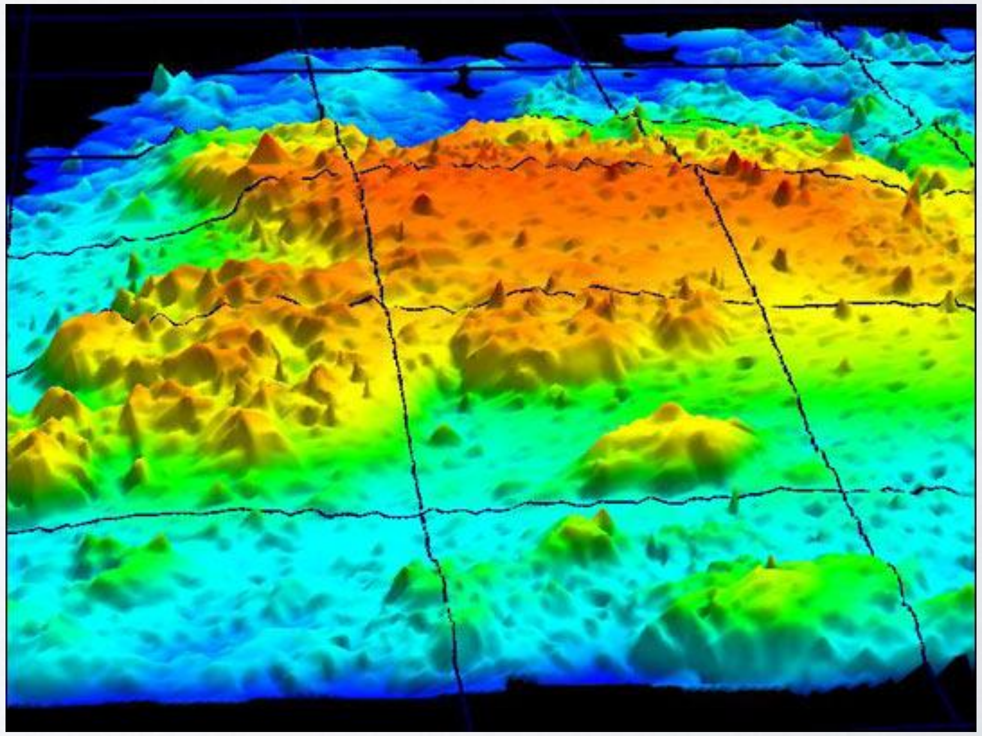
INTERACTION OF WAVES WITH IDEALIZED HIGH-RELIEF BOTTOM ROUGHNESS

Xiao Yu
Johanna H. Rosman
James L. Hench

UNIVERSITY of FLORIDA
UNC INSTITUTE OF MARINE SCIENCES
Duke NICHOLAS SCHOOL OF THE ENVIRONMENT
NSF

INTRODUCTION

- Complex topography is a common feature in many natural systems.
- In coastal environments, the flow is dominated by the oscillatory motions of waves.
- Understanding wave-topography interactions is important for predicting wave transformation, and turbulent mixing and transport.
- In large-scale coastal modeling systems, the grid resolution is much larger than scales of the topography. The small-scale physical processes need to be parameterized.
- Interactions between waves and seafloor is typically parameterized by a quadratic relation with a wave friction factor.



MODEL FRAMEWORK

- Double-Averaging framework
  - Been applied to study steady flow over vegetation and gravel bed
  - Phase-average is used as ensemble average.
  - Spatial-average over a volume that is large enough in horizontal directions to include the largest roughness elements but fine in vertical direction $u = \langle \bar{u}_w \rangle + u' + \bar{u}''_w$

$$\frac{\partial \langle \bar{u}_i \rangle}{\partial t} + \langle \bar{u}_j \rangle \frac{\partial \langle \bar{u}_i \rangle}{\partial x_j} = -\frac{1}{\rho(1-\phi)} \frac{\partial (1-\phi) \langle \bar{p} \rangle}{\partial x_i} + \frac{1}{\rho(1-\phi)} \frac{\partial (1-\phi) \tau_{ij}}{\partial x_j} - f_{Pi} - f_{Vi}$$

$$f_{P_i} = \frac{1}{\rho V_f} \int_S \bar{p} n_i dS \qquad f_{V_i} = \frac{\nu}{V_f} \int_S \frac{\partial \bar{u}_i}{\partial x_j} n_j dS$$

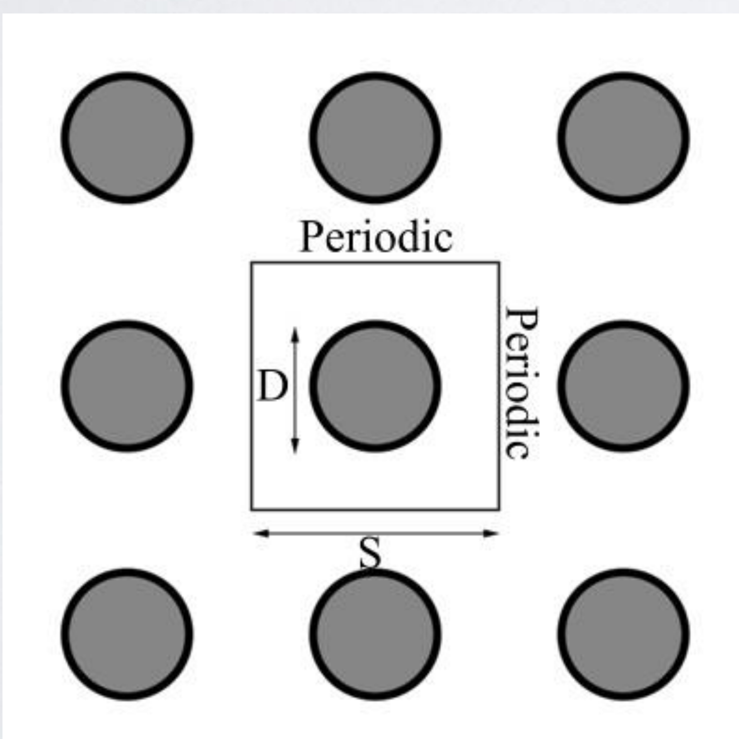
$$\tau_{ij} = -\rho \left\langle \overline{u'_i u'_j} \right\rangle - \rho \left\langle \bar{u}''_i \bar{u}''_j \right\rangle + \mu \left(\frac{\partial \langle \bar{u}_i \rangle}{\partial x_j} + \frac{\partial \langle \bar{u}_j \rangle}{\partial x_i} \right)$$

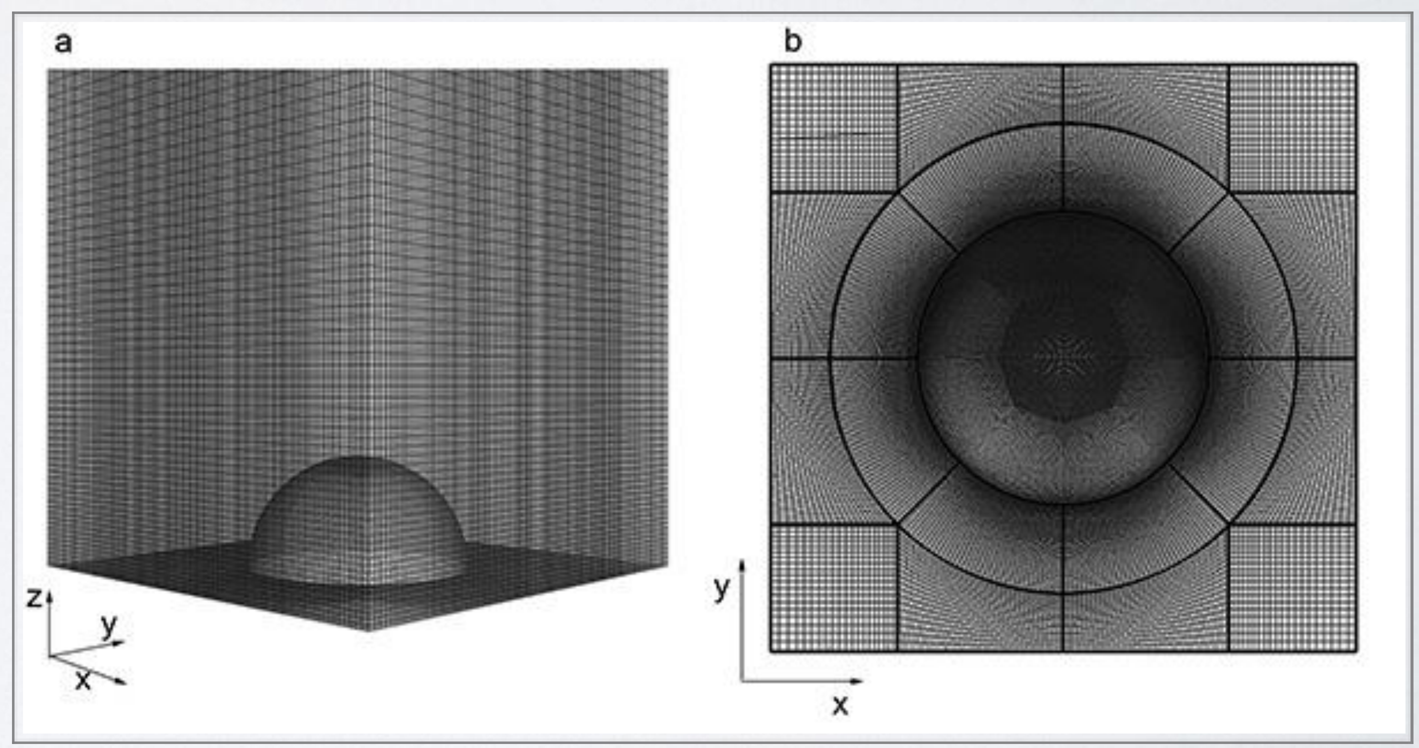
- Important Dimensionless groups

$$KC = \frac{U_\infty T}{D}, \quad \beta = \frac{D^2}{\nu T}, \quad \frac{S}{D}$$

LES MODEL SETUP

- Infinity arrays of identical evenly spaced smooth hemispheres are used as idealized bottom roughness elements. The diameter of hemispheres is 0.5 m for all cases.
- Periodic boundary conditions were implemented as both lateral boundaries.
- Large eddy Simulation with WALES subgrid closure
- Smooth wall boundary condition was applied at the surface of hemispheres with wall functions

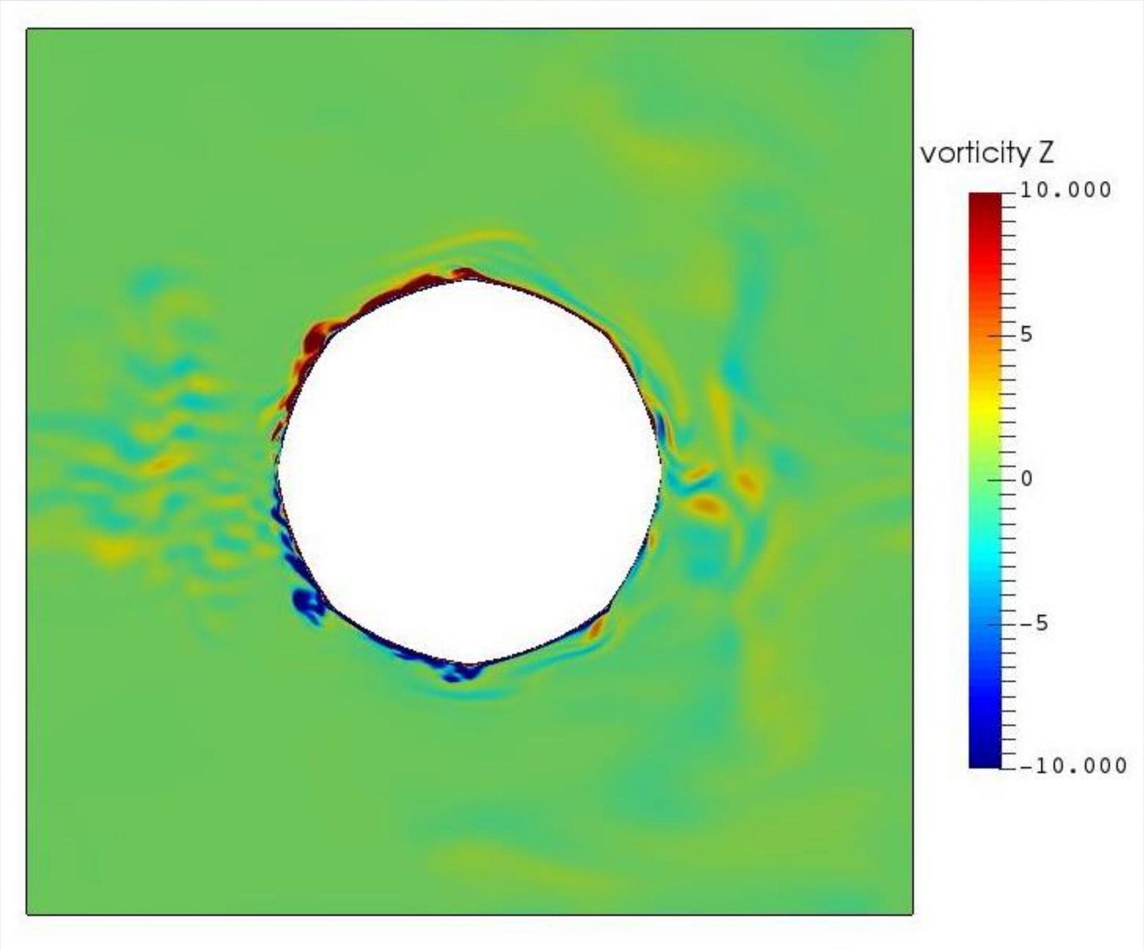




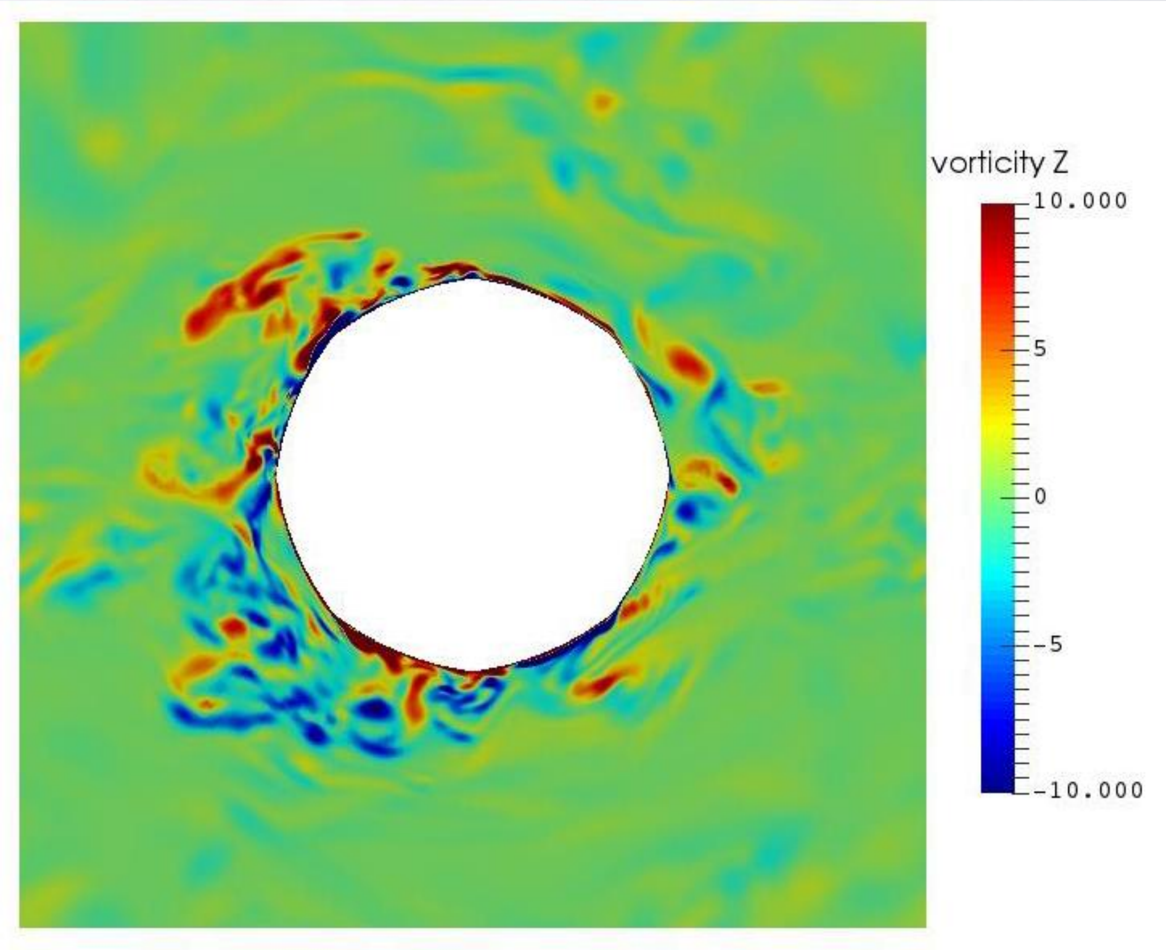
u, Xiao, Johanna H. Rosman, and James L. Hench. "Interaction of Waves with Idealized High-Relief Bottom Roughne
Journal of Geophysical Research: Oceans 123.4 (2018): 3038-3059.

MODEL RESULTS - FLOW KINEMATICS

- Two contrasting cases were chosen here to demonstrate the distinct flow pattern at different KC
  - Low KC Case with T = 20s, U = 0.05 m/s (KC = 2).
  - High KC Case with T = 20s, U = 0.3 m/s (KC = 12).



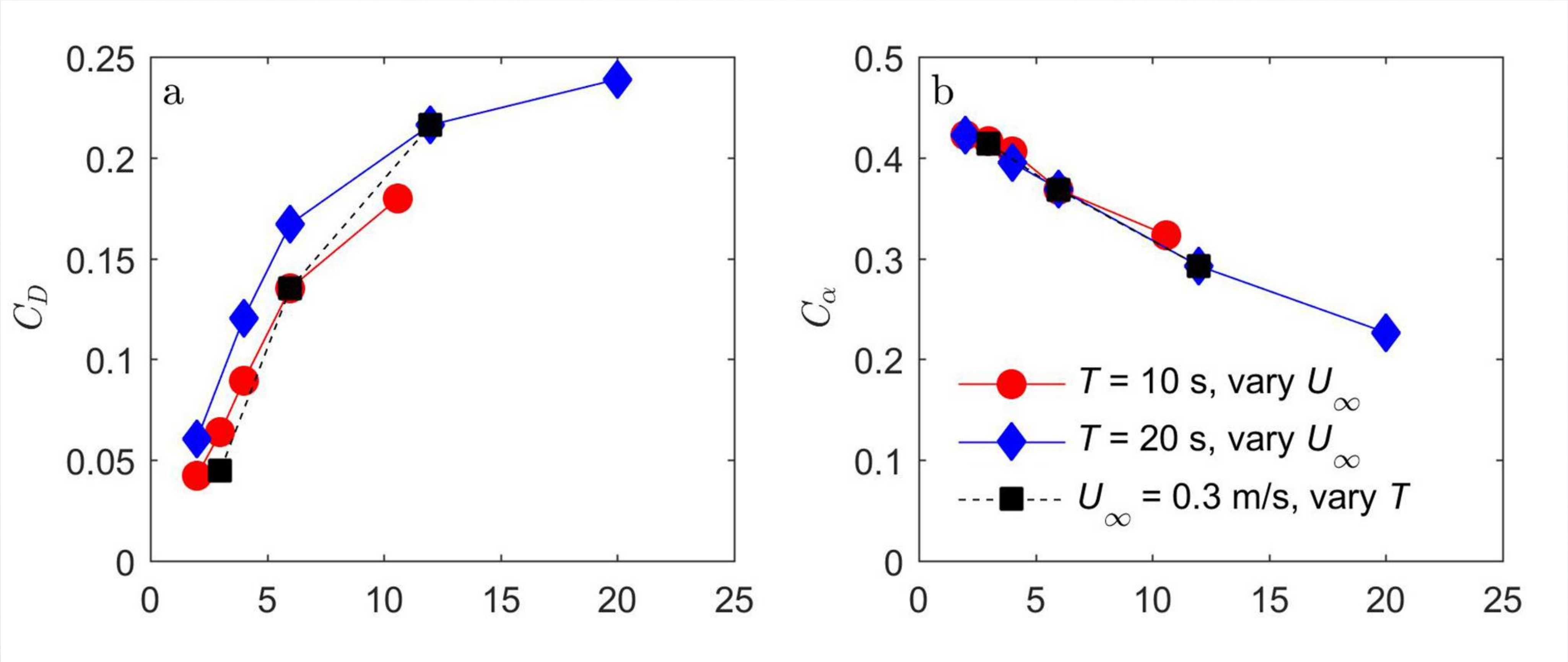
KC=2



KC=12

DRAG PARAMETERIZATION

- Total inline force is decomposed into the drag force and inertial force as in Morison equation.
- Fourier Method is used to calculate both the drag and inertia coefficient.
- Both the drag and inertia coefficients depend on KC
- Drag coefficient only differs slightly with different S/D



MOMENTUM BUDGET

- Double-Averaged Momentum Equation

$$\frac{\partial(\langle\bar{u}_w\rangle - u_\infty)}{\partial t} = \frac{\partial \tau_{xz}}{\partial z} - f_{res}$$

$$f_{res}(t) = f_d(t) + f_\alpha(t)$$

$$f_i(t) = f_\alpha(t) + f_{KF}$$

$$\tau_{xz} = \tau_{xz}^{turb} + \tau_{xz}^{disp}$$

$$f_{KF} = \rho V_{hem}\frac{du_\infty}{dt}$$

- Parameterization of Drag and Added Mass Force

$$f_d(t) = \frac{\sqrt{2}C_D\lambda_f}{\sqrt{3}(1-\phi)D}|u_\infty|u_\infty = KC\frac{U_\infty}{T}\frac{\sqrt{2}C_D\lambda_f}{\sqrt{3}(1-\phi)}\left|\frac{u_\infty}{U_\infty}\right|\frac{u_\infty}{U_\infty}$$

$$f_\alpha(t) = \frac{C_\alpha\phi}{1-\phi}\frac{\partial u_\infty}{\partial t} = \frac{U_\infty}{T}\frac{C_\alpha\phi}{1-\phi}\frac{\partial(u_\infty/U_\infty)}{\partial(t/T)}$$

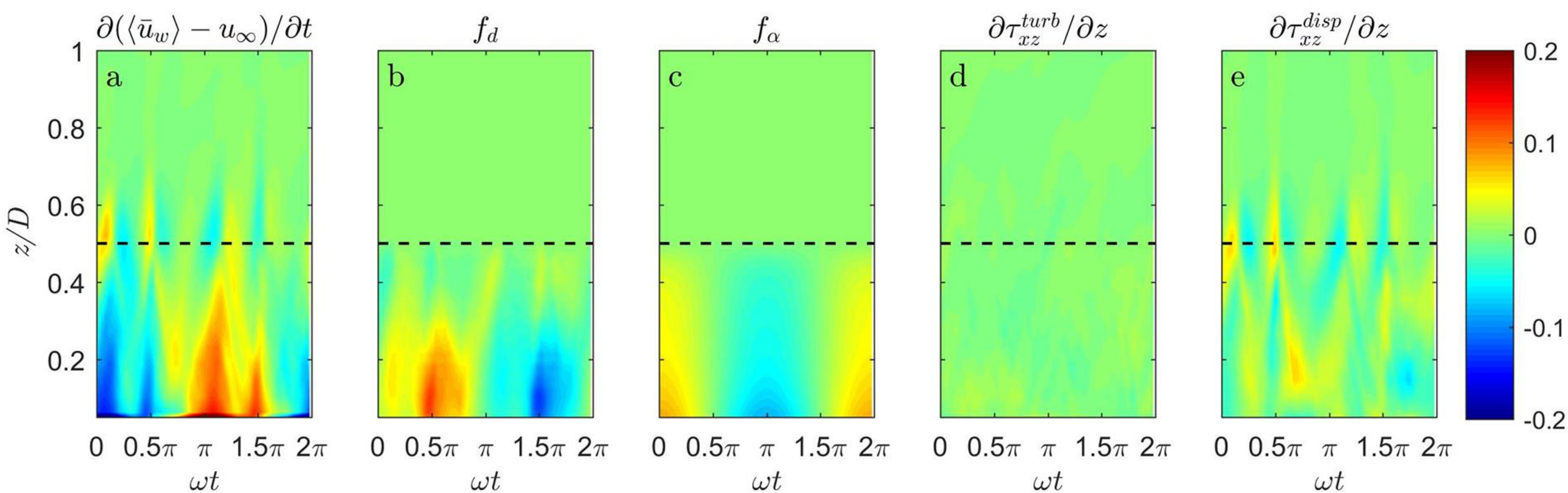
$$\lambda_f = A_{hem}/A_T$$

- Friction factor

$$f_{w,d} = \frac{\sqrt{2}C_D\lambda_f}{\sqrt{3}(1-\phi)}$$

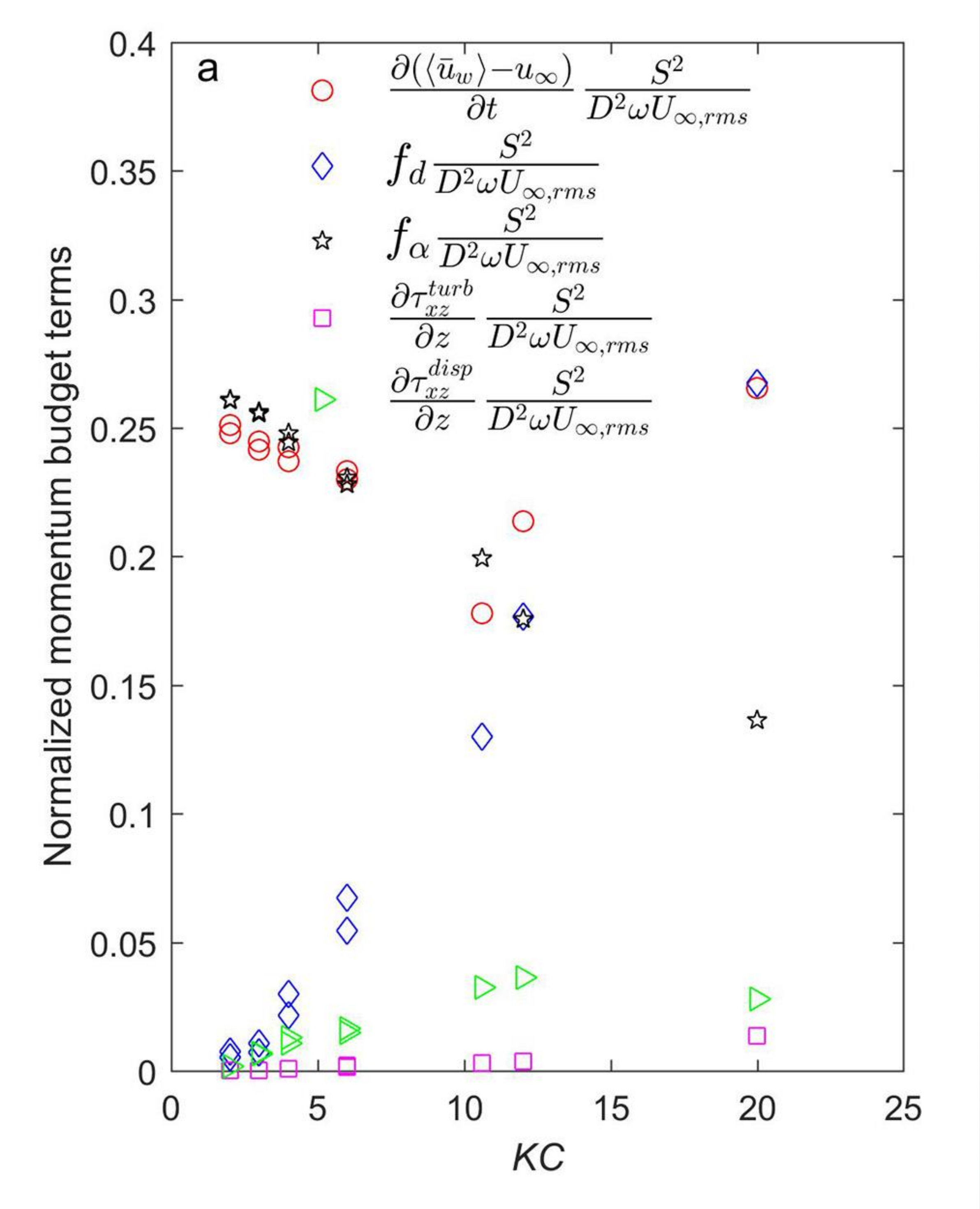
MOMENTUM BUDGET TERMS FOR KC > 1

- Normalized terms in the averaged *x*-momentum equation, normalized by $U_\infty \omega$
- The drag force and inertial force are of equal importance
- Drag force peaks near wave peak and trough, inertial force peaks near flow reversal
- The dispersive stress is significant at the top of the canopy layer and important in the vertical momentum transfer

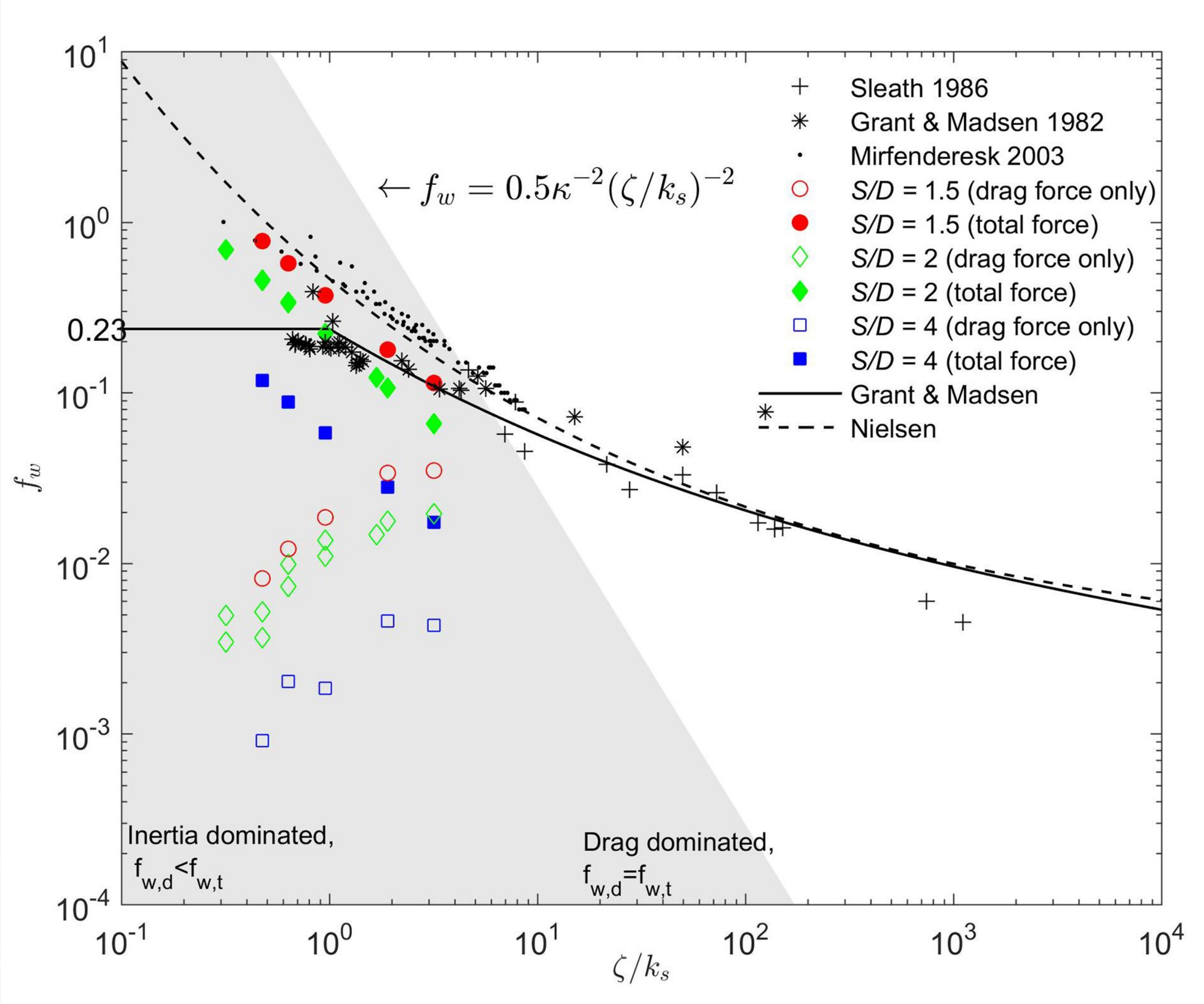


MOMENTUM BUDGET

- Results of all cases with S/D = 2 shows the drag force, and the newly derived dispersive stress increase in relative importance as KC increase
- With different ratio S/D, the same conclusion can be drawn



FRICTION FACTOR



- The empirical curves agree with each other at high KC but diverge at low KC.
- At low KC, the friction factor based on the drag force only increases with KC.

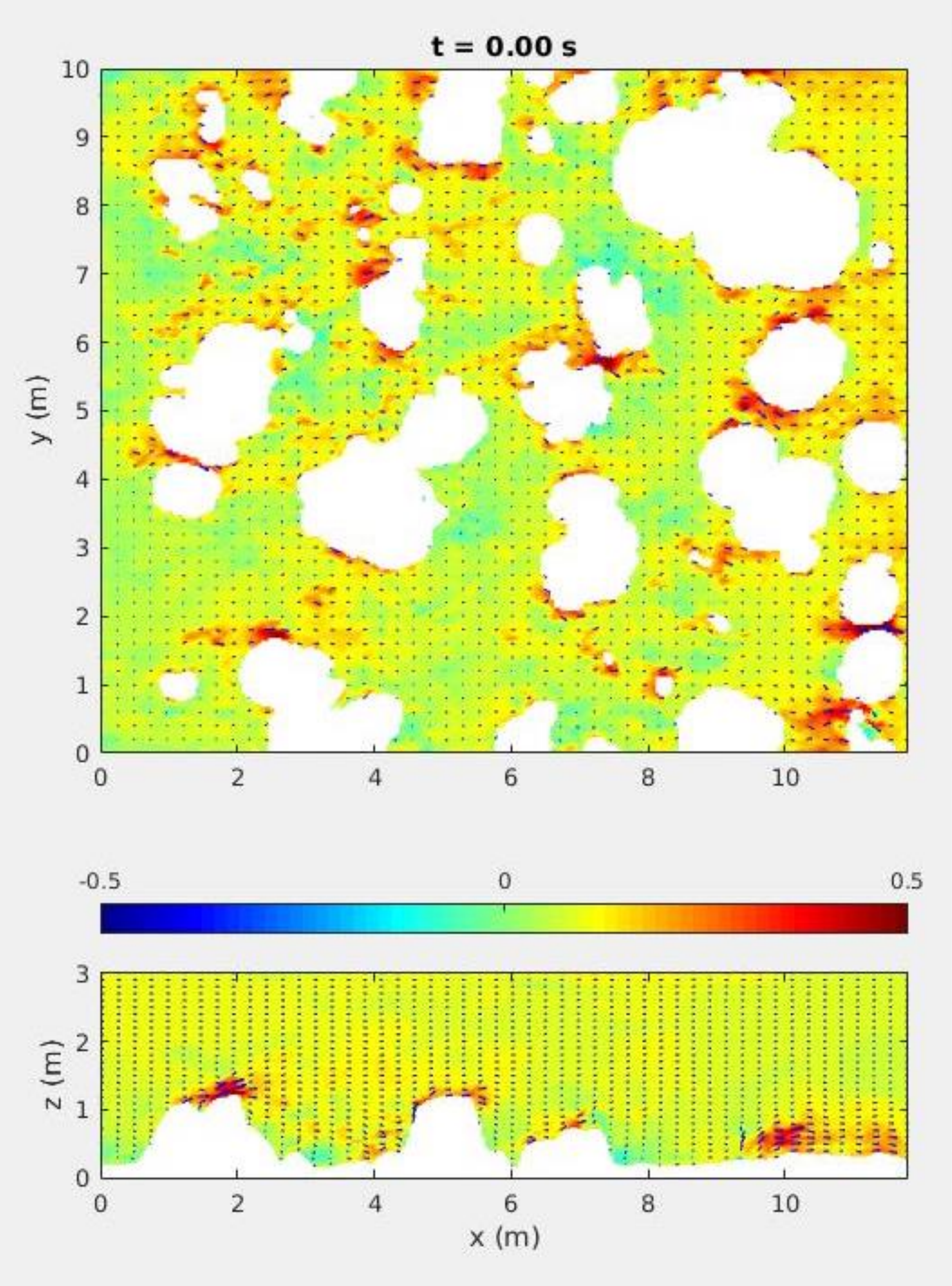
For KC>>1, drag force dominates

For KC ~ 1, inertial force dominates

CONCLUSION

- As Keulegan-Carpenter number (KC) increases, flow separation, drag force and a newly derived phase-dependent dispersive stress become increasingly important.
- Wave friction factors representing bottom drag per unit area increase over $1<KC<20$, differing from previously proposed empirical curves.
- Total force, drag force at the bottom, and shear stress above topography are very different at low KC animist be differentiated in friction parameterization.

FUTURE WORK



- Wave over real multiscale complex high-relief topography
- Wave-current interaction over complex high-relief topography
- Parameterization of drag coefficient / wave friction factor of flow over multiscale topography