Large-eddy simulations to characterize the role of turbulent and dispersive production, transport and dissipation of TKE over and within a realistic urban canopy

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Mean flow and turbulence modeling in the urban surface layer is of great importance.

- to predict exposure of population to air pollutants
- to model micro-scale weather, climate and energy use
- to study dispersion of scalars (e.g. heat / humidity / pollutants)

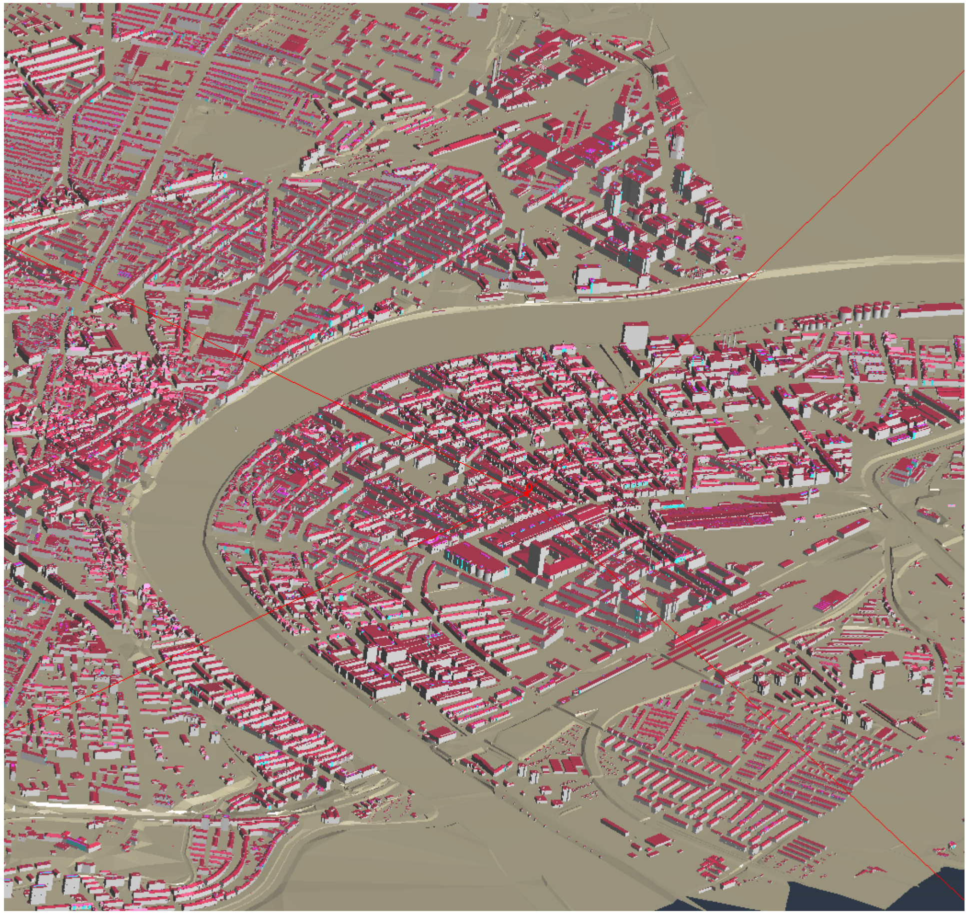
Obtaining and processing data is challenging in both experimental studies and numerical models.

- difficult to conduct representative measurements
- most numerical studies focussed on simplified geometries
- poor availability of data for comparison

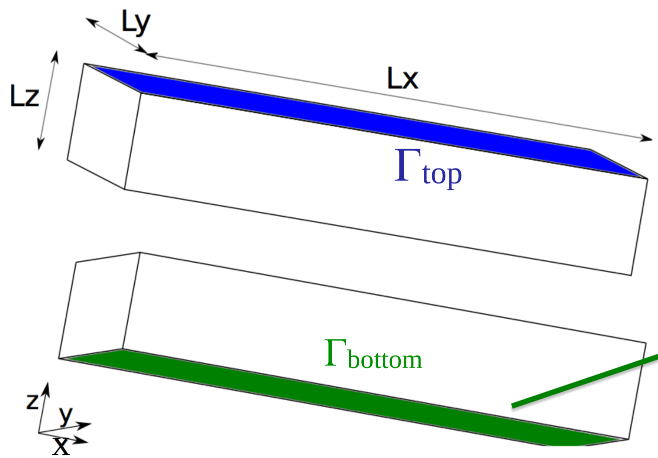
We numerically resolve the airflow over and within the urban geometry of the city of Basel (Switzerland).

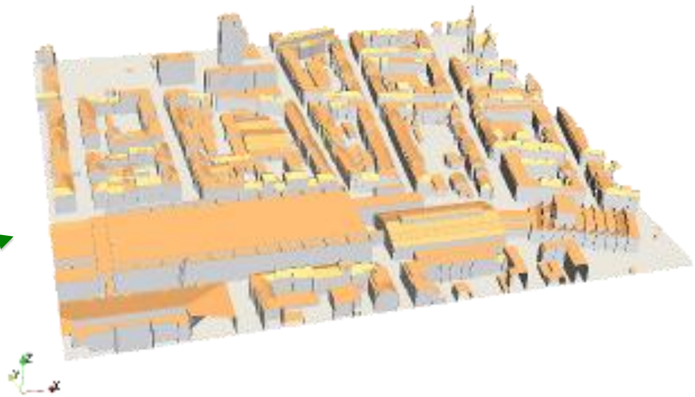
Goals

- study properties of turbulence in the urban canopy layer and roughness sublayer
- validate the algorithm against tower measurements
- determine the representativeness of tower measurements when used as surrogate of horizontally averaged terms



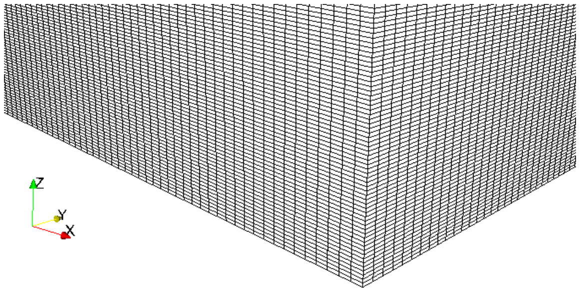
We use a large-eddy simulation (LES) approach coupled with an immersed-boundary method (IBM).





$$
\begin{cases}
\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j\left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i}\right) = -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j} + \frac{\partial \tilde{p}^*_\infty}{\partial x_i}\delta_{i1} + \tilde{f}_i \delta(x_i - x_i^\Gamma) & \text{in } \Omega \times [0,T], \\
\frac{\partial \tilde{u}_i}{\partial x_i} = 0 & \text{in } \Omega \times [0,T], \\
\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0 & \text{in } \Gamma_{top} \times [0,T], \\
w = 0 & \text{in } \Gamma_{top} \times [0,T], \\
(\mathbf{u}\cdot\mathbf{n})\mathbf{n} = 0 & \text{in } \Gamma_{bottom} \times [0,T], \\
\tau_w = \left(\frac{\kappa[\mathbf{u}-(\mathbf{u}\cdot\mathbf{n})\mathbf{n}]}{\ln(1+\Delta/z_0)}\right)^2 & \text{in } \Gamma_{bottom} \times [0,T].
\end{cases}
$$

Discretization and setup of simulations.



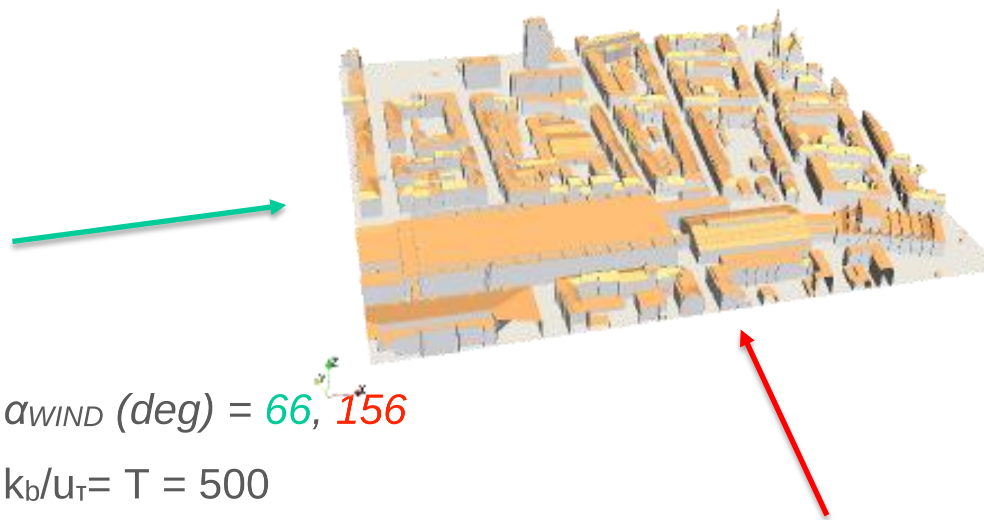
Cartesian discretization

- Mixed approach in space (Fourier expansions + finite differences)
- Fully explicit second order-accurate Adam-Bashforth time advancement
- Operator splitting to solve the system in a decoupled fashion

References: J.D. Albertson et al. (1999), Bou-Zeid et al. (2005), Chester et al. (2007).

Setup of simulations.

- Domain size (m) = 512 x 512 x 160
- N_x x N_y x N_z = 512 x 512 x 160
- $z_0 = \Delta/15; \Delta/30$
- u_τ (m/s) = 1



- α_{WIND} (deg) = 66, 156
- $k_b/u_\tau = T = 500$
- SGS 1: Static Smagorinsky (C_s=0.1)
- SGS 2: Lagrangian Scale Dependent Smagorinsky

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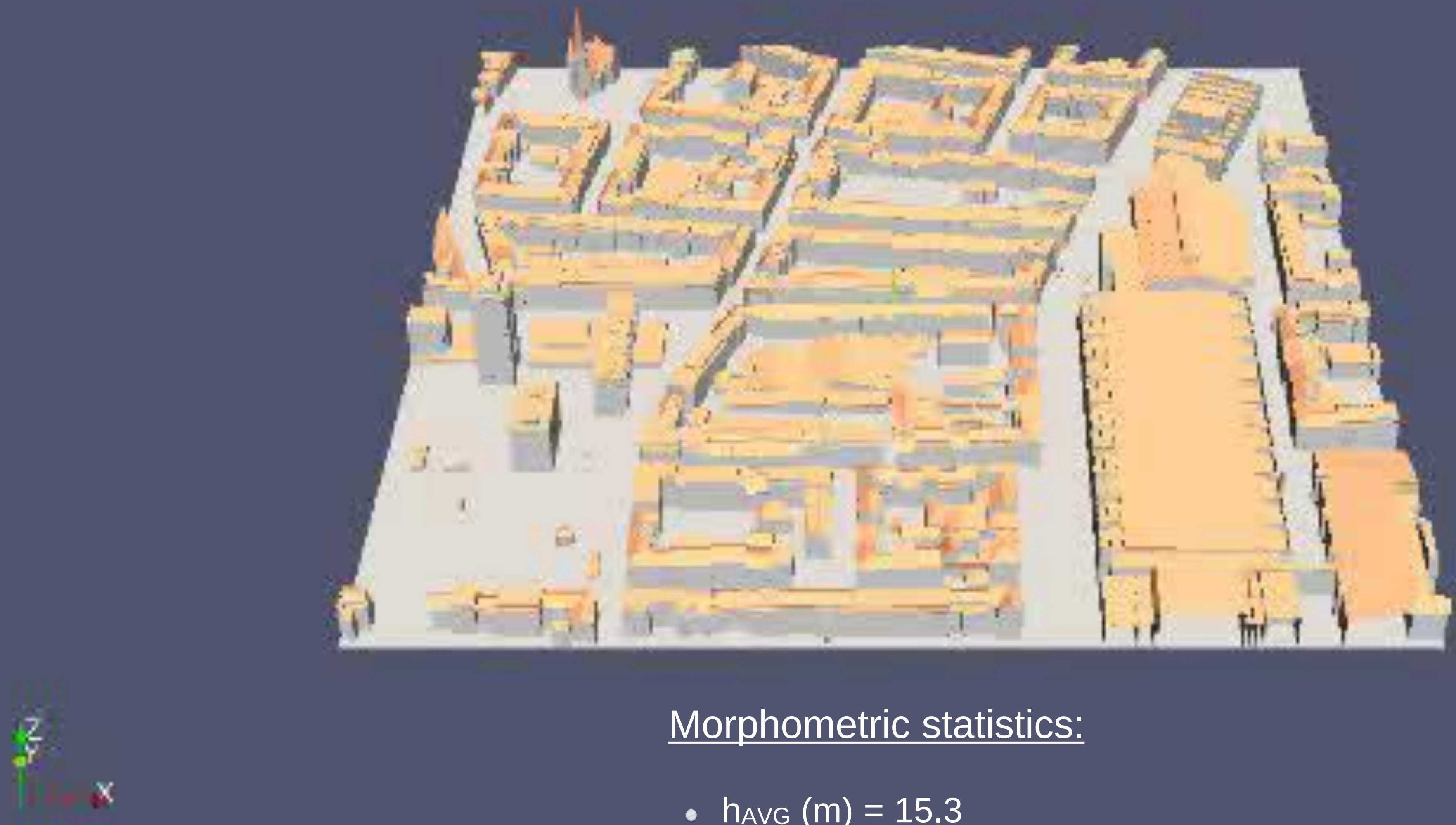
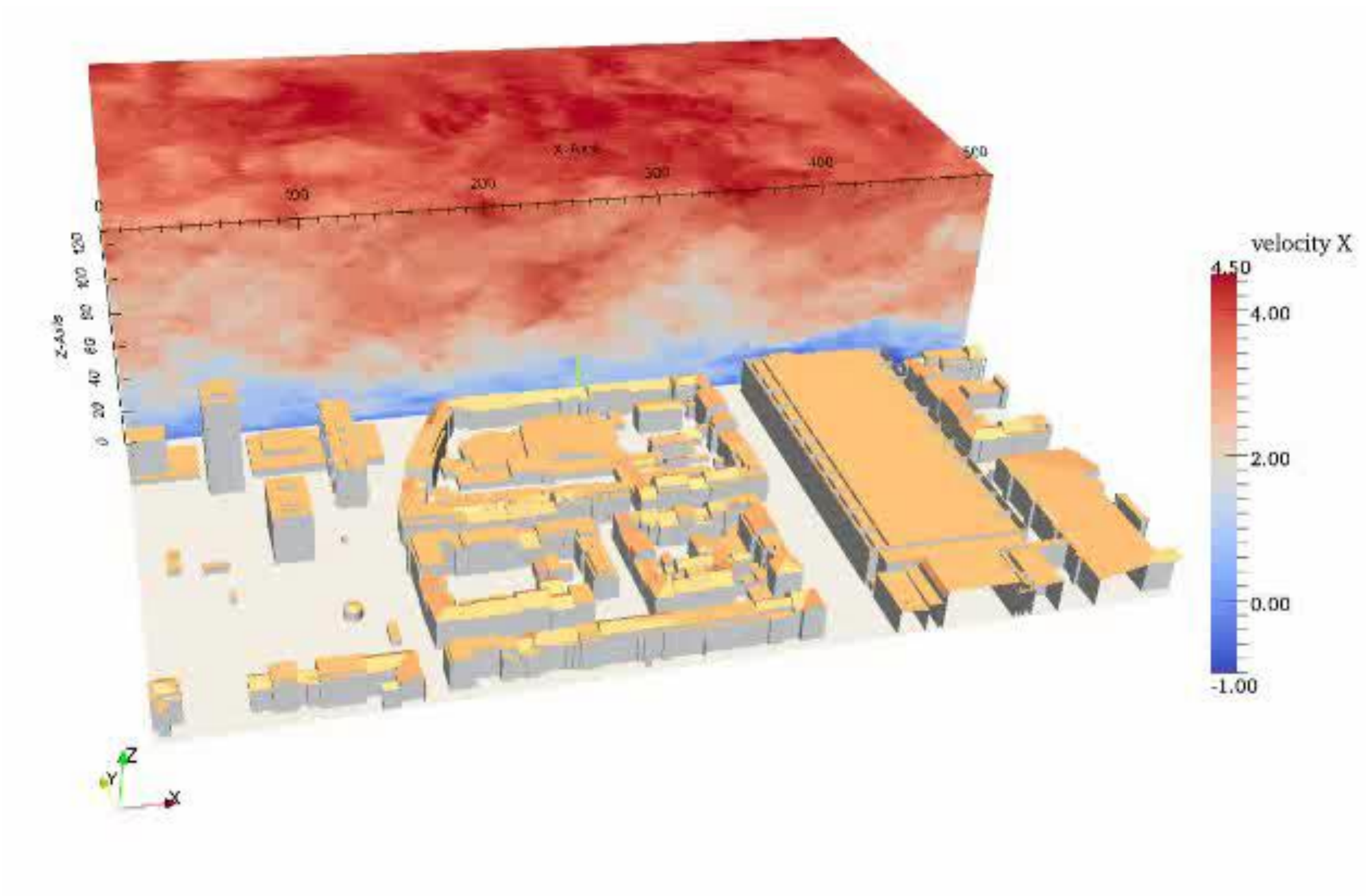


<u>Morphometric statistics:</u>

- h_{AVG} (m) = 15.3
- h_{MAX} (m) = 60
- σ_h (m) = 8.9

The LES closure allows to resolve the energetic scales of the flow and models the small (subgrid) scale features.



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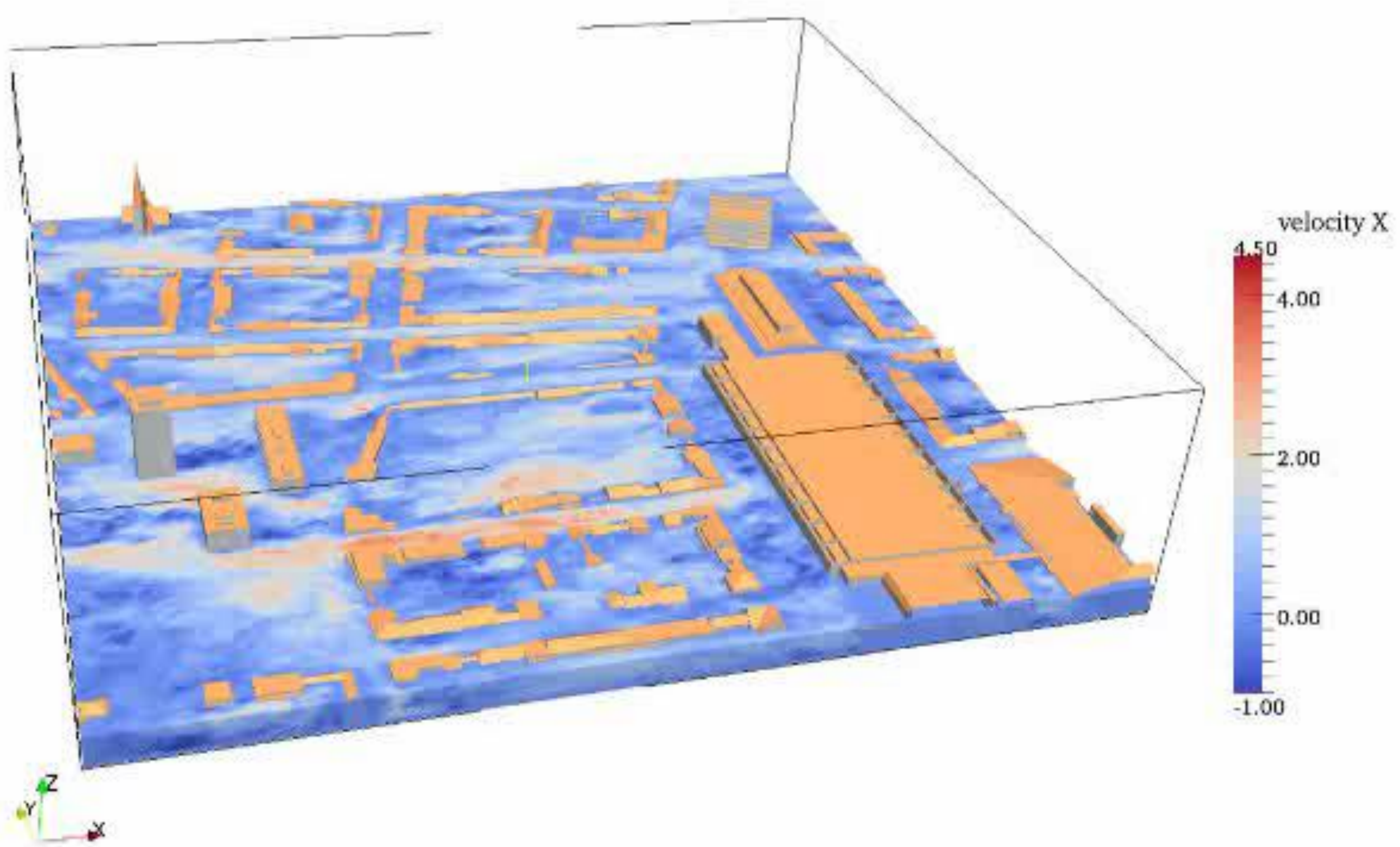
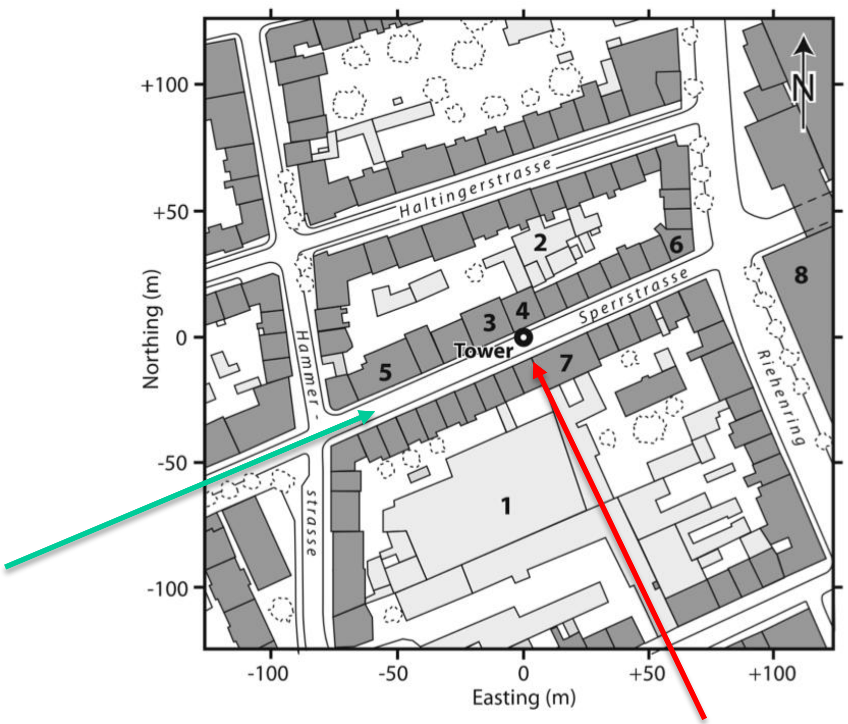
The LES closure allows to resolve the energetic scales of the flow and models the small (subgrid) scale features.



We validate results against experimental data,
that were collected during the
Basel Urban Boundary Layer Experiment (Rotach et al. 2005).



Christen et al. (2009)

Map of the urban morphometry in the surroundings of the tower location.

31.7 m profile tower
6 sonic anemometers

- *α_{WIND} (deg) = 66, 156*

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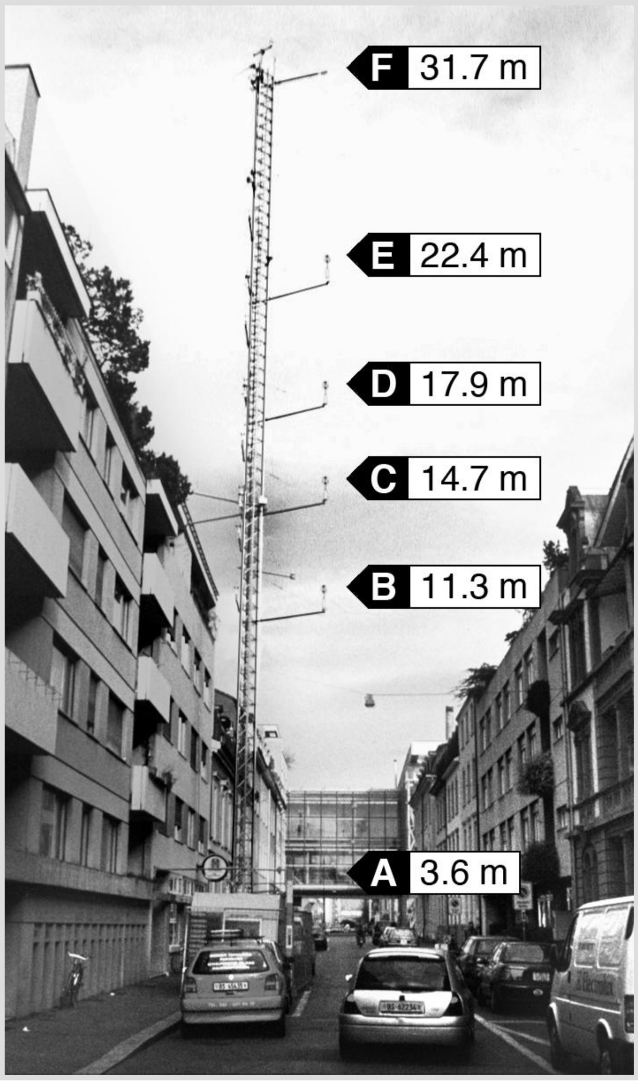
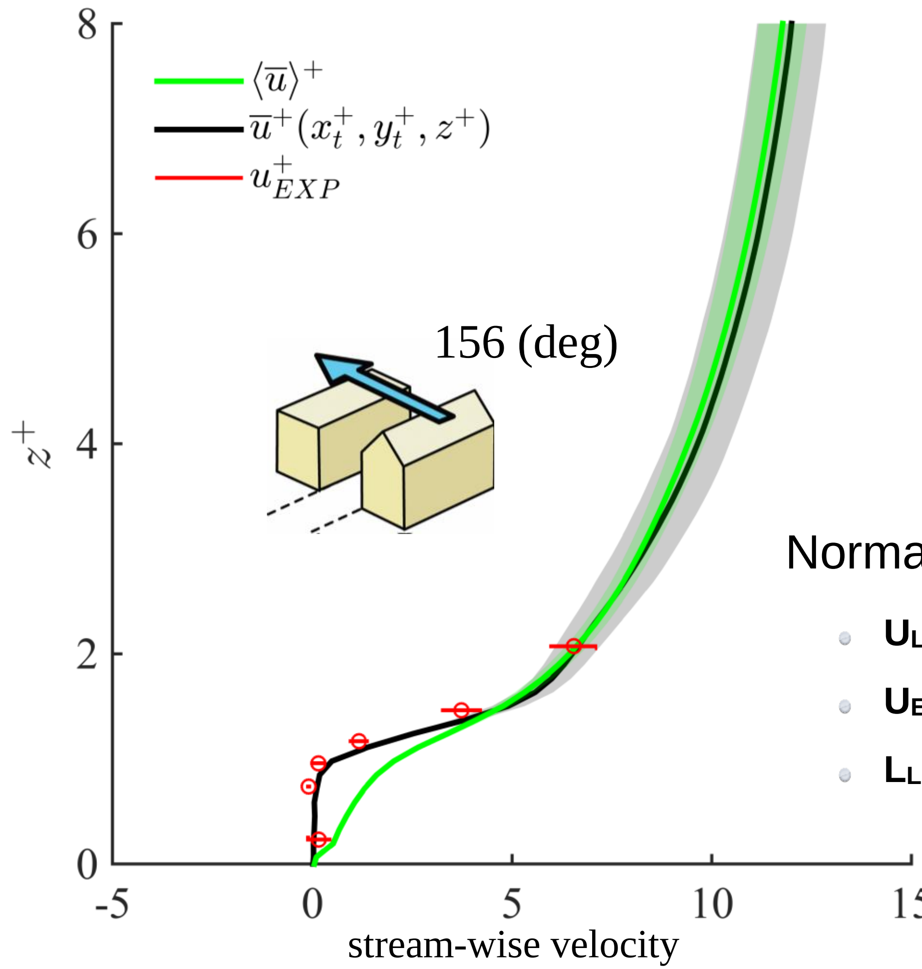
Mean profiles compare well against tower measurements for the considered angles of approaching wind.

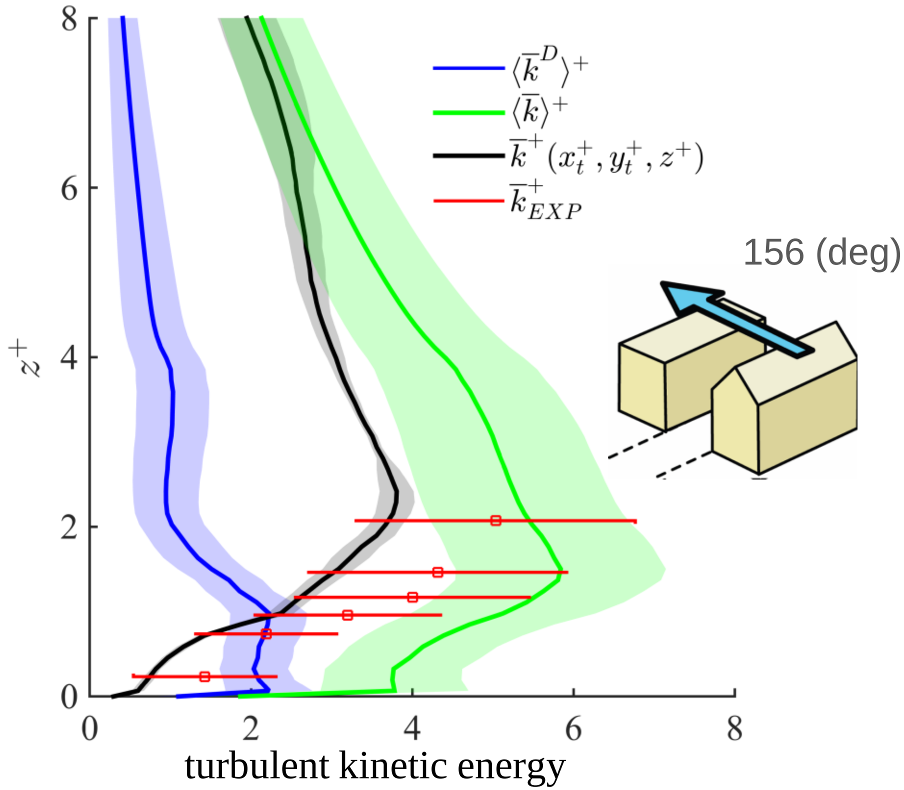


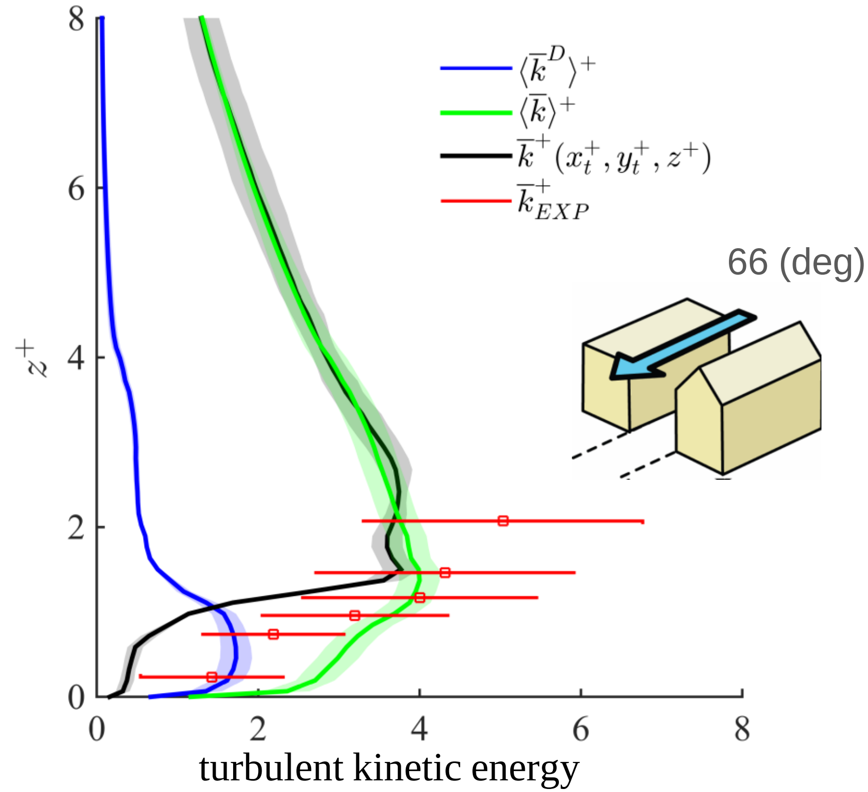


Normalization scales

- **U_{LES}** = $u_{\tau, LES}$ (z=31.7 m)
- **U_{EXP}** = $u_{\tau, EXP}$ (z=31.7 m)
- **L_{LES}** = **L_{EXP}** = 15.3 m

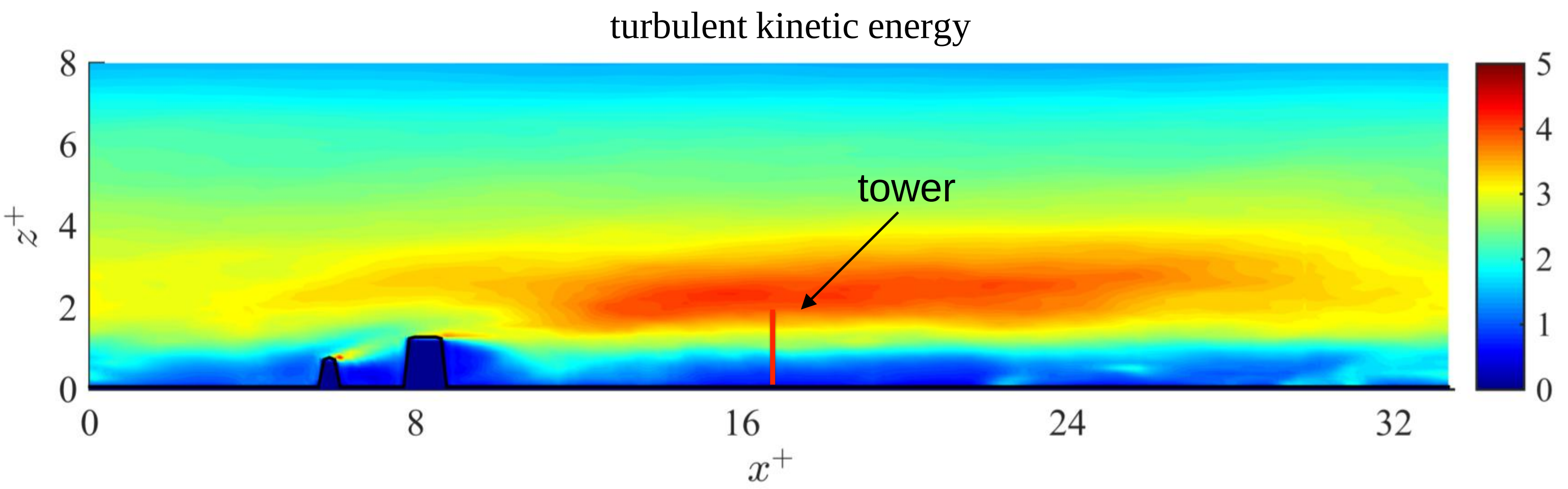
Turbulent Kinetic Energy (k^+) peaks at $1.5h^+$. Wake Kinetic Energy (k^{+D}) is significant in the UCL.



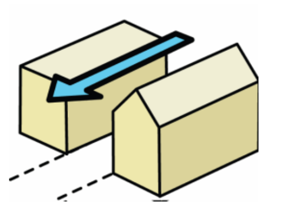


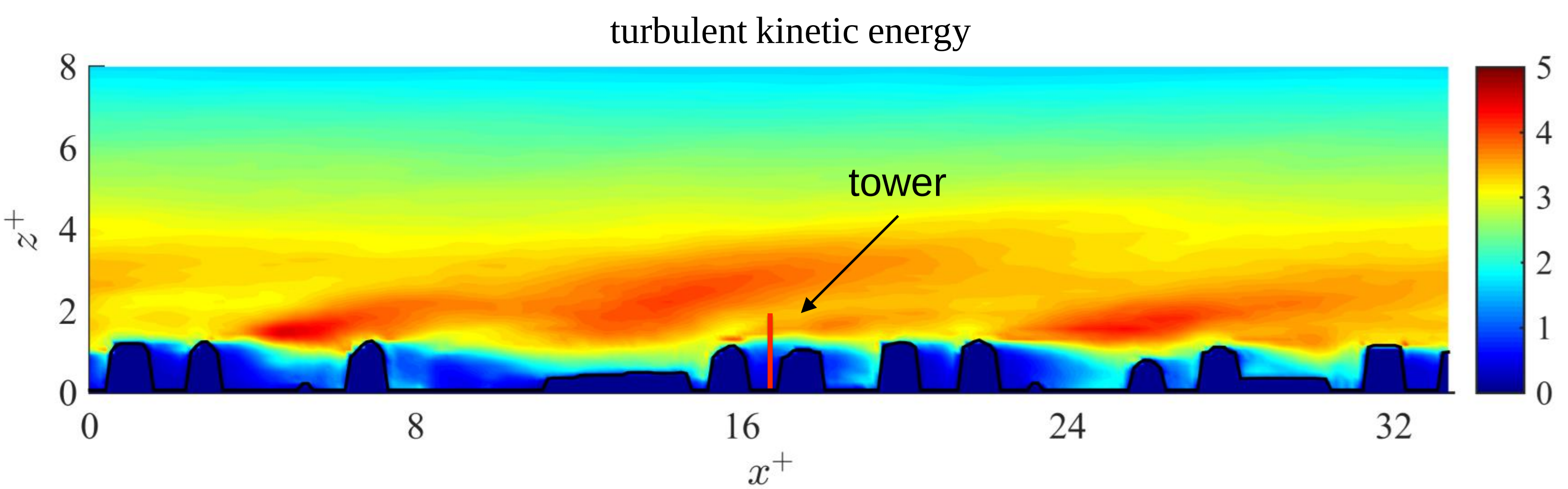
- LES sampled at tower location under-estimates k
- local measurements are hardly representative of horizontally averaged quantities in the UCL and lower RSL

k^+ peaks in the thin shear layers that separate from the rooftops.

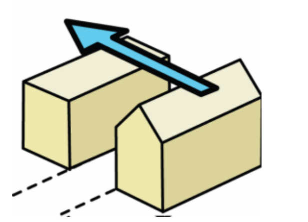


66 (deg)





156 (deg)



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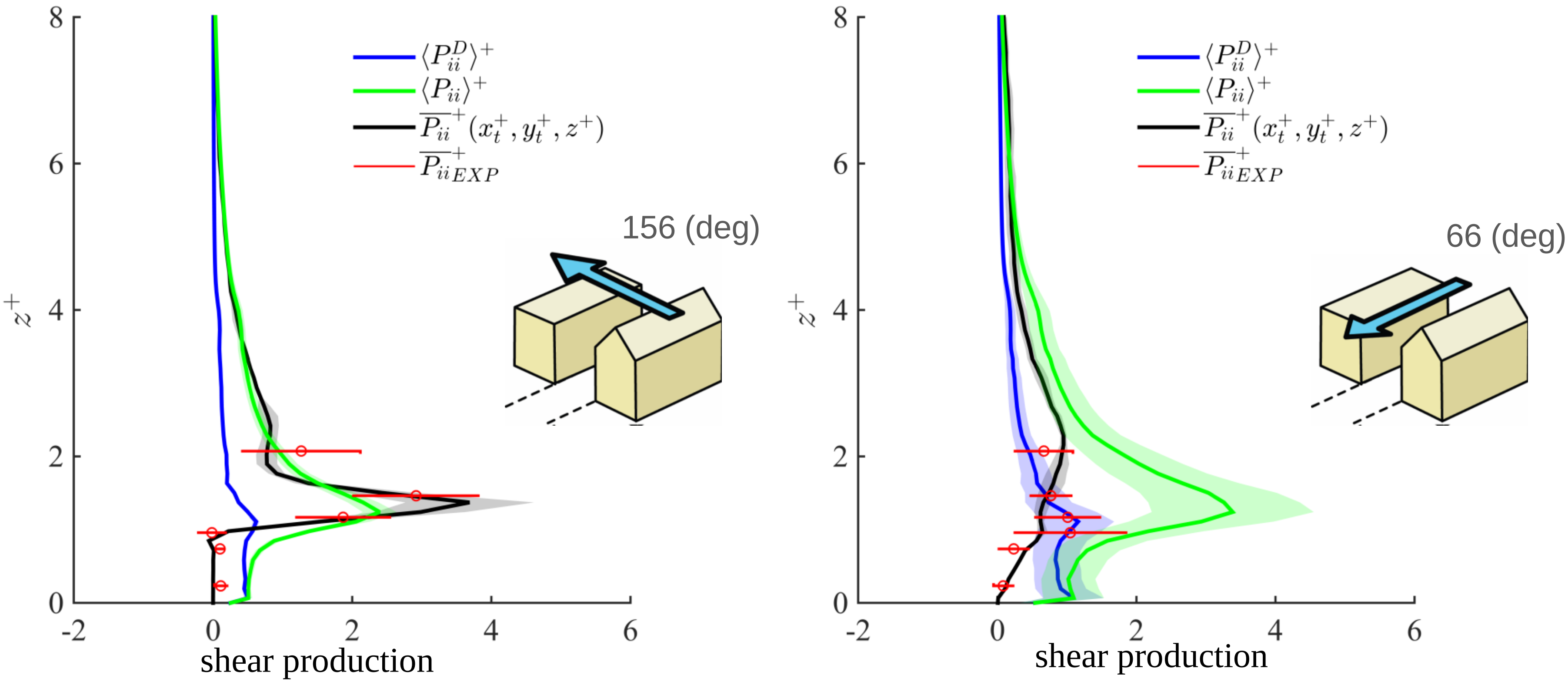
k^+ budget equation within the double averaging approach:

$$
\partial k/\partial t = \underbrace{-\langle \overline{\tilde{u}_i' \tilde{w}'} \rangle \frac{\partial \langle \overline{\tilde{u}_i} \rangle}{\partial z}}_{P_{ii}} \underbrace{- \left\langle \overline{\tilde{u}_i' \tilde{w}'}'' \frac{\partial \overline{\tilde{u}}_i''}{\partial z} \right\rangle}_{P^D_{ii}} - \frac{1}{\Lambda_a} \frac{\partial}{\partial z} \Big(\underbrace{\Lambda_a [\langle \overline{\tilde{u}_i' \tilde{u}_i' \tilde{w}'} \rangle / 2}_{T_{ii}} + \underbrace{\langle \overline{\tilde{w}}'' \overline{\tilde{u}_i' \tilde{u}_i'}'' \rangle / 2}_{T^D_{ii}} + \underbrace{\langle \overline{\tilde{\pi}' \tilde{w}'} \rangle]}_{\Pi_{ii}} \Big)
$$

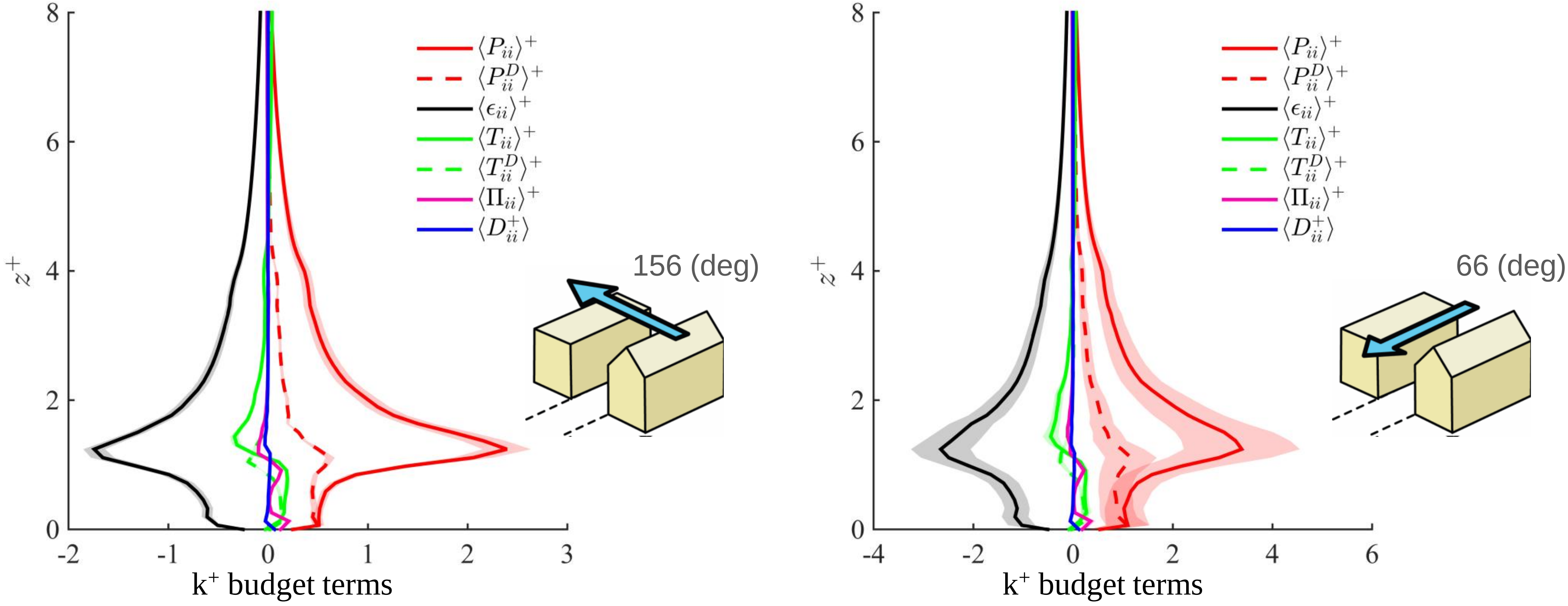
$$
\underbrace{- \frac{1}{\Lambda_a} \frac{\partial \Lambda_a \langle \overline{\tilde{u}_i' \tau_{i3}'^{SGS}} \rangle}{\partial z}}_{D_{ii}} \underbrace{- 2\nu_T \langle \overline{\tilde{S}_{ij}' \tilde{S}_{ij}'} \rangle}_{\varepsilon_{ii}} = 0,
$$

Shear production peaks above the mean roof height and dispersive production is significant in the UCL.



- Good matching between measurements and LES profiles
- Locally computed terms are qualitatively in agreement with global quantities

P_{ii} overcomes subgrid dissipation (ε^+) in the RSL. Pressure transport is significant in the near wall regions.



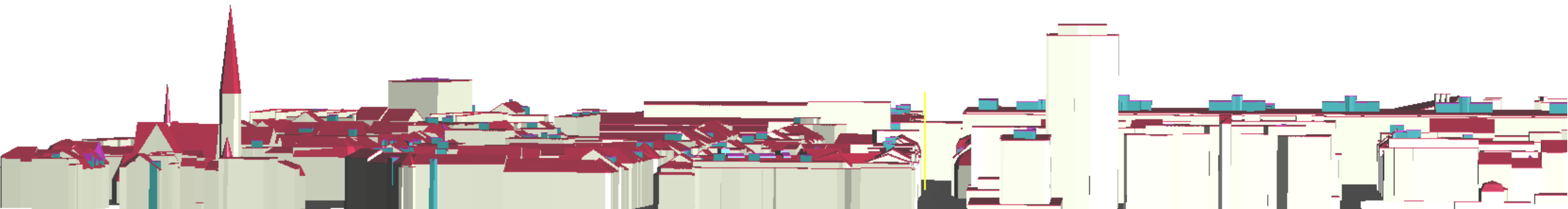
- transport are relocating TKE
- Π_{ii} is contributing in the near wall regions and at the P_{ii} peak

Conclusions

- LES + IBM compare well against experimental measurements, validating the approach
- Tower measurements are only in qualitative agreement with horizontally averaged quantities
- Production overcomes dissipation in the lower RSL and transport term are relocating TKE down in the UCL and further up in the boundary layer
- dispersive terms in the lower RSL and UCL are significant

Future research directions

- Include an analysis of wake and mean kinetic energy budget equations
- Analyze turbulent and dispersive momentum flux budget equations



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Thank you!

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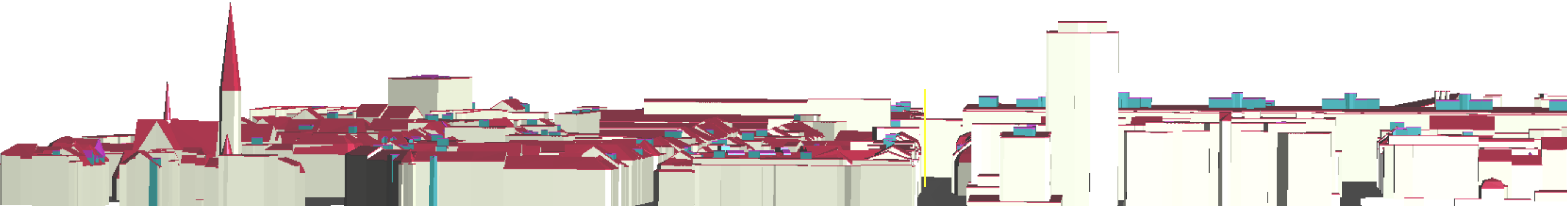
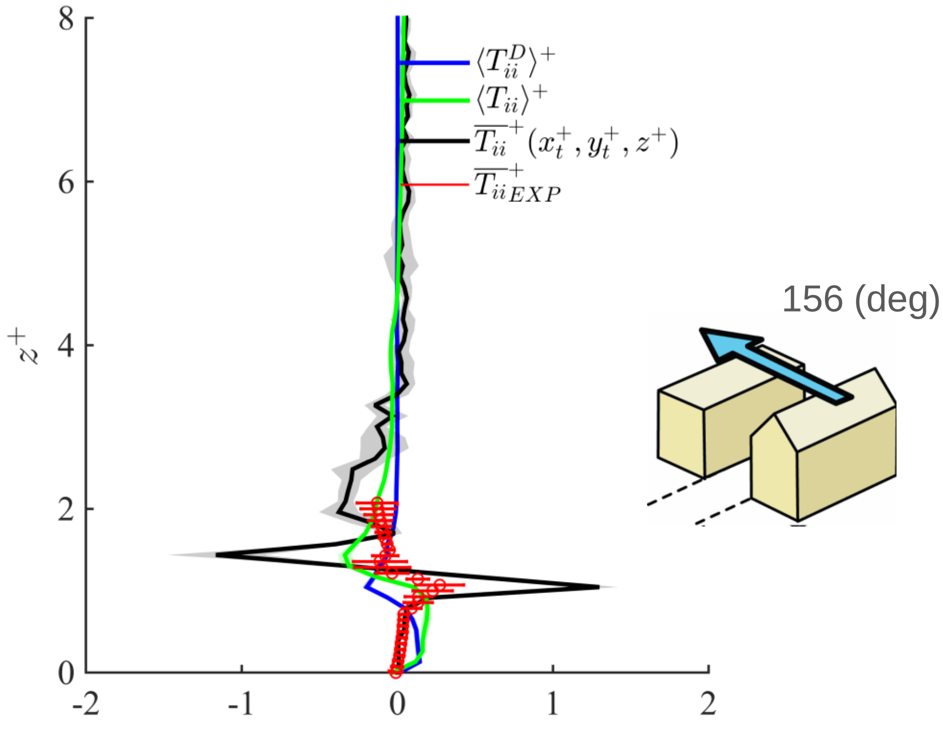
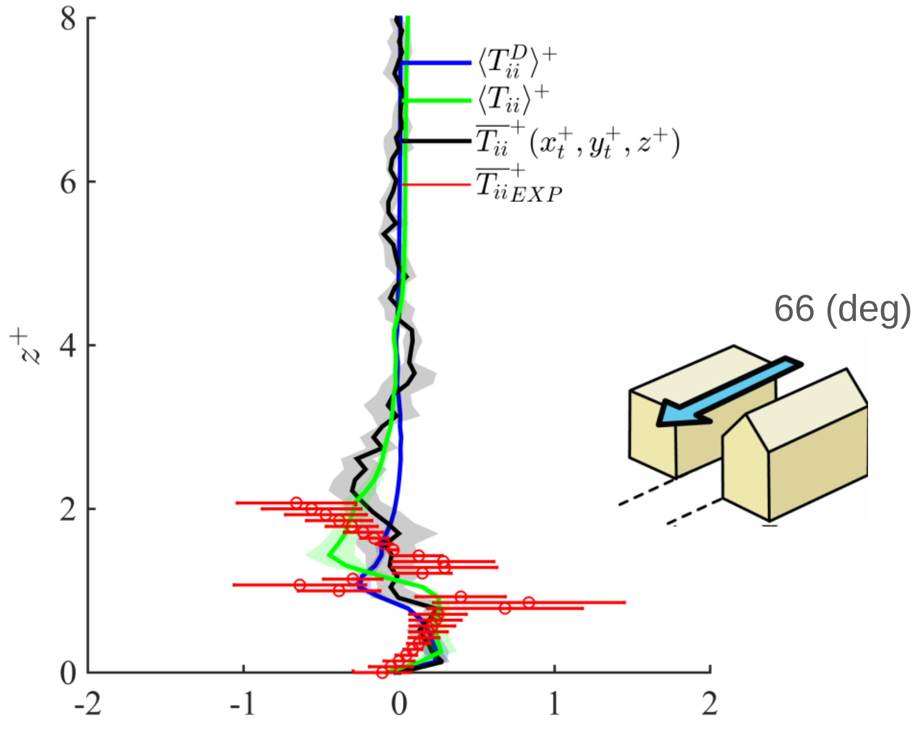


Turbulent transport (T_{ii}) relocates k away from its peak region.





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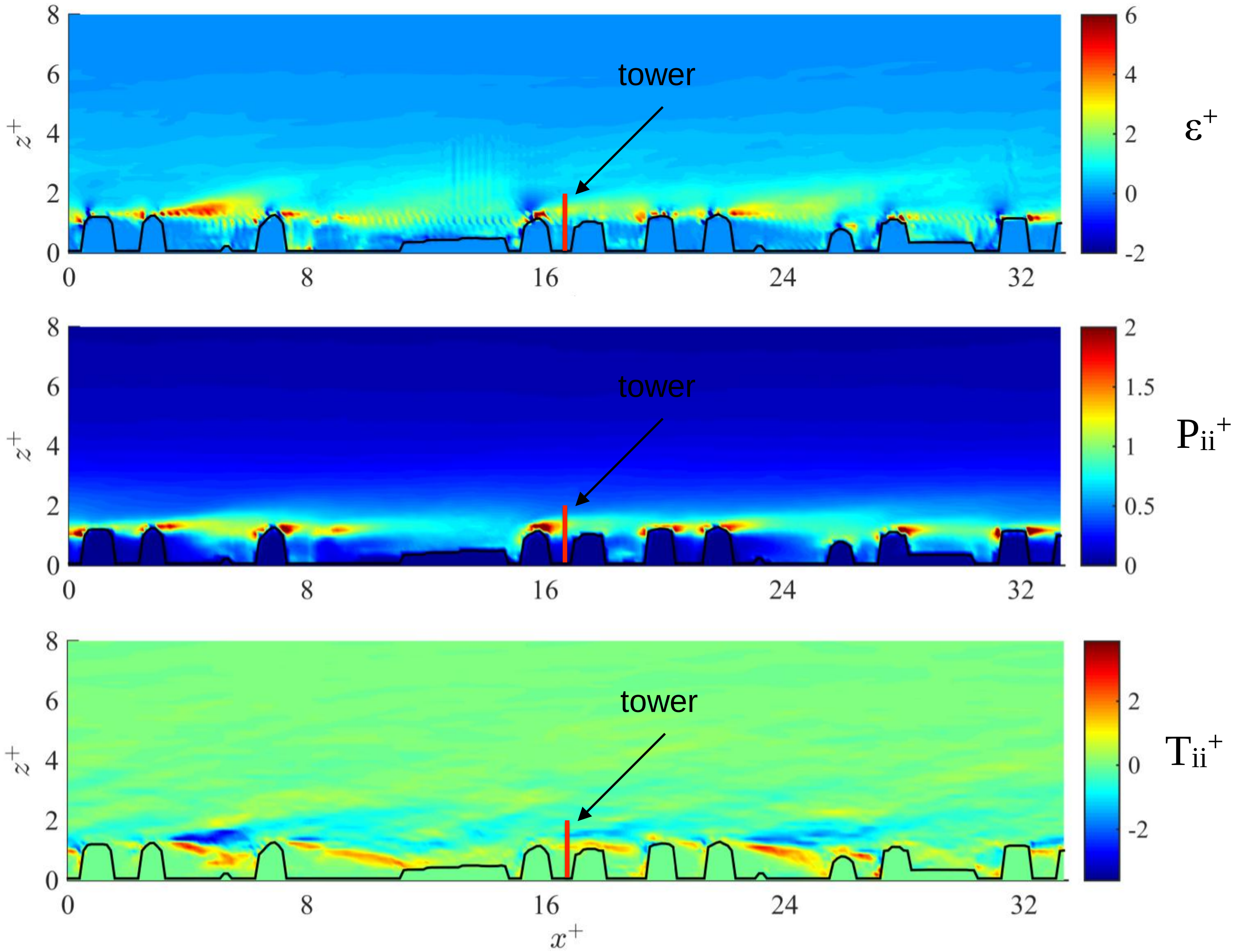
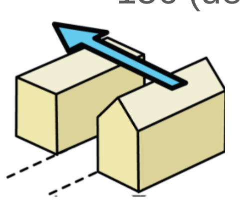
- **U_{EXP}** = $u_{\tau, EXP}$ (z=31.7 m)
- **L_{LES}** = **L_{EXP}** = 31.7 m

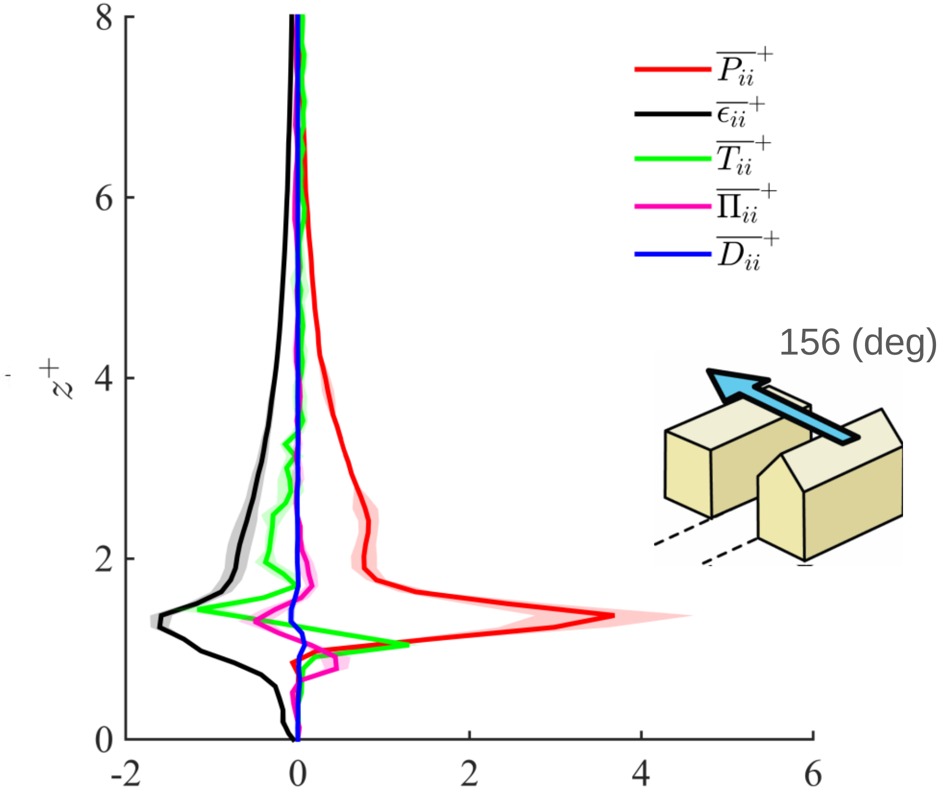
- LES sampled at tower location over-estimates T_{ii}
- dispersive transport T_{ii}^D behaves like T_{ii}

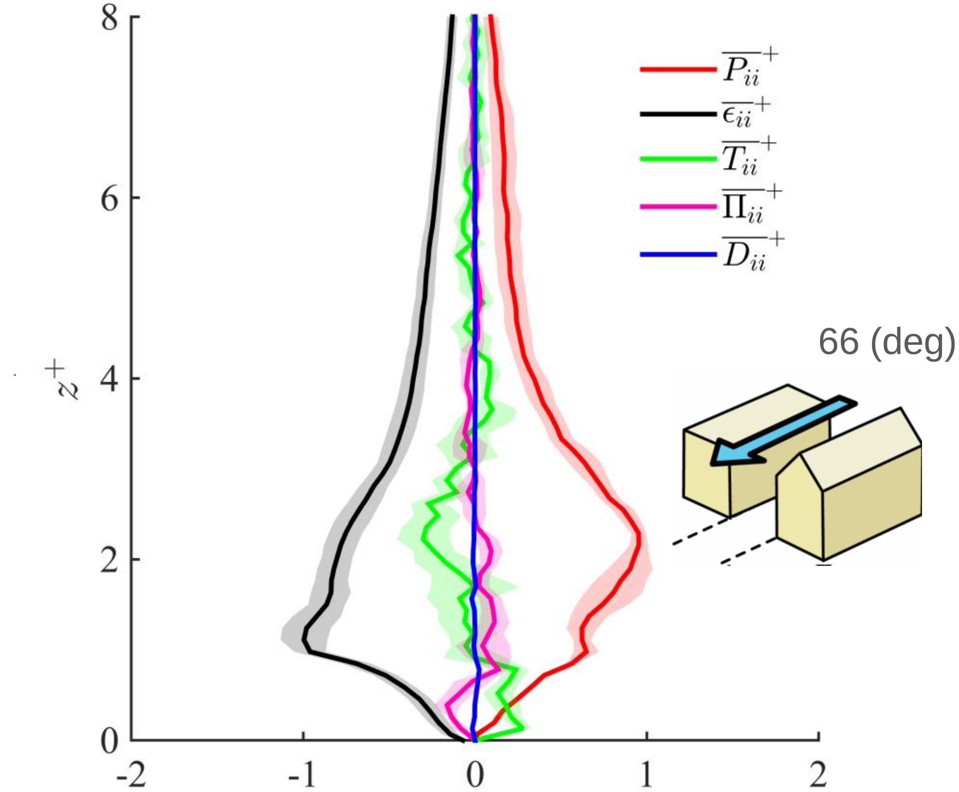
Spatial distribution of k⁺ budget terms.





k budget at tower location…





- $\mathbf{U_{LES}} = u_{T,\,LES}$ (z=31.7 m)
- $\mathbf{U_{EXP}} = u_{T,\,EXP}$ (z=31.7 m)
- $\mathbf{L_{LES}} = \mathbf{L_{EXP}}$ = 31.7 m

- LES sampled at tower location under-estimates k
- dispersive transport behaves like TT

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