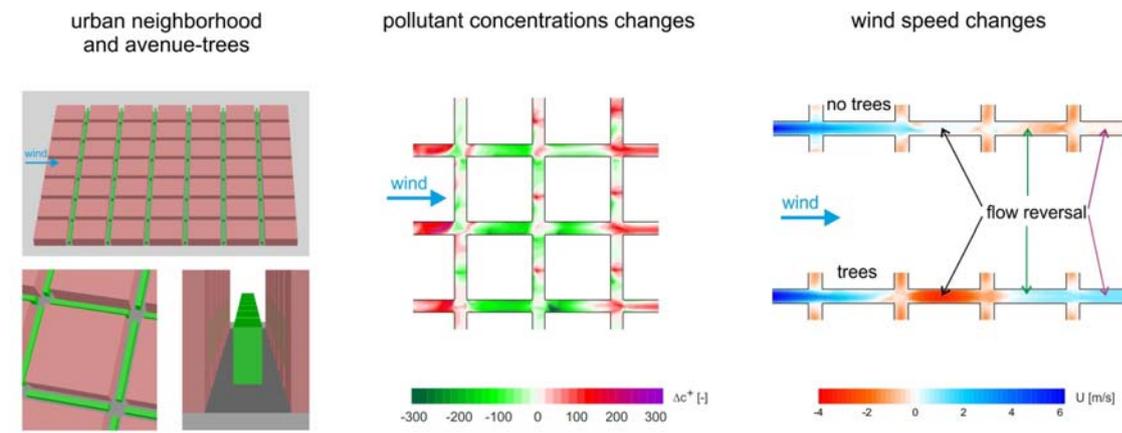


## Influence of avenue-trees on air quality at the urban neighborhood scale. Part II: Traffic pollutant concentrations at pedestrian level

Christof Gromke, Bert Blocken

### Graphical abstract



### Highlights

- The impacts of trees on flow and dispersion in an urban neighborhood was studied.
- Trees cause quantitative and qualitative changes (flow reversals) in the wind field.
- Trees cause low to moderate increases in average concentrations (<13.2%).
- Trees cause strong locally restricted changes in concentrations (-87 to +1378%).
- Avenue-trees have to be considered for reliable urban air quality assessments.

### Abstract

Flow and dispersion of traffic-emitted pollutants were studied in a generic urban neighborhood for various avenue-tree layouts by employing 3D steady RANS simulations with the realizable  $k$ - $\epsilon$  turbulence model. In comparison to the tree-free situation quantitative and qualitative changes with flow reversal in the wind field were observed. Low to moderate increases (<13.2%) in the neighborhood-averaged pollutant concentration were found at pedestrian level. An approximately 1% increase in the neighborhood-averaged concentration was obtained with each percent of the street canyon volumes being occupied by vegetation for occupation fractions between 4 and 14%. The overall pattern of concentration changes relative to the tree-free situation was similar for all avenue-tree layouts. However, pronounced locally restricted decreases or increases in concentration (-87 to +1378%) occurred. The results indicate the necessity to account for existing or planned avenue-trees in neighborhood scale dispersion studies. Their consideration is prerequisite for reliable urban air quality assessment.

### Capsule

The effects of avenue-trees on flow and dispersion in an urban neighborhood were studied to assess their impacts on natural ventilation and air quality in complex urban geometries.

### Keywords

air quality, pollutant dispersion, vegetation, avenue-trees, built environment

## **1. Introduction**

In the recent years, a number of wind tunnel and Computational Fluid Dynamics (CFD) studies have shown that trees in urban street canyons generally result in increased traffic-emitted gaseous pollutant and particulate matter concentrations (e.g. (Balczo et al., 2009; Buccolieri et al., 2009; Gromke and Ruck, 2012, 2009, 2007; Gromke, 2011; Gromke et al., 2008; Li et al., 2013; Moonen et al., 2013; Salim et al., 2011)). The reason for this is the flow resistance of tree crowns which slows down the wind and reduces the air exchange between the street canyon and surrounding. As a consequence, the dispersion of near-ground emitted traffic pollutants is limited and they accumulate within the canyon, in particular below the crown canopy level of dense avenue-tree stands. However, all above-mentioned studies were restricted to the street canyon scale, i.e. flow and pollutant dispersion were investigated within an isolated canyon. Investigations of flow and pollutant dispersion on the scale of two intersecting streets or street canyons were addressed in CFD studies by (Buccolieri et al., 2011; Vos et al., 2013) and (Wania et al., 2012). They also found increases in traffic pollutant concentrations in the presence of avenue-trees. The above mentioned findings from wind tunnel and CFD studies obtained at generic street canyon geometries were recently corroborated by a field study in a street flanked by detached buildings in Auckland, New Zealand by (Salmond et al., 2013). They measured lower wind velocities and increased traffic pollutant concentrations below the tree crowns during the leaf-on period in comparison to the leaf-off period.

However, air quality studies in a network of urban street canyons with avenue-trees representative of an urban neighborhood have not yet been performed. Recently, research has been undertaken to study dispersion and ventilation in actual or generic building block arrays with tree-free streets (e.g. Boppana et al., 2010; Borrego et al., 2006, 2003; Buccolieri et al., 2010; Carpentieri et al., 2012; Di Sabatino et al., 2007; Garbero et al., 2010; Hamlyn et al., 2007; Hang et al., 2011; Panagiotou et al., 2013; Pascheke et al., 2008; Princevac et al., 2010; Ramponi et al., 2014; Soulhac et al., 2012, 2011, 2003; Xie and Castro, 2009). It is evident that such study areas provide a more relevant description of the effects of trees on flow and pollutant dispersion than those with isolated street canyons or intersections. They enable to more realistically capture the complexity of flows within the urban canopy layer and the air and pollutant exchange at intersections and between street canyon sections. Study areas of this type allow to investigate how traffic pollutants are redistributed within street networks, what are the effects of avenue-trees in a canyon on flow and concentrations in the neighboring canyons and finally to address the question whether or not certain tree layouts, e.g. spaced trees or grouped and spaced trees, are beneficial for air quality on the neighborhood scale.

In this study flow and pollutant dispersion in the presence of avenue-trees on the urban neighborhood scale are investigated using CFD. The study is the second of a two-part contribution. The companion paper, Part I (Gromke and Blocken, 2014), introduces the generic urban neighborhood, its layout and the computational domain, and describes the numerical methods and settings. Furthermore, it details quality assessment and assurance studies which were performed to guarantee reliable CFD simulations of flow and pollutant dispersion in the urban environment with avenue-trees. In this part, Part II, the results of the CFD simulations on the impact of various layouts of avenue-trees on flow and pollutant dispersion in the urban neighborhood are presented and discussed. In the remainder of Part II, [Section 2](#) introduces the layouts of avenue-trees in the street canyons. Results and analyses of concentration and flow fields at pedestrian level are presented and discussed in [Section 3](#). Summary and Conclusions are given in [Section 4](#).

## 2. Material and Methods

The urban neighborhood together with an outline of the computational domain and the numerical setting as well as a description of the vegetation model are given in Section 2 of Part I (Gromke and Blocken, 2014) of this two-part contribution. Here, an overview of the scenarios with different avenue-tree layouts in the urban neighborhood is provided in Fig. 1. In total, seven avenue-tree layouts (scenarios 2 - 8) and the tree-free situation (scenario 1) as a reference were investigated. Scenarios with continuous rows of trees (scenario 2), with rows of spaced trees (scenario 3, 4) as well as with rows of grouped and spaced trees were studied (scenario 5 - 8). The layout of trees in scenarios 3 and 4, in 5 and 6, and in 7 and 8 are in each case complementary. Common to scenarios 2 to 8 is that the tree rows consisting of crowns of 6 m width and 12 m height, starting 6 m above the street level, are always positioned horizontally centered in the street canyon sections of width  $W = 18$  m, height  $H = 30$  m and length  $L = 90$  m, see Fig. 1 in Part I (Gromke and Blocken, 2014). All tree crowns are modeled with a vertically uniform profile of leaf area density (LAD) which was set to  $LAD = 1 \text{ m}^2\text{m}^{-3}$  and the leaf drag coefficient ( $C_d$ ) was set to  $C_d = 0.2$ , see Eq. (4) - (6) in Part I (Gromke and Blocken, 2014). As already mentioned in Part I, these values can be considered typical for deciduous trees commonly found in urban street canyons. The purpose was not to model a specific tree species. Next to the layout of the avenue-trees, Fig 1 also indicates the crown volume fraction (CVF). The crown volume fraction is defined as the volume occupied by tree crowns within a street canyon section, i.e. within a volume of  $18 \times 30 \times 90 \text{ m}^3$ .

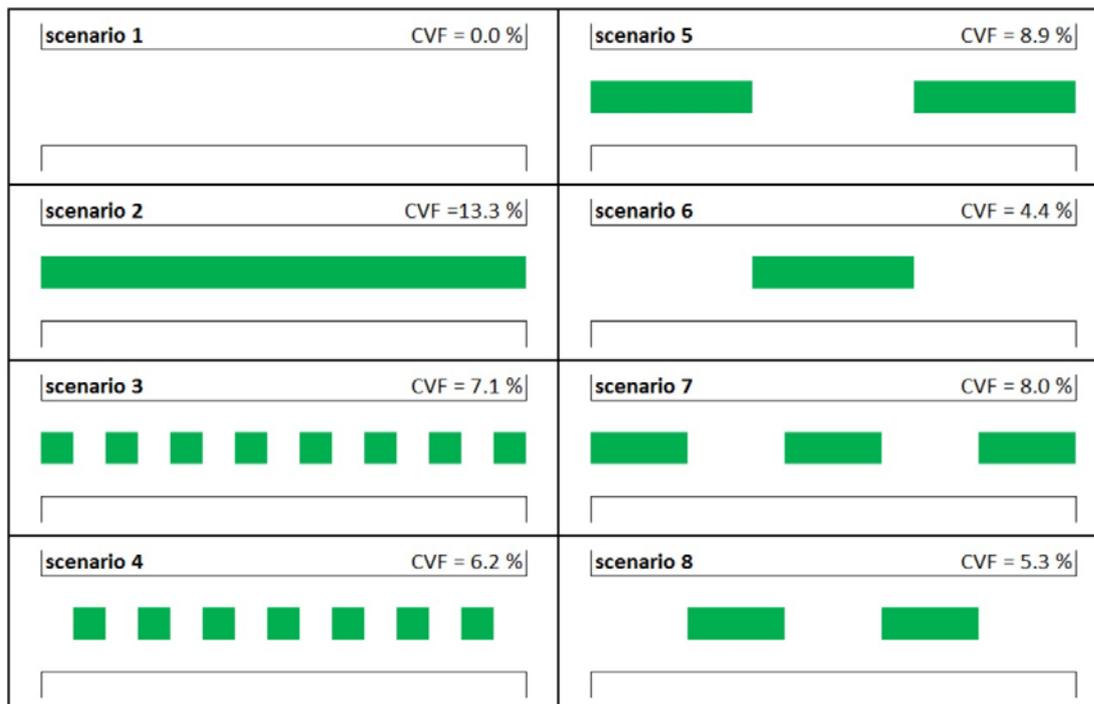


Fig. 1: Overview of avenue-tree layouts in the street canyon sections in scenarios 1 to 8 (CVF = crown volume fraction).

### 3. Results and Discussion

#### 3.1 Pollutant Concentrations and Flow Fields in the Tree-Free Neighborhood (Scenario 1)

The normalized pollutant concentrations  $c^+$  at pedestrian level (2 m above ground) in the tree-free neighborhood (scenario 1) are shown in Fig. 2 where the concentrations of the pollutants released from the street surface area are normalized according to

$$c^+ = \frac{c U_{ref}}{Q_{area}} \quad (1)$$

with  $c$  the concentration obtained by the simulations,  $U_{ref}$  the approach flow velocity at building height  $H$  and  $Q_{area}$  the emission flux per unit area from the street surface. Notice that due to symmetric boundary conditions only half of the total pedestrian level is shown (see Fig. 1 in Gromke and Blocken, 2014).

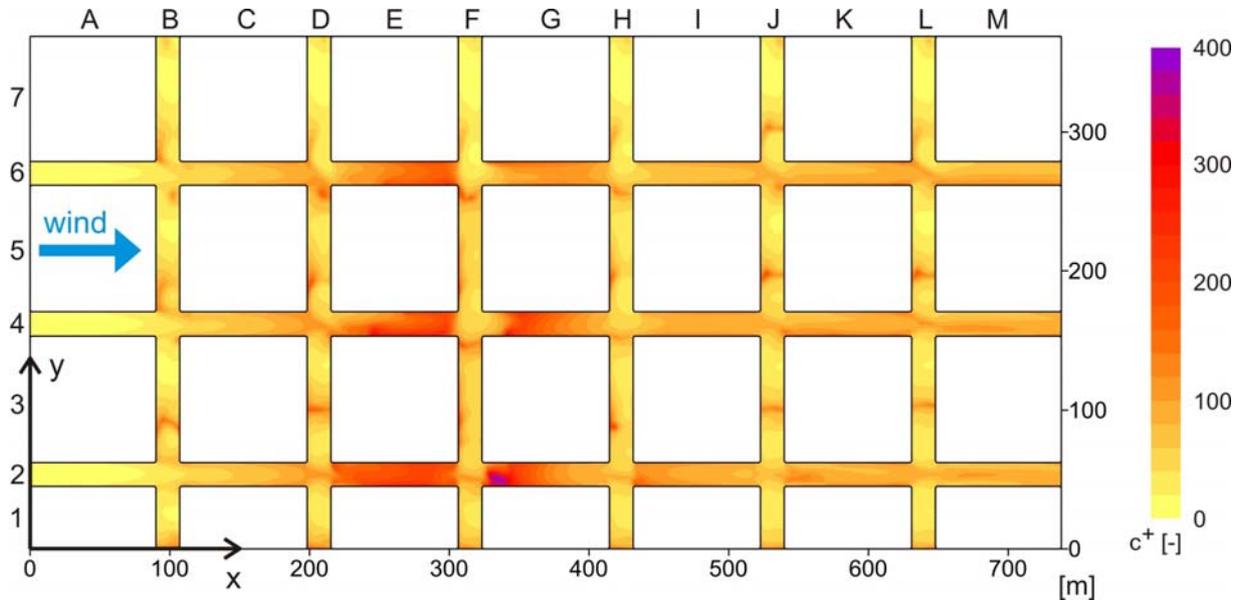


Fig. 2: Normalized pollutant concentrations  $c^+$  at 2 m height in the tree-free neighborhood (scenario 1).

In the wind-parallel streets (row 2, 4, 6) a continuous concentration build-up in the windward first canyons is present until the highest concentrations are reached in columns E and G with a local maximum in street canyon section G2 (Fig. 2). Downwind of column G, the pollutant concentrations are lower and show a comparatively more homogeneous distribution in streamwise ( $x$ ) direction within each wind-parallel street row. In the wind-perpendicular canyons (column B, D, F, H, J, L), also a general increase in concentrations is present up to the third spanwise street (column F); however, the overall pollutant levels across the different spanwise street columns do not vary as much as in the wind-parallel street rows. Overall, the concentrations in the wind-parallel street canyons are larger than those in the wind-perpendicular canyons. The latter is a very interesting and noteworthy finding because in street canyon dispersion studies usually only the condition of perpendicular approach wind is investigated as this is considered to result in the highest concentration charges. However, the present study reveals

higher concentrations in the wind-parallel than in the wind-perpendicular street canyons. This indicates the need to account for various approach wind directions for reliable air quality assessment.

From Fig. 2 the question may arise whether or not the studied neighborhood consisting of 7 x 7 building blocks is already sufficiently large to obtain developed conditions which would manifest in either a streamwise non-changing or repeating flow and concentration pattern. In Fig. 2, the street canyons leeward of column H exhibit a rather slight changing concentration pattern in streamwise direction and hence suggest close-to-developed conditions. However, the question concerning developed conditions is not pivotal in this work. As stated before, the present research was motivated by the fact that former studies focused on single street canyons. The present neighborhood is thus a considerable step closer to reality. Moreover, in reality, coherent built-up areas (city quarters, neighborhoods, ...) are always of limited size and are separated by smaller or larger unbuilt terrain or traffic infrastructure terrain.

The maximum concentrations in columns E and G around the intersections with the spanwise streets of column F can be explained by the flow field at pedestrian level (Fig. 3). There is first of all a continuous accumulation of traffic pollutants in the wind-parallel street canyons by the bulk flow in streamwise (x) direction. Moreover, this flow slows steadily down in streamwise direction at pedestrian level, comes almost to rest in column E and reverses in columns G and I (Fig. 3a). Consequently, the emissions from the street surface get less diluted and pollutants from columns G and I are also advected towards column E. In addition to that, pollutants from the spanwise streets are transported by the mean flow into the wind-parallel street canyons (Fig. 3b). The lower concentrations on the intersections F2, F4 and F6 are attributed to the relative strong upward velocity at pedestrian level (Fig. 3c) which removes the pollutants from there.

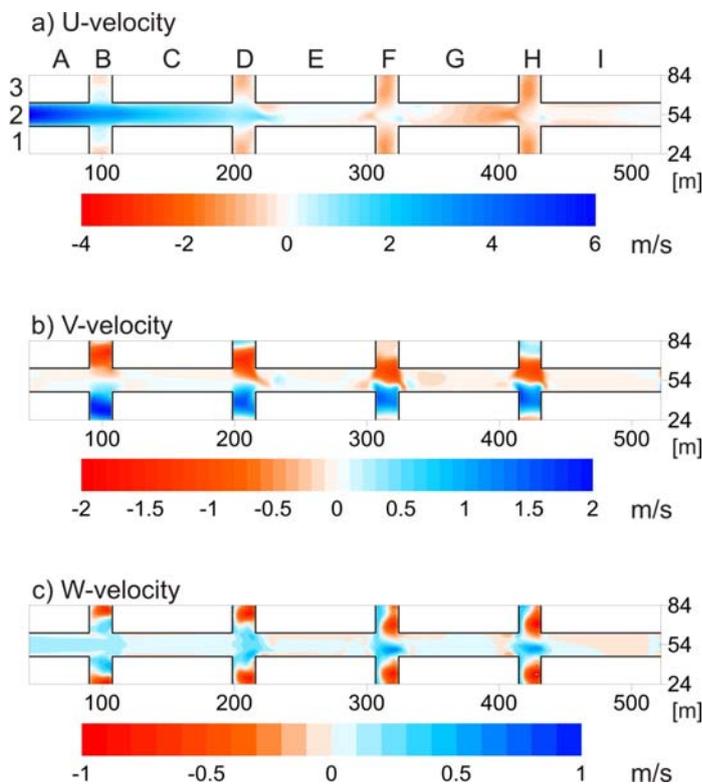


Fig. 3: Velocities at 2 m height in the tree-free neighborhood (scenario 1). See Fig. 2 for directions of velocity components.

### 3.2 Pollutant Concentrations and Flow Fields in the Neighborhoods with Avenue-Trees (Scenarios 2 - 8)

The neighborhood with continuous avenue-tree rows in its street canyons (scenario 2) is addressed next. Fig. 4 presents the difference in normalized concentrations  $\Delta c^+$  referred to the tree-free neighborhood (scenario 1), i.e.  $\Delta c^+_{s2} = c^+_{s2} - c^+_{s1}$ . The contour plot reveals concentration increases as well as decreases in comparison to the tree-free scenario with the most prominent changes in the wind-parallel street canyons. The wind-parallel street canyon sections (row 2, 4, 6) are either dominated by section-wide concentration increases or decreases with extensive increases in columns C, I and K and extensive decreases in columns E and G. In contrast, in the wind-perpendicular street canyon sections (column B, D, F, H, J, L), areas of concentration increases and decreases are side by side present. Overall, the changes in the wind-parallel street canyon sections are quite homogenous over the spanwise (y) direction within each column (i.e. column A, C, E, G, I, K and M) and those in the wind-perpendicular street canyon sections show generally a similar pattern over the spanwise (y) direction within each column (i.e. column B, D, F, H, J and L) with mostly concentration decreases in their peripheral parts close to the intersections but increases in a narrow area in their central part and rather small streamwise changes in a single canyon. Compared to the tree-free neighborhood (scenario 1), considerable local changes in the normalized concentrations ranging from  $\Delta c^+ = -344$  to  $+269$  [-] are found. In terms of relative changes, i.e.  $\Delta c^+/c^+_{s1}$ , local concentration increases of up to 1378% and decreases of up to 87% are found. However, the relative change in the neighborhood-averaged concentration at pedestrian level is compared to the locally restricted changes rather moderate with an increase of 13.2%.

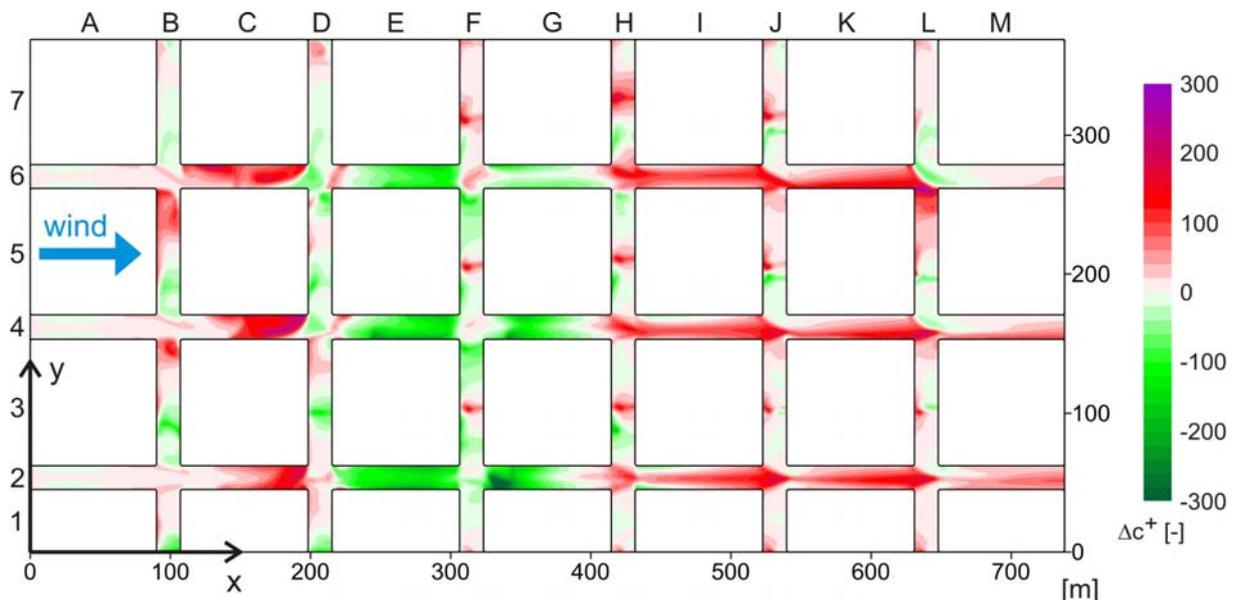


Fig. 4: Difference in normalized pollutant concentrations  $\Delta c^+$  at 2 m height in the neighborhood with continuous avenue-tree rows (scenario 2) compared to the tree-free neighborhood (scenario 1), see Fig. 2.

The flow field at pedestrian level exhibits (Fig. 5) characteristic differences to that in the tree-free neighborhood (scenario 1), see Fig. 3. In the wind-parallel canyons, the bulk flow in streamwise direction slows down sooner after entering the neighborhood and it comes to a reverse flow with relative high

velocity in column E (Fig. 5a). This reverse flow purges out the pollutants and brings them into the wind-parallel canyons of column C. In columns G and I the flow at pedestrian level is again directed in streamwise direction whereas in the tree-free neighborhood a reverse flow is present (Fig. 3a). Air from the spanwise streets streams into the wind-parallel canyons at the intersections (Fig. 5b); however, the flow velocities are lower than in the tree-free scenario (Fig. 3b). For columns E, G and I, the contour plots indicate two helical counter-rotating streamwise vortices as can be seen by the flows in spanwise (y) direction oriented from the building facades towards the canyon center (Fig. 5b) and the downward flows at the facades and upward flow below the tree crowns (Fig. 5c).

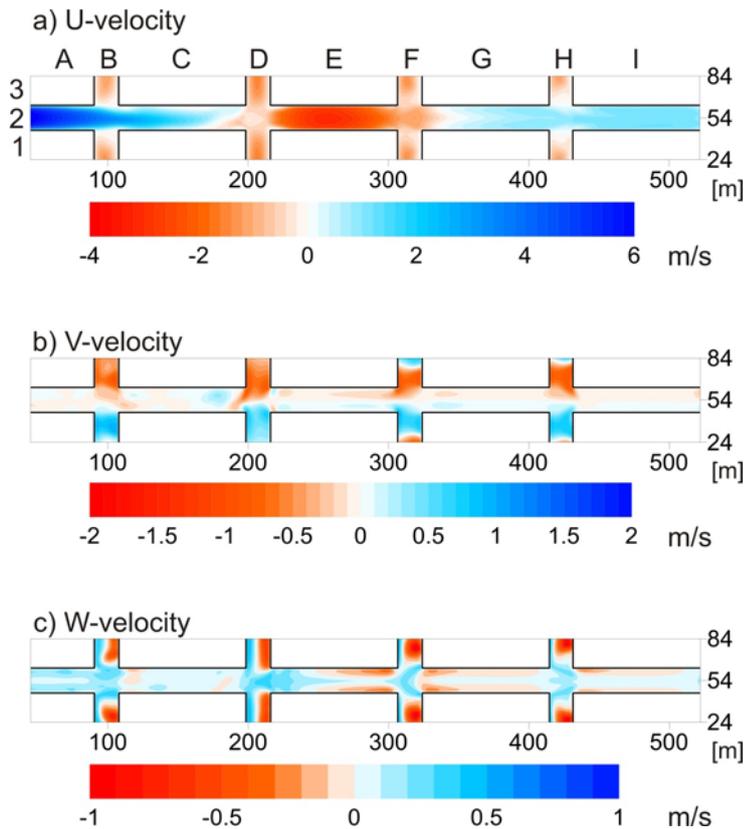


Fig. 5: Velocities at 2 m height in the neighborhood with continuous avenue-tree rows (scenario 2). See Fig. 2 for directions of velocity components.

The overall changes in concentrations at pedestrian level in the remaining scenarios with discontinuous avenue-tree rows (Fig. 1) resemble those of the neighborhood with the continuous avenue-tree rows (scenario 2) as shown in Fig. 4. In general, for all scenarios overall decreases are found in the wind-parallel street canyons of columns E and G, and increases in the other columns when compared to the tree-free neighborhood. For the wind-perpendicular canyons generally overall decreases in the columns D and F, and increases in the remaining ones are observed.

In the following, the changes in concentrations are analyzed as averages over all street canyon sections within one column (column-averaged), e.g. as average over sections A2, A4 and A6 for the wind-parallel sections in column A, and as average over sections B1, B3, B5 and B7 for the wind-

perpendicular sections in column B. The concentrations at the intersections are not included. This type of averaging was performed since the overall concentration levels and their changes on the street canyon section scale were quite homogeneous in spanwise ( $y$ ) direction, see e.g. Fig. 2 and Fig. 4. Fig. 6 shows column-averaged concentrations for the wind-parallel and wind-perpendicular street canyon columns (left and right panels, respectively) as differences in normalized concentration  $\Delta c_{si}^+ = c_{si}^+ - c_{s1}^+$  and as relative changes in normalized concentration  $\Delta c_{si}^+ / c_{s1}^+$  (top and bottom panels, respectively).

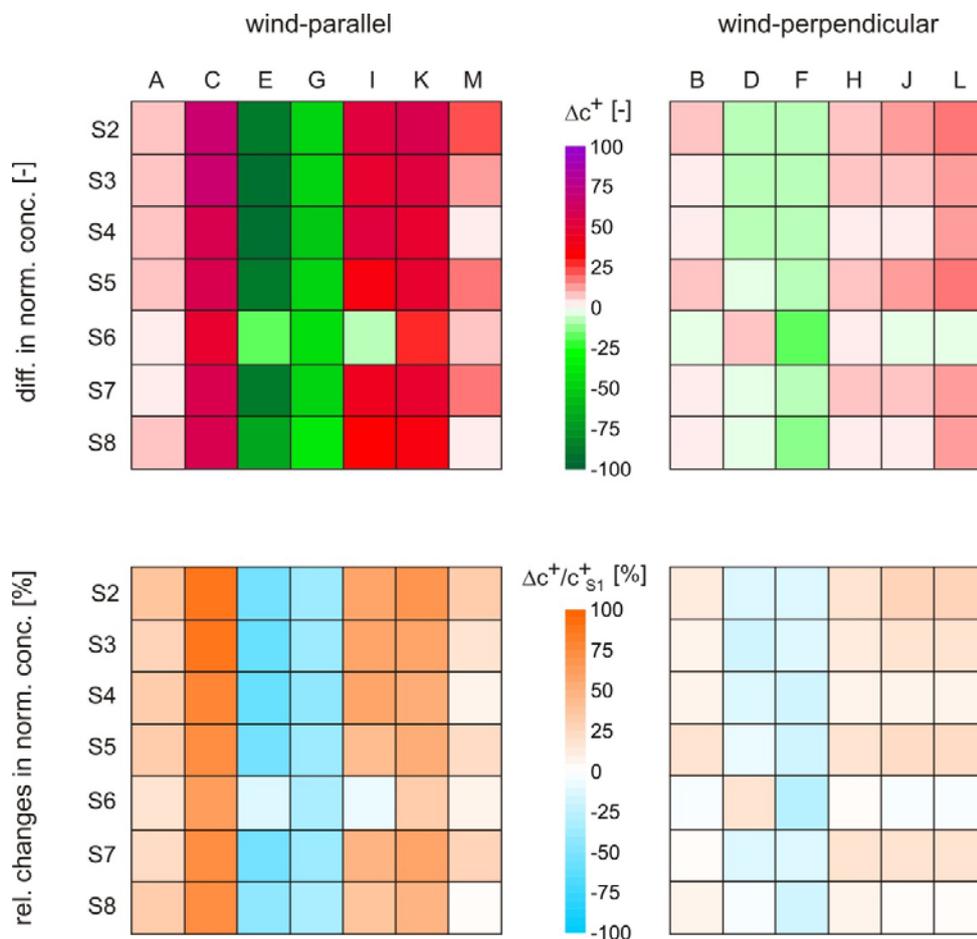


Fig. 6: Changes in column-averaged concentrations for the wind-parallel street canyon sections (left) and wind-perpendicular street canyon sections (right) for the different scenarios (S2 - S8) with reference to the tree-free neighborhood (scenario 1). Differences in normalized concentration  $\Delta c^+$  (top) and relative changes in normalized concentration  $\Delta c^+ / c_{s1}^+$  (bottom).

At first glance the different avenue-tree layouts resulted generally in qualitatively similar changes in the concentration fields over all scenarios with the exception of scenario S6 where also qualitative changes can be found. The changes due to avenue-trees in terms of normalized concentrations (Fig. 6, top) as well as in terms of relative changes (Fig. 6, bottom) are more pronounced in the wind-parallel than in the wind-perpendicular street canyons. For all scenarios, the largest column-averaged increases occur in the wind-parallel street canyon sections of column C. Here, average increases  $\Delta c^+$  between 47.1 and 67.0 [-] corresponding to relative changes of 62% and 88% are found relative to the tree-free neighborhood. The largest column-averaged decreases occur in the third wind-parallel street canyon

sections (column E) with reductions of up to  $\Delta c^+ = 94.0$  [-] corresponding to a relative change of -59%. In the wind-perpendicular street canyons, the implications of avenue-trees on pollutant concentrations are clearly smaller. The changes in column-averaged concentrations range from  $\Delta c^+ = -15.1$  to 17.9 [-], or expressed in relative changes from -27% to 36%.

Fig. 7 shows the relative change in concentration averaged over the entire neighborhood for all scenarios with trees relative to the tree-free neighborhood, i.e.  $\Delta c_{si}^+/c_{s1}^+$ , over the crown volume fraction (CVF). The neighborhood-averaged relative concentration increases at pedestrian level are except for one scenario smaller than 10% for the tree layouts studied. The largest relative change of 13.2% was found for the neighborhood with continuous avenue-tree rows (scenario 2). Overall, the increase scales approximately linearly with the crown volume fraction (CVF). To a first approximation, it can be said that one percent crown volume fraction results in a one percent increase in the neighborhood-averaged pollutant concentration at pedestrian level as can be seen by comparison with the identity line (1:1) in Fig. 7.

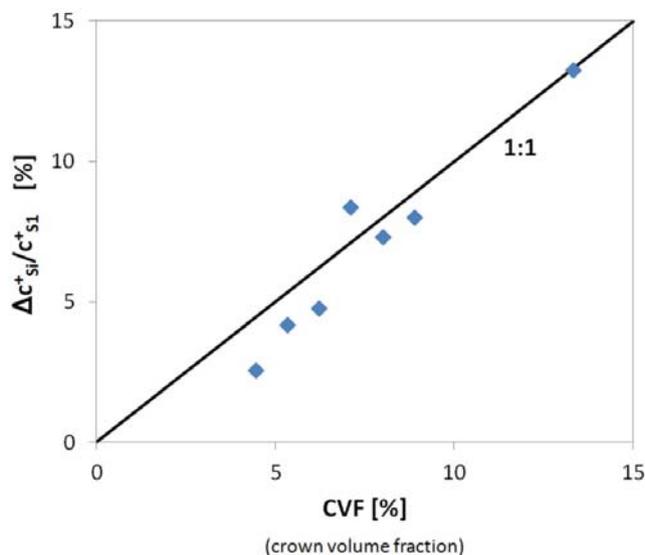
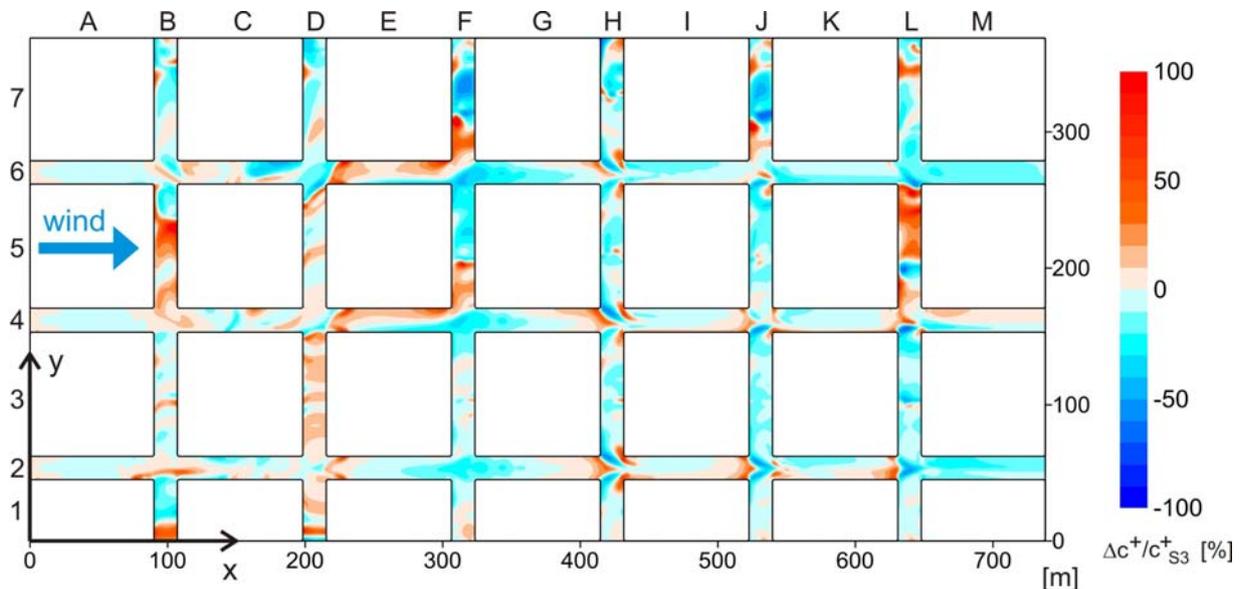


Fig. 7: Relative change in neighborhood-averaged concentration  $\Delta c_{si}^+/c_{s1}^+$  versus the crown volume fraction (CVF).

The discontinuous avenue-tree row with alternating gaps of one tree width was simulated for two variants, namely with trees at shifted positions constituting street canyon sections with trees at their outermost positions (scenario 3) and without trees at these positions (scenario 4), see Fig. 1. Since both scenarios exhibit almost the same biomass with 8 or 7 trees per street canyon section and have comparable crown volume fractions of CVF = 7.1 and 6.2%, respectively, they are employed to analyze the influence of the tree positions on traffic pollutant concentrations. In particular the fact of a tree either being present or missing at the outermost street canyon section position may result in a different flow field in the vicinity of the street canyon / intersection interface and hence affect the concentrations in a wide part of a street canyon section.

Fig. 8 shows the relative changes in normalized concentrations at pedestrian level between scenario 4 and scenario 3, i.e.  $\Delta c_{s4-s3}^+/c_{s3}^+$ . The neighborhood-averaged concentration in scenario 4 is 3.3% lower than in scenario 3. However, street canyon sections predominantly characterized by increases as well as decreases are present. For a large part of the neighborhood, relative changes smaller than 30% are found. The relative changes are larger in the outer parts of the neighborhood than

in the central part. In particular pronounced relative changes occur in the wind-perpendicular street canyon sections F7 and L5 with local relative changes between  $\approx -70$  and  $90\%$ .



*Fig. 8: Relative changes in normalized concentration  $\Delta c^+/c^+_{s3}$  between scenario 4 and scenario 3, see Fig. 1 for scenarios.*

On the intersections and at the street canyon section ends commonly marked local changes are found, revealing concentration increases as well as decreases. They reflect the impact and importance of the outermost tree on flow and dispersion at these locations. Under the premise that the effect originating from the slightly different biomasses is minor, the impact of the outermost tree position on the local relative changes in pollutant concentrations is remarkable. The intersection-averaged relative changes in concentration between scenario 4 and scenario 3 are shown in Fig. 9a. With the exception of 3 cases, the intersection-averaged concentrations are always lower when the outermost tree position is free with differences of up to  $-25.3\%$ . Averaged over all intersections, the concentrations are  $9.9\%$  lower in scenario 4 which is 3 times more than the relative change in neighborhood-averaged concentration ( $-3.3\%$ ). The relative changes in concentrations at the street canyon section ends are displayed in Fig. 9b-d. The street canyon section end was defined as the outermost part with a length of either 6, 12 or 18 m, corresponding to 1, 2 or 3 tree crown width, respectively. In general, the data points for the intersections of the street canyon rows 2 and 4 lie close together in comparison to row 6, suggesting that effects from the wind-parallel boundary of the neighborhood are no longer significant in those rows. Focusing on the inner area of the neighborhood, i.e. rows 2 and 4 and columns D to J, the concentrations in the street canyon section ends are increased in scenario 4 for the majority of locations except for those in column F where stronger decreases of  $\approx -15$  to  $-20\%$  are present. In conclusion it can be said that omitting trees at the outermost positions (i.e. scenario 4 vs. scenario 3) generally results in lower pollutant concentrations on the intersections and to both increased and decreased concentrations at the street canyon section ends.

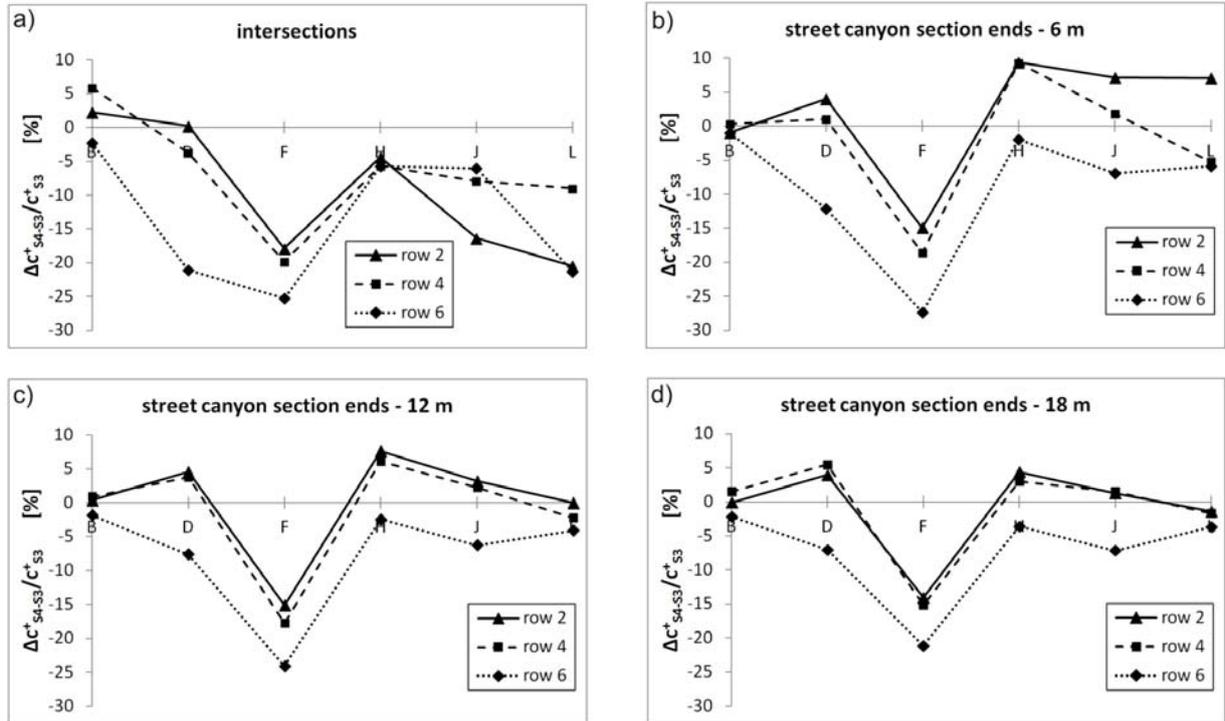


Fig. 9: Averaged relative changes in normalized concentration  $\Delta c^+ / c_{s3}^+$  between scenario 4 and scenario 3 on the intersections (a) and at the street canyon section ends (c-d).

### 3.3 Similarity Analysis

As noted in Section 3.2, overall resemblances in the concentration fields at pedestrian level for the scenarios with avenue-trees were found. In order to analyze and quantify the similarity between the different scenarios S1 to S8, correlation coefficients according to

$$\rho_{ij} = \frac{\text{cov}(c_i, c_j)}{\sigma(c_i) \sigma(c_j)} \quad (2)$$

were calculated, where  $c_i$  and  $c_j$  are the concentrations in the scenarios  $i$  and  $j$ ,  $\text{cov}$  is the covariance and  $\sigma$  the standard deviation. In the context here, the correlation coefficients are a measure of the spatial similarity between the local deviations from the neighborhood-averaged concentrations of two scenarios. The correlation coefficients were calculated based on two approaches. In the first approach, they were calculated with the concentration values themselves (*classical approach*). However, since a few locations with extreme large deviations potentially can surpass many locations with small deviations, this type of correlation coefficient is not unconditionally an appropriate measure for the spatial similarity for the vast majority of locations. Hence, in the second approach, the concentration deviations were binarized by “+1” in the case of a positive deviation from the neighborhood-averaged concentration and by “-1” in the case of a negative deviation (*binarized approach*). The resulting correlation coefficients are an appropriate measure for the spatial similarity in the sense that every location is equally weighted.

Tab. 1 shows the resulting 8 x 8 matrices of correlation coefficients. Since the matrices are symmetric, the entries below the main diagonal were used for a graphical representation where bigger dots indicate larger correlations. All correlation coefficients according to both approaches are positive, indicating that, on average, deviations from the neighborhood-averaged concentrations are equal in sign for all scenarios. Independent of the tree layout, every of the studied cases yields overall to the same tendencies in concentration relative to the neighborhood-averaged concentration. The strongest similarity based on both approaches is found between scenarios S2 and S3 and scenarios S3 and S4. In particular the pronounced similarity between the latter scenarios suggests that the overall concentration field is not so much influenced by the layout of trees but rather by the total crown volume fraction (CVF) which is very similar in scenarios S3 and S4. The weakest similarities are found between the tree-free scenario S1 and the tree scenarios (S2 - S8). This means that independent of the tree layout, neighborhoods with avenue-trees are more similar among each other than to the tree-free neighborhood. Among the tree scenarios, the lowest correlation coefficients are found in combination with scenario S6, which, with its single tree patch in the street canyon center, is apparently characteristically different in terms of tree layout compared to the other scenarios (Fig. 1).

Tab. 1: Correlation coefficients between scenarios S1 - S8. Classical approach (top) and binarized approach (bottom).

	S1	S2	S3	S4	S5	S6	S7	S8
S1	-	0.34	0.35	0.34	0.39	0.57	0.40	0.42
S2	●	-	0.88	0.85	0.86	0.58	0.87	0.78
S3	●	●	-	0.88	0.87	0.59	0.88	0.80
S4	●	●	●	-	0.83	0.58	0.86	0.83
S5	●	●	●	●	-	0.58	0.88	0.77
S6	●	●	●	●	●	-	0.62	0.71
S7	●	●	●	●	●	●	-	0.77
S8	●	●	●	●	●	●	●	-

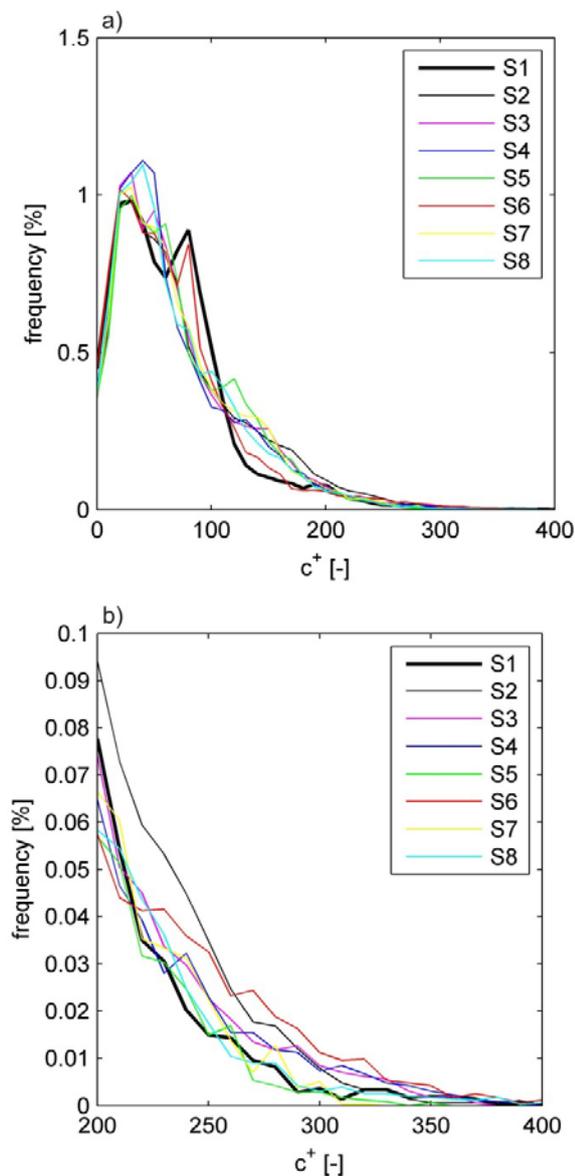
	S1	S2	S3	S4	S5	S6	S7	S8
S1	-	0.48	0.48	0.46	0.47	0.61	0.52	0.51
S2	●	-	0.76	0.74	0.73	0.48	0.74	0.68
S3	●	●	-	0.76	0.72	0.51	0.74	0.69
S4	●	●	●	-	0.69	0.50	0.73	0.73
S5	●	●	●	●	-	0.52	0.74	0.63
S6	●	●	●	●	●	-	0.53	0.57
S7	●	●	●	●	●	●	-	0.64
S8	●	●	●	●	●	●	●	-

Except for the tree-free scenario, the correlation coefficients according to the classical approach are always larger than those according to the binarized approach. Larger coefficients according to the classical approach imply the increased frequency of locationwise correlations of deviations of equal sign over locationwise correlations of deviations of unequal sign. However, since the differences in the correlation coefficients are rather small with  $|\rho_{ij,cl} - \rho_{ij,b}| < 0.15$ , suggest, given the overall similarity noted in [Section 3.2](#), that the obtained correlation coefficients are not strongly influenced by the correlation of extreme large deviations.

### 3.4 Pollutant Concentration Density Distributions

With respect to air quality and its impact on human health, the exceedance of threshold values is generally of most interest. Limits for ground level concentrations of outdoor air pollutants are given in national and international air quality laws and standards or guidelines. They often state threshold values for short term and long term exposure and comprise averaging periods of 1 to 24 hours or of one year, respectively. Threshold values of various air pollutants for different countries worldwide can be found in databases (e.g. AirBase, 2014; Airlex, 2014).

As a resource to assess the implications of avenue-trees on the exceedance probability of limit values, the relative frequency of pollutant concentrations over all locations in the neighborhood was determined. Fig. 10 displays the density distributions of the normalized concentrations for all scenarios (bin size  $\Delta c^+ = 10$ ). Scenarios S1 and S6 exhibit rather bimodal density distributions whereas the density distributions of the remaining scenarios can be considered as unimodal to a first approximation. Overall and without further analysis, the normalized concentration densities appear roughly gamma-distributed. As can be seen from Fig. 10a, the relative frequencies of normalized concentrations  $c^+ < 70$  are elevated in the scenarios with avenue-trees in comparison to the tree-free scenario (S1). In the range  $70 < c^+ < 110$ , the relative frequencies are lowered and finally for  $c^+ > 110$  elevated again (Fig. 10a, b).



*Fig. 10: Relative frequency of normalized pollutant concentrations.*

Whether or not the exceedance probability of a threshold value is increased due to an avenue-tree layout depends on the actual concentration  $c$  in the tree-free neighborhood and its limit value. For example, assume the actual concentration  $c$  of a certain pollutant species is slightly below its limit value at a certain number of locations in the tree-free neighborhood. If the corresponding normalized concentration is  $c^+ \approx 110$ , then the limit value is exceeded at an increased number of locations in the presence of avenue-trees. Whereas, if the corresponding normalized concentration is  $c^+ \approx 70$ , then the limit value is exceeded at a fewer number of locations in the presence of avenue-trees.

#### **4. Summary and Conclusions**

The effects of avenue-trees on flow and dispersion of traffic-emitted pollutants at pedestrian level in a generic urban neighborhood were analyzed with Computational Fluid Dynamics (CFD). Significant modifications in the flow field were found due to trees, comprising quantitative changes in wind velocity, i.e. decelerations or accelerations, as well as qualitative changes in the flow, i.e. different vortex structures and flow reversals. With respect to air quality, avenue-trees resulted in increased neighborhood-averaged concentrations, showing a 1% increase relative to the tree-free situation per percent crown volume fraction (CVF). The maximum relative increase in average concentration was 13.2% for a continuous avenue-tree row with CVF = 13.3%. A spatially resolved analysis revealed pronounced locally restricted increases as well as decreases in concentrations relative to the tree-free situation (-78 to +1378%) with stronger changes in the wind-parallel than in the wind-perpendicular street canyons. Overall, the changes were fairly homogeneously distributed within each street canyon section and over a column of sections oriented perpendicular to the approach flow direction. Column-averaged increases up to 88% and decreases up to 59% relative to the tree-free situation were found. The pattern of concentration changes was similar for all avenue-tree layouts, meaning that concentration increases (decreases) generally occurred in the same street canyon sections in all scenarios. This was further substantiated by a statistical similarity analysis where correlation coefficients larger than 0.58 between the scenarios with avenue-trees were found. A comparison of the two scenarios with discontinuous avenue-tree rows with alternating gaps of one tree width showed that the layout with the outermost tree position being empty was on average beneficial for the pollutant concentrations on the intersections (-9.9%). The concentration density distribution was classified as roughly gamma-distributed. The relative frequencies of *low* concentrations (here:  $c^+ < 70$ ) and of *high* concentrations (here:  $c^+ > 110$ ) were increased in neighborhoods with avenue-trees whereas for *moderate* concentrations (here:  $70 < c^+ < 110$ ) lower relative frequencies with respect to tree-free situation were noted. Consequently, a general statement whether or not avenue-trees lead to a higher exceedance probability of limit values is not possible since it depends on the actual concentration and the limit value itself.

In comparison to former studies on the influence of avenue-trees on flow and pollutant concentrations at the street canyon scale and intersection scale (e.g. Balczo et al., 2009; Buccolieri et al., 2011, 2009; Gromke and Ruck, 2012, 2009, 2007; Gromke, 2011; Gromke et al., 2008; Li et al., 2013; Moonen et al., 2013; Salim et al., 2011; Vos et al., 2013; Wania et al., 2012), qualitative and not only quantitative changes in the flow field were observed at the neighborhood scale. The qualitative changes indicate on the one side the necessity to perform studies at the urban neighborhood rather than at the street canyon scale and on the other side to account for avenue-trees, or more general all types of vegetation typical for built-up environments, in microscale urban air quality studies. Both aspects are imperative prerequisites for reliable and meaningful pollutant dispersion modeling and a realistic urban air quality assessment.

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#### **References**

AirBase, 2014. AirBase - the European Air quality dataBase.

- Airlex, 2014. Airlex - Worldwide Air Quality Legislation.
- Balczo, M., Gromke, C., Ruck, B., 2009. Numerical modeling of flow and pollutant dispersion in street canyons with tree planting. *Meteorol. Z.* 18, 197–206.
- Boppana, V.B.L., Xie, Z.-T., Castro, I.P., 2010. Large-eddy simulation of dispersion from surface sources in arrays of obstacles. *Bound.-Layer Meteorol.* 135, 433–454.
- Borrego, C., Tchepel, O., Costa, A.M., Amorim, J.H., Miranda, A.I., 2003. Emission and dispersion modelling of Lisbon air quality at local scale. *Atmos. Environ.* 37, 5197–5205.
- Borrego, C., Tchepel, O., Costa, A.M., Martins, H., Ferreira, J., Miranda, A.I., 2006. Traffic-related particulate air pollution exposure in urban areas. *Atmos. Environ.* 40, 7205–7214.
- Buccolieri, R., Gromke, C., Di Sabatino, S., Ruck, B., 2009. Aerodynamic effects of trees on pollutant concentration in street canyons. *Sci. Total Environ.* 407, 5247–5256.
- Buccolieri, R., Salim, S.M., Leo, L.S., Di Sabatino, S., Chan, A., Ielpo, P., de Gennaro, G., Gromke, C., 2011. Analysis of local scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. *Atmos. Environ.* 45, 1702–1713.
- Buccolieri, R., Sandberg, M., Di Sabatino, S., 2010. City breathability and its link to pollutant concentration distribution within urban-like geometries. *Atmos. Environ.* 44, 1894–1903.
- Carpentieri, M., Salizzoni, P., Robins, A., Soulhac, L., 2012. Evaluation of a neighbourhood scale, street network dispersion model through comparison with wind tunnel data. *Environ. Model. Softw.* 37, 110–124.
- Di Sabatino, S., Buccolieri, R., Pulvirenti, B., Britter, R., 2007. Simulations of pollutant dispersion within idealised urban-type geometries with CFD and integral models. *Atmos. Environ.* 41, 8316–8329.
- Garbero, V., Salizzoni, P., Soulhac, L., 2010. Experimental study of pollutant dispersion within a network of streets. *Bound.-Layer Meteorol.* 136, 457–487.
- Gromke, C., 2011. A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies. *Environ. Pollut.* 159, 2094–2099.
- Gromke, C., Blocken, B., 2014. Influence of avenue-trees on air quality at the urban neighborhood scale. Part I: Quality assurance studies and turbulent Schmidt number analysis for RANS CFD simulations, submitted to *Environmental Pollution*.
- Gromke, C., Buccolieri, R., Di Sabatino, S., Ruck, B., 2008. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations—evaluation of CFD data with experimental data. *Atmos. Environ.* 42, 8640–8650.
- Gromke, C., Ruck, B., 2007. Influence of trees on the dispersion of pollutants in an urban street canyon—experimental investigation of the flow and concentration field. *Atmos. Environ.* 41, 3287–3302.
- Gromke, C., Ruck, B., 2009. On the impact of trees on dispersion processes of traffic emissions in street canyons. *Bound.-Layer Meteorol.* 131, 19–34.
- Gromke, C., Ruck, B., 2012. Pollutant concentrations in street canyons of different aspect ratio with avenues of trees for various wind directions. *Bound.-Layer Meteorol.* 144, 41–64.
- Hamlyn, D., Hilderman, T., Britter, R., 2007. A simple network approach to modelling dispersion among large groups of obstacles. *Atmos. Environ.* 41, 5848–5862.
- Hang, J., Li, Y., Sandberg, M., 2011. Experimental and numerical studies of flows through and within high-rise building arrays and their link to ventilation strategy. *J. Wind Eng. Ind. Aerodyn.* 99, 1036–1055.
- Li, J.-F., Zhan, J.-M., Li, Y.S., Wai, O.W., 2013. CO<sub>2</sub> absorption/emission and aerodynamic effects of trees on the concentrations in a street canyon in Guangzhou, China. *Environ. Pollut.* 177, 4–12.
- Moonen, P., Gromke, C., Dorer, V., 2013. Performance assessment of Large Eddy Simulation (LES) for modeling dispersion in an urban street canyon with tree planting. *Atmos. Environ.*

- Panagiotou, I., Neophytou, M.K.-A., Hamlyn, D., Britter, R.E., 2013. City breathability as quantified by the exchange velocity and its spatial variation in real inhomogeneous urban geometries: An example from central London urban area. *Sci. Total Environ.* 442, 466–477.
- Pascheke, F., Barlow, J.F., Robins, A., 2008. Wind-tunnel modelling of dispersion from a scalar area source in urban-like roughness. *Bound.-Layer Meteorol.* 126, 103–124.
- Princevac, M., Baik, J.-J., Li, X., Pan, H., Park, S.-B., 2010. Lateral channeling within rectangular arrays of cubical obstacles. *J. Wind Eng. Ind. Aerodyn.* 98, 377–385.
- Ramponi, R., Blocken, B., Janssen, W., de Coo, L., 2014. CFD simulation of ventilation performance of generic urban configurations with different urban densities and equal and unequal street widths. submitted.
- Salim, S.M., Cheah, S.C., Chan, A., 2011. Numerical simulation of dispersion in urban street canyons with avenue-like tree plantings: Comparison between RANS and LES. *Build. Environ.* 46, 1735–1746.
- Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., Henshaw, G.S., 2013. The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. *Sci. Total Environ.* 443, 287–298.
- Soulhac, L., Puel, C., Duclaux, O., Perkins, R.J., 2003. Simulations of atmospheric pollution in Greater Lyon an example of the use of nested models. *Atmos. Environ.* 37, 5147–5156.
- Soulhac, L., Salizzoni, P., Cierco, F.-X., Perkins, R., 2011. The model SIRANE for atmospheric urban pollutant dispersion; part I, presentation of the model. *Atmos. Environ.* 45, 7379–7395.
- Soulhac, L., Salizzoni, P., Mejean, P., Didier, D., Rios, I., 2012. The model SIRANE for atmospheric urban pollutant dispersion; part II, validation of the model on a real case study. *Atmos. Environ.* 49, 320–337.
- Vos, P.E., Maiheu, B., Vankerkom, J., Janssen, S., 2013. Improving local air quality in cities: To tree or not to tree? *Environ. Pollut.* 183, 113–122.
- Wania, A., Bruse, M., Blond, N., Weber, C., 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *J. Environ. Manage.* 94, 91–101.
- Xie, Z.-T., Castro, I.P., 2009. Large-eddy simulation for flow and dispersion in urban streets. *Atmos. Environ.* 43, 2174–2185.