Convective atmospheric boundary layer using Large Eddy Simulation

U. Vigny[a,b], L. Voivenel[b], S. Zeoli[a], P. Benard[b]

[a] Université de Mons (UMONS), Polytechnic Faculty, Belgium
[b] CORIA, CNRS UMR6614, Normandie Université, INSA and University of Rouen, France

18th EAWE PhD Seminar - 2022

Theme: Wind farms and wakes

Context: Global warming

Context

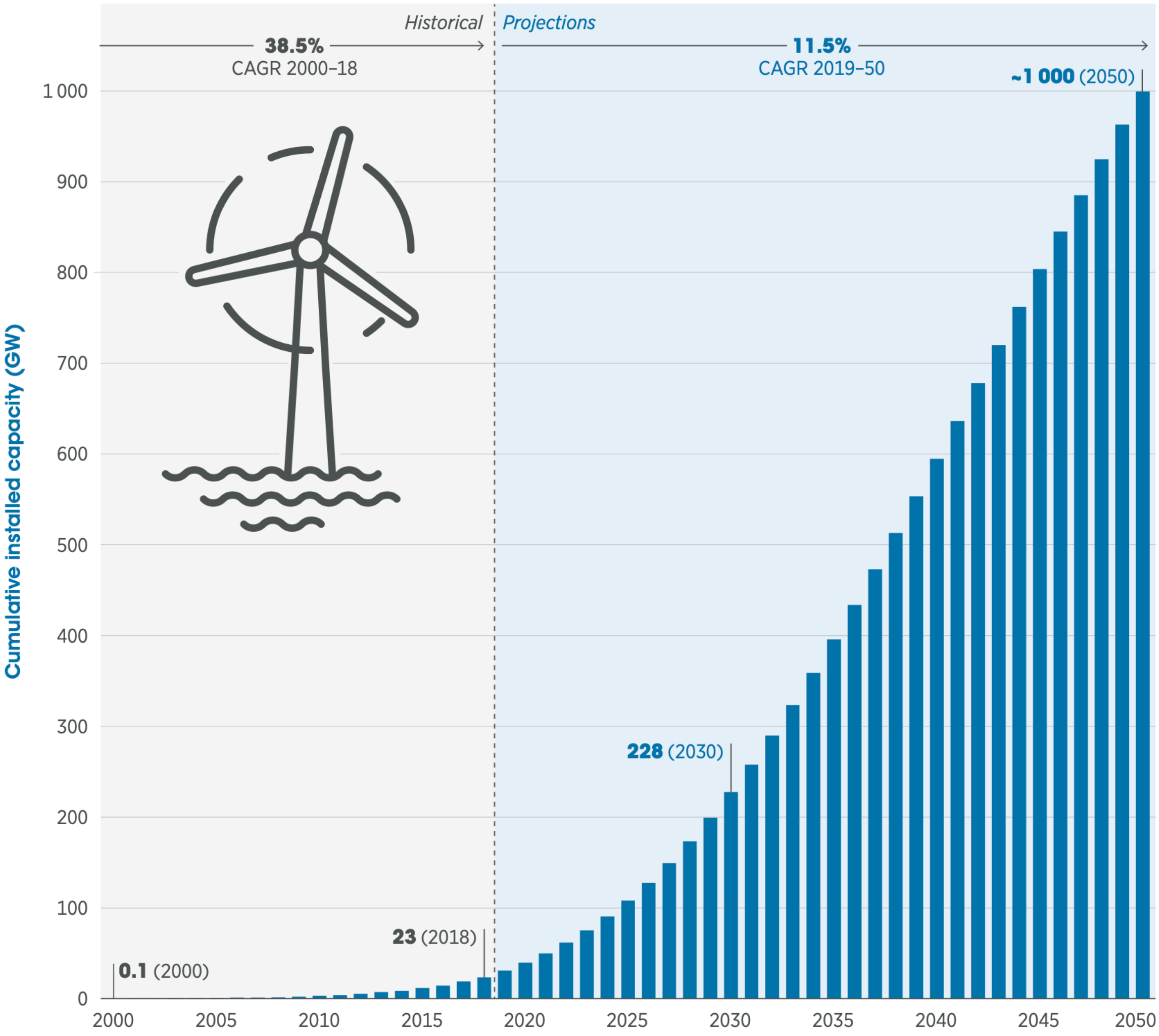
- Carbon neutral 2050
  - Reduce CO_2 emissions
  - Shift energy production

Wind energy

- Potential
  - $30 - 39\ PWh/year$ potential in Europe
- Competitiveness
  - competitive LCOE
  - Carbon footprint
- Prevision
  - X10 in 30 years

Power production

- Strong and regular wind
- Efficiency
- Wind turbine size



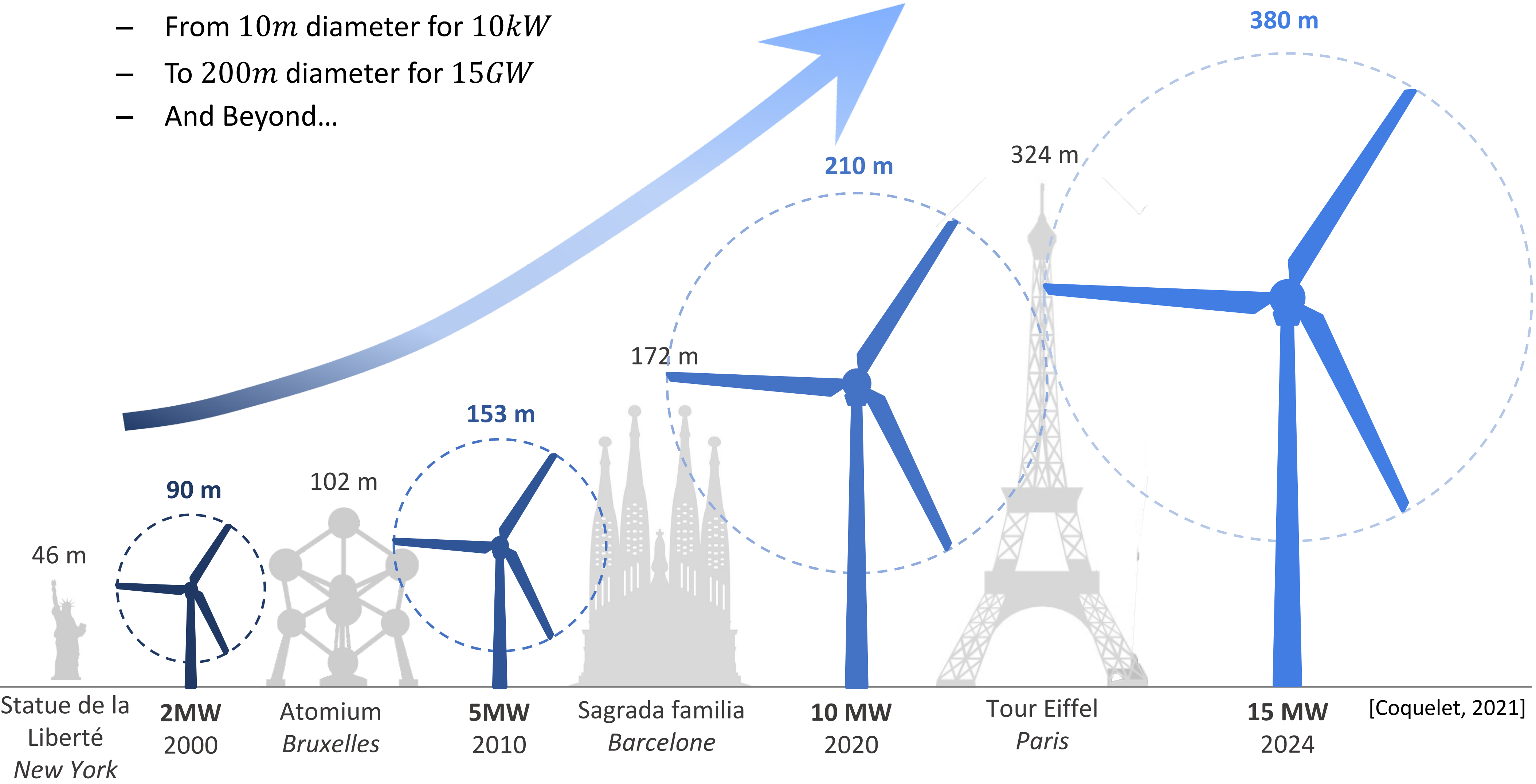
[Irena, 2019]

---

[1] IRENA (2019), *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper)*, International Renewable Energy Agency, Abu Dhabi.

Wind turbine modelling

- Offshore rotor size continues to grow
  - From $10m$ diameter for $10kW$
  - To $200m$ diameter for $15GW$
  - And Beyond…



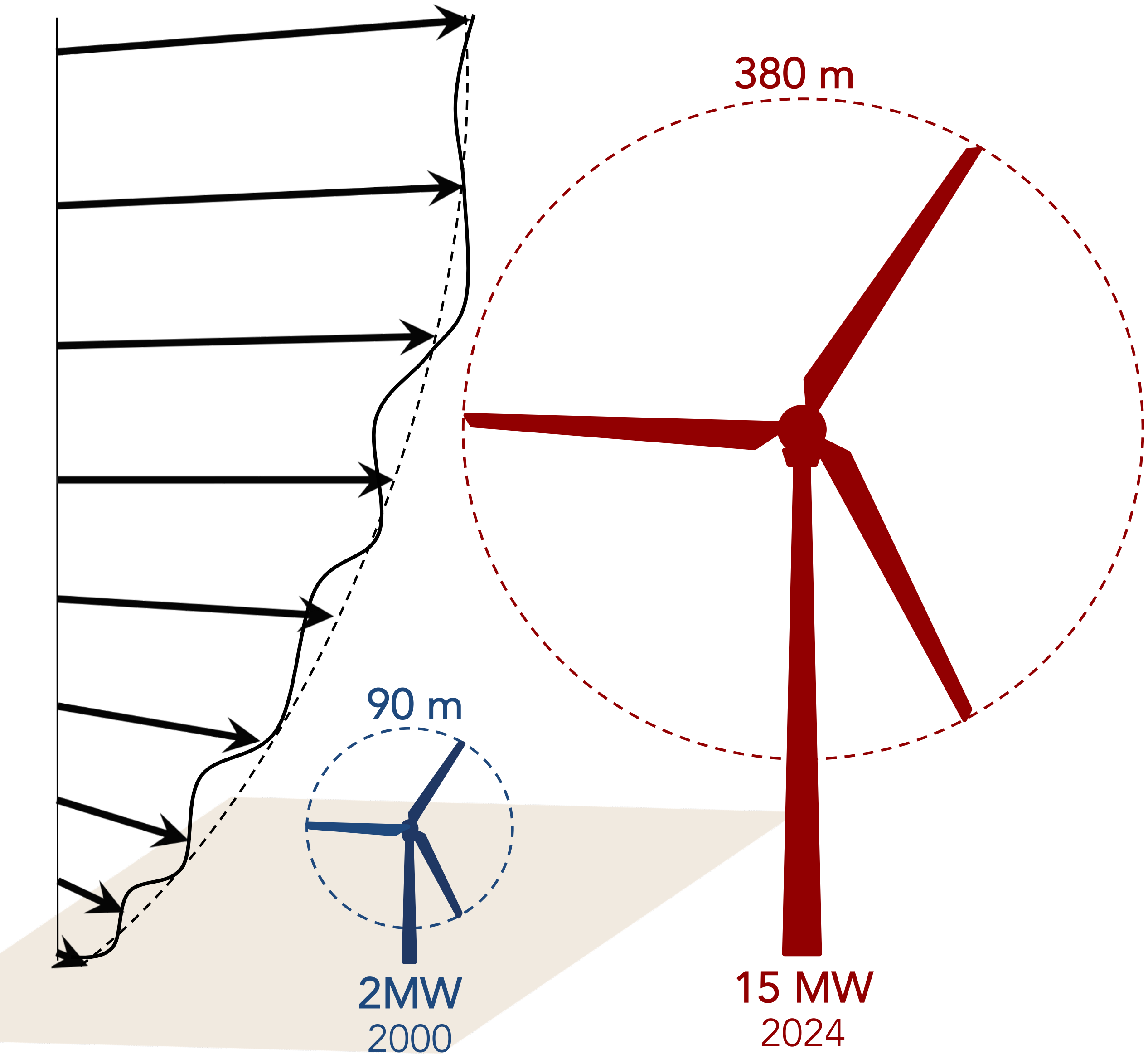
[Coquelet, 2021]

→ Different flow physics

---

[1] Enevoldsen et al. 2019, Examining the trends of 35 years growth of key wind turbine components.

Microscale to Mesoscale



Weather study

Meso-scale

- Free atmosphere $\sim O[10km]$
  - Constant temperature gradient
  - Non-turbulent
- Inversion layer $\sim O[100m]$
  - Discontinuity in temp & velocity
  - Strong thermal stability
  - Rigid lid on top of the ABL
- Mixed layer $\sim O[500m]$
  - Neutral, stable, convective ABL
  - Turbulent layer

Small scale study

Micro-scale

- Inertial sublayer $\sim O[50m]$
  - Bluk exchange of mass, momentum and heat (wind-waves)
- Wave boundary layer $\sim O[1m]$
  - Impacted by the motion of the waves
- Viscous sublayer $\sim O[1mm]$
  - Important viscous fluid forces

→ Mixed layer impact on wind turbines

---

[1] Deskos et al. 2021 Review of Wind-Wave coupling models for Large-Eddy Simulation of Marine Atmospheric Boundary Layer

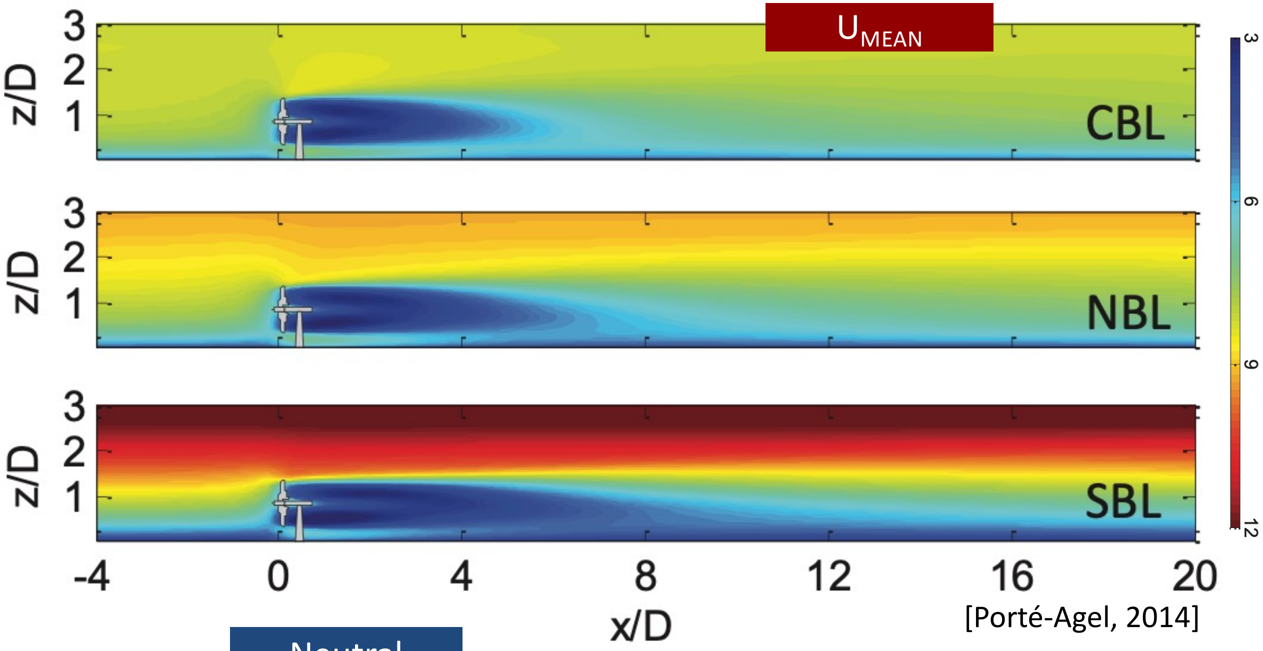
The Mixed layer

Why the study

- Wind turbine wakes
  - Recovery, size
  - velocity definit, turbulence
- Wind turbine aerodynamics
  - Power production, loads, fatigues

Why a challenge

- Thermal effect
  - Neutral, Stable, Convective



[Porté-Agel, 2014]

How to Model

- Monin-Obukhov similarity theory[1]

$$\frac{u(z)}{u_\tau} = \frac{1}{\kappa}\left[\ln\left(\frac{z+z_0}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right]$$

$$\frac{\theta(z)-\theta_w}{\theta_*} = \frac{1}{\kappa}\left[\ln\left(\frac{z+z_0}{z_0}\right) - \Psi_h\left(\frac{z}{L}\right)\right]$$

$$\Psi_{m/h} = \int_0^{z/L} \frac{1-\phi_{m/h}}{\xi}\, d\xi$$

Neutral

$$\begin{cases} \phi_m(z/L) = 0 \\ \phi_h(z/L) = 0 \end{cases}$$

Stable

$$\begin{cases} \phi_m(z/L) = 1 + \gamma_m \frac{z}{L} \\ \phi_h(z/L) = 1 + \gamma_h \frac{z}{L} \end{cases}$$

Convective

$$\begin{cases} \phi_m(z/L) = \left(1 - \beta_m \frac{z}{L}\right)^{-1/4} \\ \phi_h(z/L) = \left(1 - \beta_h \frac{z}{L}\right)^{-1/2} \end{cases}$$

- Obukhov length: $L = -\frac{u_\tau^3 \theta_0}{\kappa g q_w}$
- Friction velocity: u_τ
- Roughness length: z_0
- Von Karman $\kappa = 0.37 \sim 0.41$
- Wall temperature: θ_w
- Heat flux: $q_w = \theta_* \times u_\tau$

---

[1] Monin & Obukhov, 1954. Basic laws of turbulent mixing in the surface layer of the atmosphere

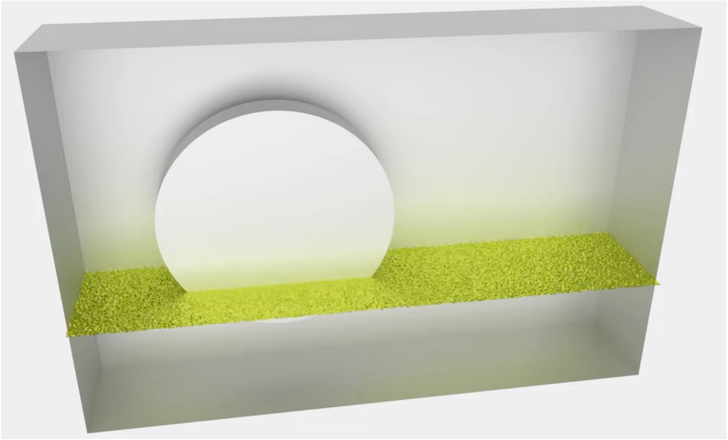
[2] Foken T. 2006. 50 years of the Monin-Obukhov similarity theory

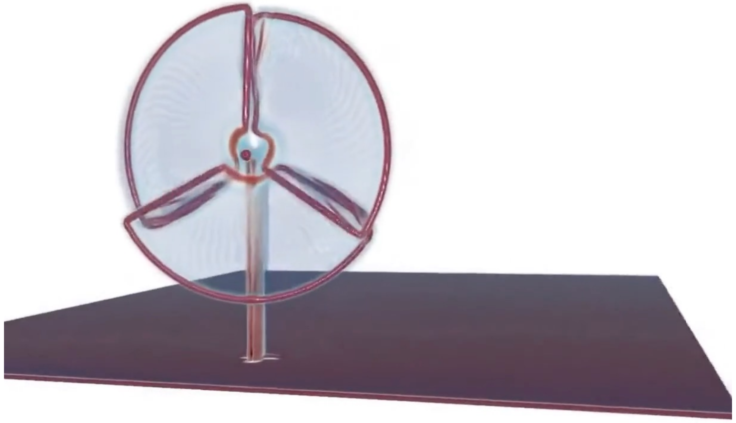
Simulation Framework

- Long term goal → Accurate analyse of the interaction between wind turbines and ABL
- Presently → Convective ABL simulation

- Large Eddy Simulation → Large scale resolution, small scale modelling

- YALES2 features
  - **Unstructured meshes** and adaptive grid refinement
  - **Low-Mach number** Navier-Stokes equations (incompressible and **variable density**) solved with projection method
  - Double domain decomposition[1]
  - Highly efficient solvers for linear system inversion (PCG, DPCG)[2]
  - **4th order** central finite volume method and **4th order** time integration[3]
  - Suited for **massively parallel computing** (>32 000 procs)
  - Actuator Line Method[4]





---

[1] Moureau et al. 2011 Comptes Rendus Mécanique

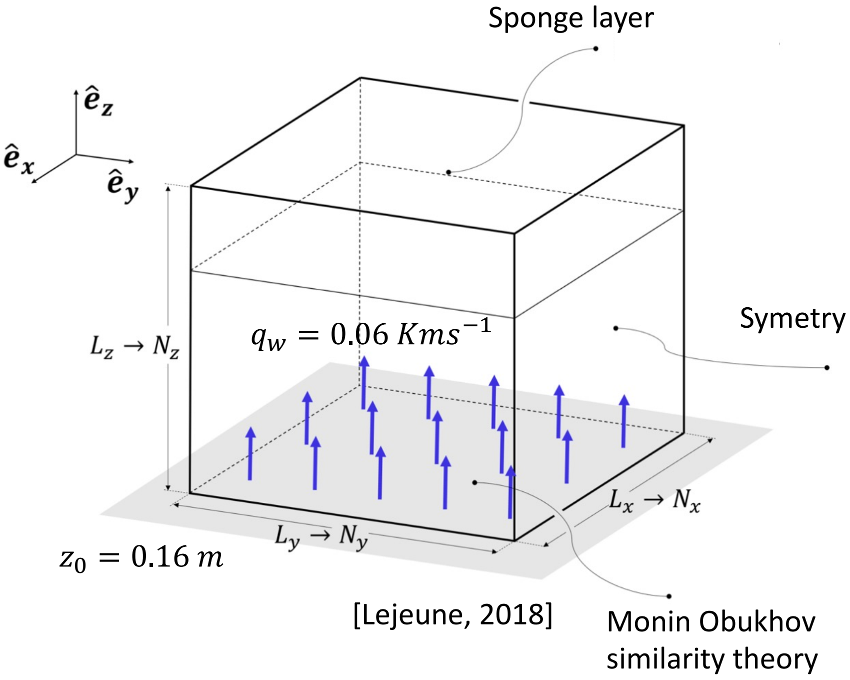
[2] Malandain et al. 2013 JCP

[3] Kraushaar M, 2011 Ph.D. thesis INPT

[4] Bénard et al. 2018 Computers & Fluids

Application to a dry convective boundary layer

- Willis & Deardorff test case:
  - Periodic box
    - Uniformly heated $q_w = 0.06\ Kms^{-1}$
    - Initial temperature $\theta_0 = 299.7\ K$
    - Initial height $z_m = 1350\ m$
  - Inversion layer
    - $\frac{d\langle\theta\rangle}{dz} = 0.003\ K.m^{-1}$
  - Random perturbation
    - $r \in [-0.5; 0.5]$



[Lejeune, 2018]

Initial velocity profile

$$w(z) = \begin{cases} 0.1r\left(1 - \frac{z}{z_m}\right) w_c^0, & if\ \ 0 < z \le z_m \\ 0, & if\ \ z > z_m \end{cases}$$

Initial temperature profile

$$\theta(z) = \begin{cases} \theta_0 + 0.1r\left(1 - \frac{z}{z_m}\right) \theta_c^0, & if\ \ 0 < z \le z_m \\ \theta_0 + (z - z_m)\frac{d\langle\theta\rangle}{dz}, & if\ \ z > z_m \end{cases}$$

- 3 comparison studies
  - JG. E. Willis & J. W. Deardorff 1974 → 1st experimental setup
  - J. W. Deardorff & G. E. Willis 1985 → Further results
  - H. Schmidt & U. Schumann 1988 → LES

Case	W&D	S&S	This work
Top BC	insulate	Radiation	Sponge Layer
Lateral BC	wall	Symetry	
Lower BC	heat exchanger	Monin-Obukhov similarity theory	
SGS Model	/	TKE Based	Smagorinsky
Initial contidions	/	Mixed layer topped by fluctuations	
Comp. domain	water	160×160×48	256×256×128
Physical domain	$114{\times}122{\times}76\ cm$	$8000 \times 8000 \times 2400\ m^3$	

---

[1] Willis & Deardorff, 1974. JAS

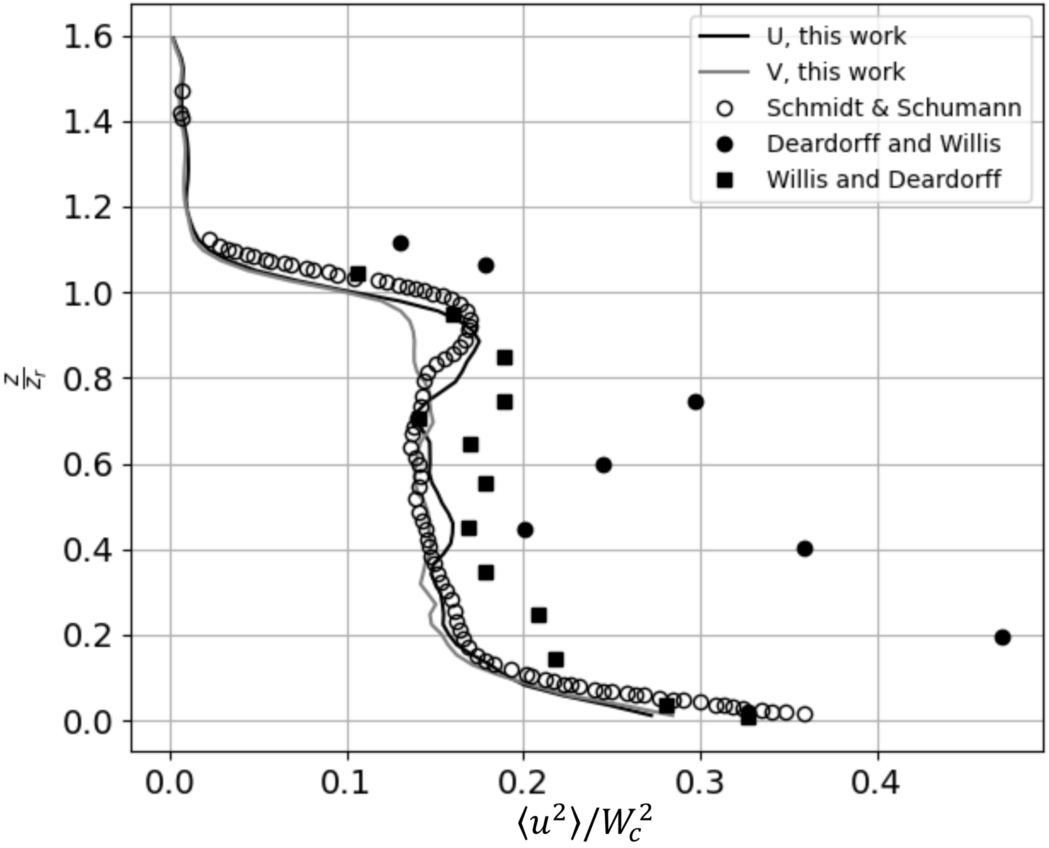
[2] H. Schmidt & U. Schumann, 1989. JFM

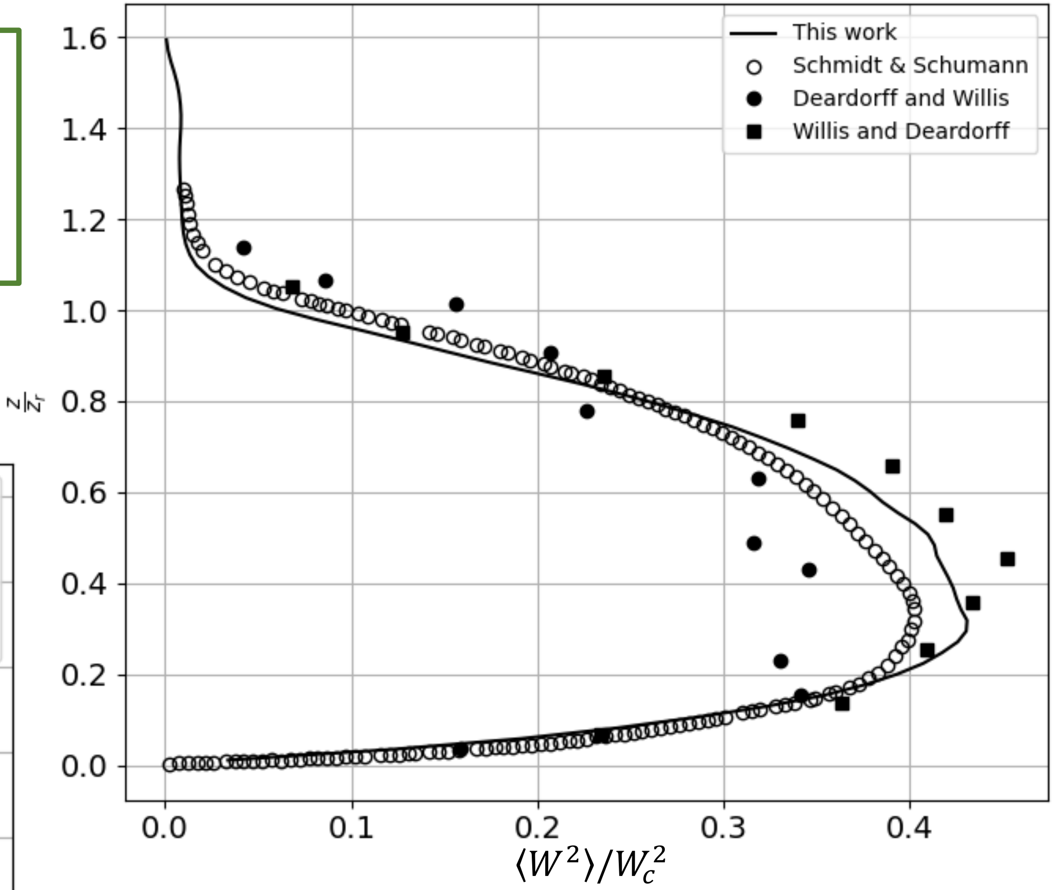
[3] Deardorff & Willis, 1985. BLM

Horizontal & vertical velocity variance

- Matches Schmidt & Schumann numerical results
- Deardorff & Willis: higher horizontal velocity variances

→ Due to surface heat flux horizontal variation





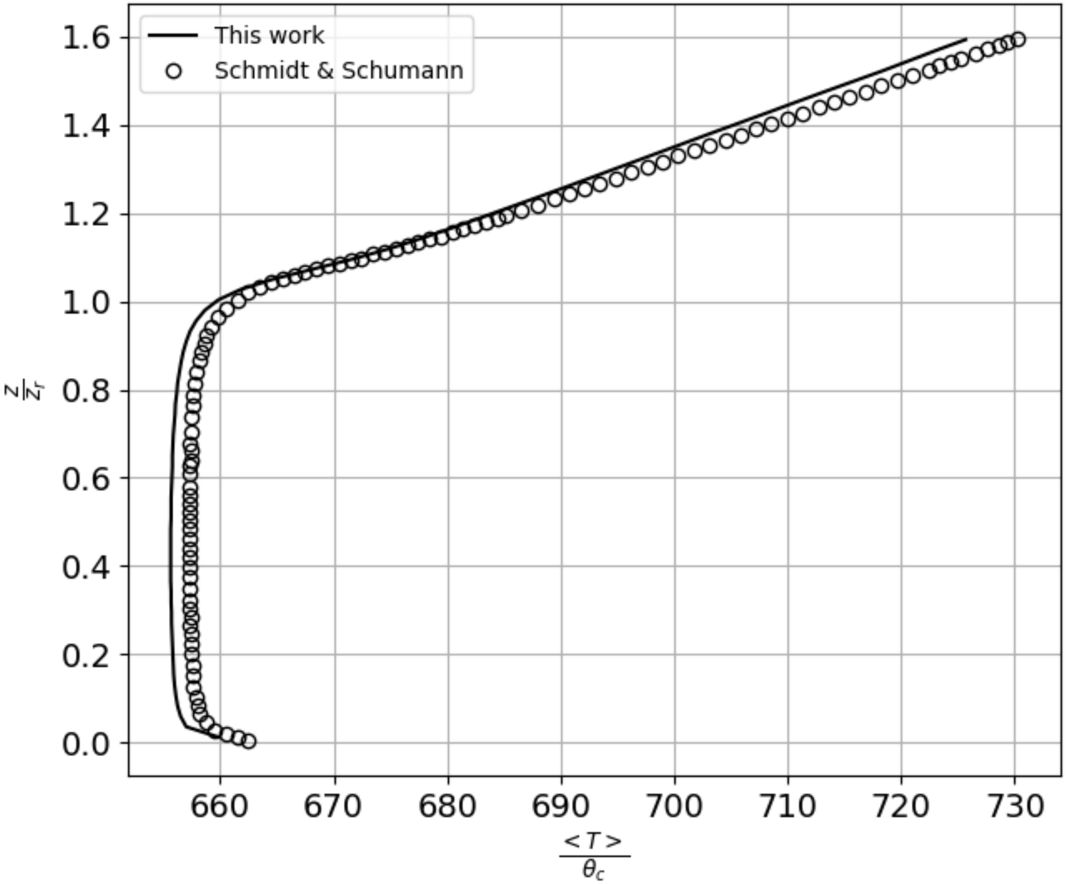
- Vertical → buoyancy (larger overall)
- Horizontal → presure fluctuations (predominant at the mixed layer edges)

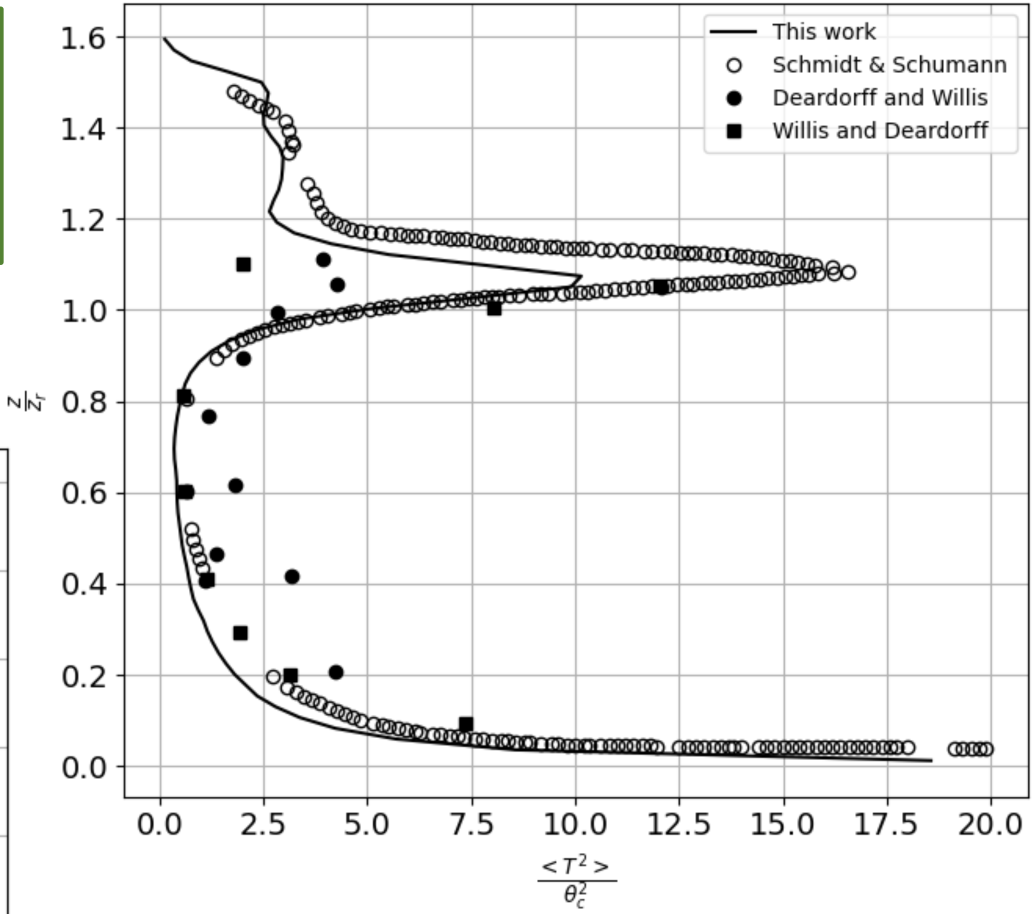
→ Overall lower horizontal than vertical velocity variance

Mean temperature & temperature variance

- Mean Temperature
  - Constant temperature in the mixed layer (intense turbulent mixing)
  - Quasi-steady state reached

→ Matches numerical results





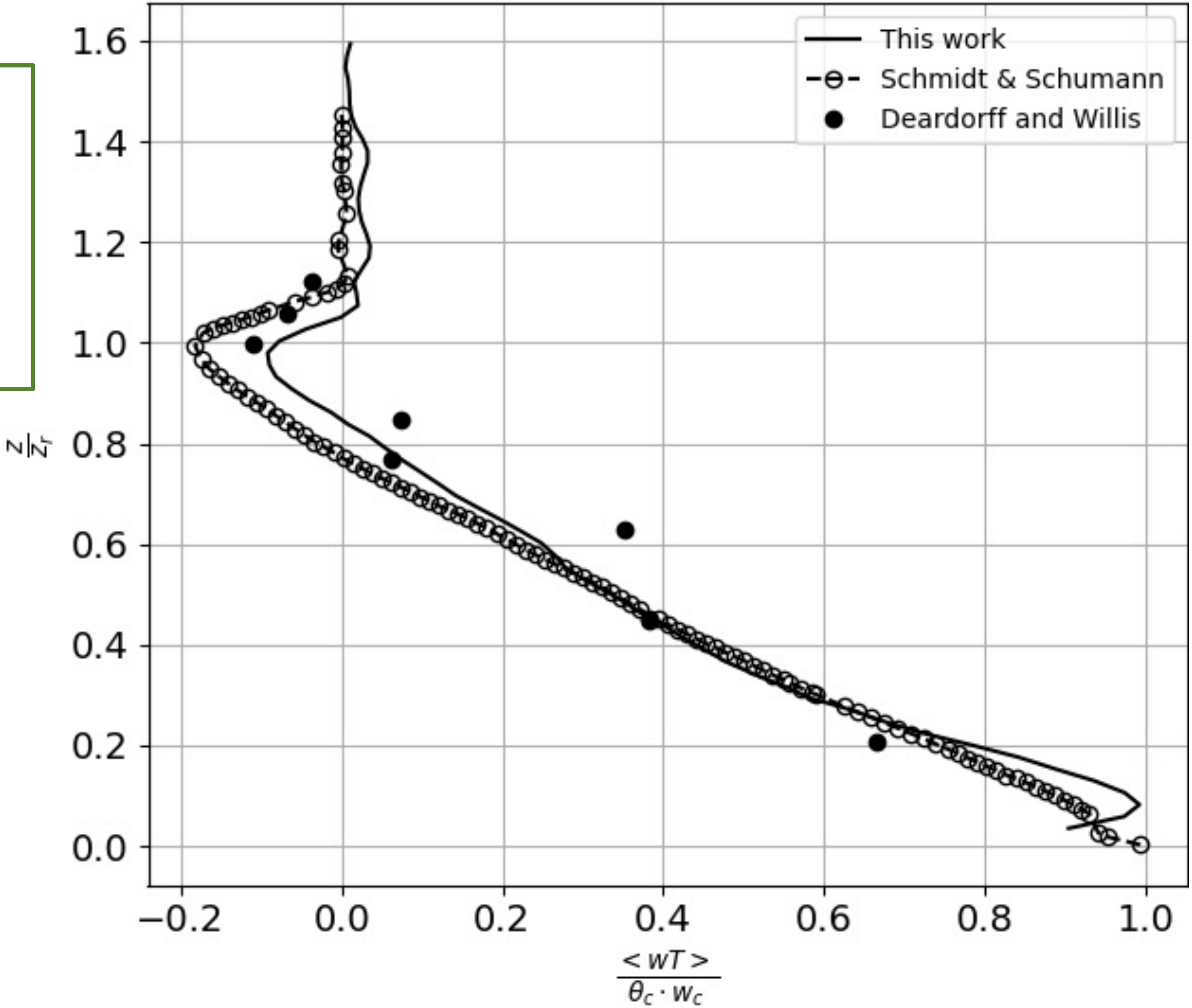
- Temperature variance
  - Heat flux and temperature gradient product
  - Low overall
  - High at the mixed layer edges

→ Matches both experimental & numerical results

Vertical heat flux

- Trends as expected
  - Linear decreasing with height (constant heating rate)
  - Stable at the inversion layer

→ Matches both experimental & numerical results



Conclusion and further work

Conclusion

- Implementation of the Monin-Obukhov similarity theory into YALES2
- Application on a literature test case
- Validation with experimental and numerical literature results

Perspectives

- Convective boundary layer wind farm simulation
- Stable boundary layer consideration

UMONS
Université de Mons

coria
UMR 6614