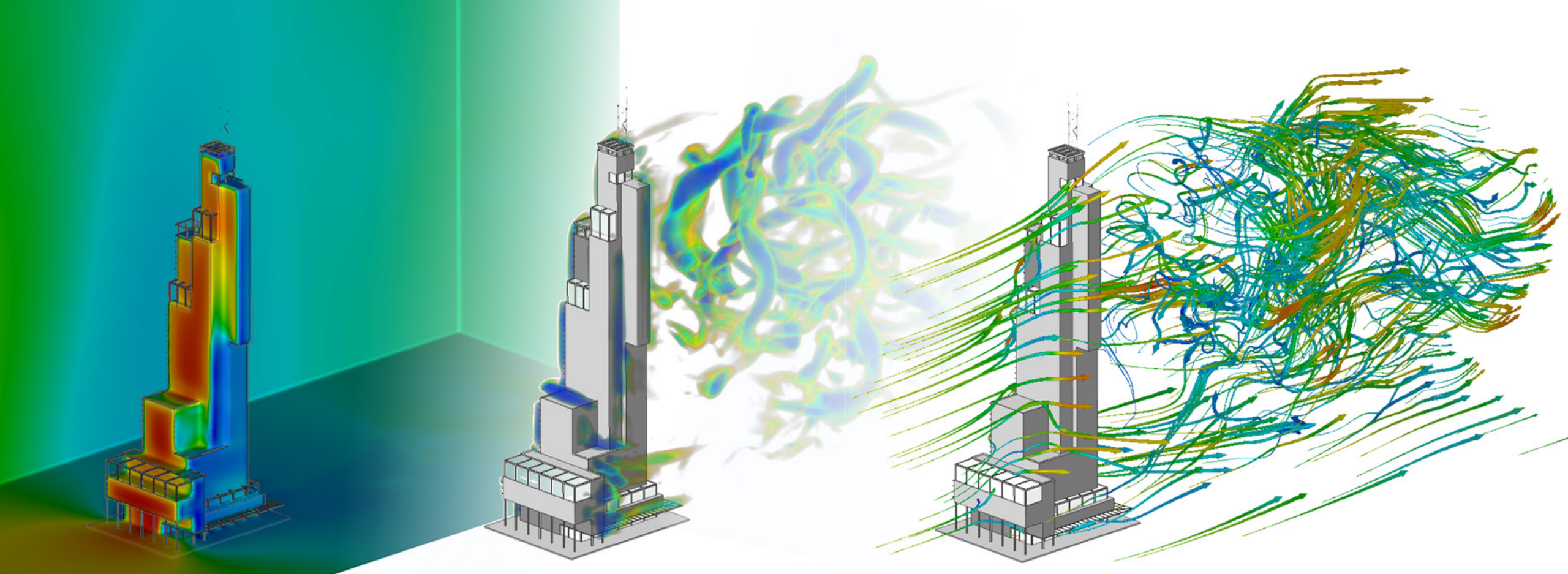




Estimation of the wind load on buildings using GPU-based large eddy simulation

Bálint PAPP¹, Gergely KRISTÓF¹ & Christof GROMKE²

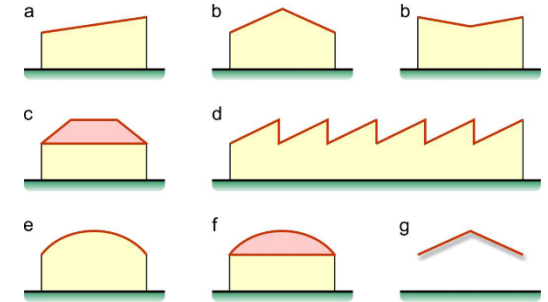
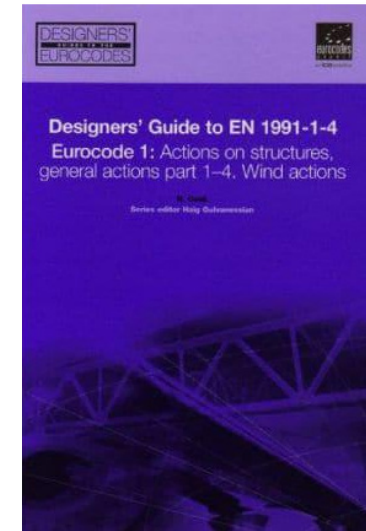
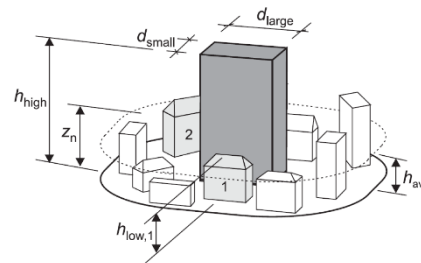
¹ Department of Fluid Mechanics, Faculty of Mechanical Engineering, Budapest University of Technology and Economics

² Laboratory of Building and Environmental Aerodynamics, Institute for Hydromechanics, Karlsruhe Institute of Technology



Wind load on buildings

- **Eurocode (EN 1991-1-4)**
- **Wind tunnel measurement**
- **CFD**
 - Steady-state or transient simulation?
 - Turbulence model: RANS, SAS, or LES?
 - Uncertainties of the inflow boundary conditions:
ABL: $u(z)$, $I_u(z)$

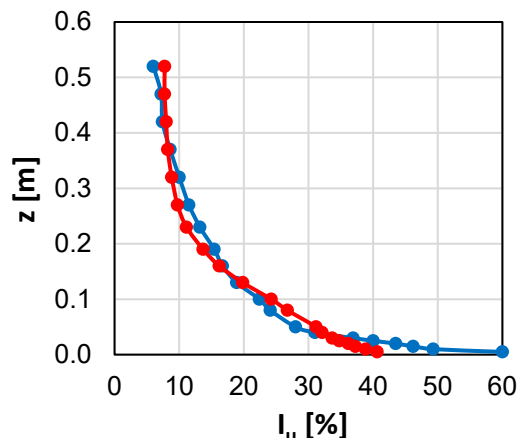
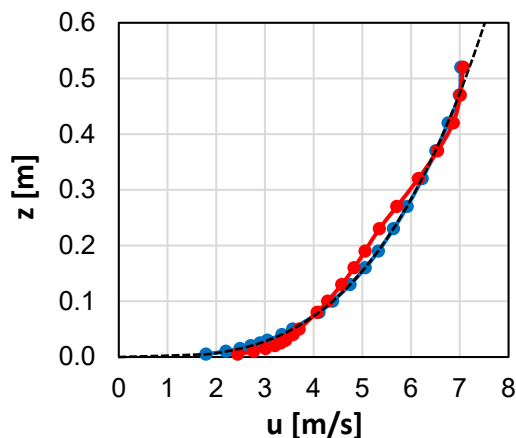


The numerical wind tunnel



ANSYS Discovery Live

- GPU-based large eddy simulation:
dynamic wind loads
- Relatively short fetch (≈ 2 m)
- Inlet boundary condition:
turbulent atmospheric boundary layer

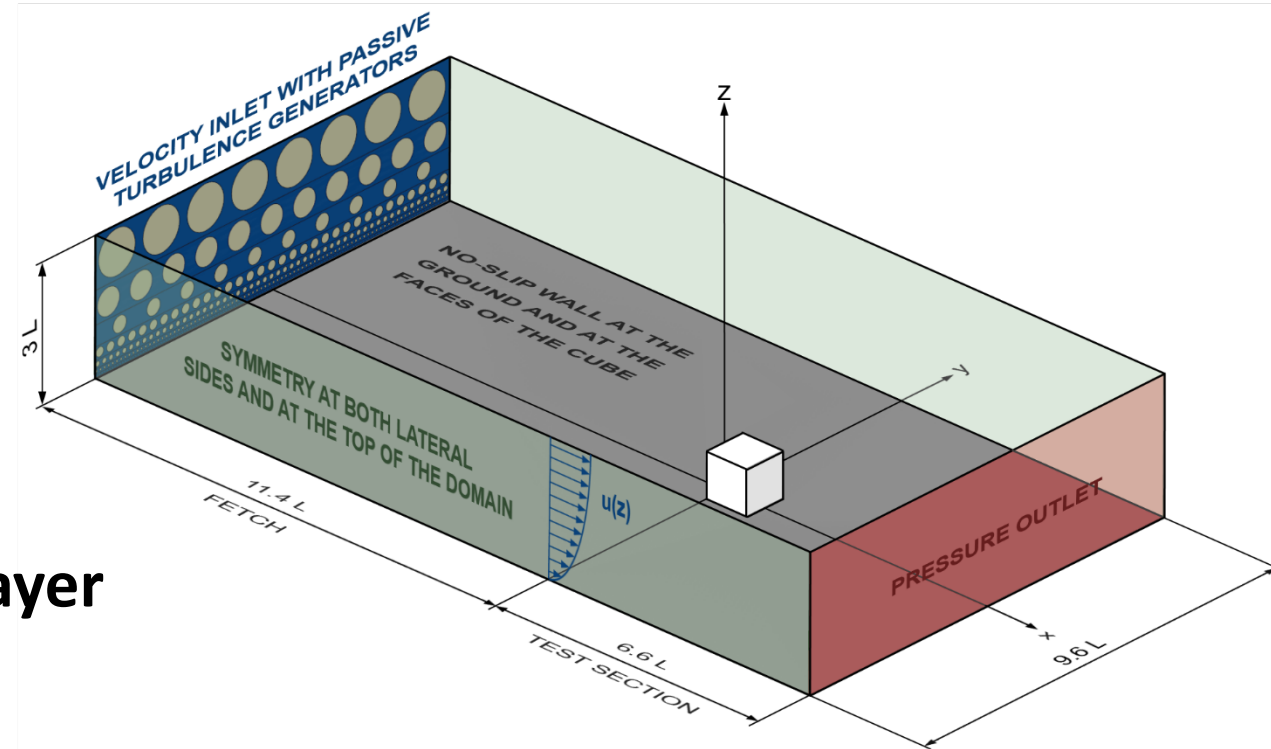


—●— Wind tunnel

—●— Discovery Live

----- Power law profile

$$\rightarrow u(z) = u_{ref} \left(\frac{z}{z_{ref}} \right)^{\alpha_u} = 4,39 \left(\frac{z}{0,1 \text{ [m]}} \right)^{0.3} \left[\frac{\text{m}}{\text{s}} \right]$$

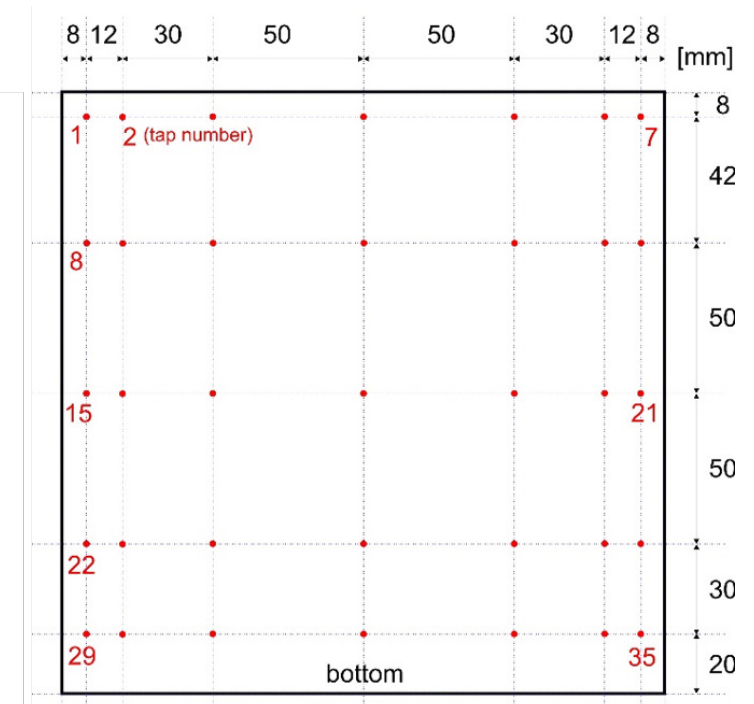
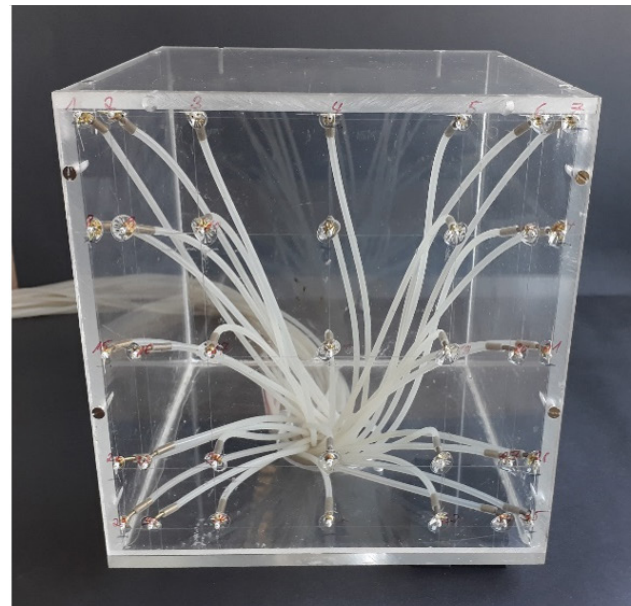
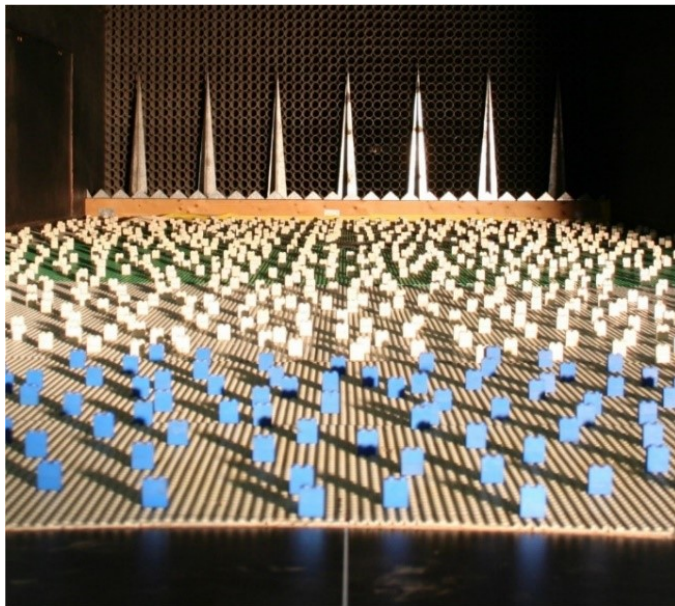


The real boundary layer wind tunnel

- KIT: Laboratory of Building and Environmental Aerodynamics
- 6 m long fetch (preparation section)
- Cube model: $L = 20$ cm, 35 pressure taps on one side
- Pressure coefficient distributions: 0° , 45°

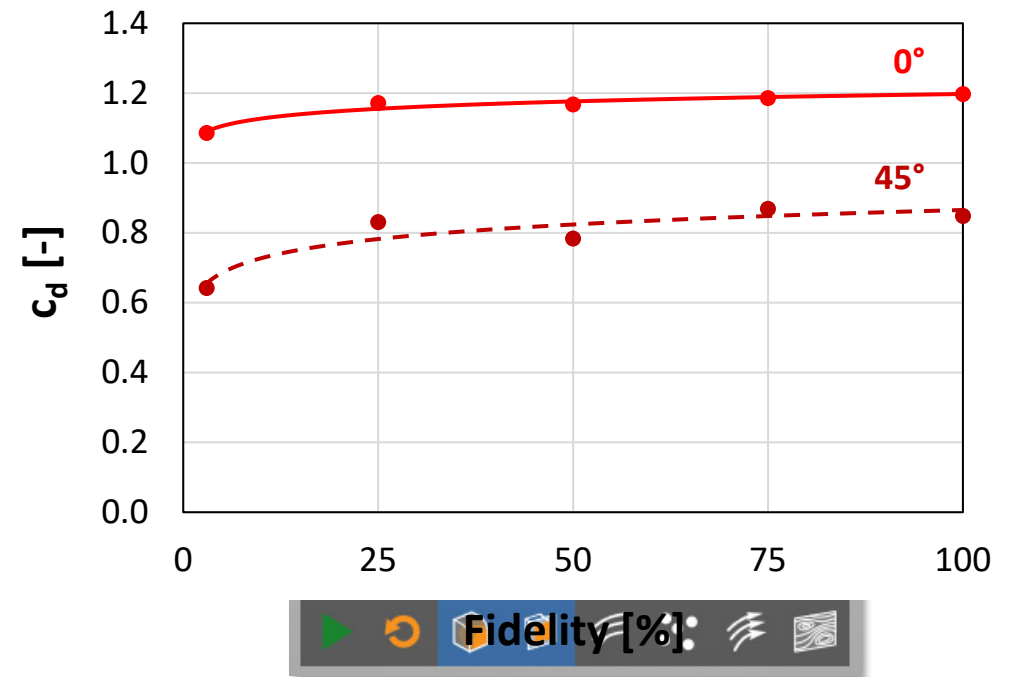


$$c_p(t) = \frac{p(t) - p_{ref}}{\frac{\rho}{2} (u(L))^2}$$

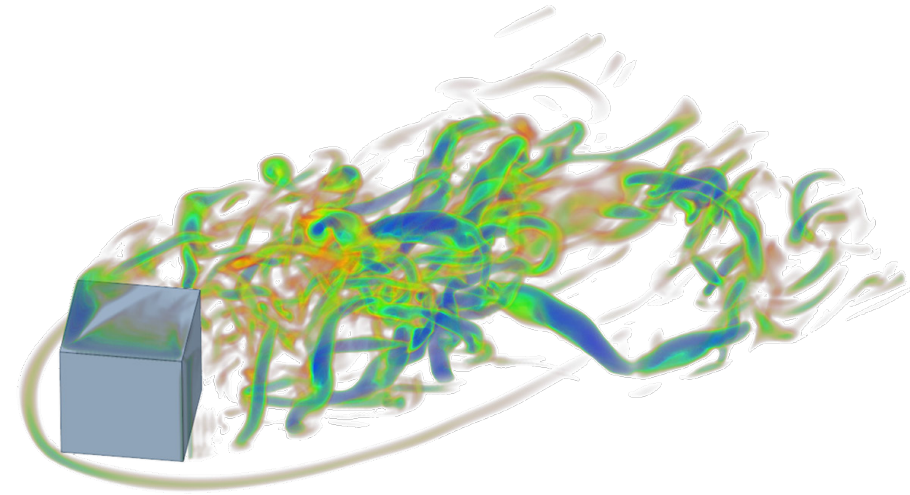
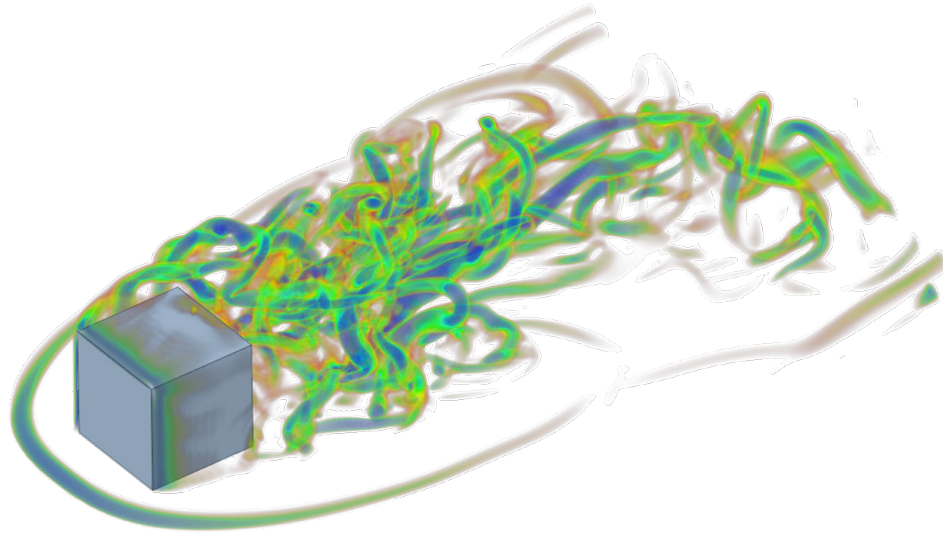


Mesh convergence

- **Equidistant Cartesian grid**, generated automatically by the software
- **Cell size: $\Delta x \approx L/26$**
 - GPU VRAM, domain size, *Fidelity*
- Drag coefficient: $c_d = \frac{F_d}{p_{dyn,ref} A_{ref}}$
- **Slightly oscillating convergence**
 - Turbulence model: LES
 - Discretization error



Fidelity [%]	Estimated cell size [mm]	Cell size uncertainty [%]	Cell count [million]	Average time step size [s]	Drag coefficient [-] 0° / 45°
100	7.74	± 0.58	9.0	$5.2 \cdot 10^{-4}$	1.09 / 0.64
75	8.45	± 0.18	6.9	$5.4 \cdot 10^{-4}$	1.17 / 0.83
50	9.71	± 3.04	4.5	$6.9 \cdot 10^{-4}$	1.17 / 0.78
25	15.52	± 1.72	2.1	$9.4 \cdot 10^{-4}$	1.19 / 0.87
3	38.33	± 4.36	0.074	$3.0 \cdot 10^{-3}$	1.20 / 0.85



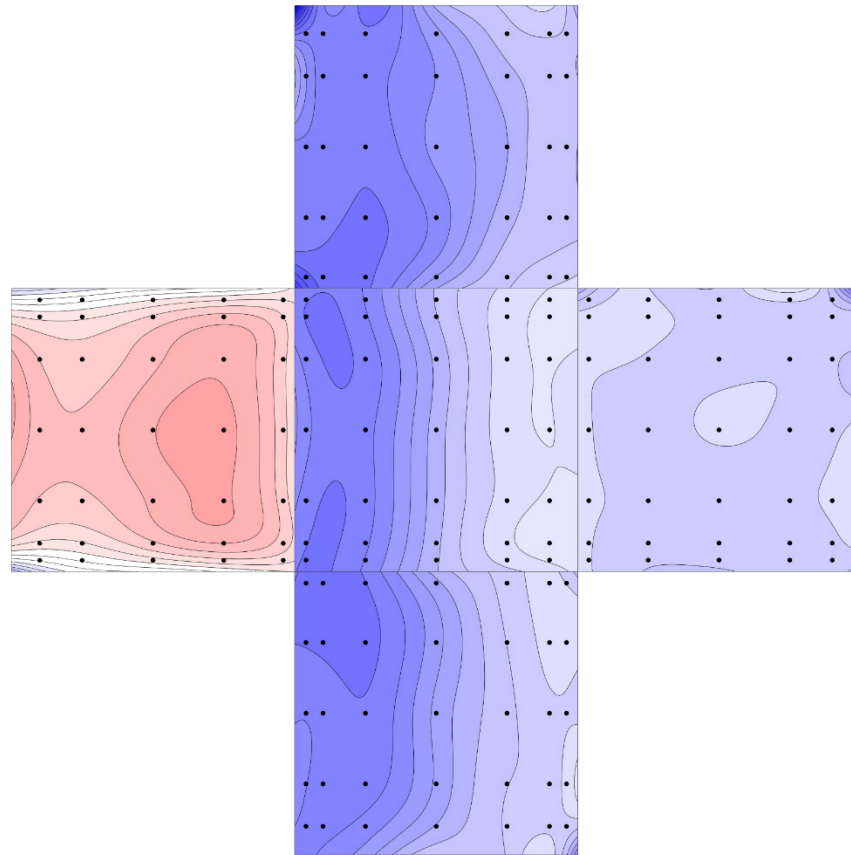
Results, validation

- Mean surface pressure distribution
- Distribution of the surface pressure fluctuations
- Pressure power spectra
- Comparison to previous measurement results

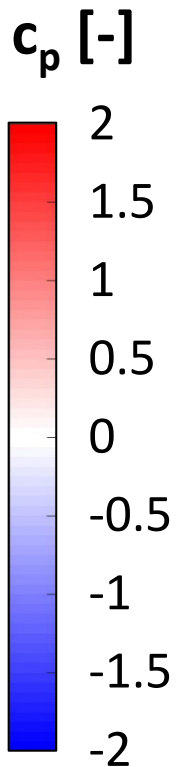
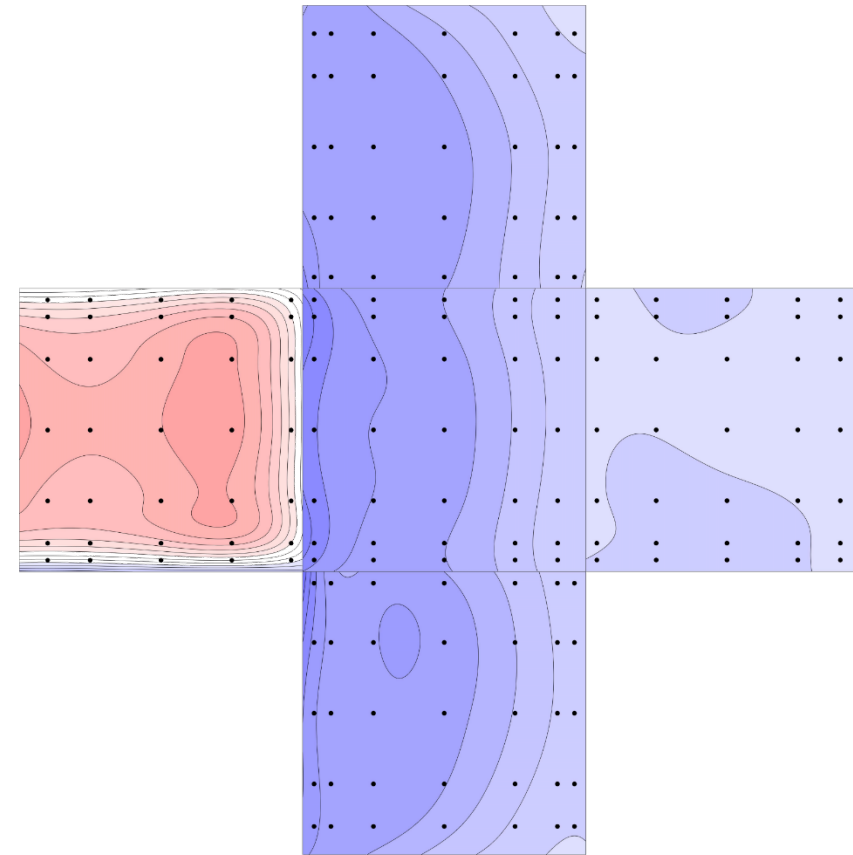


Mean surface pressure distribution – wind direction: 0°

Wind tunnel measurement

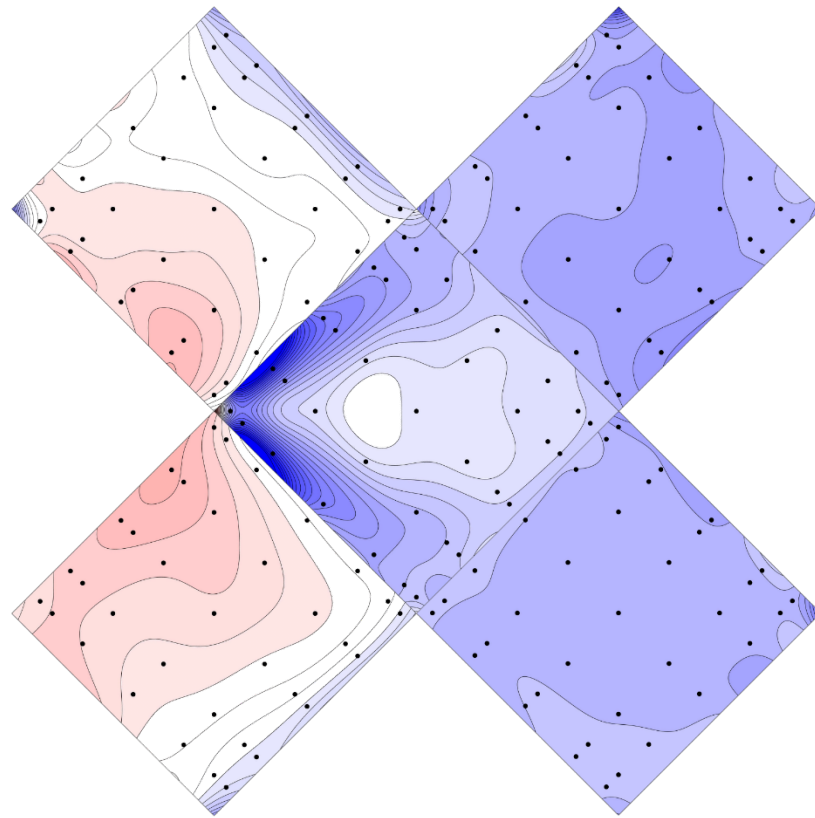


Discovery Live (CFD simulation)

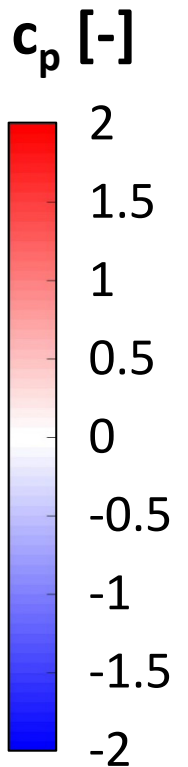
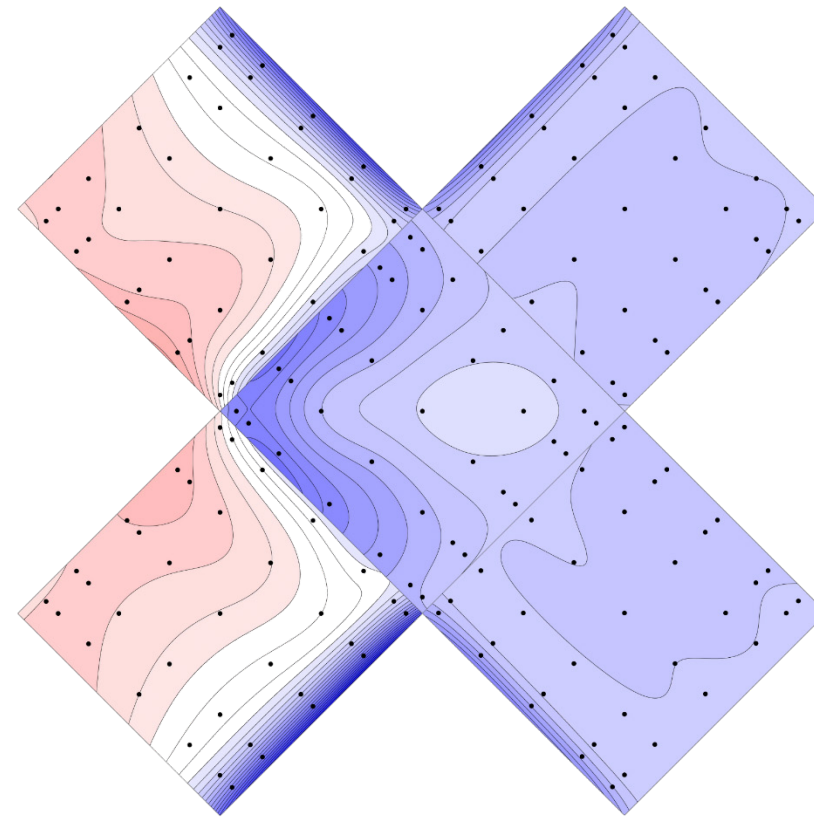


Mean surface pressure distribution – wind direction: 45°

Wind tunnel measurement

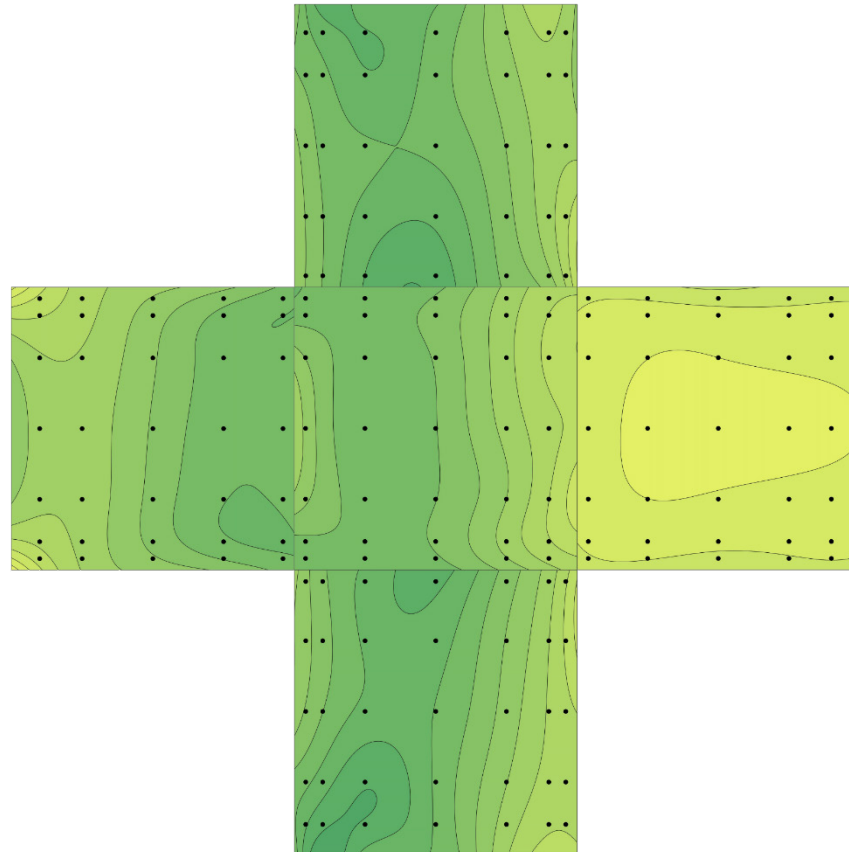


Discovery Live (CFD simulation)

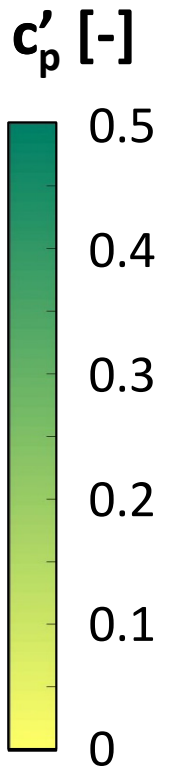
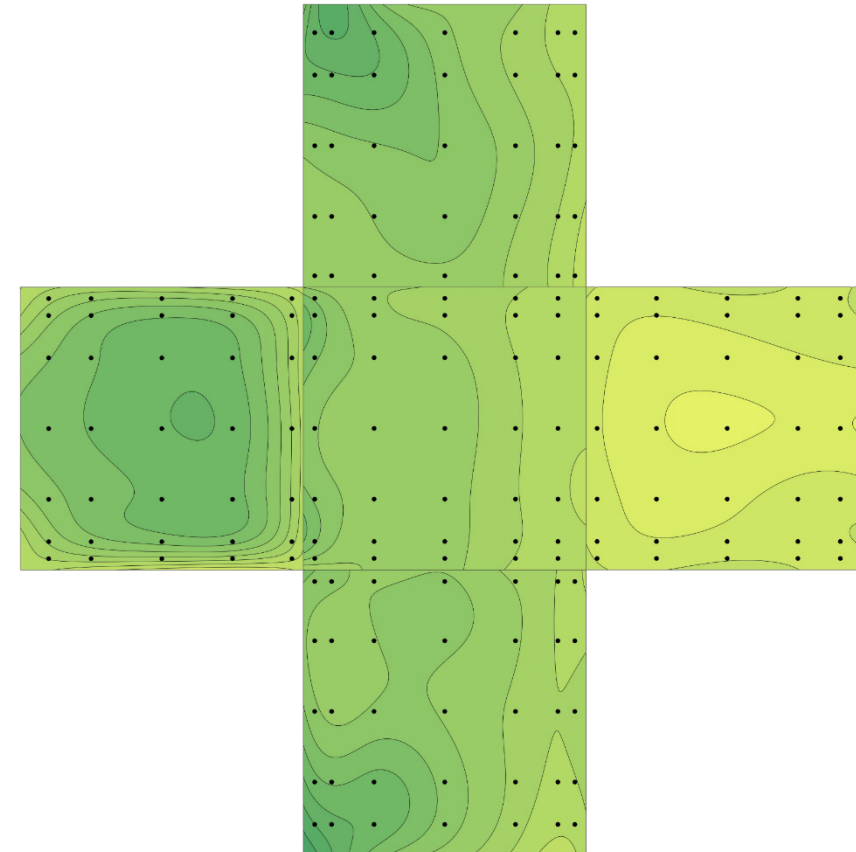


Fluctuation of the surface pressure distribution – wind direction: 0°

Wind tunnel measurement

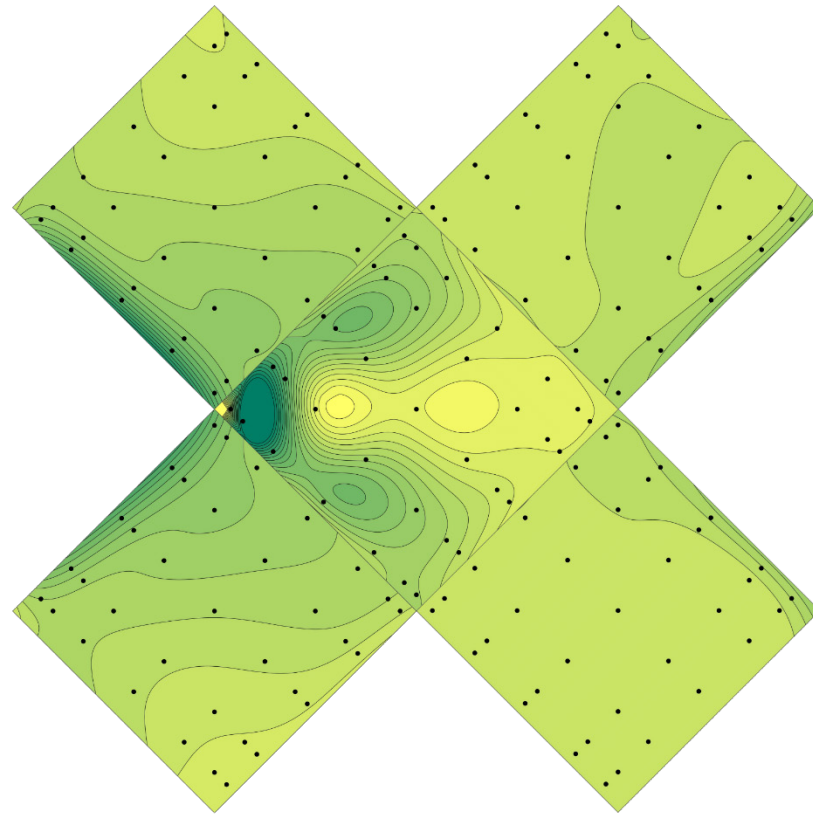


Discovery Live (CFD simulation)

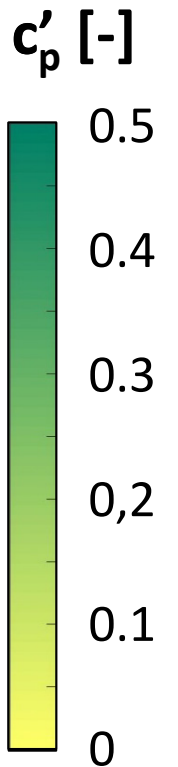
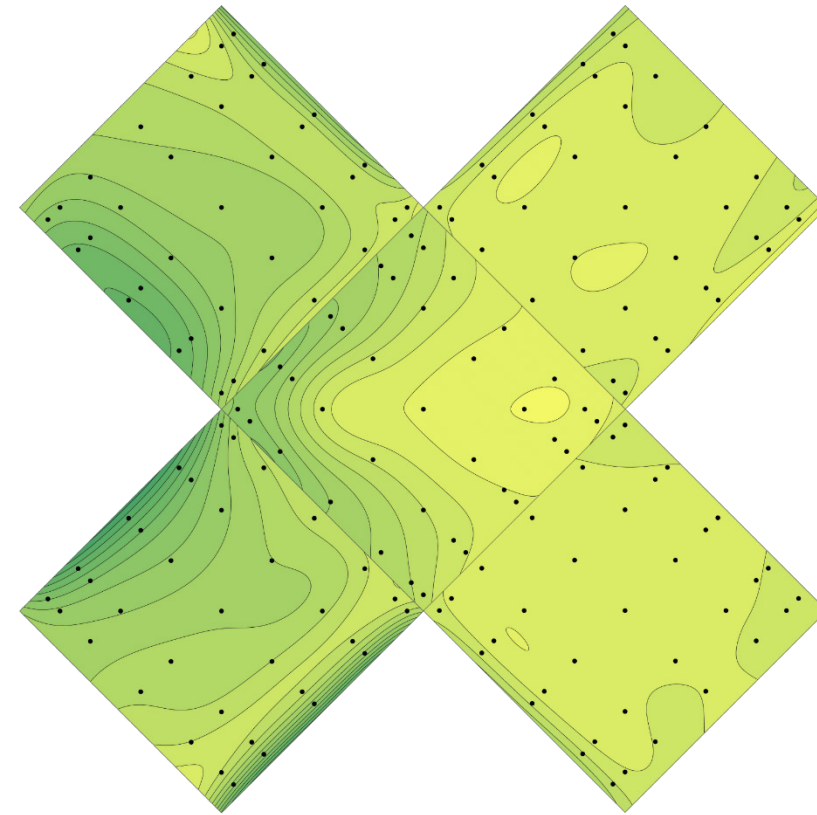


Fluctuation of the surface pressure distribution – wind direction: 45°

Wind tunnel measurement



Discovery Live (CFD simulation)



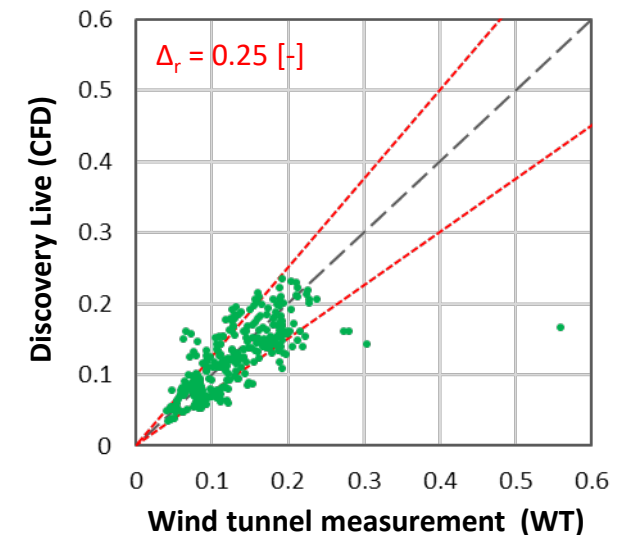
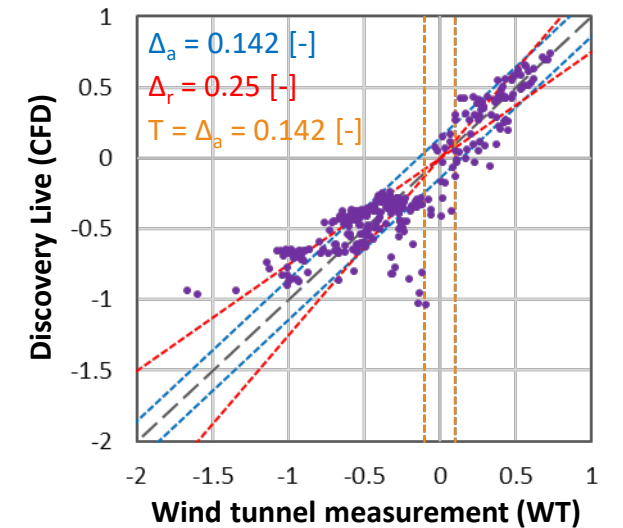
Validation metrics

Chang and Hanna (2004), Franke et al. (2009)

Performance metric	Mean	Fluctuations	Target value
Correlation coefficient	0.898	0.734	1
Hit rate ($q_{25\%}$)	0.589	0.663	1
FAC2	0.920	0.983	1
FB	0.091	- 0.055	0
MG	N.A.	0.951	1
NMSE	N.A.	0.098	0
VG	N.A.	1.076	1
AAD (Montazeri and Blocken, 2013)	0.150	0.026	0

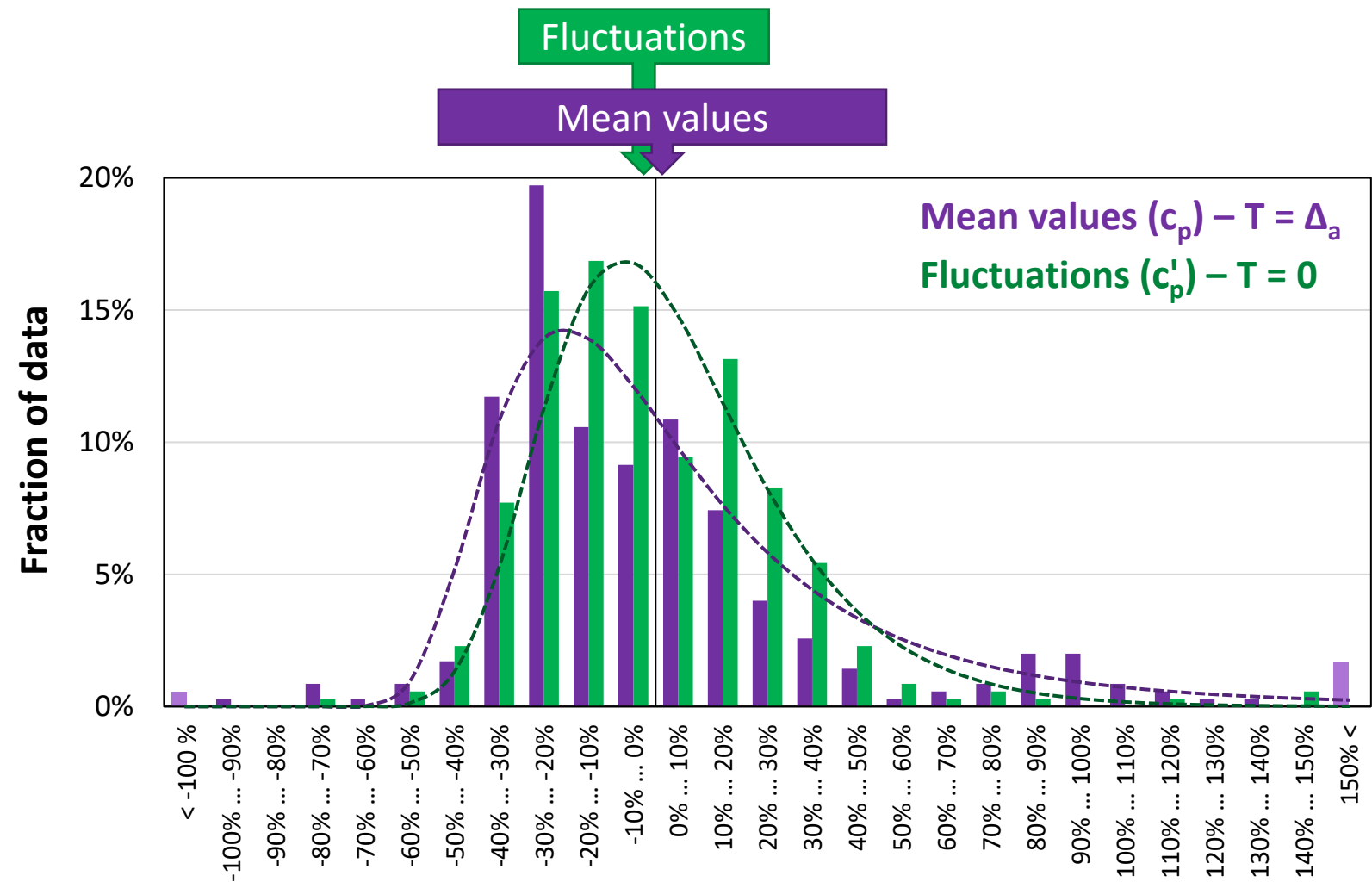
Relative deviation in the 2×350 measurement points:

$$RD_i = \frac{WT_i - CFD_i}{WT_i} \quad \text{if} \quad |WT_i| > T$$



Distribution of the relative deviations

$$RD_i = \frac{WT_i - CFD_i}{WT_i} \quad \text{if} \quad |WT_i| > T$$

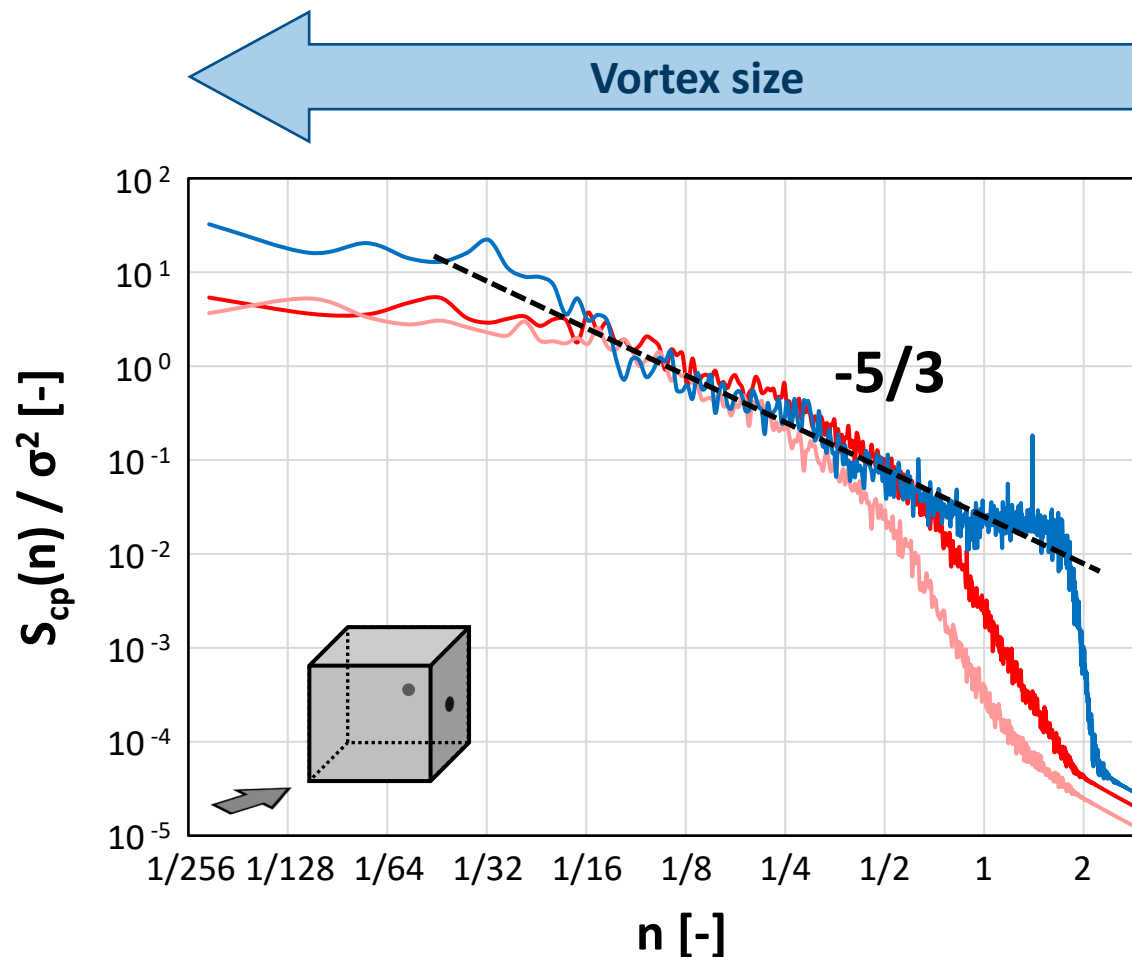
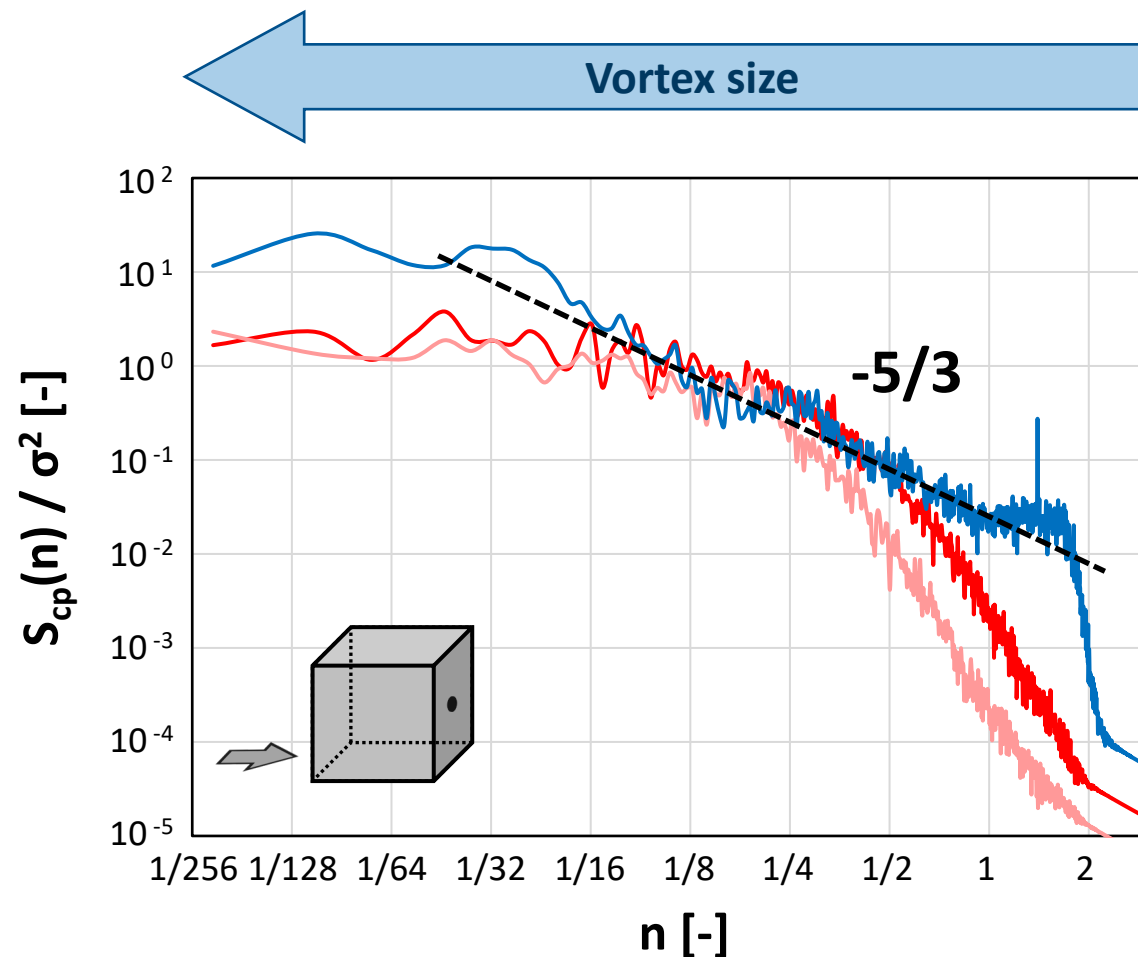


Continuous **Generalized Extreme Value distributions (GEV)**

	$RD(c_p)$ [%]	$RD(c'_p)$ [%]
Mode	-25,47	-12,413
Mean	0,66	-1,49
Standard deviation	47,77	26,66
Skewness	-3,46	0,93
Kurtosis	41,80	1,48

Pressure power spectra

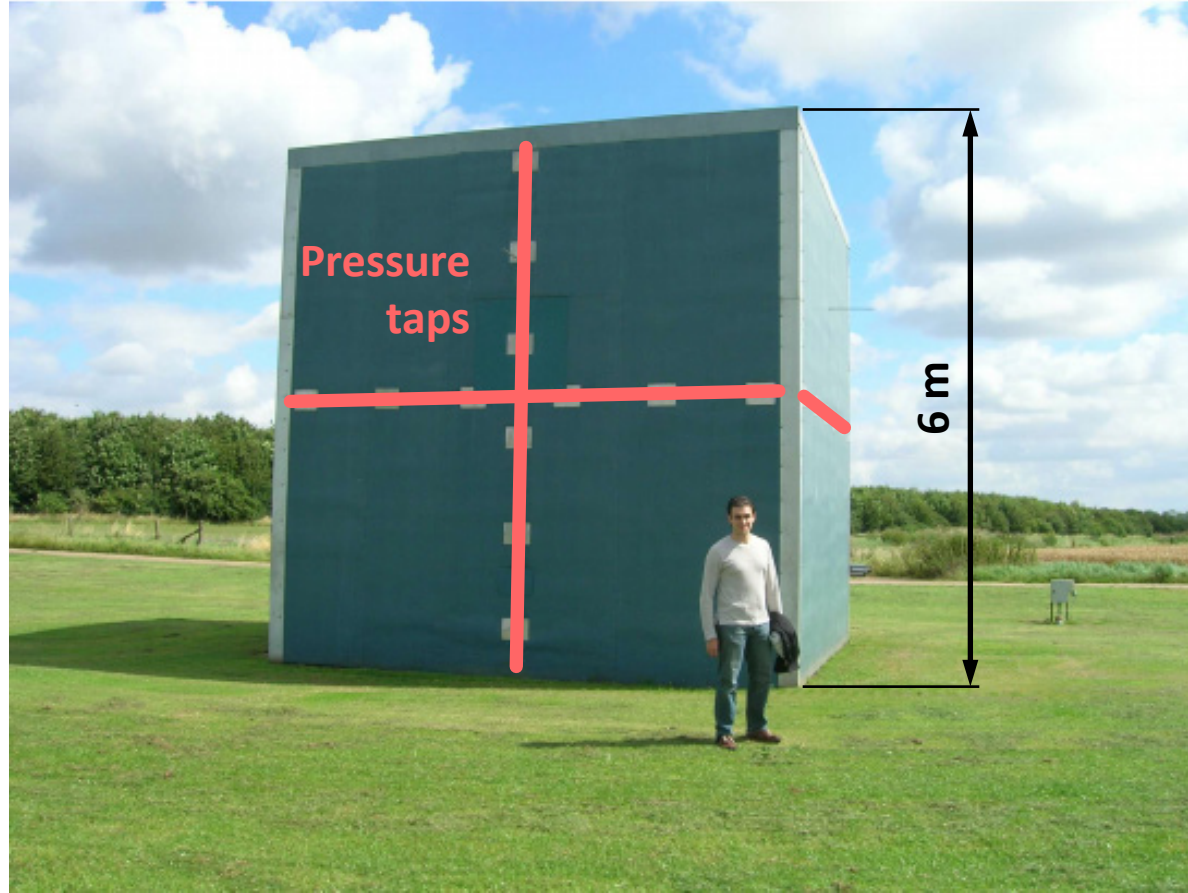
$$n = f \frac{L}{u(L)}$$



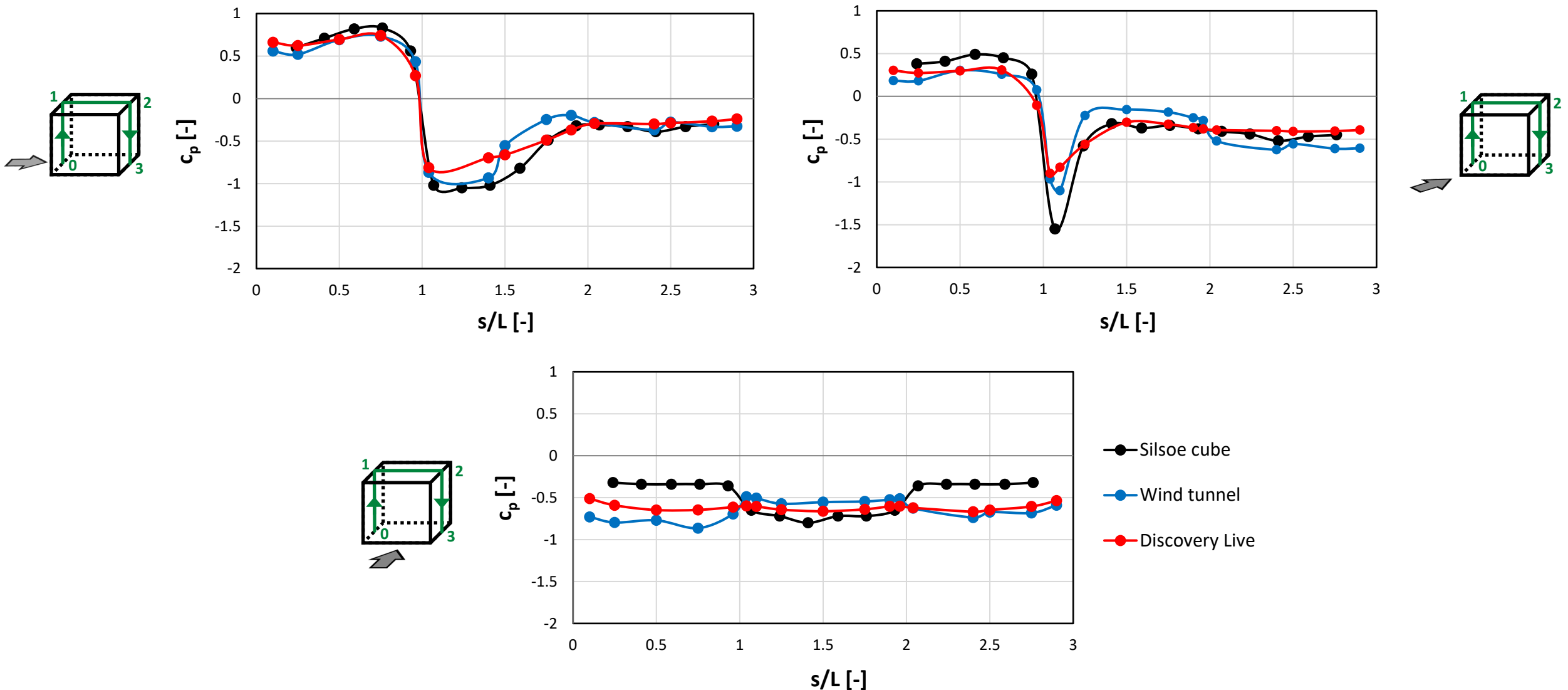
— Discovery Live (100%) — Discovery Live (25%) — Wind tunnel ---- Inertial subrange (Kolmogorov spectrum)

Comparison to field measurements

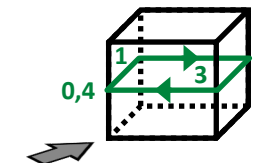
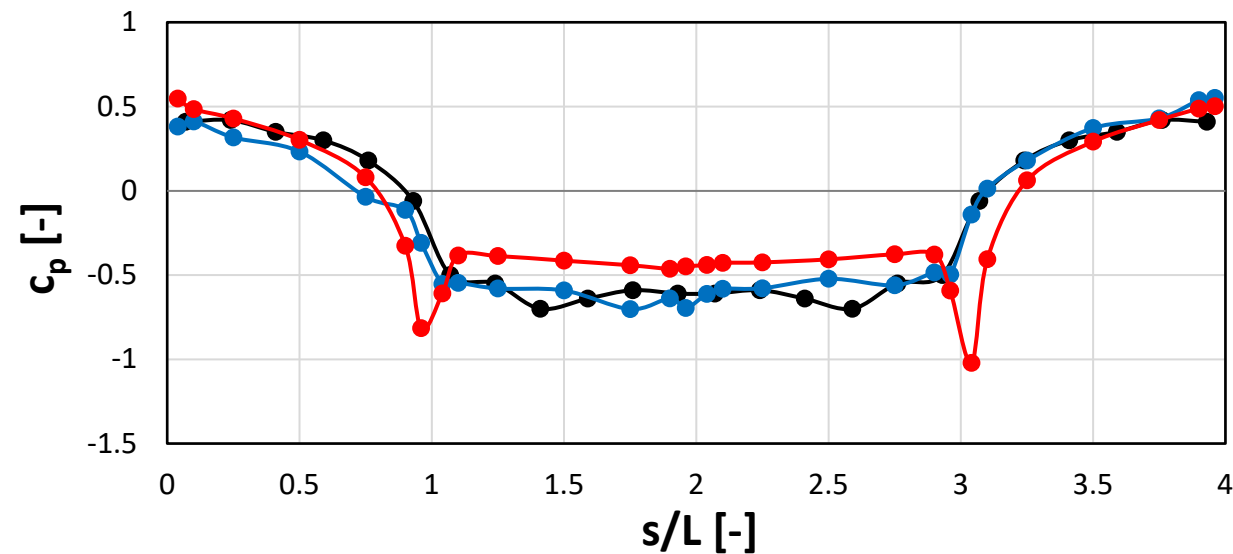
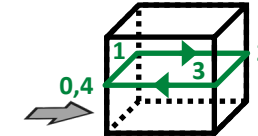
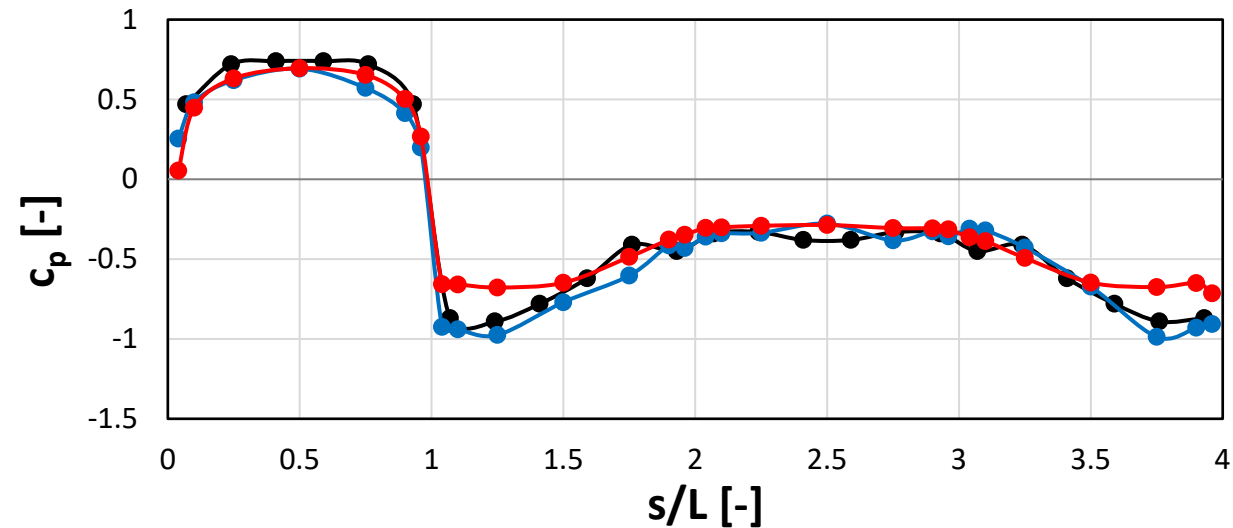
- **Silsoe experiment** (Richards et al. 2001, 2002, 2004, 2006, 2008, 2012a, 2012b)



Comparison to field measurements – vertical rings



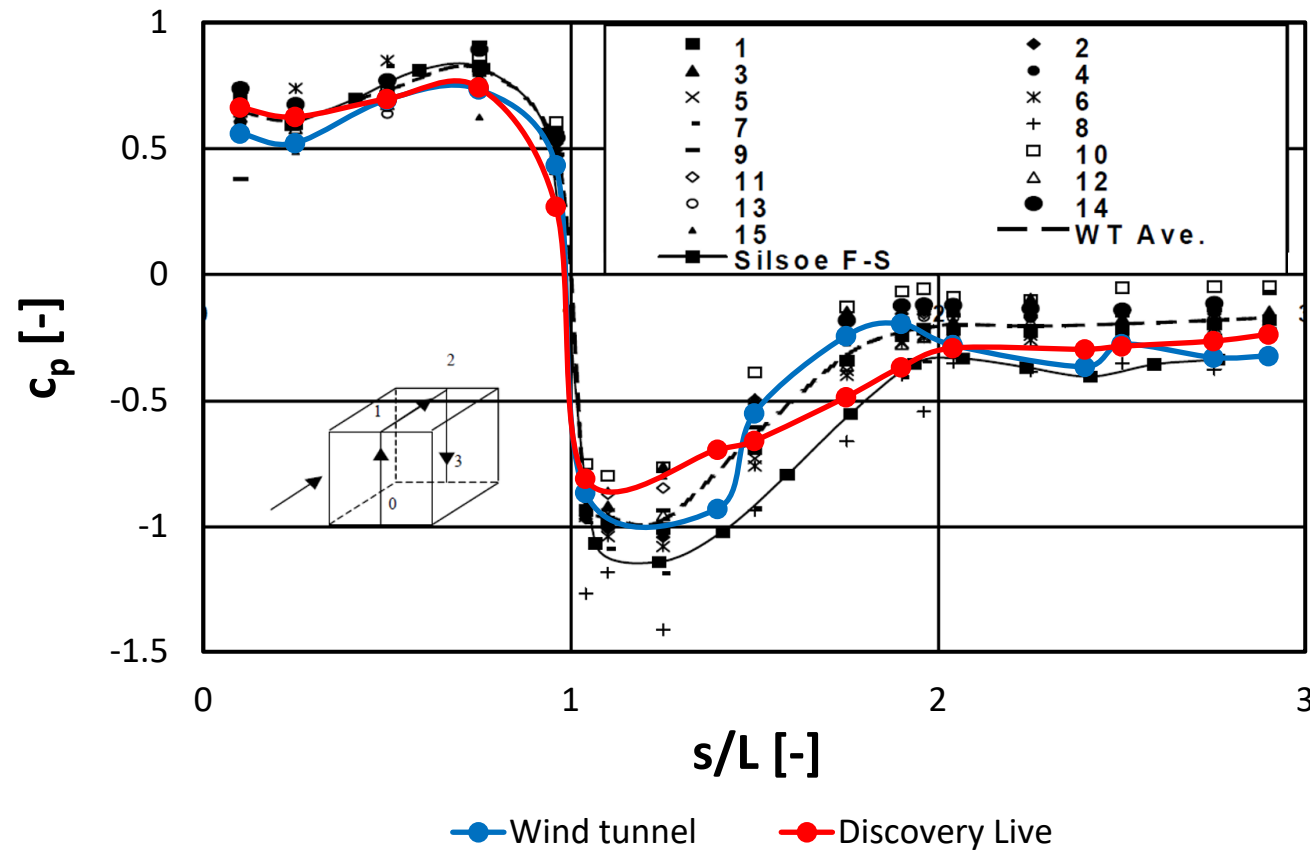
Comparison to field measurements – horizontal rings



—●— Silsoe cube —●— Wind tunnel —●— Discovery Live

Comparison to further wind tunnel test

- Hölscher and Niemann (1998) → Richards et al. (2001)



Advantages

- Extremely fast LES
- Turbulent atmospheric boundary layer
- Automated meshing
- Validated results:
 - Mean surface pressure distribution
 - Surface pressure fluctuations
 - Pressure power spectra
- Good agreement with field measurements
- Same accuracy as the wind tunnel results

Drawbacks

- "Black box"
- Equidistant Cartesian grid
 - Discretization error
 - Gradients to be resolved in more detail
 - Frequency limits
 - Not suitable for streamlined buildings, bluff bodies only

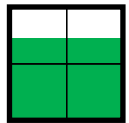
The above errors can be decreased by using a GPU with higher VRAM capacity!

The numerical wind tunnel can be an efficient tool for simulating the dynamic wind load of cuboid buildings.

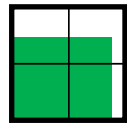


The mesh interference method

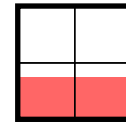
- How does the **equidistant Cartesian mesh** resolve the geometry?



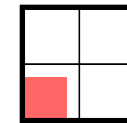
Resolved



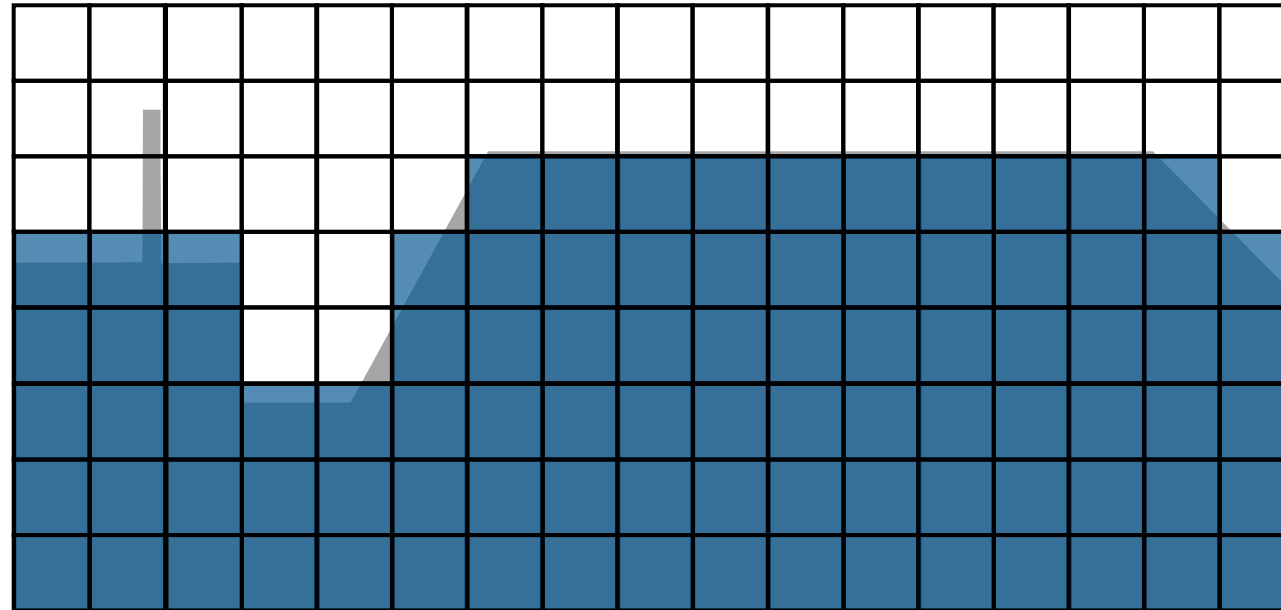
Resolved



Unresolved

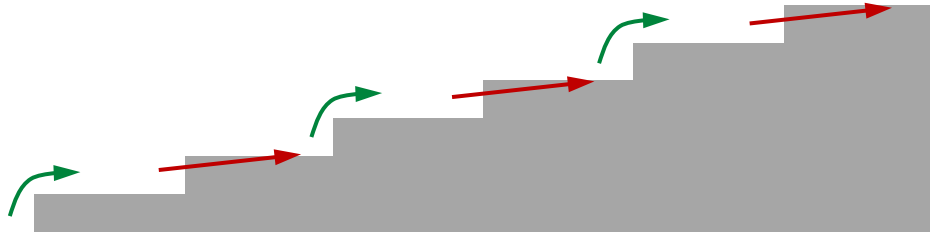


Unresolved



The mesh interference method

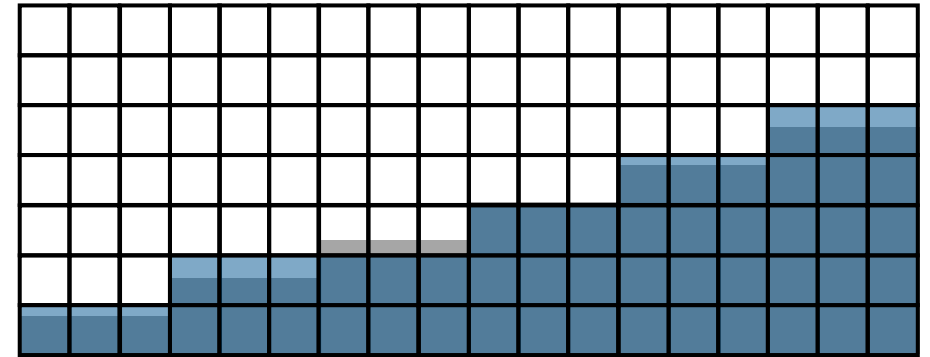
- 1) Analysis of the streamlines: which steps are captured?



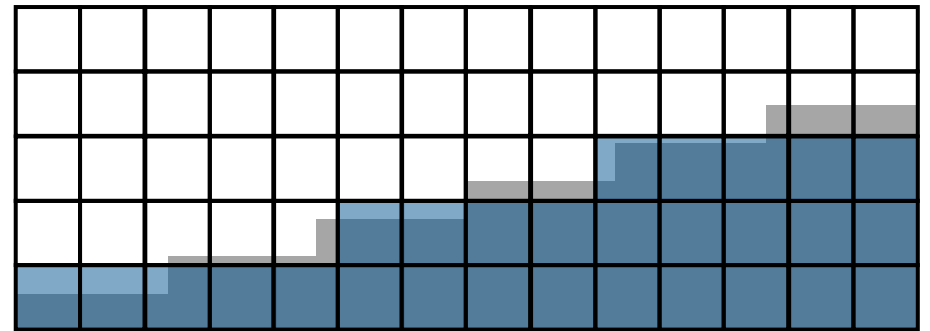
- 2) Interference pattern: **RRSRRR**
- 3) Simulation of different hypothetical grid resolutions
- 4) Determining the range of the grid sizes which produce the same interference pattern in theory:

$$\Delta x \pm u$$

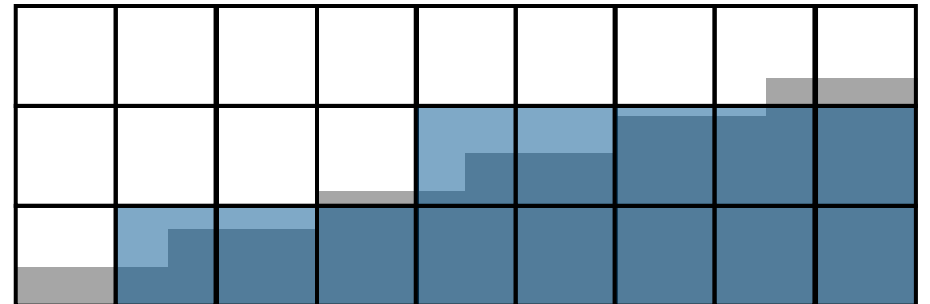
RRSRRR



RSRSRS



SRSRRS



Validation metrics

$$R = \frac{(\overline{O} - \overline{O})(\overline{P} - \overline{P})}{\sigma_O \sigma_P}$$

$$q = \frac{1}{N} \sum_{n=1}^N i_n \quad \text{where} \quad i_n = \begin{cases} 1 & \text{if } \left| \frac{(O_n - P_n)}{O_n} \right| \leq \Delta_r \text{ or } |O_n - P_n| \leq \Delta_a \\ 0 & \text{egyébként} \end{cases}$$

$$FAC2 = \frac{1}{N} \sum_{n=1}^N i_n \quad \text{where} \quad i_n = \begin{cases} 1 & \text{if } 0.5 \leq \frac{P_n}{O_n} \leq 2 \text{ or } |O_n|, |P_n| \leq \Delta_a \\ 0 & \text{else} \end{cases}$$

$$FB = \frac{\overline{O} - \overline{P}}{0.5 (\overline{O} + \overline{P})}$$

$$MG = \exp(\ln \tilde{O} - \ln \tilde{P}) \quad \text{where} \quad \tilde{O} = \max(O, \Delta_a) \quad \text{and} \quad \tilde{P} = \max(P, \Delta_a)$$

$$NMSE = \frac{(\overline{O} - \overline{P})^2}{\overline{O} \overline{P}}$$

$$VG = \exp\left(\frac{(\ln \tilde{O} - \ln \tilde{P})^2}{2}\right) \quad \text{where} \quad \tilde{O} = \max(O, \Delta_a) \quad \text{and} \quad \tilde{P} = \max(P, \Delta_a)$$

$$AAD = |\overline{O} - \overline{P}|$$

$$RD = \frac{O - P}{O} \quad \text{ha} \quad |O| > T$$

