LES study of the impacts of swells on the atmospheric boundary layer

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Presentation Outline

Ⅰ Introduction

- Background
- Research objectives

Ⅱ Method

- Mesh transformation
- Numerical method
- Simulation setup

Ⅲ Results

- Wave-induced velocity
- Wave-induced pressure
- Profiles of mean wind and turbulence

Ⅳ Conclusions

- Conclusions
- Future work

I

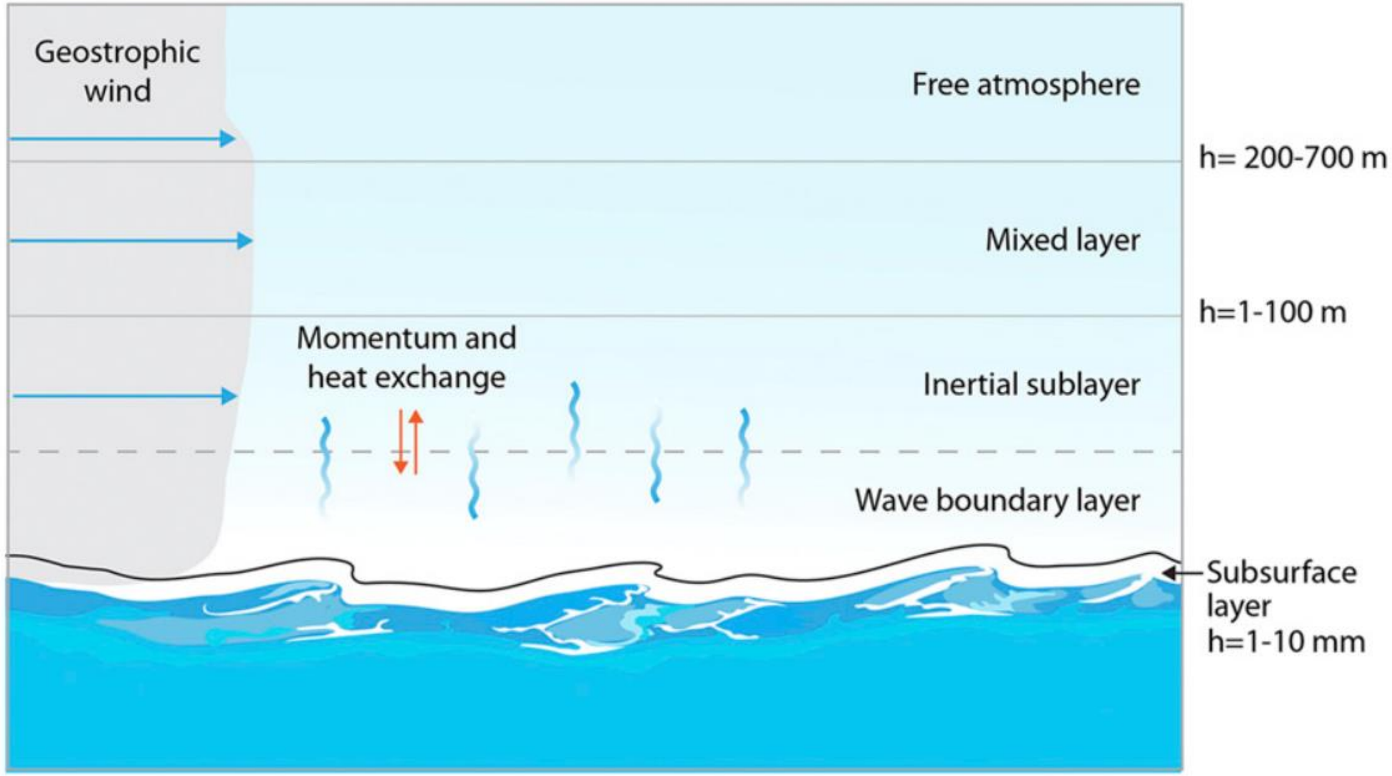
Introduction

Introduction

Background

- Waves affect the exchange of momentum, energy and mass between the atmosphere and ocean.
- Wave effects depends on multiple environmental factors, including wind-wave states and stability conditions.

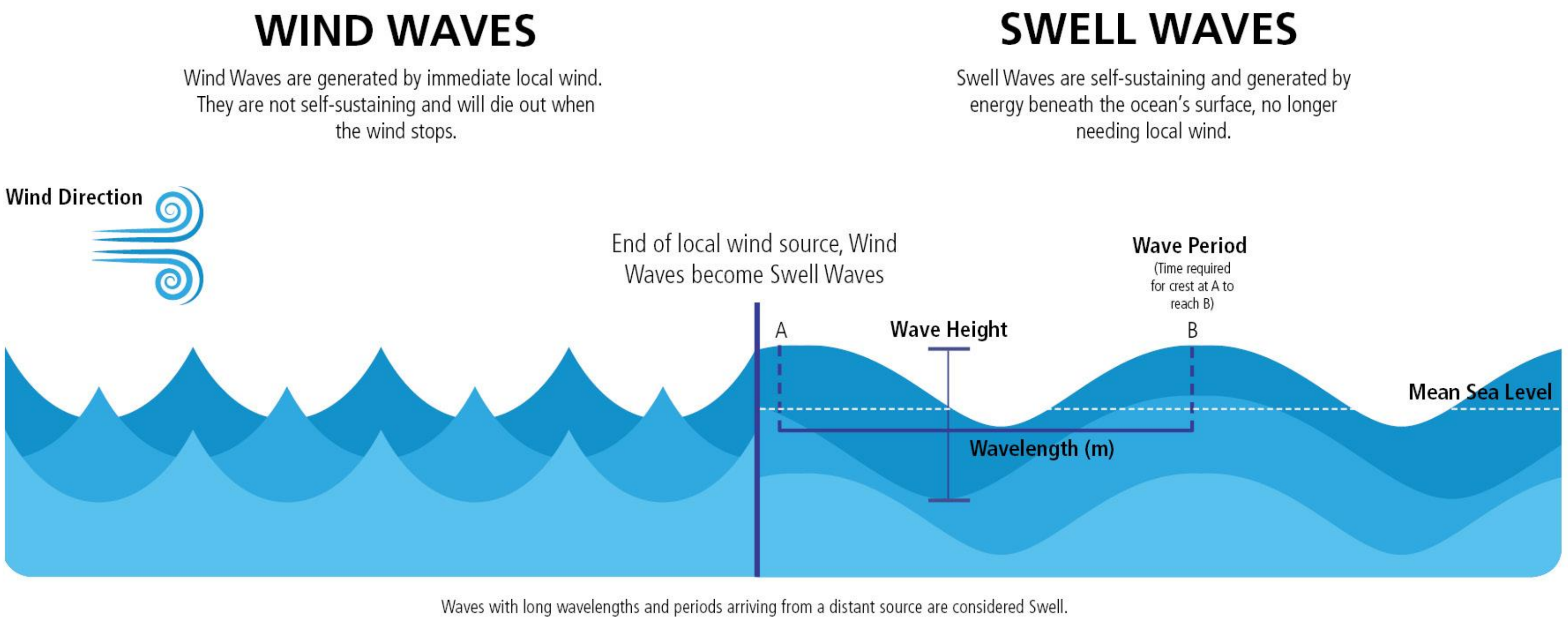
The vertical structure of Marine Atmospheric Boundary Layer (MABL)[1]



1. Deskos, G., Lee, J. C., Draxl, C., & Sprague, M. A. (2021). Review of Wind–Wave Coupling Models for Large-Eddy Simulation of the Marine Atmospheric Boundary Layer. *Journal of the Atmospheric Sciences*, *78*(10), 3025-3045.

Introduction

Background



Observations in Atlantic ocean: In low to modest wind, disequilibrium between the wind and wave is the most common state, i.e. waves propagate faster than wind and with a misaligned direction[1].

1. Sullivan, P. P., Edson, J. B., Hristov, T., & McWilliams, J. C. (2008). Large-eddy simulations and observations of atmospheric marine boundary layers above nonequilibrium surface waves. *Journal of the Atmospheric Sciences*, *65*(4), 1225-1245.

Introduction

Background

Wave-induced disturbances decay exponentially with height.

- Semedo, A., Saetra, Ø., Rutgersson, A., Kahma, K. K., & Pettersson, H. (2009). Wave-induced wind in the marine boundary layer. Journal of the Atmospheric Sciences, 66(8), 2256-2271.

Waves can still have strong impacts on the atmosphere.

- Smedman, A., Högström, U., Sahlée, E., Drennan, W. M., Kahma, K. K., Pettersson, H., & Zhang, F. (2009). Observational study of marine atmospheric boundary layer characteristics during swell. Journal of the atmospheric sciences, 66(9), 2747-2763.
- Sullivan, P. P., Edson, J. B., Hristov, T., & McWilliams, J. C. (2008). Large-eddy simulations and observations of atmospheric marine boundary layers above nonequilibrium surface waves. Journal of the Atmospheric Sciences, 65(4), 1225-1245.

Introduction

Research Objectives

- **To develop a modelling tool that is able to reproduce the wave-induced effects.**
- **To investigate wave effects on the atmospheric boundary layer flow.**

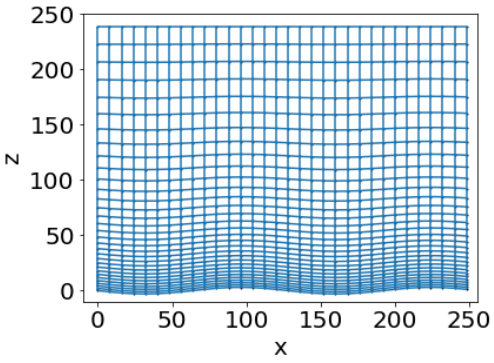
Ⅱ

Method

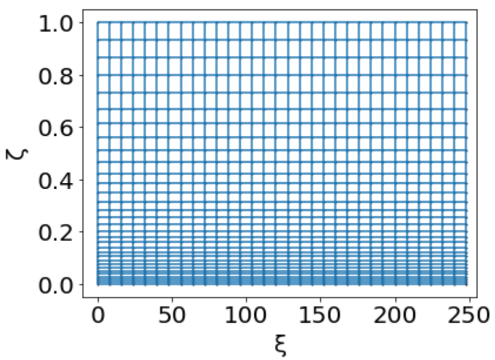
Method

Mesh transformation

- Resolve the geometries of the wave surface

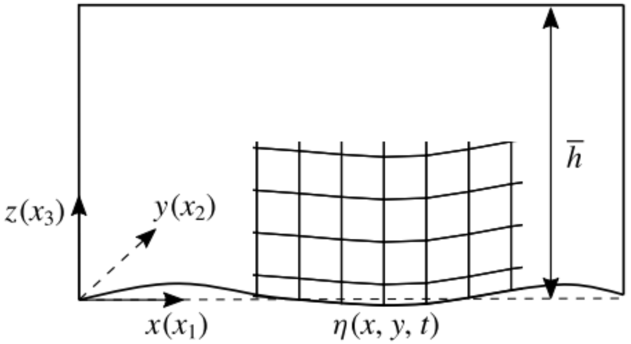


Physical Domain



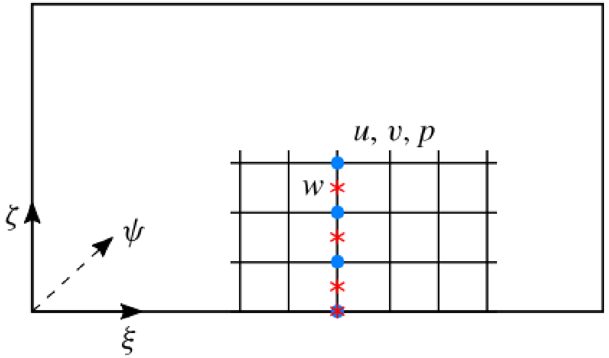
Computational Domain

Coordinate transform



Physical Domain

$$\tau = t$$
$$\xi = x$$
$$\psi = y$$
$$\zeta = \frac{z - \eta(x, y, t)}{\bar{h} - \eta(x, y, t)}$$



Computational Domain

Method

Numerical method

Continuity equation $$\frac{\partial u}{\partial \xi}+\zeta_x\frac{\partial u}{\partial \zeta}+\frac{\partial v}{\partial \psi}+\zeta_y\frac{\partial v}{\partial \zeta}+\zeta_z\frac{\partial w}{\partial \zeta}=0$$

Momentum equation

$$\begin{aligned}\frac{\partial u}{\partial \tau}+\zeta_t\frac{\partial u}{\partial \zeta}=&-(\frac{\partial uu}{\partial \xi}+\zeta_x\frac{\partial uu}{\partial \zeta})-(\frac{\partial uv}{\partial \psi}+\zeta_y\frac{\partial uv}{\partial \zeta})-\zeta_z\frac{\partial uw}{\partial \zeta}\\&-f_2w+f_3(v-v_g)-\frac{1}{\rho_0}(\frac{\partial p}{\partial \xi}+\zeta_x\frac{\partial p}{\partial \zeta})\\&-(\frac{\partial}{\partial \xi}+\zeta_x\frac{\partial}{\partial \zeta})(\overline{u''u''}-\frac{2}{3}e)-(\frac{\partial}{\partial \psi}+\zeta_y\frac{\partial}{\partial \zeta})(\overline{u''v''})-\zeta_z\frac{\partial}{\partial \zeta}(\overline{u''w''})\end{aligned}$$

$$\begin{aligned}\frac{\partial v}{\partial \tau}+\zeta_t\frac{\partial v}{\partial \zeta}=&-(\frac{\partial vu}{\partial \xi}+\zeta_x\frac{\partial vu}{\partial \zeta})-(\frac{\partial vv}{\partial \psi}+\zeta_y\frac{\partial vv}{\partial \zeta})-\zeta_z\frac{\partial vw}{\partial \zeta}\\&-f_3(u-u_g)-\frac{1}{\rho_0}(\frac{\partial p}{\partial \psi}+\zeta_y\frac{\partial p}{\partial \zeta})\\&-(\frac{\partial}{\partial \xi}+\zeta_x\frac{\partial}{\partial \zeta})(\overline{v''u''})-(\frac{\partial}{\partial \psi}+\zeta_y\frac{\partial}{\partial \zeta})(\overline{v''v''}-\frac{2}{3}e)-\zeta_z\frac{\partial}{\partial \zeta}(\overline{v''w''})\end{aligned}$$

$$\begin{aligned}\frac{\partial w}{\partial \tau}+\zeta_t\frac{\partial w}{\partial \zeta}=&-(\frac{\partial wu}{\partial \xi}+\zeta_x\frac{\partial wu}{\partial \zeta})-(\frac{\partial wv}{\partial \psi}+\zeta_y\frac{\partial wv}{\partial \zeta})-\zeta_z\frac{\partial ww}{\partial \zeta}\\&+f_2u+g\frac{\theta_V-\langle\theta_V\rangle}{\langle\theta_V\rangle}-\frac{1}{\rho_0}(\zeta_z\frac{\partial p}{\partial \zeta})\\&-(\frac{\partial}{\partial \xi}+\zeta_x\frac{\partial}{\partial \zeta})(\overline{w''u''})-(\frac{\partial}{\partial \psi}+\zeta_y\frac{\partial}{\partial \zeta})(\overline{w''v''})-\zeta_z\frac{\partial}{\partial \zeta}(\overline{w''w''}-\frac{2}{3}e)\end{aligned}$$

Turbulence closure and discretization

- Turbulence closure

  1.5-order Deardorff (1980)

- Time advance

  3-order Runge-Kutta

- Advection scheme

  5-order upwind Wicker and Skamarock (2002)

- Pressure solver

  multigrid

Method

Simulation setup

- Mesh

N_x, N_y, N_z = 256, 256, 160

$\Delta_x, \Delta_y, \Delta_z$ = 4.6875, 4.6875, 2.0 ~ 16.0 m

- Geostrophic wind

u_g, v_g = 5.0, 0.0 m/s

- Stability condition

neutral

- Simulation time

20h + 20min

- Vertical boundary condition

cyclic

- Bottom boundary condition

$$\eta(t,x) = A\sin[k(ct-x)]$$

$$u(t,x) = \omega A\sin[k(ct-x)]$$

$$w(t,x) = \omega A\cos[k(ct-x)]$$

Table of wave parameters

Case ID	Wave amplitude	Wave length	Wave phase speed	Wave direction
1	-	-	-	-
2	1.6 m	100m	12.5 m/s	following
3	1.6 m	100m	12.5 m/s	opposing

Ⅲ

Results

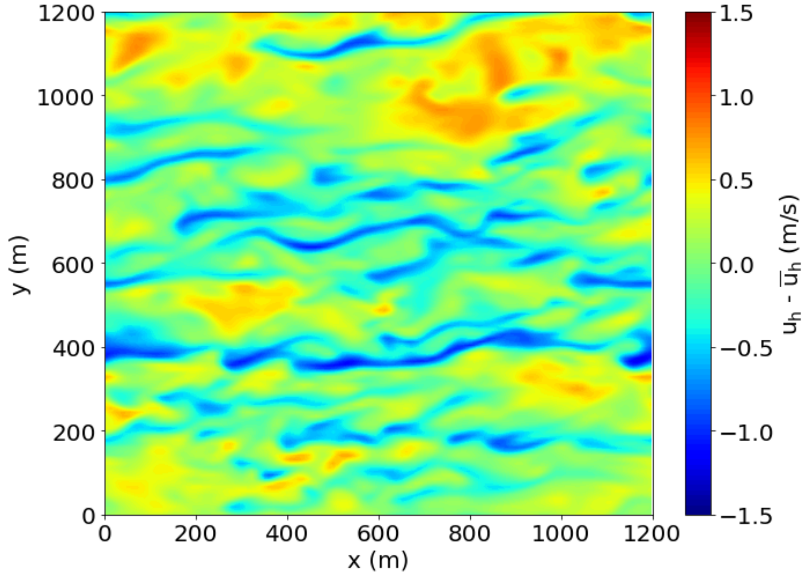
Results

Wave-induced velocity

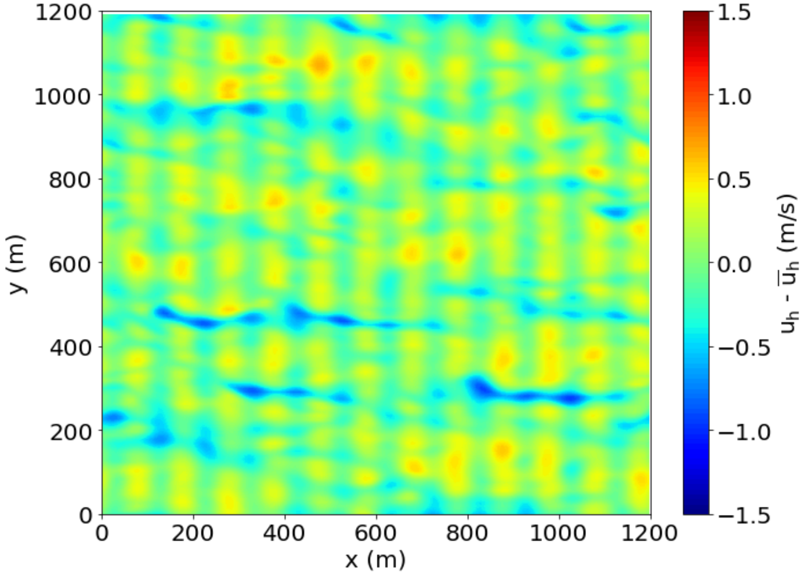
- Fluctuation of horizontal velocity at x-y plane

The strength of wave-coherent flow structures depend on the wind-wave condition and the height.

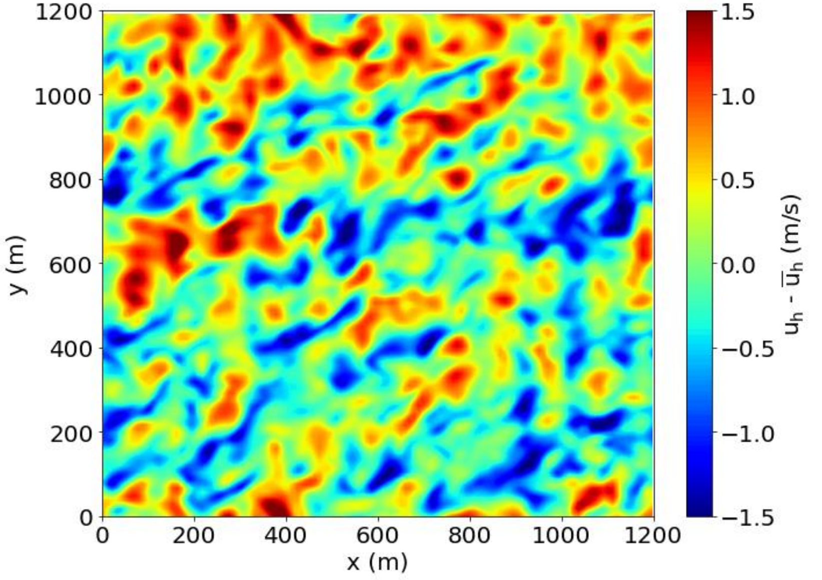
no wave



wind following wave



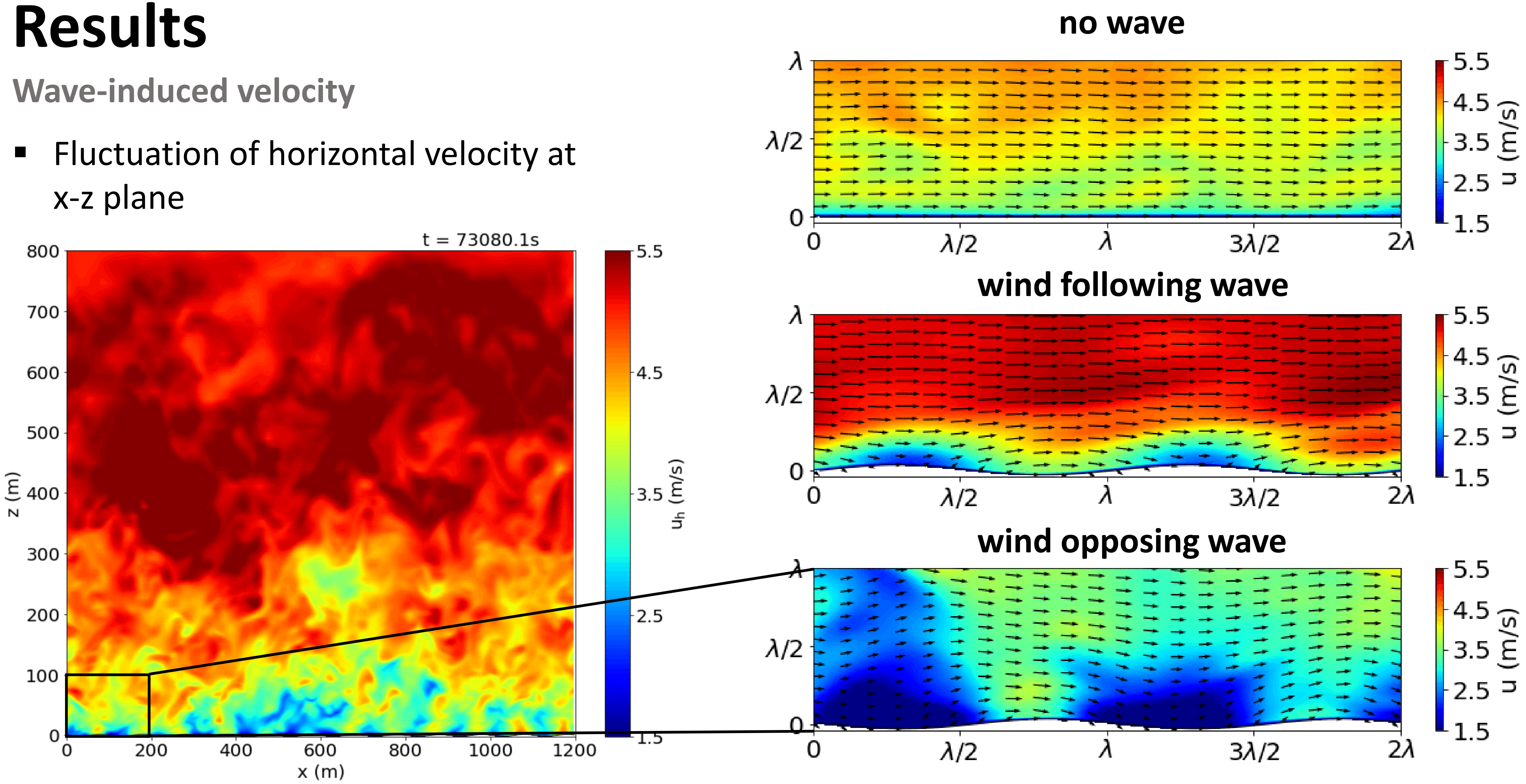
wind opposing wave



Results

Wave-induced velocity

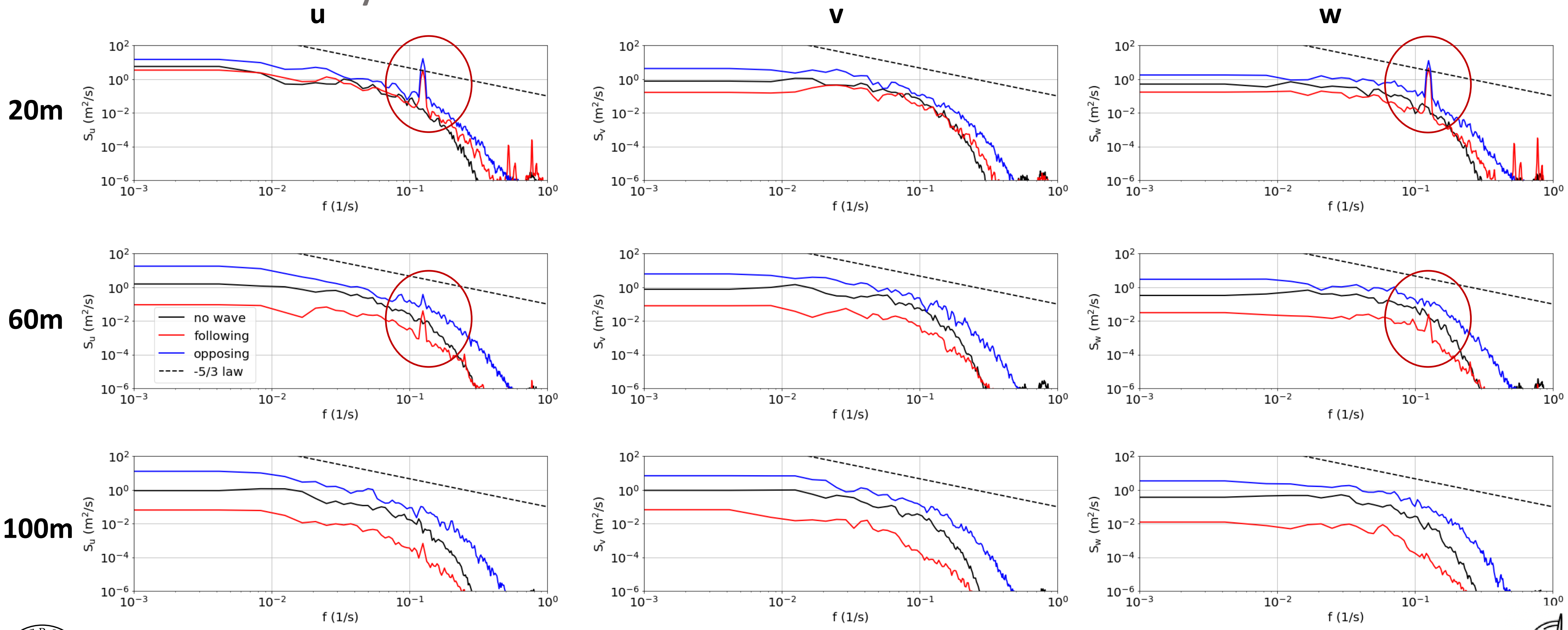
- Fluctuation of horizontal velocity at x-z plane



Results

Wave-induced velocity

Power spectral density curves at various heights

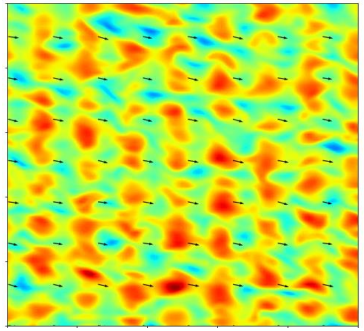


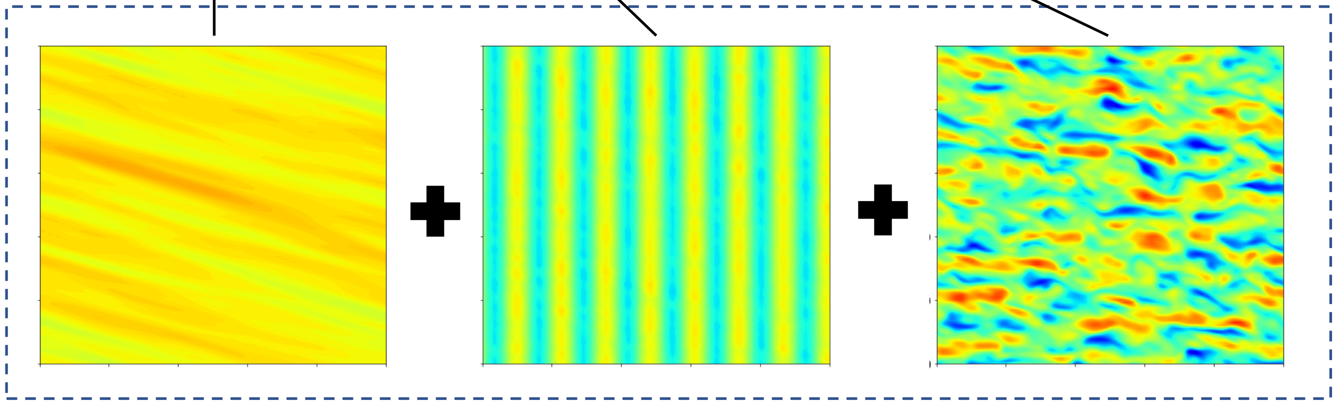
Results

Wave-induced velocity

- tri-decomposition of velocity

$$\bar{u} + \tilde{u} + u' = u$$





wave-induced velocity

=

phase-averaged velocity

-

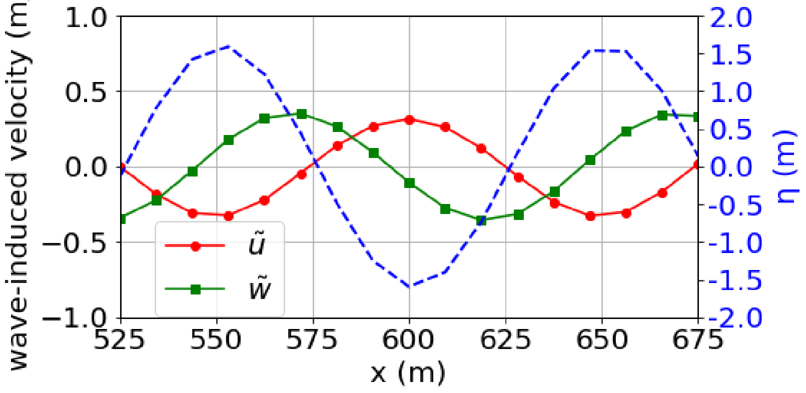
time-averaged velocity

$$\sum_{k=0}^{N-1} u(t + kT, x, y, z) \Big/ N$$

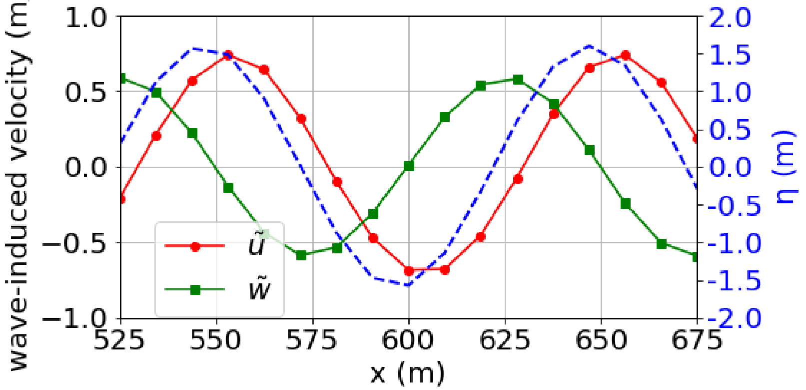
Results

Wave-induced velocity

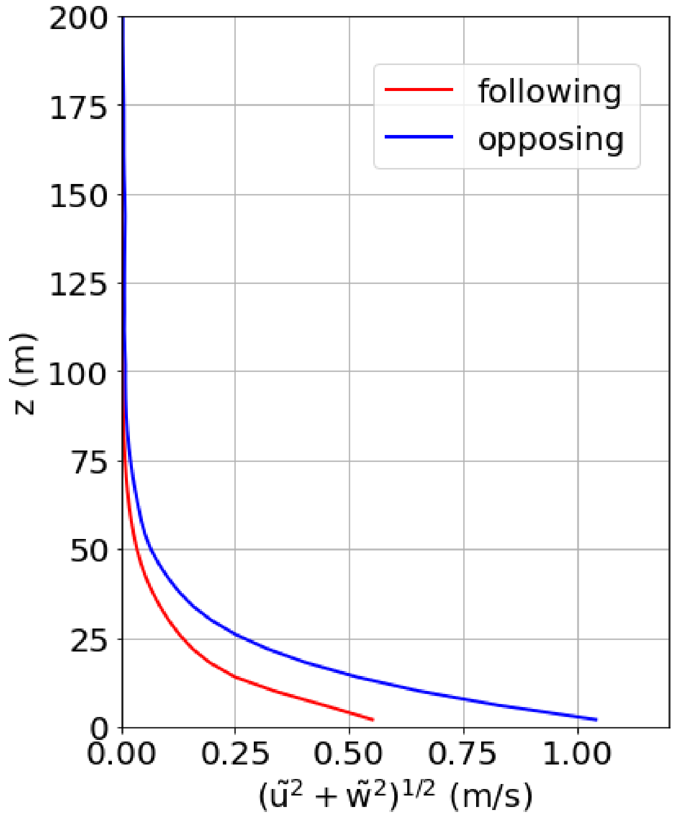
wind following wave

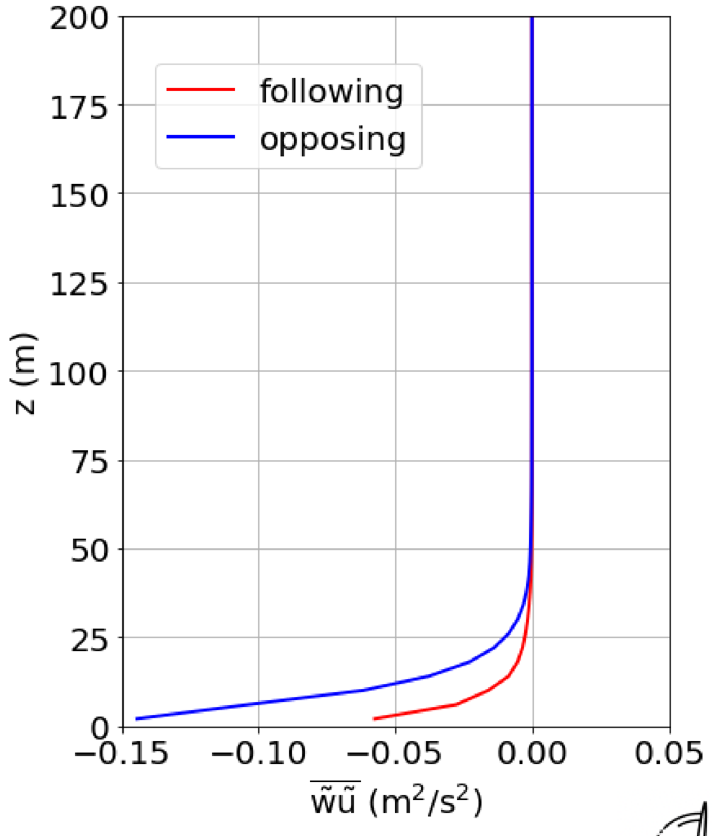


wind opposing wave



- Profiles of wave-induced velocity and stress

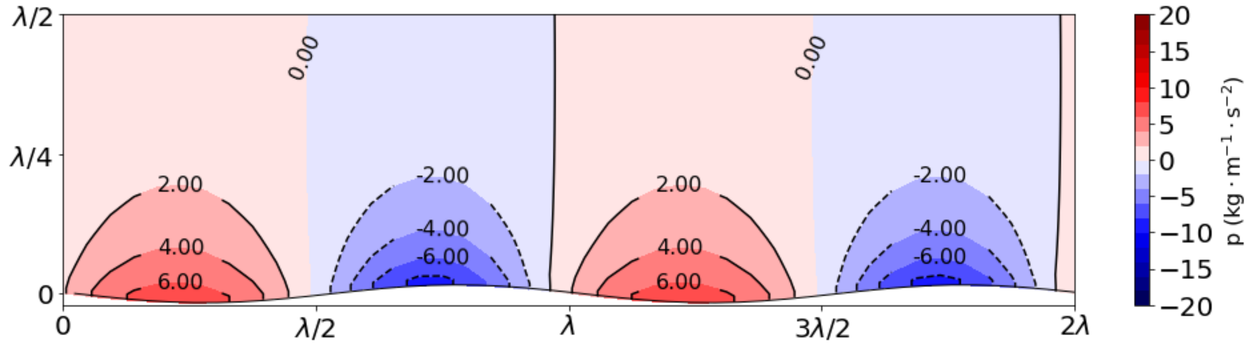




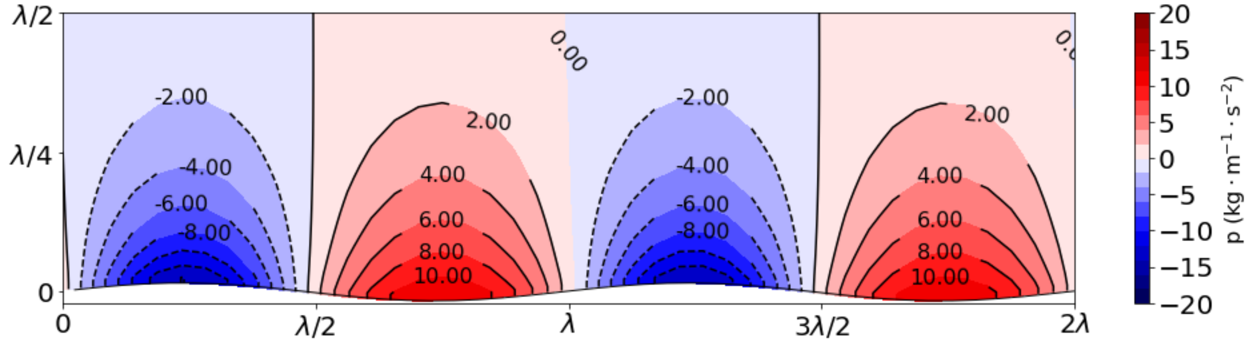
Mesh transformation

Wave-induced pressure

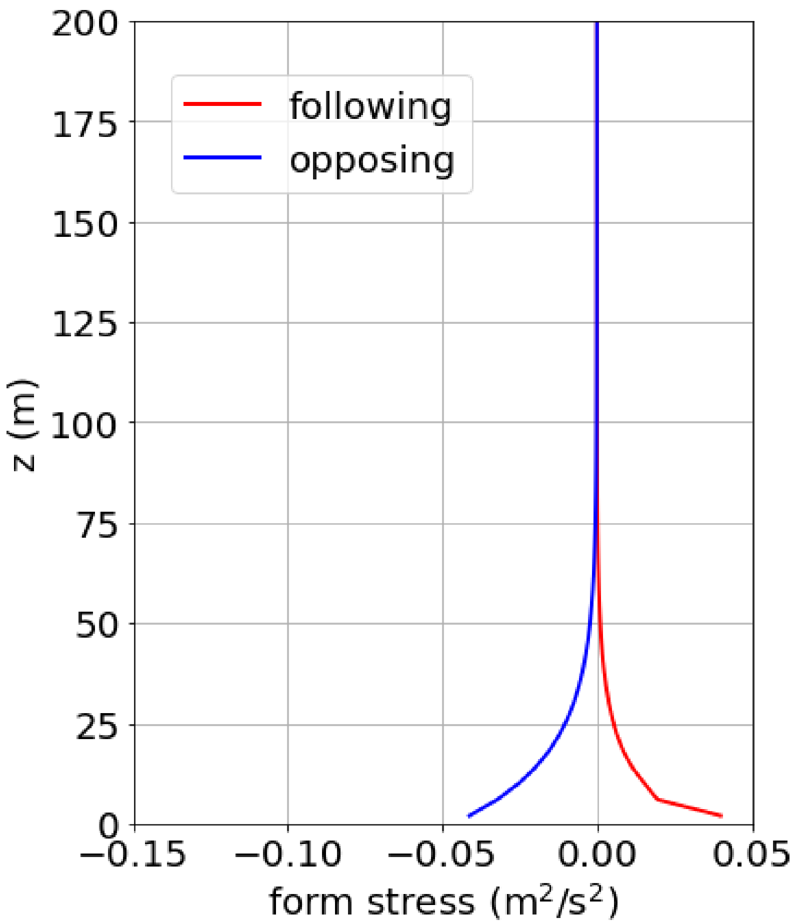
Wind following wave



Wind opposing wave



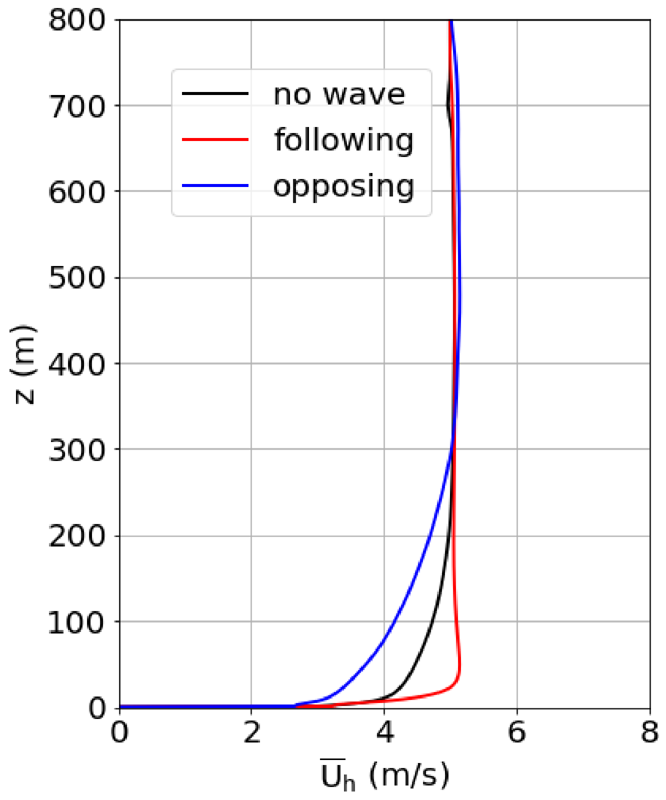
- pressure distribution along the surface

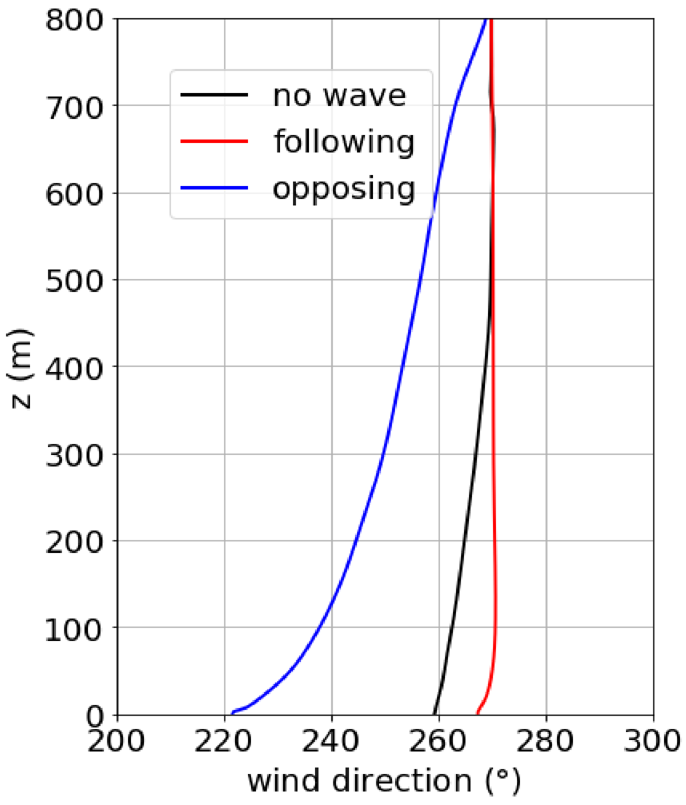


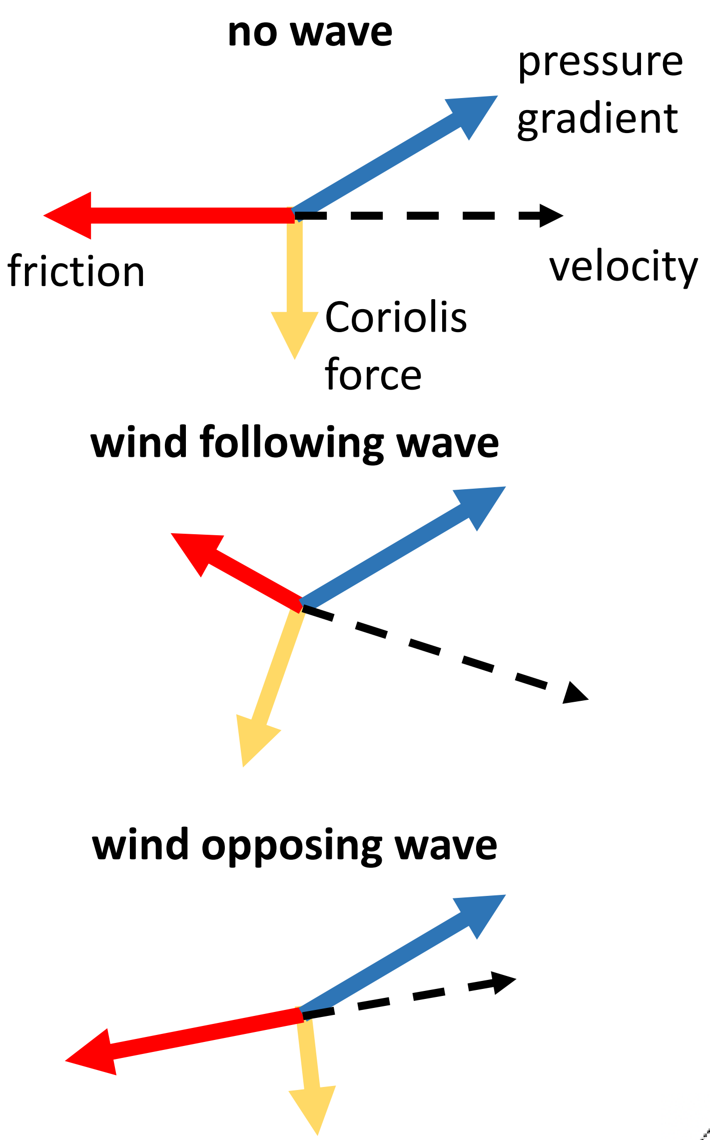
Results

Profiles of the mean wind

- Mean wind



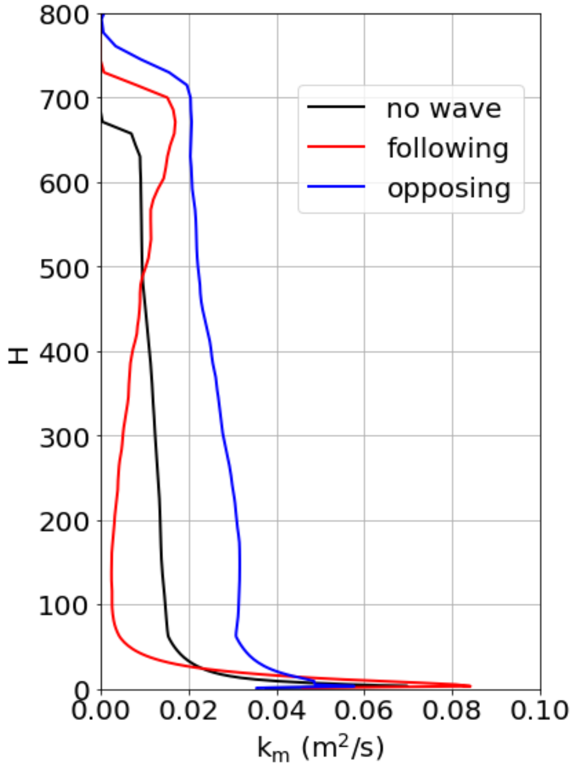


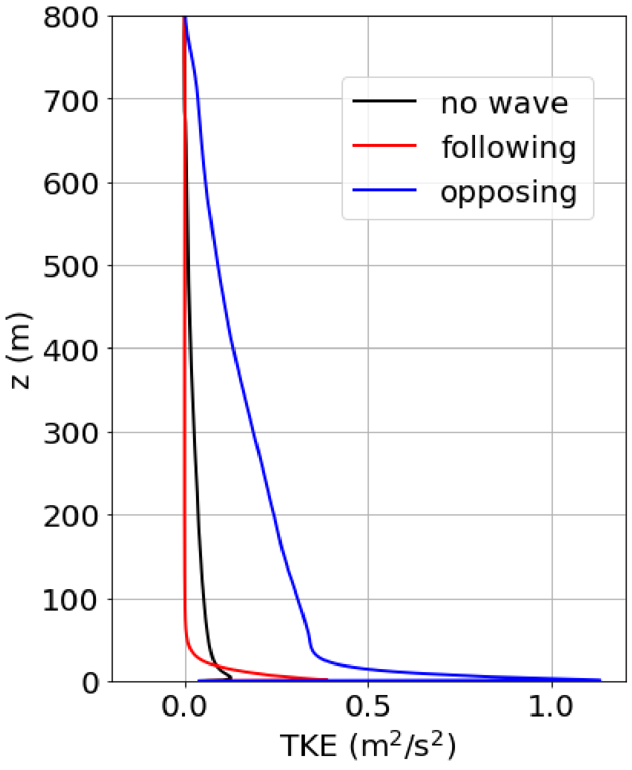


Results

Profiles of the turbulence kinetic energy

- Turbulence





- The wind-following (-opposing) wave reduces (increases) the momentum flux near the surface.
- The wind shear is mitigated (enhanced) by the wave-induced stress. As a result, the TKE decreases (increases).

Ⅳ

Conclusions

Conclusions

- Conclusions

1. Strong waves can induce highly coherent flow structures (within the height of half wave length) that increase the turbulent intensity near the surface.
2. The asymmetric pressure distribution together with wave-induced momentum fluxes act as a thrust or drag force and modify the wind shear and wind veer across the whole boundary layer.

- Future work

- ☐ Effects of irregular waves.
- ☐ How wave effects change with stability conditions.
- ☐ Waves effects on a wind farm.

Thank you for your attention!

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