August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Wind tunnel experiment on footprints of a block-arrayed urban canopy model in the neutrally stratified boundary layer

Hongyuan Jia [1], Chao Lin [1], Hideki Kikumoto [1]

[1] *The University of Tokyo, Tokyo, Japan, jhy@iis.u-tokyo.ac.jp*

SUMMARY:
Sensors are widely used to monitor the physical quantities in the atmospheric boundary layer. Accurate footprint modeling of sensors is important to analyze the measurement data in the urban area. This study conducted the wind tunnel experiment to measure the footprints of a block-arrayed urban canopy model in the neutrally stratified boundary layer. The tracer concentration and flow velocity were simultaneously measured to evaluate the footprints of concentration and its vertical flux for four different horizontal positions around a block and two different heights above blocks. According to the result, the horizontal distributions of footprints change with different measurement positions due to the heterogenous flow field caused by the urban canopy, and the main features can be divided into two patterns for the sensors along the building and the open street. Meanwhile, the shape and extension area are dependent on the measurement height. Besides, the concentration footprints have larger influential areas than the flux footprints because the scalars which are horizontally transported to the sensor do not contribute to the vertical flux. This experimental database can be used to validate the numerical modeling approaches for footprint and gain insights about the footprint features in the urban area.

Keywords: footprint, wind tunnel experiment, urban canopy

1. INTRODCUTION

The development of sensing technologies has enabled us to monitor the flow velocity, atmospheric pollutants dispersions, and energy transportation in the atmospheric boundary layer. However, because the measurement is the integrated product of all potential sources in the upwind area, it is important to interpret these big data by the footprint function for the precise management of the sources.

The footprint function describes the response of a sensor to each elemental surface source area in upstream (Schmid 2002). It has been widely used in the analysis of measurements (Sugawara et al. 2021), source distribution estimation (Lauvaux et al. 2016), and sensing strategy design (Levin et al. 2020). Even though in the early stage, the footprint was mostly used in agriculture and forestry, where the terrain is mainly the homogenous surface, in recent years, the growing interest can be observed in the urban area where the footprint is highly affected by the inhomogeneous terrain and complex turbulent flow (Vesala et al. 2008). Researchers have proposed different modeling approaches based on complicated computational fluid dynamics techniques to accurately estimate the footprint in the built area (Hellsten et al. 2015). However, these methods have not been comprehensively validated due to the lack of experimental database for the urban canopy model, especially that the flux footprint requires simultaneous measurements of flow velocity and concentration during the experiment.

In this research, a wind tunnel experiment was conducted to measure the concentration and vertical flux footprint function for a block-arrayed urban canopy model in the neutrally stratified boundary layer. The objective is to build a validation database for the numerical modeling approaches and elucidate the features of footprints in the urban canopy.

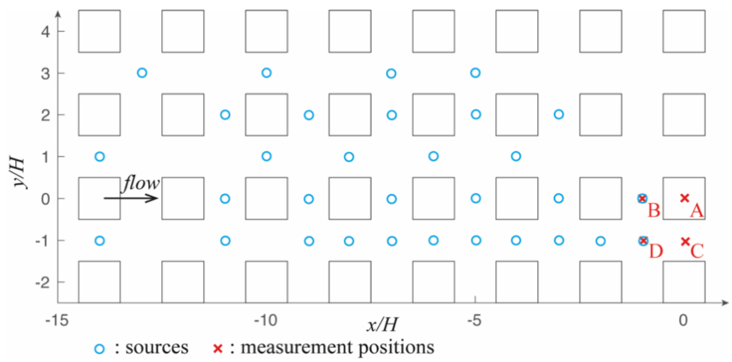

Figure 1. Schematic of the urban canopy model, sources and measurement positions.

2. EXPERIMENTAL METHOD

Experiments were conducted in a boundary layer wind tunnel at the Institute of Industrial Science, the University of Tokyo. Its test section is $1.8m(height) \times 2.2m(width) \times 16.47m(length)$. The atmospheric boundary layer was generated by spires and roughness cubes in the upstream to ensure the mean streamwise velocity of the inflow follows the power law with the exponent of 0.24. The urban canopy model was formed by 11 rows × 9 columns cubes with the edge of $H = 0.06m$. The reference velocity U_r at the reference height $H_r = 2H$ is 1.33 m/s. The Reynolds number based on U_r and H_r is about 1.3×10^4.

The footprints were measured for four positions: above the roof (A), wake region (B), the road between buildings (C), and cross-section (D) as shown in Fig. 1, and two measurement heights for each position $z_m = 1.25H, 1.5H$. The source is designed to be a movable bronze tube with an upward circular opening with the diameter $d = 1\,mm$ because the footprint describes the response of a fixed sensor to different sources. The source was tightly taped on the floor at different positions as shown in Fig. 1. The pure ethylene (C_2H_4) was used as the tracer gas with the emission strength of $q_s = 1 \times 10^{-6} m^3/s$.

The vertical flow velocity was measured by a constant temperature anemometer with a split-fiber probe (55R55, Dantec), and the concentration was measured by a fast flame ionization detector (FID). 9×10^4 sampling data (90 s) was recorded with 1000 Hz at each measurement point. The probe and FID were placed close to each other (< 5 mm) to realize the simultaneous measurements. In the flux calculation, the response time lag between the FID and the probe is determined to be 0.05 s based on the correlation analysis of time series data.

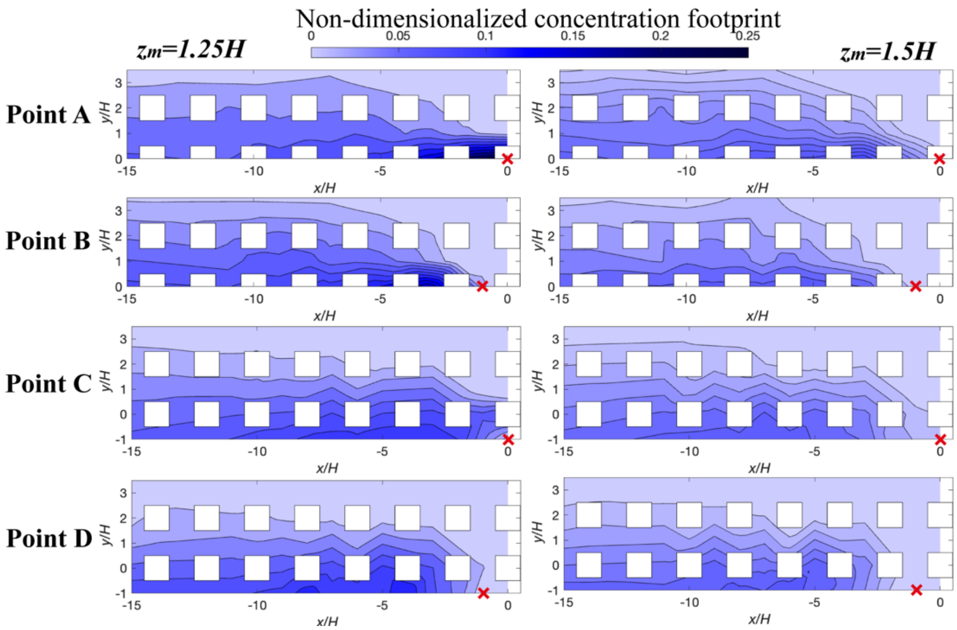

Figure 2. The concentration footprints for four measurement positions. (Left: $z_m = 1.25H$; Right: $z_m = 1.5H$)

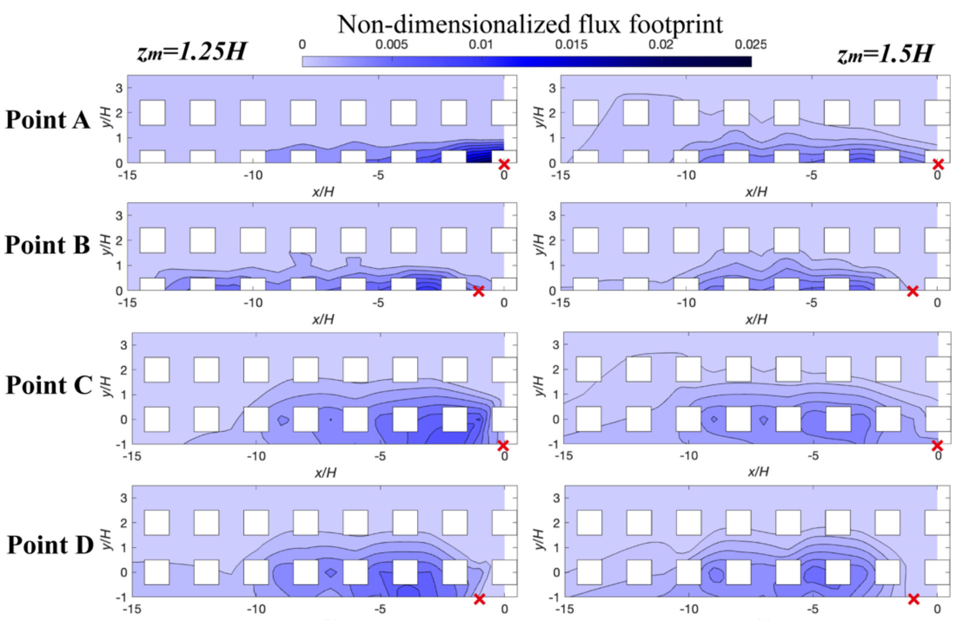

Figure 3. The flux footprints for four measurement positions. (Left: $z_m = 1.25H$; Right: $z_m = 1.5H$)

3. RESULTS AND DISCUSSIONS

The footprint function is defined by $\eta = \int_x f(\boldsymbol{x}_\mathrm{m}|\boldsymbol{x}_\mathrm{s})q_s(\boldsymbol{x}_\mathrm{s})d\boldsymbol{x}$. Here, $\boldsymbol{x}_\mathrm{s}$ and $\boldsymbol{x}_\mathrm{m}$ are the coordinates of the source and the target sensor, q_s is the source strength. $f(\boldsymbol{x}_\mathrm{m}|\boldsymbol{x}_\mathrm{s})$ denotes the footprint value between them. η is the measurement quantity. For a small emission opening in the current research, the time-averaged concentration and flux footprint values were estimated and nondimensionalized based on $f_c(\boldsymbol{x}_\mathrm{m}|\boldsymbol{x}_\mathrm{s}) = \eta_c(\boldsymbol{x}_\mathrm{m})U_r H^2/(C_{gas}q_s(\boldsymbol{x}_\mathrm{s}))$ and $f_f(\boldsymbol{x}_\mathrm{m}|\boldsymbol{x}_\mathrm{s}) =$

$\eta_f(\boldsymbol{x}_\mathrm{m})H^2/(C_{gas}q_s(\boldsymbol{x}_s))$ respectively. C_{gas} is the gas concentration in the injected flow of the source.

Fig. 2 shows the distribution of concentration footprints for four measurement positions, which can be roughly divided into two patterns. For $z_m = 1.25H$ at Point A and B, the footprint concentrates on the central row of cubes and disperse into the adjacent open streets. The peaks are located at the first wake region in the upstream. In contrast, the footprints of Point C and D mainly distribute at the central open street. The peaks are about $3H$ upstream of the sensors. Besides, for all four points, with the increasing of measurement height, the footprints have flatter slopes and wider extension, where smaller peak values and larger distance between the peak and the sensor can be confirmed.

Fig. 3 summarizes the vertical flux footprints of four points. Same as the concentration footprints, the flux footprints can also be divided into two patterns, which indicates the heterogeneous features caused by different measurement positions in the urban area. Moreover, the flux footprints also become flatter when z_m is higher. However, the flux footprints have smaller influential sizes than the concentration footprints. It demonstrates that the concentration from far sources was transported to the sensor in the horizontal plane so it will not contribute to the vertical flux. The footprints of Point A and B only gather around the central row of cubes, while the footprints of Point C and D are wider in the spanwise direction. All the footprint values are positive because the sensors are above the roof, and the tracers released from the bottom surface move upwards from the canopy vortex and reach the sensor.

4. CONCLUSIONS

This research measured the concentration and flux footprints of four positions in a block-arrayed urban canopy model at the neutrally stratified boundary layer wind tunnel experiment. According to the results, the footprints in the urban area demonstrate heterogenous features at different the measurement positions. The distributions are also affected by the measurement height. The concentration footprint has larger response area than the flux footprint. This database can be used to validate the numerical modeling approaches. Other measurement heights and more complicated canopy configurations will be considered in the future research.

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