Advances in modelling wind farm blockage in thermally-stratified atmospheric boundary layers

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Pacific Institute *for the* Mathematical Sciences

OVERVIEW

- Wind Farm Blockage
- Atmospheric Gravity Waves
- Advances in Simulation Tools
- Advances in Engineering Models

WIND FARM BLOCKAGE

Wind

Ørsted cuts IRR target after n data for blockage, wake effec

Ørsted A/S (CPH:ORSTED) today l term target for unlevered lifecycle return (IRR) related to seven offsh projects after taking into conside developments.

The Danish energy major now ex unlevered lifecycle IRR, capacity-v average of 7%-8% for the Borssele Gode Wind 3, Borkum Riffgrund 3 Changhua 1&2a and 2b&4 and Re projects, all of which have been a company set a return target of 7.5

Orsted Lowers Offsh Warns of Industrywi

The industry leader now expects lower ra issues.

JOHN PARNELL | OCTOBER 30, 2019

Wake effect: Ørsted has moved to update its output forecasts. (Credit: Ørsted)

Blockage effect that hit Orsted shares 'could be bigger issue for onshore wind'

Industry experts say phenomenon a factor at 'any wind farm, onshore or offshore, large or small'

3 January 2020 15:01 GMT *UPDATED 3 January 2020 15:03 GMT*

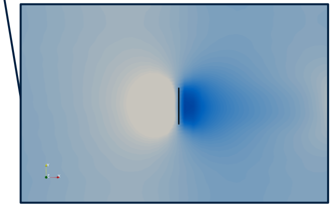
By Andrew Lee

WIND FARM BLOCKAGE

Wind farm upstream flow deceleration, i.e. **blockage**, can lead up severe power losses under strong stability and it is currently not fully modeled by engineering wake models.

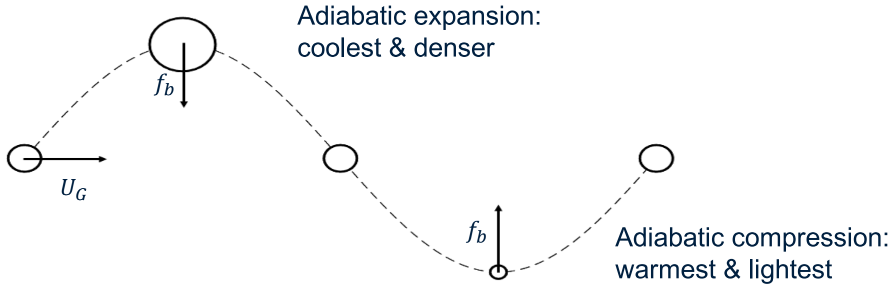
- **Global blockage** arises from the interaction of the wind farm with the thermally stratified atmosphere.

- **Local blockage** arises from local pressure perturbation and is also observed in fully neutral conditions.

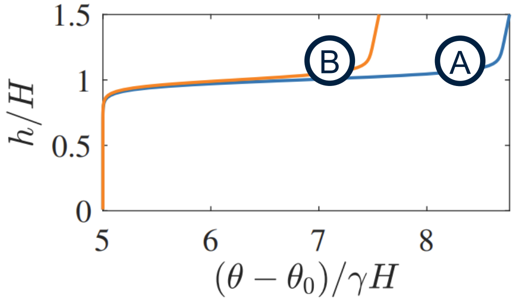


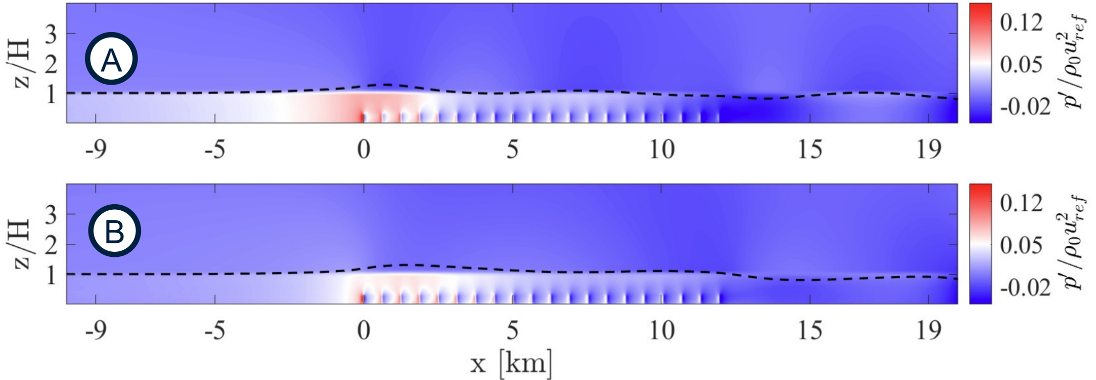
ATMOSPHERIC GRAVITY WAVES

Gravity waves are of two types: **interfacial** (2D) and **internal** (3D). They develop inside the inversion layer and above the atmospheric boundary layer (ABL) respectively, where thermal stratification exists, as the ABL is perturbed from equilibrium.



Lapse-rate and inversion strength to model atmosphere stability.





I. Advances in Simulation Tools

II. Advances in Low-cost Engineering Models

RESOLVING WIND FARM / GRAVITY WAVE COUPLING

- **Atmospheric turbulence** (possibly affected by stability): off-line precursor or concurrent-precursor method
- **Large variety of scales involved**: possibility to perform mesh grading in all directions
- **AGW reflections and interactions**: concurrent-precursor method and Rayleigh damping
- **Highly parallel**: use of state-of-the-art parallel libraries such as *OpenMPI*, *PETSc*, *HYPRE* and *HDF5*.

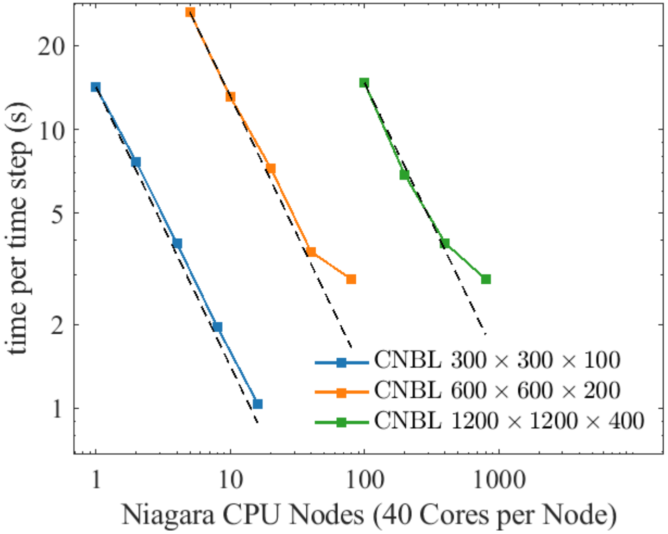
Software	Open source	Concurrent Precursor	Highly parallel	Method	Terrain
SOWFA (NREL)	YES	NO	NO	Finite-volume	Body fitted
SP-Wind (KU-Leuven)	NO	YES	-	Pseudo-spectral	NO
WiRE-LES (EPFL)	NO	YES	-	Pseudo-spectral	Body fitted
PALM (Leibniz Universität Hannover)	YES	NO	YES	Finite-volume	IBM + body fitted
EllipSys3D (DTU)	NO	NO	-	Finite-volume	Body fitted
ExaWind (NREL, ORNL, SNL)	YES	NO	YES	Finite-volume	Body fitted
TOSCA	YES	YES	YES	Finite-volume	IBM + body fitted

TOSCA: TOOLBOX FOR STRATIFIED CONVECTIVE ATMOSPHERES

- Incompressible LES solver with (optional) Coriolis forces and Boussinesq approximation
- Buoyancy force evaluated by solving a transport-diffusion equation for the potential temperature
- Dynamic Smagorinsky SGS model with Lagrangian averaging

$$
\begin{aligned}
\frac{\partial u_i}{\partial x_i} &= 0 \\
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_j u_i) &= -\frac{\partial}{\partial x_i}\left(\frac{p}{\rho_0}\right) + \frac{\partial}{\partial x_j}\left[\nu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\rho_k}{\rho_0} g_i - 2\epsilon_{ijk}\Omega_j u_k + s_i + f_i \\
\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial x_j}(u_j \theta) &= \frac{\partial}{\partial x_j}\left(\nu_{eff}\frac{\partial \theta}{\partial x_j}\right)
\end{aligned}
$$

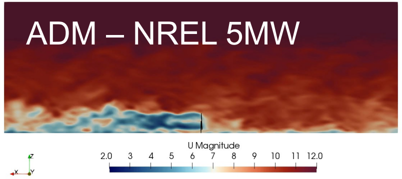
f_i is wind turbine body force, s_i accounts for extra sources.

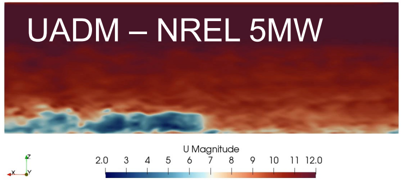


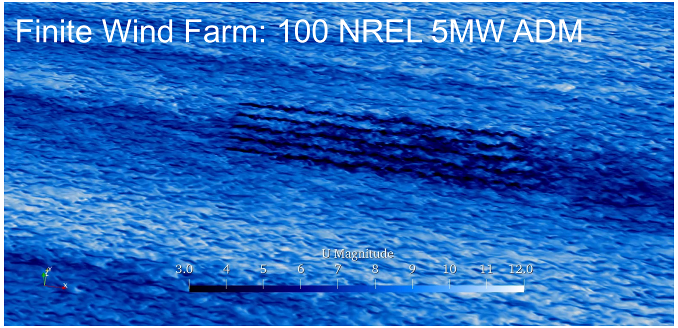
- Wind turbines: actuator models (ALM, ADM, Uniform-ADM, AFM, canopy models); fully-resolved via immersed boundary method (IBM)
- Complex terrain: immersed boundary method (extended for moving bodies)
- Overset mesh

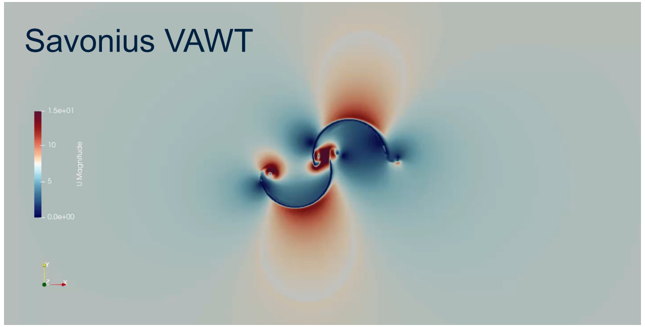
THE TOSCA PROJECT

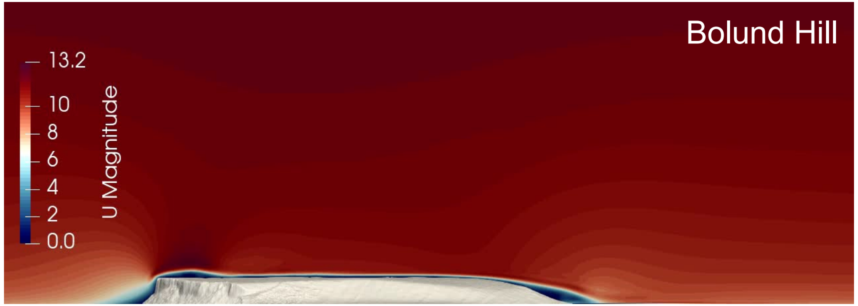
TOSCA preprint
and GitHub link:

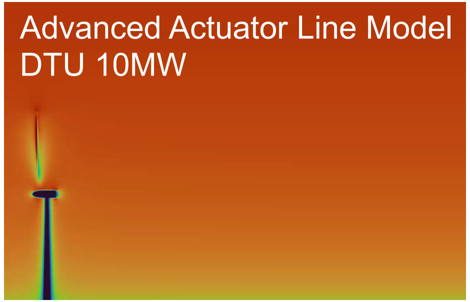


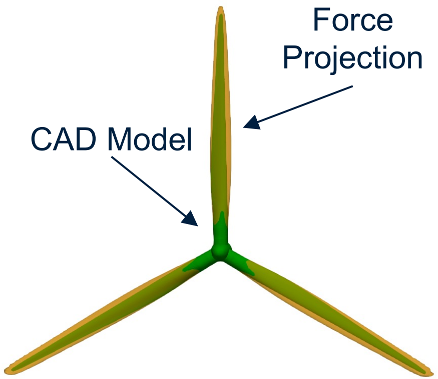




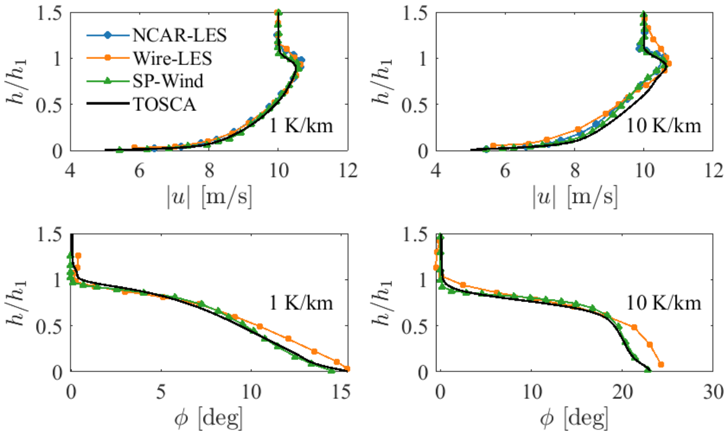


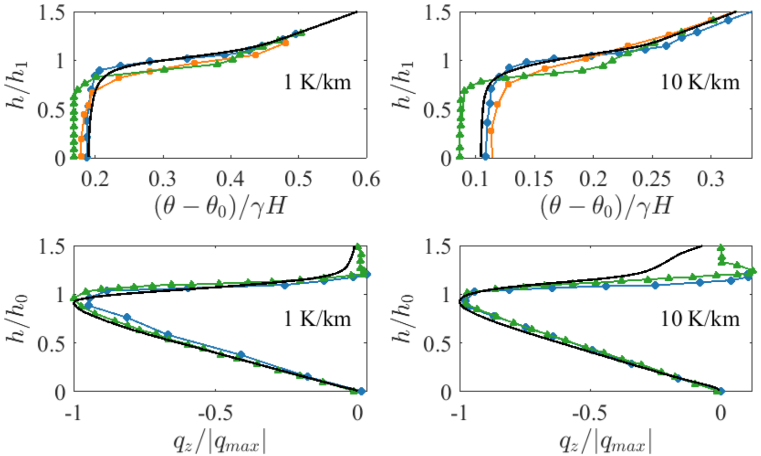


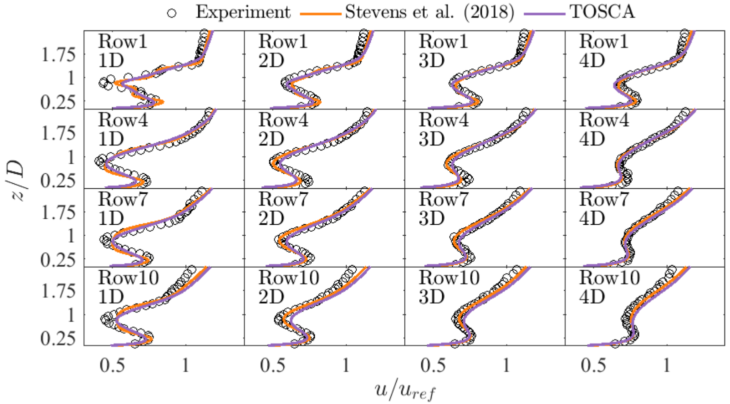




TOSCA VALIDATION





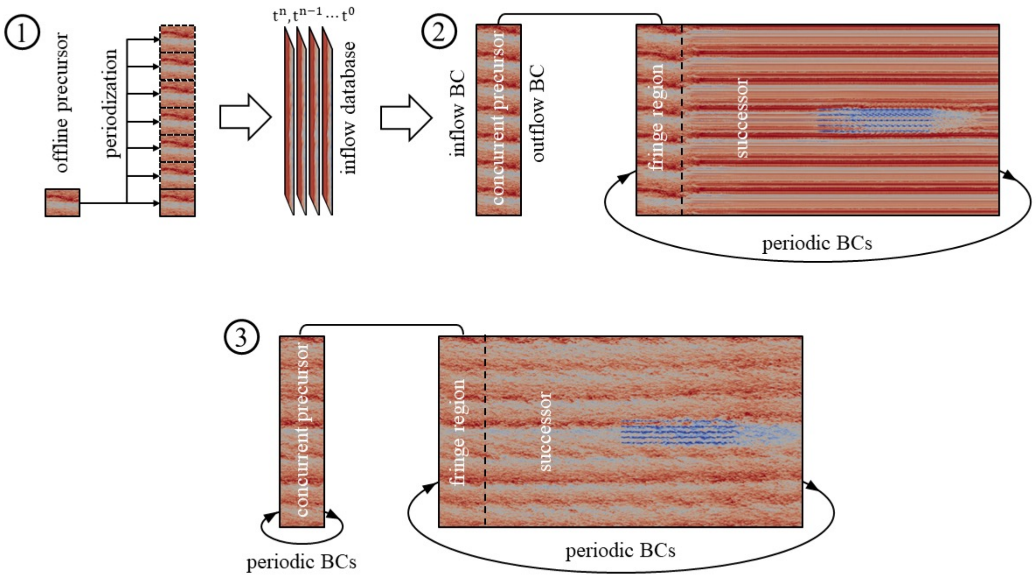


- Actuator models validated on isolated wind turbines with and without atmospheric turbulence, as well as wind turbine clusters

- Extensive validation of CNBL simulations against other codes

FINITE WIND FARM LES - METHODOLOGY

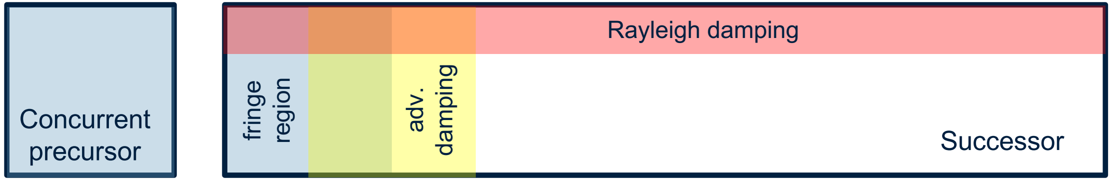
To save computational resources in ABL spin-up phase, we developed a hybrid off-line/concurrent precursor method, consisting of three phases:



1. Off-line precursor is run on a suitable domain for several model-hours (100k s), slices are saved and stored
2. Inflow-outflow boundary conditions are used in the concurrent-precursor domain for one flow-through time, **inflow slices are periodized** in the spanwise direction
3. Concurrent precursor's boundary conditions are switched to periodic, and solution is carried on for the desired amount of time.

FINITE WIND FARM LES - METHODOLOGY

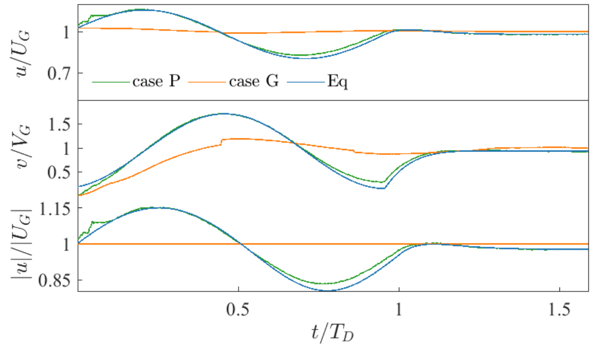
- Off-line precursor uses a **hub-height velocity controller**.
- Mean potential temperature controller to avoid inversion layer growth.
- Geostrophic damping source term added to the momentum equation to damp inertial oscillations



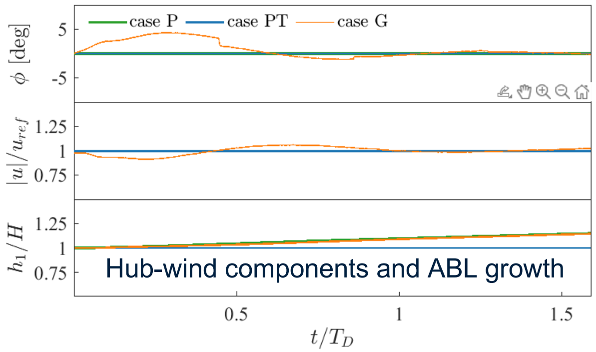
Our approach allows:

- Final temperature profiles independent of time (via T controller)
- Ground temperature is constant & comparable across codes (via p controller)
- Hub-height velocity is specified
- Temperature is uncontrolled in the successor; inversion layer is freely displaced

Geostrophic wind components



$$\begin{cases} \frac{\partial u}{\partial t} + 2\alpha f_c(u-U_G) + f_c(V_G - v) = 0 \\ \frac{\partial v}{\partial t} + 2\alpha f_c(v - V_G) - f_c(U_G - u) = 0 \end{cases}$$



LES - PRECURSORS

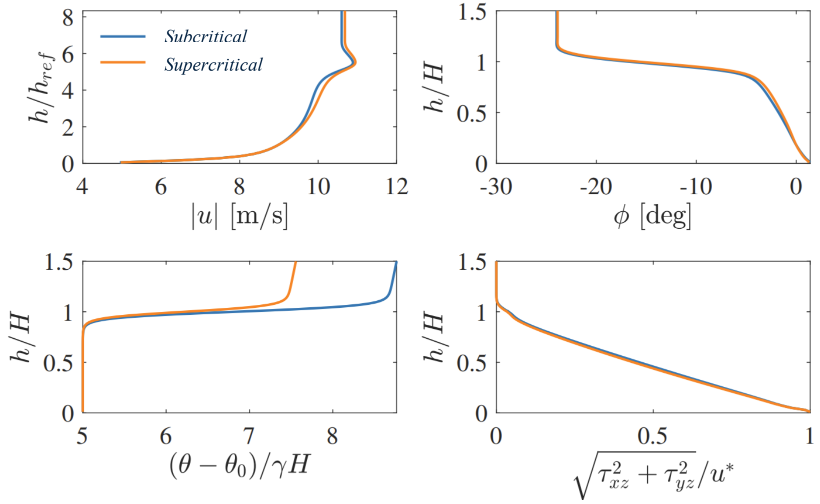
Non-dimensional ABL parameters are chosen in the high wind farm-gravity wave interaction region (Allaerts and Meyers, 2019).

u_{ref} [m/s]	h_{ref} [m]	θ_0 [K]	Δh [m]	γ [K/km]	H [m]	f_c [1/s]	z_0 [m]
9.0	90	300	100	1	500	$9.6057 \cdot 10^{-5}$	0.05

Inversion Froude number:

$$F_r = \frac{U_b}{\sqrt{Hg\,\Delta\theta/\theta_{ref}}}$$

F_r determines whether interface waves travel faster (***subcritical***) or slower (***supercritical***) than the flow speed, varying the amount of blockage.

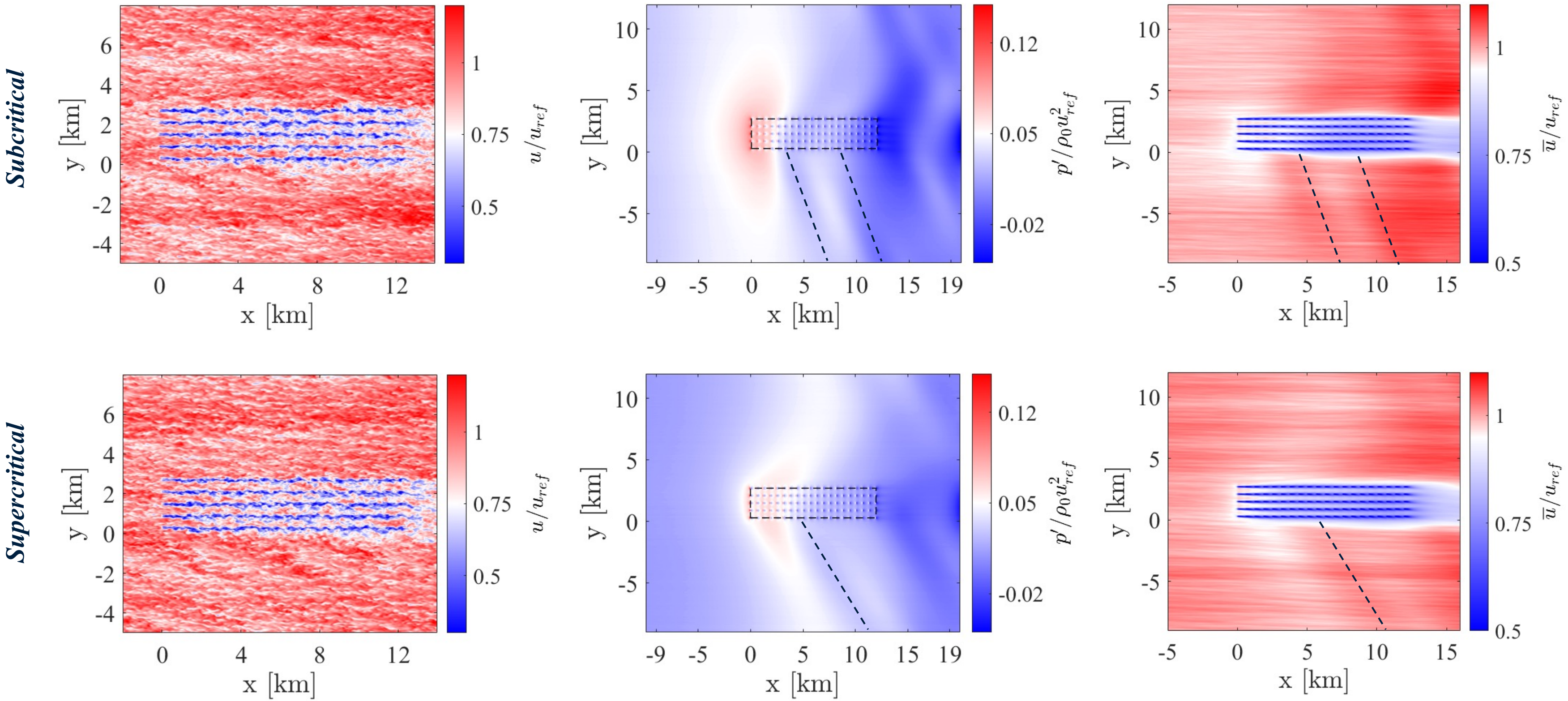


Subcritical	$F_r \approx 0.9$	$\Delta\theta = 7.312$
Supercritical	$F_r \approx 1.1$	$\Delta\theta = 4.895$

1. Wind and shear stress profiles almost identical,
2. Cases only differ in thermal stratification,
3. Reduced models not accounting for stability would produce identical results.

LES – SUCCESSOR WITH 100 NREL 5-MW TURBINES

Gravity wave-induced pressure perturbations change considerably from subcritical to supercritical conditions, affecting the mean velocity field.



I. Advances in Simulation Tools

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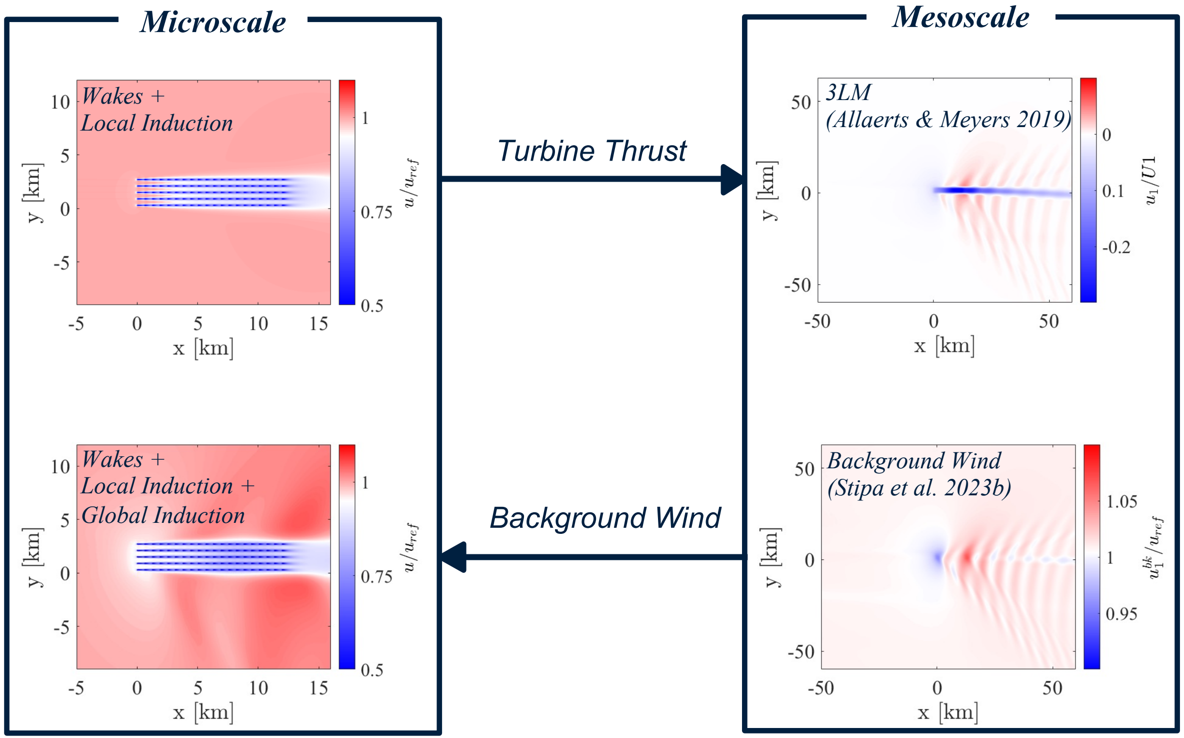
WIND FARM BLOCKAGE – MULTI SCALE COUPLED MODEL

Represent the effect of gravity wave-induced pressure gradients through an heterogeneous «**background**» velocity field.

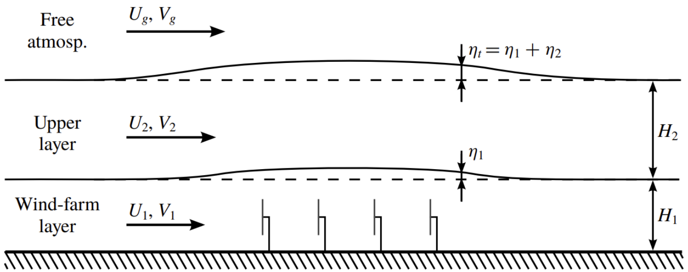


This requires:

1. Wake superposition method where the background wind varies in space.
2. Solve a modified set of 3-layer equations.
3. Reconstruct wind speed from depth-average to actual wind.
4. Knowledge of the unperturbed ABL background state.

MULTI SCALE COUPLED MODEL – WIND RECONSTRUCTION

1. The 3LM solves for perturbation velocities, pressures and BL displacement: $\boldsymbol{u}_1$, $\boldsymbol{u}_2$, p, η respectively.
2. To avoid wake double counting the 3LM was coupled to wake models by correcting U_∞ upstream the wind farm.



Allaerts & Meyers (2019)

Depth-averaged linearized Navier-Stokes equations for the wind farm layer:

$$\begin{cases} U_1\dfrac{\partial u_1}{\partial x} + V_1\dfrac{\partial u_1}{\partial y} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial x} = -f_c v_1 + \dfrac{D_{11}}{H_1}(u_2-u_1) + \dfrac{D_{12}}{H_1}(v_2-v_1) - \dfrac{C_{11}}{H_1}u_1 - \dfrac{C_{12}}{H_1}v_1 - \dfrac{f_x}{H_1} \\ U^1\dfrac{\partial v_1}{\partial x} + V^1\dfrac{\partial v_1}{\partial y} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial y} = f_c u_1 + \dfrac{D_{21}}{H_1}(u_2-u_1) + \dfrac{D_{22}}{H_1}(v_2-v_1) - \dfrac{C_{21}}{H_1}u_1 - \dfrac{C_{22}}{H_1}v_1 - \dfrac{f_y}{H_1} \\ U_1\dfrac{\partial \eta_1}{\partial x} + V_1\dfrac{\partial \eta_1}{\partial y} + H_1\left(\dfrac{\partial u_1}{\partial x} + \dfrac{\partial v_1}{\partial y}\right) = 0 \end{cases}$$

3. Compute the pressure perturbation field using the 3LM, using turbine thrust as a forcing term.
4. Run a modified set of 3-layer equations w/o wind farm forcing, using p as forcing term (implicitly fixes η), to compute $\boldsymbol{u}_1^{bk}$, $\boldsymbol{u}_2^{bk}$

Depth-averaged linearized Navier-Stokes reconstruction equations for the wind farm layer:

$$\begin{cases} U_1\dfrac{\partial u_1^{\mathrm{bk}}}{\partial x} + V_1\dfrac{\partial u_1^{\mathrm{bk}}}{\partial y} = -f_c v_1^{\mathrm{bk}} + \dfrac{D_{11}}{H_1}(u_2^{\mathrm{bk}}-u_1^{\mathrm{bk}}) + \dfrac{D_{12}}{H_1}(v_2^{\mathrm{bk}}-v_1^{\mathrm{bk}}) - \dfrac{C_{11}}{H_1}u_1^{\mathrm{bk}} - \dfrac{C_{12}}{H_1}v_1^{\mathrm{bk}} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial x} \\ U^1\dfrac{\partial v_1^{\mathrm{bk}}}{\partial x} + V^1\dfrac{\partial v_1^{\mathrm{bk}}}{\partial y} = f_c u_1^{\mathrm{bk}} + \dfrac{D_{21}}{H_1}(u_2^{\mathrm{bk}}-u_1^{\mathrm{bk}}) + \dfrac{D_{22}}{H_1}(v_2^{\mathrm{bk}}-v_1^{\mathrm{bk}}) - \dfrac{C_{21}}{H_1}u_1^{\mathrm{bk}} - \dfrac{C_{22}}{H_1}v_1^{\mathrm{bk}} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial y} \end{cases}$$

Average matching procedure:

$$\sqrt{\left(U_1+u_1^{\mathrm{bk}}\right)^2 + \left(V_1+v_1^{\mathrm{bk}}\right)^2} = \frac{u^*(x,y)}{\kappa(H_1-z_0)}\int_{z_0}^{H_1}\left(\ln\left(\frac{z}{z_0}\right)\right)dz$$

$$\mathbf{U_b}(\mathbf{x}) = \frac{u^*(x,y)}{\kappa}\left(\ln\left(\frac{z}{z_0}\right)\cos\left(\phi(z)\right)\mathbf{i} + \ln\left(\frac{z}{z_0}\right)\sin\left(\phi(z)\right)\mathbf{j}\right)$$

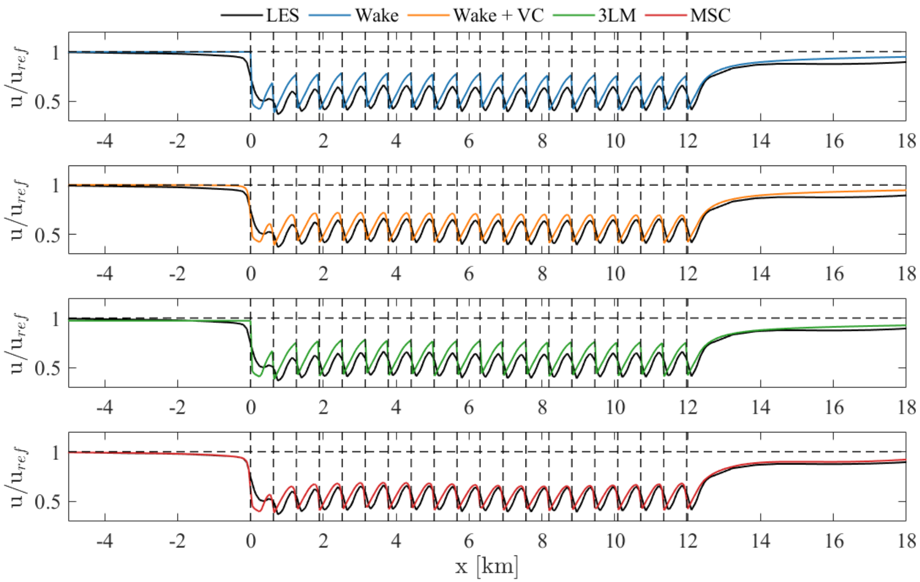
5. Retrieve $\boldsymbol{U}_b(\boldsymbol{x})$ by matching the average of a log-law profile in the first layer

RESULTS

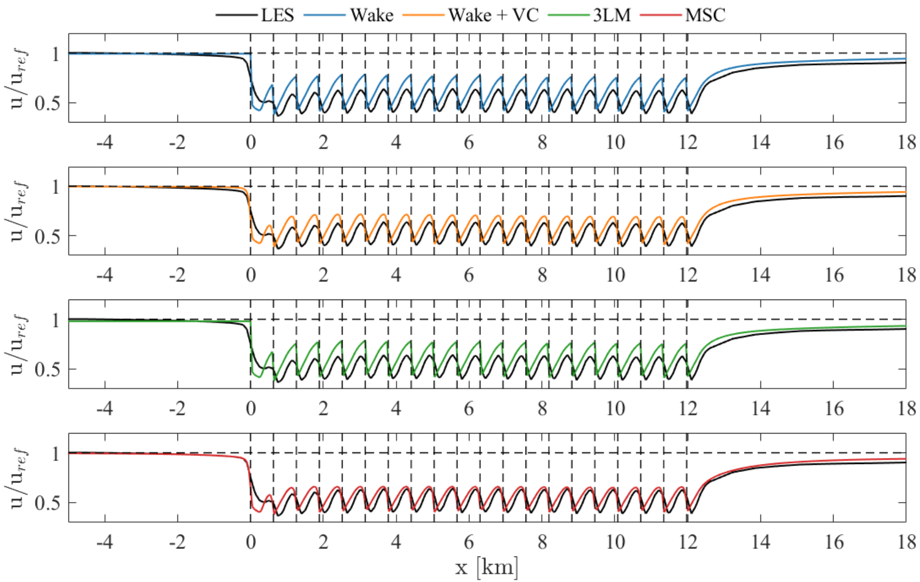
The MSC model provides a **local coupling** between the meso and microscale:

1. Background velocity varies at each location and accounts for global blockage
2. Local blockage and wake effects are given by a wake + local induction model
3. The model runs in ≈ 30 s per wind speed and direction in Matlab (further optimization is possible)

Row-aveaged velocity, subcritical case:



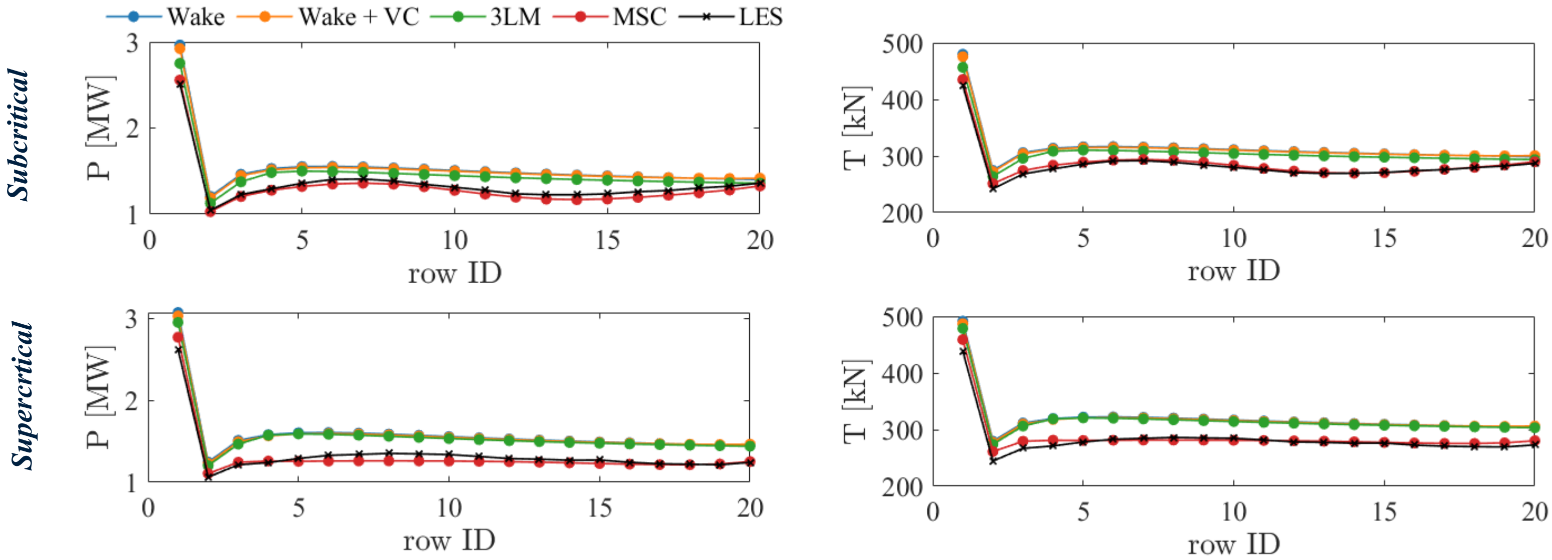
Row-aveaged velocity, supercritical case:



RESULTS

1. Subcritical case shows higher blockage at first row
2. Gravity wave-induced pressure gradients increase turbine power inside the wind farm in the subcritical regime

Row-averaged thrust and power distributions:



RESULTS

1. Subcritical case shows higher blockage at first row
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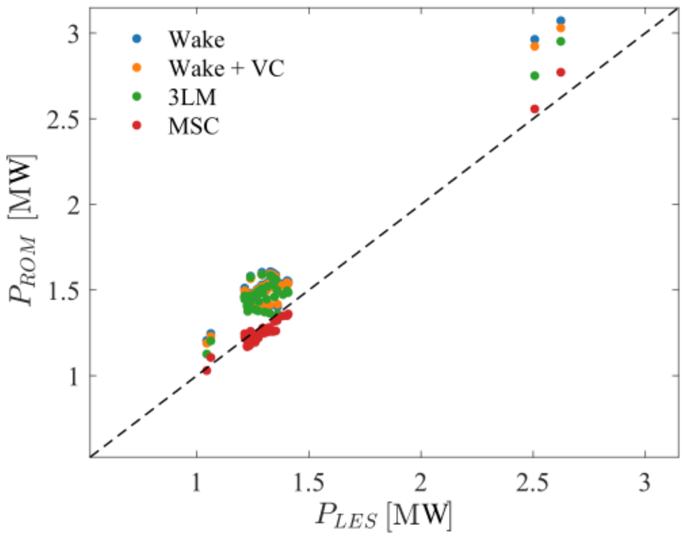
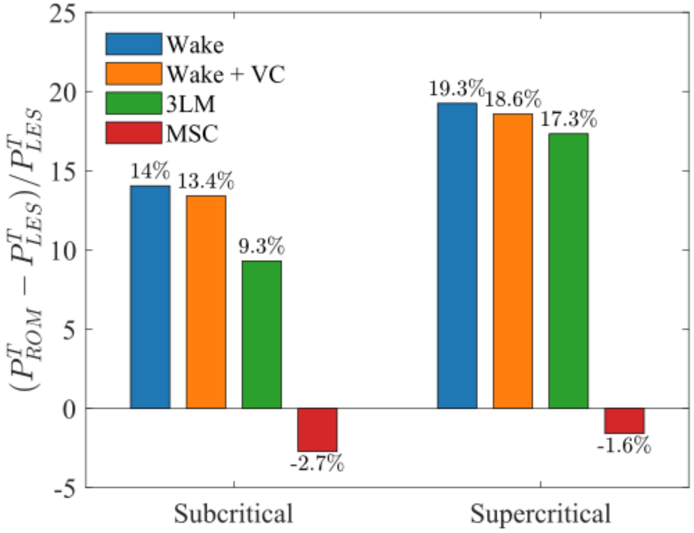
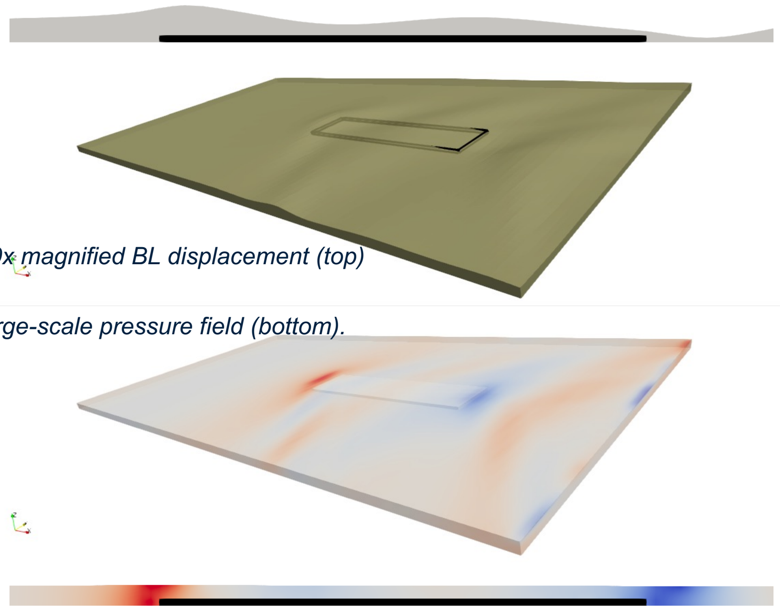
Local and global turbine power errors:





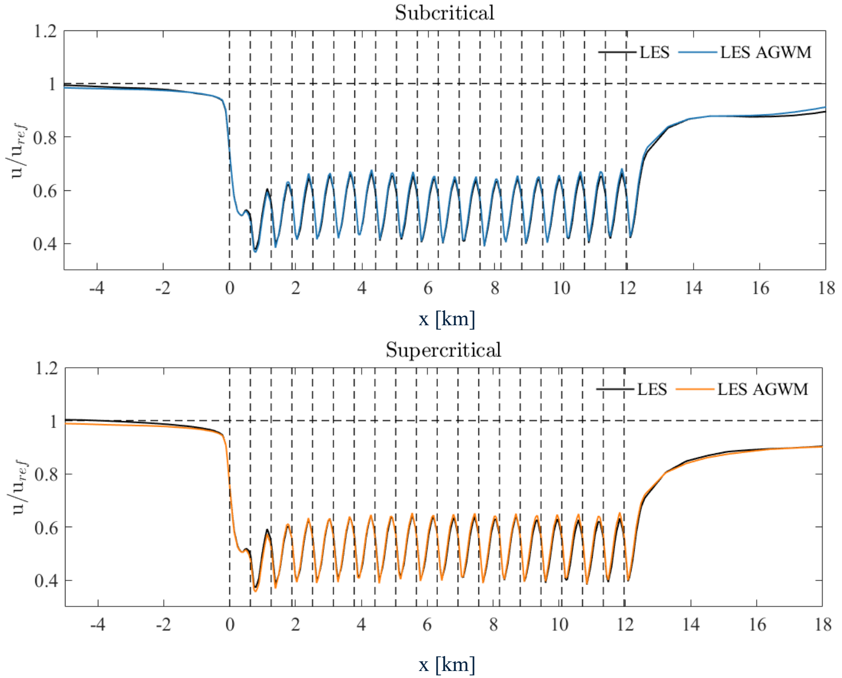
FUTURE WORK

1. Gravity waves have a major impact on wind farm performance, but capturing them within LES is extremely challenging and computationally demanding: impossible to simulate farm-farm interaction.
2. Can we model gravity waves just as we model turbulence? Or at least can we model their effect on the wind farm and the flow?



20x magnified BL displacement (top)

large-scale pressure field (bottom).



CONCLUSIONS

1. Global blockage strongly depends on potential temperature profile.
2. Gravity waves reflections at the domain boundaries need to be opportunely handled in LES.
3. The multi-scale coupled (MSC) framework is able to capture wind farm-gravity wave interaction.
4. MSC model underestimates power for the whole wind farm by less than 3% in both cases.
5. Wake model alone (w or w/o local induction) overpredicts power by more than 15% in both cases.
6. We can model the effect that gravity waves have on the wind farm without actually capturing them.

THANK YOU

Mohammad Haji Mohammadi

Sebastiano Stipa

Arjun Ajay

UBC

UBCO CFD LAB

TOSCA
UBCO CFD LAB

UL Solutions

Openwind

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