Wind turbine wakes in forest and neutral plane wall boundary layer - large-eddies simulations

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Turbulent inflow for wind turbine wake simulations

Efficient atmospheric boundary layer simulations in the presence of the forest are crucial for understanding the wind turbine wake flow above canopies. Since the pioneering large-eddy simulation (LES) of Shaw and Schumann (1992), forests have been modeled as a porous body of horizontally uniform leaf-area density a(z) with a constant drag coefficient c_d in LESs.

For computational efficacy we use three dimensional MPI decomposition (Piotrowski et al. 2014). In this experiment, two independent equation systems indicated with upper indices a and b are solved simultaneously in one code:

\[ \nabla \cdot \mathbf{u}^a = 0 \]
\[ \frac{d\mathbf{u}^a}{dt} = -\nabla p^a + \nu \nabla^2 \mathbf{u}^a + \mathbf{f}_{wind}^a + D(\mathbf{v}^a) \]
\[ \frac{d\mathbf{u}^b}{dt} = -\nabla p^b + \nu \nabla^2 \mathbf{u}^b - c_d \mathbf{u} \cdot \nabla \mathbf{u} - 2 \eta_r \mathbf{u} \frac{\nabla \cdot \mathbf{u}^b}{\mathbf{u} \cdot \nabla \mathbf{u}} \]

For computational efficacy we use three dimensional MPI decomposition (Piotrowski et al. 2011). The equations are cast in Cartesian coordinates and contain velocity field \( \mathbf{u} \), density normalized pressure \( p^a \), eddy viscosity \( \nu_{eddy} \), momentum flux \( \tau_{ij} \) and \( \mathbf{r} \) as time scale for dissipation inside the forest. We solve continuity equation (1), momentum equation (2) with wind turbine thrust \( F_{turbine} \) proportional to local time filtered velocity \( \langle U \rangle \) and thrust coefficient \( c_{thrust} \). The forest drag follows Shaw & Schumann (1992). For sub-grid scale turbulent kinetic energy \( \varepsilon \), we solve equation (3) as Schumann (1975).

The instantaneous turbulence structure of \( u(x,y) - U_{xy} \)

Instantaneous fields show the difference between the streamwise velocity \( u \) and the area mean \( U_{xy} \) two meters above the ground in the plane wall (top) and two meters above the forest canopy (bottom) for the last simulated time step. The Streaks with relatively low/high momentum are more pronounced above the forest.

Objectives

How can we simulate the boundary layer turbulence with all coherent structures correctly and efficiently upstream of the wind turbine wake? How does the wind turbine wake differ in both boundary layer regimes?

Incorporating two hydrodynamic solvers in EULAG

Governing equations in Boussinesq approximation

The hydrodynamic equations are solved with the multiscale geophysical flow solver EULAG (Smolarkiewicz et al. 2014). In this experiment, two independent equation systems indicated with upper indices a and b are solved simultaneously in one code:

\[ \nabla \cdot \mathbf{u}^a = 0 \]
\[ \frac{d\mathbf{u}^a}{dt} = -\nabla p^a + \nu \nabla^2 \mathbf{u}^a + \mathbf{f}_{wind}^a + D(\mathbf{v}^a) \]
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Conclusions

Our new methodology is successfully applied. The fully developed horizontally homogenous boundary layer turbulence is exactly reproduced at the domain inlet. The required coherency, as well as the higher order statistics of the turbulent flow are maintained.

The fields do not need to be stored to or read from disk as done by Churchfield et al. (2012), nor do the fields need to be transferred with MPI communication to the other solver as in the approach by Stevens et al. No fringe region (as used by Stevens et al. 2014) is required.

The computational time increases by less than a factor of two in EULAG as only the hydrodynamical core needs to be executed twice.