Mean flow and momentum transport in heterogeneous urban canopies

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Motivation: Urban heterogeneity

A worldwide growing urban population puts cities are under increasing pressure from resource scarcity, air pollution and climate change. These challenges demand a better understanding of the local climate effects of urban environments.

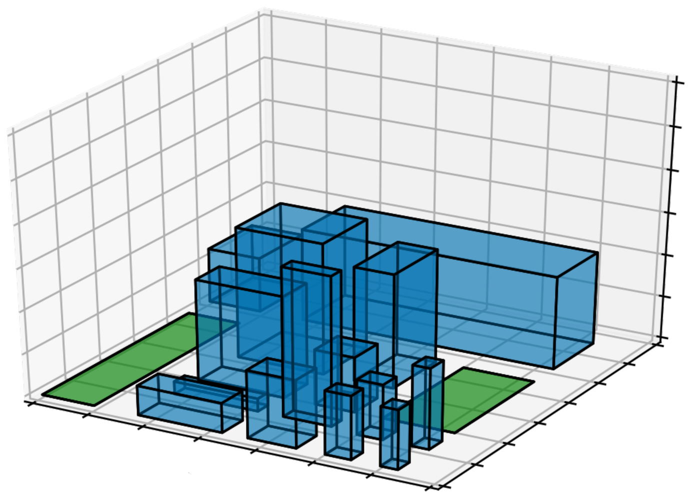

Figure 1: Generating an urban landscape model with building blocks and green space.

Figure 2: Urban heterogeneity in the city of London. ©User:Colin and Kim Hansen/Wikimedia Commons

One complexity of modelling urban climate comes from the heterogeneity of urban areas. Densely mixed building units of various sizes and shapes, complex road networks, paved surfaces, water and urban vegetation all interact with each other and the atmosphere.

Dales-Urban LES model

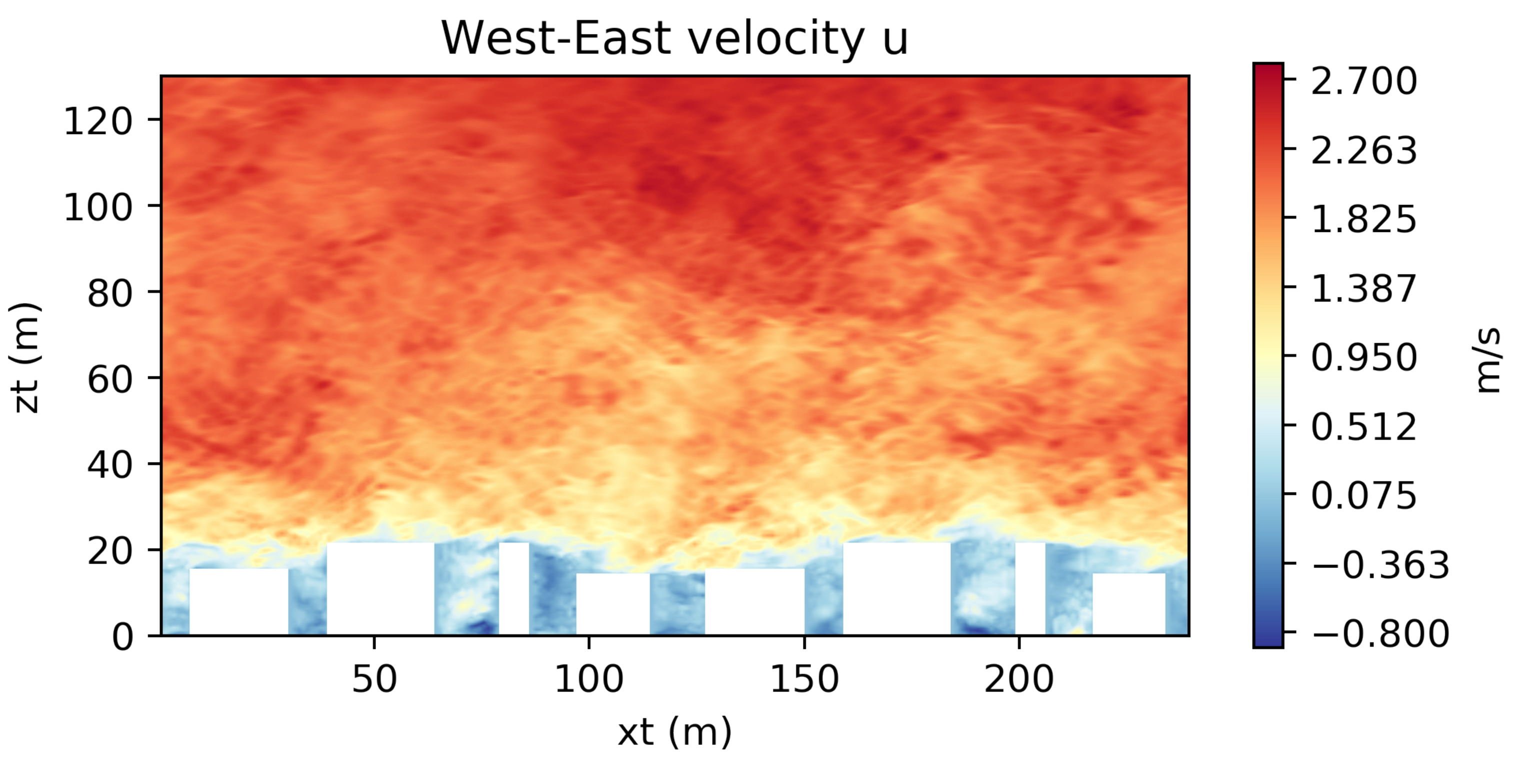

Figure 3: Instantaneous streamwise velocity field with heterogeneous surface.

Dales-Urban is a Large-Eddy Simulation (LES) model that resolves the turbulent urban flow field at resolutions of 1 m and 0.5 s.

Momentum balance of the governing equation

Decomposition of variables into space-time mean $\langle\bar{\cdot}\rangle$, space variations of time mean $\bar{\cdot}''$ and fluctuations $\cdot'$, and averaging the governing Navier-Stokes equations in horizontal space $\langle\cdot\rangle$, and time $\bar{\cdot}$ yields the vertical momentum balance:

$$\underbrace{\frac{\partial}{\partial z}\left(\underbrace{\langle\overline{w'u'}\rangle}_{\text{turbulent flux}} + \underbrace{\langle\bar{w}''\bar{u}''\rangle}_{\text{dispersive flux}} \underbrace{-\nu\frac{\partial\langle\bar{u}\rangle}{\partial z}}_{\text{viscous flux}}\right)}_{\tau} + \underbrace{\underbrace{\frac{1}{\rho A}\int_{\partial\Omega_{xy}}\bar{p}''n\,dS}_{\text{form drag}} \underbrace{-\frac{\nu}{A}\int_{\partial\Omega_{xy}}\frac{\partial\bar{u}_i''}{\partial n}\,dS}_{\text{skin drag}}}_{D} = \underbrace{\underbrace{\langle\bar{F}\rangle}_{\text{pressure forcing}}}_{F}$$

Vertical transport: heterogeneity increases momentum sinks

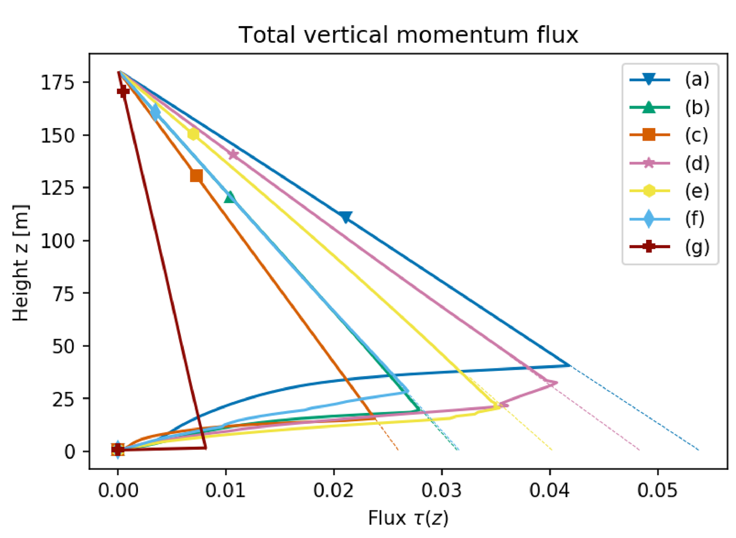

Figure 4: Total vertical transport of horizontal momentum τ, including extrapolated forcing $\hat{F}$ to the domain bottom surface.

The total vertical momentum flux describes the vertical movement in the flow. The rate of downwards momentum transport is highest around the top of the urban canopy, and more heterogeneous layouts tend to have larger momentum sinks. The integrated drag term plays an important role as momentum sink and correlates to maximum building height z_{max} and average height plus deviation $z_H + \sigma_H$, respectively. Turbulent fluxes are the main contributor to the vertical momentum transport, dispersive fluxes contribute within and close above the urban canopy.

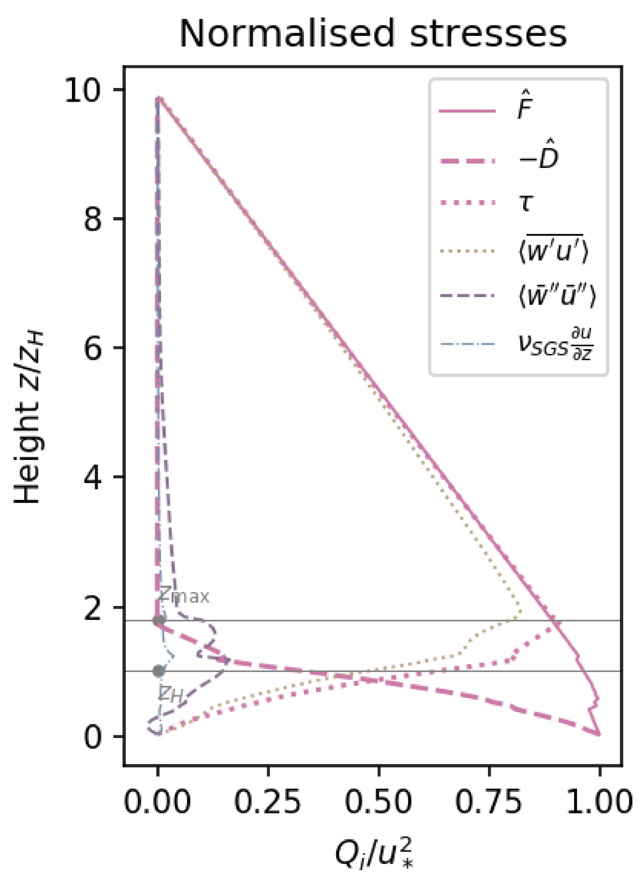

Figure 5: Contributions from the integrated terms of the momentum balance equation to vertical momentum transport.

Simulation setups with varying heterogeneity

Simulations of different urban landscapes (a to f), which share a similar building density λ_p and wind-facing surface λ_f. The landscapes vary in street geometry, building plan area and building height. A reference simulation (g) contains no urban elements.

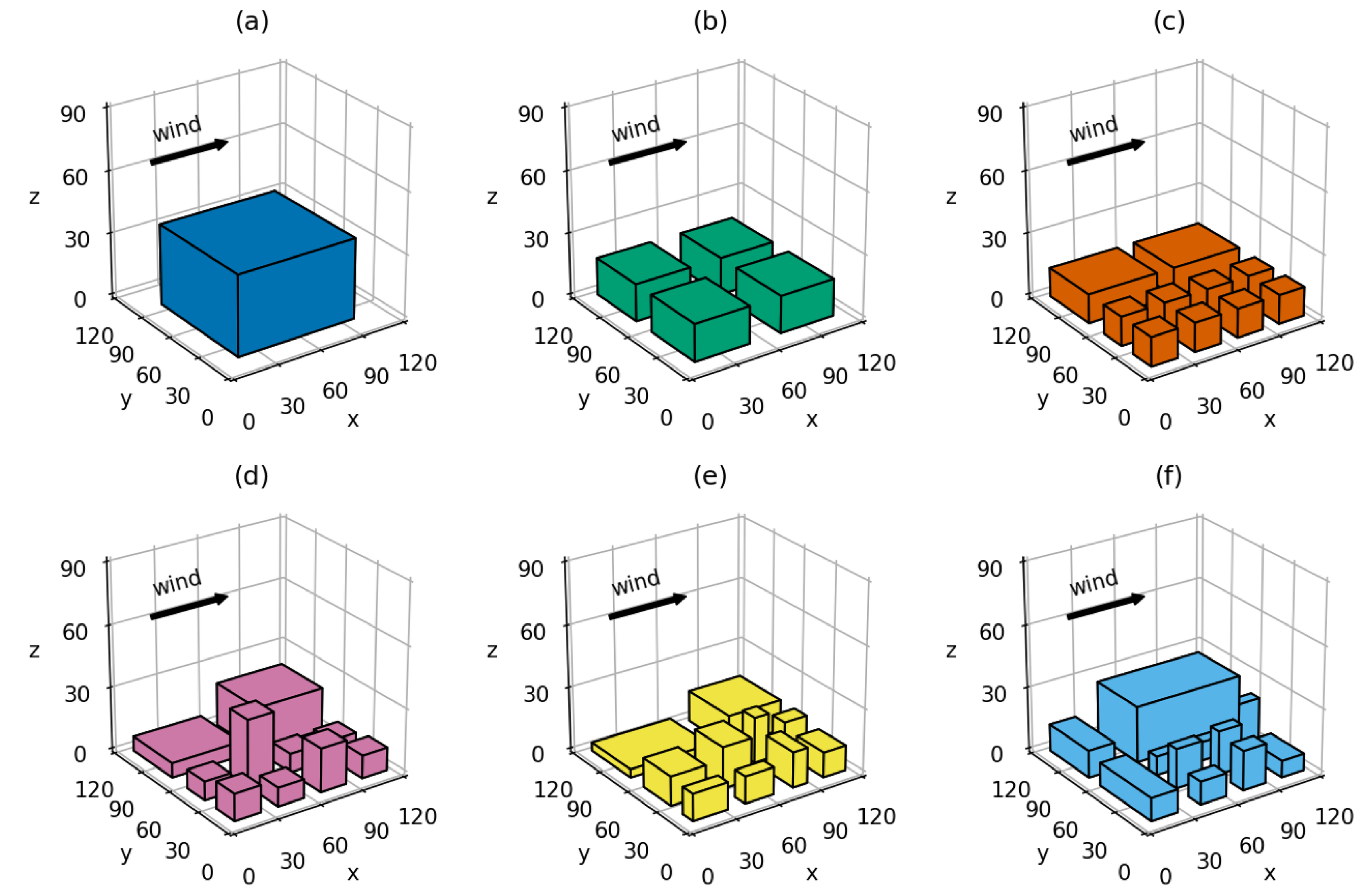

Figure 6: Block layouts for six simulations (a) to (f) with varying heterogeneity.

	λ_p	λ_f	n_b	z_{max}	z_H	σ_H	H/W	W/R
(a)	0.46	0.22	1	39 m	39 m	0 m	1.03	0.32
(b)	0.45	0.22	4	18 m	18 m	0 m	0.82	0.37
(c)	0.46	0.22	10	14 m	14 m	0 m	1.17	0.33
(d)	0.46	0.22	10	32 m	18.07 m	8.43 m	1.18	0.33
(e)	0.46	0.22	10	22 m	15.57 m	4.04 m	1.15	0.35
(f)	0.45	0.24	10	27 m	18.27 m	7.16 m	1.25	0.33

Table 1: Block statistics: plan area fraction λ_p, frontal aspect ratio λ_f , number of blocks n_b, maximum block height z_{max}, weighted average block height z_H, block height standard deviation σ_H, block height to canyon width average H/W, canyon to combined block and canyon width average W/R.

Mean flow: distinct flow profiles with heterogeneity

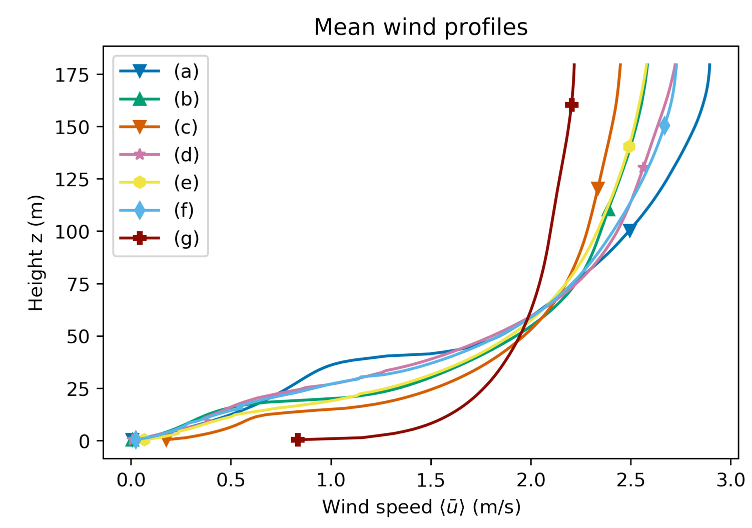

Figure 7: Averaged vertical wind velocity $\langle\bar{u}\rangle$ of simulations (a) to (g). The volume-averaged flow rate of all simulations is $u = 2$ m/s.

Building blocks obstruct the mean flow and a logarithmic boundary layer profile develops above the urban canopies. The flat surface (g) shows a typical boundary-layer profile. Setups (a) to (c) with homogeneous building heights show a clear distinction between canopy flow and free flow. Velocity profiles changes from concave (within) to convex (above canopy). Setups (d) to (f) with heterogeneous building heights have a gradual regime change and lack a clear separation of above- and within-canopy flow.

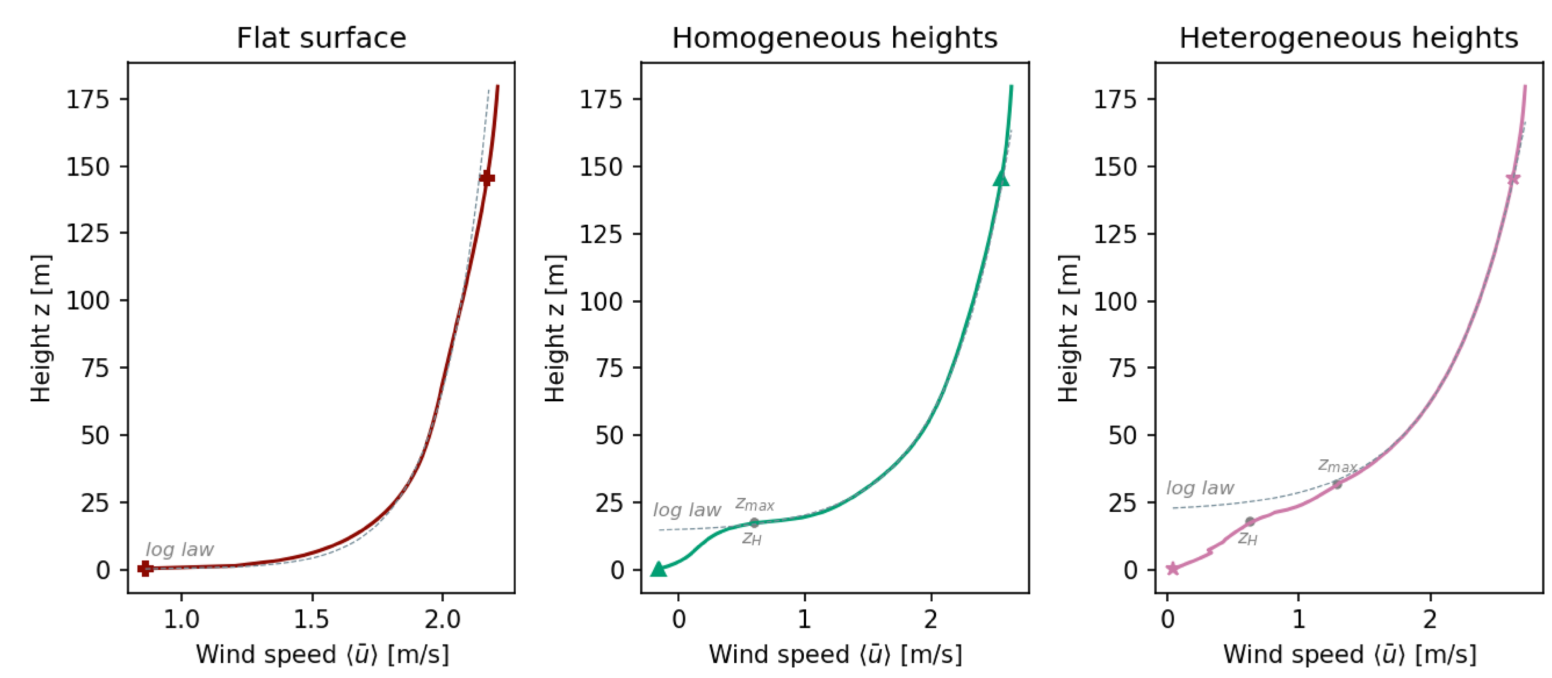

Figure 8: Mean wind flow regimes for flat surface, homogeneous and heterogeneous building heights.

Conclusions

- Heterogeneous building layouts produce distinct flow regimes and vertical momentum flux profiles, parameters λ_p and λ_f are not sufficient to describe them.
- Greater momentum sinks result from larger turbulence-related momentum fluxes and building-induced drag. Heterogeneity parameters such as z_{max}, z_H and σ_H are predictors for an increased rate of momentum loss within urban canopies.

References

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