Revisiting the flow regimes for urban street canyons using the numerical Green's function

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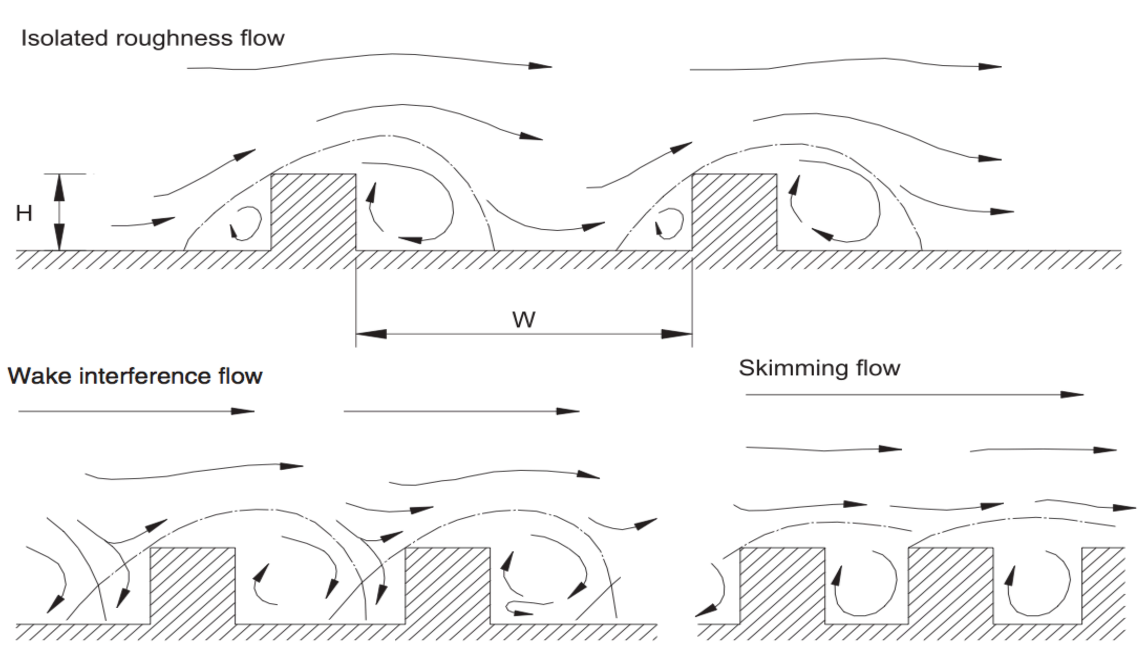
Abstract

Theoretical predictions about urban boundary-layer flows are difficult to obtain. As an alternative to three-dimensional CFD simulations, vortex interactions can be analysed with the numerical Green's function. The Green's function characterises the strength and scale of vortex interactions and reflects the influence of the boundaries. Using the numerical Green's function, the regime transitions from isolated roughness to wake interference and wake interference to skimming flow are determined as a function of the aspect ratio. There is good agreement with LES and the accepted transition values. For further details see **[1]**.

1. Urban flow regimes

The existence of distinct urban flow regimes is well-established **[2]**:



For AR=H/W, transitions occur around **AR_1~0.3 and AR_2~0.7** in the street-canyon limit (L→∞) **.**

Fig.1: Schematic illustration of different flow regimes **[2]**.

Despite the importance of this classification schema, there has been little work explaining why the transitions occur where they do. Most of the work is fairly old, e.g., physical explanations based on the presence of a double-eddy structure **[3]** and numerical simulations in 2-D **[4]**.

The absence of theoretical understanding is surprising. Obviously useful predictions can be made for many turbulent flows. But urban turbulence is neither homogeneous nor isotropic...

3. Numerical Green's function

The Green's function corresponds to the induced streamfunction. For brevity we only show G_x, i.e., Ψ_x or the induced vertical velocity.

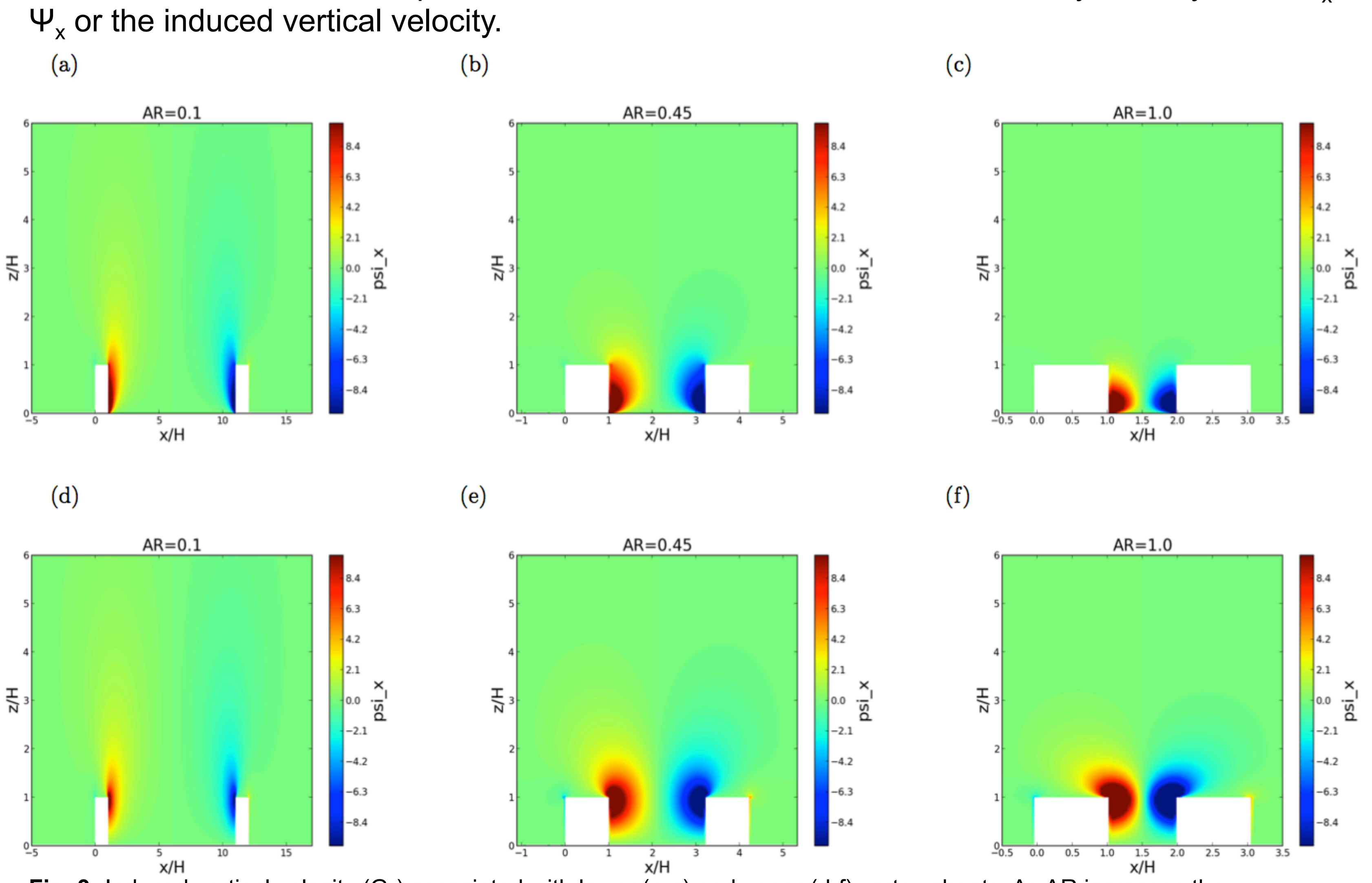


Fig. 3: Induced vertical velocity (G_x) associated with lower (*a-c*) and upper (d-f) vortex sheets. As AR increases the interactions between the canyon eddies (i) strengthens as the separation between them decreases; (ii) weakens as localisation near the source increases. This leads to a non-monotonic dependence on AR.

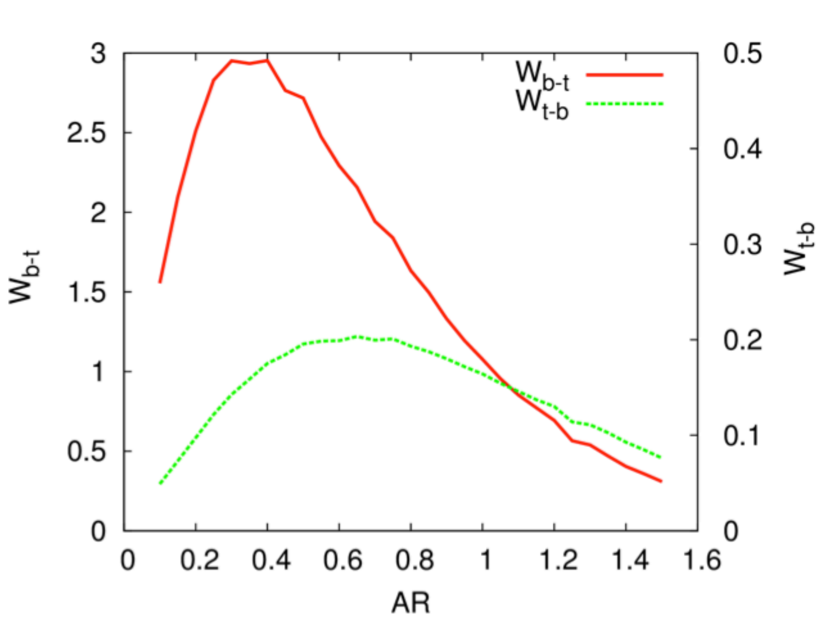


Fig. 4: Induced vertical velocities versus aspect ratio for vorticity sources at the bottom (*red*) and top (*green*) of the canyon. The peaks occur around AR_1~0.35 and AR_2~0.75.

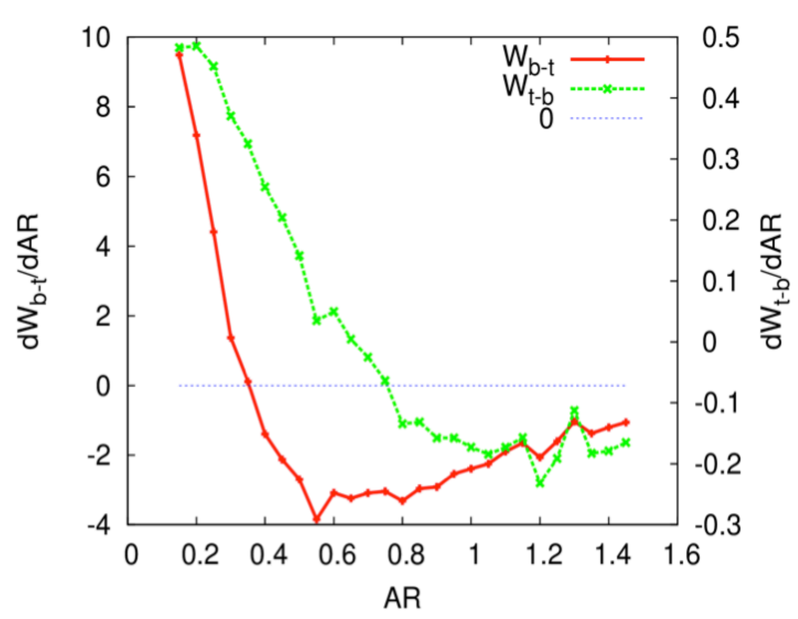


Fig. 5: First derivatives of the induced vertical velocities with respect to the aspect ratio. The peaks occur at AR_1=0.35±0.05 and AR_2=0.75±0.05.

2. Green's function and 2-D vortex dynamics

Analytical solution is difficult. Nevertheless progress can be made by focusing on the vorticity dynamics. The effects of the boundaries are manifested through the Green's function of the Laplacian operator. The Green's function governs all vortex interactions by determining their strength and scale. Hence knowledge of how the Green's function changes with the aspect ratio should provide insight into the regime transitions.

In vortex dynamics the Green's function describes the solution induced by a point vortex **[5]**. For simplicity we restrict ourselves to 2-D:

$$q = \nabla^2 \psi \qquad \psi = \int_{\mathcal{D}} d\boldsymbol{x}' G(\boldsymbol{x}|\boldsymbol{x}') q(\boldsymbol{x}')$$

In an unbounded domain the Green's function G(**x**|**x'**) = G(**x'**|**x**) but this is not true in general.

Calculating the Green's function at every point is impractical. Hence we model the canyon flow using a pair of vortex sheets — one at the bottom and one at the roof level — and examine how G(**x**) changes with AR.

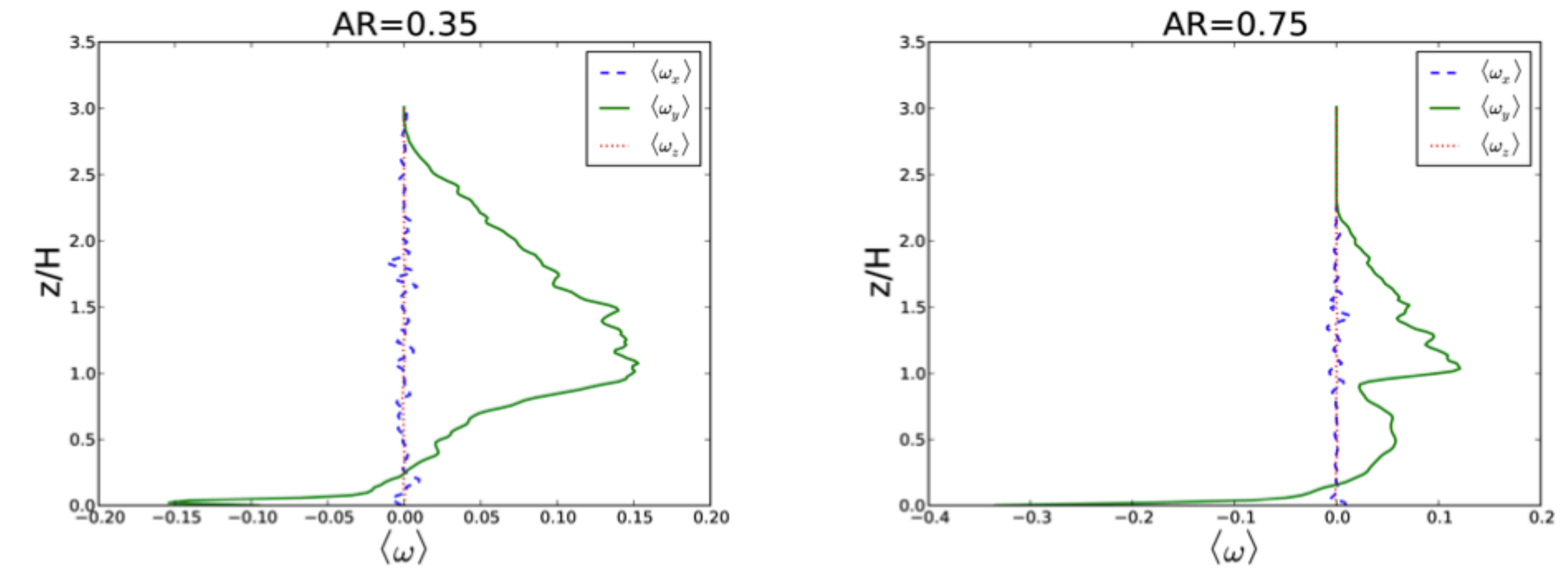


Fig. 2: Vertical profiles of the vorticity components. The spanwise vorticity dominates, implying that the flow is approximately 2-D.

4. Comparison with LES

Using the LES model PALM **[6]**, turbulent flow in a single street canyon was simulated. The configuration followed **[7]**.

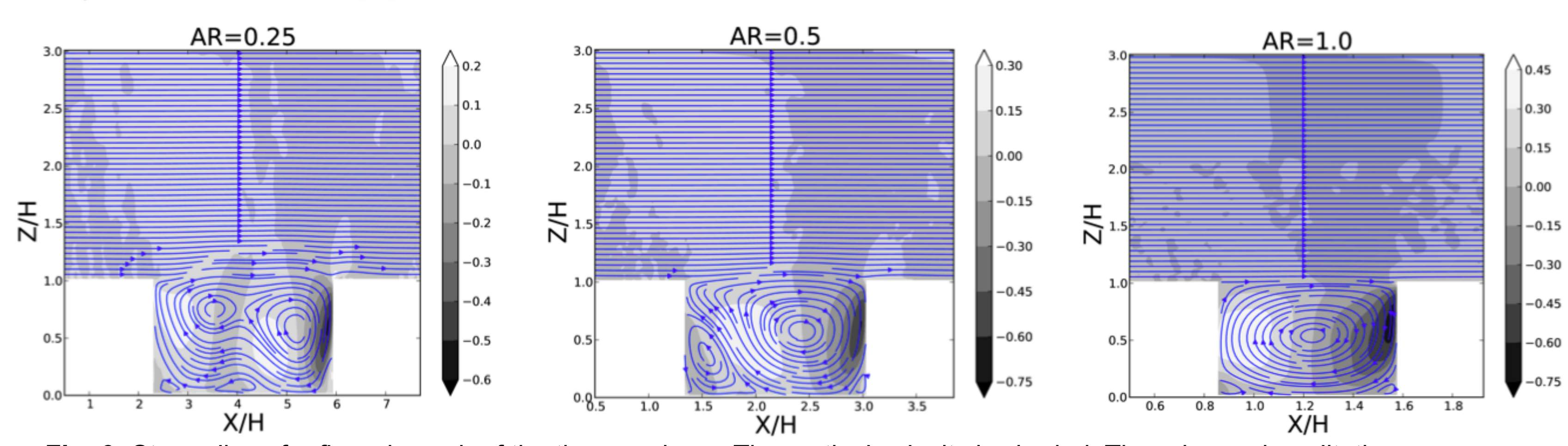
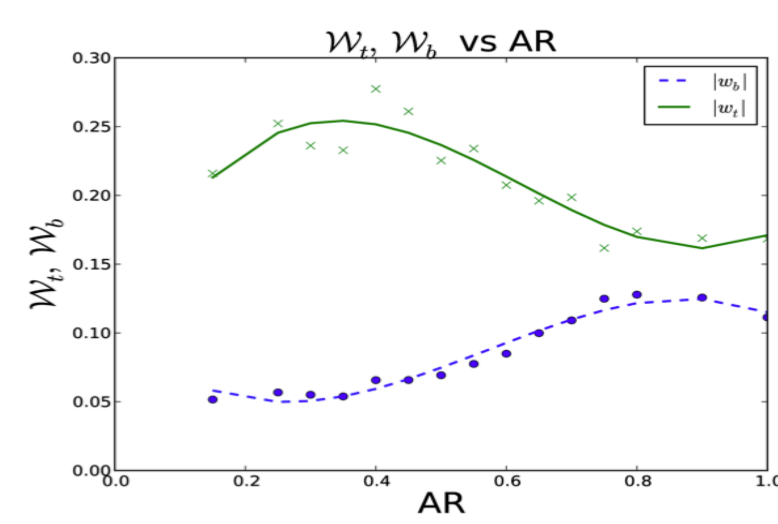


Fig. 6: Streamlines for flows in each of the three regimes. The vertical velocity is shaded. There is good qualitative agreement with published studies **[8]**.

Fig. 7: Vertical velocities at the top and bottom of the canyon. The peaks occur at $AR_{1,w}$=0.425±0.05 and $AR_{2,w}$=0.85±0.05. This behaviour is in accord with the predictions from the Green's functions.



5. Future work

Application to uneven street canyons is being investigated. The Green's function approach may be useful for parameterisation.

References

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