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MODELLING THE IMPACTS OF URBAN TREES ON AIR QUALITY IN STREETS

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Abstract: Models are commonly used to study air quality in urban areas, which are known to be areas of poor air quality. To model air pollutant concentrations at a fine scale (street) and over entire cities, fast running codes are developed such as the Model of Urban Network of Intersecting Canyons and Highways (MUNICH). They used simplified parameterizations especially for transport. Although they can not reproduce finely the street micrometeorology, they can reproduce the gradients of concentrations between the streets and the urban background. These transport parameterizations have been recently improved and the effect of the tree crown was included in MUNICH. Planting trees in cities has been widely developed nowadays mainly for their capacity to decrease temperatures and limit the urban heat island. Tree effects on air quality are various, they can have a positive impact by capturing pollutants by dry deposition. However, trees reduce air flow in the street and limit pollutant dispersion. They also emit volatile organic compounds (BVOCs) that can lead to ozone and secondary organic aerosol production. The objective of this study is to analyse and compare these three effects of trees on air quality based on simulation results from MUNICH. For the test case presented here, the tree aerodynamic effect is the main effect, it induces an increase of the concentrations (up to +10%). The decrease of concentrations due to dry deposition is very limited (less than 1%). The BVOC emission has a negligible impact on particle formation at the local scale.

Key words: *air quality modelling, street-network model, urban tree, biogenic emissions, volatile organic compounds*

INTRODUCTION

Urban areas concentrate population and human activities inducing higher pollutant emissions. The presence of high buildings and artificial impervious surfaces strongly modifies the energy and water balances and reduces air flow inside streets. These processes lead to a degradation of the air quality especially at the street level due to traffic related emissions. Models are widely used tools for understanding processes and predicting air quality. They can be of various types and resolutions depending on the system studied. At the street level, higher pollutant concentrations are often observed compared to the concentrations in the urban background and they cannot be represented using chemical-transport models that have spatial resolution of the order of kilometer. Computational Fluid Dynamics (CFD) models coupled to chemistry/aerosol models may be used to compute the pollutant concentrations over limited areas of cities, but they are too expensive to use over a whole city. Hence, simplified street-network models, such as the Model of Urban Network of Intersecting Canyons and Highways (MUNICH, http://cerea.enpc.fr/munich/), are developed. They include the main processes that influence pollutant concentrations: emissions, transport, deposition, chemistry and aerosol dynamics. However, the streets are not discretized finely, but in MUNICH concentrations are assumed to be homogeneous in each street segment. The complex street micrometeorology is simplified by considering only the vertical transfer between the street and the background and the horizontal transfer between the streets. Urban trees are usually not taken into account in simplified street-network models. However, planting trees in cities is largely promoted for all the ecosystem services vegetation can bring (improve human thermal comfort, limit water runoff, store carbon and enhance human well-being). Regarding tree effect on air quality, trees represent surfaces available for pollutant dry deposition, and hence can contribute to reduce air pollutants concentrations. However, trees also emit volatile organic compounds, which may affect air quality and the presence of trees in street canyons reduces the wind velocity in the street and limits pollutant dispersion. Recent developments were done to include these tree effects on air quality in MUNICH. The tree aerodynamic effect, that has been largely studied with CFD models, was parameterized based on CFD simulations using the open-source code Code_Saturne (https://www.code-saturne.org/). Dry deposition of gas and aerosols on street surfaces and tree leaves are modelled using existing parametrizations based on a resistive approach. BVOC emissions are added in the street following the Guenther approach. The objective of this study is to compare the effects of urban trees on air quality.

MATERIALS & METHODS

Setup of MUNICH simulations without tree

To model and analyse the effects of trees on air quality at street level, this study relies on a test case where simulations are performed over a Paris suburb (Kim et al., 2022). The street network is composed of 577 streets located in an eastern suburb of Paris (Kim et al., 2018). MUNICH considers homogeneous street segments with homogeneous pollutant concentrations. Several processes are modelled: emission of traffic-related pollutants, using emission factors from the COPERT methodology, advection between street segments, and vertical transfers between the street and the background (Maison et al., 2022a). These transfers depend on the meteorological conditions above the street, computed with WRF (Weather Research and Forecasting) simulations (Lugon et al., 2020) and the background concentrations, computed with Polair3D simulations (Sartelet et al., 2018; André et al., 2020). The gas-phase chemistry occurring in the street is based on the CB05 scheme (Yarwood et al., 2005), with additional reactions to represent the formation of condensables (Sartelet et al., 2020). The aerosol dynamics is simulated with the SSH-aerosol model, which is coupled to MUNICH (Lugon et al., 2021; Kim et al., 2022). Dry deposition on street walls and ground is considered using a resistive approach and the parametrizations of Zhang et al. (2002; 2003) and Hicks et al. (1987) for gaseous pollutants and the parametrizations of Zhang (2001) for aerosols. A detailed description of the reference case can be found in Kim et al. (2022).

Addition of trees in MUNICH simulations

Simulations are performed over the entire street network but trees are added in only one street, corresponding to the boulevard Alsace Lorraine (BAL) (48°51'08.1"N 2°30'38.0"E). The total length of BAL is 1140m, and trees are added every 10 m. Trees are assumed to be *Sophora japonica*, and their characteristics are listed in Table 1.

Table 1. Street and tree characteristics simulated

Category	Symbol	Definition	Value	Unit
Average street characteristics (BAL)	H	Building height	8.6	m
	W	Street width	27.5	m
	a_r	Street aspect ratio	0.31	-
Tree characteristics	LAI	Leaf area index	9.0	$m^2.m^{-2}$
	h	Tree crown height	8.0	m
	r	Tree crown radius	2.5	m
	h_t	Tree trunk height	3.0	m

The three main tree effects on air quality are considered in MUNICH. First, the tree crown slows down air flow inside the street and limits pollutant dispersion; this aerodynamic effect was parameterized in a previous study (Maison et al., 2022b) by modifying the expression of the horizontal and vertical transports. Then, in addition to street surfaces, dry deposition of gas and aerosols on tree leaves are considered. It is also parameterized with a resistive approach assuming that the gaseous species can be deposited on the leaf cuticle or on the mesophyll by entering through the stomata following Wesely (1989); Walmsley and Wesely (1996) and that the aerosols can only be deposited on the leaf cuticle following Zhang (2001). The eventual resuspension is not considered here. Finally, BVOC emissions from trees are added inside the street. The emissions factors of isoprene and three monoterpene species (α-pinene, β-pinene and limonene) are calculated with the empiric approach of Guenther et al. (1995), Guenther (2000) and Owen et al. (2001). The emissions factors are functions of biotic factors dependent on the tree, as the leaf biomass, and of abiotic factors, as the photosynthetically active radiation (PAR) and the leaf surface temperature. Because estimating the leaf surface temperature would require an advanced plant physiology model, most air quality models assume that the leaf temperature equals the air temperature to compute BVOC emission factors. The simulations are performed on a warm and sunny summer day (July 18, 2014), where the air temperature varies between 22.0°C at 5:00 am (UTC) and 34.8°C at 3:00 pm with a daily average value of 28.7°C. The PAR reaches 1979.4 µmol.m^{-2}.s^{-2} at noon. These meteorological conditions lead to relatively high emissions of BVOC (maximum values of 552.5 µg.s^{-1} per tree for isoprene and 13.7 µg.s^{-1} per tree for monoterpenes). The wind speed above the street is between 1.6 m.s^{-1} at 5:00 am and 4.8 m.s^{-1} at 4:00 pm (daily average value of 3.2 m.s^{-1}). The angle between the wind direction and the street orientation is 20° until 2:00 a.m., then it increases to become perpendicular to the street (about 90°) between 8:00 a.m. and 7:00 p.m. and finally decreases to 45° at midnight.

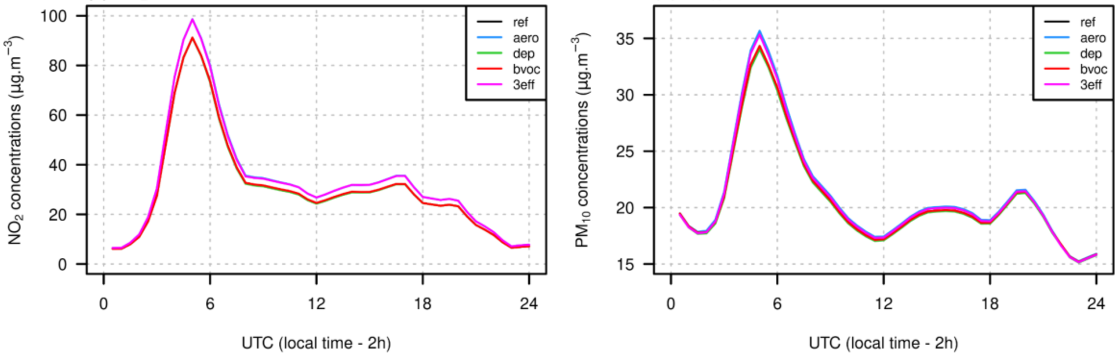
In order to study these effects individually and then combined, five simulations are performed. One reference simulation without tree (ref), three simulations with each of the specific tree effects (aero: tree aerodynamic effect, dep: dry deposition on leaves and bvoc: BVOC emission) and finally, one simulation with the three tree effects combined (3eff). To go further in the analysis of the interaction between tree effect and aerosol dynamics, two additional simulations are performed by deactivating the condensation of aerosol (ref and aero without condensation).

RESULTS & DISCUSSION

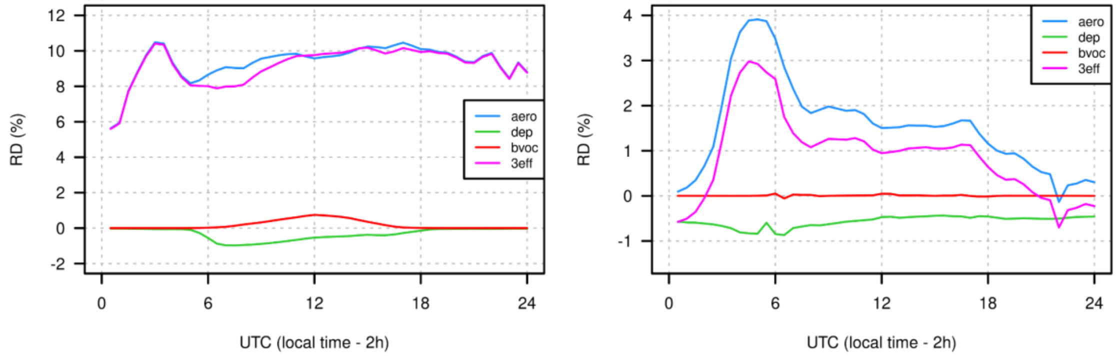
The temporal evolution of the concentrations in the street, expressed in μg.m^{-3}, is compared between the simulation cases in fig. 1a for nitrogen dioxide (NO_2) and fig. 1b for particulate matter less than 10 µm in diameter (PM_{10}). To quantify the impact of trees, the relative deviation (RD) of concentrations (in %) is calculated between the simulations with and without trees, as shown in fig. 1c for NO_2 and fig. 1d for PM_{10}. The daily average and maximum concentrations and relative tree effects are also compared between the simulations for a larger number of species in Table 2.

Figure 1. Temporal evolution (a, b) and relative deviation (RD) (c, d) of NO_2 (a, c) and PM_{10} (b, d) concentrations in the street for the five simulations.

(a) NO_2 concentrations (b) PM_{10} concentrations



(c) Relative deviation of NO_2 concentrations (d) Relative deviation of PM_{10} concentrations



The observed concentrations in fig. 1a and 1b are higher around 5 a.m., which corresponds to the traffic peak hour, combined to a low wind situation (< 2 m.s^{-1}) that limits the dispersion of pollutants. The afternoon traffic peak induces a lower increase of concentrations because emissions are lower, more spread in time, and the wind speed is higher. Trees do not change the temporal variations. Figures 1c and 1d show that for all species, the tree aerodynamic effect is the main effect that leads to an increase in concentrations, which is significant for NO_2 and for particles emitted in the street by traffic such as black carbon (BC_{10} in Table 2). The dry deposition on leaves is low and leads to less than 1% decrease in concentrations. BVOC emitted by the trees induces a small increase of NO_2 during daytime (up to 0.7%). Table 2 shows that the increase in organic particles (org_{10}) due to the BCOV oxidation at the street scale is negligible, because at this scale, oxidation is not rapid enough to produce condensable compounds. This induces a non-significant increase in $PM_{2.5}$ and PM_{10} concentrations. The aerodynamic effects on inorganics ($inorg_{10}$) is mostly related to the condensation of ammonia (NH_3) emitted by traffic, which condenses with nitric acid to form ammonium nitrate. The effects on organics are linked to the condensation of emitted semi volatile organic compounds and to the increase of inorganics, leading to enhanced condensation of organic hydrophilic condensables brought from the background to the street.

Table 2. Average (avg) and maximum (max) concentrations and relative deviations (RD) for various species and for the five simulations.

Species	**Concentration (µg.m^{-3})**										**RD (%)**							
	ref		**aero**		**dep**		**bcov**		**3eff**		**aero**		**dep**		**bcov**		**3eff**	
	avg	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**	**avg**	**max**
NO_2	30.5	91.2	33.4	98.7	30.4	91.1	30.6	91.2	33.3	98.6	9.4	10.5	-0.3	-1.0	0.2	0.7	9.2	10.4
$PM_{2.5}$	17.2	26.8	17.5	27.7	17.1	26.6	17.2	26.8	17.4	27.5	1.3	3.7	-0.5	-0.8	0.01	0.1	0.7	2.9
PM_{10}	20.8	34.3	21.1	35.7	20.6	34	20.8	34.3	21	35.3	1.6	3.9	-0.6	-0.9	0.01	0.1	0.9	3.0
org_{10}	5.5	8.7	5.6	9.0	5.5	8.6	5.5	8.7	5.5	8.9	0.9	3.7	-0.7	-1.3	0.02	0.2	0.01	2.4
$inorg_{10}$	2.4	3.6	2.4	3.8	2.4	3.6	2.4	3.6	2.4	3.8	0.7	4.5	-0.5	-1.0	0.01	0.3	0.1	3.3
NH_3	3.3	4.2	3.3	4.2	3.3	4.2	3.3	4.2	3.3	4.2	0.4	3.6	-0.3	-0.9	0.00	0.1	0.1	3.6
BC_{10}	1.2	3.0	1.3	3.2	1.2	2.9	1.2	3.0	1.2	3.1	4.5	6.7	-0.8	-1.0	0.00	0.0	3.5	5.6

CONCLUSION

The comparison of tree effects on air quality at the street level demonstrates that the tree aerodynamic effect is predominant at the street level and leads to a significant increase in NO_2 concentration, and to pollutants emitted by traffic. This suggests that trees should not be planted in streets with high traffic emissions. Dry deposition of gas and particles on leaves is limited, therefore, we cannot rely only on this process to significantly improve air quality in streets. In the case studied here, temperature and BVOC emissions are quite high, and it shows that at the local scale the tree emissions have a limited impact on particle formation, because the residence time is too low to oxidise the emissions and produce condensables.

Note that the simulations were performed on a specific day here and that the tree effects on concentrations depend on street and tree characteristics, time of the year, and meteorological conditions.

The perspective of this work is to better estimate the BVOC emissions by using parameterizations of the leaf surface temperature instead of assuming it is equal to the air temperature, and to take into account the shadow created by buildings on the radiative budget. MUNICH will be coupled with an urban climatic model including a modelling of the tree water stress that can influence BVOC emissions. The effect at the city scale will be studied by running simulations with MUNICH coupled to a chemistry transport model over the entire city of Paris, taking into account the diversity of trees.

REFERENCES

André, M., Sartelet, K., Moukhtar, S., Andre, J. M. and Redaelli, M., 2020: Diesel, petrol or electric vehicles: What choices to improve urban air quality in the Ile-de-France region? A simulation platform and case study. Atmospheric Environment **241**, 117752.

Guenther, A., 2000: Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. Atmospheric Environment **34**(12–14), 2205–2230.

Guenther, A., Hewitt, C. N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., Mckay, W. A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J. and Zimmerman, P., 1995: A global model of natural volatile organic compound emissions. Journal of Geophysical Research **100**(D5), 8873.

Hicks, B. B., Baldocchi, D. D., Meyers, T. P., Hosker, R. P. and Matt, D. R., 1987: A preliminary multiple resistance routine for deriving dry deposition velocities from measured quantities. Water, Air, and Soil Pollution **36**(3–4), 311–330.

Kim, Y., Wu, Y., Seigneur, C. and Roustan, Y., 2018: Multi-scale modeling of urban air pollution: development and application of a Street-in-Grid model (v1.0) by coupling MUNICH (v1.0) and Polair3D (v1.8.1). Geoscientific Model Development **11**(2), 611–629.

Kim, Y., Lugon, L., Maison, A., Sarica, T., Roustan, Y., Valari, M., Zhang, Y., André, M. and Sartelet, K., 2022: MUNICH v2.0: A street-network model coupled with SSH-aerosol (v1.2) for multi-pollutant modelling. Geoscientific Model Development Discussion [preprint].

Lugon, L., Sartelet, K., Kim, Y., Vigneron, J. and Chrétien, O., 2020: Nonstationary modeling of NO2, NO and NOx in Paris using the Street-in-Grid model: coupling local and regional scales with a two-way dynamic approach. Atmospheric Chemistry and Physics **20**(13), 7717–7740.

Lugon, L., Sartelet, K., Kim, Y., Vigneron, J. and Chrétien, O., 2021: Simulation of primary and secondary particles in the streets of Paris using MUNICH. Faraday Discussion. **226**(0), 432–456.

Maison, A., Flageul, C., Carissimo, B., Tuzet, A. and Sartelet, K., 2022a: Parametrization of Horizontal and Vertical Transfers for the Street-Network Model MUNICH Using the CFD Model Code_Saturne. Atmosphere **13**(4), 527.

Maison, A., Flageul, C., Carissimo, B., Wang, Y., Tuzet, A. and Sartelet, K., 2022b: Parameterizing the aerodynamic effect of trees in street canyons for the street network model MUNICH using the CFD model Code_Saturne. Atmospheric Chemistry and Physics **22**(14), 9369–9388.

Owen, S. M., Boissard, C. and Hewitt, C. N., 2001: Volatile organic compounds (VOCs) emitted from 40 Mediterranean plant species: VOC speciation and extrapolation to habitat scale. Atmospheric Environment **35**(32), 5393–5409.

Sartelet, K., Couvidat, F., Wang, Z., Flageul, C. and Kim, Y., 2020: SSH-Aerosol v1.1: A Modular Box Model to Simulate the Evolution of Primary and Secondary Aerosols. Atmosphere **11**(5), 525.

Sartelet, K., Zhu, S., Moukhtar, S., André, M., André, J. M., Gros, V., Favez, O., Brasseur, A. and Redaelli, M., 2018: Emission of intermediate, semi and low volatile organic compounds from traffic and their impact on secondary organic aerosol concentrations over Greater Paris. Atmospheric Environment **180**, 126–137.

Walmsley, J. L. and Wesely, M. L., 1996: Modification of coded parametrizations of surface resistances to gaseous dry deposition. Atmospheric Environment **30**(7), 1181–1188.

Wesely, M. L., 1989: Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models. Atmospheric Environment **23**(6), 1293–1304.

Yarwood, G., Rao, S., Yocke, M., and Whitten, G., 2005: Updates to the carbon bond chemical mechanism: CB05. US EPA Final Report, 161 pp.

Zhang, L., 2001: A size-segregated particle dry deposition scheme for an atmospheric aerosol module. Atmospheric Environment **35**(3), 549–560.

Zhang, L., Brook, J. R. and Vet, R., 2003: A revised parameterization for gaseous dry deposition in air-quality models. Atmospheric Chemistry and Physics **3**(6), 2067–2082.

Zhang, L., Moran, M. D., Makar, P. A., Brook, J. R. and Gong, S., 2002: Modelling gaseous dry deposition in AURAMS: a unified regional air-quality modelling system. Atmospheric Environment **36**(3), 537–560.