Wind tunnel experiments of flow and dispersion in building arrays

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ABSTRACT

Wind tunnel experiments on regular arrays of buildings were conducted in the environmental wind tunnel in the EnFlo laboratory at the University of Surrey. The model canopy comprised a square array of 14×21 rectangular blocks ($1h \times 2h$) with height $h = 70$ mm. Preliminary measurements of velocity, turbulence and tracer concentrations were made for 3 wind directions: 0, 45 and 90°. The results from this first experimental campaign along with numerical simulations have shown that the canopy has obstacles sufficiently long compared with their heights to yield extensive flow channelling along streets. Across the whole of the downwind half of the long street the flow for the present canopy is closely aligned with the obstacle faces, despite the 45° flow orientation aloft. This supports the suggestion that the streets are long enough to be representative for street network modelling approaches; shorter streets would probably not be sufficient and it will be interesting to see how well network models can predict concentrations in the present canopy. The extensive array and the small scale of the model posed challenging problems for reaching the desired high accuracy needed to validate the numerical simulations. The improvements in the methodology will be presented and discussed at the conference. The wind tunnel data, along with LES and DNS simulations, are being used to understand the behaviour of flow and dispersion within regular array with a more realistic geometry than the usual cuboids. This integrated methodology will help developing parametrisations for improved street network dispersion models.

INTRODUCTION

The accidental or deliberate release of hazardous airborne materials in densely populated areas is a contemporary threat that poses new scientific and modelling challenges. The dispersion modelling community is faced with the task of providing first responders with models that allow for a fast but accurate prediction of plume pathways, enabling to make informed decisions for evacuation and sheltering procedures.

DIPLOS (Dispersion of Localised Releases in a Street Network, http://www.diplos.org) is a collaborative project between institutions in the UK and France that aims to develop and improve dispersion parameterizations in emergency response tools like the street-network based dispersion model SIRANE (Soulhac *et al.*, 2011).

The work presented here concentrates on the EnFlo wind tunnel experiments, discussing the difficulties faced in obtaining sufficiently high quality simulations, the results obtained so far and the plans for further experiments.

WIND TUNNEL EXPERIMENTS

All experiments were conducted in the environmental wind tunnel in the EnFlo laboratory at the University of Surrey. This is an open-circuit tunnel with a working section that is 20 m long and 3.5 × 1.5 m in cross-section. The model canopy comprised a square array of 294 (14 × 21) $h \times 2h \times h$ rectangular blocks with height $h = 70$ mm, mounted on a turntable whose axis of rotation was some 14 m downstream of the test-section entrance. The origin of the rectangular coordinate system was set at the turntable (and model) centre, with x in the streamwise direction and z upwards. Figure 1 shows the arrangement for the orientation defined as $\theta = 0°$–i.e. with the oncoming flow perpendicular to the longer sides of the array obstacles. The array was curtailed at its corners in order to fit the turntable and thus allow ease of rotation to any desired angle. Note that the boundary layer upstream of the array was initiated by a set of five Irwin spires, 1.26 m in height, and developed over surface roughness comprising a staggered array of relatively sparsely distributed thin plates 80 mm × 20 mm (width and height, respectively), with spacing 240 mm in both x and y. The boundary layer at the start of the urban array ($x = -2$ m) was thus about $14h$ in depth and was found to be reasonably homogeneous across the span with no systematic spanwise variations. Measured velocities were within ±5% of the spanwise mean. An internal boundary layer grew from the leading edge of the array, but conditions within the canopy, assessed for example by measurements along a spanwise street for the $\theta = 0°$ orientation, were essentially independent (i.e. within the experimental uncertainty) of the particular street downwind of the fifth street from the start of the array. Two reference ultrasonic anemometers mounted downstream of the array in the tunnel exit ducts were used to ensure that all the experiments were undertaken at the same freestream velocity in the approach flow (2 m/s). The Reynolds number based on obstacle height and the velocity at that height in the upstream boundary layer was about 7400, or about 830 when based on the friction velocity u_τ (i.e. $Re_\tau = hu_\tau/\nu$, where ν is the kinematic viscosity). The boundary layer was thus well within the fully-rough-wall regime.

Velocity and turbulence measurements were made using a two-component Dantec laser Doppler anemometer (LDA) system with a FibreFlow probe of outside diameter 27 mm and focal length 160 mm. This provided a measuring volume with a diameter of 0.074

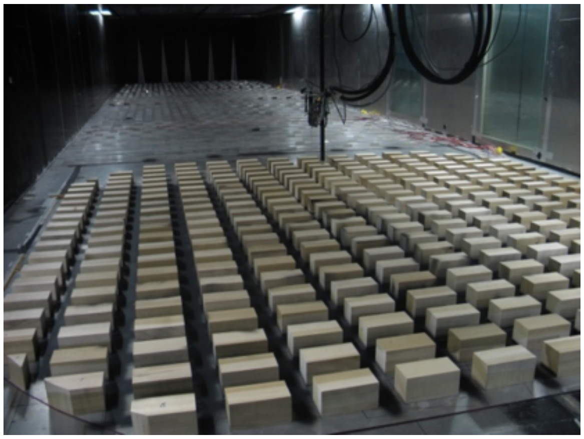

Figure 1. Looking upstream in the wind tunnel. The array is in the $\theta = 0^\circ$ orientation.

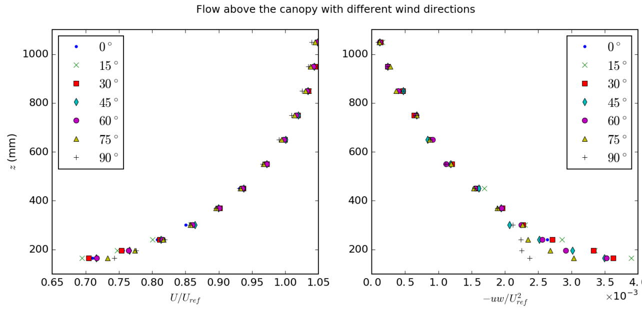

Figure 2. Spanwise averaged profiles of velocity and vertical momentum fluxes above the canopy (normalised using the free-stream velocity) with different wind directions.

mm and a length of 1.57 mm. Measurements in the local U ? W plane within the street network (i.e. in planes aligned with the streets) were obtained by use of a small mirror set at 45° beneath a downward pointing probe. The flow was seeded with micron sized sugar particles at a sufficient level to attain data rates around 150 Hz. In general, data collection times were 2.5 min, selected to control the standard error in the results. This led to a typical standard error in U of 2%, in u^2 of 10% and in w^2 of 5%, and corresponds to an averaging time of about $200T$, where T is defined as an eddy turnover time, $T = h/u_\tau$. Our confidence is based on use of this LDA system over a long period of time, with a range or orientations and geometries (with or without the mirror system). There were many instances of the same variables being measured in different ways, without (for example) probe blockage problems becoming apparent. However, a potential source of significant error in the measurements was due to positioning uncertainty relative to the local buildings and tunnel co-ordinates. For example, an orientation error of 0.1° in the array alignment to the wind-tunnel axis would result in a positioning error of about 2.5 mm relative to the buildings over a 1.5 m lateral traverse (i.e. in the y-direction), assuming the traverse itself to be perfectly aligned with the tunnel co-ordinates. There are inevitable imperfections in any wind tunnel and traverse installation and these had particular significance in this case because of the large volume over which results were required. In broad terms, the positional error in any horizontal plane was typically 2 mm. The implications obviously depend on the gradients of flow properties at any given location and resulting uncertainties were greatest in the thin shear layers downstream of the block surfaces (i.e. the side-walls and roof). The consequence of small errors in height relative to the local building roof level were obvious in initial experiments. This particular issue was resolved by use of a small ultrasonic height gauge attached to the traversing arm – in this way local height uncertainties (i.e. relative to the adjacent block) were reduced to about ±0.5 mm. The results presented here were obtained with this device in use.

Further practical issues directly affecting the flow were the accuracy of rotation of the array and its alignment relative to the approach flow. The 0° orientation proved by far the most demanding in these respects as any, albeit small, departure from the ideal set-up generated a small cross-flow in the street network. Dispersion measurements would then show a plume axis that drifted to one side, as indeed was observed in preliminary experiments that became the motivation for technique and hardware improvements. Ultimately, these resulted in plume-axis drift that was less than 1°; it is hard to see that anything substantially better can be achieved. Finally, it is worth noting that the 45° array orientation case was far less sensitive to these matters, or rather that any consequent effects were far less obvious.

Velocity and turbulence measurements were made using a two-component laser Doppler anemometer (LDA). All three components of velocity were measured in different experiments. Measurements in the local U-W plane within the street network (i.e. in planes aligned with the streets) were obtained by use of a small mirror set at 45° beneath a downward pointing probe. In general, data collection times were 2.5 minutes, selected to control the standard error in the results. Tracer concentration measurements were performed by tracing small amounts of propane released at point sources within the building array, measured by using a fast flame ionisation detector (FFID). The averaging time was similar to the velocity measurements, and the two techniques were often combined to obtain simultaneous measurements of velocity and concentration, thus being able to calculate turbulent mass fluxes.

FLOW AND CONCENTRATION MEASUREMENTS

The major focus within the DIPLOS project is the canopy region itself (i.e. flow, turbulence and dispersion in and just above the $z \leq h$ region) but it is of interest first to consider the flows above the canopy and for various wind directions. Spanwise averaged profiles are presented in Figure 2.

Some selected results from the preliminary velocity and concentration measurements within and above the canopy are presented in figures 3 to 9. The preliminary dataset included several vertical profiles within the urban array (heigths spanning from $0.45h$ to $3.5h$) with measurements of two velocity components (U, V), concentrations (C) and correlated quantities (uv, uc and vc), and a horizontal mapping in two layers at $z = 0.5h$ (U, V, C and correlated quantities) and $z = 1.5h$ (concentrations only) for three wind directions (0, 45 and 90°). The tracer was released from a single source behind a building close to the centre line.

The final data set include measurements for all three velocity (and turbulence) components as well as tracer concentrations and both mean and turbulent mass fluxes measured over the array in three wind directions (0, 15 and 45°). Measurements were repeated for three different source locations (within an intersection, in the short street and in the long street) and the measurement grid included both a coarse plume mapping over the entire array and two high resolution grids in selected "modules", one close to the source and the other in the far field.

Other experiments included short duration releases ("puffs") and dual FFID configurations to measure two-point correlations in the urban array. Some results and analysis from this final dataset will be presented at the conference.

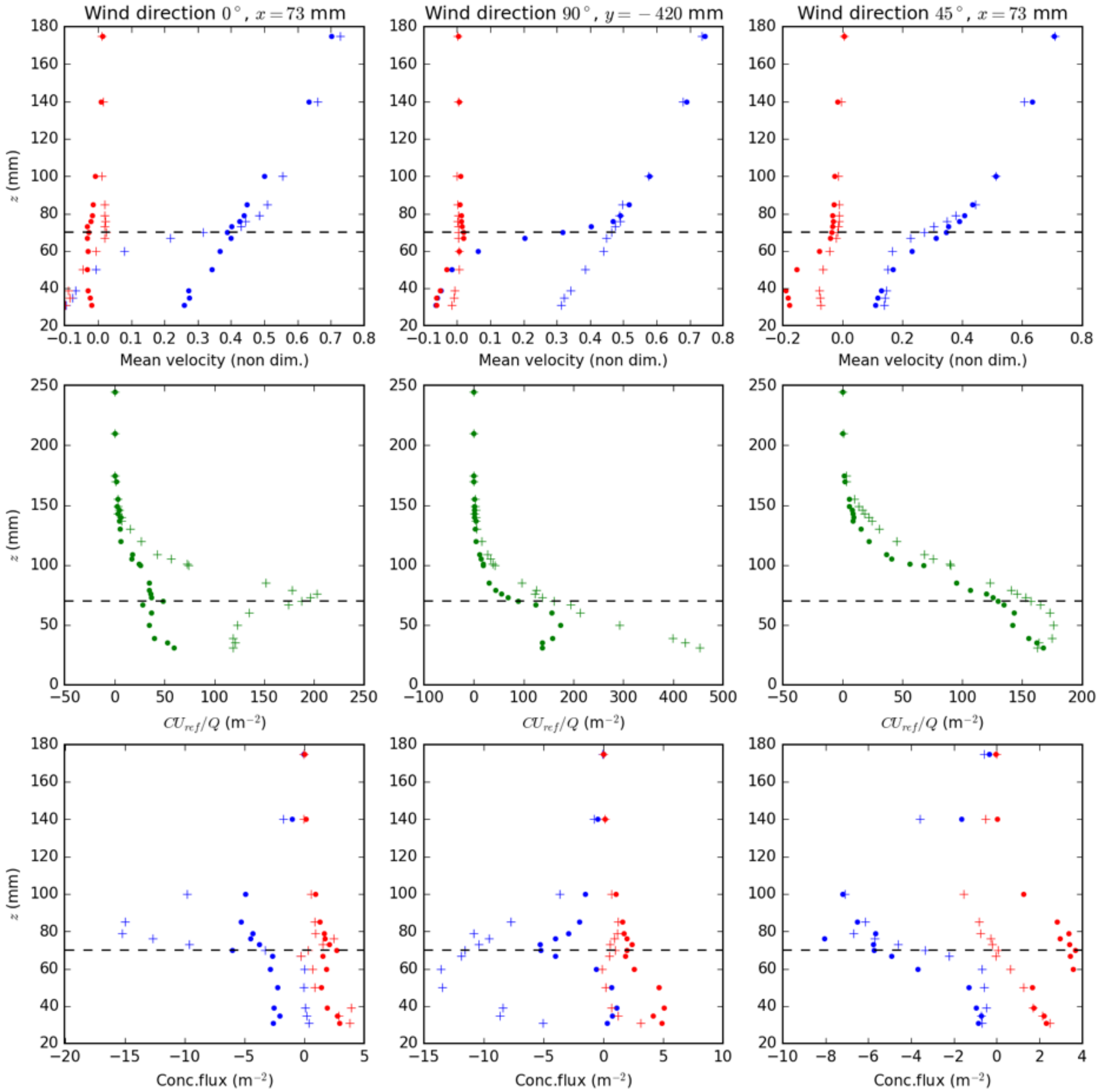

Figure 3. Selected velocity, concentration and concentration flux profiles. Blue = U/U_{ref} and uc/Q; red = V/U_{ref} and vc/Q; '+' represent profiles at $y = 0$ (0°), $x = 3$ mm (90°), $y = -315$ mm (45°); '.' represents profiles at $y = -105$ mm (0°), $x = -67$ mm (90°), $y = -420$ mm (45°)

EFFECT OF ISOLATED TALL BUILDINGS

In modern cities one can often find buildings which surmount the surrounding canopy. These tall buildings can be isolated or form a group, typically in modern city centres. Heist *et al.* (2009) examined experimentally and numerically the flow around an isolated building in a regular neighbourhood of buildings forming streets and closed courtyards. They noted large velocities in the spanwise direction which were caused by the presence of the tall building and vertical velocities downwind of the tall building reaching 25% of the freestream wind velocity. Brixey *et al.* (2009) used the same building configuration as Heist *et al.* (2009) for wind-tunnel and numerical simulations of scalar dispersion from line sources. They found that the vertical dispersion and the vertical extent of the plume in the wake of the tall building is greatly enhanced. The spanwise flow towards the tower also increased the width of plumes from sources further away from the tall building laterally.

Preliminary experiments included flow visualisations and velocity measurements on a modified array, were one of the building was made taller ($2h$ or $3h$), as shown in figure 10. These experiments have been carried out for the 0° wind direction and some results are presented in figures 11 and 12.

CONCLUSION AND FUTURE WORK

Wind tunnel measurements of flow and concentrations in an urban-like array were performed in the framework of the DIPLOS project. Preliminary results are available for different wind directions, within and above the regular building canopy. The experimental database includes three components of mean velocity and turbulence, as well as concentrations, concentration fluctuations and concentration fluxes.

The extensive array and the small scale of the model posed challenging problems for reaching the desired high accuracy needed

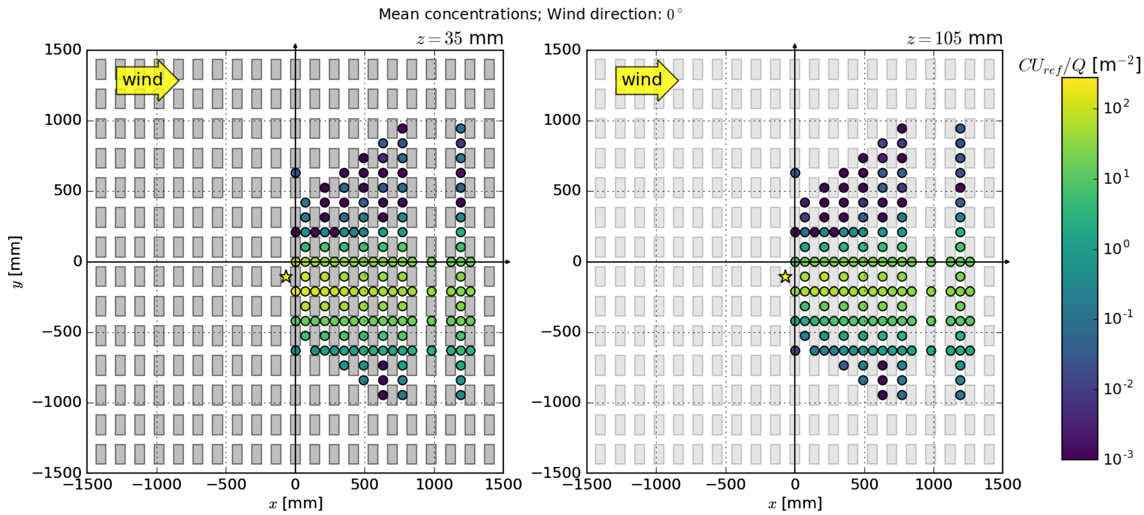

Figure 4. Non dimensional concentrations within (left) and above (right) the canopy for the 0° case.

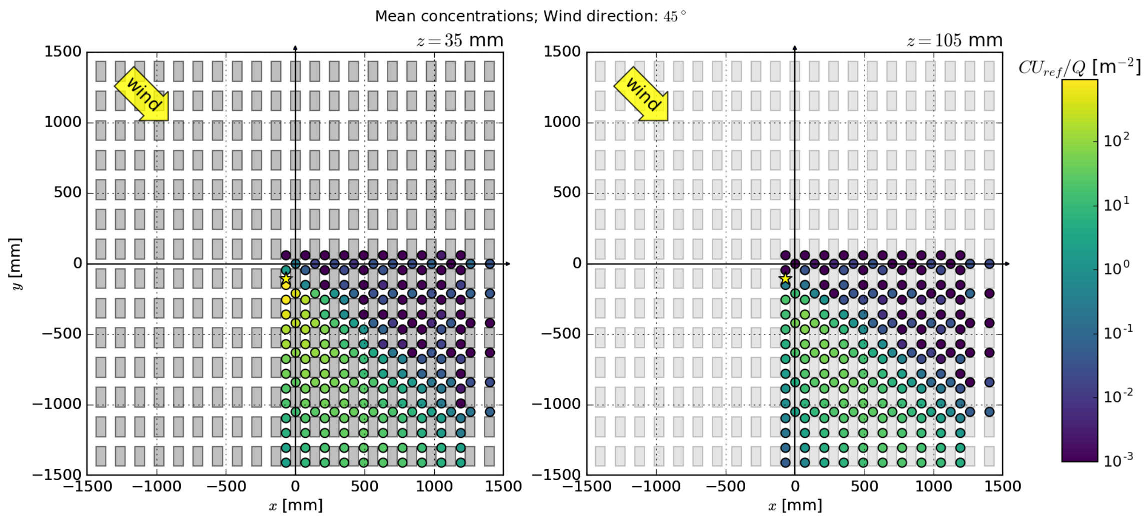

Figure 5. Non dimensional concentrations within (left) and above (right) the canopy for the 45° case.

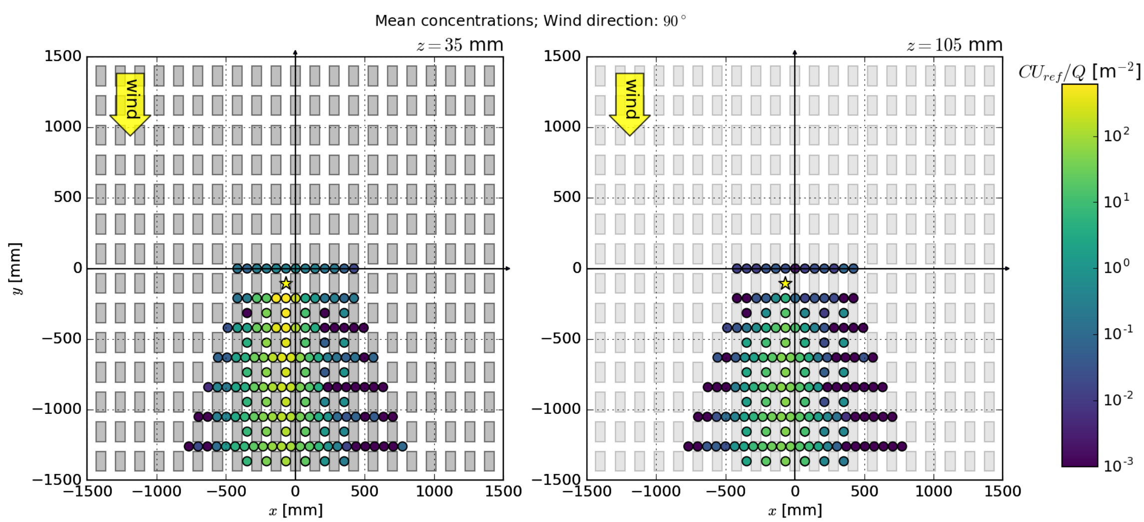

Figure 6. Non dimensional concentrations within (left) and above (right) the canopy for the 90° case.

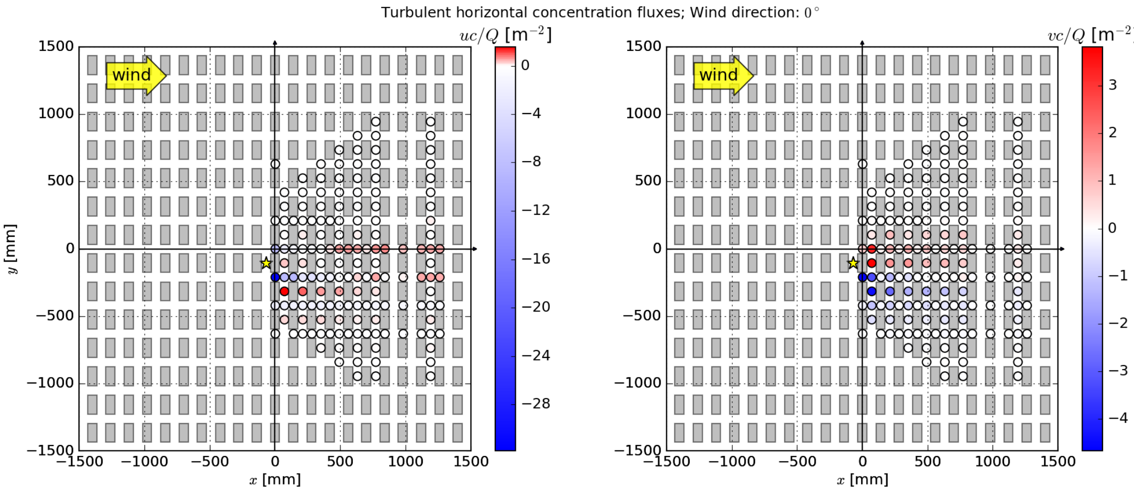

Figure 7. Horizontal turbulent mass fluxes within the canopy for the 0° case.

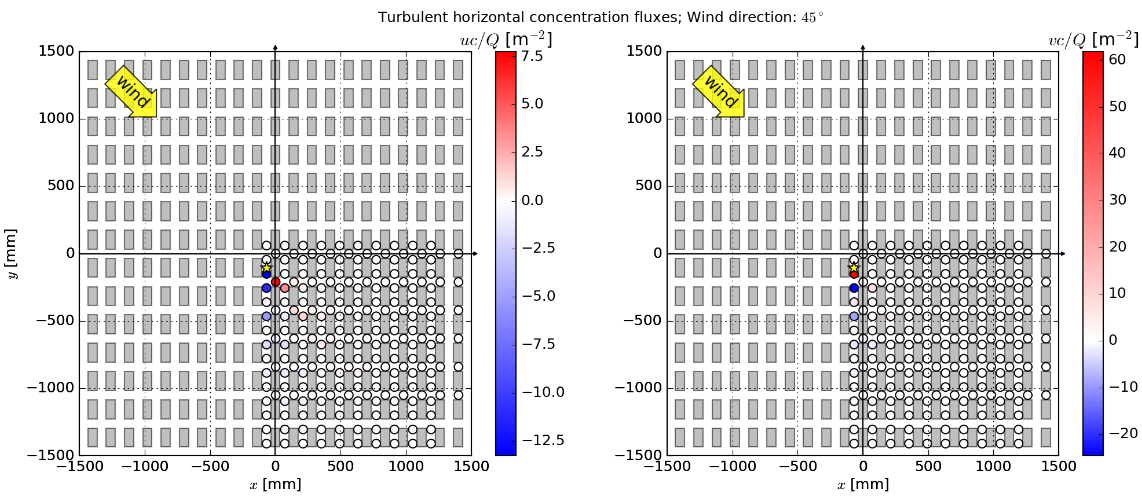

Figure 8. Horizontal turbulent mass fluxes within the canopy for the 45° case.

to validate the numerical simulations. The improvements in the methodology will be presented and discussed at the conference.

The wind tunnel data, along with LES and DNS simulations, are being used to understand the behaviour of flow and dispersion within regular array with a more realistic geometry than the usual cuboids (Castro *et al.*, 2017). This integrated methodology will help developing parametrisations for improved street network dispersion models.

When a tall building is placed into the regular array the flow changes significantly. Larger vertical velocities allow significant advective vertical scalar fluxes. Scalar from ground level sources in front of the tall building is transported mainly sideways around the building.

A higher spatial resolution data set has been produced both for the regular array and the "tall building" scenario. The wind directions tested are 0°, 15° and 45°. Vertical concentration fluxes are also available in the final data set. Some selected results will be presented ad the conference.

ACKNOWLEDGEMENTS

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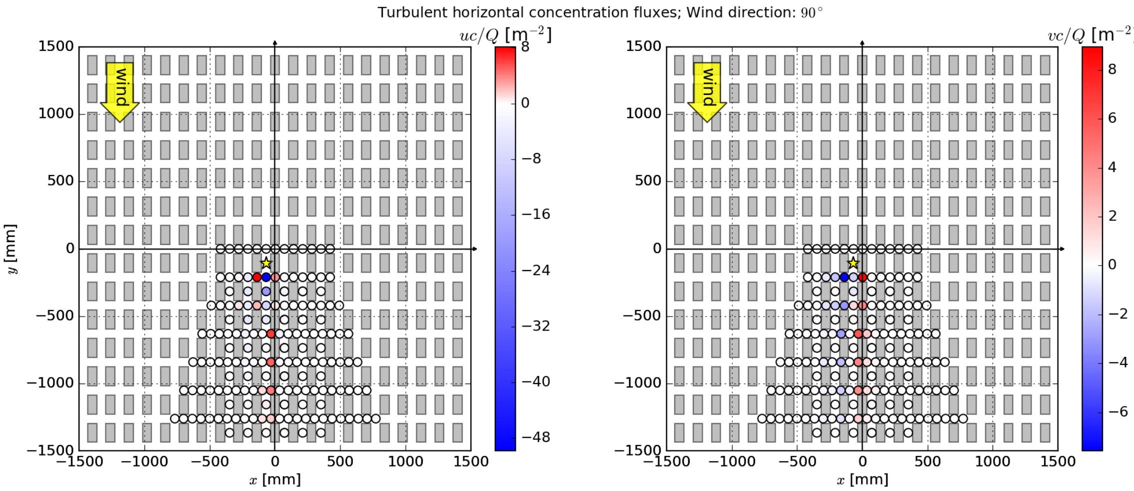

Figure 9. Horizontal turbulent mass fluxes within the canopy for the 90° case.

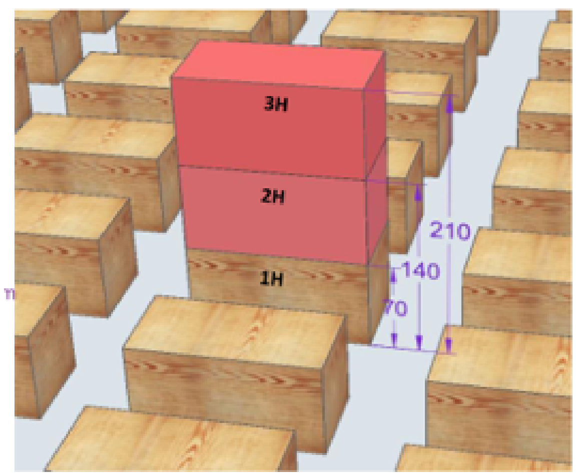

Figure 10. Rendering of the "tall building".

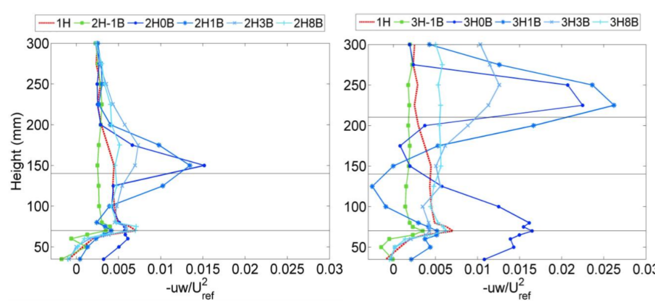

Figure 12. Selected Reynolds stress profiles at various distances downwind (0B = street below tall building, 1B = 1 street downwind 0B, and so on).

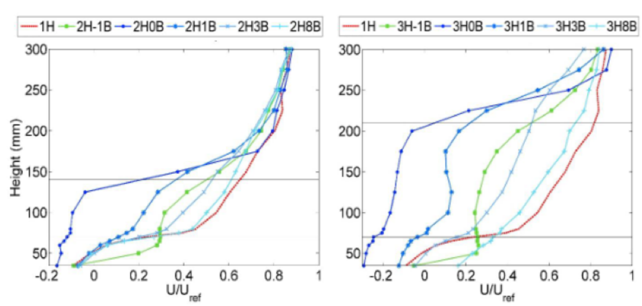

Figure 11. Selected vertical velocity profiles at various distances downwind (0B = street below tall building, 1B = 1 street downwind 0B, and so on).