Large Eddy Simulation of Offshore Wind Farm

Hamid Sarlak
J. N. Sørensen & R. Mikkelsen

DTU- The Technical University of Denmark
hsar@mek.dtu.dk

Nov 7, 2011

Flow Center Meeting RisøDTU.

Motivation

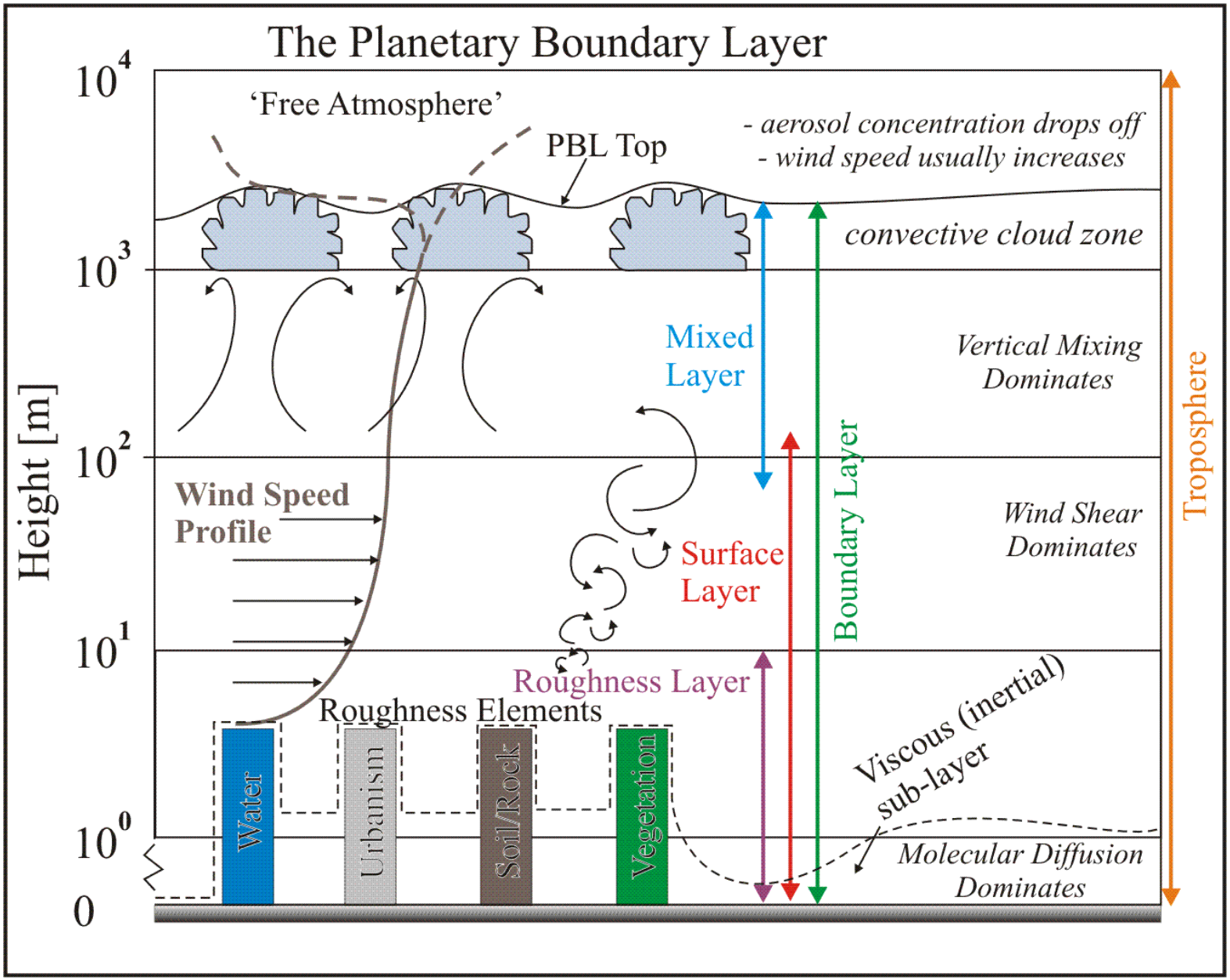
fig.: Turbulence field behind the Horns Rev 1 offshore wind turbines. Photo: Christian Steiness

- Modeling different atmospheric boundary layer regiems
- Implementation of improved wind turbine modeling techniques
- Implementation of improved LES modeling techniques

Outline

- Introduction to ABL
- Introduction to wind turbine modeling
- Simulation results
- Conclusions
- Acknowledgement

PBL Introduction



Stable vs. Convective ABL

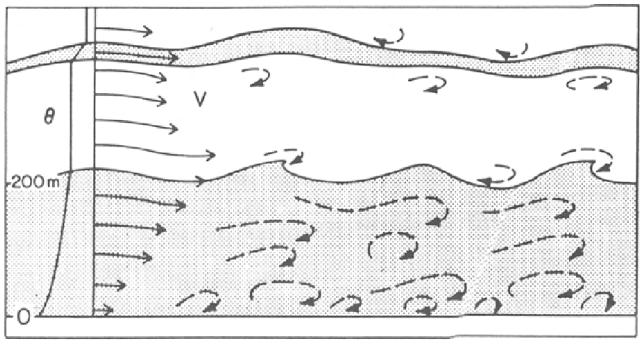


Fig. 5. An artist's conception of the stably stratified boundary layer, showing its small eddies, shallow depth, overlying jet, and mean wind and temperature gradients.

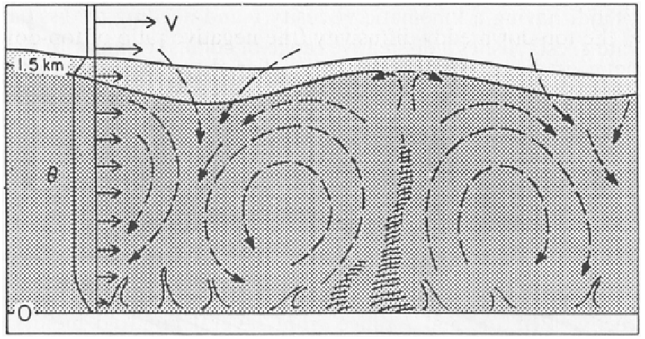


Fig. 4. An artists's conception of the convective boundary layer, showing its large eddies, capping inversion, and well-mixed mean profiles of wind and potential temperature.

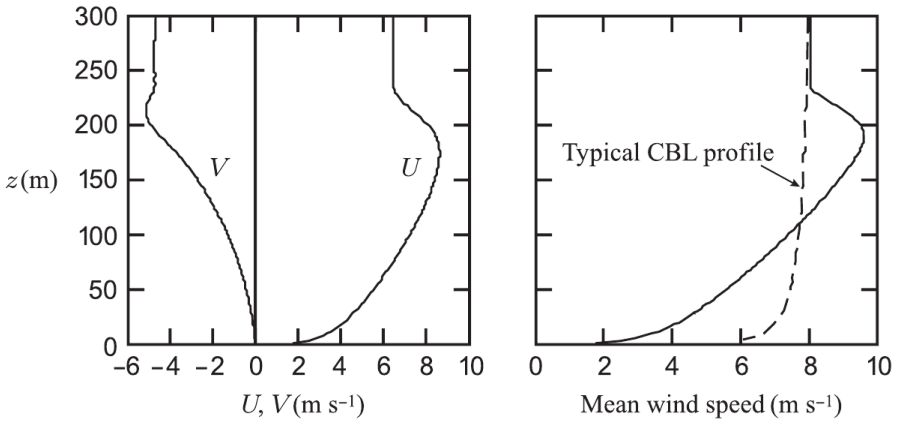
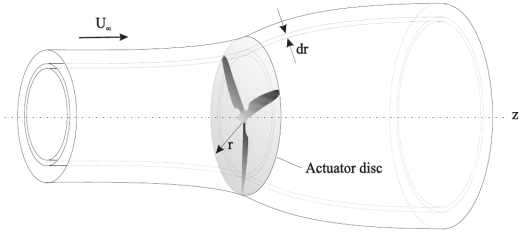
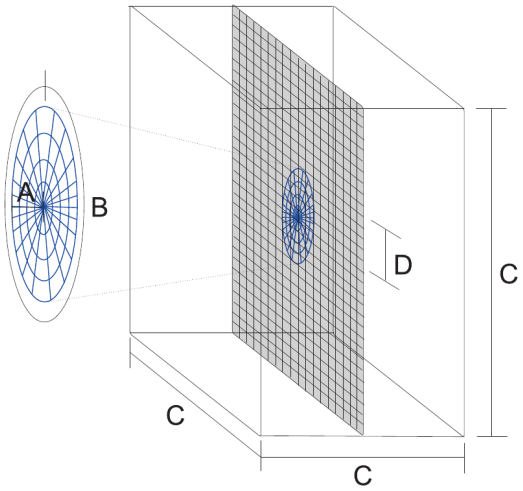


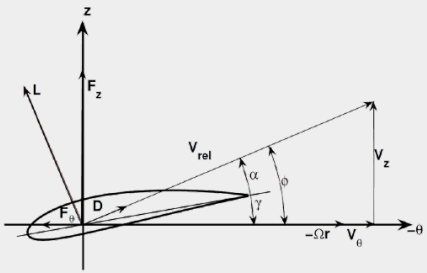
Figure 12.1 Left: Profiles of mean wind components in an SBL, in coordinates aligned with the surface wind, as calculated through LES. Right: The profile of mean wind speed, and for comparison a CBL mean speed profile calculated from Wilson's formula, Eq. (10.18), with $L = -15$ m, $z_0 = 0.01$ m, $u_* = 0.46$ m s^{-1}, and the same mean horizontal pressure gradient. The contrast in surface-layer mean wind speeds between the CBL and SBL cases is striking. LES data courtesy Peter Sullivan, NCAR.

fig.: Upper-left: Stably stratified ABL, Upper-right: Convective ABL Left: Velocity profiles in SBL/CBL (Wyngaard, J.)

Wind Turbine Modeling (1): Actuator Disc





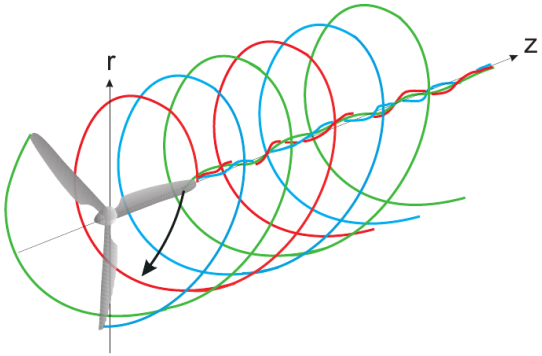


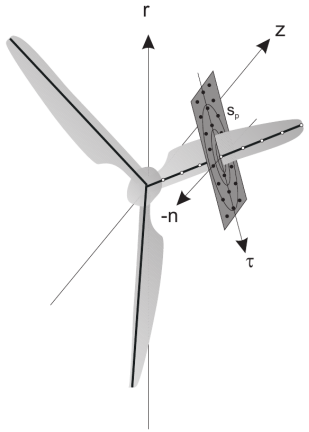
$$\boldsymbol{f}_{2D} = (L, D) = \frac{1}{2}\rho V_{rel}^2 c(C_L \boldsymbol{e}_L, C_D \boldsymbol{e}_D)$$

$$\boldsymbol{f}_\epsilon = \boldsymbol{f} \otimes \eta_\epsilon, \qquad \eta_\epsilon(d) = \frac{1}{\epsilon^2 \pi^{3/2}} \exp\left[-\left(\frac{d}{\epsilon}\right)^2\right]$$

fig.: Actuator Disc Concept and Modeling

Wind Turbine Modeling (2): Actuator Line





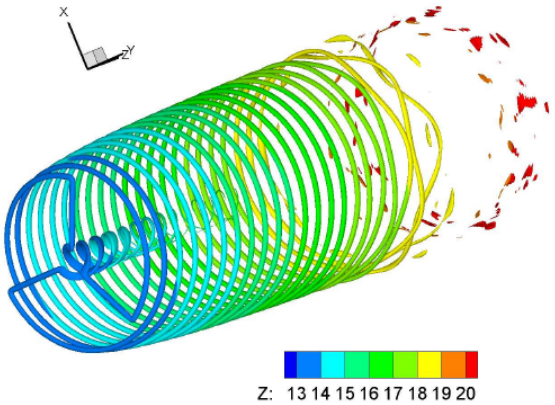


fig.: Actuator Line Concept and Modeling

Governing Equations

$Navier - Stokes$ equations must be solved:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\begin{aligned}\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) &= -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} \\ &+ \delta_{i3} g \frac{\tilde{\theta} - \langle \tilde{\theta} \rangle}{\theta_0} + f_c \epsilon ij3 \tilde{u}_i - \frac{f_i}{\rho} + F_i \end{aligned} \tag{2}$$

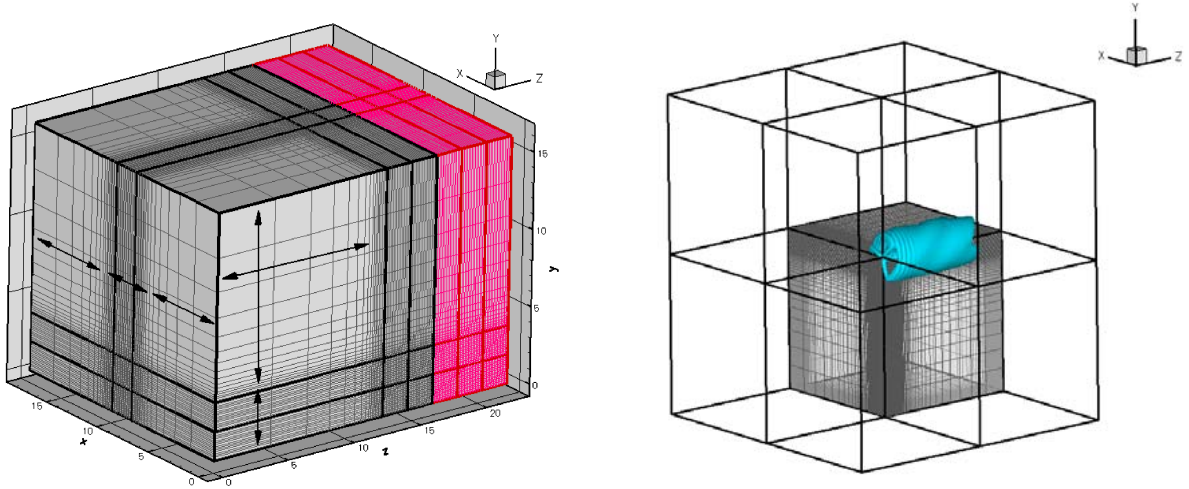
$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \alpha \frac{\partial^2 \tilde{\theta}}{\partial x_j^2} \tag{3}$$

Where

$\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$	*SGS momentum flux*
$q_i = \widetilde{u_j \theta} - \tilde{u}_j \tilde{\theta}$	*SGS heat flux*
$\tilde{p}^* = \tilde{p} + \rho \tilde{u}_i \tilde{u}_j / 2$	*modified pressure*
f_c, f_i, F_i	*Coriolis parameter, WT loading, Ext. forcing (wind etc.)*
$\tilde{\theta}, \alpha$	*Potential Temperature, Air thermal diffusivity*

CFD Platform, Ellipsys3D

- Parallelized 3D CFD solver developed in DTU/Risø
- Finite volume discretization of *Navier-Stokes* equation
- Written in general curvilinear coordinates using multi-block topology
- Written in Fortran



(a) Block structure (2 superblocks of 3^3 blocks)

(b) Velocity iso-surface downstream rotor

fig.: Meshing in Ellipsys3D

Wind farm simulation

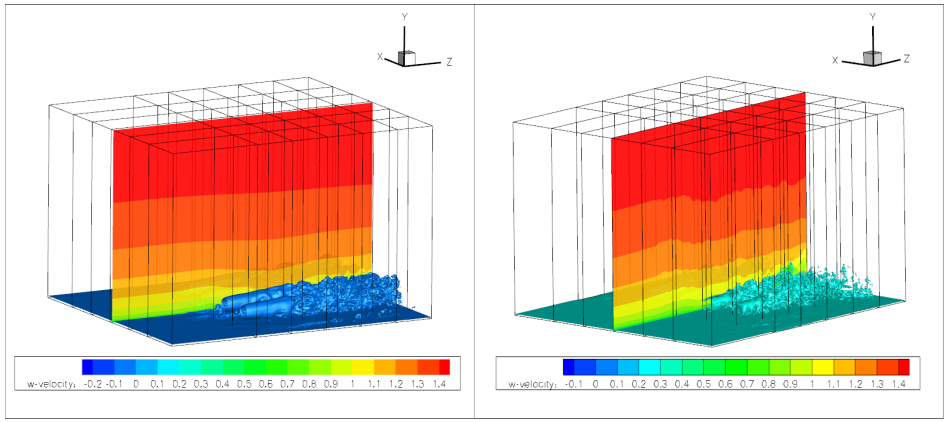


fig.: Wind farm simulation in laminar (left) and turbulent (right) flows

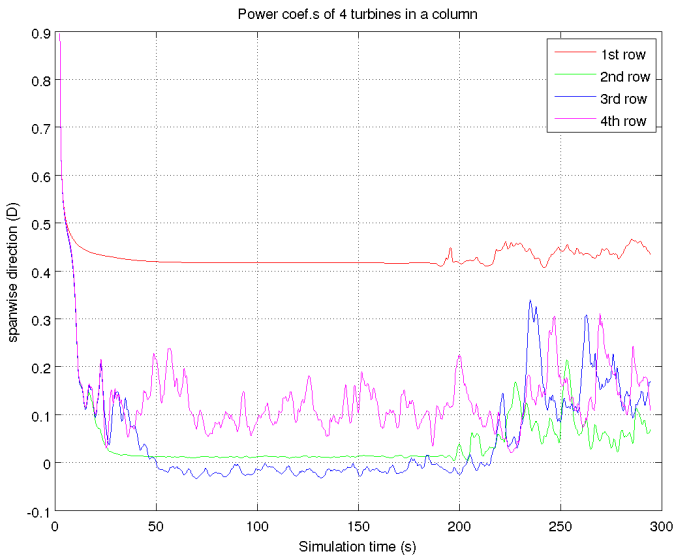


fig.: Power coefficient in time for four turbines downstream

Wind farm simulation-Contd.

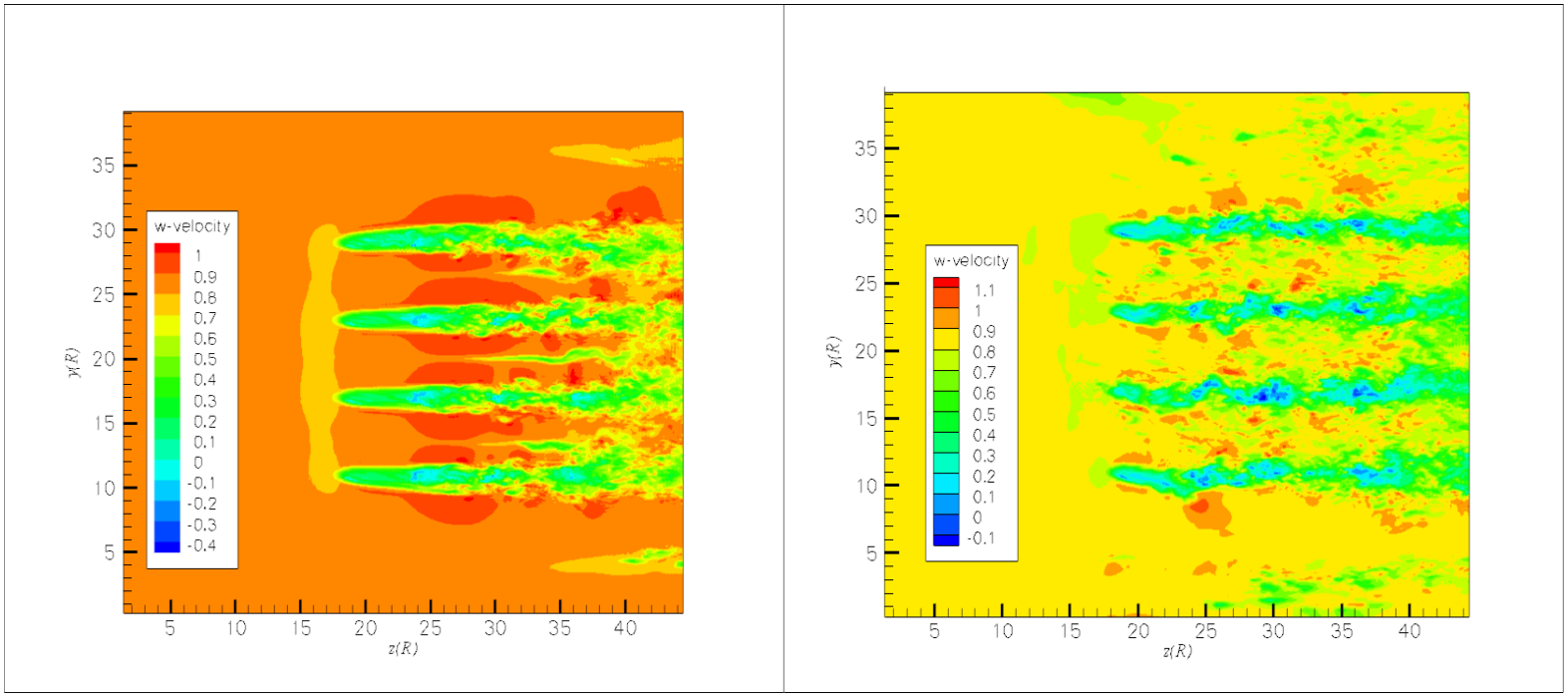


fig.: Wind velocity at hub height in laminar (left) as well as turbulent (right) flow

Wind farm simulation-Contd.

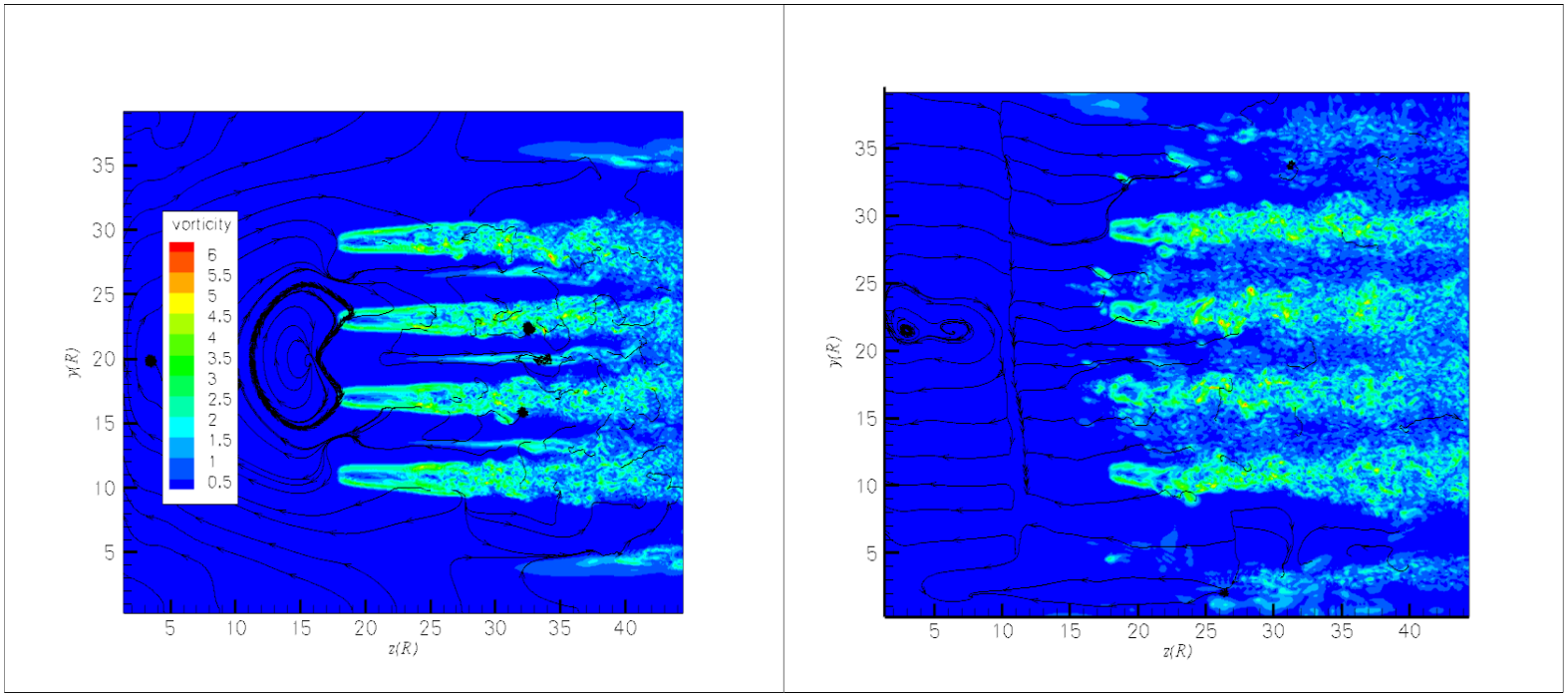


fig.: Vorticity distribution at hub height in laminar (left) as well as turbulent (right) flow

Wind farm simulation-Contd.

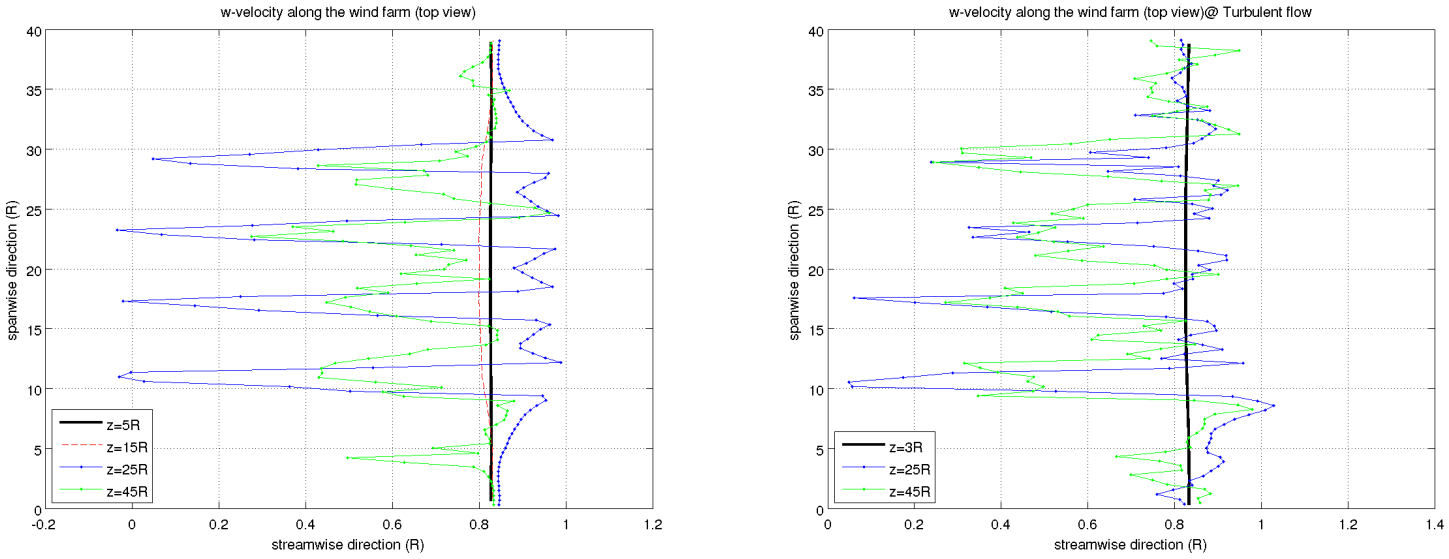


fig.: Streamwise velocity deficit in laminar (left) and turbulent (right) flows

Future work

- Include buoyancy effects through Modification of momentum eqn, Adding heat equation, Modification of SGS terms for buoyancy effect
- Applying dferent turbulence modeling strategies including dynamic pure LES and hybrid methods to come up with a general comparison
- Looking at the ABL with wind farm(s) included and comparison with available data

Conclusions

- Thermal stratification plays an important role in wind supply for wind farms
- Modeling techniques may be used instead of simulations to account for velocity profiles and turbulence intensities
- Improvements for wind turbine modeling (e.g. controller implementation)
- There is room for improvements in LES applicable in wind farms (*e*.g. wall models, SGS models)

DTU

References and Further reading

S. Ivanell (2009)
Numerical Computation of Wind turbine Wakes.
PhD Thesis, Gotland University .

F. Porte-Agel et. al. (2011)
Large-eddy simulation of atmospheric boundary layer ow through wind turbines and wind farms.
J. Wind Eng. Ind. Aerodyn. doi:10.1016/j.jweia.2011.01.011

M. Calaf et. al (2010)
Large eddy simulation study of fully developed wind-turbine array boundary layers.
Phys. of Fluids 22(015110).

J. C. Wayngaard (2010)
Turbulence in the atmosphere.
Cambridge University Press.

Acknowledgement

This research was carried out as part of the *Statkraft Ocean Energy Research Program*, sponsored by Statkraft (*www.statkraft.no*). This support is gratefully acknowledged.

Thanks for your attention