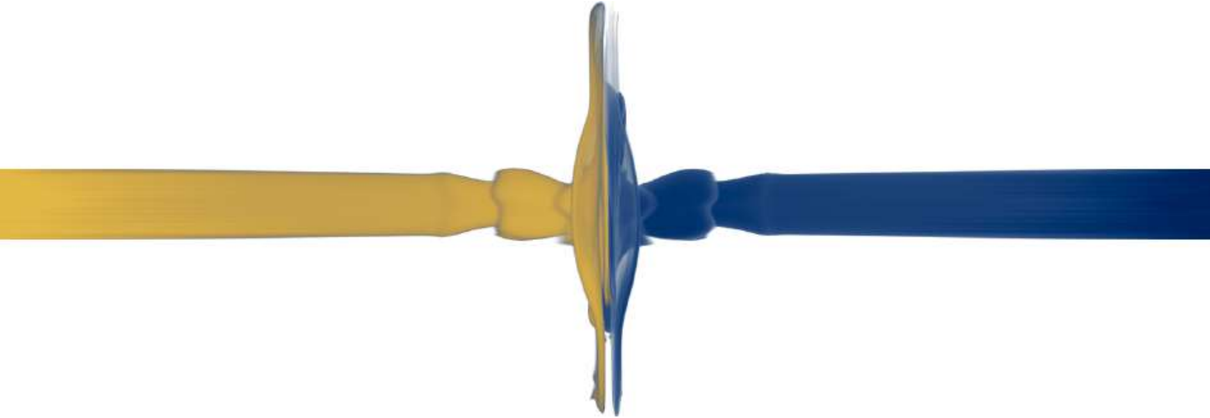
Towards High-Fidelity Digital Twins of Offshore Wind Turbines Utilizing State-of-the-Art Heterogeneous Supercomputers



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University of Liverpool | EU Horizon Project SeaDream | October 3, 2025

Motivation

Ensemble simulations of hemodynamics in moving vessels

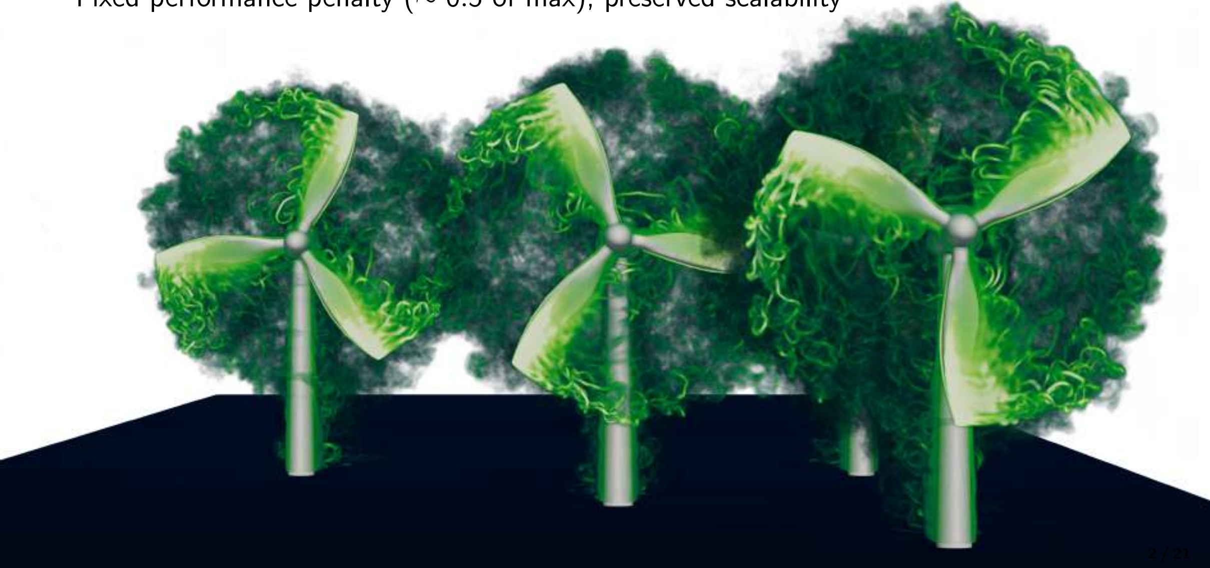
Foreseeing the next generation of Aircraft

- **Efficient FSI needed**

Open Source High Performance LBM for Heterogeneous Clusters

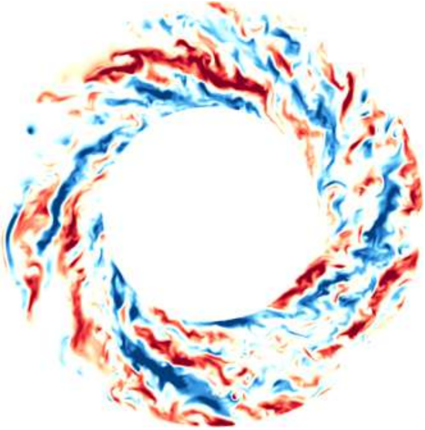
Motivation: Wind Park

- Two-way coupled LES-HLBM-FSI, Re $:= 1.2e6$, $n_{\text{cells}} := 1.5e9$
- Used 4xH100 on HoreKa Teal, $\sim$ 8h simulation time
- Fixed performance penalty (~ 0.5 of max), preserved scalability

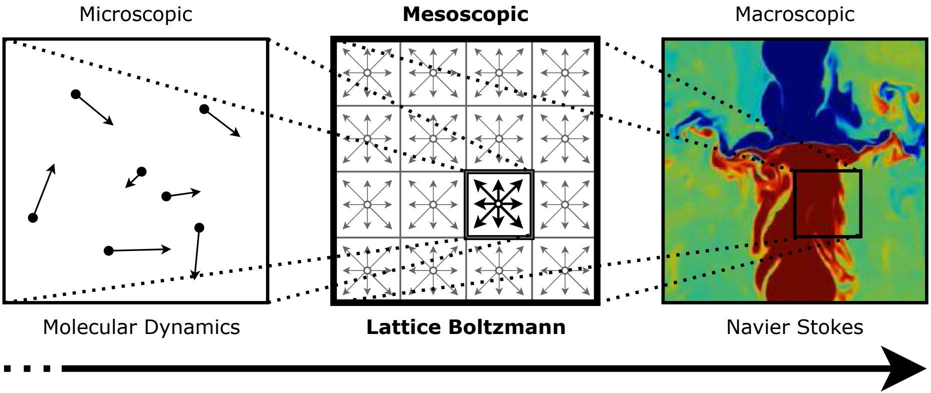


Outline

- Methodology
- Validation
- Performance

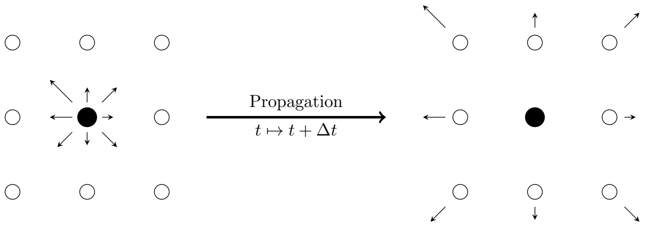


Lattice Boltzmann Methods



Lattice Boltzmann Methods

Discretization on **Regular Lattice** using discrete velocity stencil
Separation into **Collide & Stream** steps



Collision is perfectly parallel computation

Streaming exchanges data in local neighborhood

Boundary Conditions / Coupling operates on data in local neighborhood

- **"All non-linearities local, all non-localities linear"**

Method: HHRRLBM-WMLES-FSI

. . . *homogenized hybrid regularized recursive lattice Boltzmann method* for *wall-modeled large eddy simulations* of *fluid-structure interaction* problems.

HHRRLBM	Moving boundary model, collision step
WM	Approximation of unresolved boundary layer
LES	Approximation of unresolved turbulent eddies
FSI	Boundaries are actually moving and structure response is modeled

Target Equation: FBNSE

macroscopic view Incompressible flows in time-dependent geometries

considered as filtered Brinkman–Navier–Stokes equations

discretized as homogenized LBM

The filtered Brinkman–Navier–Stokes equations

$$\begin{cases} \boldsymbol{\nabla} \cdot \bar{\boldsymbol{u}} = 0, & \text{in } \Omega \times I, \\ \frac{\partial \bar{\boldsymbol{u}}}{\partial t} + \bar{\boldsymbol{u}} \cdot \boldsymbol{\nabla} \bar{\boldsymbol{u}} = -\frac{\boldsymbol{\nabla} \bar{p}}{\rho} + \nu_{\mathrm{mo}} \boldsymbol{\nabla}^2 \bar{\boldsymbol{u}} + \frac{\nu_{\mathrm{mo}}}{K} \bar{\boldsymbol{u}} - \boldsymbol{\nabla} \cdot \mathrm{T}_{\mathrm{sgs}}, & \text{in } \Omega \times I, \end{cases} \tag{1}$$

for filtered pressure $\bar{p}$, velocity $\bar{\boldsymbol{u}}$ density ρ on spatial domain $\Omega \subseteq \mathbb{R}^3$ and time $I \subseteq \mathbb{R}_{>0}$.

HHRRLBM *can be considered* 2nd order approximation of FBNSE.

Collision step: HHRRLBM

The filtered and homogenized LB equation

$$f_i(\boldsymbol{x} + \xi_i \triangle t, t + \triangle t) = f_i^{\mathrm{eq}}(\boldsymbol{x}, t) + \left(1 - \frac{1}{\tau_{\mathrm{eff}}(\boldsymbol{x}, t)}\right) \tilde{f}_i^{(1)}(\boldsymbol{x}, t), \quad \text{in } \Omega_{\triangle x} \times I_{\triangle t}, \tag{2}$$

for distributions f_i along q discrete velocities ξ_i on a regular lattice $\Omega_{\triangle x} \subset \Omega \subseteq \mathbb{R}^3$ with cell size $\triangle x$ at discrete times $I_{\triangle t} \subset I \subseteq \mathbb{R}_{\geq 0}$, step size $\triangle t$. Using:

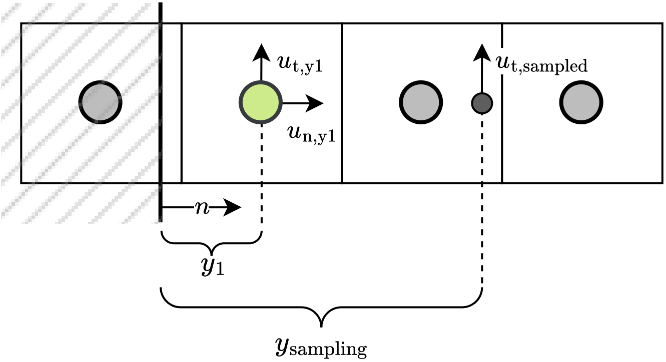
$$\tilde{f}_i^{(1)}(\boldsymbol{x}, t) = \sigma f_i^{(1)}(\boldsymbol{x}, t) - (1 - \sigma) f_i^{(1,FD)} \text{ for } \sigma \in [0, 1], \tag{3}$$

$$\widehat{\boldsymbol{u}}(\boldsymbol{x}, t) = (1 - d(\boldsymbol{x}, t))\boldsymbol{u}(\boldsymbol{x}, t) + d(\boldsymbol{x}, t)\boldsymbol{u}^{\mathrm{B}}(\boldsymbol{x}, t), \tag{4}$$

$$d(\boldsymbol{x}, t) = 1 - \frac{\triangle x^2 \nu \tau_{\mathrm{mo}}}{K(\boldsymbol{x}, t)}. \tag{5}$$

WMLES

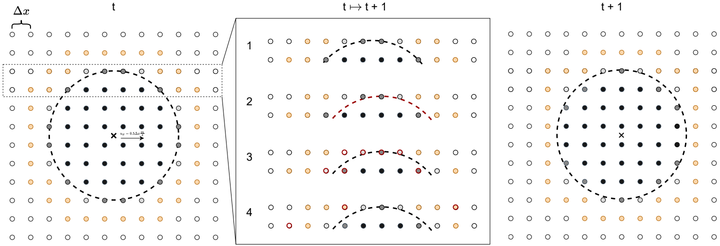
- Set non-zero friction velocity from empirical Spalding wall function
- Finite difference approximation of shear stresses



$$0 = \frac{u}{u_{\tau_w}} + \frac{1}{E}\left(\exp\left(\kappa\frac{u}{u_{\tau_w}}\right) - 1 - \kappa\frac{u}{u_{\tau_w}} - \frac{1}{2}\left(\kappa\frac{u}{u_{\tau_w}}\right)^2 - \frac{1}{6}\left(\kappa\frac{u}{u_{\tau_w}}\right)^3\right) - y\frac{u_{\tau_w}}{\nu}$$

is solved for the friction velocity u_{τ_w} using Newton iteration.

FSI

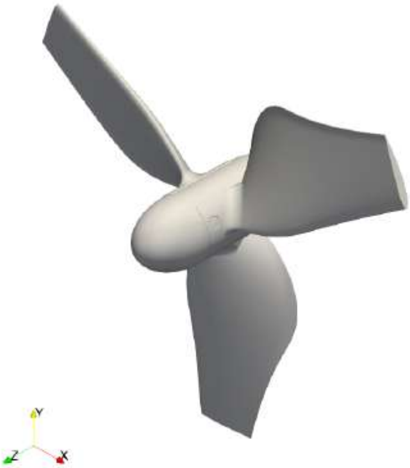


Let $\phi(\mathrm{x}, t)$ be the signed distance to the solid surface, $\epsilon_h = \epsilon\Delta x$ the width of the transition region coupled to Δx and $s : \mathbb{R} \to [0, 1]$ a transition function. Then

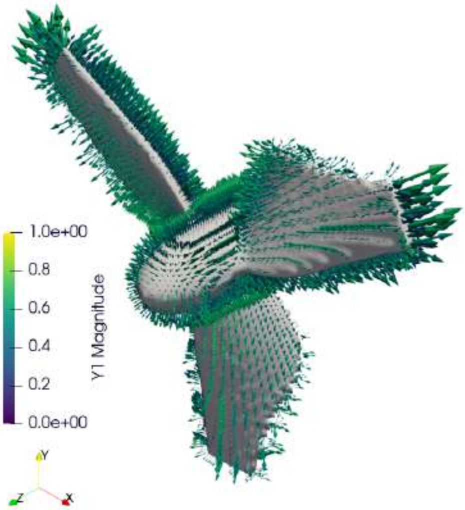
$$d(\mathrm{x}, t) := \begin{cases} 0 & \text{if } \phi(\mathrm{x}, t) \leq -\frac{\epsilon_h}{2} \\ s(\phi(\mathrm{x}, t)) & \text{if } \phi(\mathrm{x}, t) \in (-\frac{\epsilon_h}{2}, \frac{\epsilon_h}{2}) \\ 1 & \text{if } \phi(\mathrm{x}, t) \geq \frac{\epsilon_h}{2} \end{cases} \tag{6}$$

is the lattice porosity.

Example: Representations of rotor geometry for wall-modeling

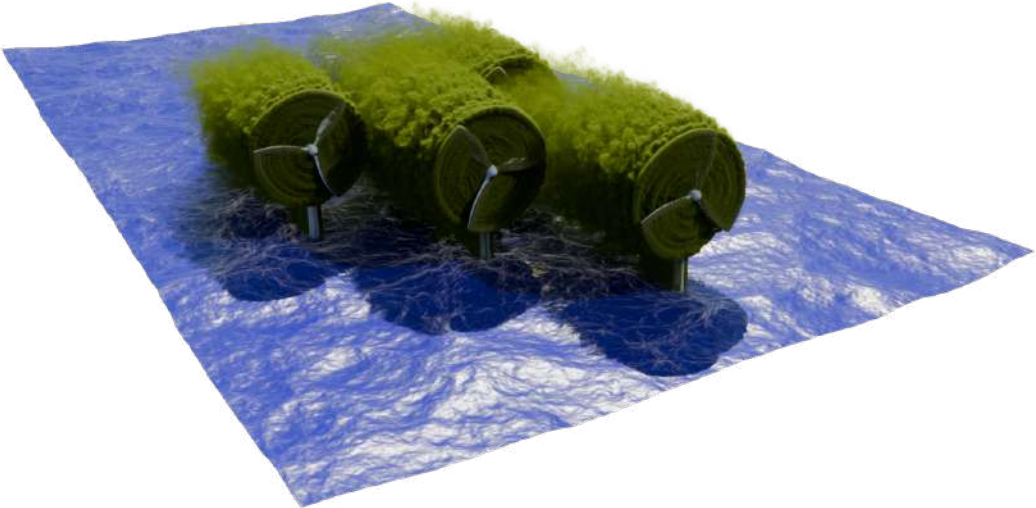


Cleaned rotor geometry as STL

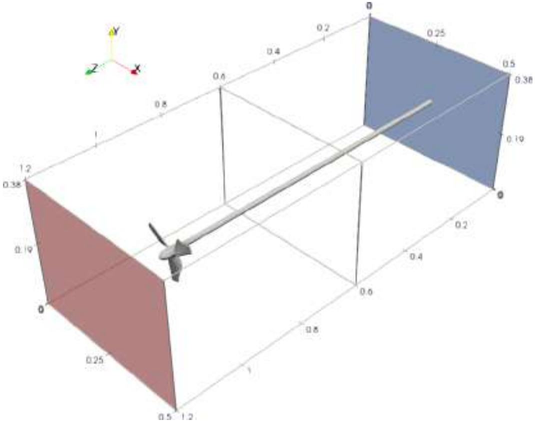


Level set of $d(x) = \frac{1}{2}$ and y_1 normals

Validation



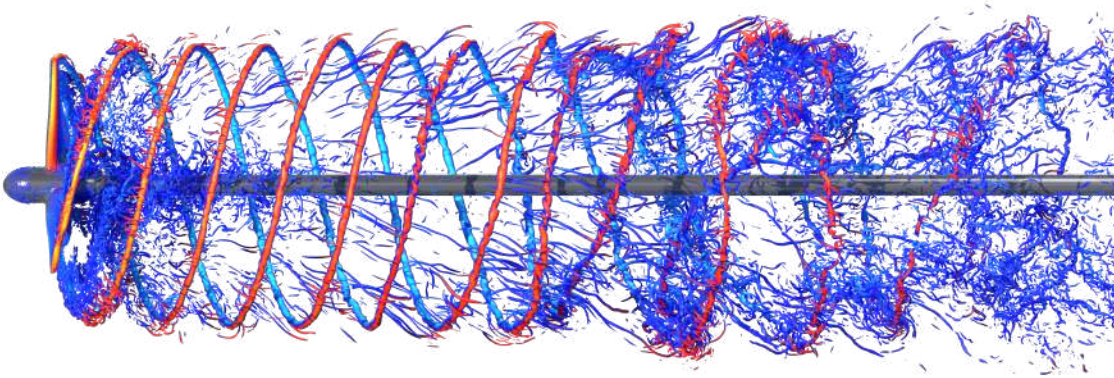
Reference Setup: Experimental, Actuator line, Blade-resolved



$$r := 0.09\,\mathrm{m}$$
$$f := 3\,\mathrm{Hz}$$
$$u_\infty := 0.56\,\mathrm{m\,s^{-1}}$$
$$\mathrm{Re} \approx 40\,000$$

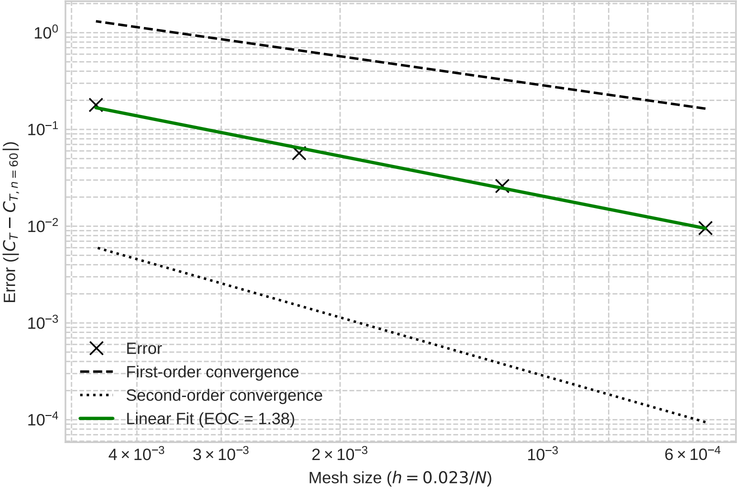
André Ribeiro et al. *Blade-resolved and actuator line simulations of rotor wakes*. In: Computers & Fluids. DOI: `10.1016/j.compfluid.2024.106477`. 2025.

First Impression



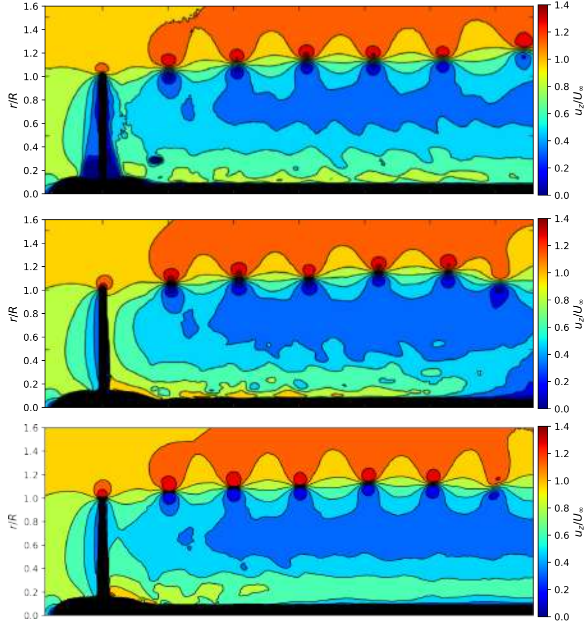
Rendering of Q-criterion at $Q = 1 \times 10^4$ for $N = 60$, colored by axial velocity

Experimental Order of Convergence: Thrust Coefficient



N	#Cells [1e6]	C_T
60	4053	0.96299
40	1200	0.97256
20	150	0.93696
10	18	0.90608
5	2	1.14215

Comparison of phase-averaged axial velocity on a z-r plane

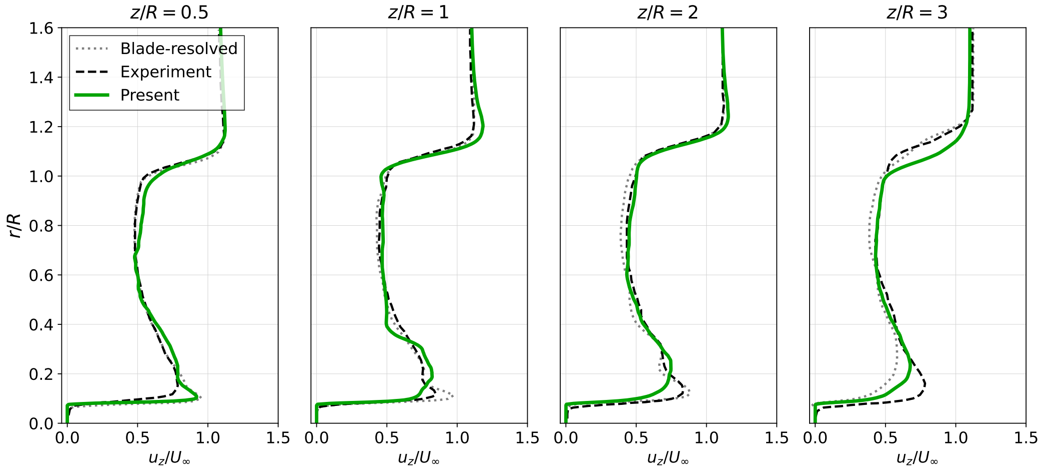


Experiment

Ribeiro et al. blade-resolved

Present

Phase-averaged axial velocities



Time and azimuthal-averaged axial velocity at different radial lines

Performance

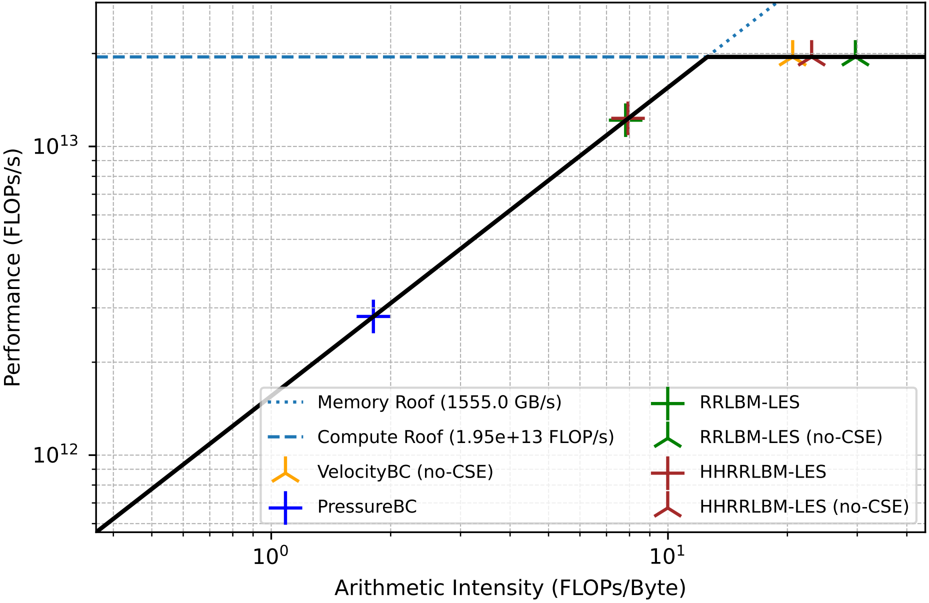
Characteristics of (HH)RRLBM-LES

Dynamics	BW [bytes]	Operations [FLOPs]			Performance [MLUPs]		
		No-CSE	CSE	Reduction	No-CSE	CSE	Speedup
RRLBM	152	4512	1189	2.90	2885	6411	2.22
HHRRLBM	204	4697	1618	3.79	2373	4252	1.79

Table: Arithmetic- / bandwidth intensity and isolated speedup on A100 GPU

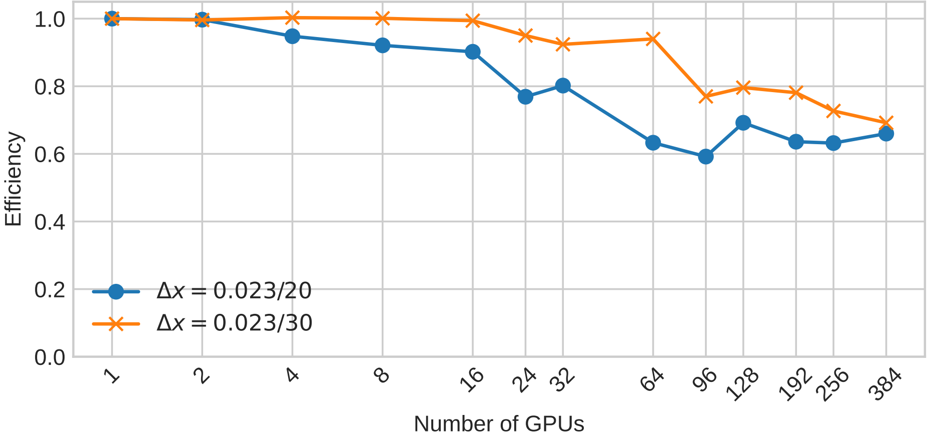
- **CSE transparently yields good performance improvements**

Roofline Analysis of HHRRLBM-LES



Analysis of Weak Scaling

One turbine per GPU, 30×10^6 resp. 110×10^6 cells each
Max. problem size 12×10^9 resp. 41×10^9 cells
Peak throughput $\approx 562 \times 10^9$ cells per second

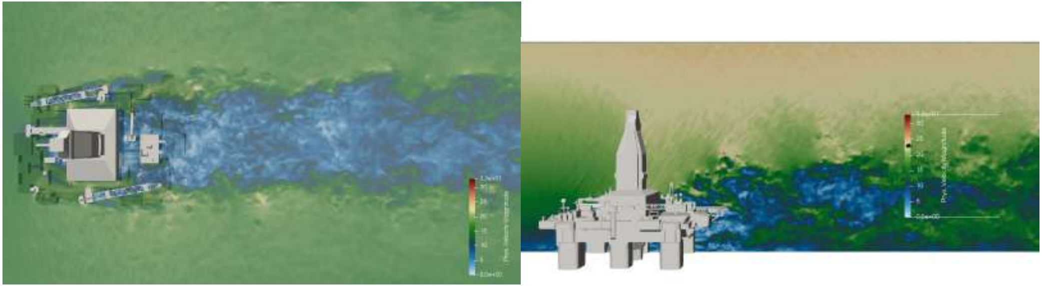


384 NVIDIA A100 GPUs on the Karolina supercomputer at IT4I, Czech Republic

SeaDream Networking in Liverpool

Connected with Dr. Neale Watson (Mechanical and Aerospace Engineering)

- **Started collaboration on CFD for offshore structures**



Summary

OpenLB offers all ingredients for high-fidelity digital twins of wind farms

- . . . has previously been validated for urban flows
- . . . now validated for single rotors
- . . . and scalable to farms of hundreds of them

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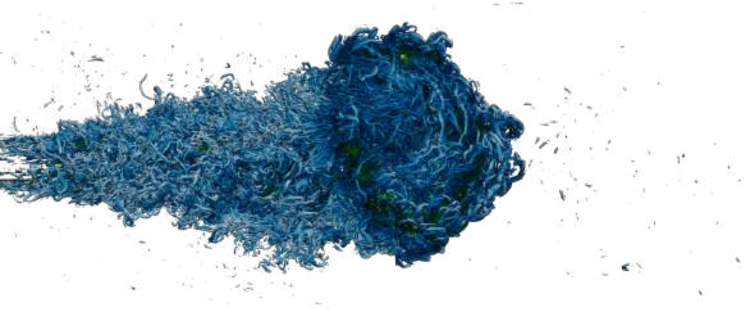

Check out openlb.net for further information and see you at the Spring School :)

Springschool 2026

9th Spring School

Lattice Boltzmann Methods with OpenLB Software Lab

Liverpool, England, UK, 23. – 27. March 2026

- For scientists and industrial users
  - **Option Beginners**: comprehensive theoretical lectures on LBM, mentored training on case studies using *OpenLB*
  - **Option Advanced**: bring your own problem
- Knowledge exchange & networking at poster session, lunches, dinner, coffee breaks, excursion
- More Info: www.openlb.net/spring-school

Executive committee:
John Bridgeman, Davide Dapelo, Mohaddeseh Musavi Nezhad, Mathias J. Krause, Shota Ito, Stephan Simonis

Invited speakers:
Timm Krüger, Halim Kusumaatmaja, Timothy Reis, Pierre Boivin, Julien Favier