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Impact of trees on gas concentrations and condensables in a 2-D street canyon using CFD coupled to chemistry modeling [☆]

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ABSTRACT

Trees grown in streets impact air quality by influencing ventilation (aerodynamic effects), pollutant deposition (dry deposition on vegetation surfaces), and atmospheric chemistry (emissions of biogenic volatile organic compounds, BVOCs). To qualitatively evaluate the impact of trees on pollutant concentrations and assist decision-making for the greening of cities, 2-D simulations on a street in greater Paris were performed using a computational fluid dynamics tool coupled to a gaseous chemistry module. Globally, the presence of trees has a negative effect on the traffic-emitted pollutant concentrations, such as NO₂ and organic condensables, particularly on the leeward side of a street. When not under low wind conditions, the impact of BVOC emissions on the formation of most condensables within the street was low owing to the short characteristic time of dispersion compared with the atmospheric chemistry. However, autoxidation of BVOC quickly forms some extremely-low volatile organic compounds, potentially leading to the formation of ultra-fine particles. Planting trees in streets with traffic is only effective in mitigating the concentration of some oxidants such as ozone (O₃), which has low levels in cities regardless of this, and hydroxyl radical (OH), which may slightly lower the rate of oxidation reactions and the formation of secondary species in the street.

1. Introduction

Urban air pollution is an important global issue and has been reported as being responsible for almost nine million premature deaths in 2015 (Forouzanfar et al., 2016; Landrigan et al., 2018). Observations of high concentrations of nitrogen dioxide (NO₂) and particulate matter (PM) of aerodynamic diameters lower than 2.5 μm and 10 μm (PM_{2.5} and PM₁₀) in urban streets have been attributed to traffic emissions and reduced atmospheric ventilation (Gottlicher et al., 2010; Thorpe and Harrison, 2008; Markku, 2015). As these pollutants have adverse health effects (Speizer et al., 1980; Weinmayr et al., 2010; WHO, 2021) and human exposure to outdoor pollution is high due to the pollutants' high concentrations (Lugon et al., 2022), improving street-level air quality is beneficial for human health (Finkelstein and Jerrett, 2007; Chen et al., 2017; Yuchi et al., 2020).

Planting vegetation along streets is considered an effective method to mitigate air pollution. However, the impact of trees on the air quality within urban street canyons is subject to complex processes. The

presence of trees affects street ventilation and changes pollutant dispersion (Gromke and Ruck, 2007; Buccolieri et al., 2009; Abhijith et al., 2017), leading to high concentrations of pollutants emitted by traffic, such as NO₂ and PM (Vos et al., 2013). However, trees can absorb pollutants and retain them via deposition (Nowak et al., 2006; Currie and Bass, 2008; Escobedo et al., 2011). The deposition velocity varies with the vegetation type and the different pollutants (Buccolieri et al., 2009), depending on both the reactivity and the Henry's Law constant of the pollutant (Wesely, 1989). Several models have been developed to evaluate the deposition effects from simple constant deposition velocity models (Nowak et al., 2006, 2013; Pugh et al., 2012; Baraldi et al., 2019) to more complex models that estimate the deposition velocities as the inverse of the sum of resistances (Baldocchi et al., 1987; Hirabayashi et al., 2012; Cabaraban et al., 2013; Selmi et al., 2016). In addition, the presence of trees in streets can affect atmospheric chemistry. Trees emit biogenic volatile organic compounds (BVOCs), which may lead to the formation of O₃ in cities (Calfapietra et al., 2013; Churkina et al., 2015, 2017), because the chemical regimes of cities are usually VOC-limited

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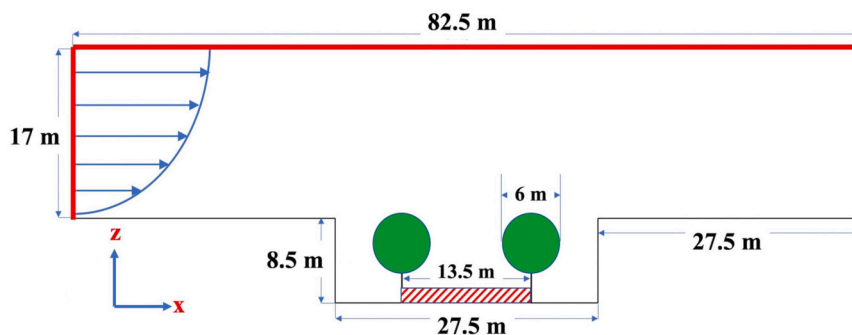


Fig. 1. Simulation domain. Tree crowns are cylindrical, as shown by the two circles. Between the trees, the traffic zone is modelled as a surface source, as shown by the stripe lines.

(Sartelet et al., 2012; Seigneur, 2019), however, this may be minimal at the street scale where O_3 concentrations are generally quite low (Kwak and Baik, 2014). Furthermore, BVOC emissions may lead to the formation of PM (Churkina et al., 2017). BVOCs may be oxidized by O_3 and radicals such as hydroxyl (OH) to form organic condensables (Seigneur, 2019). Condensable species are gaseous compounds that may condense onto particles depending on the environment. Organic condensables also have an anthropogenic origin and may be emitted directly by traffic (Sartelet et al., 2018).

To study the combined effects of these tree-related processes, various numerical modeling techniques have been developed, ranging from simple street models (Maison et al., 2022; Lugon et al., 2020) to more complex Computational Fluid Dynamics (CFD) models. CFD models are powerful tools for estimating pollutant concentrations and fluxes at small scales (with feasible grid refinement less than 1 m). Pollutants are treated as passive scalars in most CFD models due to the high impact of atmospheric and morphological conditions, and chemical reactions are not considered (Zhang et al., 2020). This may lead to an underestimation of pollutant concentrations, particularly for NO_2 and organic condensables (Lugon et al., 2020). Therefore, chemical models are coupled with CFD models to represent the transport of pollutants and their interactions (Baker et al., 2004; Grawe et al., 2007; Baik et al., 2007; Kikumoto and Ooka, 2012; Liu and Leung, 2008; Garmory et al., 2009; Kwak and Baik, 2012; Kwak et al., 2013; Zhong et al., 2014). Most chemical models have been designed originally for O_3 formation and so often ignore condensable formation (Kim et al., 2011).

In this study, a modified version of the chemical mechanism CB05 (Yarwood et al., 2005) that considers the formation of condensables (Chrit et al., 2017; Sartelet et al., 2020) was coupled to a RANS ($k-\epsilon$) turbulence model to investigate air quality in a street canyon, focusing on the two-dimensional flow in the vertical cross-section (Vardoulakis et al., 2003). As the physico-chemical processes linked to the presence of trees in street canyons have antagonistic impacts on air quality (circulation, deposition, and chemistry), the objective of this study is to evaluate their relative and overall impacts to provide guidance to aid decision-making with respect to the greening of cities. The model is presented in the second section. Sensitivity tests are undertaken and the results are presented in the third section to qualitatively evaluate the impacts of the different tree-related processes. The influence of these processes on atmospheric compounds, such as NO_2 , CO, and inorganic and organic condensables, is discussed to provide a qualitative estimation of the local-scale impact of trees on the mitigation of air pollutants in street canyons.

2. Methodology

CFD simulations were performed with Code_Saturne (Archambeau et al., 2004; Milliez and Carissimo, 2007) using the RANS approach with a $k-\epsilon$ linear production for turbulence (Guimet and Laurence, 2002). The gas-phase mechanism, coupled with the CFD model, is a modified

version of CB05 (Yarwood et al., 2005) which considers condensables (Sartelet et al., 2020).

2.1. Domain of study

The street canyon “Boulevard Alsace-Lorraine” (in east Paris), as discussed in Kim et al. (2018), was modelled by a two-dimensional regular grid with a resolution of 0.5 m. The geometry of the model corresponded to the average aspect ratio of the street. Fig. 1 shows the domain used in the simulation. The canyon height (H) was 8.5 m, and the width (W) 27.5 m, corresponding to a moderate aspect ratio of 0.31 (Sini et al., 1996; Lugon et al., 2020). Trees were located on both sides of the street and were placed every 10 m along the street’s length. The center of the crown was placed at a height of 6 m and extended along the street length, with crown radius of 3 m. The tree canopy structure was described by the leaf area index (LAI), which is a commonly-used indicator of the number of leaves for different types of vegetation. As the model was 2-D, the crown of trees was modelled as a cylinder and the LAI 3-D of the vegetation converted to LAI 2-D (Maison et al., 2022). The roadway, determined as the traffic zone, was placed between the trees, as shown by the striped zone in Fig. 1. The height of the vehicle zone, where the traffic produced turbulence mixes and diluted traffic emissions, was assumed to be 1.5 m according to Solazzo et al. (2008) and Niroomand et al. (2021). The inlet was set at the lower x boundary (left, Fig. 1) and at the top of the domain. The outlet was set at the upper x boundary of the domain (right, Fig. 1).

2.2. Air flow around trees

In areas covered by trees, the turbulent flow was computed using a porosity model (Zaidi et al., 2013). The canopy of trees exerted an aerodynamic drag force on the flow, which reduced the speed and changed the turbulence structure. It was modeled by a source term in the momentum and turbulence equations, which are detailed in section 1.1 in the supplementary materials.

2.3. Emissions from traffic and vegetation

CO, NH_3 , NO_x and VOC emissions from traffic exhaust (Kim et al., 2022) and monoterpene and isoprene emissions from trees were considered in the model. Hourly-varying traffic emissions were those reported by Kim et al. (2022) and relied on emission factors from the COPERT methodology (Computer Program to calculate Emissions from Road Transport, version 2019, EMEP/EEA, 2019). The characteristics of the Japanese pagoda tree (*Styphnolobium japonicum*), a common species in Paris known widely as “*Sophora Japonica*” were used, with a 2-D LAI of $4 \text{ m}^2 \text{ m}^{-2}$. Isoprene (ISOP) and monoterpenes (α -pinene API, β -pinene BPI and limonene LIM) account for the largest fraction (Guenther et al., 1995) of VOCs emitted by trees and therefore were the only emissions considered. The emissions were modelled using standard parameterizations, as detailed in section 1.3 in the supplementary materials.

Table 1
List of simulations and their configurations.

Case id	BVOC emissions	Dry deposition on urban surfaces	Dry deposition on vegetation surfaces	Date	Tree
ref_A/ref_J	no	yes	no	April/July	no
0_J	no	yes	no	July	yes
1_A/1_J	yes	yes	yes	April/July	yes
2_J	no	yes	yes	July	yes
3_J	yes	no	yes	July	yes
4_J	yes	yes	no	July	yes

2.4. Dry deposition

Gaseous pollutants can be deposited on urban surfaces such as streets, building walls and vegetation. Deposition on urban surfaces is achieved by imposing a mass flux on the boundary faces, while deposition on vegetation surfaces is achieved by using a sink term in the transport equation, as detailed in section 1.2 in the supplementary materials.

The formulations used to represent dry deposition on urban surfaces were based on Chérin et al. (2015), Hicks et al. (1987) and Wesely (1989). Deposition on trunks was ignored because gaseous pollutants are mainly affected by leaves in the tree canopy. The deposition velocity on trees was estimated using surface resistance and the quasi-laminar layer resistance (Wesely, 1989; Erisman et al., 1994).

2.5. Boundary conditions

As the simulation domain is small and low in height, the atmosphere was assumed to be neutral. The wind from the inlet was assumed to be unidirectional and perpendicular to the direction of the street, as shown in Fig. 1. The wind profile at the inlet above the street canyon was assumed to follow the semi-empirical logarithmic function:

$$u_x = \frac{u_*}{\kappa} \times \log \left(\frac{z - H + z_0}{z_0} \right), \quad (1)$$

where u_* is the friction velocity, κ is the Von Karman constant (0.42), H is the building height (8.5 m), and z_0 is the surface roughness of the building roof. The turbulent kinetic energy k and dissipation rate ε at the inlet are calculated as follows:

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \text{ and } \varepsilon = \frac{u_*^3}{\kappa(z - H + z_0)} \text{ with } C_\mu = 0.09. \quad (2)$$

The time-varying inflow was driven by the meteorological parameters. Hourly-varying meteorological conditions (friction velocity (ms^{-1}), temperature (K), and specific humidity (g kg^{-1})) and the background concentrations of the gas-phase compounds above the street were obtained from the regional-scale simulations of Sartelet et al. (2018). At each time step, a linear interpolation provided inlet profiles.

2.6. Model parameters

Surface roughness (z_0) was detailed for different urban surfaces, set at 1 m on roof surfaces (Wiernga, 1993), and 0.1 m on walls and road surfaces in the canyon, considering the urban furniture (windows, balconies, pavements, etc.).

The turbulent dispersion of pollutants is described by the turbulent Schmidt number (Sc_t) under the simple gradient diffusion hypothesis. According to Tominaga and Stathopoulos (2007), Sc_t ranges between 0.2 and 1.3, and the optimum choice of this parameter depends on the local flow characteristics. In this study, the best model for measurement comparison was obtained with $Sc_t = 0.4$. The model without trees was evaluated by comparing the simulated concentrations of NO_2 and PM_{10} to measurements for a day in April reported by Lin et al. (2022).

2.7. Case study

Tree-related processes (VOC emissions by trees, atmospheric dry depositions, and aerodynamic effects of tree crowns) and chemical reactions influence the evolution of concentrations in the street. Simulations were performed for a few hours in July, when the temperature and tree VOC emissions were high, and also for a few hours in April, when NO_2 measurements were available (Lin et al., 2022).

Table 1 lists the simulations and adopted configurations. In the reference cases for April (case ref_A) and July (case ref_J), trees were not considered. In case 1_J and 1_A, all trees-related processes were considered, while case 0_J only considered the aerodynamic effect. Sensitivity tests were performed and analyzed by comparison with case 1_J, except for the aerodynamic effect, which used case 0_J as the reference case. In each sensitivity test, one process was ignored (case 2_J for BVOC emissions, case 3_J for dry deposition on urban surfaces, and case 4_J for dry deposition on vegetation surfaces), as detailed in Table 1. The difference between the two simulations was quantified using the relative deviation (RD_{C_i}) of the spatially averaged street concentration of the street (from the ground to the roof level), which is defined as follows:

$$RD_{C_i} = \frac{C_i - C_{i-0}}{C_{i-0}} \times 100\% \quad (3)$$

where C_i represents the average street concentration in a sensitivity test and C_{i-0} represents the average street concentration in the reference case.

Each sensitivity simulation lasted 3.5 h, on July 18, 2014 (or on April 30, 2014) from 2.30 p.m. to 6 p.m. (local Paris time, GMT + 2), with a constant time step of 1 s. The first 30 min corresponded to the model spin-up time, and the analysis was performed for the remaining 3 h.

The impact of tree-related processes was assessed for several gaseous species, including those emitted by traffic (NO , NO_2 , NH_3 , and CO), O_3 , radical OH, and condensable HNO_3 (which may condense with NH_3 to form inorganic particles of ammonium nitrate). For organic compounds, three groups of organic condensables were studied: biogenics, formed from the oxidation of monoterpenes and isoprene (Bio. cond.), anthropogenics, formed from the oxidation of xylenes and toluene (Ant. cond.), and anthropogenic intermediate, semi-, and low-volatility organic compounds (ISVOC), which are directly emitted by traffic and oxidized in the atmosphere.

The characteristic times of dispersion and reaction were calculated to compare the dispersion rate with the chemical reaction rates. For dispersion, the street-average concentration was assumed to evolve following an exponential function for a transient period under constant wind conditions as follows:

$$C(t) = C_0 + (C_\infty - C_0) \left(1 - \exp \left(-\frac{t}{\tau_D} \right) \right) \quad (4)$$

where C_0 is the initial street concentration of a compound, C_∞ is the concentration at the end of the transient period, and τ_D is the characteristic dispersion time.

The characteristic reaction time τ_R considers the production/consumption of a reactive compound by different chemical reactions. This is approximated as follows:

Table 2

Summary of tree impacts on the street-average concentrations of different species in the street. The column Ref. corresponds to the average concentrations of the case 1_J. The columns VOC, Dep urb, Dep tree, Aerodyn. and Synth. correspond to the impact of VOC emissions, deposition on urban surfaces, deposition on trees, aerodynamic effects and overall effects, respectively.

Species	Ref. 1_J $\mu\text{g m}^{-3}$	VOC % (2_J - 1_J) %	Dep urb (3_J - 1_J) %	Dep tree (4_J - 1_J) %	Aerodyn (ref_J - 0_J) %	Synth July (ref_J - 1_J) %	Synth April (ref_A - 1_A) %
NO	22.0	0.9	-0.4	-0.9	-27.5	-27.6	-27.8
NO ₂	42.3	-0.7	1.5	3.5	-23.8	-21.5	-16.1
NH ₃	2.8	0.0	1.2	3.6	-6.3	-2.0	-9.0
CO	158	0.0	0.0	2.2	-10.5	-8.7	-7.3
HNO ₃	2.6	0.7	5.9	25.0	0.3	21.8	26.2
O ₃	82.5	-0.3	0.9	3.2	6.1	8.8	10.7
OH	3.1×10^{-4}	17.4	-0.4	-1.4	13.6	26.4	9.0
Bio cond.	4.3	-0.2	0.0	0.0	0.0	-0.2	-0.1
ELVOC	1.6×10^{-4}	-73.9	0.7	2.4	-14.3	-78.0	-55.1
Ant cond.	0.8	0.1	0.0	-0.01	-0.2	-0.1	-0.2
ISVOC	5.5	0.04	0.1	0.7	-15.0	-14.1	-16.7

$$\tau_R = \frac{\bar{C}}{|R_P - R_C|} \quad (5)$$

where \bar{C} is the average concentration, R_P is the production rate, and R_C is the consumption rate.

3. Results

The impacts of different tree-related processes on the evolution of concentrations were estimated. The processes involve tree VOC emissions, dry deposition on vegetation and urban surfaces, and aerodynamic influence of tree crowns on the dispersion. Finally, the overall impact of these processes on the pollutant concentrations in the streets was evaluated. Table 2 illustrates the impact of different processes using the relative deviation of the street-averaged concentrations (RD_{C_i}) between the two simulations.

3.1. Impact of tree VOC emissions

Tree VOC emissions had a limited impact (lower than 1%) on the gas-phase reactive compounds: NO, NO₂, and O₃. However, the street-averaged concentration of radical OH was significantly reduced by approximately 17%. The production of O₃ by the tree VOC emissions was low in the high-NO_x chemical regime of the street (approximately 0.2%). Therefore, the production of OH by O₃ photolysis was low. The OH concentration decreased because it was consumed by the VOC emitted by the trees. The evolution of NO₂, OH, and the chemical regime are detailed in Figures 1 and 2 in the supplementary materials.

This decrease in OH also resulted in a slight decrease in HNO₃ (0.7%), which was formed from the oxidation of NO₂. This low decrease in HNO₃ most likely has a low impact on inorganic aerosol concentrations.

For organic compounds, the monoterpene and isoprene concentrations increased substantially owing to tree VOC emissions, reaching on average 467% and 5,000%, respectively, over the simulation period. Monoterpene and isoprene were oxidized to form biogenic organic condensables (see Figure 3 in the supplementary materials). However, tree VOC emissions had a low impact on the mass of organic condensables at the local scale (Table 2). In the model, a representation of the condensable formation was built from chamber experiments with a limited number of model species. The formation of condensables was simplified by only one oxidation step of the precursor. The oxidation characteristic time was typical of what was observed in chambers, but it might not represent the fast-forming compounds, such as those produced from autoxidation (Ehn et al., 2014), which were only modelled in this study for the autoxidation of monoterpenes. For monoterpenes, one oxidation step by O₃, NO₃ and OH directly led to the formation of modelled condensables (of note, BIA0D, BiA1D, BiA2D, BiNIT, Monomer

and Dimer). Only the formation of extremely-low volatile compounds (ELVOC) with very low saturation vapor pressure (Ehn et al., 2014), from monoterpene autoxidation, which was represented by two model species (Monomer and Dimer), was enhanced because it involved fast reacting radical species. Although the ELVOC concentrations largely increased (by 276% on average), they were low compared to other organic concentrations, with a maximum of $1.5 \times 10^{-4} \mu\text{g m}^{-3}$. Panels (a) and (b) of Fig. 3 show the spatial distribution of the time averaged ELVOC concentrations. This increase was mostly near the leeward side of the street.

For isoprene, biogenic condensables were modelled as for monoterpenes, from the limited number of model species in chamber experiments. Some of these species were produced from the oxidation of intermediate products such as isoprene nitrates (ISON), first-order OH reaction products of isoprene (ISOR), methacrolein (MACR) and methacryloyl peroxyxynitrate (MPAN). Although the concentrations of these intermediate products largely increased with tree VOC emissions (ISON + 47.39%, ISOR + 1195.18%, MACR + 1101.37% and MPAN + 136.17%), the formation of condensables was not significantly affected.

Owing to the long time required for monoterpenes and isoprene to undergo oxidation in the atmosphere (Seigneur, 2019), secondary organic condensables did not seem to have sufficient time to form in the street, except for those formed from autoxidation. A better representation of the fast-forming condensables from radicals is desirable to determine more accurately the influence of monoterpenes and isoprene emissions on condensable concentrations.

3.2. Impact of VOC emissions in the street with low-wind speed

Although some intermediate oxidized species, such as MACR and MPAN were significantly produced with the addition of tree VOC emissions, the production of condensables was limited because of the long time required for the oxidation reactions to complete. To illustrate this, the characteristic times of the OH reactions, τ_R , and the dispersion of the flow, τ_D , were compared.

The concentration of CO was used for the calculation of τ_D because of its low reactivity. τ_D was estimated to be approximately 32 s. For OH, τ_R was approximately 86 s with tree VOC emissions and 154 s without tree VOC emissions, i.e., it is at least twice the characteristic time of dispersion, highlighting the low value of the characteristic time of dispersion.

This low characteristic time of dispersion may be due to the high wind speed at the inlet of 5 ms^{-1} at 25 m. With a lower wind speed of 0.7 ms^{-1} at 25 m, the characteristic time of dispersion was 186 s. To assess the effect of wind speed, two more sensitivity tests with the same configuration as cases 1_J and 2_J were conducted at low wind speeds (cases 5_J and 6_J). Fig. 2 compares the condensable concen-

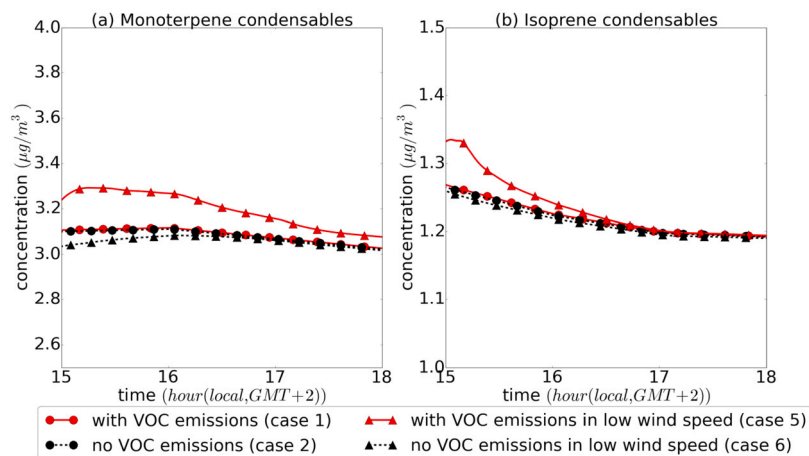


Fig. 2. Condensable concentrations in high-wind speed and low-wind speed conditions, (a) condensables from monoterpene, (b) condensables from isoprene.

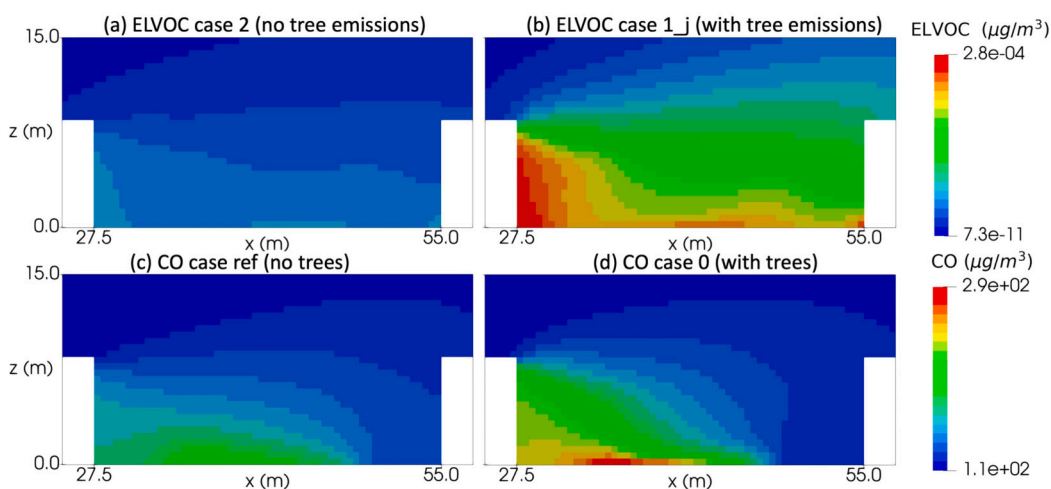


Fig. 3. Temporally-averaged concentration of ELVOCs (panels (a) and (b)) and CO (panels (c) and (d)) in and above the street.

trations from the oxidation of monoterpenes and isoprene, when tree VOC emissions were considered or not under high- and low-wind speed conditions. The production of condensables was more significant in the low-wind speed condition than in the high-wind speed condition, with a time-averaged increase of approximately 5% for monoterpene condensables and 7% for isoprene condensables, compared to less than 1% for both under the high-wind speed condition.

3.3. Atmospheric dry deposition

To evaluate the impact of atmospheric dry deposition, case 1_J, which considered dry deposition on both urban and vegetation surfaces (tree crowns), was compared to cases 3_J and 4_J, which considered only urban and vegetation surfaces, respectively. Here, urban surfaces refer to the building walls and the ground in the canyon. The impact varies with species due to properties such as solubility (Henry coefficient) and volatility.

For all species studied, the impact of deposition on urban surfaces was low (less than 1%, except for HNO_3 (6%)). For most species, the deposition on vegetation surfaces was slightly higher than that on urban surfaces, but it remained low (lower than 4%). However, as is shown in Figure 4 in the supplementary material, HNO_3 is shown to be more affected by deposition due to its high solubility, particularly on leaf surfaces. This resulted in a significant reduction in HNO_3 concentrations (25%), which may restrain the gas/particle partitioning and the formation of secondary aerosols.

3.4. Aerodynamic impact of tree crowns

A comparison of the flow fields in Figure 5 in the supplementary material shows that, in general, the presence of trees reduced the turbulent viscosity in the canyon, which indicates that the turbulent dispersion of pollutants was reduced. The characteristic time of dispersion increased from 21 to 32 s with the trees present, under which conditions the horizontal wind velocity was higher in the middle and near the windward side of the street, and lower on the leeward side. This indicates that the residence time was higher on the leeward side, which was more prone to pollutant accumulation.

The variation in the flow field affects both the dispersion of pollutants and their concentrations. Table 2 shows that the aerodynamic effect of tree crowns significantly increased the street average concentration for species emitted by traffic (NO, NO_2 , CO, NH_3 , ISVOC). Owing to the presence of tree crowns, species were less dispersed and accumulated more in the traffic zone, resulting in a higher street average concentration. However, the aerodynamic effect of tree crowns significantly reduced the concentrations of reactive oxidants in the atmosphere, such as O_3 and OH radical, because these species were more consumed by reactions with traffic exhaust emissions such as NO.

To analyze the aerodynamic effect of tree crowns on spatial distribution, CO is studied, because it is relatively unaffected by the chemistry at the urban scale (Seigneur, 2019) compared to other species. Panels (c) and (d) of Fig. 3 present the CO concentration in and above the street with and without tree crowns. The CO concentration was much higher in the street than in the background above the street, due to

traffic emissions, regardless of the presence of trees. The highest concentration was observed on the leeward side of the street because of the reverse flow. Trees led to a significant increase in concentrations near the leeward side, and a small decrease near the windward side. The presence of trees accentuated the concentration differences between the leeward and the windward sides.

3.5. Overall impact of trees

The overall impact of trees was evaluated by comparing the Case ref (without trees) and the Case 1 (with trees) for both April and July (Table 2). The presence of trees led to a large increase in the concentrations of NO, NO₂, CO and ISVOC emitted by traffic, mainly due to the aerodynamic effects. The overall impact was similar in April and in July. The increase ranged from 7% for CO to 28% for NO.

The presence of trees led to a large decrease in the concentrations of the oxidants O₃ and OH, by 9%-11% and 9%-26%, respectively. O₃ concentrations were low in streets because of the traffic emissions of NO_x. The decrease of O₃ and OH were both partly due to the increase in NO_x (aerodynamic effect), but also due to the dry deposition for O₃ and tree VOC emissions for OH. Owing to the high wind speed in the canyon, this decrease in oxidant concentrations had a very low impact on organic condensables, which were almost not modified by trees, except for ISVOCs, because they were directly emitted by traffic.

From those results, it can be inferred that the presence of trees likely leads to an increase in particle concentrations in the street, as particles are directly emitted by traffic and would accumulate due to aerodynamic effects. Furthermore, the increase in organic condensables at low wind speeds may lead to the formation of organic particles. The evolution of inorganic particles is less clear, as it depends on the evolution of inorganic condensables and the limiting factor for the formation of ammonium nitrate, i.e., HNO₃ or NH₃ concentrations. These evolved in the opposite direction, with the HNO₃ concentrations reduced by trees (by 22% to 26%) because of dry deposition on leaf surfaces, while NH₃ increased because it was emitted by traffic.

4. Conclusions

In this study, the effects of trees on gaseous species and condensable concentrations in a street canyon were investigated by a coupled CFD-gas-chemistry model to evaluate the impact of trees on mitigating pollutant concentrations.

Different gaseous species are sensitive to various tree-related processes. Trees grown in streets cannot mitigate the concentrations of pollutants emitted by traffic because the aerodynamic effect dominates. The pollutant concentrations accumulate at the pedestrian level near the leeward side of the street. For oxidants, trees reduce the average concentrations of O₃ and OH radicals, thereby decreasing the formation of secondary species. However, this decrease is not very important for the formation of condensables, and O₃ concentrations are low in streets regardless of this. The concentrations of organic condensables increase slightly due to the oxidation of tree-emitted VOC, especially on the leeward side, while the formation of ELVOC from autoxidation is enhanced, potentially leading to the formation of ultra-fine particles. For inorganic condensables, the impact of vegetation is balanced, with HNO₃ reduced owing to the dry deposition effect on tree leaves, while NH₃ increased due to the aerodynamic effects of trees.

In this study, the geometry of the street canyon was simplified to a 2-D representation with a perpendicular wind direction. However, further studies with a more realistic 3-D geometry-based model and more complex street networks are important to acquire conclusions more representative of individual districts, alongside with a field measurement campaign to provide a robust validation. The radiative effects of trees and the aging of tree-emitted VOCs at the regional scale should also be considered in future models.

CRediT authorship contribution statement

Yunyi Wang: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Cédric Flageul:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alice Maison:** Formal analysis. **Bertrand Carissimo:** Conceptualization, Formal analysis, Funding acquisition, Writing – review & editing. **Karine Sartelet:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code and data used in this study are openly available in <https://doi.org/10.5281/zenodo.7180003>.

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