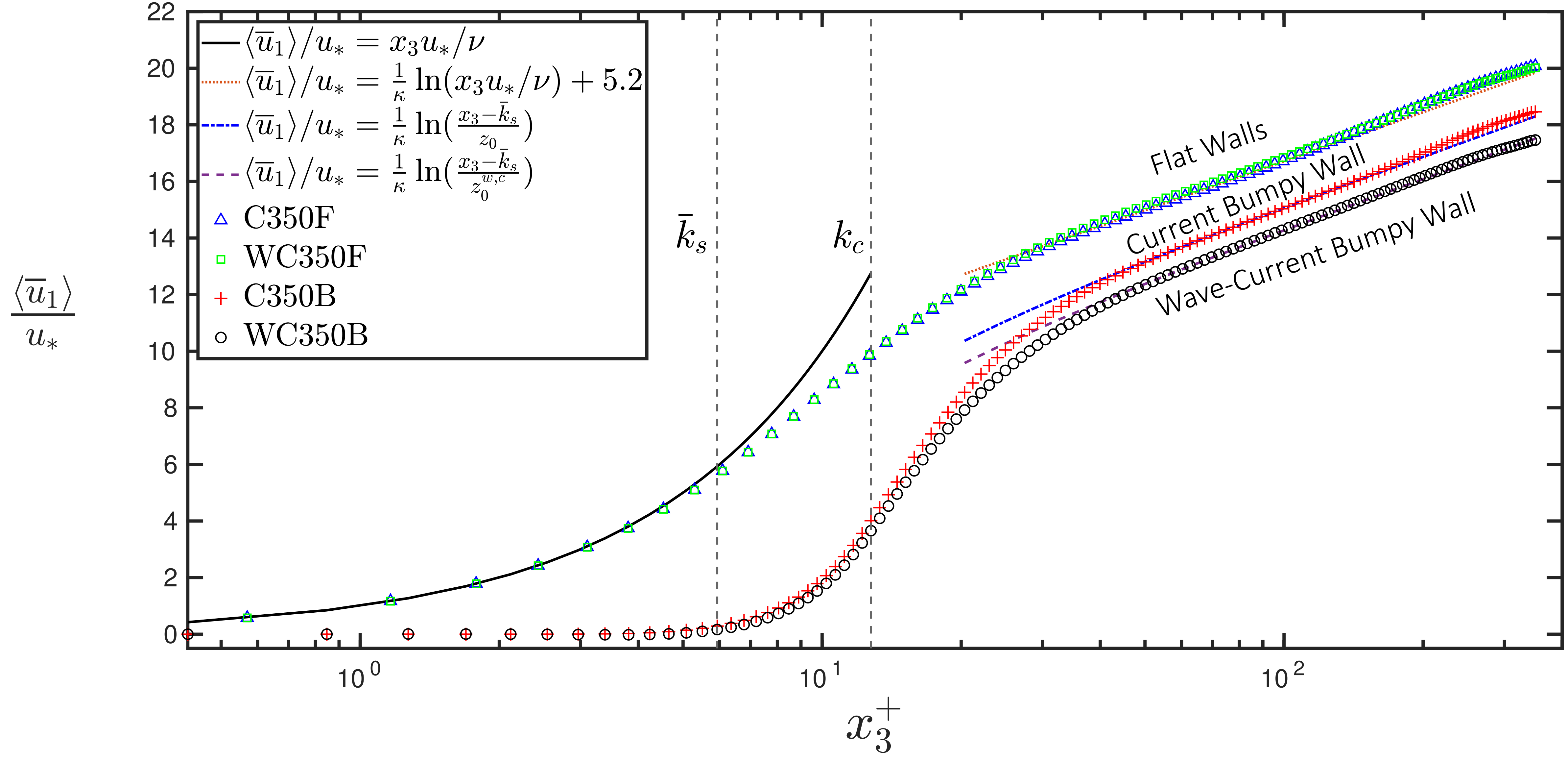

Wave-Current-Roughness Interactions

$$0 = \Pi_c + \frac{\partial \langle \bar{\tau} \rangle}{\partial x_3} + \cancel{U_b \omega \overline{\cos(\omega t)}} \quad \Rightarrow \quad \frac{\langle \bar{\tau} \rangle}{u_*^2} = 1 - \frac{x_3}{H}$$

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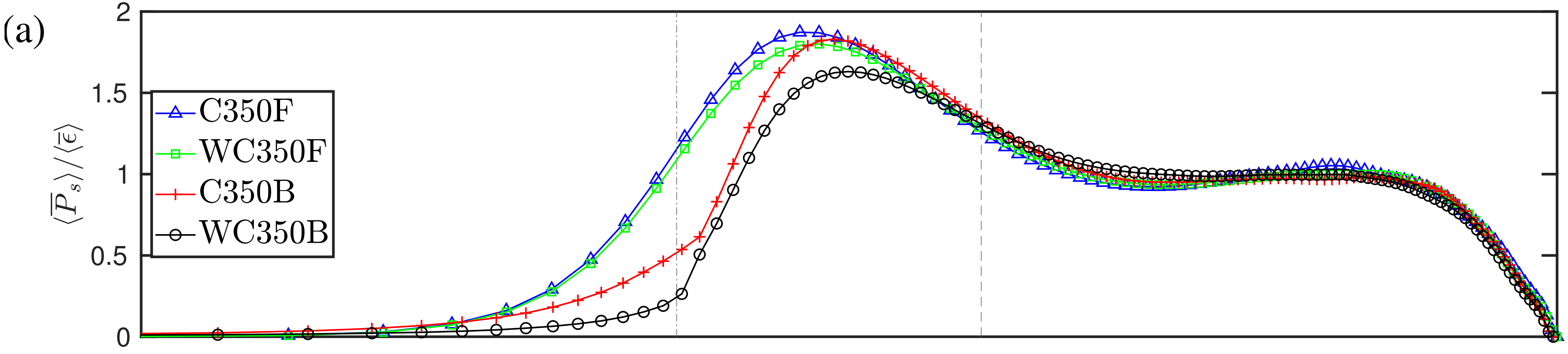

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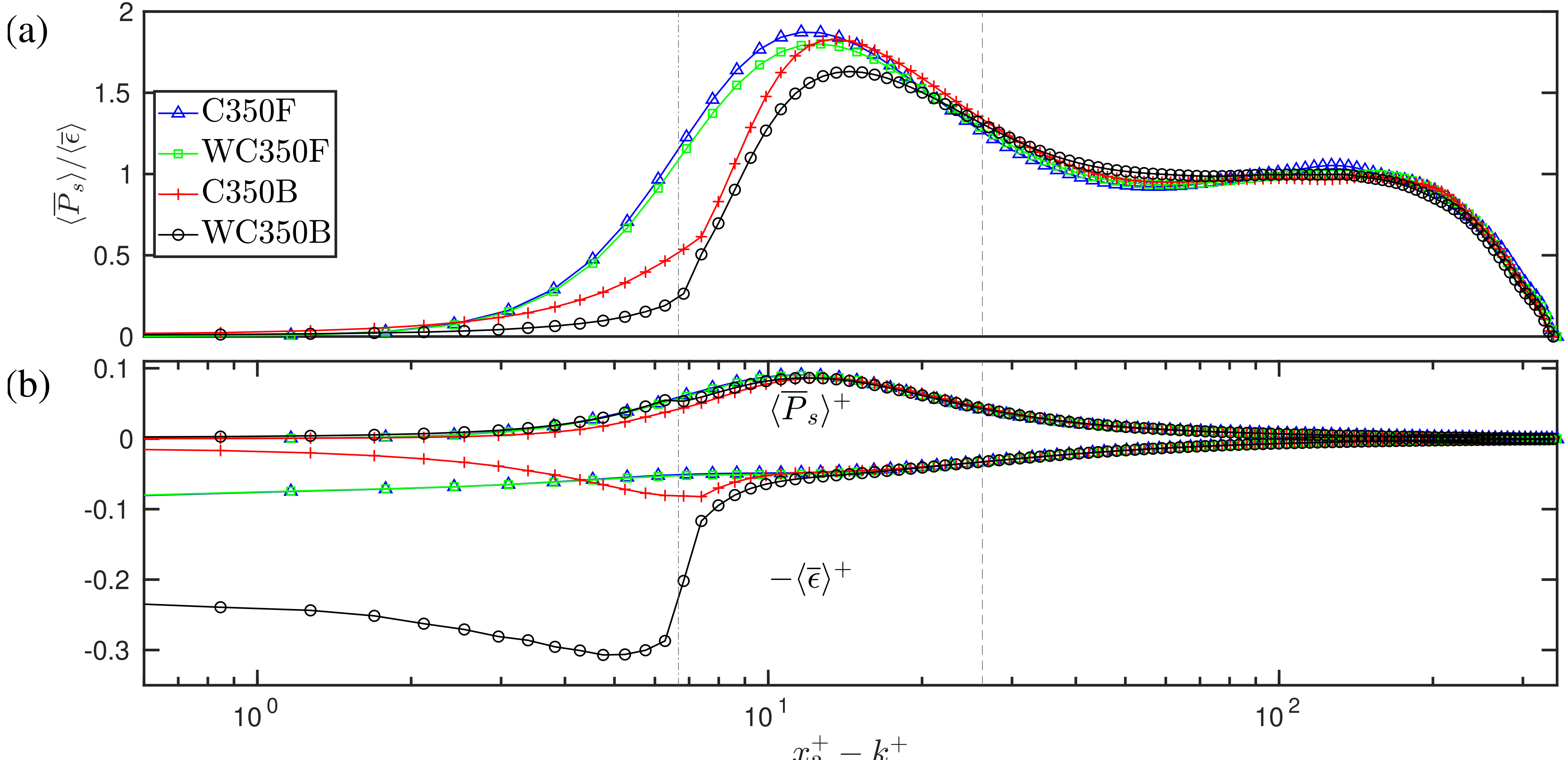

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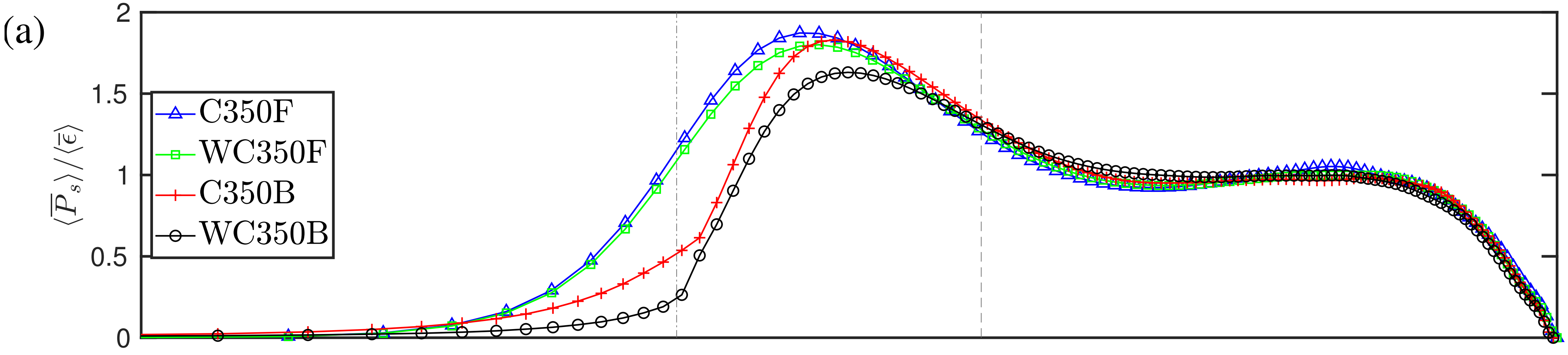

- Drag coefficient increases by 11% due to waves
- Time-averaged production/dissipation decreases
- Pressure-strain correlations play a major role

Patil & Fringer (2023) – Journal of Fluid Mechanics

Wave-Coral Boundary Layers

- Coral reef systems are at risk across the world
  - Sensitive to the ecosystem they inhabit
  - Deep symbiotic connections with other aquatic and ecological components (*Lowe & Falter, 2015*)

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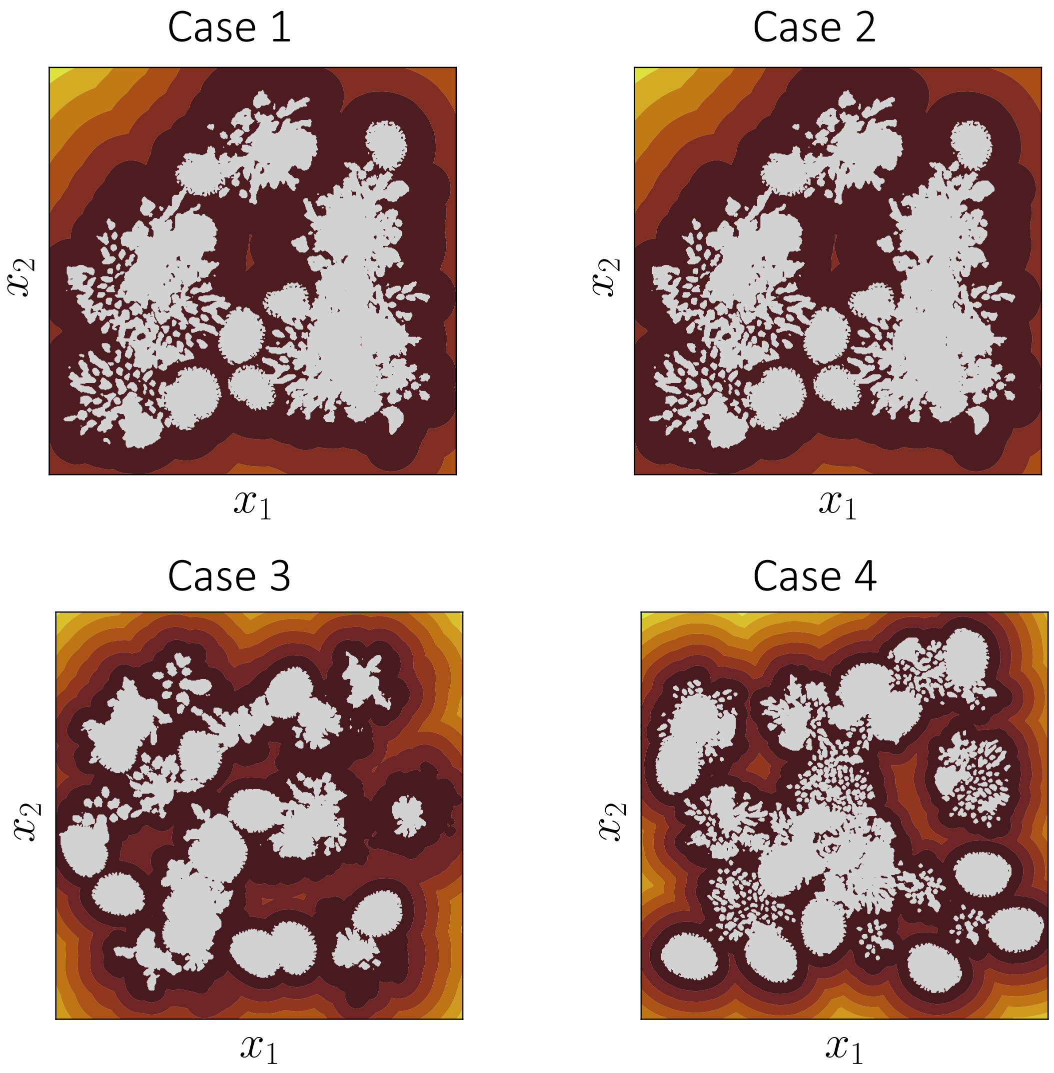

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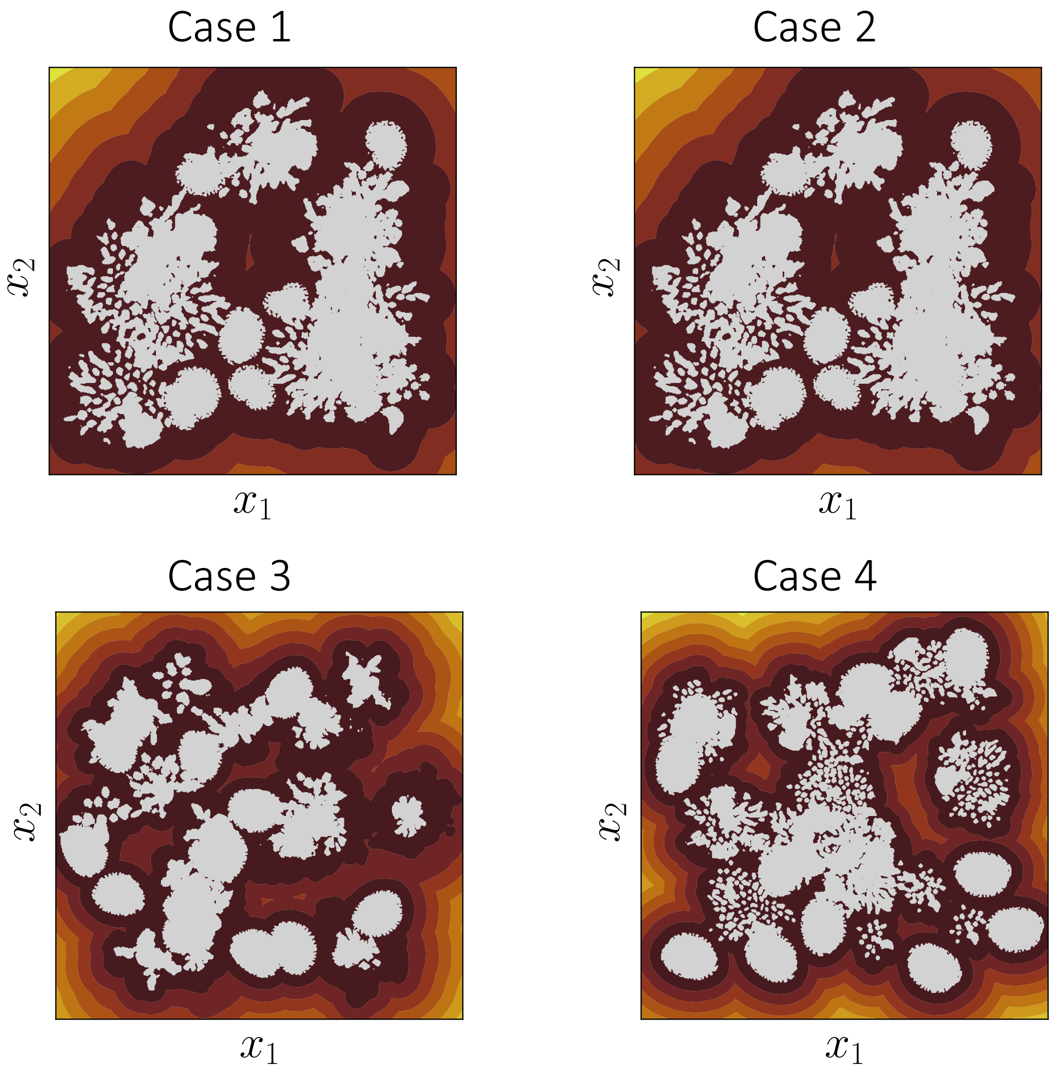

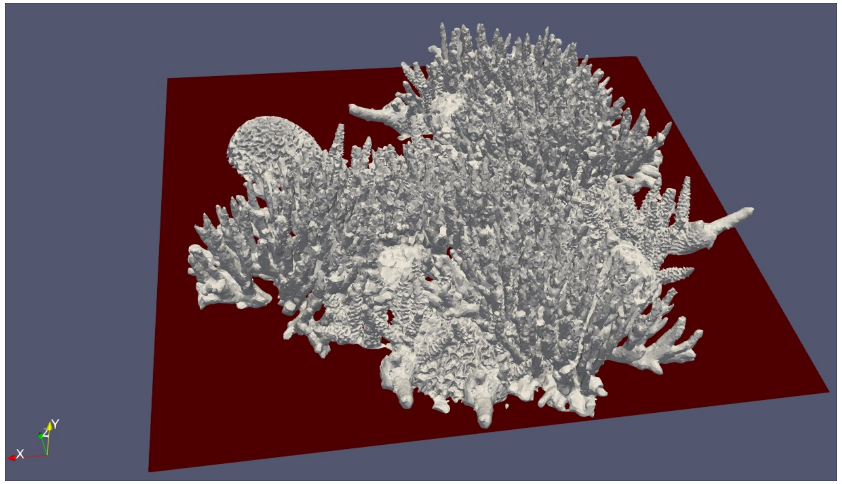

Q: How does coral morphology affect the hydrodynamic response?

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$$\partial_t u_i + \partial_j u_j u_i = -\frac{1}{\rho_0}\partial_i p + \nu \partial_j \partial_j u_i + \underbrace{U_b \omega \cos(\omega t)}_{\text{Waves}} + \underbrace{F_{IBM}}_{\text{Roughness}}$$

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Wave Velocity – Velocity scale
Wave Period – Time scale
Mean coral height – Length Scale
Ignoring the IBM force

$$\partial_t u_i + \Gamma \partial_j u_j u_i = \Gamma\left(-\partial_i p + \frac{1}{Re_b^k}\partial_j \partial_j u_i\right) + \cos(\omega t)$$

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Waves Roughness

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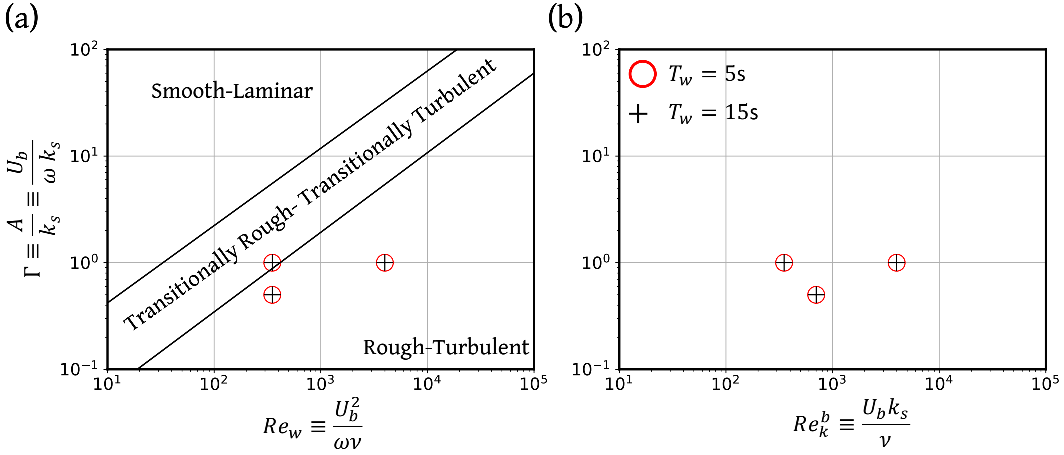
$$\Gamma = \frac{U_b}{\omega k_s} = \frac{A}{k_s}$$

$$Re_b^k = \frac{U_b k_s}{\nu}$$



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Waves

Roughness

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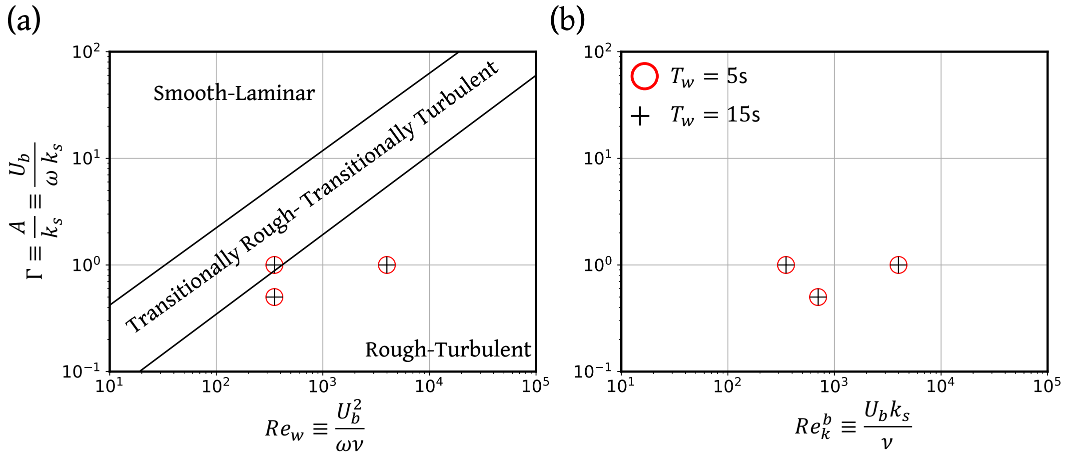
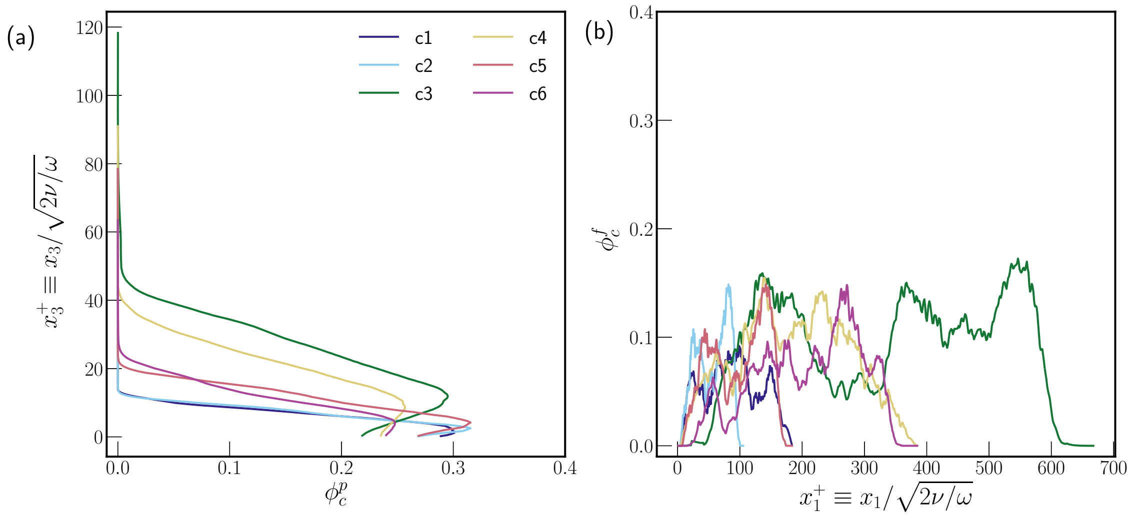
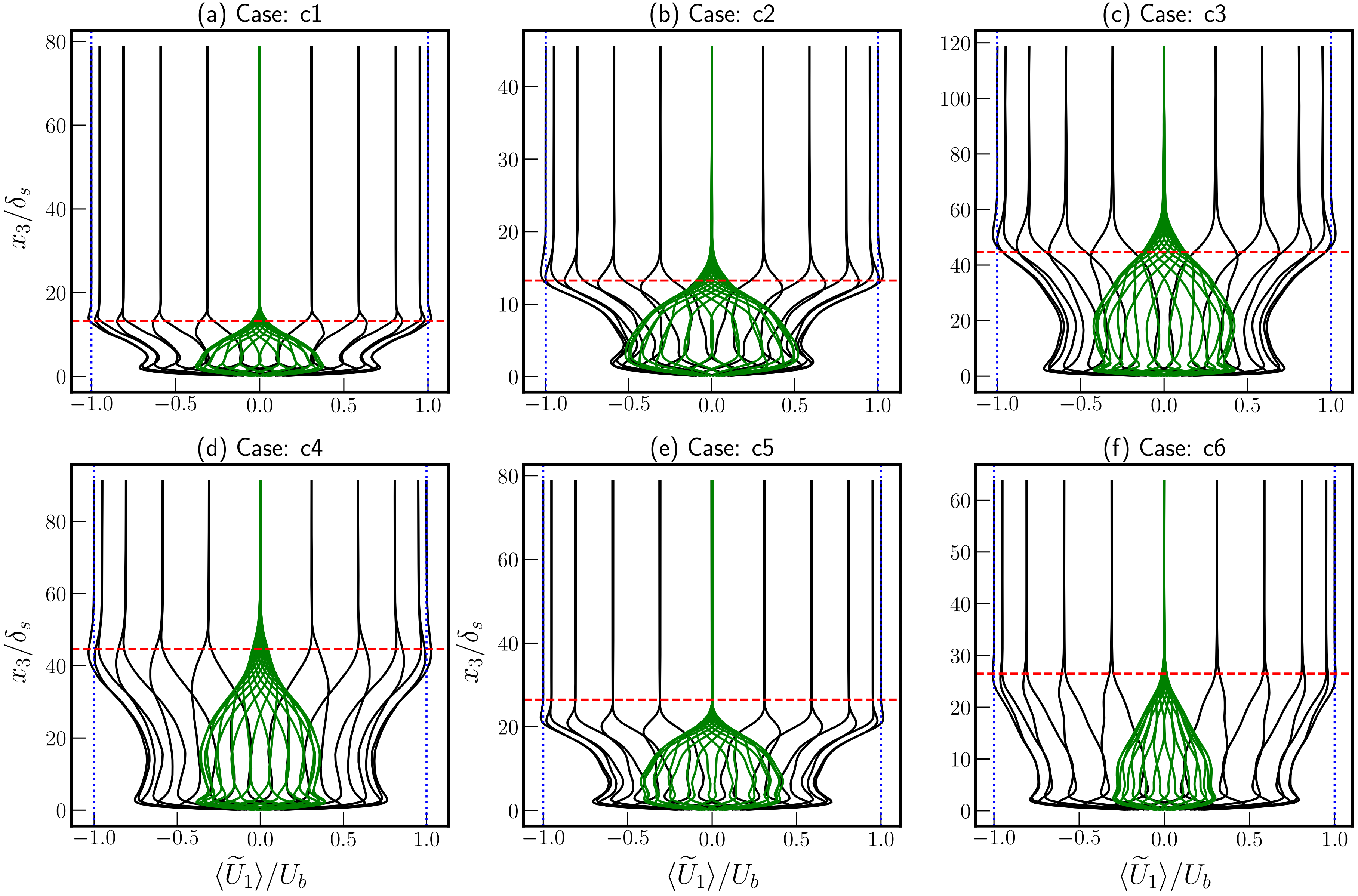
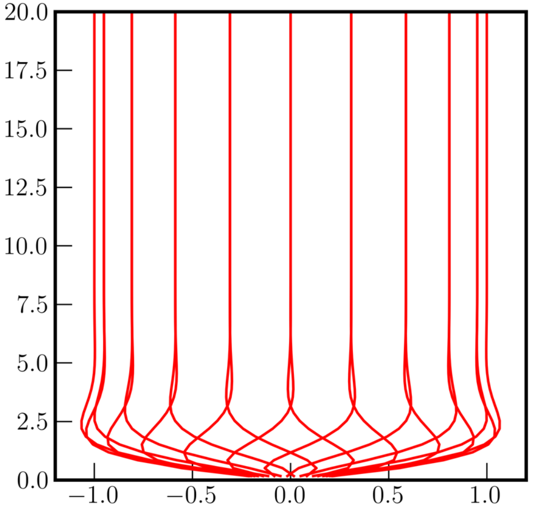




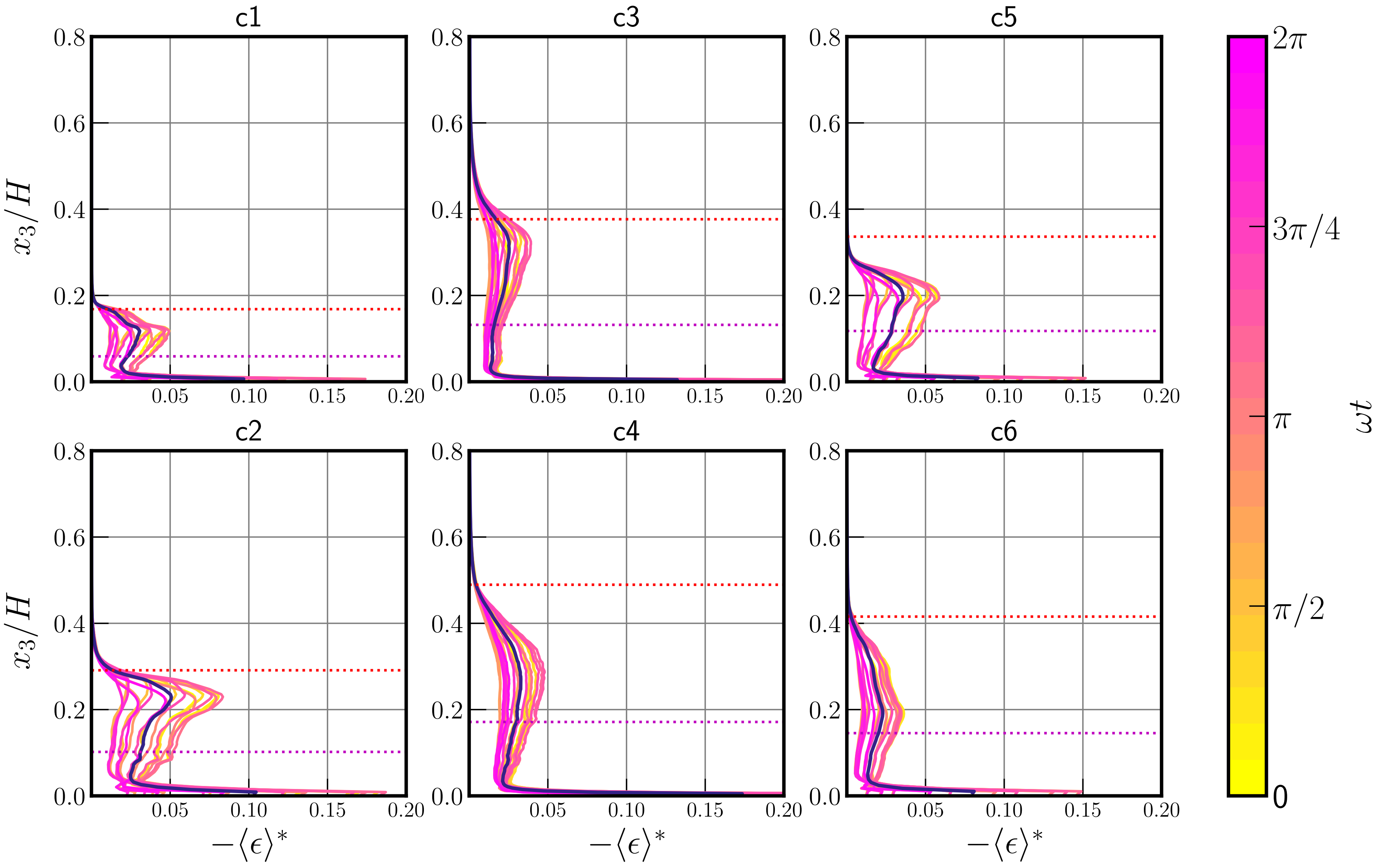
Case Name	A_c^p/A^p	A_c^f/A^f
c1	0.4456	0.2850
c2	0.5250	0.4273
c3	0.4638	0.6100
c4	0.4655	0.5764
c5	0.5250	0.4303
c6	0.4207	0.6235



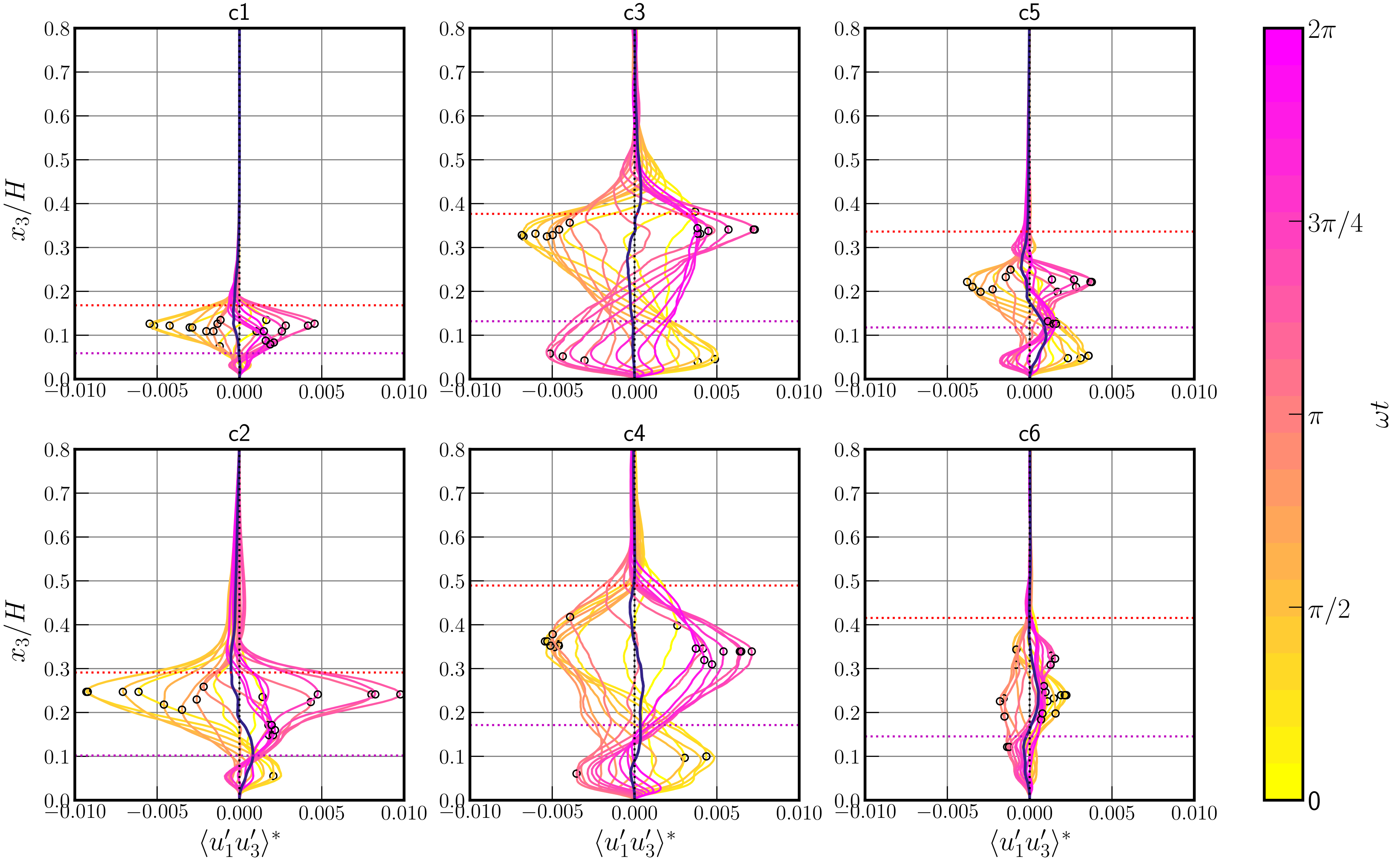
Green Data = Red - Black



- All the TKE dissipation occurs within the canopy region
  - Forward and backwards phases are symmetric



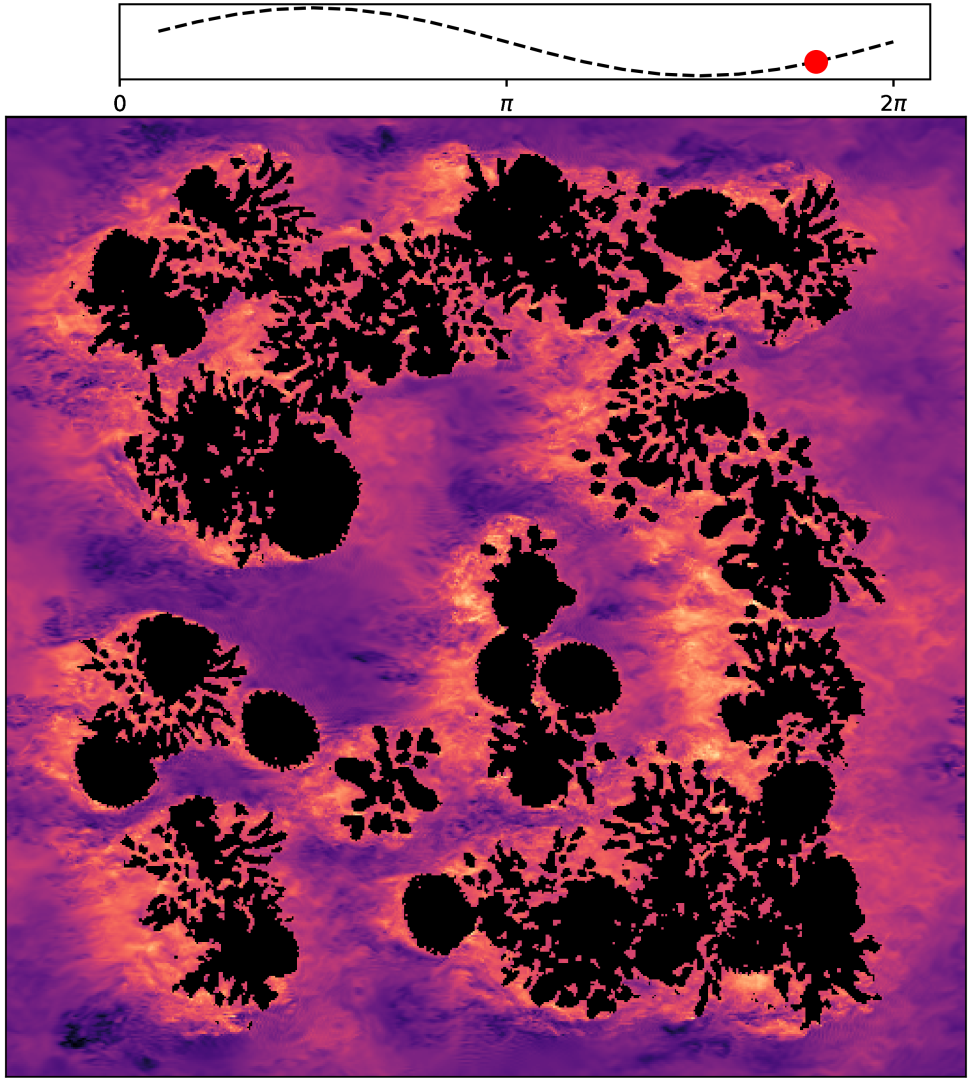
Reynolds stress



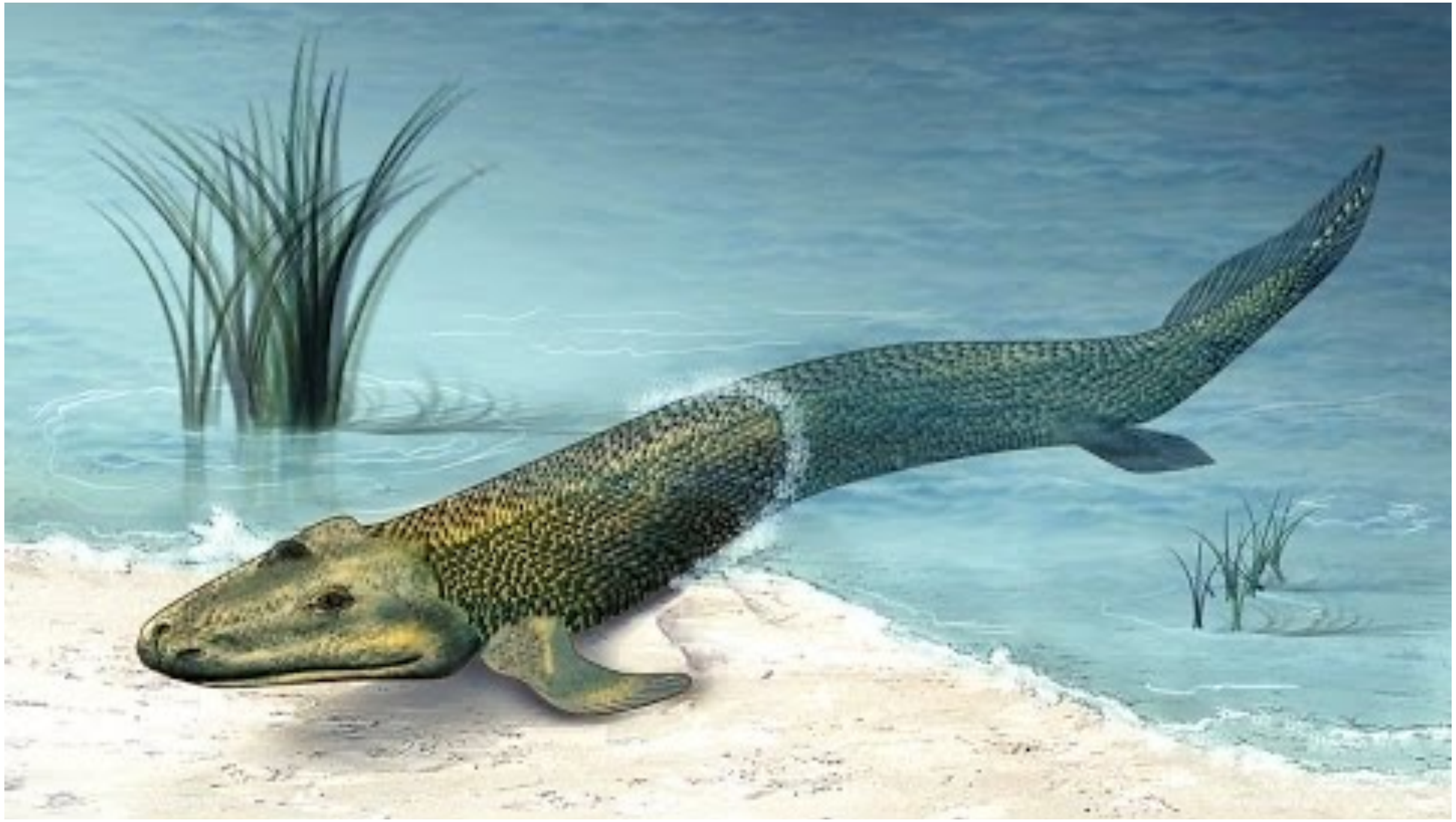
KEY POINTS

- Identical response at the small scales
- Weak correlation between coral morphology and flow response
- Computational framework can resolve the roughness and turbulence!

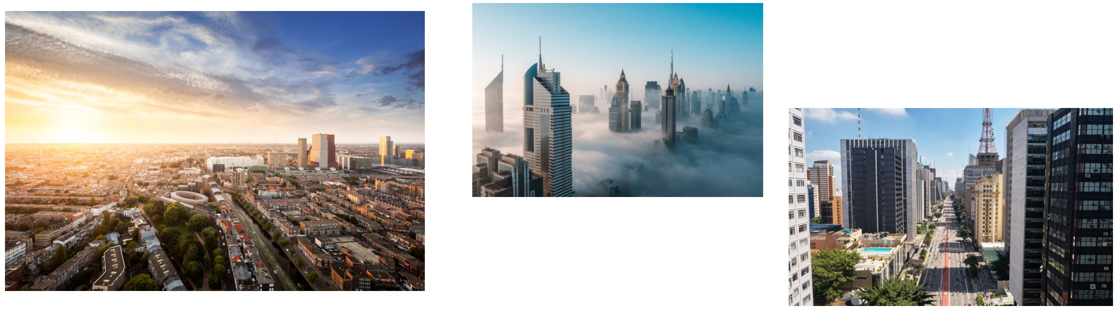
In Review
Patil & Garcia-Sanchez (2024?) – Journal of Geophysical Research: Oceans



First attempt at Evolution?



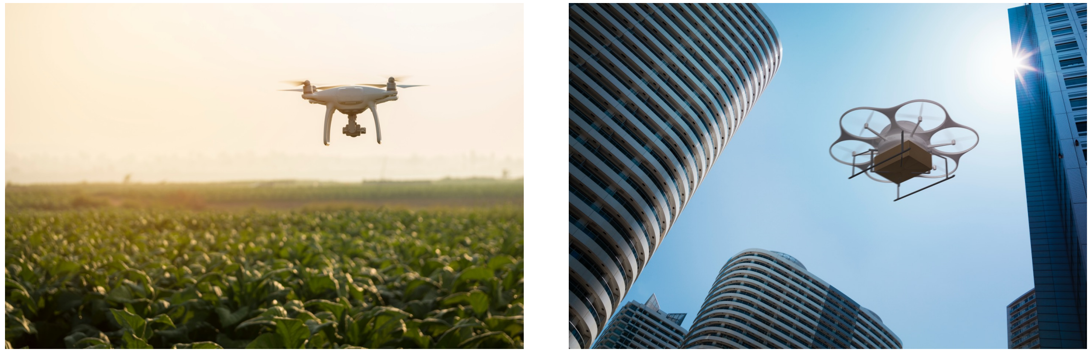
Impact of Geometry – Urban Fluid Dynamics



- Car-centric built environment
  - SO_x & NO_x concentration worsen (*Wolf et al. 2020*)
- EU Response: Lower CO_2 acceptable limits (*Fit for 55, Council of the EU 28/03/2023*)
- Vertical extensions – Wind loading concern

Potential (Partial) Solution?

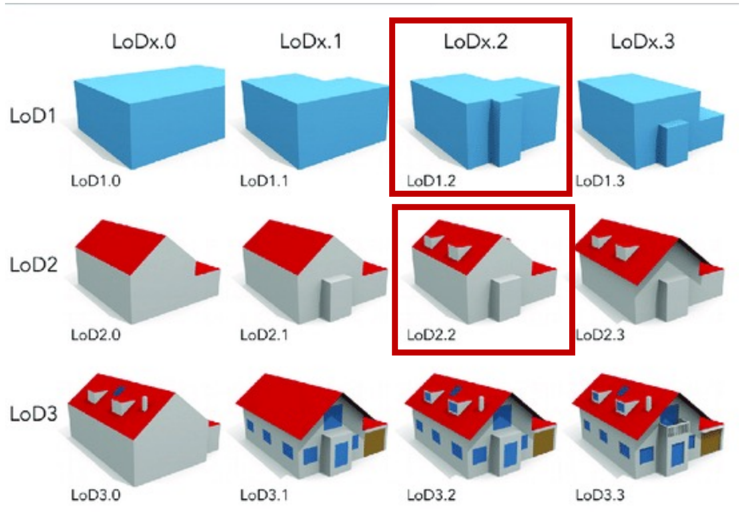
UAV’s as alternatives to last-mile transit (*Elsayed & Mohamed, 2020; Lemardelé et al. 2021; Cui et al., 2024*)



Impact of Geometry

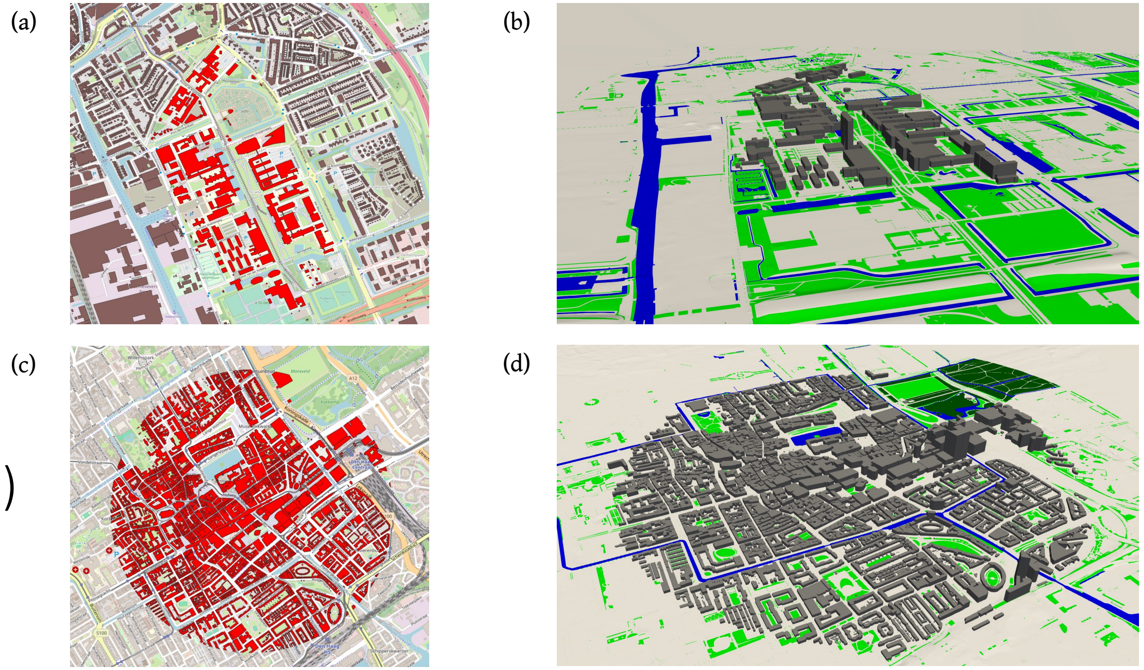
Steady-State RANS equations – Finite Volume + SIMPLE

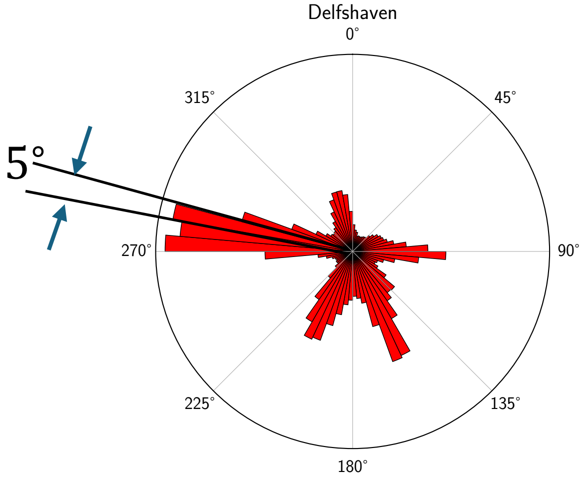
- Two equation closure (K-Epsilon)
- Best Practice Guidelines for mesh design (*Franke et al., 2011; Blocken, 2015*)



TU Delft Campus

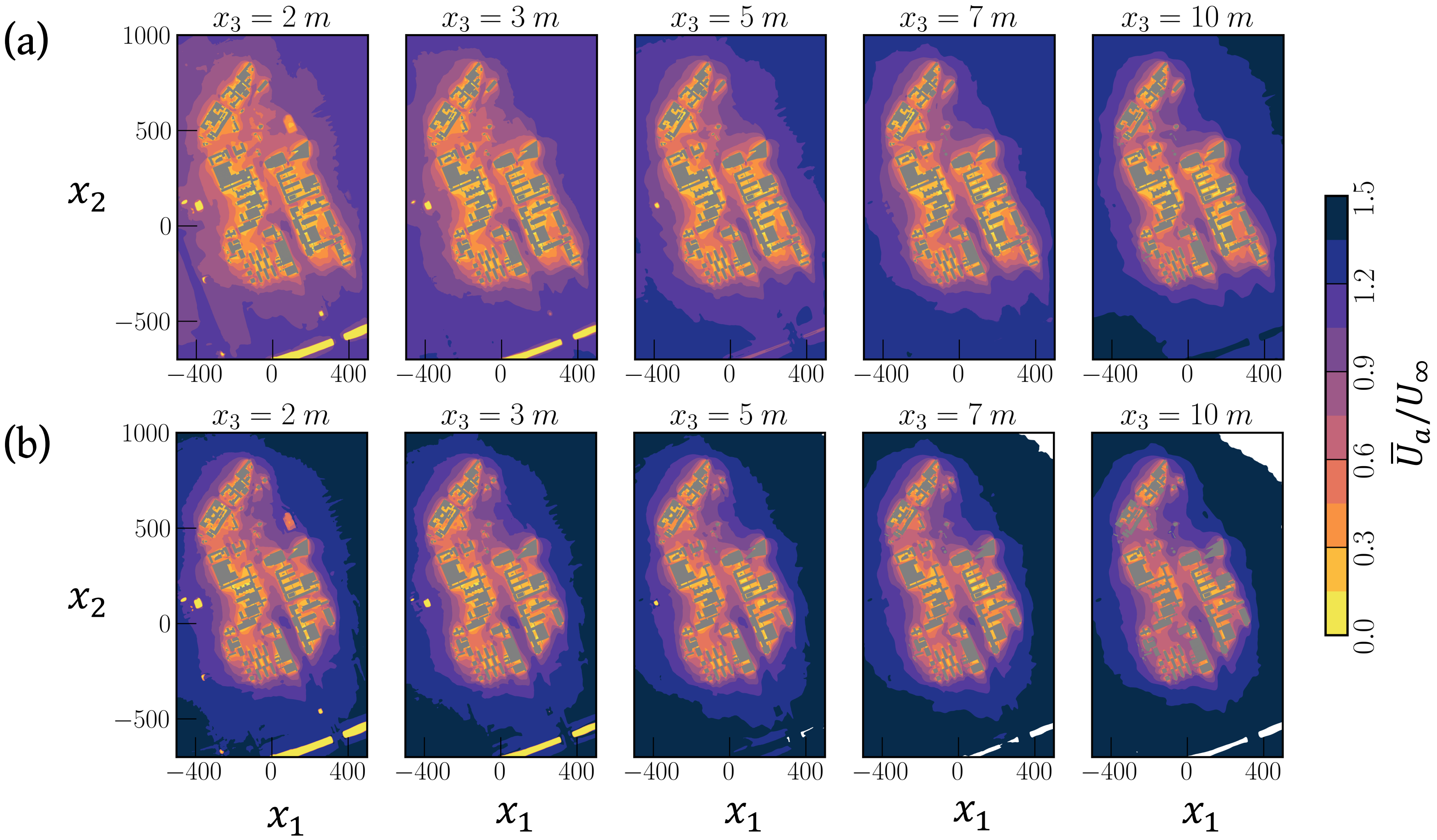
Den Haag (The Hauge)





Case: TU Delft campus

$$\overline{U_a} = \frac{1}{N_\theta} \Sigma_{i=1}^{i=N_\theta} w_i |U_i|$$



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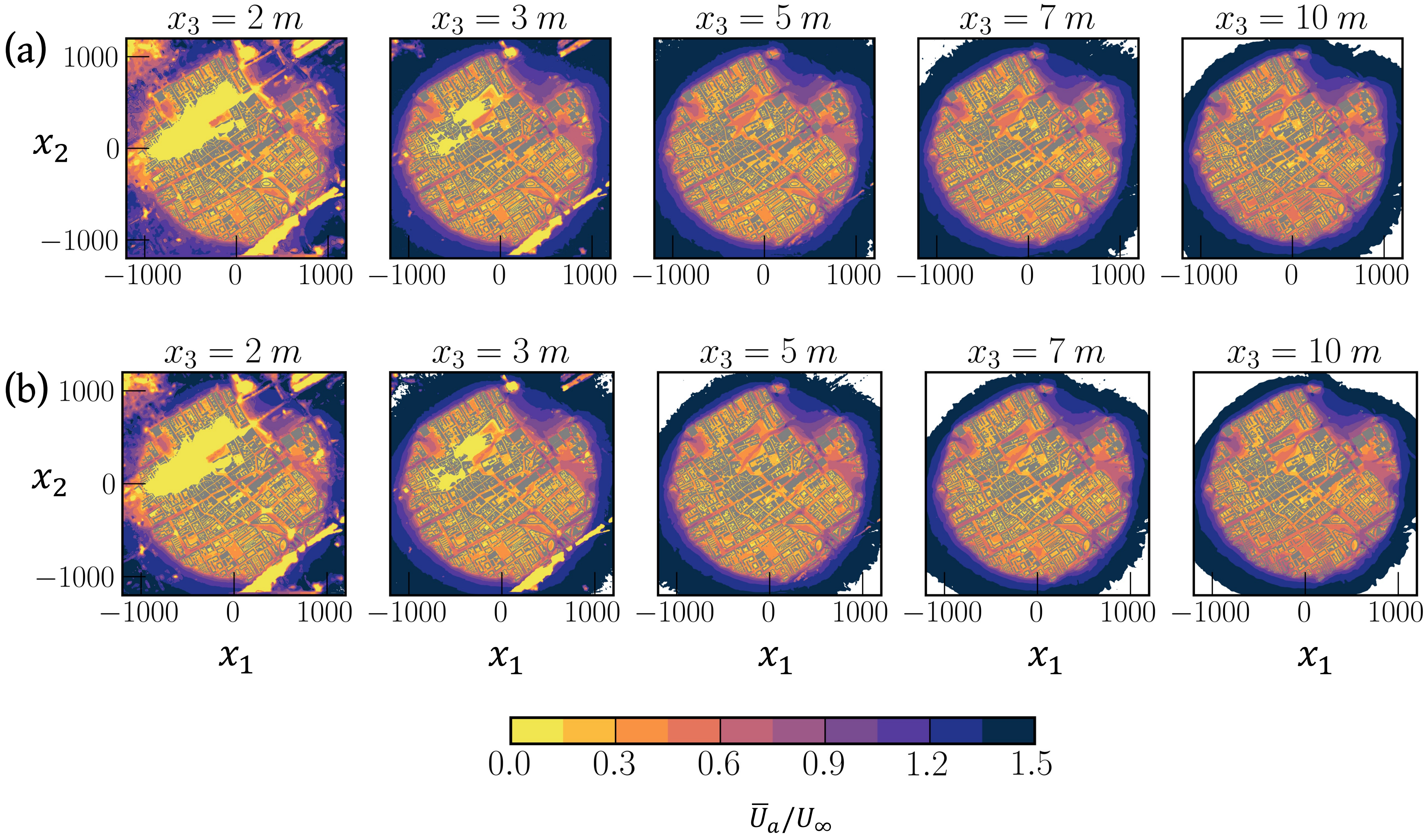
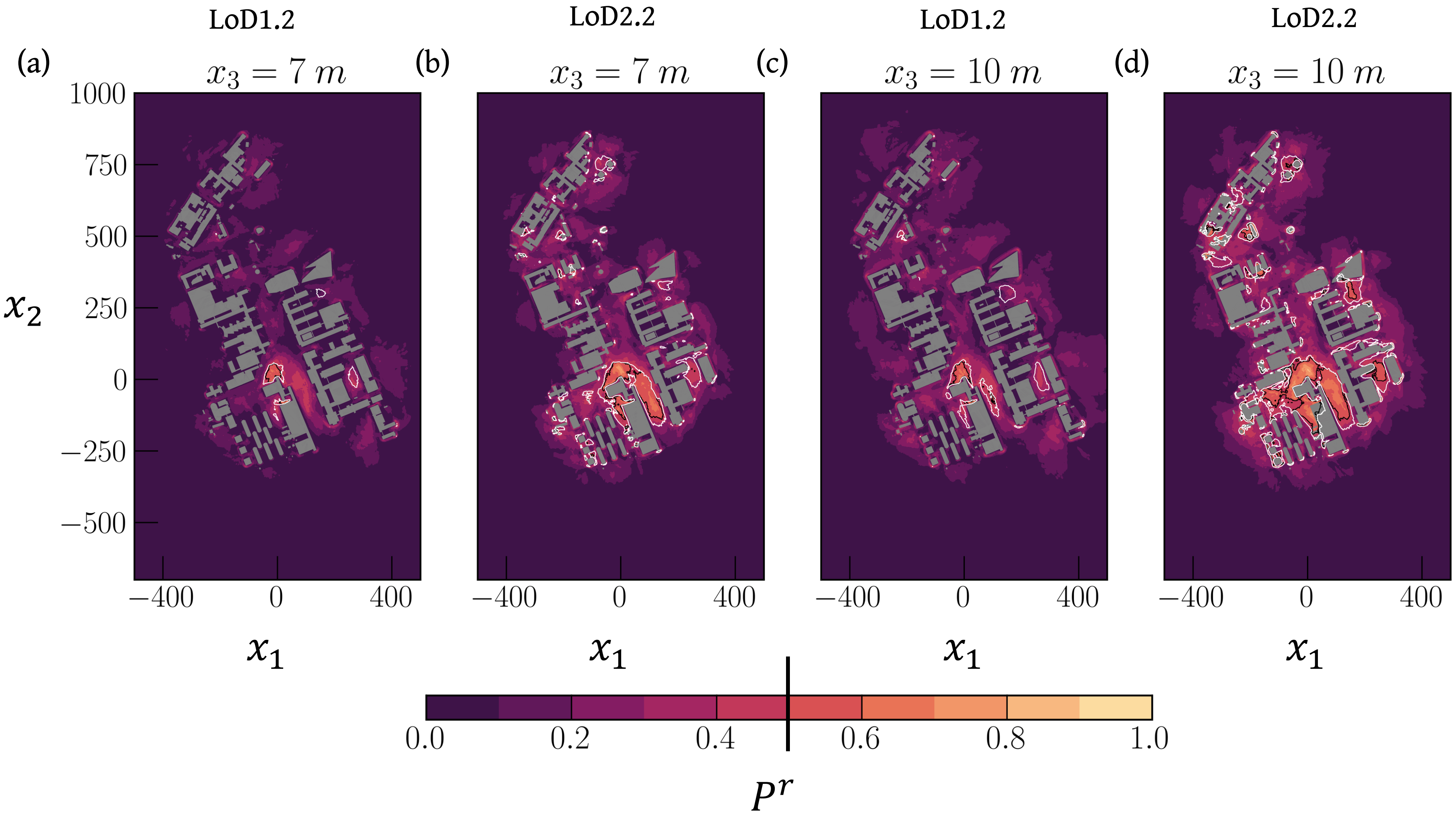


Case: TU Delft campus

$$P_r \equiv P(U^* > \alpha \;\cap k^* > \beta)$$

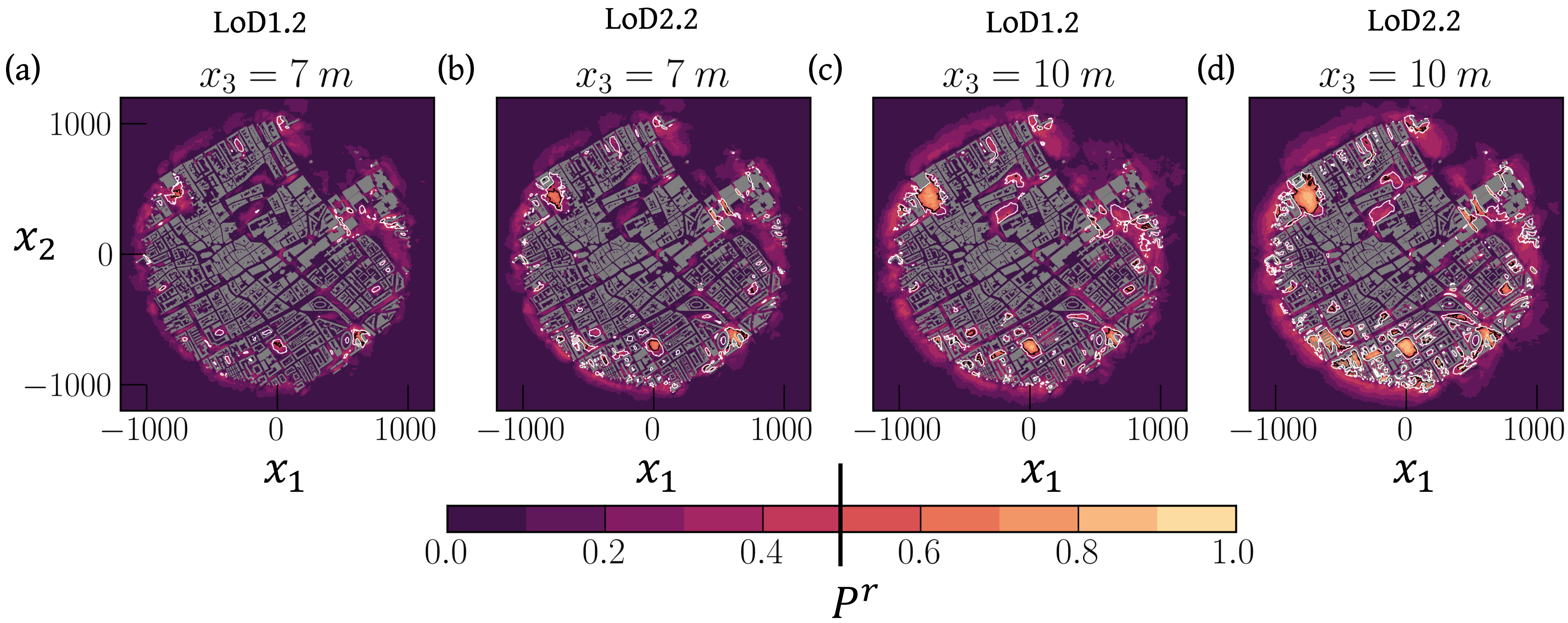
$$U^* = \frac{|U_i|}{U_\infty}$$

$$k^* = \frac{k}{U_\infty^2}$$



Case: Den Haag (The Hauge)

$$P_r \equiv P(U^* > \alpha \ \cap k^* > \beta) \qquad U^* = \frac{|U_i|}{U_\infty} \qquad k^* = \frac{k}{U_\infty^2}$$

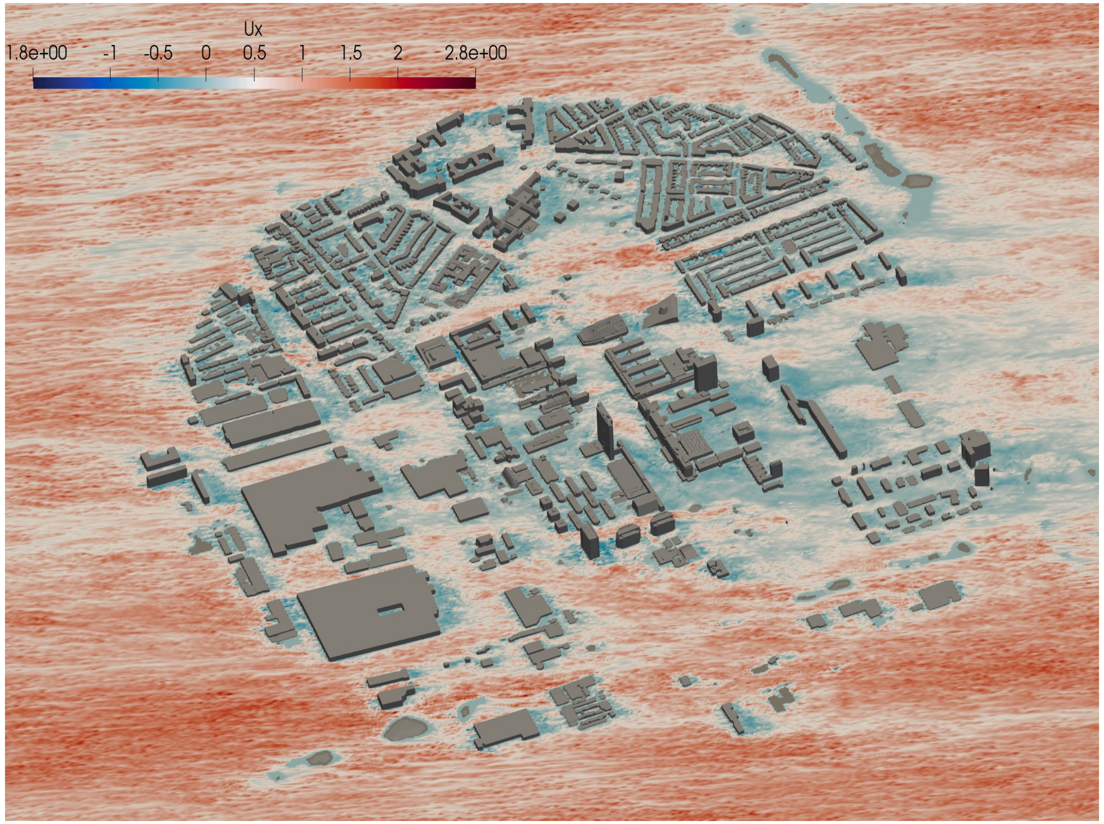


Future Vision

- The Level of Detail (LoD) has a large effect on the hydrodynamic response
  - Industry-standard LoD 1.2 massively underpredicts the risk
  - Average velocity is not a good metric for comparison
- Angular resolution can introduce systematic bias

Future Work

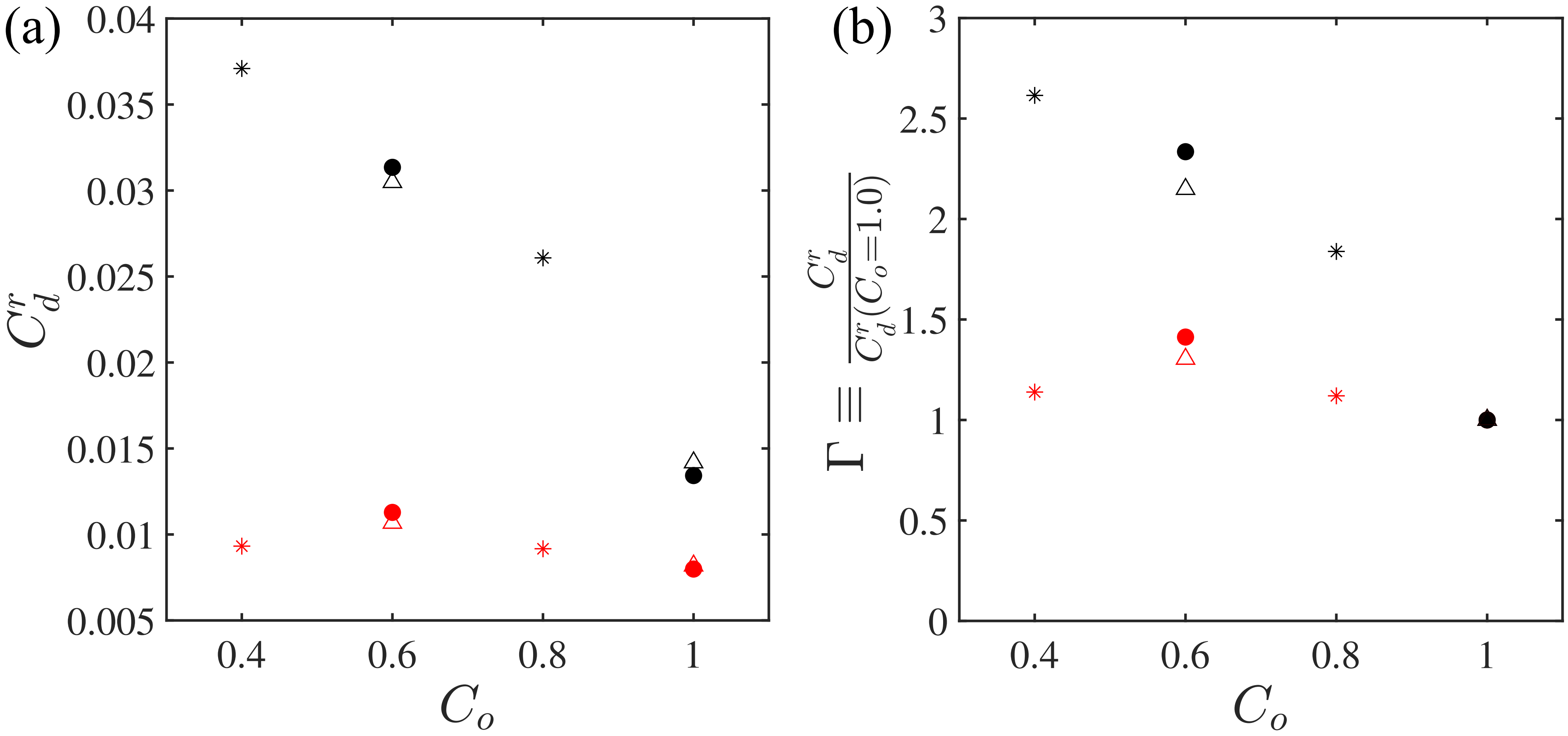
- Baseline 1-degree resolution dataset for validity checks
- Multi-fidelity method for at-scale or reduced-scale computational framework

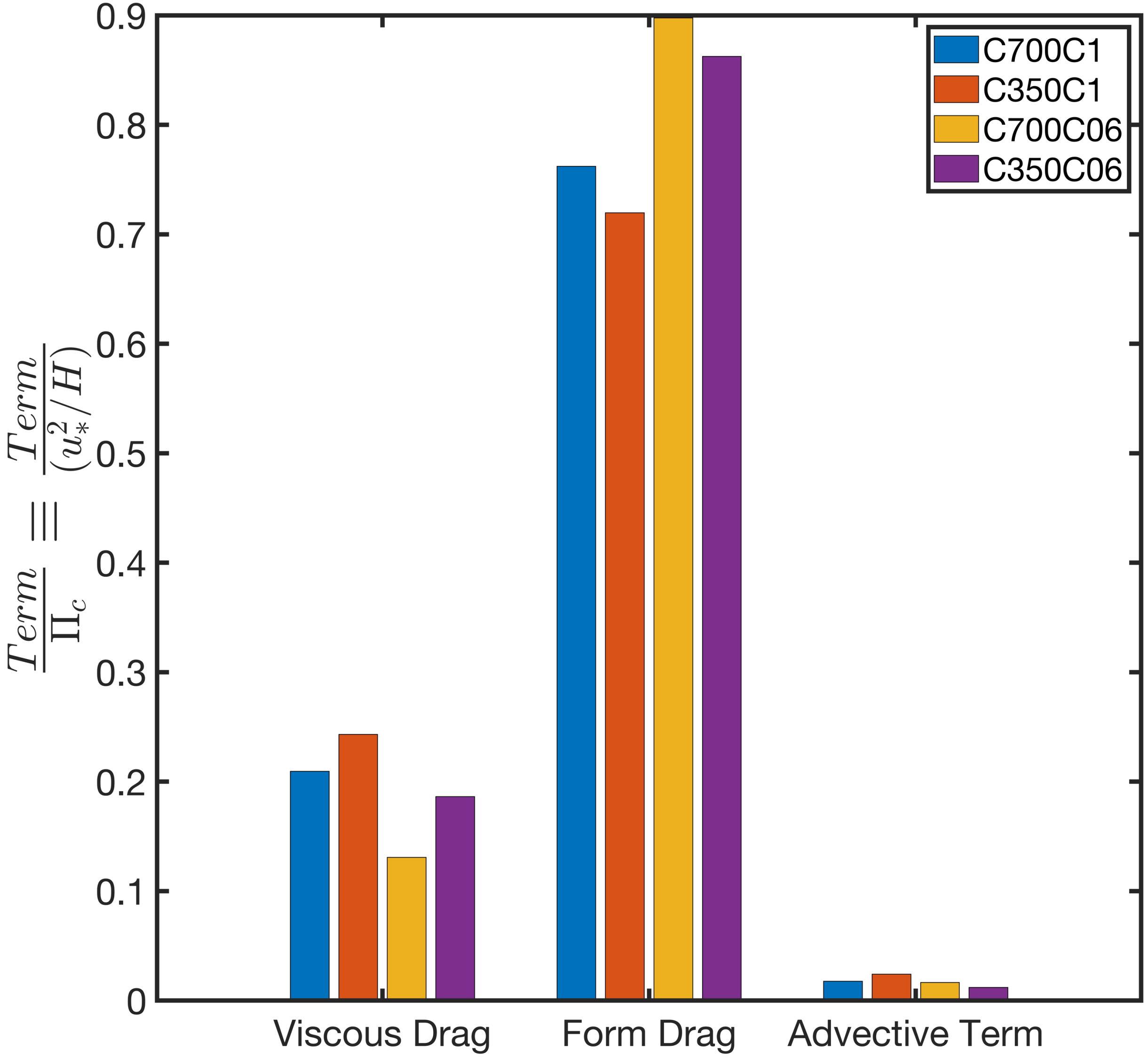


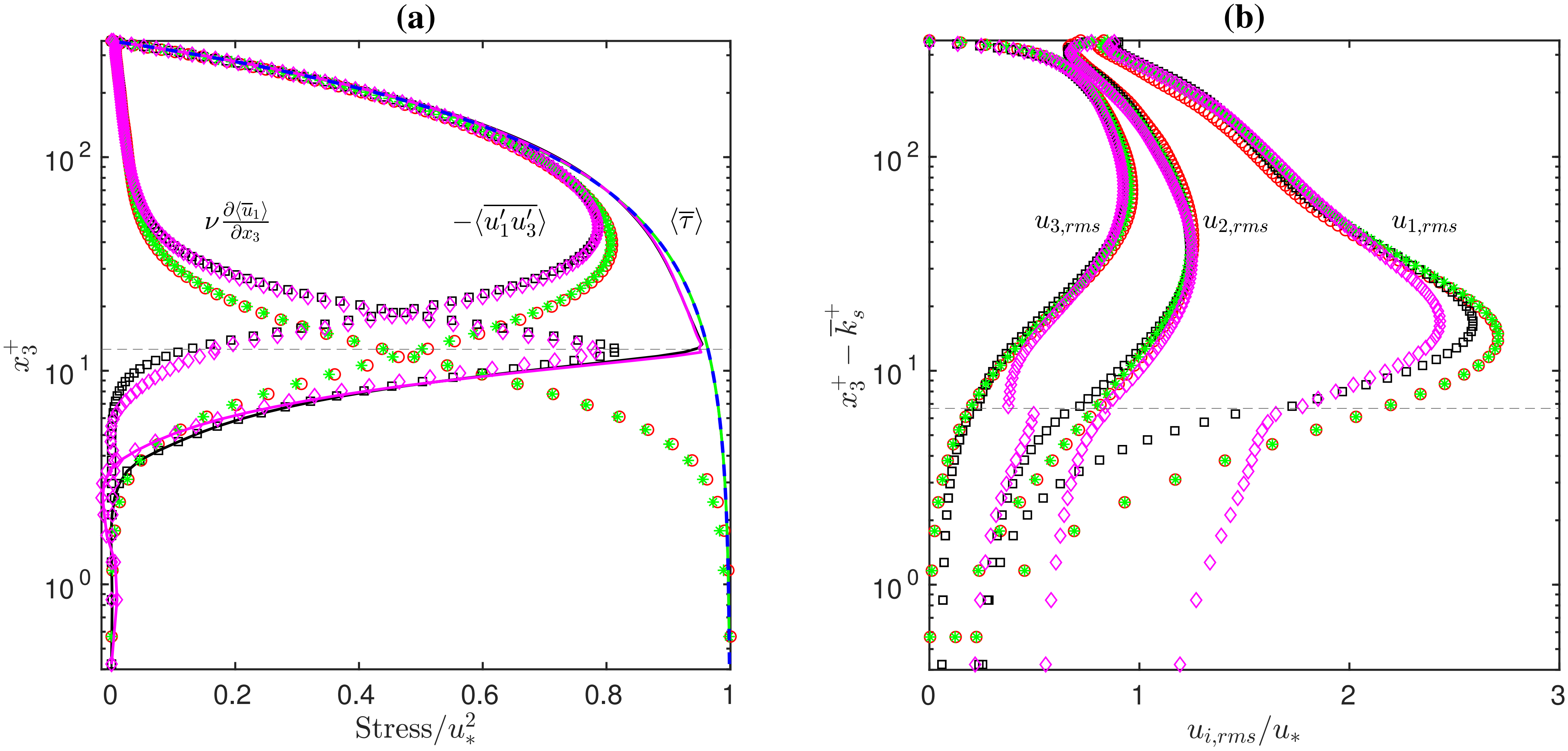
Thank you!

Extra Slides

Connecting Roughness & Flow




0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\frac{Term}{\Pi_c} \equiv \frac{Term}{(u_*^2/H)}$
Viscous Drag
Form Drag
Advective Term
C700C1
C350C1
C700C06
C350C06


(a)
(b)
$\nu \frac{\partial \langle \overline{u}_1 \rangle}{\partial x_3}$
$-\langle \overline{u_1' u_3'} \rangle$
$\langle \overline{\tau} \rangle$
x_3^+
10^2
10^1
10^0
0
0.2
0.4
0.6
0.8
1
Stress/u_*^2
$u_{3,rms}$
$u_{2,rms}$
$u_{1,rms}$
$x_3^+ - \overline{k}_s^+$
0
1
2
3
$u_{i,rms}/u_*$