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Experimental and numerical simulations of airflow over semi-realistic and realistic urban geometries

Matthew Coburn[1], Christina Vanderwel[2], Steven Herring[3], Zheng-Tong Xie[4]

[1] *University of Southampton, UK, m.coburn@soton.ac.uk*
[2] *University of Southampton, UK, c.m.vanderwel@soton.ac.uk*
[3] *University of Southampton, UK, s.herring@soton.ac.uk*
[4] *University of Southampton, UK, zxie@soton.ac.uk*

SUMMARY:
Past work has shown that coupling can exist between atmospheric air flows at street scale (O(0.1 km)) and city scale (O(10 km)). Unfortunately, it is generally impractical at present to develop high-fidelity urban simulations capable of capturing such effects. This limitation imposes a need to develop better parameterisations for meso-scale models but an information gap exists in that past work has generally focused on simplified urban geometries and assumed the buildings to be on flat ground. This study aimed to address this gap in a systematic way by using the large eddy simulation method with synthetic turbulence inflow boundary conditions including significant local terrain features. The LES data were processed to obtain averaged vertical profiles of time-averaged velocities and second order turbulence statistics. The inclusion of terrain can have a considerable effect on global quantities, such as the depth of the spanwise-averaged internal boundary layer and spatially-averaged turbulent kinetic energy (TKE), but the effects of adding terrain on local time-mean velocity and TKE at a given above ground height can be more significant. These highlight the impact that local terrain features (O(0.1 km)) may have on near-field dispersion and the urban micro-climate.

Keywords: Street-Scale Terrain, Large Eddy Simulation, Above-Ground-Level Height

1. INTRODUCTION

At present operational meso-scale models are unable to predict the details of urban flows at street and neighbourhood scale (i.e O(1 km)). Although finely resolved urban simulations can be generated by engineering computational fluid dynamics (CFD) codes (e.g. Antoniou et al., 2017; Gronemeier et al., 2020; Han et al., 2017; Inagaki et al., 2017; Tolias et al., 2018; Xie and Castro, 2009) over scales from 1 m to neighbourhood scale, larger city-scale simulations (i.e O(10 km)) are generally impractical. This presents a significant limitation, as past work has shown that two-way coupling can exist not just between the urban boundary layer properties measured at street scale (O(0.1 km)) and neighborhood (O(1 km)),and city scales (O(10 km)) but also between the street scale and city scale (Barlow et al., 2017; Fernando, 2010). Such coupling can be particularly pronounced when the urban area includes features such as a single or cluster of tall buildings (Fuka et al., 2018; Han et al., 2017; Hertwig et al., 2019), or a sharp change in topography (Blocken et al., 2015; Coburn, 2023; Coburn et al., 2023; Conan et al., 2016; Limbrey et al., 2016).

The development of simulations which accurately capture the coupling between street and city scales challenges both numerical and experimental approaches in many respects. This study uses numerical simulations to examine a selected heterogeneous area containing urban geometry and small sharp changes in topography (O(0.1 km)) in a systematic way which is difficult to achieve through wind and water tunnel experiments, or field observations.

Although it is known that coupling may exist between street and city scale flows, considerable uncertainty remains regarding the importance of small-scale topographic features in influencing street scale (O(0.1km)) and neighbourhood scale (O(1km)) urban flows. This highlights a need for new studies to investigate and understand the effects of small-scale topographic features on street (O(0.1 km)) to neighborhood (O(1km)) scales, before considering the coupling between neighborhood and city scales.

2. OUTLINE OF THE CURRENT WORK

The city of Southampton lies at the confluence of the Test and Itchen rivers and the urban area contains numerous small valleys, one of which is shown by vertical lines at different spanwise locations in Fig. 2, across the University of Southampton Highfield campus (1). This made the campus a suitable area for conducting a study to examine the importance of small (O(0.1km)), sharp, changes in topography within a real urban area.

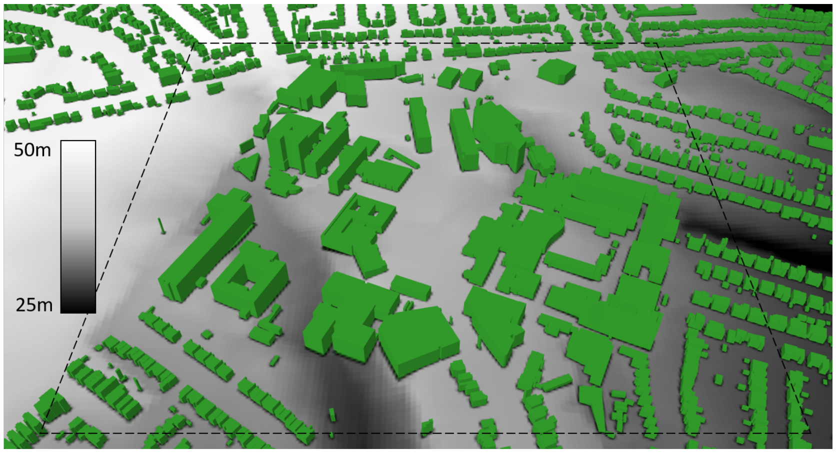

Figure 1. Three-dimensional geometry and terrain contours (above sea-level) of the University of Southampton Highfield campus. The dashed frame shows the extent of computational domain.

The approach adopted for assessing the significance of small scale topography within an urban area was to compare the results of simulations of atmospheric air flows around the buildings on the University of Southampton Highfield campus for cases in which the buildings were on flat ground and on terrain including the small-scale topography. To validate the numerical modelling method for neutral atmospheric conditions, advantage was taken of the availability of high resolution PIV data from a water tunnel experiment at the University of Southampton.

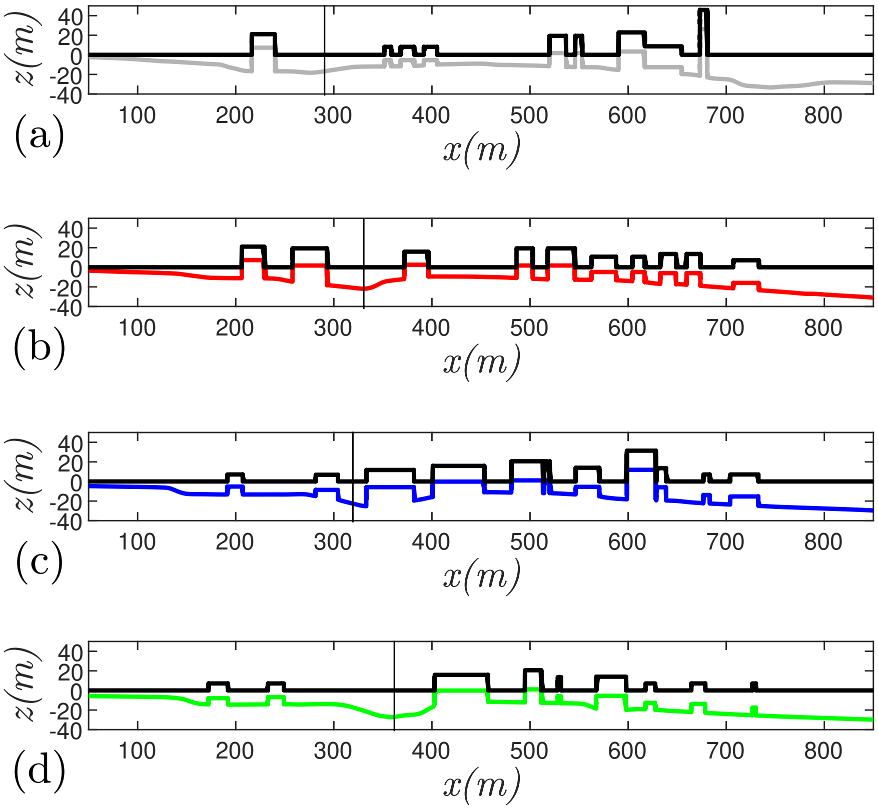

Figure 2. Streamwise terrain and building profiles at typical spanwise locations.

3. CONCLUSIONS

A systematic comparison of LES predictions of atmospheric airflows over the flat and real terrains showed that capturing terrain effects is crucial, where the height change of a street-scale (O(0.1km) topographic feature is of the same order of magnitude as the neighbourhood buildings. The case study showed that when the atmospheric boundary layer (ABL) passes over a built environment with a downslope it experiences less aerodynamic resistance compared to when the terrain is flat. This results in less TKE, a faster growth in total boundary layer depth (AGL), and a slow-growing IBL (AGL). This is due to the so-called "diffuser" effect. Conversely, if the ABL passes over an upslope, it is expected to experience greater aerodynamic resistance compared to a built environment on flat terrain, resulting in a reduced total boundary layer thickness.

To enable corrections to be developed for experimental and numerical data acquired from flat terrain simulations, it is crucial to quantify and understand how street-scale terrain variations modulate the local mean velocity and turbulence statistics at a certain height AGL. The study has shown that the ratio between real-terrain and flat- streamwise velocity data on the same horizontal coordinates, and at the same AGL height correlate positively very well with the terrain elevation, with a maximum ratio greater than 2, and a minimum less than 0.5. This is because the local boundary layer cannot immediately adjust to the street-scale terrain variations. Subsequently, a high streamwise mean velocity is expected on the same AGL height over an high terrain elevation, vise versa. Within the study domain, the global (average) gradient of the west-east downslope was much smaller than the local terrain gradients, so the global average gradient contributed little contribution to the strong modulations observed in the local mean velocity field. In other words, this real terrain's modulation on the mean streamwise velocity field is in the similar manner and strength in an east-west wind passing the upslope. At a height immediately above the urban canopy (e.g. $z_{AGL} = 2.3h$), a similar modulation on the local mean velocity is weaker but still evident.

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REFERENCES

Antoniou, N., Montazeri, H., Wigo, H., Neophytou, M. K.-A., Blocken, B., and Sandberg, M., 2017. CFD and wind-tunnel analysis of outdoor ventilation in a real compact heterogeneous urban area: Evaluation using "air delay". Building and Environment 126, 355–372.

Barlow, J., Best, M., Bohnenstengel, S. I., Clark, P., Grimmond, S., Lean, H., Christen, A., Emeis, S., Haeffelin, M., Harman, I. N., et al., 2017. Developing a research strategy to better understand, observe, and simulate urban atmospheric processes at kilometer to subkilometer scales. Bulletin of the American Meteorological Society 98, ES261–ES264.

Blocken, B., Hout, A. van der, Dekker, J., and Weiler, O., 2015. CFD simulation of wind flow over natural complex terrain: Case study with validation by field measurements for Ria de Ferrol, Galicia, Spain. Journal of Wind Engineering and Industrial Aerodynamics 147, 43–57.

Coburn, M., 2023. High fidelity modelling of neighbourhood-scale environments. PhD thesis, University of Southampton.

Coburn, M., Vanderwel, C., Xie, Z.-T., and Herring, S. J., 2023. Experimental and Numerical Simulations of Airflow over Semi-Realistic and Realistic Urban Geometries. Boundary-Layer Meteorology , to be submitted.

Conan, B., Chaudhari, A., Aubrun, S., Beeck, J. van, Hämäläinen, J., and Hellsten, A., 2016. Experimental and numerical modelling of flow over complex terrain: the Bolund hill. Boundary-layer meteorology 158, 183–208.

Fernando, H., 2010. Fluid dynamics of urban atmospheres in complex terrain. Annual review of fluid mechanics 42, 365–389.

Fuka, V., Xie, Z.-T., Castro, I. P., Hayden, P., Carpentieri, M., and Robins, A. G., 2018. Scalar fluxes near a tall building in an aligned array of rectangular buildings. Boundary-layer meteorology 167, 53–76.

Gronemeier, T., Surm, K., Harms, F., Leitl, B., Maronga, B., and Raasch, S., 2020. Validation of the dynamic core of the PALM model system 6.0 in urban environments: LES and wind-tunnel experiments. Geosci Model Develop Discuss, 1–26.

Han, B.-S., Park, S.-B., Baik, J.-J., Park, J., and Kwak, K.-H., 2017. Large-eddy simulation of vortex streets and pollutant dispersion behind high-rise buildings. Quarterly Journal of the Royal Meteorological Society 143, 2714–2726.

Hertwig, D., Gough, H. L., Grimmond, S., Barlow, J. F., Kent, C. W., Lin, W. E., Robins, A. G., and Hayden, P., 2019. Wake characteristics of tall buildings in a realistic urban canopy. Boundary-Layer Meteorology 172, 239–270.

Inagaki, A., Kanda, M., Ahmad, N. H., Yagi, A., Onodera, N., and Aoki, T., 2017. A numerical study of turbulence statistics and the structure of a spatially-developing boundary layer over a realistic urban geometry. Boundary-Layer Meteorology 164, 161–181.

Limbrey, E. G., Macdonald, J. H., Rees, J., and Xie, Z. T., 2016. the Clifton Suspension Bridge site.

Tolias, I., Koutsourakis, N., Hertwig, D., Efthimiou, G., Venetsanos, A., and Bartzis, J., 2018. Large Eddy Simulation study on the structure of turbulent flow in a complex city. Journal of Wind Engineering and Industrial Aerodynamics 177, 101–116.

Xie, Z.-T. and Castro, I. P., 2009. Large-eddy simulation for flow and dispersion in urban streets. Atmospheric Environment 43, 2174–2185.