Laboratory of
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Large-Eddy Simulations of the Atmospheric Boundary Layer

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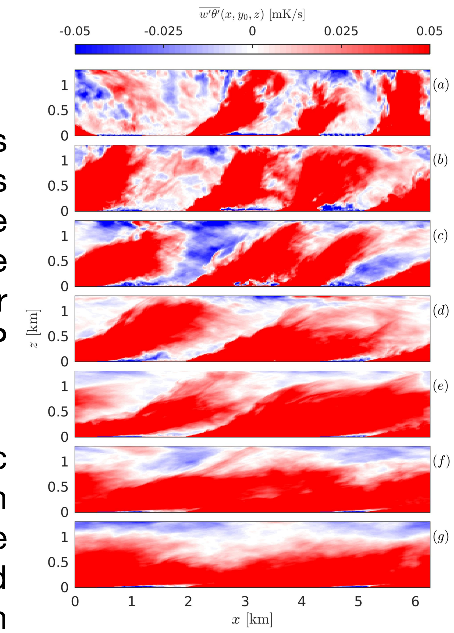
Abstract

Studying the fundamental nature of turbulence in the first kilometer of the atmosphere requires integrating the Navier-Stokes equations, including conservation of mass. Large-Eddy Simulation (LES) is the appropriate numerical technique given the very high Reynolds number values that characterize the atmospheric flow, and hence the very large range of turbulent scales embedded within the flow. The numerical code uses a pseudo-spectral framework, where the horizontal directions are treated in Fourier space and the vertical direction in physical space. The code is highly parallelized with MPI/OpenMP using a state-of-the-art pencil decomposition technique.

This framework is used to develop a new understanding of the interaction between the atmospheric boundary layer and land surface heterogeneities needed, as the current parameterizations used in weather forecast models are struggling as the numerical resolution increases. The aim is to quantify the surface energy fluxes generated by land surface heterogeneities, develop new parameterizations, and determine the limitations of traditional point measurements versus spatially-distributed measurements in traditional field experiment applications. LES can also be used to study the evolution of flow characteristics in finite-sized wind farms, and understand the influence of the farm configuration on the regions of flow-adjustment and flow equilibrium.



Vertical heat flux

(a) THE UNIVERSITY OF UTAH
(b) ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
(c) UBC

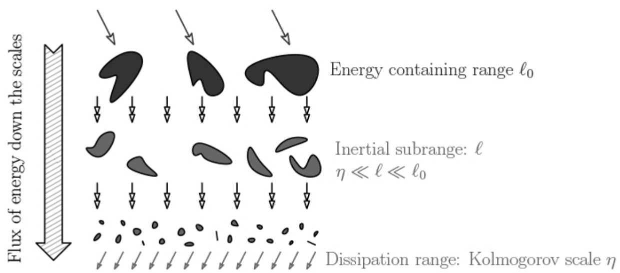
Large-Eddy Simulation Framework

Simulation of turbulent flow

What is turbulence (Kolmogorov):

large collection of turbulent scales (time and space)

cascade of energy from large to small scales

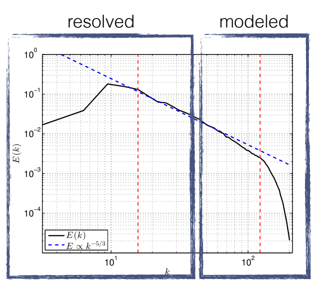


This collection of scale make the simulations of turbulent flow too challenging of our computational resources.

Large-Eddy simulation (LES)

large structures of the flow are resolved

small structures and dissipation are modeled



Governing equations:

conservation of mass, filtered incompressible Navier-Stokes equations in rotational form, temperature transport equation (advection-diffusion)

$$\partial_i \tilde{u}_i = 0,$$

$$\partial_t \tilde{u}_i + \tilde{u}_j \left(\partial_j \tilde{u}_i - \partial_i \tilde{u}_j\right) = -\frac{1}{\rho}\partial_i \tilde{p}^* - \partial_j \tau_{ij}^{\Delta,d} + g\left(\frac{\tilde{\theta} - \langle\tilde{\theta}\rangle_{xy}}{\langle\tilde{\theta}\rangle_{xy}}\right)\delta_{i3} + f_i,$$

$$\partial_t \tilde{\theta}_i + \tilde{u}_j \partial_j \tilde{\theta} = \partial_j \pi_j^{\Delta},$$

Sub-grid model:

Lagrangian scale dependent dynamic models [1][2]

Pseudo-spectral method:

- staggered grid in the vertical direction,
- spectral in horizontal directions and finite differences in vertical direction,
- dealiased using the 3/2-rule,
- Thomas algorithm for pressure solver and
- Adams-Bashforth method for time advancement

Boundary conditions:

- lateral: periodic boundary condition (from spectral treatment)
- top: stress free lid, non penetration and zero flux
- bottom: non penetration, shear and flux is imposed using the law of the wall corrected for temperature stratification and Monin-Obukhov.

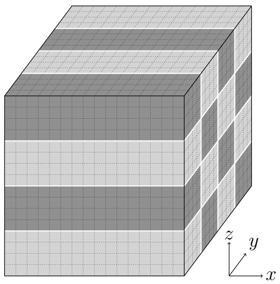
[1] Bou-Zeid, E., Meneveau, C. & Parlange, M.B., 2005. A scale-dependent Lagrangian dynamic model for large eddy simulation of complex turbulent flows. *Physics of Fluids*, 17(2), p.25105.

[2] Calaf, M., Parlange, M.B. & Meneveau, C., 2011. Large eddy simulation study of scalar transport in fully developed wind-turbine array boundary layers. *Physics of Fluids*, 23(12), p.126603.

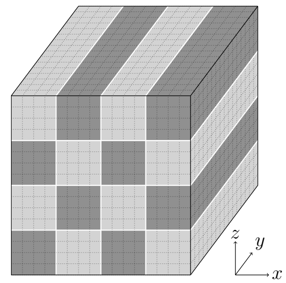
Parallelization Method

Hybrid MPI/OpenMP parallelization using a pencil decomposition 2DECOMP & FFT library [1]

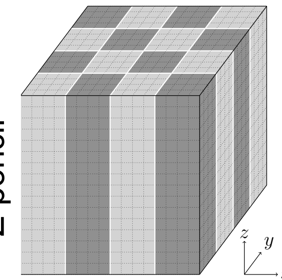
X-pencil



Y-pencil



Z-pencil



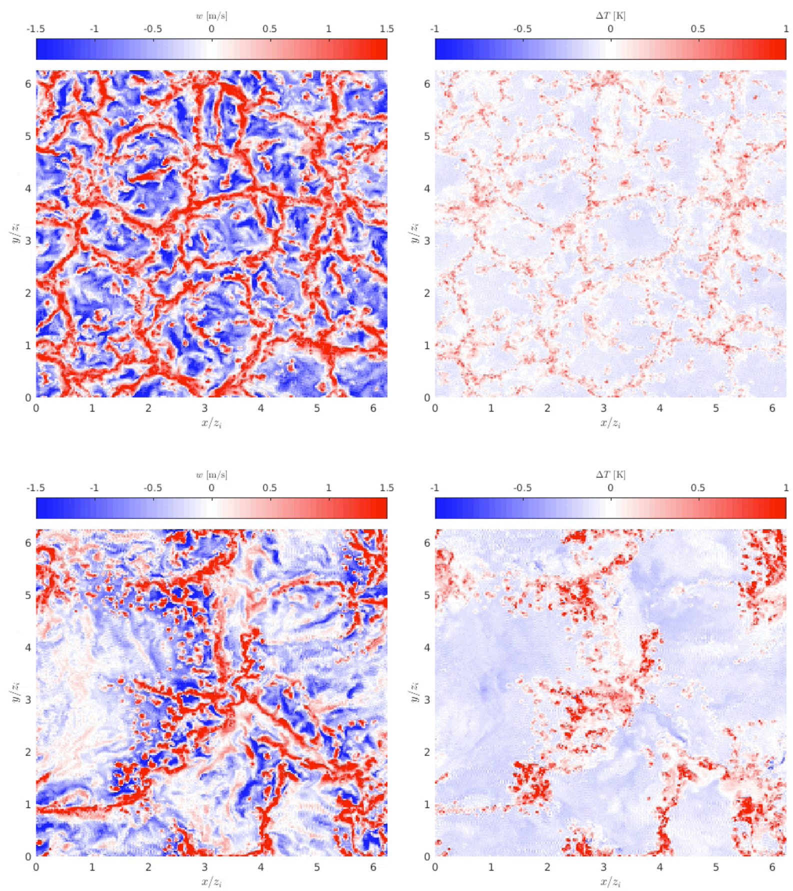
Velocity gradient	$\tilde{G}_{ij}^t = \partial_j \tilde{u}_i^t$	fft / i-fft	Fourier derivation
SGS model	$\tau_{ij}^{\Delta,t} = -2(C_S\Delta)^2 \lvert\tilde{S}^t\rvert \tilde{S}^t$	fft / i-fft	Fourier filtering for SGS model
Stress divergence	$\partial_j \tau_{ij}^{\Delta,t}$	fft / i-fft	Fourier derivation
Convective term	$\tilde{u_j}^t \left(\partial_j \tilde{u_i}^t - \partial_i \tilde{u_j}^t\right)$	fft / i-fft	Fourier filtering for dealiasing
Advection 1/2-step	$\tilde{u}_i^* = \tilde{u}_i^t + \Delta t\big[-\tilde{u_j}^t \left(\partial_j \tilde{u_i}^t - \partial_i \tilde{u_j}^t\right) + \nu \partial_j \partial_j \tilde{u_i}^t - \partial_j \tau_{ij}^{\Delta,t}\big]$		

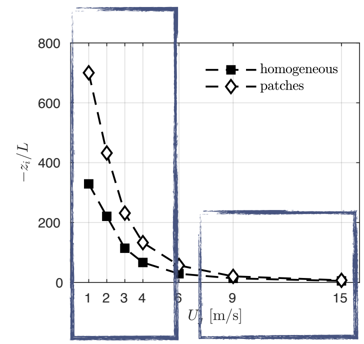
Poisson solver	$\tilde{u}_i^{n+1} = \tilde{u}_i^* - \dfrac{\Delta t}{\rho} \partial_i \tilde{p}^{t+\Delta t}$	fft / i-fft	Fourier derivation	$\rightleftarrows$	$\partial_j \partial_j \tilde{p}^{t+\Delta t} = \dfrac{\rho}{\Delta t} \partial_k \tilde{u}_k^*$

[1] Li, N. & Laizet, S., 2010. 2DECOMP & FFT-A Highly Scalable 2D Decomposition Library and FFT Interface. Cray User Group 2010 conference, pp.1–13.

Effect of the surface temperature on the CBL

Geostrophic forcing U_g=1 m/s

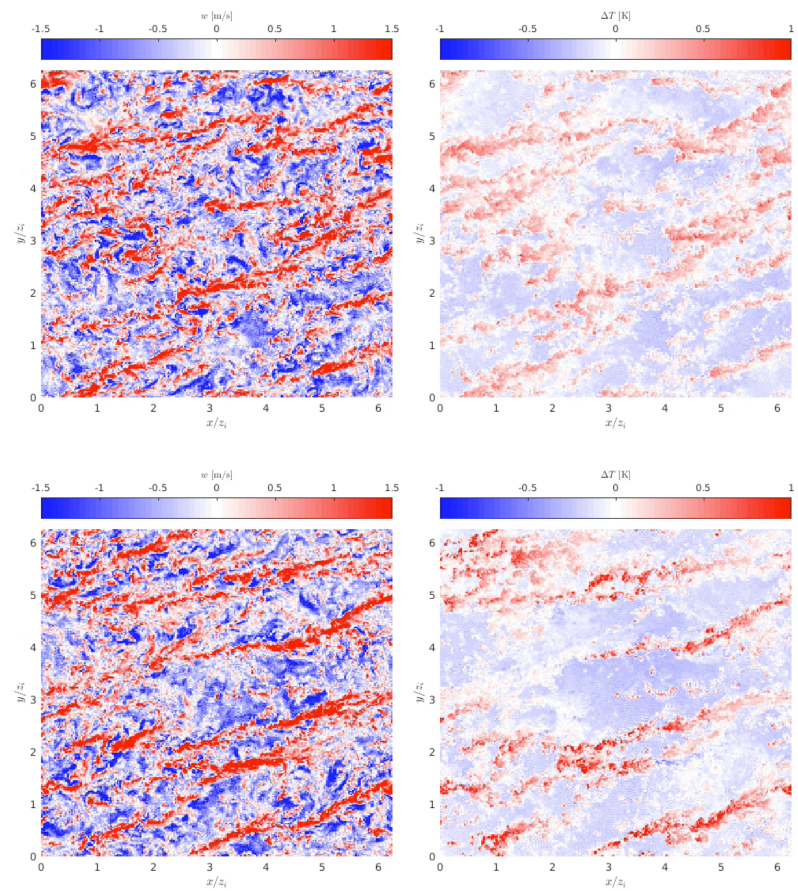




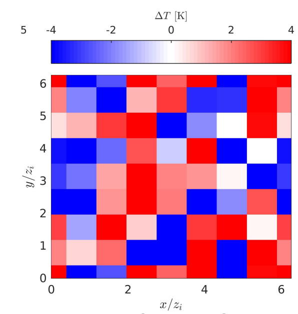
Convective cell dominated flow

Convective roll dominated flow

Geostrophic forcing U_g=15 m/s



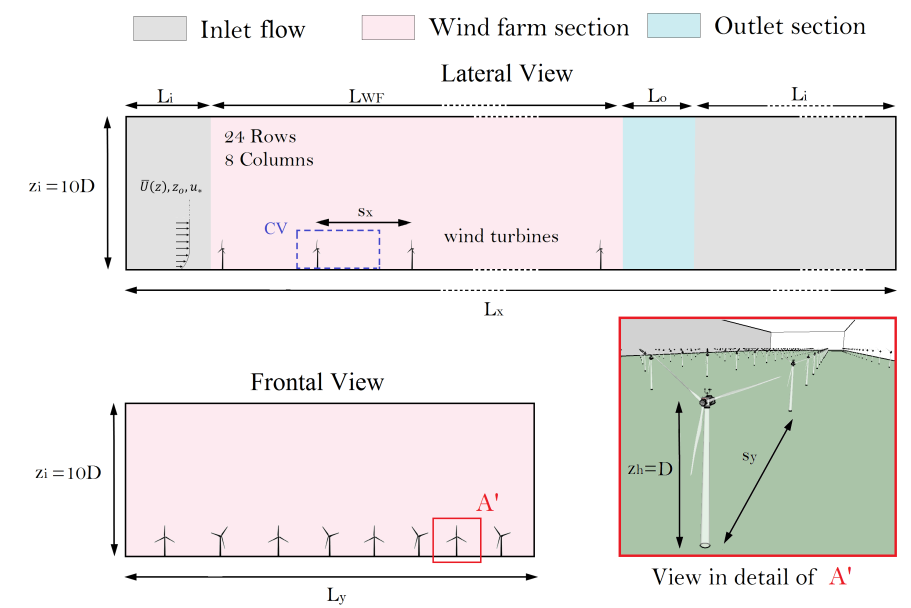
Gaussian surface temperature distribution



[1] Salesky, S.T., Chamecki, M. & Bou-Zeid, E., 2016. On the Nature of the Transition Between Roll and Cellular Organization in the Convective Boundary Layer. *Boundary-Layer Meteorology*, pp.1–28.
[2] Margairaz F., Calaf M, *Manuscript in preparation*

Evolution of the flow through a wind farm

Schematic representation of the base case wind farm configuration

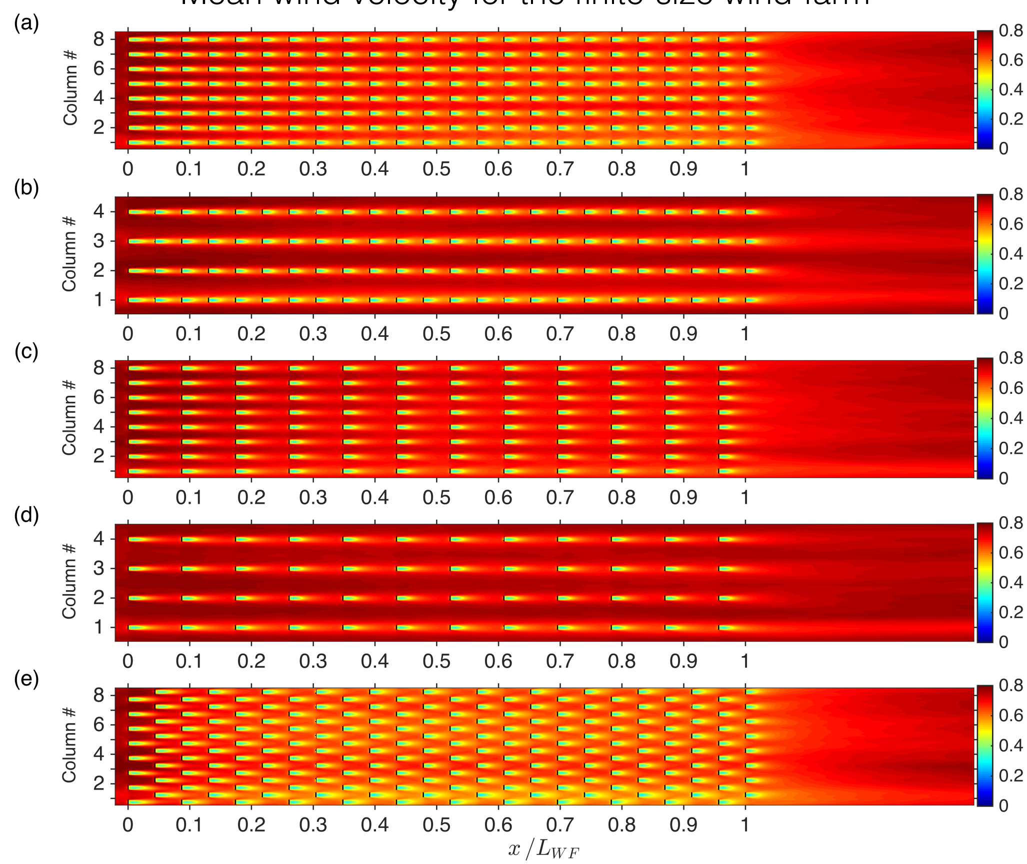


$$(l_x \times l_y \times l_z) = (32\pi \times \pi \times 1)z_i$$

$$(n_x \times n_y \times n_z) = (4096 \times 128 \times 128)$$

$$(\Delta x \times \Delta y \times \Delta z) = (24.5m \times 24.5m \times 7.85)$$

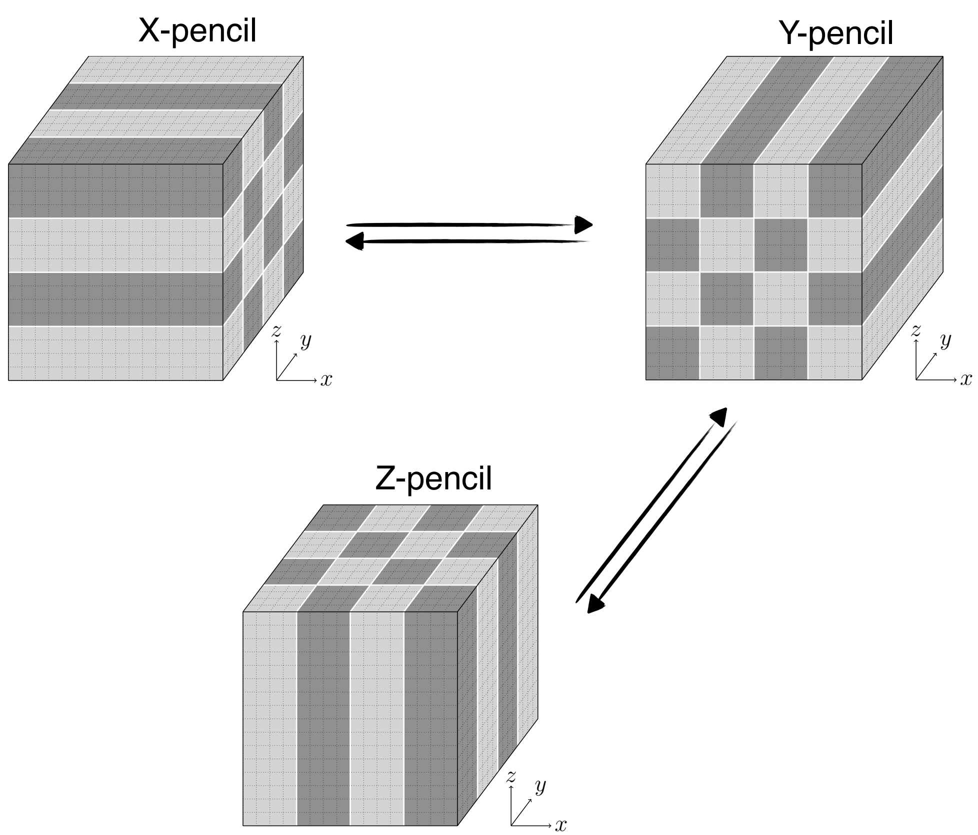
Mean wind velocity for the finite-size wind-farm



[1] V. Sharma, G. Cortina, F. Margairaz, M.B. Parlange, M. Calaf Evolution of flow characteristics through finite-sized wind farms and influence of turbine arrangement *submitted*

2DECOMP & FFT library [1]

Pencil decomposition



Scaling of the library from [1]

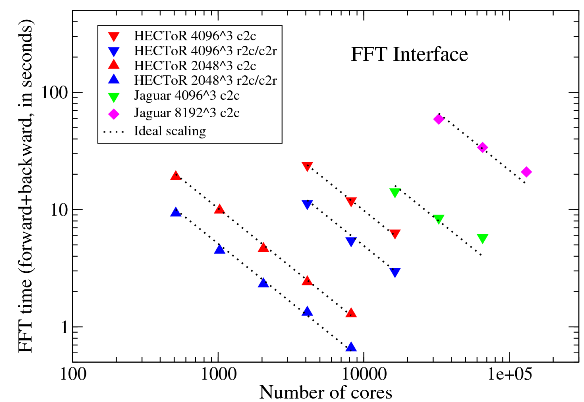


Figure 5: FFT library scaling on HECToR and Jaguar

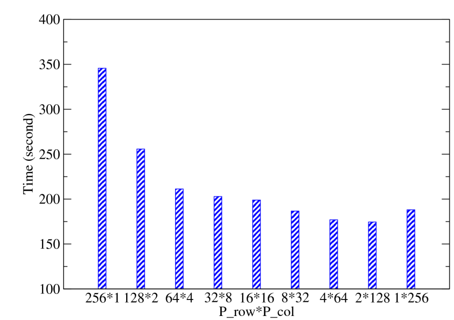


Figure 6: Communication library performance dependency on the shape of the processor grid.

[1] Li, N. & Laizet, S., 2010. 2DECOMP & FFT-A Highly Scalable 2D Decomposition Library and FFT Interface. Cray User Group 2010 conference, pp.1–13.