

LDA-FFID coupled measurements of two-height canopy flow in a wind tunnel

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ABSTRACT

Turbulent scalar exchange between plant canopies and the atmosphere is a critical yet difficult-to-model process. In this study, wind-tunnel experiments were conducted under neutrally stable conditions in an environmental wind tunnel to investigate the vertical transport of a passive scalar released from a localized point source at the top of a two-height canopy. This configuration generates complex flow interfaces distinct from classical elevated sources in turbulent boundary layers. Simultaneous profiles of velocity and scalar concentration were measured using a two-component Laser Doppler Anemometer (LDA) and a Fast Flame Ionization Detector (FFID), respectively. These measurements provide rare, highly valuable experimental data that are crucial for understanding the transport dynamics between the free atmosphere and the canopy. To address the velocity bias inherent to non-uniformly sampled, LDA-triggered measurements, a synchronized acquisition and data processing approach was developed. By applying transit-time weighting, the sampling bias in concentration moments and velocity-scalar correlations was mitigated, reducing discrepancies relative to continuous sampling to less than 3%. Furthermore, an arrival-time quantization method was successfully implemented and validated against uniformly sampled signals, enabling reliable autocorrelation and integral time-scale estimates for spectral analysis. Ultimately, these corrected techniques permit a more physically accurate representation of the S-shaped vertical flux profiles and scalar dispersion behavior unique to the roughness sublayer.

1. Introduction

The exchange of scalars between complex terrain, such as vegetation canopies or urban areas, and the atmosphere is a critical environmental process. It governs a wide range of applications, including biosphere-atmosphere exchange, forest fires, and the spread of pollution. Effective modeling of these scenarios relies on a fundamental understanding of the turbulent transport mechanisms within the region immediately above the canopy, known as the roughness sublayer (RSL). The RSL is characterized by distinct features that differ from a classic boundary layer. It is better represented by a mixing-layer analogy and is defined by the dominance of downward-moving sweep events over upward-moving ejection events in transporting momentum (Raupach et al., 1996). Above the RSL lies the inertial sublayer (ISL), where the influence of individual roughness elements fades, and the flow returns to a classic boundary layer structure that obeys the typical logarithmic velocity profile (Finnigan, 2000).

Understanding scalar transport within canopies and, in particular, the associated turbulent fluxes is essential for linking spatially distributed sources and sinks to atmospheric observations. This work examines the dispersion of a scalar from a point source in horizontally homogeneous two-height (TH) canopies, which represent height-heterogeneous landscapes and generate complex flow interfaces. The study continues our previous work (Shig et al., 2023b) in which the TH canopy-flow has been studied based on detailed PIV measurements.

Simultaneous velocity and scalar measurements in wind tunnels are commonly performed using optical or point-based techniques. Optical approaches typically combine Particle Image Velocimetry (PIV) with Planar Laser-Induced Fluorescence (PLIF), enabling spatially resolved measurements of velocity and concentration fields (Webster et al., 2001). Point-based systems generally couple Constant Temperature Anemometry (Fackrell & Robins, 1982) or Laser Doppler Anemometry (LDA) (Marro et al., 2020) with Fast Flame Ionization Detectors (FFID) to obtain simultaneous velocity and tracer-gas concentration measurements, while hot-wire/cold-wire combinations are used for concurrent velocity and temperature measurements (Marucci & Carpentieri, 2019). Despite their capabilities, these techniques present significant challenges. PIV-PLIF measurements are affected by optical alignment, laser-sheet non-uniformity, fluorescence-scattering cross-talk, and calibration uncertainties, whereas CTA-FFID and LDA-FFID systems are limited by probe interference, spatial separation between sampling volumes, synchronization requirements, frequency-response mismatches, and tracer-gas transport delays. These factors can introduce uncertainties in the estimation of turbulent scalar fluxes and velocity-scalar correlations.

Simultaneous LDA-FFID measurements were conducted in a physical model of a canopy boundary layer in a large environmental wind tunnel. A dedicated methodology for synchronized data acquisition and processing was developed, and challenges related to measurement-volume separation, signal synchronization, and statistical analysis are discussed. While a comprehensive investigation of velocity-concentration statistics is beyond the scope of this study, selected results are presented to demonstrate the applicability of the method and its main findings.

2. Experimental methods and data acquisition

The experiments were conducted in the environmental wind tunnel at the Israel Institute for Biological Research (IIBR). The working section is 15-m long with a uniform cross-section of $2 \times 2 \text{ m}^2$. The canopy model was placed on the floor of the working section, spanning an area of $\sim 11 \times 2 \text{ m}^2$, as schematically shown in Fig. 1. The canopy consists of vertical thin metal plates of two heights, 100 mm and 50 mm, with a width of 50 mm, arranged in equal amounts. Each spanwise row of elements consists of either tall or short elements in a staggered arrangement, resulting in an alternating tall-short pattern along the main flow direction (Fig. 1b). We denote x , y , and z as the streamwise, spanwise, and floor-normal coordinates (Fig. 1a). The origin of the axis is in correspondence with the location of the source outlet (Fig. 1b). For the present study, the free-stream velocity was set to $U_e = 9.5 \text{ m s}^{-1}$, resulting in a bulk Reynolds number of $Re = 5.3 \times 10^5$. Here, the bulk Reynolds number is defined as $Re = \delta U_e / \nu$, where δ is the boundary-layer thickness at the measurement location and $\nu = 1.5 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ is the kinematic viscosity of air. The boundary-layer thickness, δ , is defined as the height at which a fitted power-law velocity profile reaches U_e . The streamwise pressure gradient within the test section is negligible under these flow conditions.

Additional boundary-layer parameters are summarized in Table 1.

Table 1. Flow properties and canopy parameters for the experimental boundary layer setup.

Parameter	Value
Free-stream velocity, U_e	9.5 m/s
Boundary-layer height, δ/h	8.5
Bulk Reynolds number, Re_δ	5.3×10^5
Canopy height, h	$h = 0.1$ m (tall), $h/2 = 0.05$ m (short)
Frontal area index, λ	0.5
Friction velocity, u_*	1.01 m/s
Roughness Reynolds number, $Re_* = \frac{u_* h}{\nu}$	6.7×10^3
u_*/u_h	0.47

Simultaneous measurements of streamwise (u) and vertical (w) velocity components, and concentration c , were performed using a 2-component Laser Doppler Anemometer (LDA FiberFlow System, Dantec Dynamics, Denmark) and a Fast Flame Ionization Detector (FFID, Cambustion HFR400, UK), respectively. The flow was seeded with glycerin-based aerosol droplets (particle size of about $0.3\mu\text{m}$). Uniform seeding ensured high data acquisition rates, averaging approximately 250 Hz within the canopy ($z/h < 1$) and up to 600 Hz above it ($z/h > 1$). This spatial variation in data rate is characteristic of the LDA's burst-mode operation, which depends on local particle concentration and velocity (Velte et al., 2014).

The friction velocity, u_* , was estimated as the square root of the mean Reynolds shear stress evaluated at the canopy height (Shig et al., 2023a). Additionally, the flow is characterized by the ratio u_*/u_h (where u_h is the mean velocity at the canopy top), which serves as a measure of canopy turbulence. Both velocity scales were derived from the spatially averaged LDA profiles.

The passive scalar (pure ethane, C_2H_6) was continuously released from an L-shaped tube located $90h$ downstream from the beginning of the canopy and at a height of $h_s \approx 0.95h$. As shown in Fig. 1, the source is centered between two high elements, placing it at the canopy top, near the region of maximum shear (Shig et al., 2023a). The smoke visualization of the source is presented in Fig. 2.

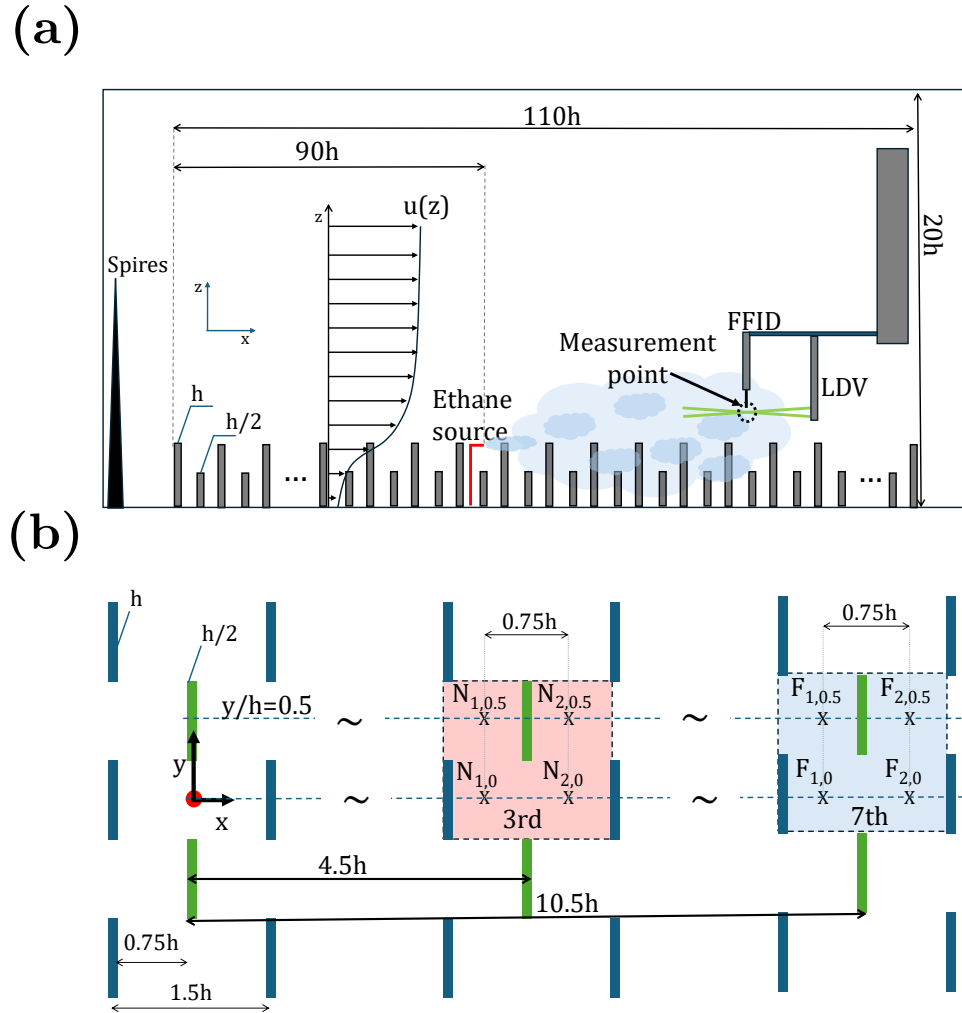


Figure 1. Schematics of the experimental setup shown in side and top views: (a) Cross-section of the tunnel working section. (b) Top view showing the layout of roughness elements forming the canopy. The red and blue shaded rectangles represent two unit-cells, referred to as the "near-cell" and "far-cell," respectively, where measurements were conducted. Crosses noted by either N or F indicate specific measurement locations. The red line in (a) and the red point in (b) mark the position of the ethane source. The canopy height is $h = 100$ mm.



Figure 2. Snapshots from the smoke visualization of the pollution source at the top of the canopy

The calibration procedure for the FFID system was developed and validated in the wind tunnel environment. The calibration is based on sampling certified calibration gases and measuring the background concentration. Concentration was measured in parts-per-million ppm (molar fraction) and then normalized by a reference concentration indicating the source strength:

$$c_s = \frac{\dot{m}_s}{h^2 u_h}, \quad (1)$$

where $\dot{m}_s$ is the source flow rate and u_h is the mean velocity at the canopy top ($z/h = 1$).

The LDA and FFID probes were mounted on a 3D traverse system, positioning the 0.25 mm FFID sampling tube in close proximity to the LDA measurement volume (Fig. 3), following the guidelines established by Marro et al. (2020). Vertical profiles of simultaneous velocity and concentration data were acquired at multiple locations near and far from the ethane source. To accurately capture the correlation statistics between the flow and the scalar, the data acquisition system was triggered by the LDA. Consequently, velocity and concentration signals were recorded simultaneously only when the seed particles passed through the LDA measurement volume.

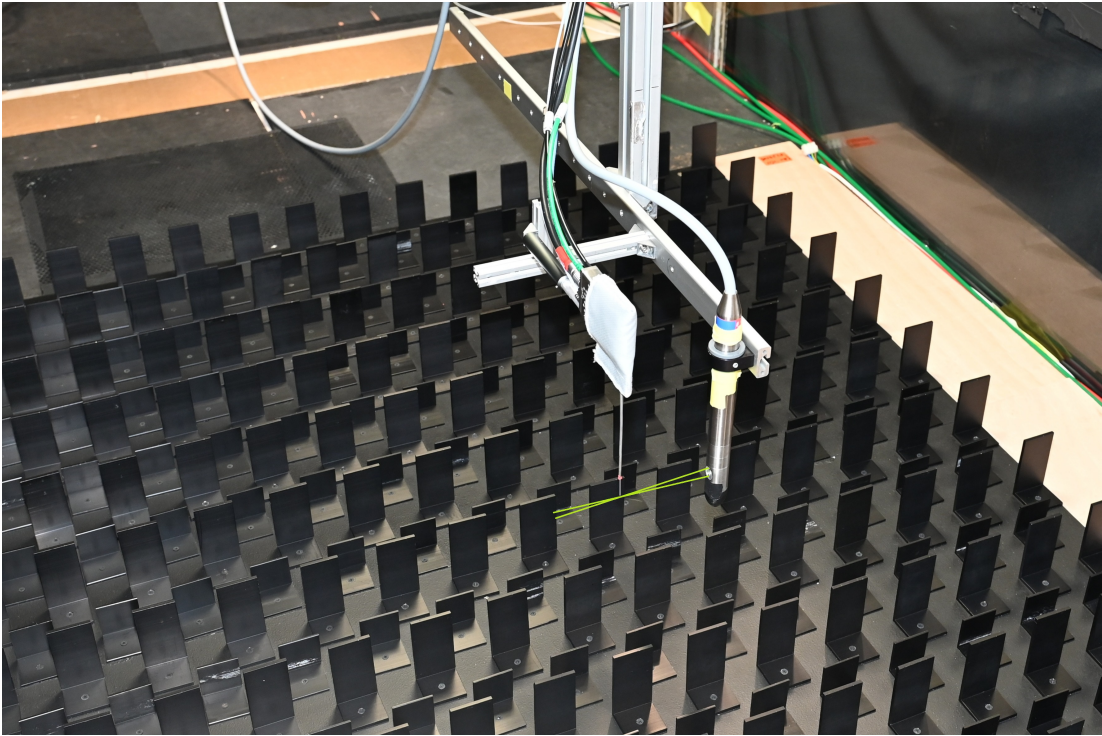


Figure 3. LDA-FFID probes configuration over the canopy model

Because of this particle-dependent triggering mechanism, concentration sampling is irregularly spaced in time and is inherently subject to the same velocity bias as the LDA, statistically favoring faster-moving particles. To compensate for this bias when calculating mean properties, each realization was weighted by its transit time within the LDA sampling volume. Following George & Lumley (1973), the time-averaged value of any measured quantity, moment or correlation, ϕ , is calculated as:

$$\bar{\phi} = \frac{\sum_{i=0}^N \phi_i \Delta t_{r,i}}{\sum_{i=0}^N \Delta t_{r,i}} \quad (2)$$

where ϕ_i is the instantaneous value of the measured quantity for the i -th particle, and $\Delta t_{r,i}$ is its corresponding transit time through the measurement volume.

To evaluate and validate this weighting function, the analog FFID concentration signal was split: it was discretely sampled via the LDA trigger and, simultaneously, recorded by an independent data acquisition system at a constant rate of 500 Hz. Figure 4 presents an example of the resulting time series for these normalized measurements. A comparison between the continuous 500 Hz trace and the LDA-triggered discrete concentration measurements clearly visualizes the velocity bias introduced by the intermittent sampling, confirming the necessity of the transit-time correction. This relative statistical weighting is shown by the gray vertical bars in Fig. 4d.

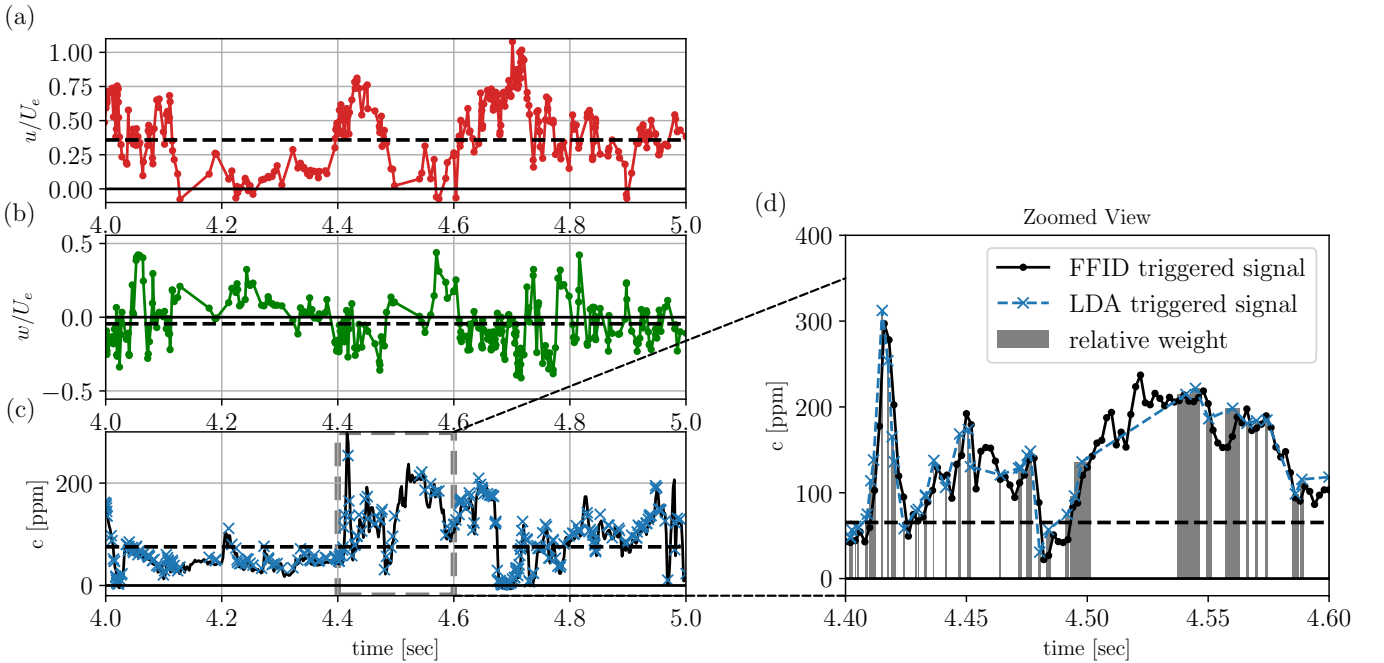


Figure 4. Simultaneous time series of normalized velocity and concentration measurements. (a) Streamwise velocity normalized by the free-stream velocity (u/U_e). (b) Vertical velocity normalized by the free-stream velocity (w/U_e). (c) Concentration showing the continuous FFID triggered signal (solid black line) overlaid with the discretely sampled LDA triggered signal (blue markers). The dashed gray rectangle indicates the region of interest expanded in panel (d). (d) Detailed, zoomed-in view of the concentration signal between $t = 4.4$ and 4.6 s. The continuous FFID triggered signal is represented by the solid black line, while the blue crosses indicate the concentration values captured synchronously with the discrete LDA particle arrivals. Gray vertical bars illustrate the relative statistical weight of each LDA sample, proportional to its respective transit time. Horizontal dashed lines denote the temporal mean values for each corresponding signal.

The acquisition time was set to $T_s = 300$ seconds for each measurement point, ensuring sufficient statistical convergence for all measured quantities. Due to the length (200 mm) of the FFID sample tube, there is a small time delay between the sample taken and the gas analysis after traveling through the sampling tube. Therefore, similar to the work of Marro et al. (2020), a time correction was applied. The corresponding time-shift value was calculated based on the device's actual operating conditions.

The mean delay in the physical sampling time relative to that of LDA was 15.6 milliseconds. Hence, all concentration signals are accordingly shifted and interpolated in time for analysis.

Measurements were taken at several locations marked by crosses in Fig. 1b within two distinct unit cells. These consisted of a near-cell (N) located $4.5h$ downstream of the source and a far-cell (F) at $10.5h$ downstream. Within each cell, four vertical profiles of simultaneous velocity-concentration data were acquired at specific locations: upstream and downstream of a tall element ($y/h = 0$), and upstream and downstream of a short element ($y/h = 0.5$). These locations are represented by the notation $N_{i,j}$ and $F_{i,j}$, where $i(\in 1, 2)$ denotes the streamwise position within the unit cell, and $j(\in 0.5, 1)$ the position along the spanwise direction (crosses in the red and blue shaded squares in Fig. 1b).

3. Results

Direct measurements of turbulent scalar fluxes are crucial for understanding the physical mechanisms that govern turbulent scalar dispersion. The simultaneous LDA-FFID measurement technique provides valuable experimental data for which very limited prior measurements are available. The transport of a passive scalar, for instance, concentration, c , in turbulent flow is governed by the advection-diffusion equation. The Reynolds-averaged advection-diffusion equation for the mean scalar concentration takes form:

$$\frac{\partial \bar{c}}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \bar{c} = D \nabla^2 \bar{c} - \nabla \cdot \overline{\mathbf{u}'c'} \quad (3)$$

The last term, $-\nabla \cdot \overline{\mathbf{u}'c'}$, represents the turbulent flux of the scalar and governs its vertical and spanwise dispersion (Stull, 2012).

The detailed turbulence statistics and flow structure for this specific canopy geometry were comprehensively analyzed in our previous work using PIV (Shig et al., 2023a). Spatially averaged statistics demonstrated that the flow exhibits canonical canopy turbulence characteristics similar to uniform-height canopy benchmarks (Harman et al., 2016; Nezu & Sanjou, 2008). The flow at the measurement region was found to be fully developed, supported by an excellent agreement of velocity statistics between the near (N) and far (F) canopy unit cells.

We first evaluate whether the transit-time weighting scheme effectively corrects the concentration bias introduced by the non-uniform LDA triggered sampling. This is achieved by comparing the weighted and unweighted LDA-triggered signals against the uniformly sampled continuous concentration signal. Figure 5 presents the vertical profiles of the mean concentration along the symmetry plane ($y/h = 0$), calculated using the uniformly sampled signal, the transit-time weighted LDA triggered signal, and the unweighted LDA triggered signal. The results clearly demonstrate that weighting the discrete signal by the particle transit time significantly mitigates the sampling bias. Applying the weighting scheme consistently reduces the discrepancy relative to the continuous signal from approximately 10% to less than 3% across all measurement locations. Similarly, performing this analysis for the concentration variance, $\overline{c'^2}$, as shown in Fig. 6, yields the same conclusion. The sampling bias in the scalar variance is effectively reduced, with the transit-time weighted average deviating by less than 3% from the uniformly sampled continuous signal.

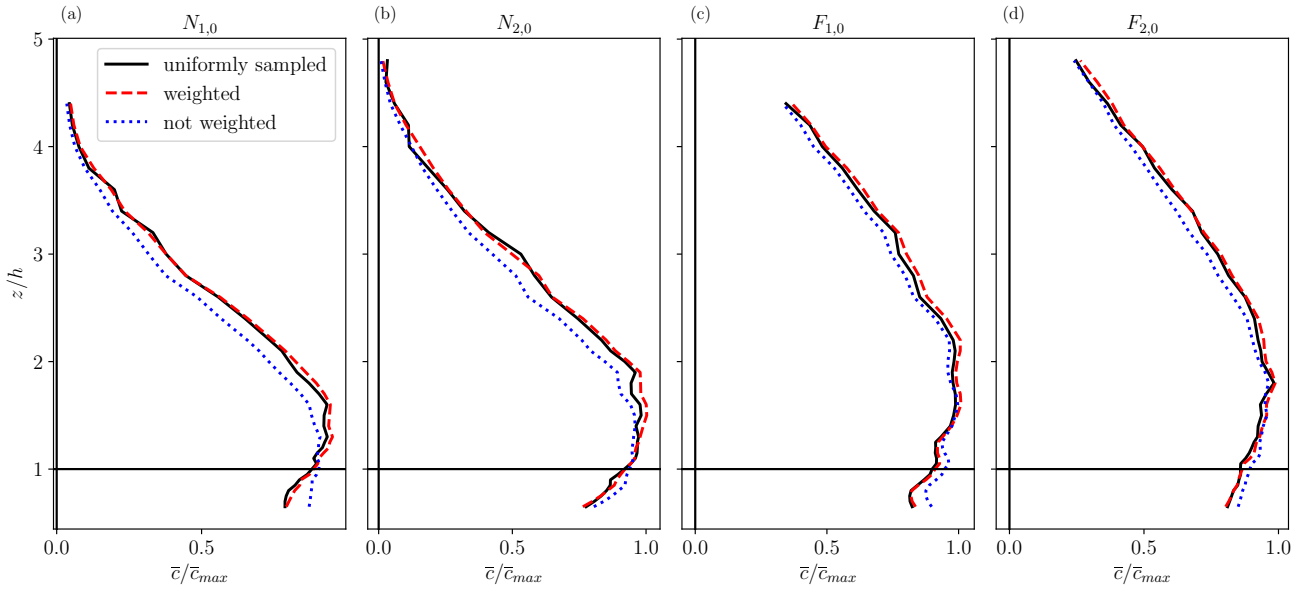


Figure 5. Vertical profiles of normalized mean concentration along the symmetry plane ($y/h = 0$). Panels (a)–(d) correspond to measurement locations $N_{1,0}$, $N_{2,0}$, $F_{1,0}$, and $F_{2,0}$, respectively. The solid line indicates the uniformly sampled continuous signal. For the discretely sampled LDA-triggered signal, the dashed line represents the transit-time weighted average, and the dotted line shows the unweighted average. The horizontal solid line denotes the canopy top height.

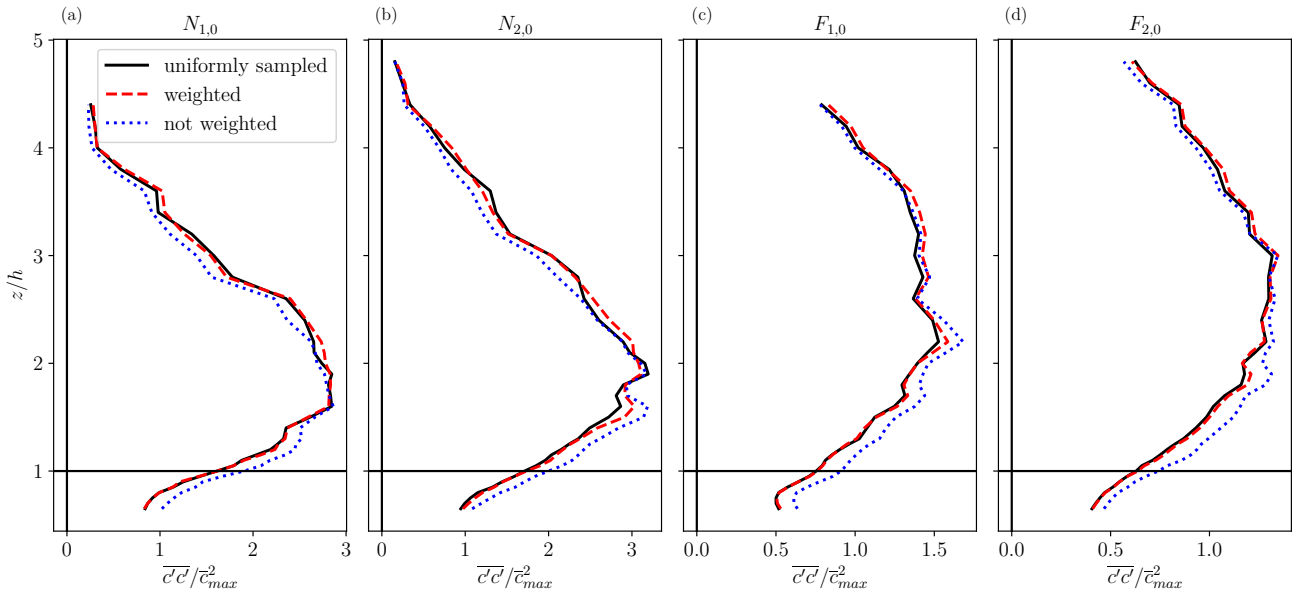


Figure 6. Vertical profiles of normalized mean concentration variance along the symmetry plane ($y/h = 0$). Panels (a)–(d) correspond to measurement locations $N_{1,0}$, $N_{2,0}$, $F_{1,0}$, and $F_{2,0}$, respectively. Line styles and symbols are identical to those in Fig. 5.

Having validated the weighting methodology, we proceed to analyze the mean concentration field. To facilitate a direct comparison across different streamwise positions, the profiles of both the mean concentration, $\bar{c}$, and the concentration variance deviation, $\overline{c'c'}$, are normalized by the local maximum

	$N_{1,0}$	$N_{2,0}$	$F_{1,0}$	$F_{2,0}$
$c_{\max}/c_s$	137.38	118.52	42.81	39.58

Table 2. Maximum normalized concentration ($c_{\max}/c_s$) at the different measurement locations.

of the mean concentration found along each respective vertical measurement line. These maximum mean values, normalized by the reference source concentration (c_s), are summarized as $\bar{c}_{\max}/c_s$ in Table 2. As expected, the spatial distribution shows that the scalar plume rises and spreads vertically as it advects downstream (Fig. 5). The variance profiles exhibit a similar upward shift and vertical broadening; however, at all downstream locations, the peak of $\overline{c'c'}$ is situated at a higher elevation than the peak of the mean concentration (Fig. 6).

These trends are consistent with the findings of Fackrell & Robins (1982) for an elevated point source in a turbulent boundary layer, as well as with the point-source canopy dispersion study by Saeedi & Wang (2015). In contrast to the elevated line-source measurements of Legg et al. (1986), where the peak relative intensity, $\sigma_{c,\max}/\bar{c}_{\max}$, drops below unity immediately downstream of the source, our point-source measurements maintain values greater than unity even in the far-field (F) cells. This sustained intensity is physically expected: narrow point-source plumes are subject to lateral meandering, which generates significantly higher concentration fluctuations along the centerline compared to a statistically two-dimensional line source, which is horizontally homogeneous.

A notable feature emerges within the canopy ($z/h < 1$), where the $\overline{c'c'}$ values for the $N_{1,0}$ and $F_{1,0}$ profiles are lower than those of their corresponding downstream profiles ($N_{2,0}$ and $F_{2,0}$). This behavior directly opposes the trend observed above the canopy ($z/h > 1$), where fluctuations strictly decay with downstream distance. We attribute this localized suppression of concentration fluctuations to the sheltering effect of the canopy elements.

Having established the validity of the transit-time weighting scheme for the scalar signal, we proceed to analyze the velocity-scalar correlations to estimate the mean turbulent scalar fluxes. Figures 7 and 8 present the vertical profiles of the mean streamwise and vertical turbulent scalar fluxes, respectively, at various locations along the symmetry plane ($y/h = 0$). These profiles were calculated both with and without the application of the weighting scheme.

It is evident that applying the transit-time weighting alters not only the magnitude of the fluxes but also the height of the zero-crossing, a parameter crucial for the accurate estimation of turbulent diffusivity. This underscores the critical importance of applying the weighting scheme to turbulent scalar flux calculations, as the unweighted approach introduces bias in both magnitude and sign.

The vertical flux profiles exhibit a distinct S-shape, which is a characteristic feature of elevated source dispersion. The zero-crossing point of the flux is situated above the canopy, and its elevation increases progressively downstream. Similarly, the peak of the mean scalar concentration is located above the canopy and rises with increasing distance from the source. This upward displacement of the plume is attributed to the high shear induced by the canopy elements, which significantly enhances vertical transport. This effect is consistent with findings from previous studies regarding dispersion from a ground source within canopy flows (Yee et al., 2006).

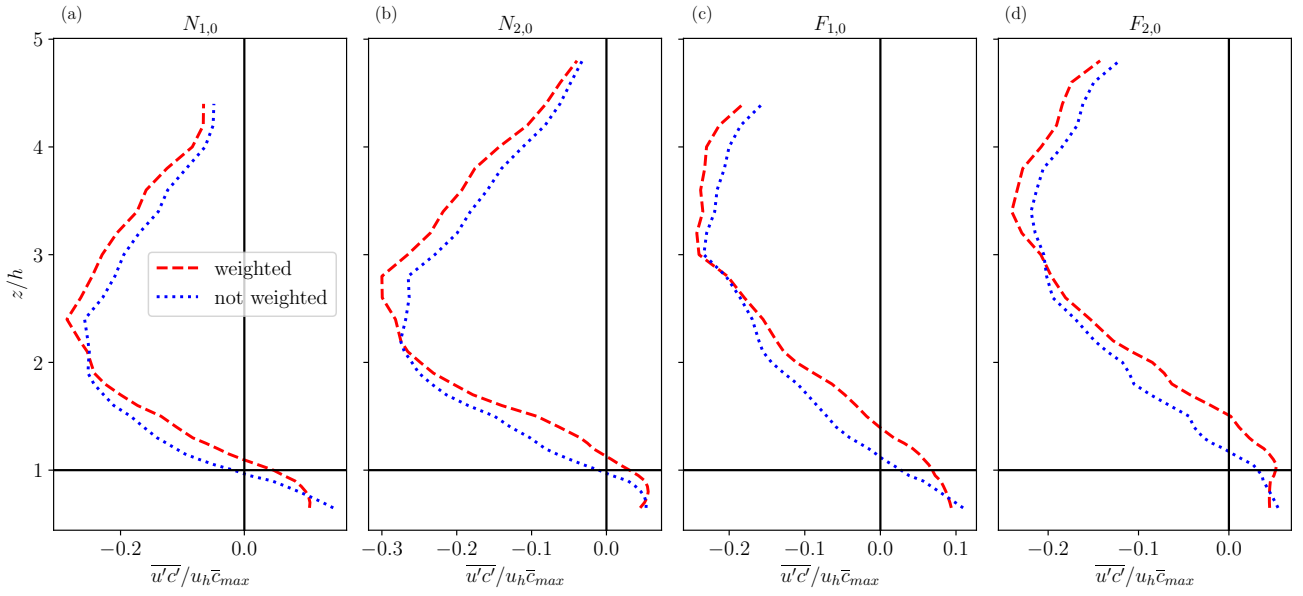


Figure 7. Vertical profiles of the normalized mean streamwise turbulent scalar flux, $\overline{u'c'}$, along the symmetry plane ($y/h = 0$). Panels (a)–(d) correspond to measurement locations $N_{1,0}$, $N_{2,0}$, $F_{1,0}$, and $F_{2,0}$, respectively. Line styles and symbols are identical to those in Fig. 5.

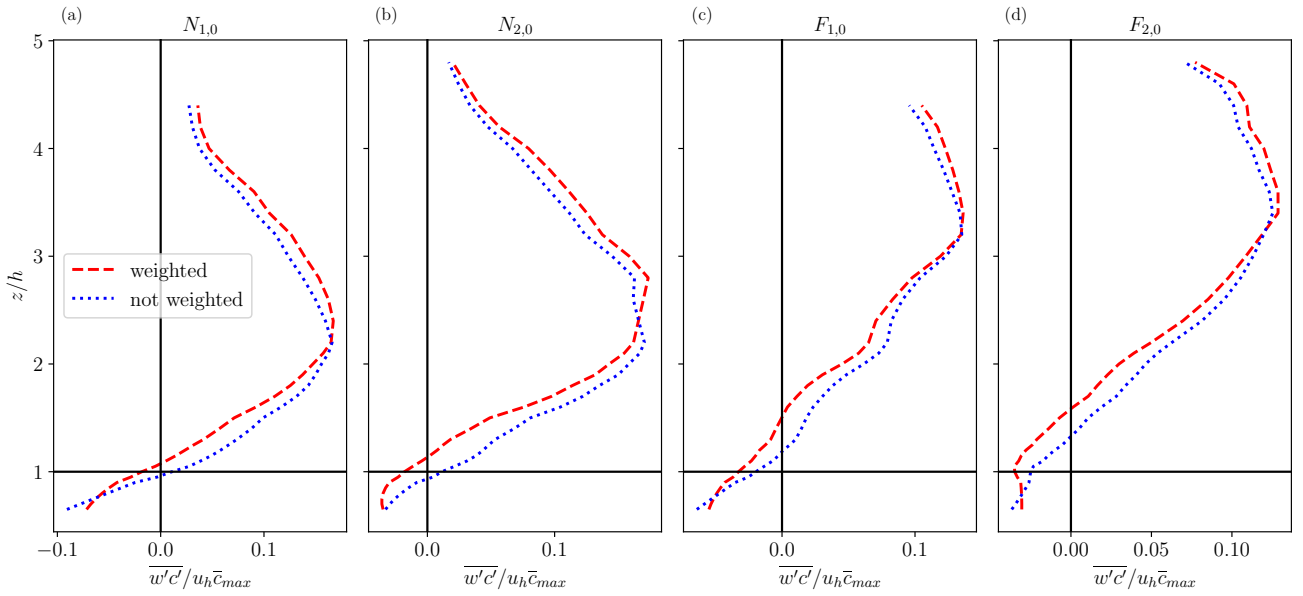


Figure 8. Vertical profiles of the normalized mean vertical turbulent scalar flux, $\overline{w'c'}$, along the symmetry plane ($y/h = 0$). Panels (a)–(d) correspond to measurement locations $N_{1,0}$, $N_{2,0}$, $F_{1,0}$, and $F_{2,0}$, respectively. Line styles and symbols are identical to those in Fig. 5.

To further analyze the temporal scales of the turbulent boundary layer flow, we evaluate the auto-correlation function, $R_\phi(\tau)$, which quantifies the temporal correlation of the fluctuating signal as a function of the time lag, τ . For a stationary fluctuating signal $\phi'(t)$, it is defined as:

$$R_\phi(\tau) = \overline{\phi'(t)\phi'(t+\tau)} \quad (4)$$

Estimating this directly from LDA data presents two main challenges: the non-uniform random sampling intrinsic to the measurement technique (Damaschke et al., 2018), and the statistical velocity bias caused by a higher data acquisition rate at higher convection velocities. To rigorously address these issues without introducing the dynamic errors associated with data interpolation, we evaluated several approaches and elected to implement an arrival-time quantization method, which provides the most robust results while allowing for efficient Fast Fourier Transform (FFT) acceleration.

Following the comparative best practices outlined by Damaschke et al. (2018), the irregular arrival times are first discretized onto a uniform temporal grid with a constant increment $\Delta\tau$. During this resampling process, missing instances within the gaps are masked with a weight of zero, while valid samples are individually weighted by their measured particle transit times. Transit-time weighting is applied as it is highly reliable for reducing the statistical bias associated with the velocity-dependent data rate.

The autocorrelation is then efficiently computed in the frequency domain. To prevent systematic errors arising from white noise components and the differing probability densities of self-products versus cross-products, all self-products ($i = j$) are explicitly removed from the correlation summations. Finally, to correct for deviations from an ideal Poisson sampling process, such as those introduced by processor dead times, the raw autocorrelation is normalized by the autocorrelation of the sampling function. If local normalization is utilized, the estimate for each specific lag is instead normalized by a localized variance estimate based only on the pairs contributing to that lag, further reducing the estimator variance at small lag times where the correlation is highest.

We leverage the availability of both the continuously sampled and the LDA-triggered concentration signals to validate whether this arrival-time quantization method accurately reproduces the autocorrelation computed from the uniformly sampled data. This comparison is presented in Fig. 9 for the measurement location $F_{1,0}$ at an elevation of $z/h = 1.1$. This specific height represents a region characterized by high turbulent shear and intensity, making it a rigorous test case for the methodology. The estimated autocorrelation from the non-uniformly sampled LDA signal exhibits excellent agreement with the uniformly sampled FFID triggered concentration signal, confirming the validity of this approach. Consequently, this established method enables the reliable computation of power spectra and integral time scales for all LDA-acquired signals.

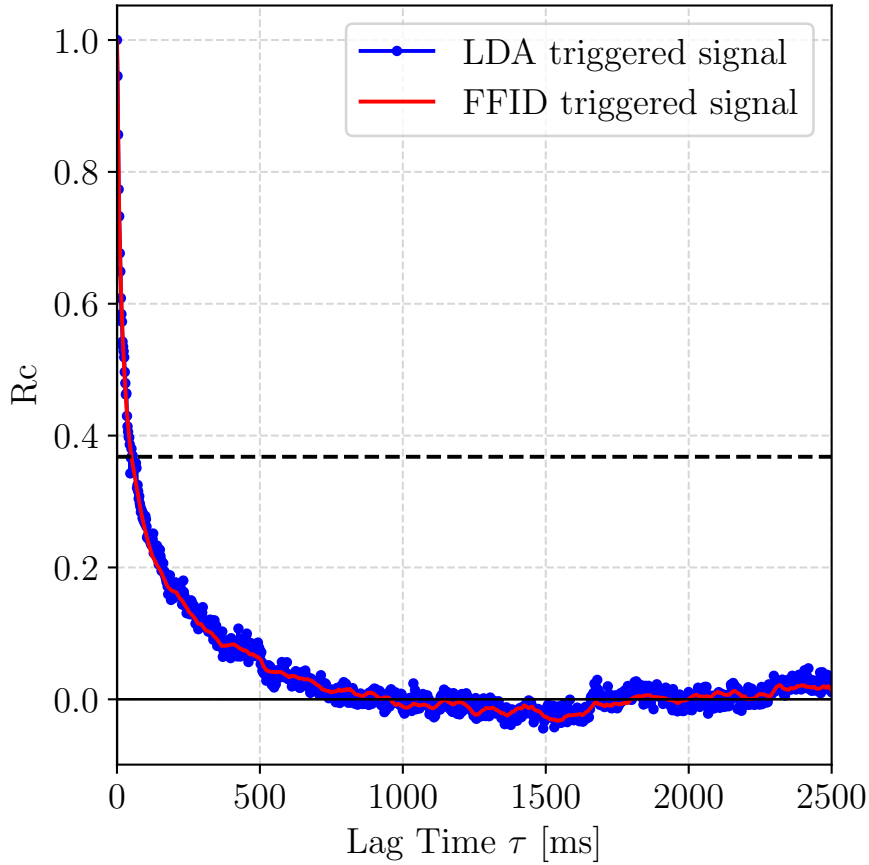


Figure 9. Comparison of the concentration autocorrelation functions obtained from the uniformly sampled continuous signal and the non-uniformly LDA-triggered signal computed using arrival-time quantization. The data corresponds to measurement location $F_{1,0}$ at a height of $z/h = 1.1$.

Finally, from the autocorrelation function we can calculate the integral time scale for each velocity component and the passive scalar. The integral time scale, T_ϕ , is estimated by integrating the autocorrelation function over the time lag:

$$T_\phi = \int_0^\infty R_\phi(\tau) d\tau \quad (5)$$

Examining Figs. 10a and 10b, the integral time scale of the streamwise velocity is consistently higher than that of the vertical velocity across all measured heights. Conversely, examining the concentration time scales (Fig. 10c), we observe that the integral time scale increases as the downstream distance from the source increases. Furthermore, within the canopy ($z/h < 1$), the concentration time scale is significantly higher than the velocity time scales. Above the canopy ($z/h > 1$), however, it rapidly decreases to values comparable to the vertical velocity time scale. This convergence suggests a strong mechanistic connection between the vertical turbulent transport and the scalar dispersion in this region.

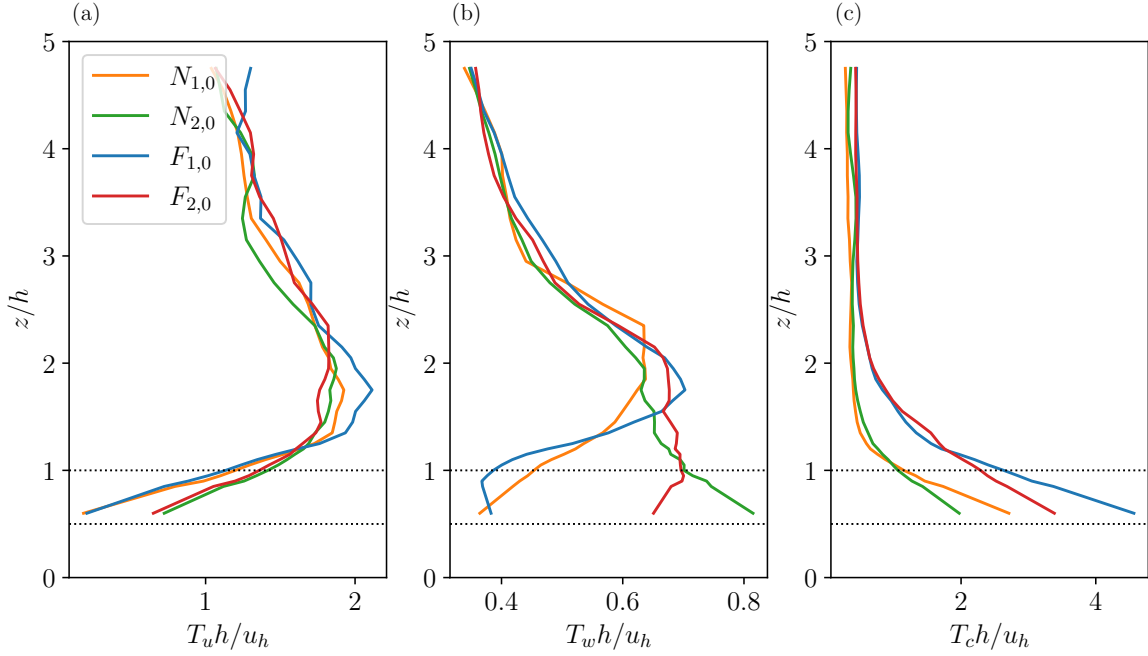


Figure 10. Vertical profiles of the integral time scales for the streamwise velocity (u), vertical velocity (w), and scalar concentration (c) evaluated along the symmetry plane ($y/h = 0$).

4. Conclusions

The coupled LDA-FFID system was successfully applied for simultaneous velocity and concentration measurements in a highly turbulent canopy flow within a large-scale environmental wind tunnel. We addressed the challenging issue of processing non-uniformly sampled data, an inherent consequence of the LDA operating principles. By comparing the discretely sampled data against a continuously sampled reference signal, we rigorously validated the transit-time weighting scheme. The weighted mean and variance of the concentration showed excellent agreement with the uniformly sampled calculations, thereby proving the efficacy of transit-time weighting even in highly turbulent environments, such as canopy flows. Furthermore, this confirms its applicability not only to velocity statistics but also to passive scalars.

Building on this validation, we evaluated the turbulent scalar fluxes, which are key parameters in determining the mean concentration field. We investigated the impact of the weighting scheme on the velocity-scalar correlations. For the case of an elevated source, where the vertical scalar flux inherently changes sign, we demonstrated that the weighting scheme significantly alters not only the magnitude of the flux but also the elevation of its zero-crossing. Thus, applying the transit-time correction is crucial for an accurate physical representation of the scalar dispersion.

Finally, we presented and validated an arrival-time quantization method to estimate the autocorrelation function from non-uniformly sampled signals, subsequently utilizing it to calculate integral time scales. Future work will focus on analyzing the velocity-scalar covariance, including its autocorrelation and corresponding cross-spectra, to further elucidate the dominant temporal and spatial scales driving turbulent scalar transport.

Acknowledgements

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Nomenclature

c	Instantaneous scalar concentration [ppm]
$\bar{c}$	Mean scalar concentration [ppm]
c'	Scalar fluctuation about the mean [ppm]
$c_{\max}$	Maximum mean concentration along a profile [ppm]
c_s	Reference concentration (source strength), Eq. (1) [ppm]
D	Molecular diffusivity [$\text{m}^2 \text{s}^{-1}$]
h	Canopy height (tall elements) [m]
h_s	Source height [m]
N	Number of samples/realizations [-]
Re_δ	Bulk Reynolds number, $Re_\delta = \delta U_e / \nu$ [-]
Re_*	Roughness Reynolds number, $Re_* = u_* h / \nu$ [-]
t	Time [s]
T_s	Sampling/record length [s]
U_e	Free-stream velocity [m s^{-1}]
u	Streamwise velocity component [m s^{-1}]
u'	Streamwise velocity fluctuation [m s^{-1}]
u_h	Mean streamwise velocity at canopy height ($z/h = 1$) [m s^{-1}]
u_*	Friction velocity [m s^{-1}]
w	Vertical velocity component [m s^{-1}]
w'	Vertical velocity fluctuation [m s^{-1}]
$\overline{u'c'}$	Streamwise turbulent scalar flux [ppm m s^{-1}]
$\overline{w'c'}$	Vertical turbulent scalar flux [ppm m s^{-1}]
x, y, z	Streamwise, spanwise, and vertical coordinates [m]
δ	Boundary-layer thickness [m]
ν	Kinematic viscosity [$\text{m}^2 \text{s}^{-1}$]
$\Delta t_{r,i}$	Transit (residence) time of particle i in the LDA sampling volume [s]
$\Delta \tau$	Time increment of the quantized lag grid [s]
τ	Time lag [s]
$R_\phi(\tau)$	Autocorrelation of ϕ [-]
T_ϕ	Integral time scale of ϕ [s]
ϕ	Generic statistical quantity [-]

Abbreviations

CTA	Constant Temperature Anemometry
FFID	Fast Flame Ionization Detector
FFT	Fast Fourier Transform
IIBR	Israel Institute for Biological Research
ISL	Inertial Sublayer
LDA	Laser Doppler Anemometer
PIV	Particle Image Velocimetry
PLIF	Planar Laser-Induced Fluorescence
RSL	Roughness Sublayer
TH	Two-height

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