On the exchange velocity in street canyons with tree planting

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1. Introduction

Tree planting has being widely recognized as a first mitigation strategy to reduce pollutant concentrations in cities. Trees (and vegetation in general) have the capability of cleaning the air by filtering out pollutants, improving the urban microclimate and reducing greenhouse gases concentrations (Litschke and Kuttler, 2008). However, recent numerical studies (e.g. Buccolieri et al., 2011; Vos et al., 2013; Abhijith and Gokhale, 2015) have shown that trees in urban street canyons also have significant effect on the street canyon breathability, impairing the air circulation and pollutant removal processes at the pedestrian zone (Janhäll, 2015). Eventually, the overall impact of trees (positive versus negative effects) at the street scale depends upon the specific synergy between meteorological conditions and both street canyon and vegetation configurations but a well-defined and universal framework is still missing; and so are field measurements needed to corroborate these theoretical and numerical results.

The goal of this paper is to investigate the effects of trees on flow and turbulence in a street canyon by means of *ad-hoc* field measurements integrated with Computational Fluid Dynamics (CFD) modelling. The field campaign was carried out prior to and after to leaf-out of trees in order to assess the effects of different tree canopy structures (i.e. with different Leaf Area Index LAI) on air circulation inside the street canyon. Results were used to estimate the exchange velocity as quantified from vertical mean and turbulent fluxes under several wind direction and different density of the canopy (with trees and tree-free).

2. Description of the study site

The investigated street canyon (namely Redipuglia St.) is located in Lecce, a medium-size city of south Italy characterized by a Mediterranean climate and a classical Mediterranean architectural design, consisting of 2-3 storey buildings and narrow street canyons (Figure 1a). Redipuglia St. is located on the western side of the city where buildings, despite the different heights, are distributed in a regular configuration (Figure 1b). The street canyon is 100m long and 12m wide, running approximately north-south (11° from North) with building heights ranging from 13m to 21m (Figure 1c). The aspect ratio H/W is ~1.2 (where H~15m is average building height and W~12m is the width of the street). Thirty-six deciduous trees (*Tilia Cordata* Mill.) are planted along both sides of the street, twenty-two of which located along the left side and fourteen along the right side. The spacing between tree trunks is approximately 4m, so that there is leaf crown interference. The average height of the branch-free trunk is about 5m and the crown extends to about 8m (Figure 1d,e,f). *Tilia Cordata* Mill. is widespread throughout Europe and is characterized by a dense pyramidal or oval crown which casts deep shade. It is commonly used in urban areas due to its predictable symmetrical shape, which makes it recommendable for shading sidewalks in residential streets.

3. Methodology

3.1 Field experiments

Flow and air temperature measurements were carried out continuously in the period 11 October - 7 December 2013 (Main Campaign hereinafter). The Main Campaign included three intense measurements periods where Leaf Area Index (LAI, m^2m^{-2}) were also performed; specifically on 11-12 October (Campaign 1 hereinafter), 8-9 November (Campaign 2 hereinafter) and 6-7 December 2013 (Campaign 3 hereinafter).

The three components of wind velocity and sonic temperature were measured at the acquisition sampling frequency of 50Hz by three GILL R3-50 sonic anemometers in Redipuglia St. (Figure 1c). Measurements were taken at three different heights. Two anemometers were positioned inside the street canyon: the first (Anemometer 1) was just below the tree crown at z=4.5m AGL (Above Ground Level) and the second (Anemometer 2) was just above the tree crown at z=8.5m AGL. Both anemometers were positioned on banisters of two balconies at the first and second floors of a 15m high building. The third anemometer (Anemometer 3) and a Vaisala HMP45C thermo-hygrometer were positioned at the roof of the same building at 18m AGL. 10-mins averages of wind direction and wind speed and 5-mins averages of turbulent fluxes (for the calculation of the exchange velocity) were computed, following standard techniques for the treatment of high frequency flow data in real scenarios (McMillen, 1988).

LAI of *Tilia Cordata* tree crowns was estimated from measurements of the photosynthetically active radiation (PAR) (light in the 400-700nm waveband) acquired by an Accu-PAR LP80 ceptometer. All measurements were taken parallel to the ground and perpendicularly to the orientation of Redipuglia St. Five replicas were done at the same measurement point just near the crown (where the sensor measured unobstructed PAR) and at its base (where i LAI is assumed to be maximum). The Leaf Area Density (LAD, m^2m^{-3}) was thus estimated dividing LAI by the depth of tree crown (3m) (Figure 1d,e,f). We will refer to large LAI of trees for Campaign 1, intermediate LAI for Campaign 2 and low LAI (leafless trees) for Campaign 3.

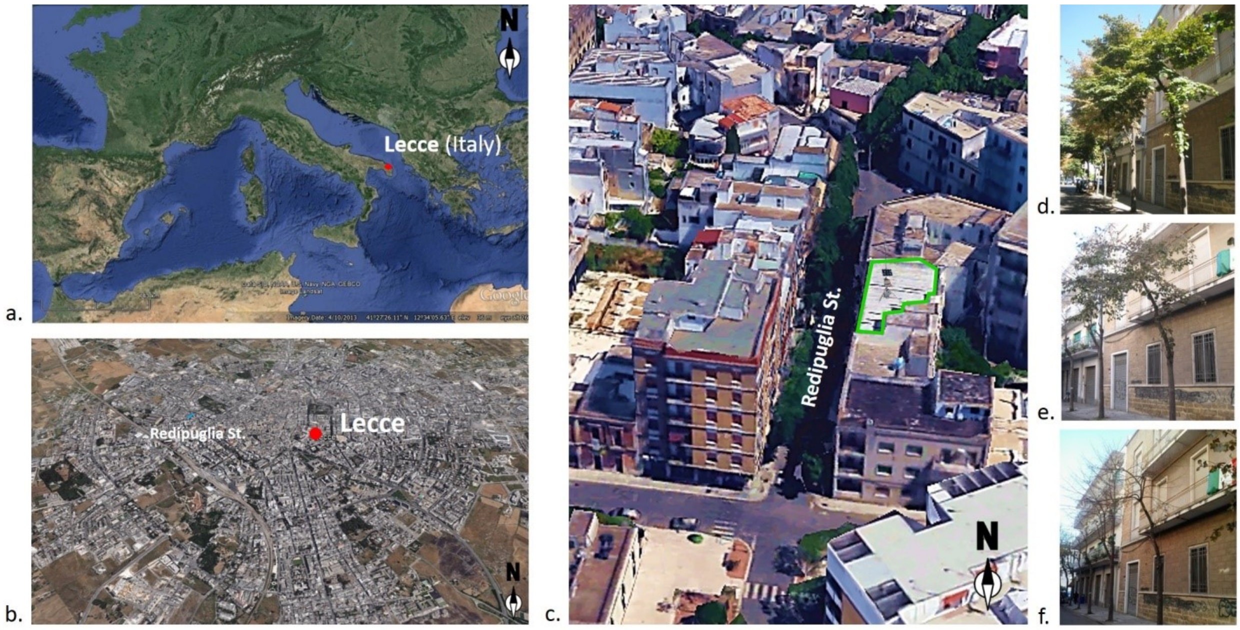

Fig. 1 (a) Position of Lecce in south-east Italy and (b) position of the street neighbourhood analysed (base maps from Google Earth). (c) View of Redipuglia St. ; the green contour indicates the building where the three sonic anemometers were located. Texture of vegetation during Campaign 1 (d), Campaign 2 (e) and Campaign 3 (f).

Note: Image (d), Campaign 1: LAI=5.21m^2m^{-2}, LAD =1.74m^2m^{-3}; Campaign 2: LAI =0.97m^2m^{-2}, LAD=0.32 m^2m^{-3}; Campaign 3: LAI=0.37 m^2m^{-2}, LAD=0.12m^2m^{-3}.

3.2 CFD simulations

3D isothermal CFD simulations were performed by means of the general purpose code Fluent (at the Dipartimento di Ingegneria dell'Innovazione - University of Salento). A preliminary analysis considered meteorological conditions recorded at 21:00 local time (when conditions inside the canyon could be assumed to be isothermal) during Campaign 1. The study area includes Redipuglia St. (with trees, large LAI). To match recorded conditions, an approaching flow was taken to be equal to the mean hourly value ($2.3ms^{-1}$) observed at a meteorological station located outside the urban area (at z=20m), with a wind direction equal to 140° (i.e. from south-south/east direction). The same simulation was performed without trees (tree-free). The Reynolds Stress Model (RSM) (Launder et al., 1989) was used. The domain was built using about one million elements, with a finer resolution within the entire building area. The smallest dimension of the elements in the x, y and z directions was 0.25m, based on grid convergence analysis. Equilibrium profiles of wind speed, turbulent kinetic energy (TKE) and dissipation rate (ε) were specified at the inlet (Di Sabatino et al., 2007), with a friction velocity u_* $=0.17ms^{-1}$ estimated from log-law curve fitting of the observed wind velocity at the meteorological station. Symmetry boundary condition was specified at the top, while at the downwind boundary a pressure-outlet condition was used. The aerodynamic characteristics of trees were modelled adding a momentum sink in the governing momentum equations, where the inertial term is parameterized using a pressure loss coefficient $\lambda=0.35m^{-1}$ estimated though C_d x LAD, where C_d is the leaf drag coefficient taken equal to 0.2 (Gromke and Blocken, 2015). For the purpose of estimating the exchange velocity (see next section), a ground-level line source was modelled along the southern part of Redipuglia St. (that is bounded by buildings at both sides) and the advection–diffusion module was used to calculate pollutant concentration. As an example, a CO emission rate $Q_U=10gs^{-1}$ was assumed.

3.3 Exchange velocity

A main parameter to estimate vertical fluxes between the street canyons and the overlying atmosphere is the exchange velocity U_e, originally introduced by Bentham and Britter (2003) as a measure of city ventilation. Several formulations has been proposed in the literature, manly based on modelling simulations, and only few studies investigated the effect of street vegetation on exchange flux and pollutant dispersion (Ng and Chau, 2011). A recent review of different approaches and results obtained from different research groups in street canyons and built-up areas is given in Panagiotou et al. (2013).

Hamlyn and Britter (2005) applied the model concept of exchange velocity as a ratio of the momentum flux to the difference between the mass flux above and below the canopy top (exchange plane of the street roof A_c), which is defined as follows (Panagiotou et al., 2013):

$$U_e = \frac{\iint(\overline{\rho u'w'} + \rho uw)dS}{\rho A_c(U_{ref} - U_c)} \tag{1}$$

The momentum flux in Eq. (1) is evaluated from the Reynolds shear stresses $(\overline{u'w'})$ and the average values of the x and z components of velocities (uw). U_{ref} is the reference velocity and U_c is the in-canopy velocity. Starting from the work by Hamlyn and Britter (2005), the aim here is to estimate the exchange velocity from field measurements and evaluate the influence of tree planting in a real street canyon. In this study, since flow and turbulence measurements were taken at three points (Anemometers locations), assuming the one-dimensionality of surface area of plane, and considering longitudinal wind speed recorded at Anemometer 3 as the reference velocity U_{ref}, the normalized exchange velocity was estimated as follows:

$$U_e/U_{ref} = \left|\frac{\overline{u'w'} + uw}{U_{ref}(U_{ref} - U_c)}\right| \tag{2}$$

where $\overline{u'w'}$ and uw were those recorded at Anemometer 2 (the available positions closest to the exchange interface between the canyons and the overlying atmosphere) and U_c is the averaged sum of longitudinal wind speed recorded at Anemometer 1 (below the tree canopy) and 2 (above the tree canopy). By using $\overline{u'w'}$ and uw recorded above the tree canopy and an average of velocities measured below and above, we expect to capture the influence of trees on the vertical exchange velocity and thus on the ventilation efficiency below the tree crown (i.e. at pedestrian level).

The exchange velocity was also calculated from CFD modelling results using the current formulation given by the ratio between the pollutant flux at roof level through the exchange surface and the difference between the spatially averaged pollutant concentration within the urban canopy and the background concentration (Buccolieri et al., 2015):

$$U_e = \frac{q_v}{(\langle\bar{C}_{canopy}\rangle - \langle\bar{C}_{bkg}\rangle)} \tag{3}$$

where q_V is the pollutant flux (kg/s) at roof level through the exchange surface A_{roof}, $\langle\overline{C}_{canopy}\rangle$ denotes the averaged pollutant concentration within the urban canopy and $\langle\overline{C}_{bkg}\rangle$ is the background concentration, i.e. pollutant concentration of the incoming atmospheric flow (in our case it is null). The value of U_e is calculated from q_V, that is computed as the residual of a balance of the pollutant fluxes entering and leavening the canyon (i.e. in the horizontal plane - while the faces are vertical planes) through the sections of the streets at its borders as follows:

$$q_V = \int_V Q_U dV - \int_A \overline{U}_i \cdot \overline{C} n_i dA \tag{4}$$

where V is the whole volume of the canyon (i denotes the x and y horizontal directions), C the calculated concentration and A the area of the street lateral sides.

4. Results and discussion

4.1 Flow and turbulence

The analysis of anemometric measurements allowed us to investigate the effects of trees on flow and turbulence within Redipuglia St. Figure 2 shows the windbreak effect in Redipuglia St. for parallel (top) and perpendicular approaching wind (bottom) during Campaign 1 (left), Campaign 2 (middle) and Campaign 3 (right). In the figures, the normalized percentage reduction of wind speed (nrU_1) was calculated as follows:

$$(1 - \frac{U_1}{U_{ref}}) \times 100 = nrU_1 \tag{5}$$

where U_1 is the longitudinal wind speed recorded at Anemometer 1. In the figure, wind directions refer to those recorded at Anemometer 3 (roof level). During Campaign 1 (large LAI) (Figure 2a) winds speed have an average reduction of 57% for parallel (top) and 50% for perpendicular wind condition (bottom). During Campaigns 2 (intermediate LAI) (Figure 2b) and 3 (low LAI) (Figure 2c) the percentage reduction decreased to 54% and 39%, respectively, for parallel approaching conditions (top), and to 37% and 43% for perpendicular approaching conditions (bottom). A significant reduction of wind speed was found during Campaign 3 for wind coming from north. This suggests that the different structure of the canopy strongly influenced the ventilation inside the canyon and this influence was higher in the case of wind approaching parallel to the street axis.

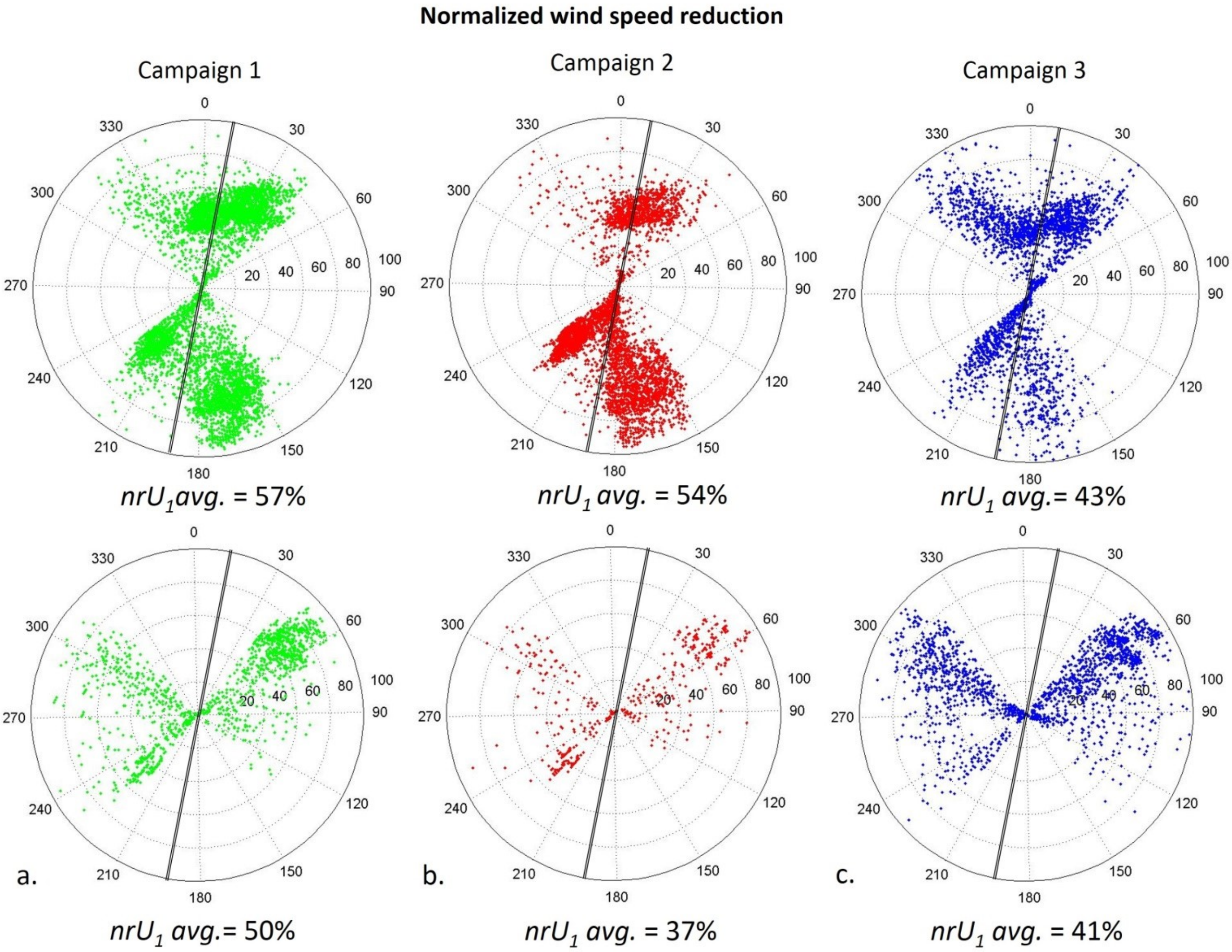

Fig. 2 Normalized percentage reduction of wind speed during Campaign 1 (a), Campaign 2 (b) and Campaign 3 (c) for parallel (top) and perpendicular (bottom) approaching wind conditions. The black line identifies the street axis direction. nrU1 avg. refers to the average wind speed reduction.

4.2 Exchange velocity

Figure 3 shows the estimated normalized exchange velocity for parallel (top) and perpendicular approaching (bottom) conditions during Campaign 1 (left), Campaign 2 (middle) and Campaign 3 (right). During Campaign 1 (Figure 3a) the average value is 0.17ms^{-1} for parallel (top) and 0.20ms^{-1} for perpendicular wind condition (bottom). During Campaigns 2 (Figure 3b) and 3 (Figure 3c) the average values became 0.17 and 0.21, respectively, for parallel approaching condition (top), and to 0.20 and 0.25 for perpendicular approaching condition (bottom). Overall, it can be noted that the effect of trees during Campaign 1 and Campaign 2 was that of lowering the exchange velocity of about 20% with respect to Campaign 3. There was thus a general increase of the exchange velocity from Campaign 1 to Campaign 3 confirming that trees partially obstructed the exchange of air between the canyon and the overlying atmosphere.

Our estimates of the normalized exchange velocity compare relatively well with estimates from previous numerical studies (see the review by Panagiotou et al., 2013). Specifically, our values are in the range they reported for a planar area index λ_p = 0.49 (that of our study site), i.e. between about 0.01 and 0.23.

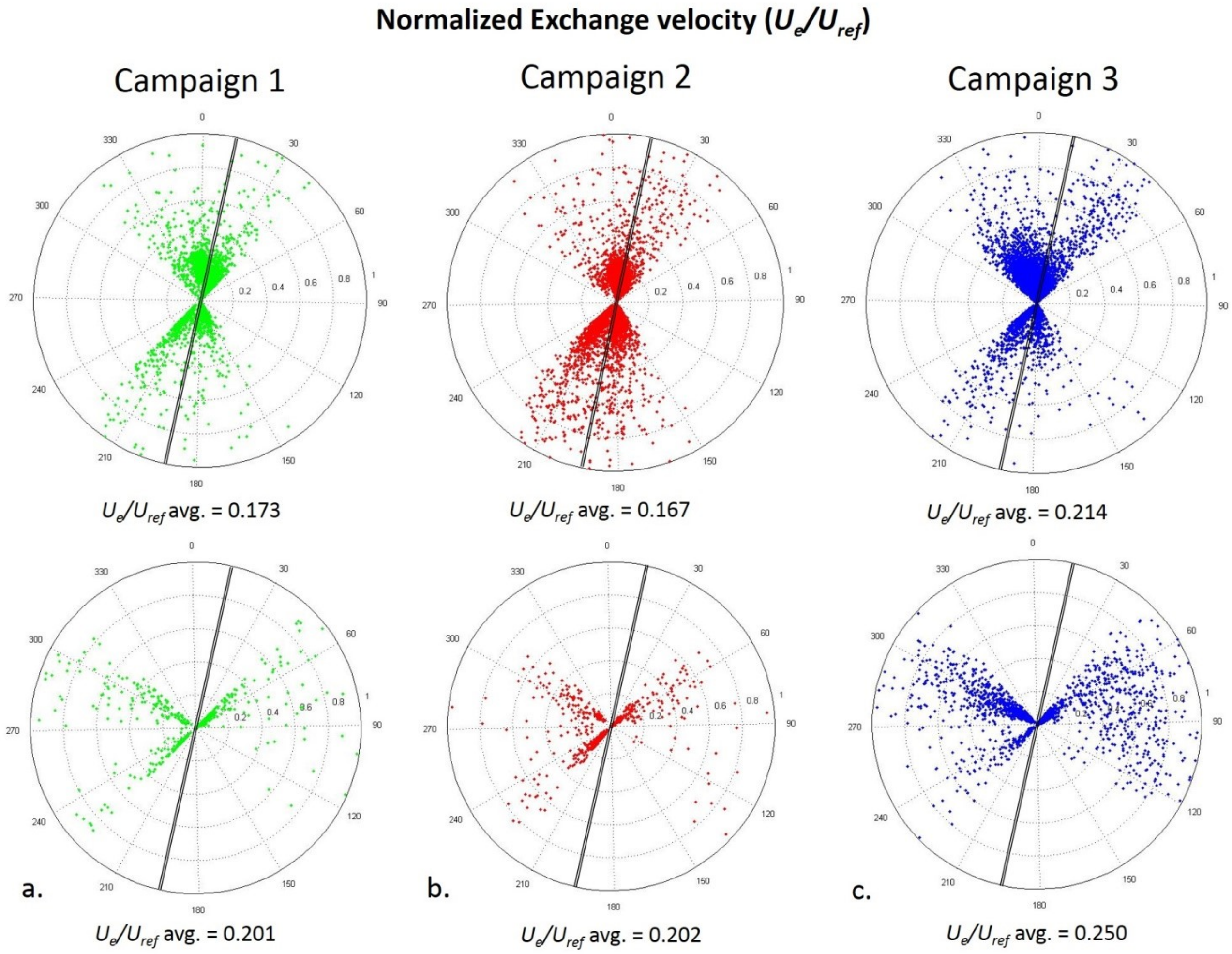

Fig. 3 Normalized exchange velocity during Campaign 1 (a), Campaign 2 (b) and Campaign 3 (c) for parallel (top) and perpendicular (bottom) wind conditions. The black line identifies the street axis direction. U_e/U_{ref} avg. refers to the average normalized exchange velocity.

Figure 4 shows the normalized exchange velocity obtained from daily averages and hourly averages (hh 14:00-15:00 and hh 21:00-22:00) over the whole Main campaign. Overall, each subfigure contains 37 values of the 51 field campaign days, since in 14 days there were missing or inaccurate data. In the figures, wind directions refer to those prevailing during the day or the investigated hours as recorded at Anemometer 3, while the circle size at each point qualitatively indicates the variability of data during the day.

From the figure, as already discussed before (Figure 4), it is evident the effect of trees in lowering the exchange velocity between the canyon and the overlying atmosphere. The figure further shows a high variability of the exchange velocity during Campaign 3, while in the presence of trees with leaves (Campaigns 1 and 2) the obstruction effect lead to lower turbulence levels and thus to lower values of the vertical exchange. This is more pronounced during isothermal conditions (Figure 4c) when the buoyancy did not increase the vertical exchange as for the convective case (Figure 4c). CFD simulations (for the case hh 21:00-22:00) confirmed what found from the field measurements, showing a lower vertical exchange (U_e/U_{ref} = 0.05) in the presence of trees compared to the tree-free case (U_e/U_{ref} = 0.06).

5. Conclusions

The effect of trees on wind speed reduction and vertical turbulent exchange between a street canyon and the overlying atmosphere was examined using high-frequency wind data measured in the city of Lecce (south Italy). It is shown that the overall effect of trees reduce street ventilation. The canyon ventilation was quantified in terms of the two adimensional variables (U_e/U_{ref}) and nrU_1, which take into account the volume of air exchanged in-out canyon in the vertical and horizontal directions respectively. Results indicated a more pronounced reduction for the case of approaching wind perpendicular to the street axis and during the night-time (during isothermal conditions).

Although in-deeper analysis are still in progress, this preliminary investigation has provided useful insights on the potential adverse effects of trees on street ventilation which may stimulate further research for a more effective urban planning.

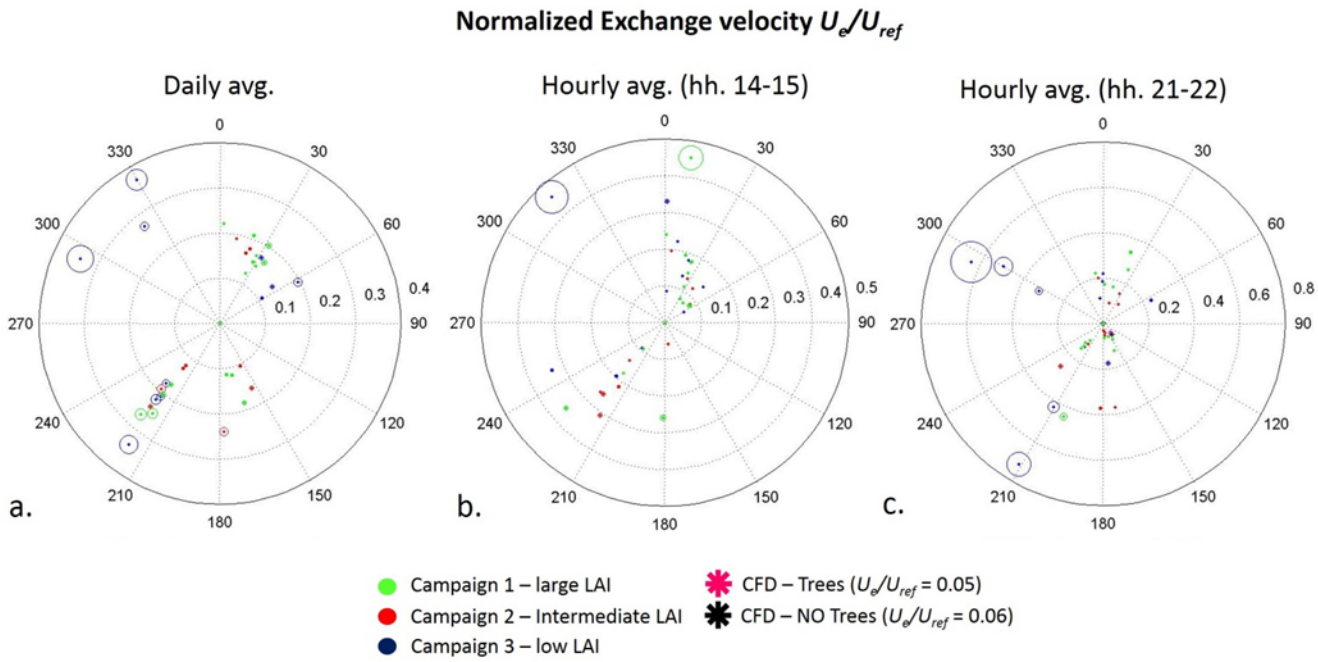

Fig. 4 Normalized exchange velocity obtained from daily averages (a), hourly averages (hh. 14:00-15:00) during light-time (b) and 1-hour averages (hh. 21:00-22:00) during night-time (c) over the whole Main campaign. The circle size at each point indicates the standard deviation. St. dev. avg. refers to the average standard deviation for each campaign.

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