TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Mechanical Engineering & Faculty of Forestry, Geosciences and Hydrosciences

Large-Eddy Simulation of Heterogeneous Canopy Flows

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Outline

Motivation

Solar power plant Lieberose, Germany

wind park in complex topography

Scaffolding tower at field site “Tharandter Wald”

Basic Equations

- Neutral atmospheric conditions (no temperature and radiation effects)
- Domain of the order of 1 km^2 (no Coriolis force and density fluctuations)

Filtered incompressible Navier-Stokes equations

$$\begin{aligned} \partial_t \overline{u}_i + \partial_j \left(\overline{u}_j \overline{u}_i \right) &= -\partial_i \overline{p} + \partial_j \left(2\nu \overline{S}_{ij} \right) + \partial_j \tau_{ij} + \overline{f}_{i,d} + \overline{f}_{i,p} \\ \partial_i \overline{u}_i &= 0 \end{aligned}$$

Plant drag force due to vegetation

$\overline{f}_{i,d} = -c_d a \left| \overline{\mathbf{u}} \right| \overline{u}_i$ where

c_d ... drag coefficient
a ... plant area density
$\overline{\mathbf{u}}$ ... filtered velocity

Subgrid Scale Model

- One-equation model of Deardorff (1980)
- Modification for canopy flows according to Shaw and Schumann (1992)

Transport equation for the unresolved turbulent kinetic energy $\overline{k''}$

$$\partial_t \overline{k''} + \partial_j \left(\overline{u}_j \overline{k''} \right) = \tau_{ij} \overline{S}_{ij} + \partial_j \left(2\nu_r \partial_j \overline{k''} \right) - C_E \frac{\overline{k''}^{3/2}}{\ell} - \frac{2\overline{k''}}{\tau}$$

SGS stresses: $$\tau_{ij} = 2\nu_r \overline{S}_{ij} - \frac{2}{3}\delta_{ij}\overline{k''}$$

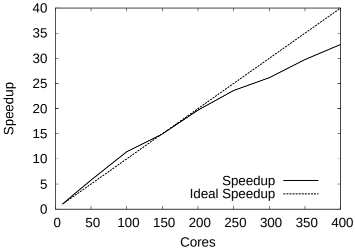
$$\nu_r = C_v \ell \overline{k''}^{1/2}$$

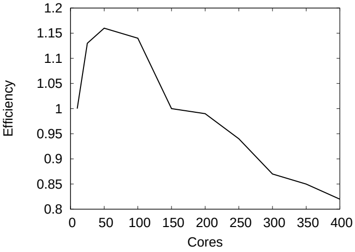
[J. Deardorff, Boundary-Layer Meteorology **18**: 495–527, 1980]

[R. Shaw and U. Schumann, Boundary-Layer Meteorology **61**: 47–64, 1992]

Finite Volume Solver OpenFOAM

- OpenFOAM ® CFD toolbox 1.6, 2nd order accuracy in time & space
- TVD fluxes of Sweby (1984) for convective terms
- Domain decomposition and MPI parallelization

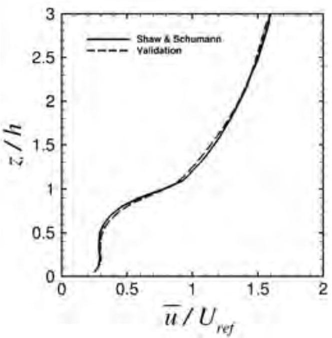


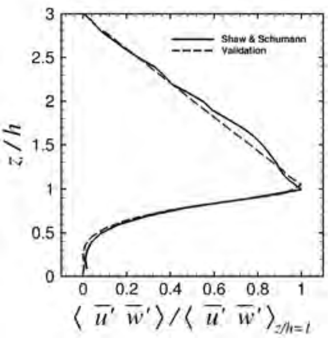


[P. Sweby, SIAM Journal on Numerical Analysis **21**: 995–1011, 1984]

Validation using Homogeneous Forest

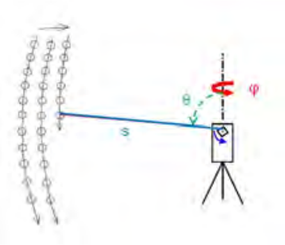
- 20 m tall forest with a PAI of 2 according to Shaw & Schumann (1992)
- Domain of 192 m $\times$ 96 m $\times$ 60 m with equally spaced mesh ($\Delta = 2$ m)
- Periodic horizontal directions, no slip condition combined with logarithmic law at the bottom and free slip at the top

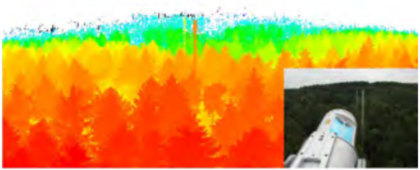




Simulation Setup

- Range finder emits a laser signal and measures time of flight or phase shift
- Deflecting unit scans sequentially at a high point rate and precision
- Coordinates gained by recording of the range and two deflection angles





Colored point cloud and scanner

Selected point cloud

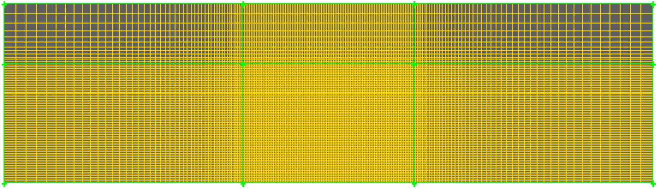
Segmented trees

Voxel representation

Simulation Setup

free slip condition

periodic

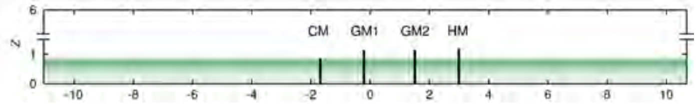


periodic

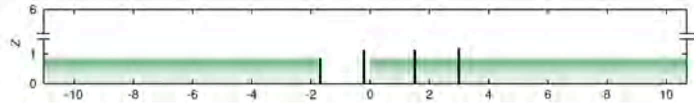
no slip condition with logarithmic law

- Domain of 760 m × 210 m × 380 m
- 15 million degrees of freedom (220 × 190 × 82 grid cells)
- Adjustment of $\overline{f}_{i,p}$ to achieve a mean velocity of ca. 4 m/s at ref. point
- Computation time of 5000 s for startup and 5000 s for statistics

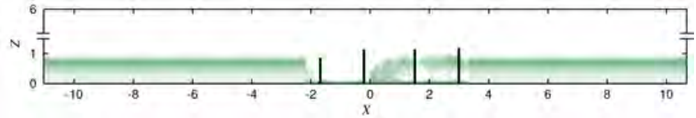
Simulation Setup



Homogeneous plant area density and no clearing (REF)



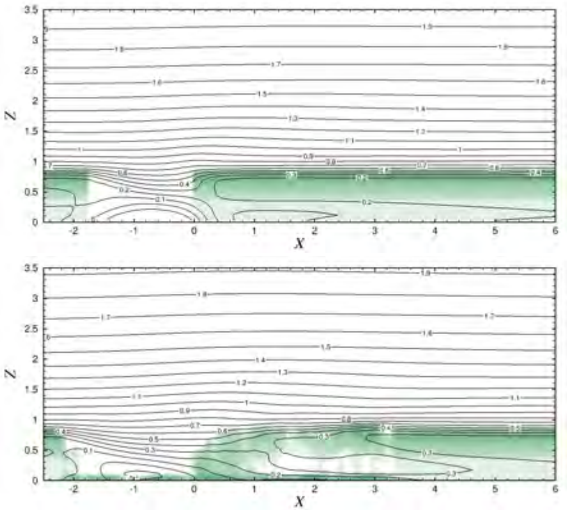
Homogeneous plant area density and 60 m clearing (HOM)



Heterogeneous plant area density from terrestrial laser scanning (HET)

[F. Schlegel et al., Boundary-Layer Meteorology, 2011 (submitted)]

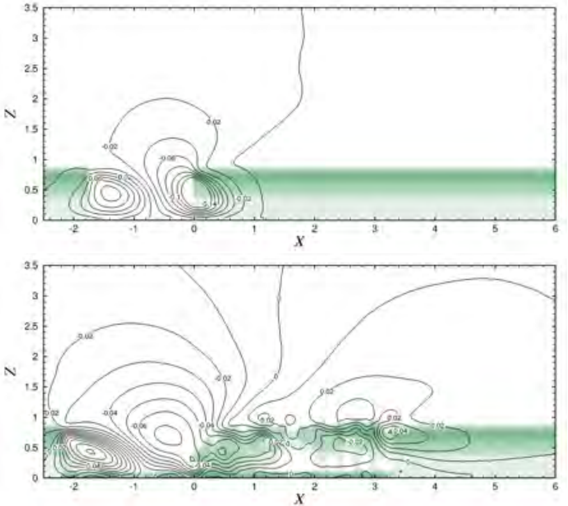
Mean Streamwise Velocity



HOM

HET

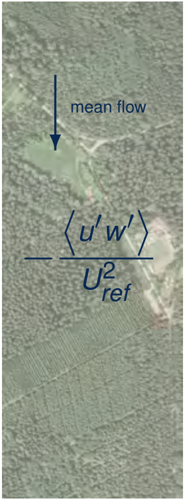
Mean Vertical Velocity

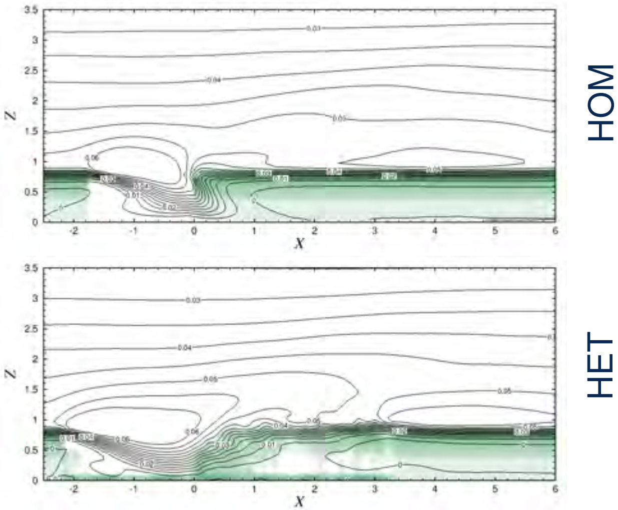


HOM

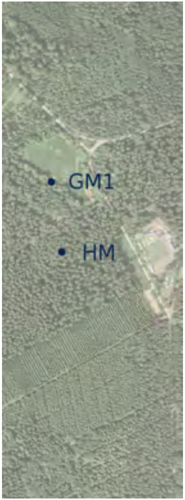
HET

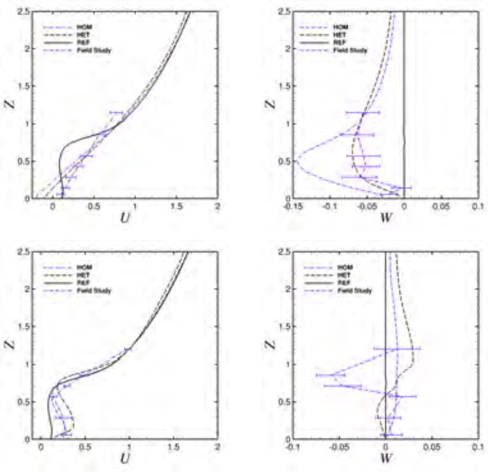
Resolved Reynolds Stresses





Comparison to Field Study

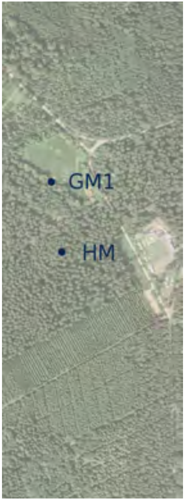


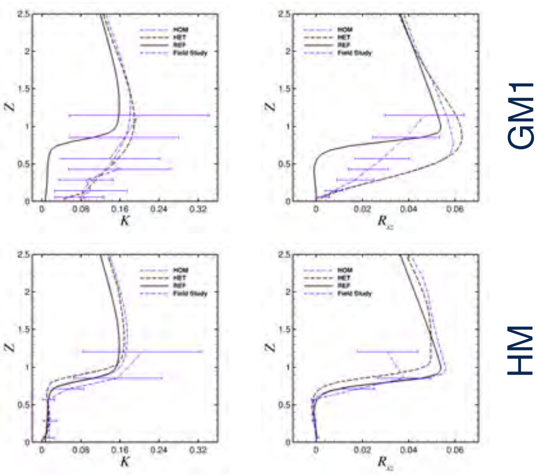


GM1

HM

Comparison to Field Study

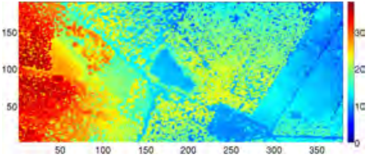




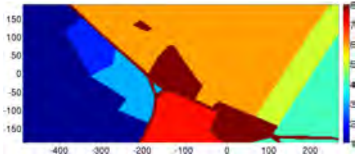
Outlook

- Minimum domain size for development of coherent eddies required
- Limitation of terrestrial laser scanning to small areas

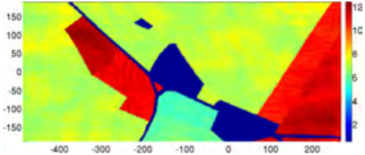
→ Virtual Canopy Generator (V-CaGe) of Bohrer et al. (2007)



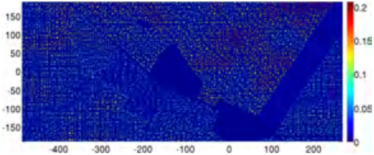
Digital crown model



Patch distribution

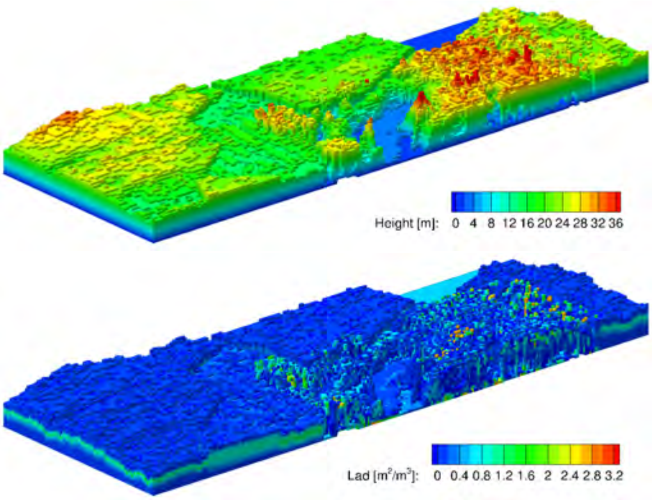


Leaf area index



Stem distribution

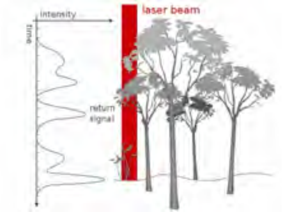
Outlook



Outlook

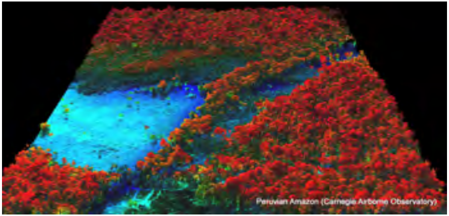
- V-CaGe still requires assumptions
- Assessment of vertical vegetation structure for large domains

$\longrightarrow$ New scanning methods like airborne and full-waveform LIDAR



Principle of full-waveform LIDAR

Image courtesy of J. Reitberger, TU München



Example of full-waveform LIDAR

Image courtesy of Carnegie Airborne Observatory

SAVE A TREE

Eat a beaver.

Appendix - Numerical Schemes

- OpenFOAM® CFD toolbox 1.6
- Central differences for diffusive fluxes and SGS stresses
- TVD fluxes of Sweby (1984) for convective terms
- Backward differencing scheme of 2nd order accuracy for time
- PISO algorithm of Issa (1985) for pressure-velocity coupling
- Domain decomposition and MPI parallelization

[I. Issa, Journal of Computational Physics **62**: 40–65, 1985]

[P. Sewby, SIAM Journal on Numerical Analysis **21**: 995–1011, 1984]

Appendix - Wall Normal Coordinate y^+

Name	Minimum	Maximum	Average
Validation	138	220	176
REF	29	293	188
HOM	26	583	246
HET	28	449	216