Fluid dynamics of Urban Tall-building clUsters for Resilient built Environments (FUTURE)

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1 INTRODUCTION AND BACKGROUND

Tall buildings are now ubiquitous in major cities to maximise the provision of housing and commerce. The mean wind field in the wake of a single 100m tall building (TB) can be significantly modified in a region about 500 m long and 300 m wide [1]; its impact on turbulence is even more significant [2], affecting pollutant dispersion and heat transfer. In the wake, the 'classical' description of the Urban Boundary Layer (UBL) no longer applies, severely restricting our ability to predict street-level winds, ventilation, and air quality. Furthermore, the impact of urban climate occurs at local (100m) and city (10km) scales; however, Numerical Weather Prediction models lack adequate representation of TB wakes because of their low spatial resolution, and Computational Fluid Dynamic scale simulations often lack a representation of the full meteorological processes (e.g. UBL scale, heating/cooling effects). Isolated buildings have been considered, but more challenging is the impact of clusters of TBs with complex wake interactions. Pilot numerical simulations around central London (Fig. 1a) highlight non-linear wake interaction effects around the TBs in the Barbican (x,y~1720m,1860m) and Gherkin clusters (x,y~2680m,1200m) in Fig 1b. Project 'Fluid dynamics of Urban Tall-building clUsters for Resilient built Environments' (FUTURE - EP/V010921/1) aims to investigate the issues above via laboratory and field experiments, numerical and analytical modelling.

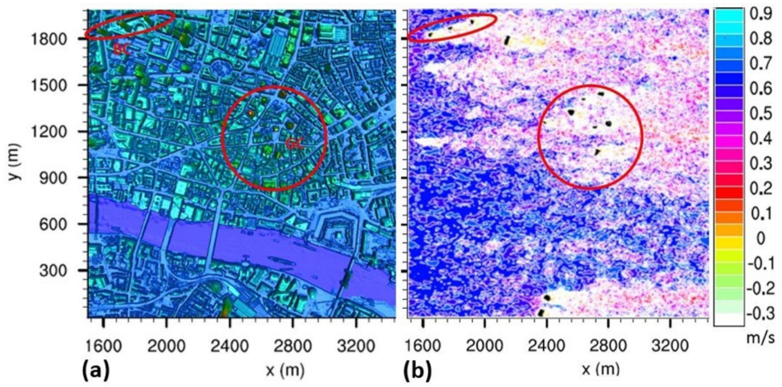

Figure 1, (a) CFD domain of the City of London with Barbican (red ellipse) and Gherkin (red circle) clusters. (b) Low-speed wake downstream of TBs at z=114m (instantaneous streamwise velocity - courtesy Z-T Xie). Flow left to right.

In summary, the aims of the project are:

1. To understand the magnitude/scale of the effects of a cluster of TBs on the UBL;
2. To identify the main parameters that govern the near and far fields within the wake;
3. To assess what can be said generically (i.e. modelled) and what remains site-specific;
4. To develop simplified (analytical) models to describe TB clusters' wakes;
5. To collate this information within a set of publicly available guidelines.

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The project is led by the University of Surrey, academic partners in the Universities of Southampton and Reading and with City of London Corporation, DSTL, Met Office, and RWDI as project partners.

2 PRELIMINARY RESULTS

Though work has organically and synergistically involved all institutions/partners in delivering the aims discussed above, for presentation purposes, results and progress are reported herein per institution.

2.1 University of Surrey

Methodology

Laboratory experiments were conducted within the EnFlo laboratory, with most of the work carried out in the Meteorological EnFlo tunnel (working section 1.5 m × 3.5 m × 20 m). A combination of Irwin spires and wall roughness were used to replicate thick UBLs, while stable thermal stability was achieved by imposing an inlet temperature profile, while cooling the floor of the tunnel. The models are placed on a circular turntable to allow for different wind directions to be considered. 3-D laser Doppler anemometry, cold wire anemometry and thermistors, and fast flame ionization detectors are used to measure velocity, temperature and concentration fields, respectively.

Progress to date

Work has focussed on idealised arrays of TB clusters where different numbers of buildings, aspect ratio, spacing and cluster size (W_A), were considered in both neutral [3,4] and stable thermal conditions [5]. Data analysis has identified characteristic wake regimes (Fig. 2) in both mean [3] and turbulence quantities [4], and their link to dispersion patterns [6]. Alongside idealised cases, a more realistic City of London (CoL) geometry was also tested for comparisons. Data analysis is ongoing.

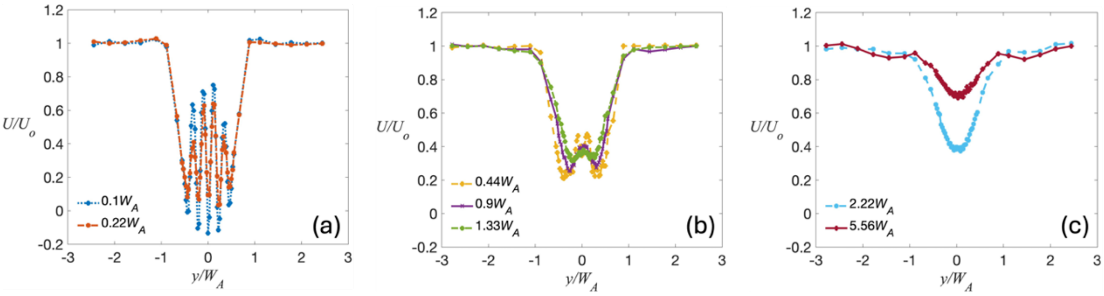

Figure 2, Wake lateral profiles of non-dimensional streamwise velocity, U/U_0, for a 5x5 array in the (a) near-wake regime, (b) transition-wake regime, and (c) far-wake regime. Adapted from [3].

2.2 University of Southampton

Methodology

Large-Eddy Simulations (LES) embedded in PALM [7] and OpenFOAM [8] were used for UBLs. Because the wake from a TB cluster can persist over long distances, large computations (e.g. up to 5 billion cells) were carried out on the national (Archer2) and local (Iridis5) supercomputing facilities, with an efficient synthetic turbulence generation [9] at the inlet. Thermal stratification was considered. An example LES domain is shown below in Fig. 3.

Progress to date

We have designed three types of LES geometries: 1) arrays of square cylinders [10,11]; 2) arrays of idealised tall buildings with a constant [12] and random height [13]; 3) an array of 17 tall buildings (i.e. CoL) [14]. The simulations [12-13] have been compared against the wind tunnel experiments. To date, we observed the following. Firstly, the slenderer buildings were less sensitive to the approaching wind direction as the integral length scale of the turbulence generated by slender TBs is significantly larger than for low-rise buildings. Secondly, for both incoming smooth and turbulent flows, the primary shedding frequencies for infinite height square cylinders, when appropriately scaled, is approximately the same as that of an isolated square cylinder. Thirdly, for incoming free-stream turbulence with an integral length scale greater than the cluster size, the dominant Strouhal number of the arrays of infinite height square cylinders is significantly reduced when compared to the smooth inflow. Finally, the cluster's

Strouhal number of the arrays of 2×2 finite height buildings is also governed by the effective cluster size despite the 3-D effect and the boundary layer interaction with the TBs.

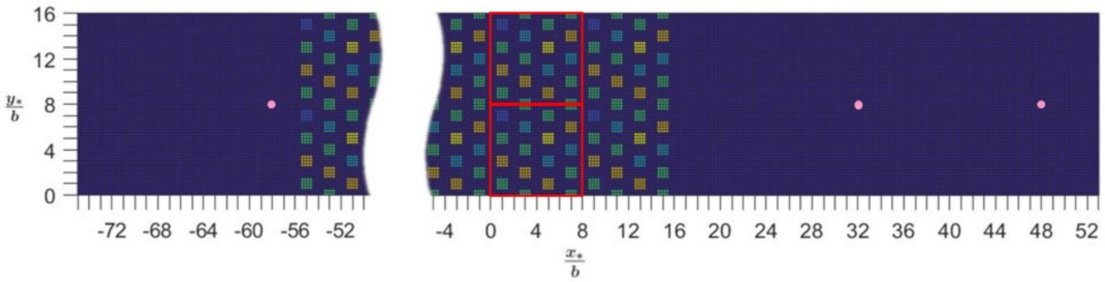

Figure 3: Streamwise-spanwise (x_*, y_*) LES domain with random height buildings (not to scale). Spatially averaged region is outlined in red. b represents the building width.

2.3 University of Reading

Work at Reading includes two separate efforts – fieldwork and simplified (analytical) modelling.

2.3.1 Fieldwork

Methodology

Following previous work studying isolated TB wakes using a Doppler Wind Lidar (DWL) in London, UK [15], wakes around two building clusters in Berlin, Germany (Fig. 4a) were studied using 2 DWLs in collaboration with the urbisphere project [16]. Observations took place from 28.6.22 to 19.9.22. At the SCHO site, a Halo-Photonic Streamline DWL was deployed on a rooftop at 87 m, and at the TUCC site, a Streamline XR DWL was on a rooftop at 80 m. Scans included regular Plan Position Indicator (PPI) at 0° elevation, giving a horizontal slice of the TB wakes at a fixed height (see Fig. 4b).

Progress to date

Analysis of PPI scans is ongoing, including boundary layer depth and vertical wind profiles measured using vertically-pointing scans. An ensemble averaging approach will be applied to instantaneous scans measured for similar wind directions and atmospheric conditions and assumed to be comparable to the relatively long time-averaged wakes measured in the wind tunnel. [15] have shown that a shorter wake was observed under unstable atmospheric conditions due to the stronger vertical mixing that reduced the velocity deficit. This was the case unless turbulence upstream of the building was enhanced (e.g. by the wake of another building). This stability dependence will be tested for TB clusters.

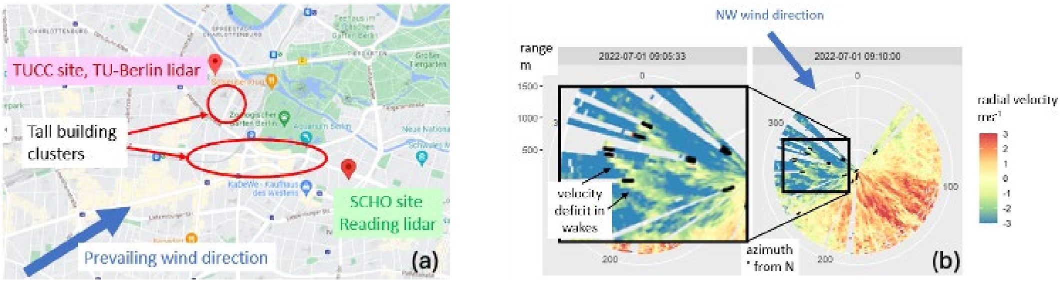

Figure 4: a) Location of DWLs used in urbisphere-Berlin experiment to study wakes around TB clusters (circled in red). b) example of PPI scan at 0° elevation from SCHO DWL, showing radial velocity. Flow coming towards DWL is blue (negative), away is red (positive). Wakes are visible as velocity deficits (yellow, near zero velocity).

2.3.2 Analytical modelling

Methodology

This work focuses on the development of simplified methods for modelling wind profiles in heterogeneous UBLs. Full solution of the PDEs governing the flow (e.g. LES) is expensive. Alternatively, an ODE with position-dependent coefficients can be solved, together with appropriate closure models. A different approach is to put the position dependence not in the coefficients, but in the index of fractional-order derivatives. In this way, the character of the differential equation does not vary spatially and the same solution method can be applied in different flow regimes. This provides a unified and economical treatment of the problem [17].

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Progress to date

Perturbation methods have been developed to provide approximate analytical solutions for the different types of ODEs that emerge [18]. These will be applied and tested with the FUTURE datasets. In addition, a simple fractional order model has been formulated and solved numerically. Comparisons with three different test datasets are shown in Fig 5. With model coefficients fixed for a given geometry, the middle portion of the wind profile can be reproduced. A more sophisticated model is needed to resolve the regions close to the ground and canopy top.

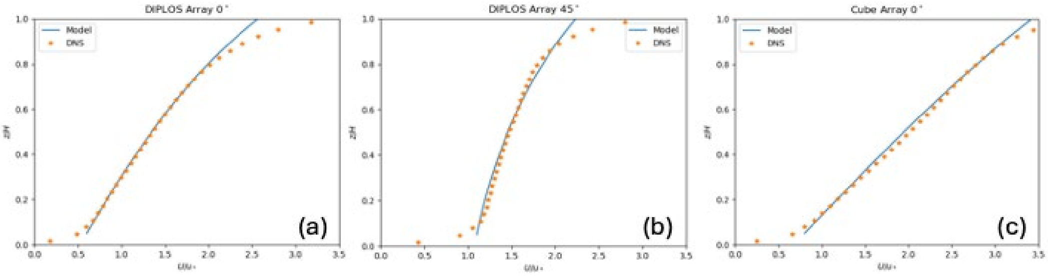

Figure 5: Examples of wind profile solutions of a fractional canopy model compared against DNS data for three different setups (a) cuboid array, 0° (b) cuboid array, 45° (c) cube array, 0°. Lines: model; circles: DNS data.

3 FURTHER INFORMATION

With the project end date of June 2025, work is still ongoing. For further information and up to date progress, please visit our website https://www.surrey.ac.uk/research-projects/future.

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