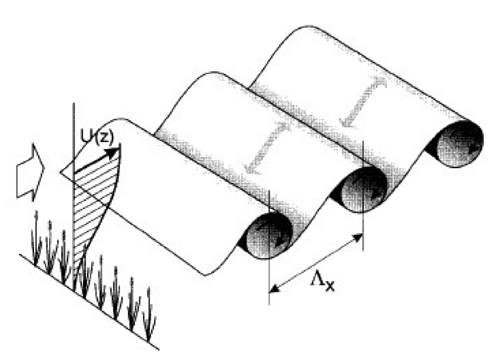
Wind turbine wakes in forest and neutral plane wall boundary layer large-eddy simulations

Josef Schröttle[a,c,*], Zbigniew Piotrowski[b], Thomas Gerz[a,**], Antonia Englberger[a], Andreas Dörnbrack[a]

[a] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
[b] Institute of Meteorology and Water Management, Warsaw, Poland
[c] Ludwig Maximilians Universität, Meteorologisches Institut, München, Germany

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_{for} in LESs.



*Kelvin-Helmholtz instabilities evolve in canopy flows due to an inflection point in the streamwise velocity profile (**left**, Finnigan 2000). Such coherent structures characterize forest canopy turbulence (Schröttle and Dörnbrack 2013). Other structures such as streaks of relatively high/low momentum are typical for neutral plane wall boundary layer turbulence (Moeng and Sullivan 1993).*

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

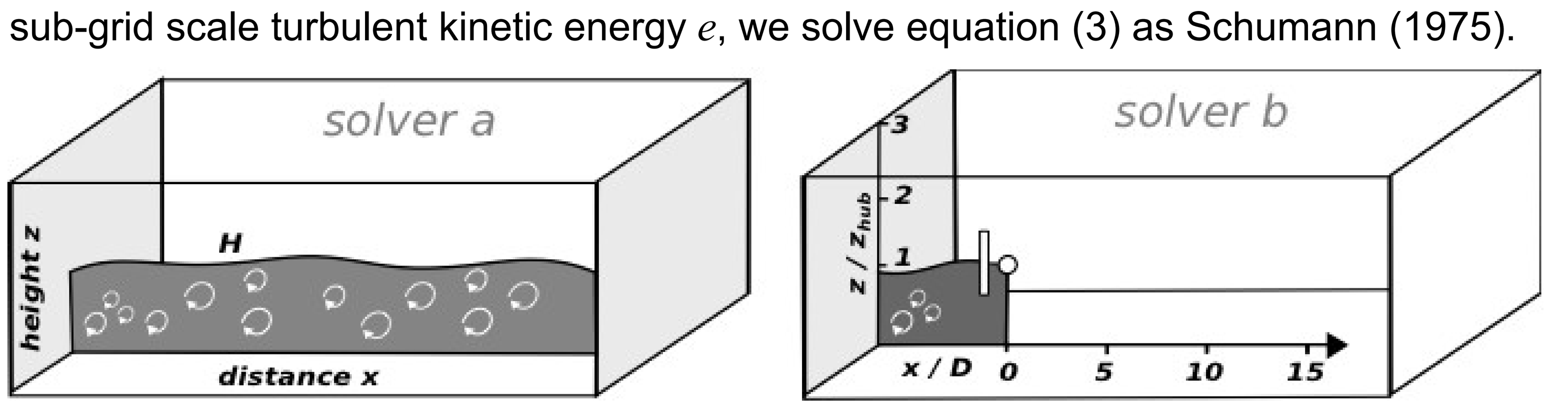
The hydrodynamic equations are solved with the multiscale geophysical flow solver EULAG (Smolarkiewicz et al. 2014). In this experiment, **two independent equation systems** indicated with upper indices *a* and *b* are solved simultaneously in one code:

$$(1)\quad \nabla \cdot \mathbf{v}^{a,b} = 0$$

$$(2)\quad \frac{d\,\mathbf{v}^{a,b}}{dt} = -\,\nabla\pi^{a,b} + \mathbf{F}(\mathbf{v}^{a,b})_{forest} + \mathbf{F}^{b}_{turbine} + \mathcal{D}(\mathbf{v}^{a,b})$$

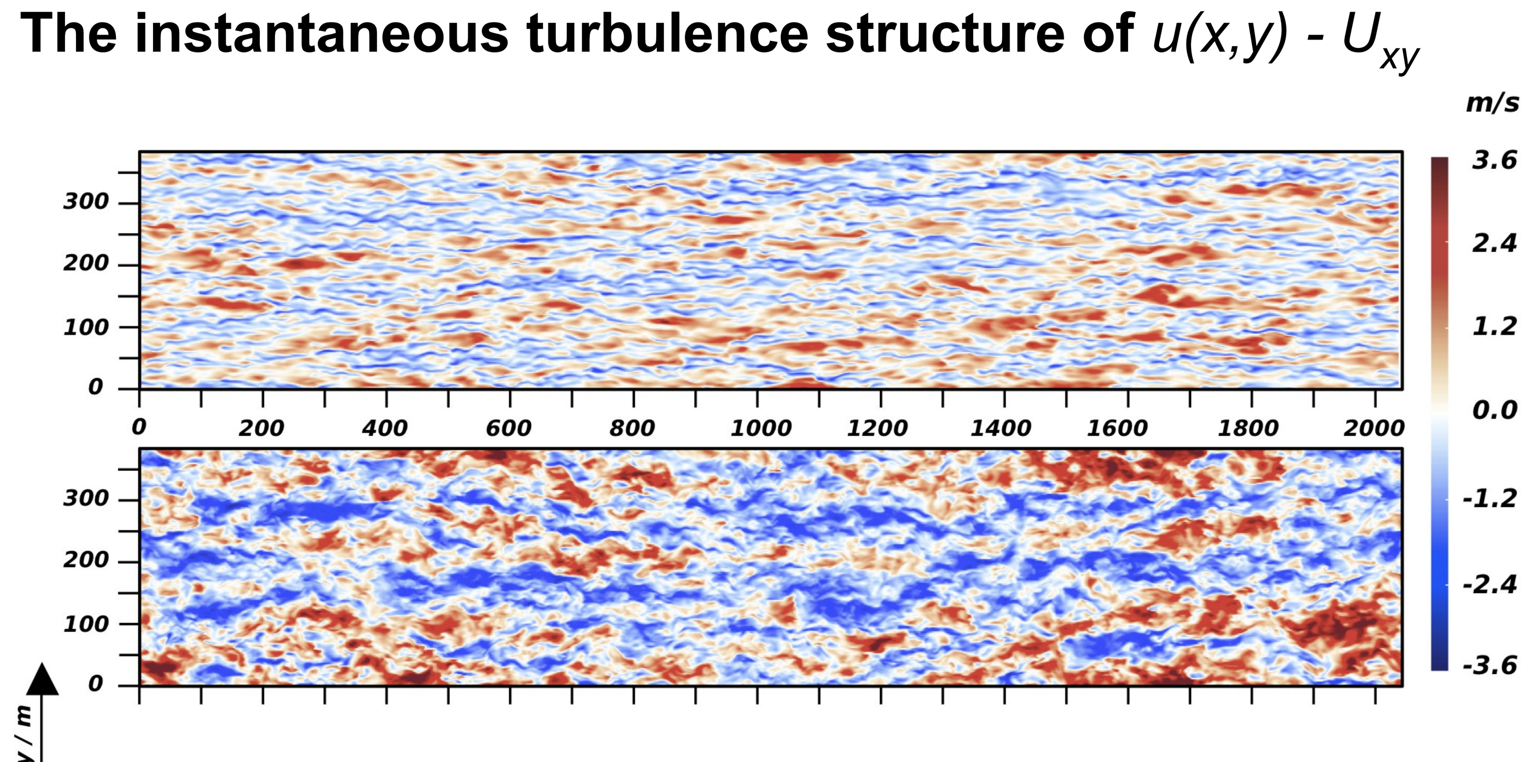
$$(3)\quad \frac{d\,e^{a,b}}{dt} = -\underbrace{\tau^{a,b}_{ij}\,\partial_{x_j}\tilde{u}^{a,b}_i}_{shear} - \nu^{a,b}_{eddy}\Delta \mathbf{v}^{a,b} - 2\frac{e^{a,b}}{\tau}$$

For computational efficacy we use three dimensional MPI decomposition (Piotrowski et al. 2011). The equations are cast in Cartesian coordinates and contain velocity field $\mathbf{v}$, density normalized pressure π, eddy viscosity ν_{eddy}, momentum flux τ_{ij} and τ as time scale for dissipation inside the forest. We solve continuity equation (1), momentum equation (2) with wind turbine thrust $\boldsymbol{F}_{turbine}$ proportional to local time filtered velocity U_D and thrust coefficient $C_T{}'$. The forest drag follows Shaw & Schumann (1992). For sub-grid scale turbulent kinetic energy e, we solve equation (3) as Schumann (1975).



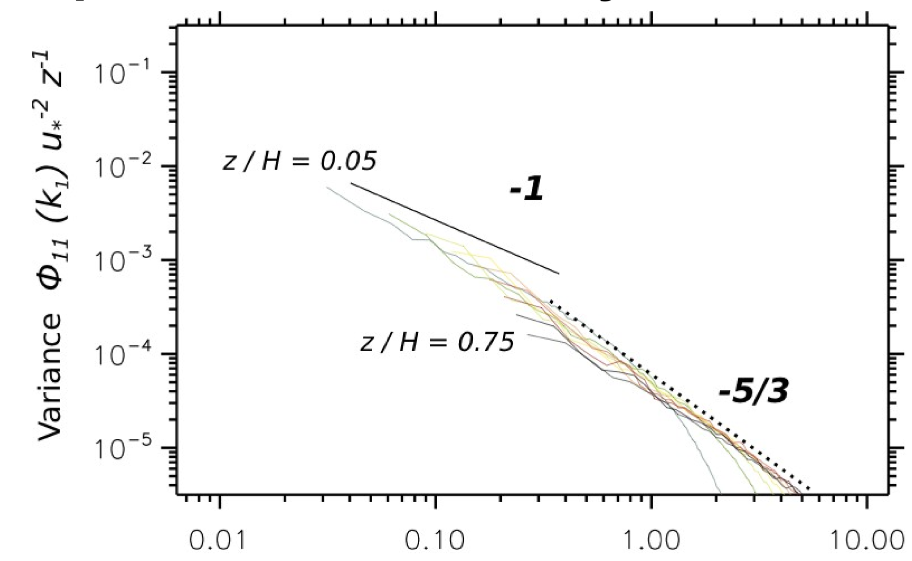
*We integrate the two hydrodynamic solvers a and b in one code simultaneously. Each solver has full access to the local flow fields of the other solver at each time step of the numerical realization. Solver a simulates a fully turbulent atmospheric boundary layer (symbolized at center plane height H, **left**) with cyclic boundaries. The fields of solver a serve as **open boundary conditions for solver** b with the wind turbine wake (**right**).*

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



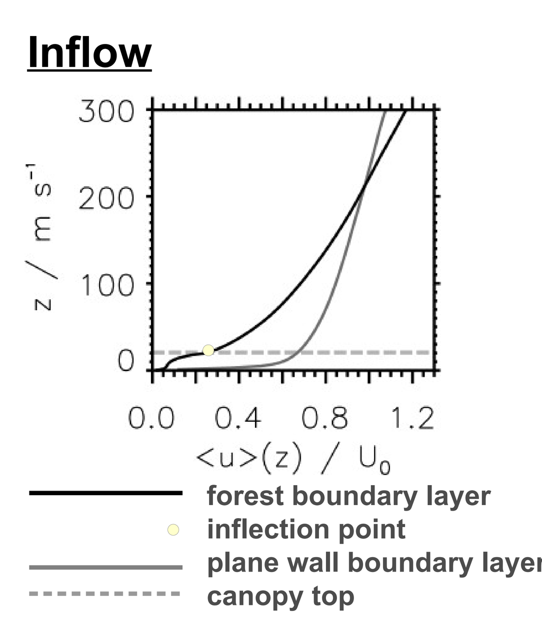
*Instantaneous fields show the difference between the streamwise velocity u and the area mean U_{xy} two meters above the ground in the plane wall (**top**) and two meters above the forest canopy (**bottom**) for the last simulated time step. The Streaks with relatively low/high momentum are more pronounced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

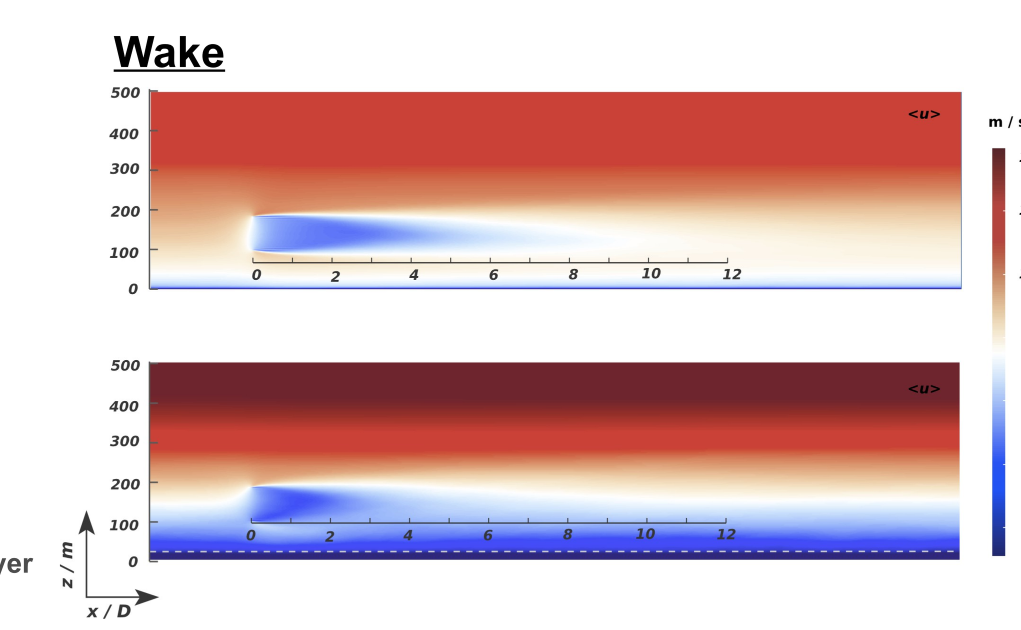
Spectra of the velocity variance in inflow turbulence



Spectra of the streamwise velocity variance show the characteristic *-1* slope *for* large scales and *-5/3* slope for smaller scales in fully developed neutral plane wall boundary layer turbulence (Perry, 1986). The spectra are normalized with the friction velocity u_* and local height z.

Wind turbine wakes in both turbulent boundary layers

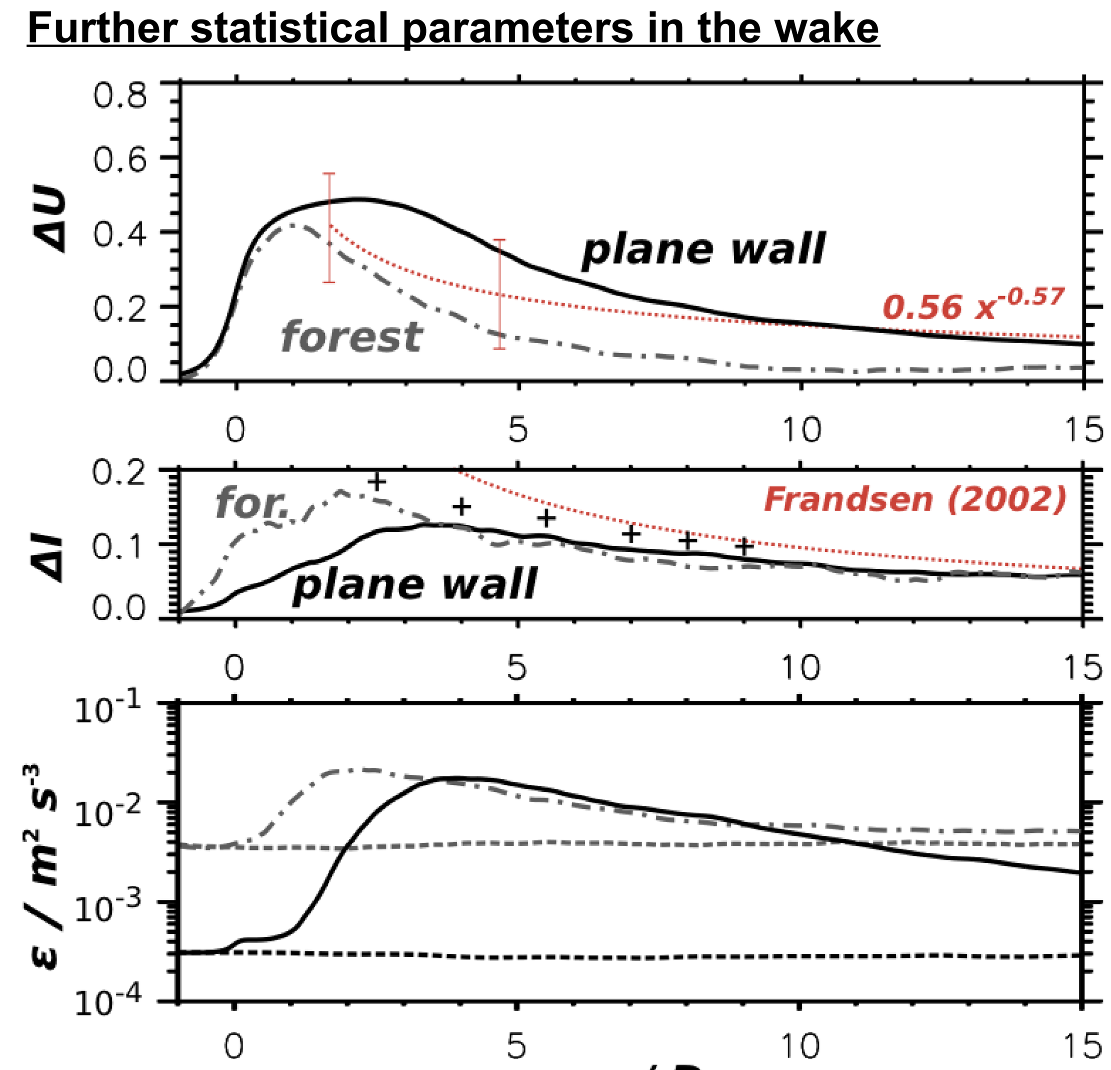




The temporal mean **stream wise velocity profile** *U(z)* is logarithmic above the plane wall and exhibits an **inflection point** above the **forest canopy**.

*At the center plane in y-direction the temporal mean velocity field is averaged over the last 30 min for the neutral plane wall (**top**) and for the forest boundary layer (**bottom**). The wake recovers earlier downstream of the wind turbine and is more asymmetric in the forest boundary layer regime.*

Further statistical parameters in the wake



Velocity deficit
$\Delta U = \frac{U_{hub} - U}{U_{hub}}$
Aitken et al. (2014b)

Added Turbul. Intensity
$\Delta I = \sigma_{u,m} \;/\; U$
+ LES by Jimenez et al. (2007)

Eddy Dissip. Rate
$\epsilon = <e>^{3/2} \;/\; dz$
range agrees with measurements by Lundquist (2015)

We calculate the wake velocity deficit in the forest and in the plane wall boundary layer at turbine hub height as function of downstream x-distance. The added turbulence intensity by the wake is calculated at the wake top shear layer. At the same position, the eddy dissipation rate is determined.

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.**

Deutsches Zentrum für Luft- und Raumfahrt e.V.
* josef.schroettle@physik.uni-muenchen.de ** thomas.gerz@dlr.de

Institut für Physik der Atmosphäre
www.dlr.de/ipa