Modelling of the coupling between an atmospheric flow and a sea state

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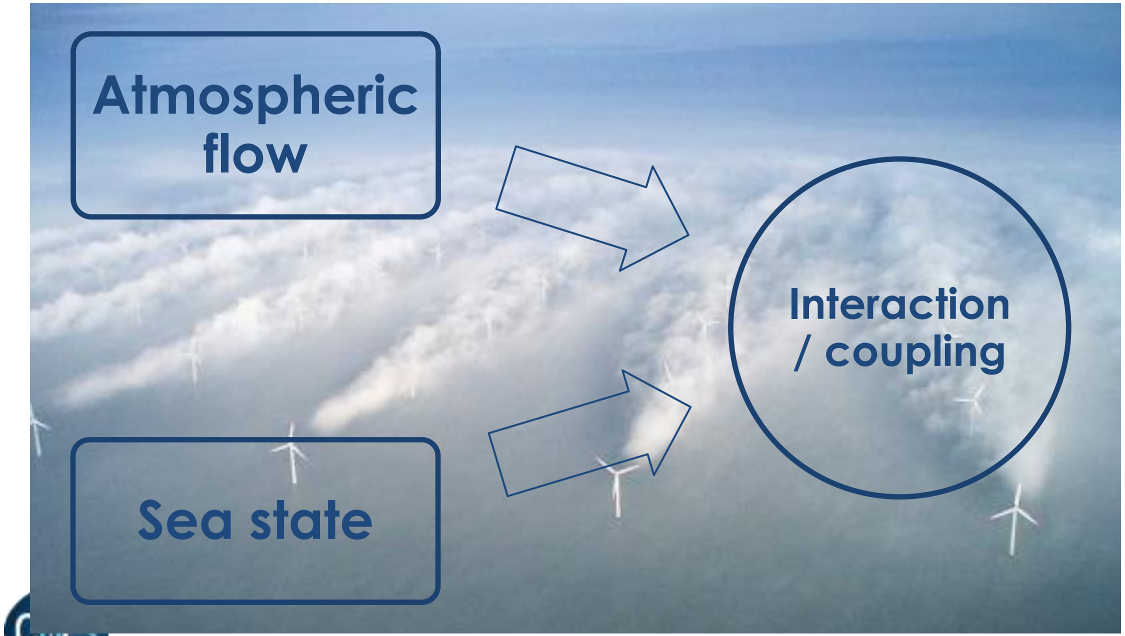
Wind-wave coupling

Introduction

Increasing offshore wind energy exploitation
&
Sea state forecast



Atmospheric flow

Sea state

Interaction / coupling

- Major factors:
  - Vertical atmospheric stability/instability
  - Wave-induced effects
- **Turbulence/transfer...**

Introduction

Simplistic hypotheses (1)

- Wind profile
  - Power law

$$U(z) = U_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha}$$

  - Logarithmic law (Monin-Obukhov)

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

- Sea surface roughness
  - Charnock's relation $z_0 = \frac{A_c {u_*}^2}{g}$ with A_c a constant
  - Local sea state features are not taken into account

Reality (1)

- Wind profile
  - Laws are not really satisfied compared to field experiments
  - Log law is not satisfied above the surface layer
- Sea surface roughness
  - A_c depends on local sea state

Objective

Fine description of the offshore wind resource and its interaction with the underlying sea state

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(1) Kalvig et al., *Exploring the gap between 'best knowledge' and 'best practice' in boundary layer meteorology for offshore wind energy*. Wind Energy, 2014

Wind-wave coupling

Context and objectives

State of the art

Numerical modelling

Results

Outlook and conclusions

Wind-wave coupling

Numerical simulations:

- **DNS** (Sullivan et al. 2000, Rutgersson et Sullivan 2005)
- **LES** (Sullivan et al. 2008, 2014)

U velocity field / monchromatic wave

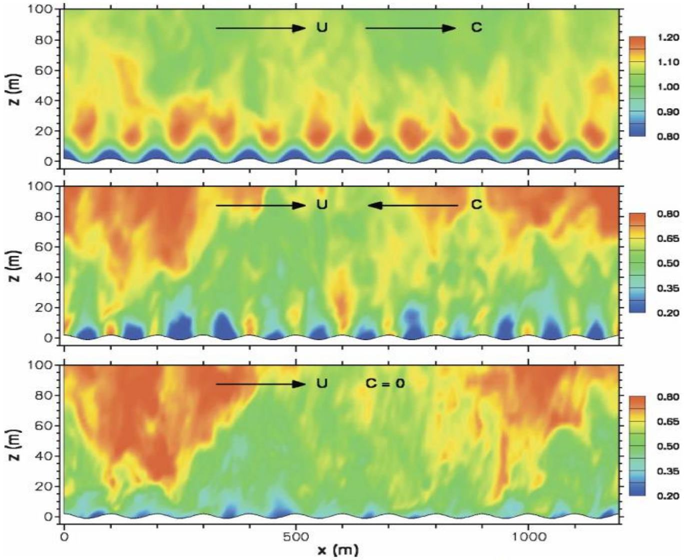
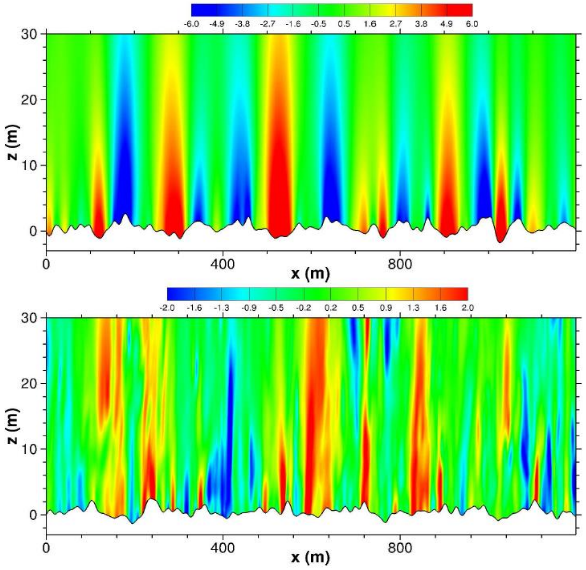


FIG. 5. Contours of the u component of the horizontal wind field for cases with moving and stationary surface waves. The no
mensional field shown is $\overline{u}/U_g$. (top) Wind following waves; (middle) wind opposing waves; and (bottom) stationary bumps. For e
case the geostrophic wind $(U_g, V_g) = (5, 0)$ m s^{-1} and the wave slope $ak = 0.1$ where the wave amplitude $a = 1.6$ m. In the top
middle panels the wave phase speed $c = 12.5$ m s^{-1}. The color bar changes between the top and middle panels. Note the superg
strophic winds near the surface in the top panel.

P pressure field / wave spectrum



$\frac{C_p}{U_{10}} \sim 4.8$ swell

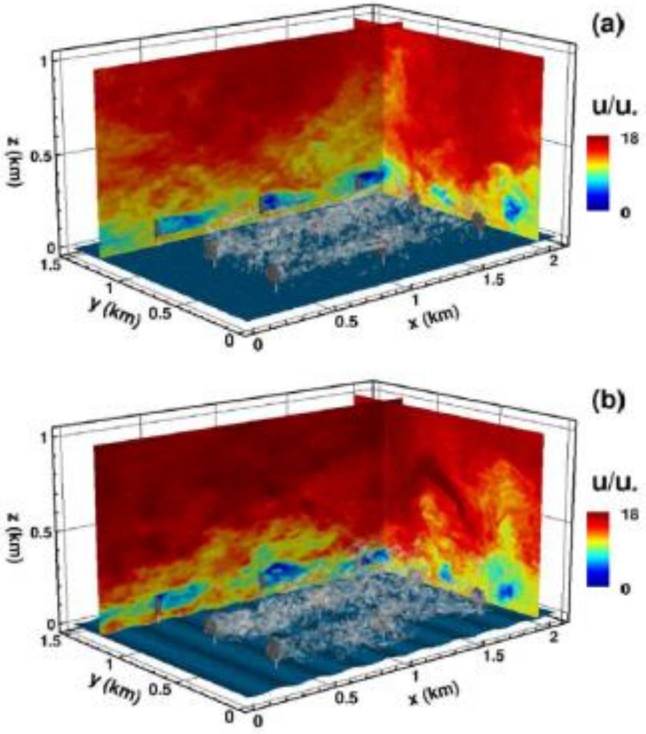
$\frac{C_p}{U_{10}} \sim 1.4$ young wave

Figure 4: Snapshot of static pressure fluctuations p'/ρ in an $x-z$ plane near the water surface. The upper panel is a swell dominated regime with wave age ~ 4.8 while the lower panel is a case near wind-wave equilibrium with wave age ~ 1.4. The wave spectrum is a Pierson-Moskowitz spectrum. Notice the coherence between the wave field and the pressure fluctuations in the case with swell. The color bar is in units of m s^{-2} and the range is different between the two cases.

Wind-wave coupling

Numerical simulations:

- ➢ Offshore wind farm modelling (Yang et al., 2014)



Incompressible Navier-Stokes flow equations

LES-HOS coupling

Wind turbines modelled with actuator disk method

Yang, Meneveau and Shen. Effect of downwind swells on offshore wind energy harvesting – A large-eddy simulation. *Renew. Energy 70*, 2014.

Wind-wave coupling

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- High-order spectral (HOS) code solving the wave propagation
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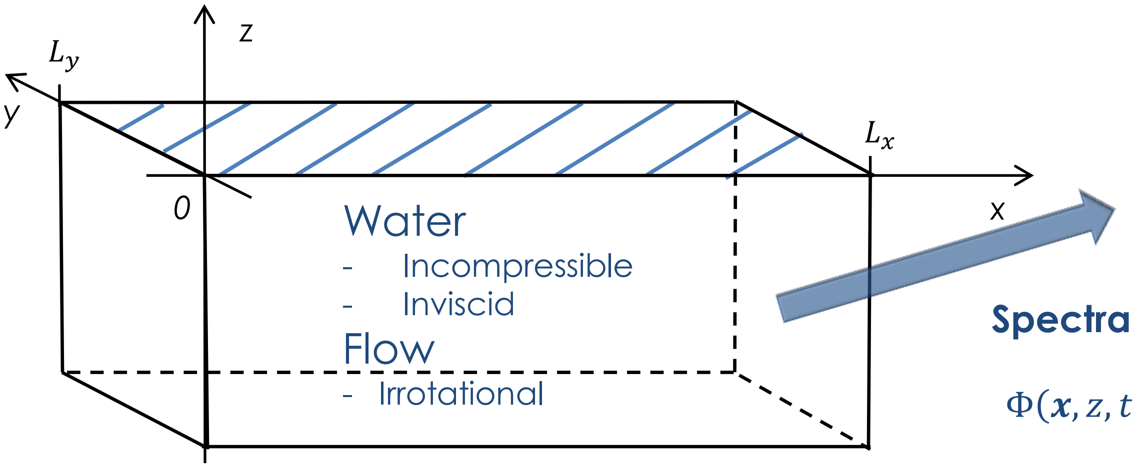
HOS formulation



Water
- Incompressible
- Inviscid

Flow
- Irrotational

Potential flow theory

$$\boldsymbol{V}(\boldsymbol{x},z,t) = \tilde{\boldsymbol{\nabla}}\Phi(\boldsymbol{x},z,t)$$

Spectral expansion

$$\Phi(\boldsymbol{x},z,t) = \sum_{i=-\infty}^{+\infty}\sum_{j=-\infty}^{+\infty} A_{ij}(t)\psi_{ij}\exp(k_{ij}z)$$

- Continuity equation ⟶ Laplace equation

$$\boxed{\Delta\Phi = 0 \quad \text{in } D}$$

- At free surface,

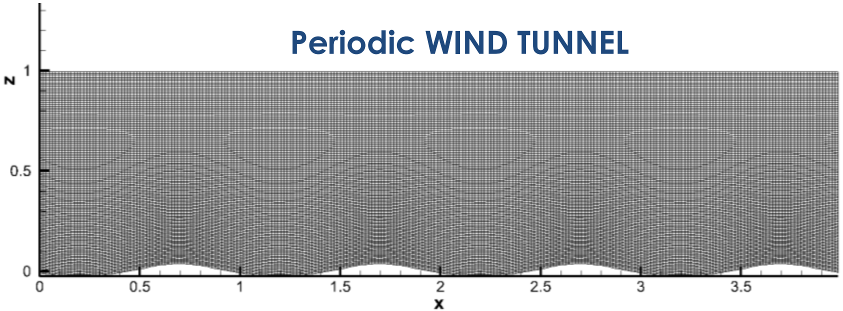
DFSBC (pressure continuity) $\frac{\partial\Phi}{\partial t} = -g\eta - \frac{1}{2}\left|\tilde{\boldsymbol{\nabla}}\Phi\right|^2 - \frac{\tilde{p}_{atm}}{\rho_w}$ at $z = \eta(\boldsymbol{x},t)$

KFSBC (slip condition) $\frac{\partial\eta}{\partial t} = \frac{\partial\Phi}{\partial z} - \boldsymbol{\nabla}\Phi.\boldsymbol{\nabla}\eta$ at $z = \eta(\boldsymbol{x},t)$

$\tilde{p}_{atm} = 0$ in classic simulations

Atmospheric code

Contribution of P.P. Sullivan, NCAR, Colorado (LabexMER mobility)



- Domain $4\lambda \times 4\lambda \times 1\lambda$
- Discretization $256 \times 256 \times 128$

NB: Typical simulations are $(3000{,}3000{,}800)$ m discretized using $(1024{,}1024{,}512)$ grid points on 2048 cores

- Input data
  - Bottom BC = **wave field**
  - Wavelength $\boldsymbol{\lambda}$
  - Initial friction velocity u_* defined with wave age $\frac{\boldsymbol{c}}{\boldsymbol{u_*}}$
- Turbulence **initialization** with **heating** flux at the bottom (flat)
- At $t = 0$ and during a few iterations, non moving and flat mesh
- $0.01 < t < 0.25$: **ramp** on the wave amplitude

Atmospheric code

CFD code

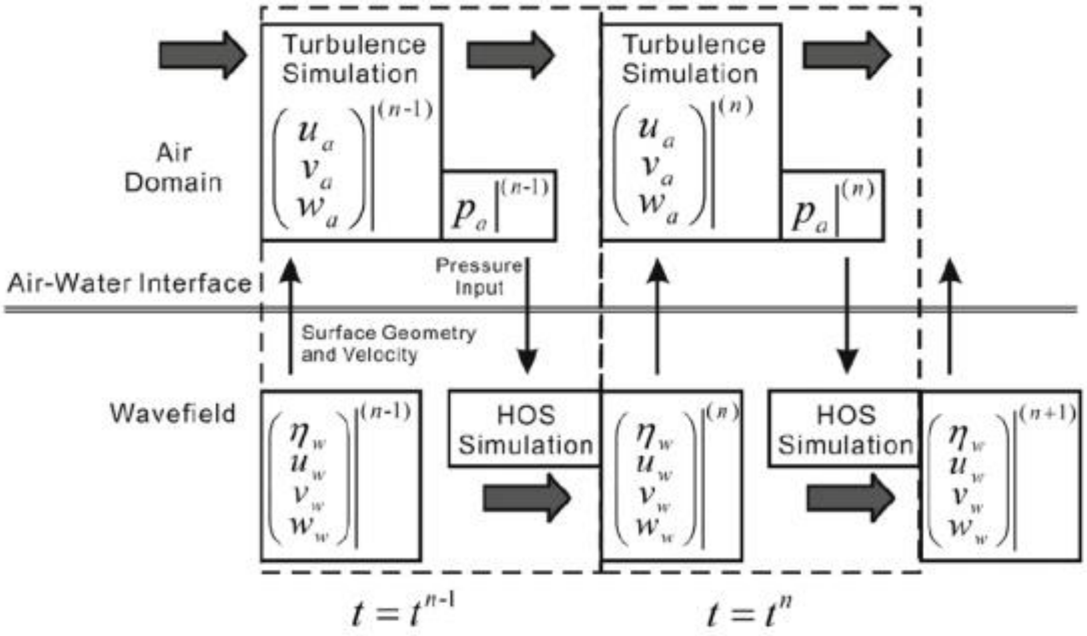
- LES modelling of the atmospheric boundary layer
- Here, incompressible air and neutral atmosphere
- **Spatially filtered** quantities $\left(u_i, p^* = \frac{p}{\rho}, e\right)$
  - GS – grid scale = resolved quantities
  - SGS – subgrid scale = modelled quantities
- **Momentum equation**

$$\underset{\substack{\downarrow \\ \text{unsteady}}}{\frac{\partial u_i}{\partial t}} = -\underset{\substack{\downarrow \\ \text{advection}}}{\frac{\partial u_j u_i}{\partial x_j}} - \underset{\substack{\downarrow \\ \text{pressure} \\ \text{gradient}}}{\frac{\partial p^*}{\partial x_i}} - \underset{\substack{\downarrow \\ \text{SGS mom.} \\ \text{flux}}}{\frac{\partial \tau_{ij}}{\partial x_j}} - \underset{\substack{\downarrow \\ \text{large-scale external} \\ \text{pressure gradient}}}{\frac{\partial \mathcal{P}}{\partial x_i}}$$

- **Surface-following** mesh
- **Fine discretization** near the free surface to decrease the dependence on the SGS modelling

Coupling procedure

Coupling with a nonlinear sea state model (eg. Yang and Shen, 2011)



Coupling through MPI communications

Yang and Shen. Simulation of viscous flows with undulatory boundaries: PartII. Coupling with other solvers for two-fluid computations. *J. Comput. Phys.*, 2011.

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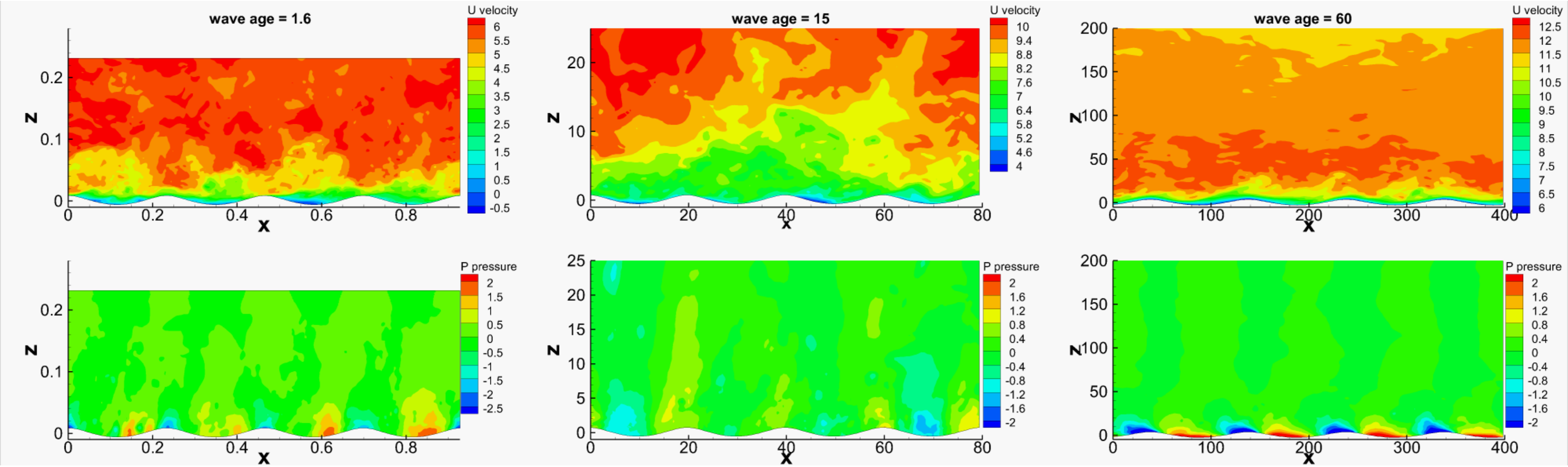
Results: one-way coupling

1) HOS-LES simulations for different wave ages

		Case 1	Case 2	Case 3
Ratio wind/ wave	**Wave age (Cp/u*)**	1.6	15	60
Wave parameters	**Wavelength λ**	0.23 m	20 m	100 m
	Period T	0.39 s	3.6 s	8 s
	Amplitude A	7.4e-3 m	6.4e-1 m	3.2 m
	Phase velocity Cp	0.60 m/s	5.6 m/s	12.5 m/s
Wind param.	**Initial friction velocity**	0.38 m/s	0.37 m/s	0.21 m/s
	U10m log law	11 m/s	10.8 m/s	6 m/s

Results: one-way coupling

1) HOS-LES simulations for different wave ages



Drag force = -0.046 N

Wave drag on wind

Drag force = -0.059 N

Wave drag on wind

Drag force = 0.16 N

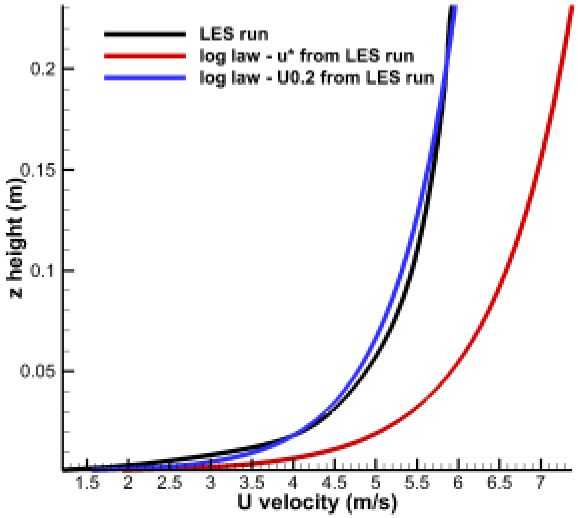
Wave thrust on wind

Results: one-way coupling

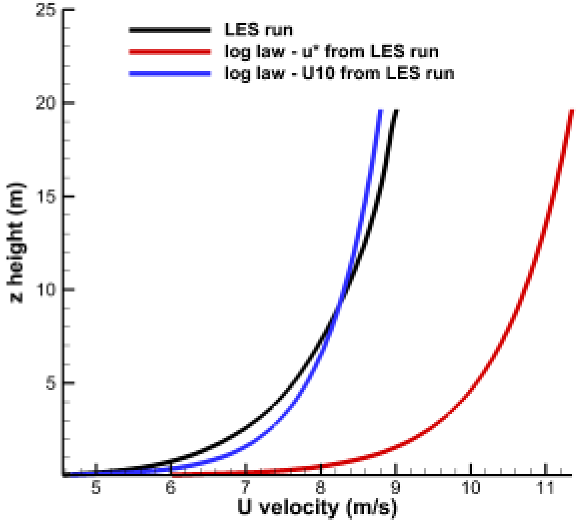
1) HOS-LES simulations for different wave ages

Log law: $U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) = \frac{\sqrt{C_D}U_{10}}{\kappa}\ln\left(\frac{z}{z_0}\right)$

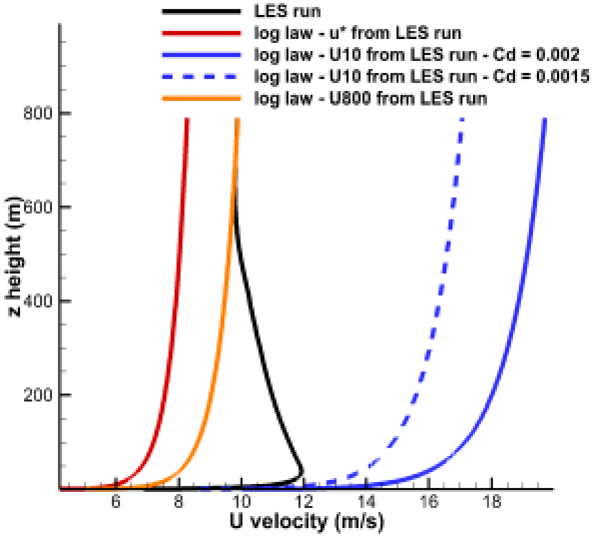
Wave age 1.6 (case 1)



Wave age 15 (case 2)



Wave age 60 (case 3)



The wind profile does not satisfy the log law (Monin-Obukhov theory), especially at high wave ages (low-level jet $^{(1)}$)

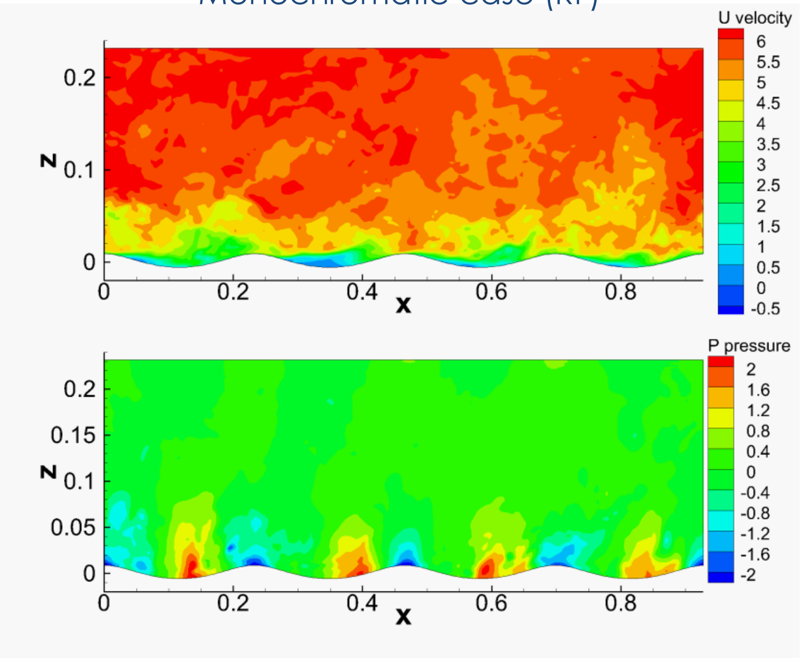
(1) Kudryavtsev et Makin, *Impact of Swell on the Marine Atmospheric Boundary Layer*. Journal of Physical Oceanography, 2003

Results: one-way coupling

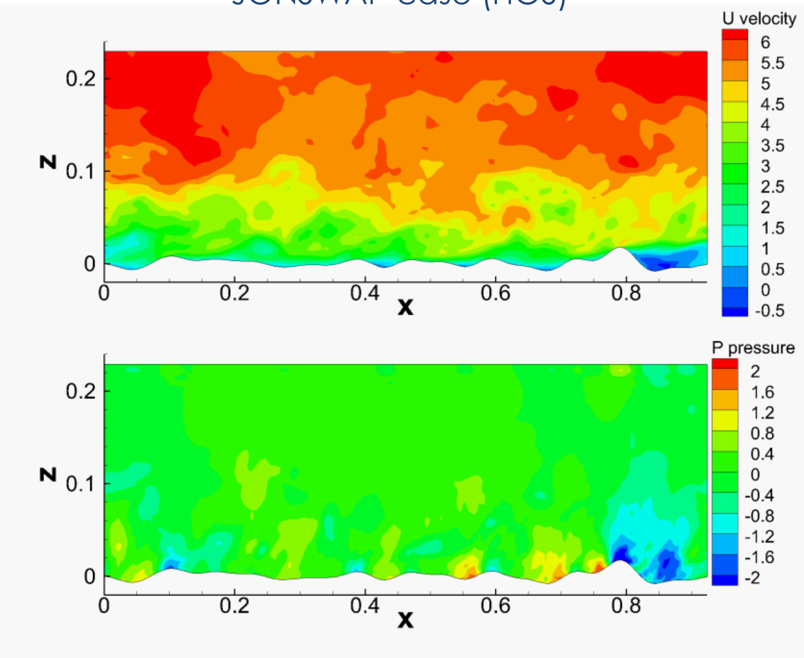
2) Monochromatic (RF) and JONSWAP(HOS) cases

- Wave age = 1.6
- RF: $\lambda = 0.23$ m, $A = 7.4e - 3$ m, $kA = 0.2$
- HOS: $H_s = 2.1e - 2$ m, $T_p = 0.39$ s ⇔ $kA = 0.2$
- Initial friction velocity = 0.38 m/s

Monochromatic case (RF)



JONSWAP case (HOS)

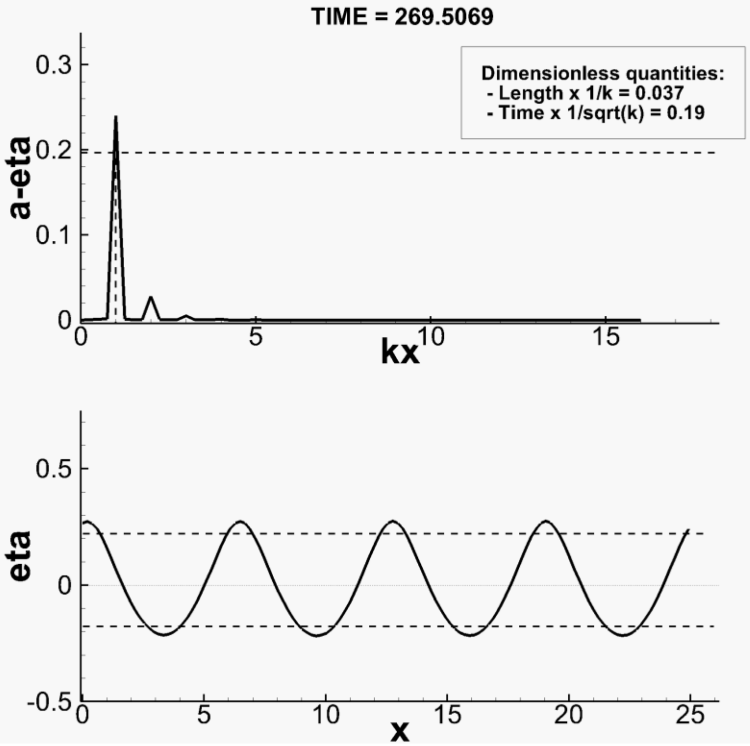


Results: two-way coupling

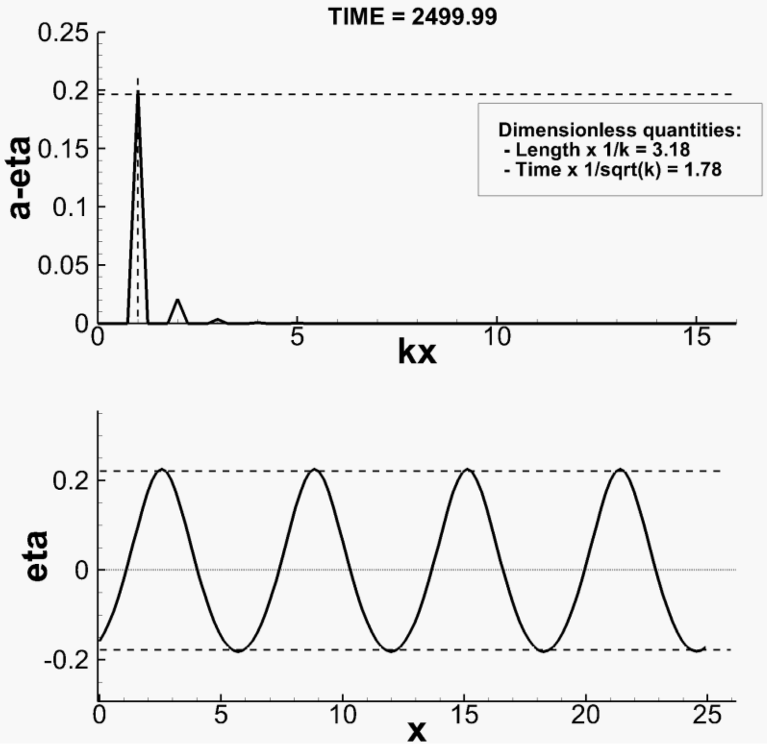
3) Monochromatic RF

$\lambda = 0.23$ m, $A = 7.4e - 3$ m, $kA = 0.2$

Wave age = 1.6



Wave age = 15



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Outlook and conclusions

- HOS-LES coupling through MPI communication
    - LES pressure to HOS
    - Wave elevation and orbital velocities from HOS to LES
- Large range of wave ages
    - At small wave ages, wind profile can be estimated through log law and parameters extracted from the LES simulation
    - Log law does not predict low-level jet at high wave age
- LES simulations to be validated with data (in process)
- Two-way coupling: a dissipation model will be implemented in HOS

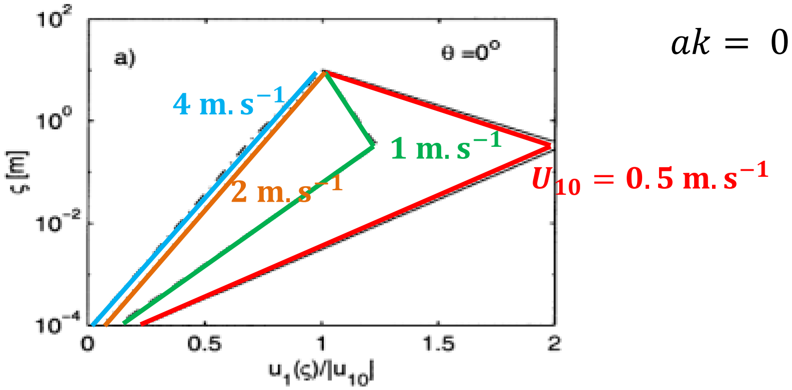
Wind-wave coupling

Thank you for your attention

Wind-wave coupling

Field experiments:

- Disturbance of the momentum flux inside the wave boundary layer and far above in the atmospheric boundary layer.
- When $\mathrm{U}_{\mathrm{wave}} > \mathrm{U}_{\mathrm{wind}}$, in some conditions
  - Low-level jet near the free surface



$ak = 0.1$ and $C = 15\ \mathrm{m.s^{-1}}$

Kudryavtsev et Makin, *Impact of Swell on the Marine Atmospheric Boundary Layer*. Journal of Physical Oceanography, 2003