Modelling the impacts of urban trees on air quality in streets

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21st HARMO conference, Aveiro, Portugal

27-30 September 2022

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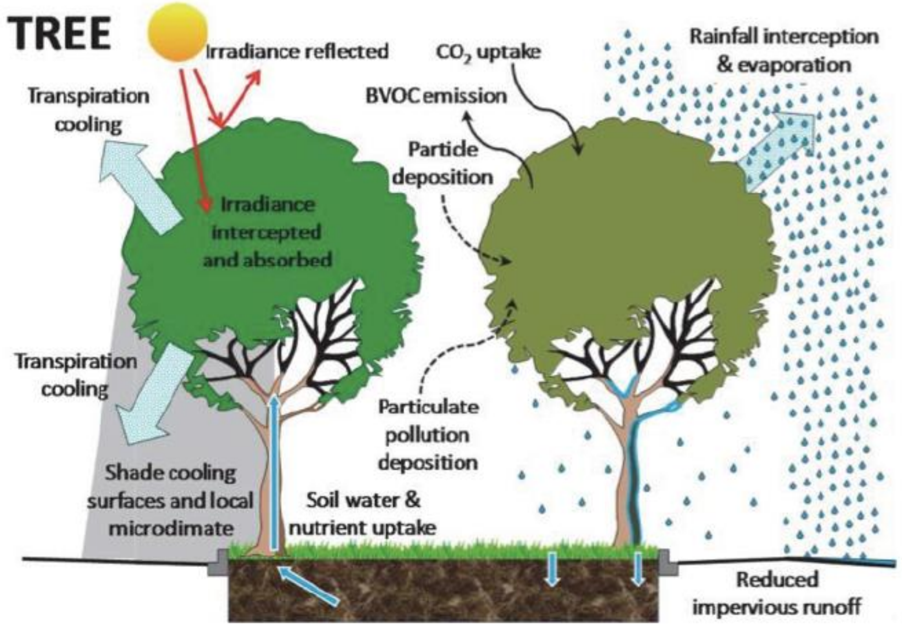
Introduction: air quality – modelling & urban trees

- **Cities**
  - dense populated areas
  - local emissions
  - air flow reduction by buildings inside streets
    → poor air quality & risk for human health

- **Modelling tools**
  - understand processes, interpret observations and forecast pollutant concentration evolutions
  - various model resolutions

- **Urban trees**
  - ecosystem services : improve thermal comfort, limit runoff, store carbon, enhance well-being
  - effects on air quality ?

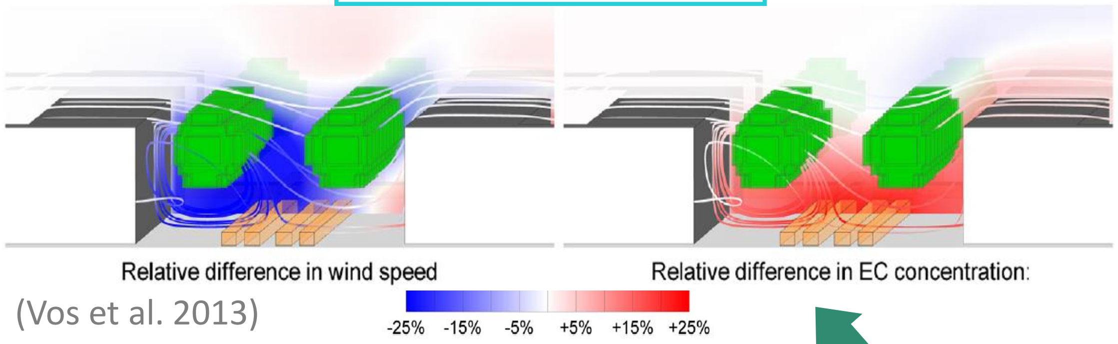
Le Monde



(Livesley et al., 2016)

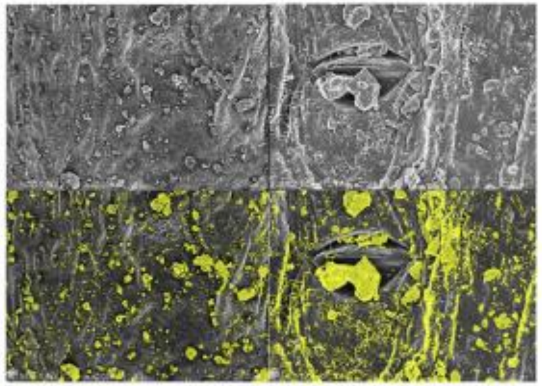
Introduction: tree effects on air quality

Aerodynamic effect



(Vos et al. 2013)

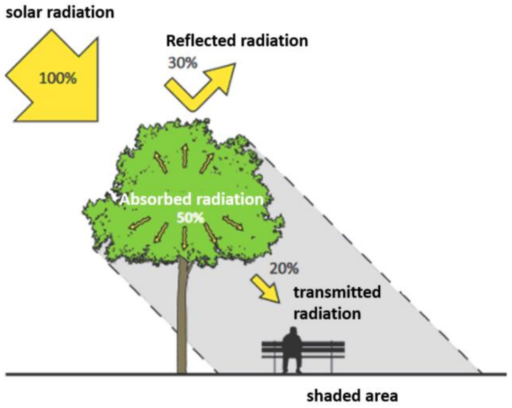
Dry deposition

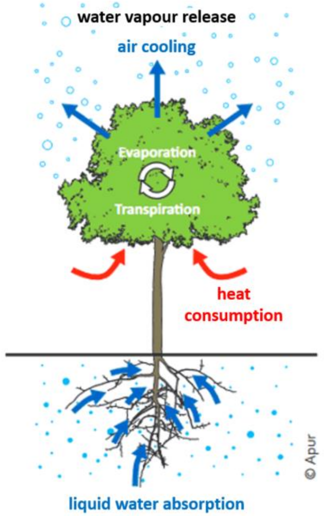


(Lin et al., 2017)

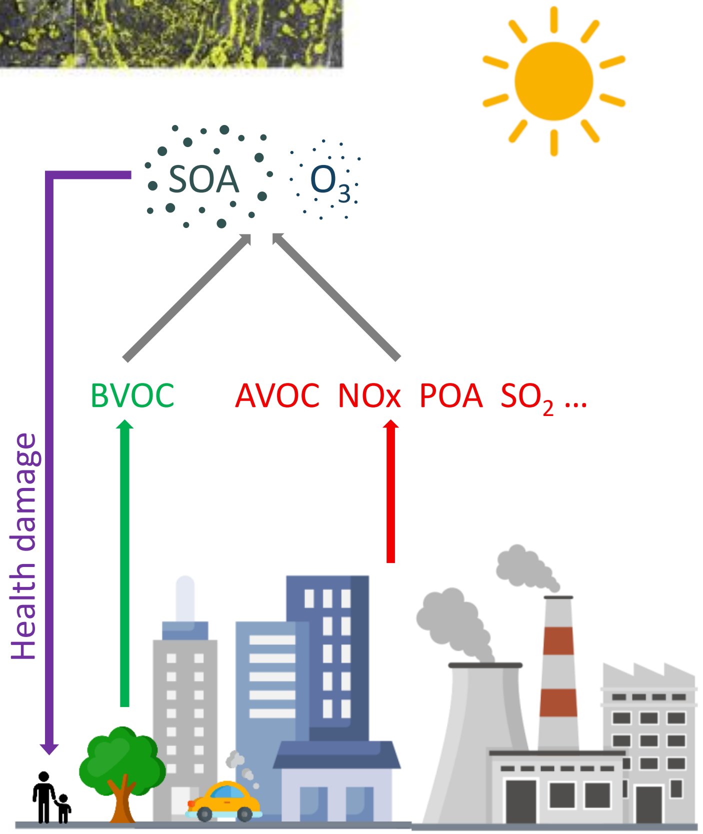
Tree effects on air quality

thermo-radiative effect





BVOC emissions



BVOC emission = f(species, biomass, temperature, radiation, age, stress)

Regional & Local-scale modelling

Chemistry-transport models

- Resolution of ~ 1km
- Simulation over regions and cities

Ex : CHIMERE, Polair3D …

=> Background urban concentrations

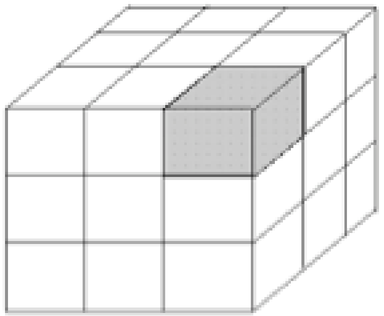
Local-scale models

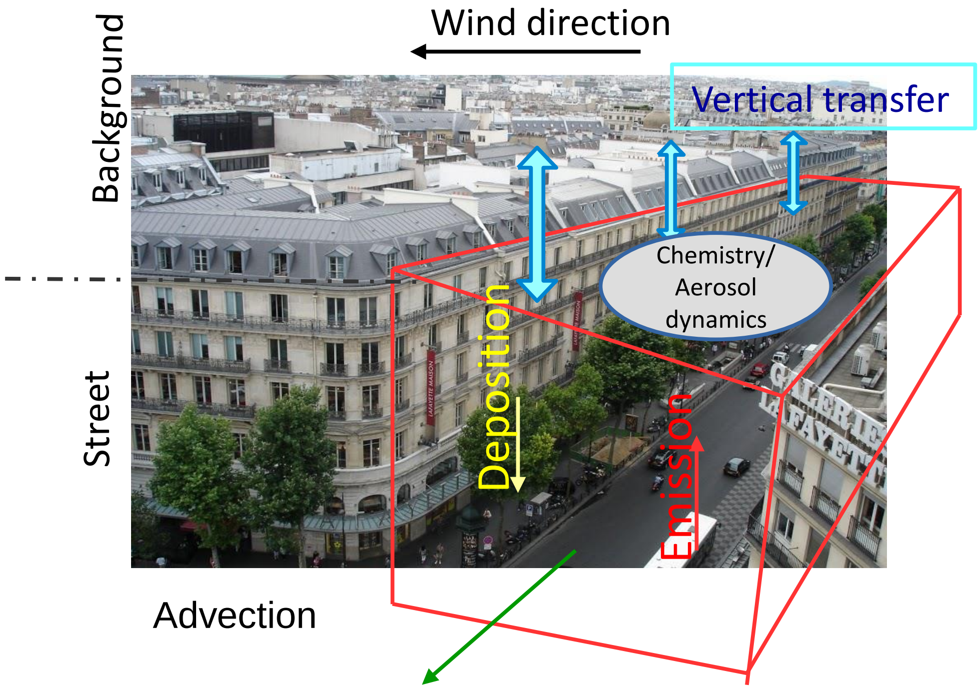
- Resolution of 1 to 100m
- Next to a road
- Street canyon
- Next to industrial sites/airports

- Model types:
- Statistical approach / Land Use Regression
- Parametric models: Gaussian *(ADMS, …)*, street canyon *(MUNICH, …)*
- Computational Fluid Dynamics models (Code_Saturne …)

2D view

3D view





How to simulate air quality **at street level** over a **whole city** ?

CFD coupled to chemistry models

⊕ precision (fine resolution) Detailed gas and aerosol chemistry

⊖ high computation cost (fine resolution + detailed gas and aerosol chemistry)

Street-network models

⊕ Fast running code (homogeneous street hypothesis) Detailed gas and aerosol chemistry

⊖ Simplifications with parametrized processes (transport & deposition)

→ Improve transport parametrization for treeless canyon & **include tree aerodynamic effect** not present in current street models

→ Add **dry deposition** on tree leaves

→ Add **BVOC emissions**

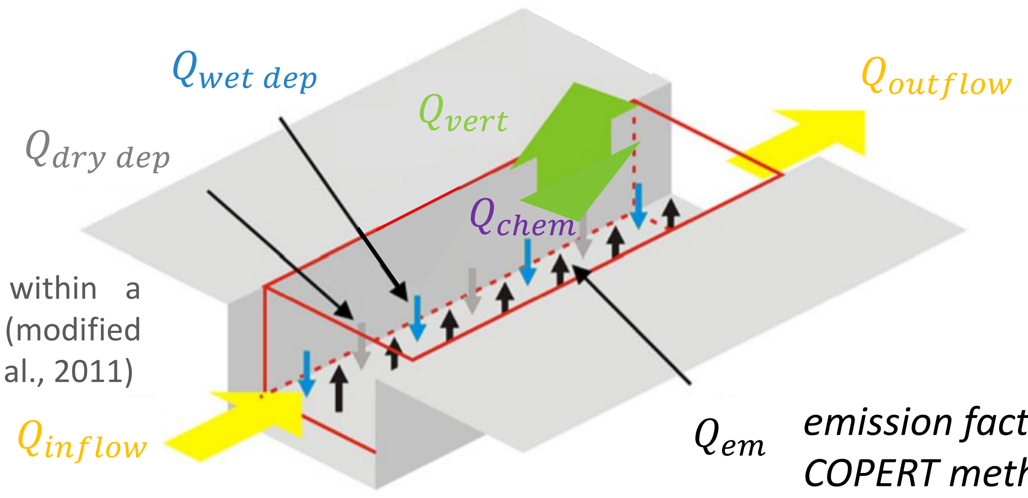
Description of MUNICH (Model of Urban Network of Intersecting Canyons and Highways)

Input data

Background concentrations *Polair3D*

Meteo. Data *WRF*

Street and tree characteristics



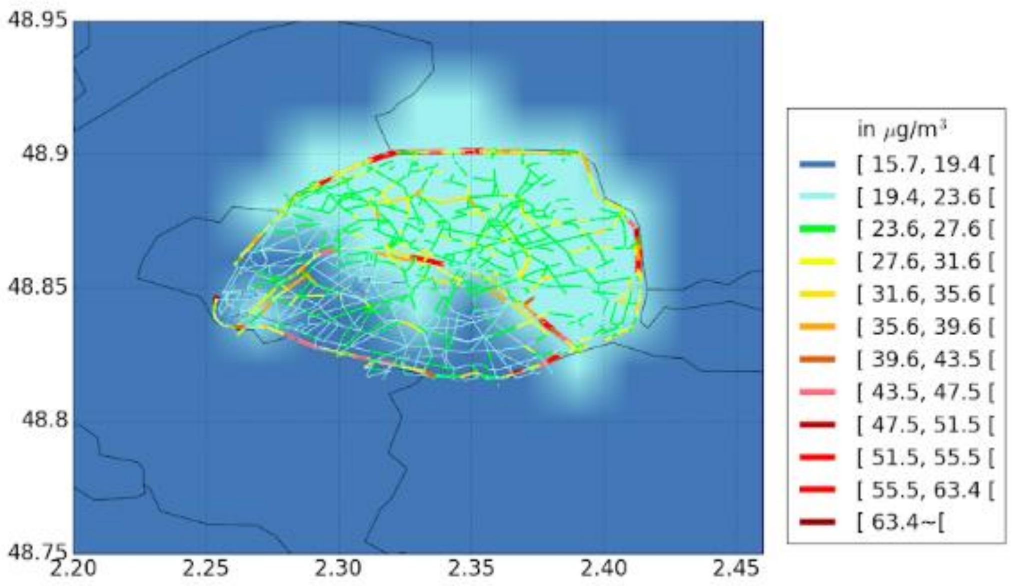
Mass balance within a street canyon (modified from Soulhac et al., 2011)

Q_{em} *emission factors from the COPERT methodology*

$$\frac{dQ}{dt} = Q_{em} + Q_{dep} + Q_{inflow} + Q_{outflow} + Q_{vert} + Q_{chem}$$

Pollutant concentrations in streets

Hypothesis: homogeneous street segments (H, W, wind speed and concentrations)



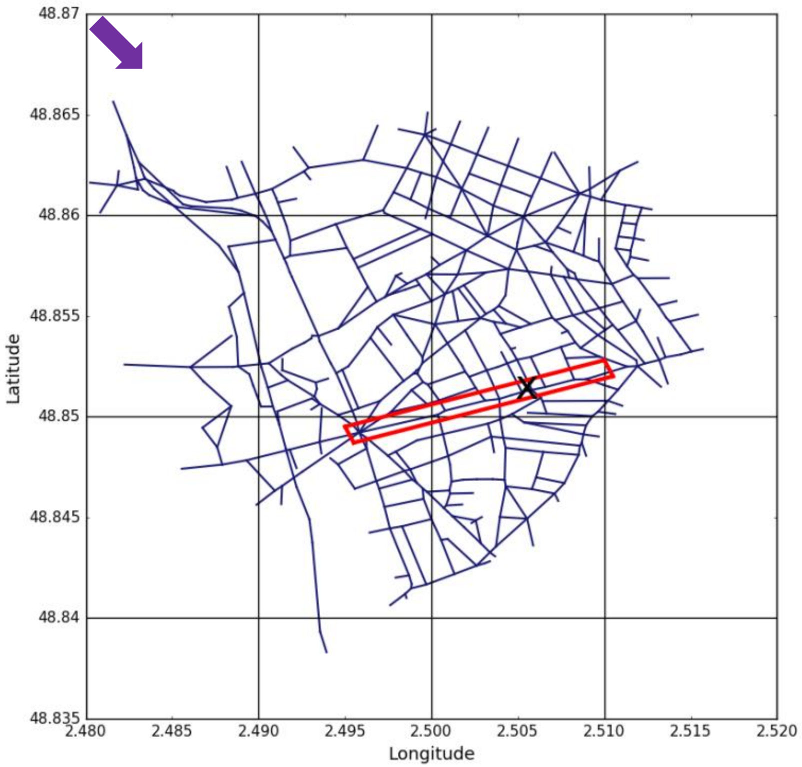
$PM_{2.5}$ concentrations simulated in Paris with MUNICH (streets) and Polair3D (CTM) (background) in 2014 (Lugon et al., 2021)

CB05 scheme (Yarwood et al., 2005; Sartelet et al., 2020) and *SSH-aerosol* (Lugon et al., 2021; Kim et al., 2022)

http://cerea.enpc.fr/munich

Street and tree characteristics

- 577 street segments located in the eastern suburbs of Paris (Kim et al., 2022)
- Trees are added in one street
- species = *Sophora japonica* (monoterpene emitter)
- 1 tree every 10m
- 24h-simulation of a warm summer day (18/07/2014)



Street network of the simulated domain located in the eastern suburbs of Paris (Kim et al., 2022)

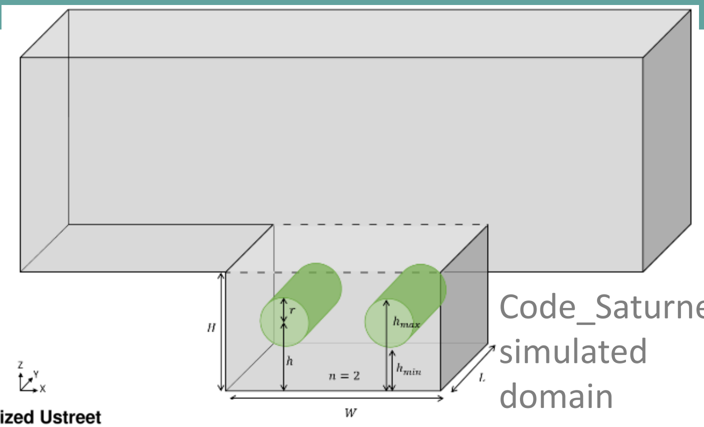
Street characteristics	building height	8.6 m
	street width	27.5 m
	street length	1140 m
	aspect ratio	0.31
Tree characteristics	leaf area index (LAI)	9.0 $m^2.m^{-2}$
	crown height	8.0 m
	trunk height	3.0 m

5 simulations:

- **ref**: street without tree
- **aero**: only aerodynamic effect
- **dep**: only dry deposition on leaves
- **bvoc**: only BVOC emissions
- **3eff**: 3 cumulated effects

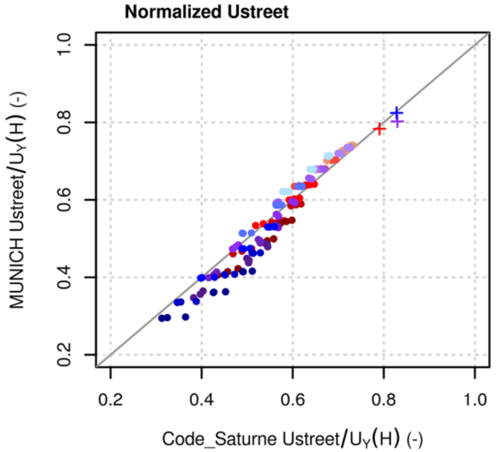
Modelling tree aerodynamic effect

- CFD simulations (Code_Saturne)
  → 3 street canyons with various H/W ratios
  → large range of tree characteristics (LAI, tree height and radius)



Code_Saturne simulated domain

- parameterization of an analytical model of wind speed profiles in sparse vegetated canopies to a **street canyon with trees**



→ **Horizontal** flux of pollutant: $\boldsymbol{Q_{in/outflow} = U_{street}\, HW\, C_{street}}$

average wind speed in the street $= f(H, W, z_0, u_*, \varphi, \boldsymbol{LAI}, \boldsymbol{h})$

surface of exchange

concentration

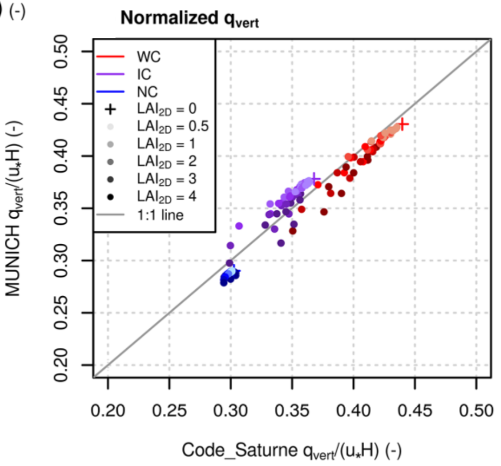
→ **Vertical** flux between the street and the background: $\boldsymbol{Q_{vert} = q_{vert}\, WL\, \frac{C_{street} - C_{background}}{H}}$

vertical transfer coefficient $= f(H, W, u_*, PBLH, \boldsymbol{LAI})$

surface of exchange

vertical gradient of concentration

Above street meteo.
Street characteristics
Tree characteristics

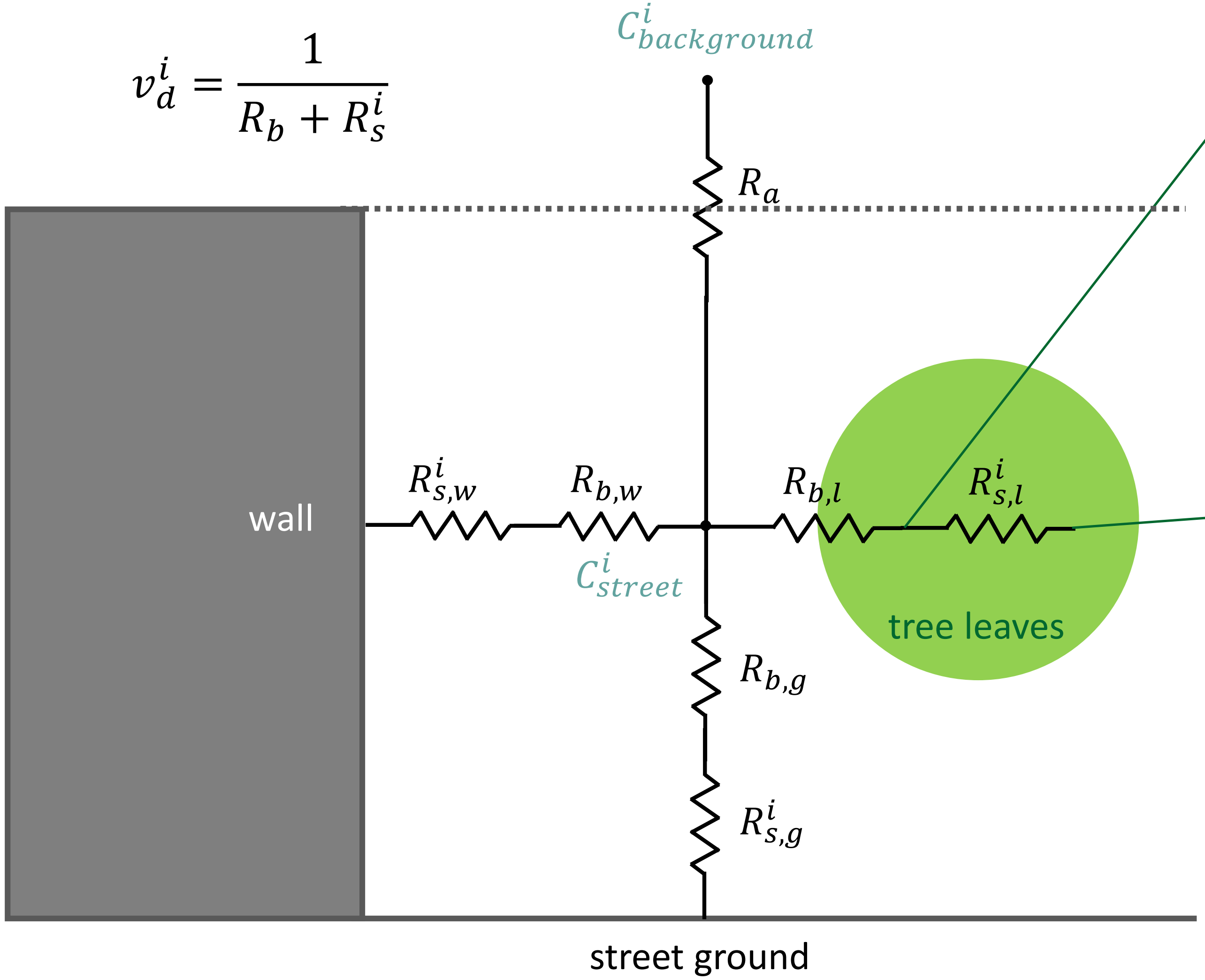


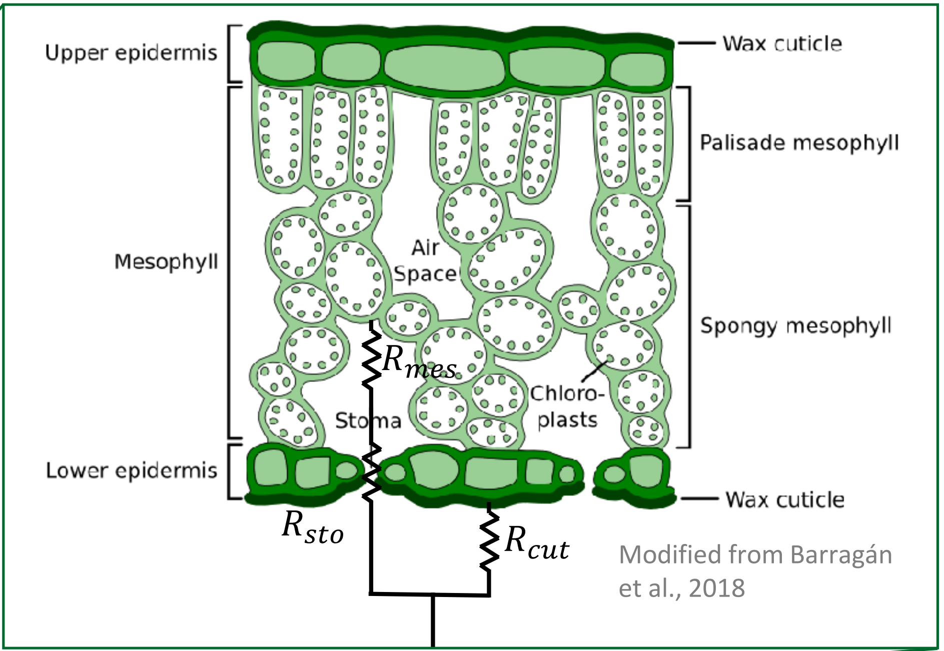
Maison et al., 2022a; 2022b

Modelling dry deposition on street and tree leaf surfaces

$$Q_{dep} = v_d^i \, S \, C_{street}^i$$

$$v_d^i = \frac{1}{R_b + R_s^i}$$





Modified from Barragán et al., 2018

Using parameterizations based on a **resistive approach** for:

- gas (Hicks et al., 1987; Walmsley and Wesely, 1996; Wesely, 1987; Venkatram and Pleim, 1999; Zhang et al., 2002; 2003)
- aerosols (Giardina and Buffa, 2018; Zhang, 2001).

Modelling BVOC emissions

Emission factor = f(tree species, BVOC, biomass)

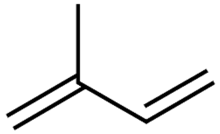
Emission: $E = EF\,\gamma_T\,\gamma_P$

dimensionless factors representing abiotic factors (meteo)

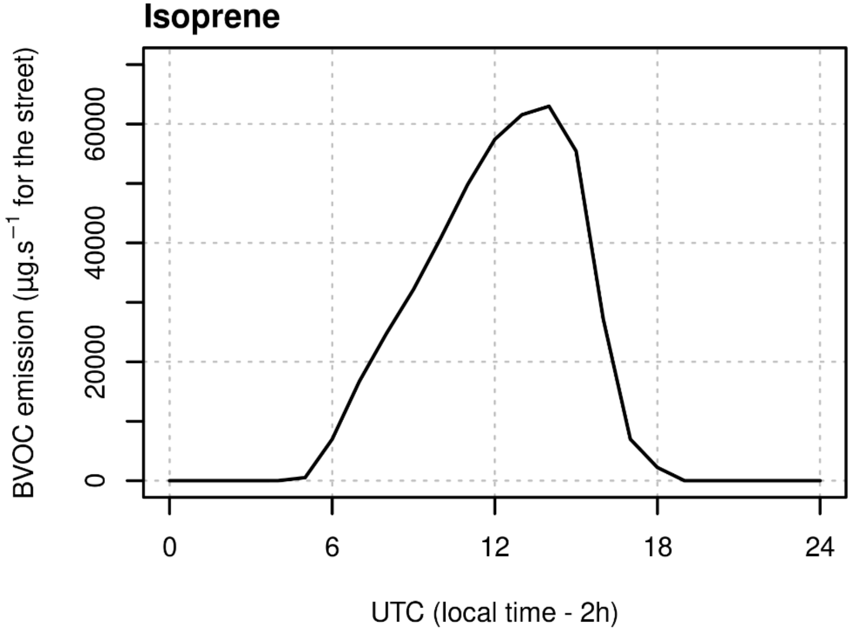
Leaf surface temperature (≈ air temperature)

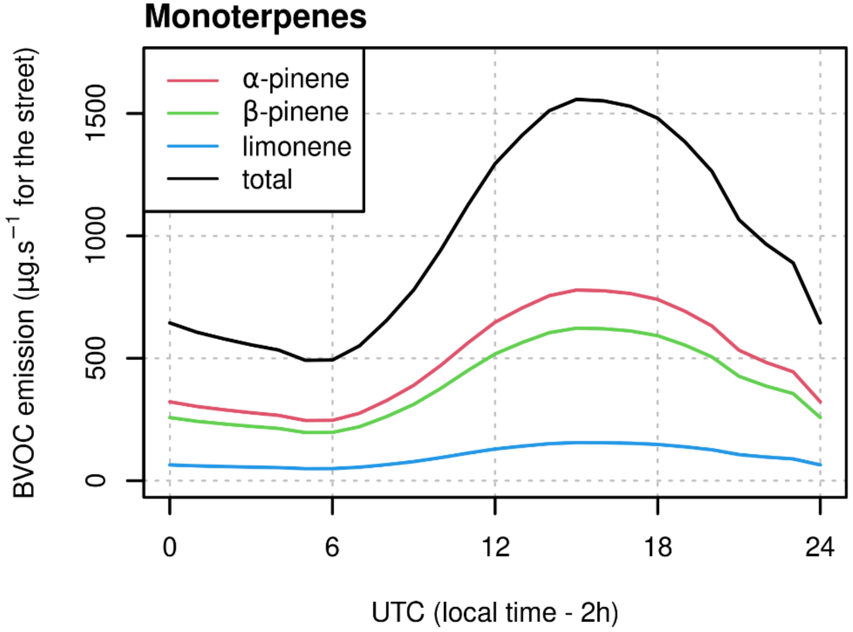
PAR

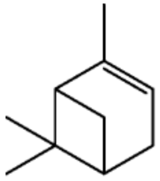
(Baghi et al., 2012; Curtis et al., 2014; Guenther, 2000; Guenther et al., 1995, 1999; Owen et al., 2001)



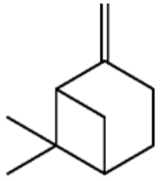
isoprene



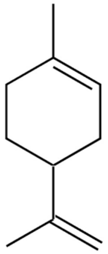




α-pinene



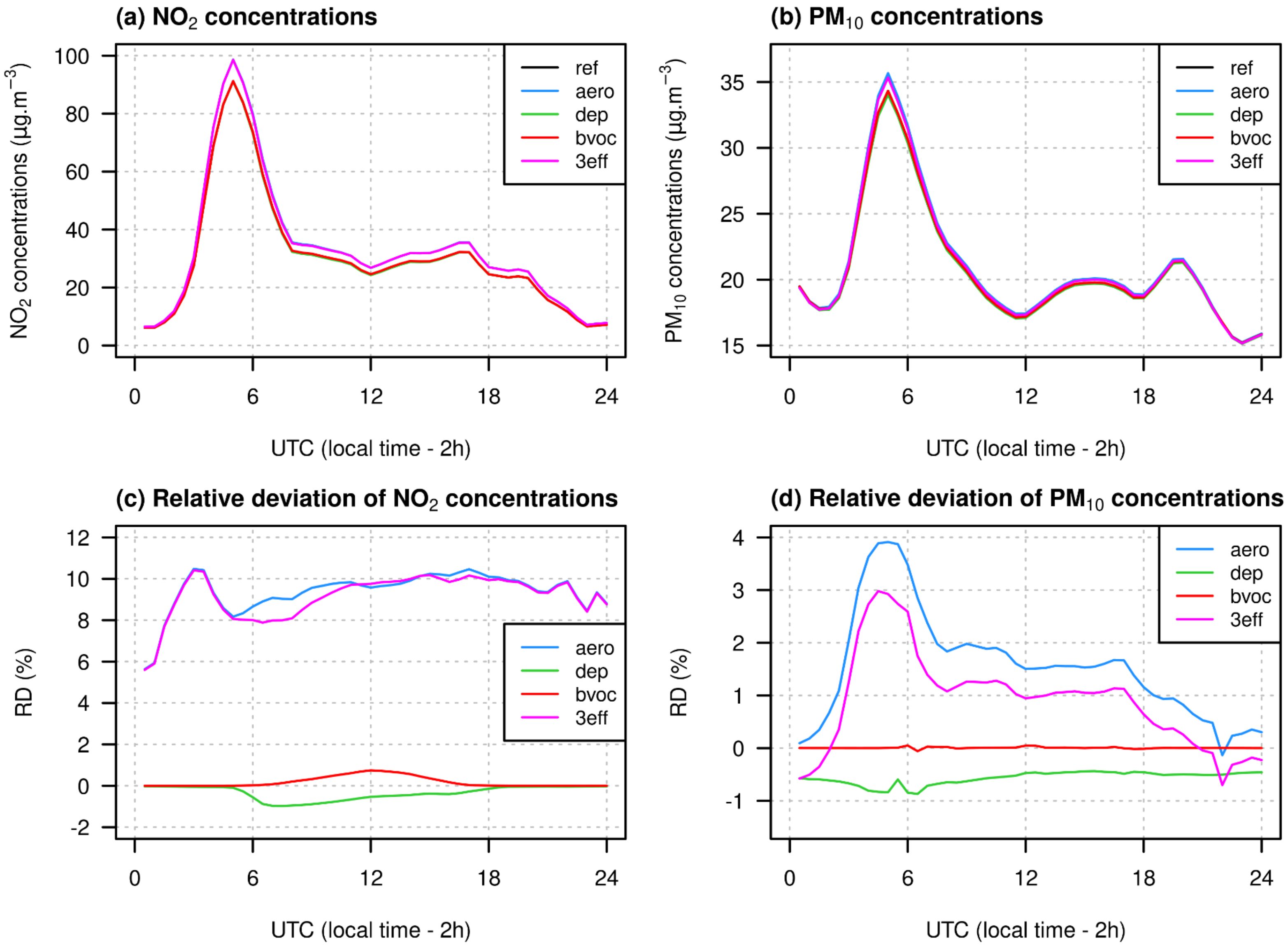
β-pinene



limonene

Daily temporal evolution of BVOC emissions for the whole street.

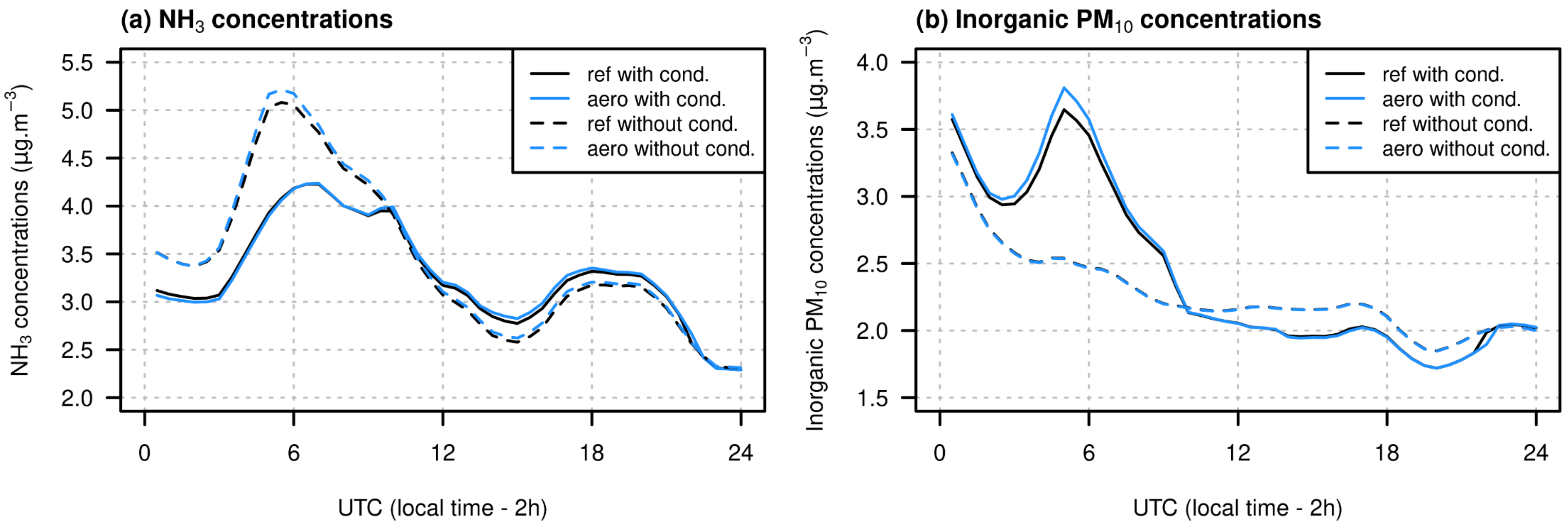
Results: comparison of tree effects on street concentrations



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.

- **aerodynamic effect is predominant** for species emitted by traffic (NO_2, BC, CO …)
  → dispersion of pollutants is limited and they accumulate in the street
- **dry deposition** on leaves is **not very important** (< 1%)
- **effect of BVOC emissions is limited** at the street level in terms of particle mass

Results: complex interactions between physical processes and chemistry



Temporal evolution of NH_3 (a) and inorganic PM_{10} (b) concentrations in the street for the ref and aero simulations with and without condensation.

- aerodynamic effect is not visible on NH_3 concentrations because when condensation is activated:
  → **NH_3 condensates** to form ammonium nitrates and inorganic particles
  → aerodynamic effect is then visible on **inorganic PM_{10}** concentrations

- formation of organic particles is also increased via org/inorg interactions

Conclusion

- A pluridisciplinary and multi-scale study that aims to include **tree effects in air quality models**:
  - parametrize **aerodynamic effect**
  - add gas and aerosol dry **deposition** on leaves
  - account for **BVOC** tree emissions

- At the **street level**
  - the **aerodynamic effect is predominant** for compounds emitted by traffic or reacting with those.
  - the **dry deposition effect is low**
  - the **BVOC emission effect is low in terms of particle mass**, but it could be higher:
    - for particle number concentration (formation of extremely-low volatile compounds at the street scale)
    - at the city level

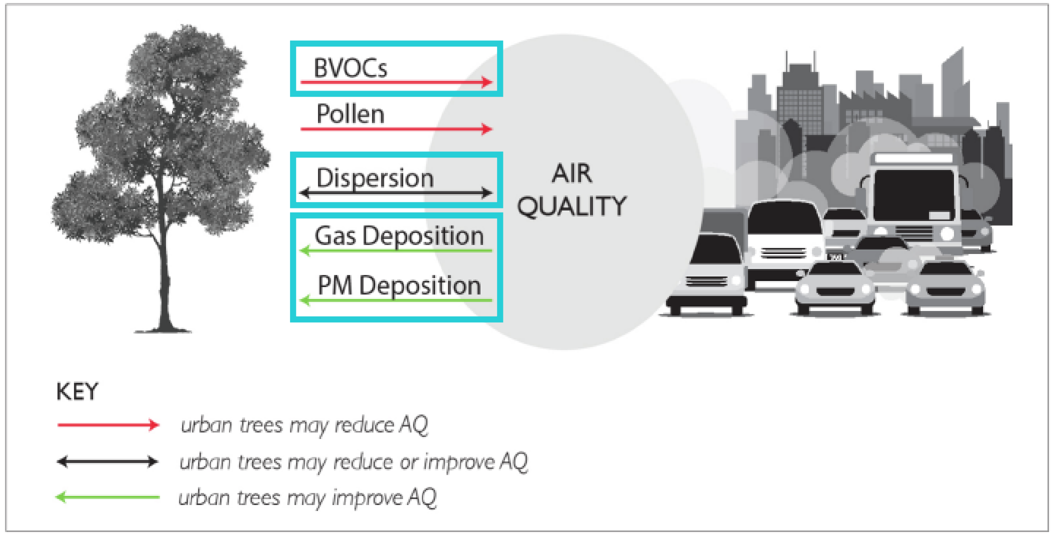
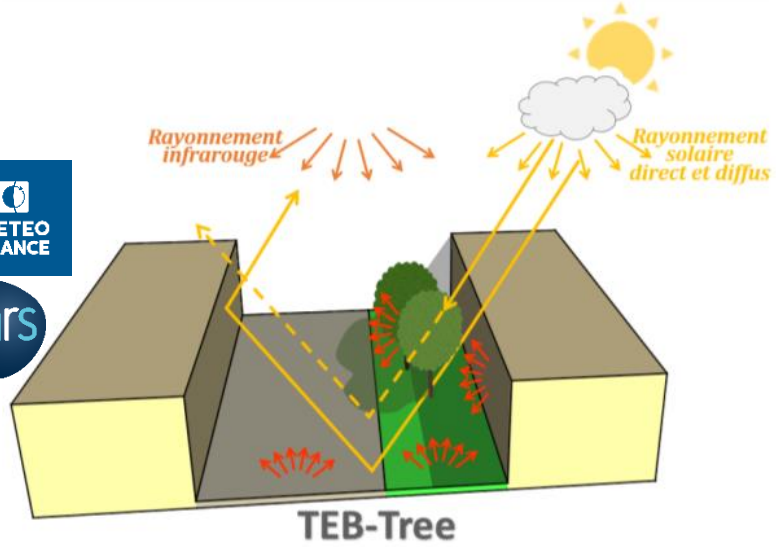


Fig. 2. Links between urban trees and air quality.

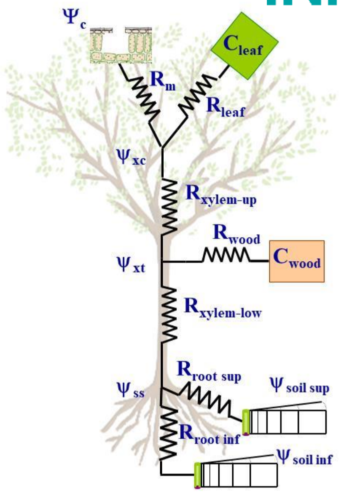
Eisenman et al., 2019

Perspectives

- Link BVOC emissions to **urban micro-climate** and **tree water status**
- Account for the **thermo-radiative effect of trees on street chemistry**
  - → coupling air quality model to urban climate and soil-plant-atmosphere models

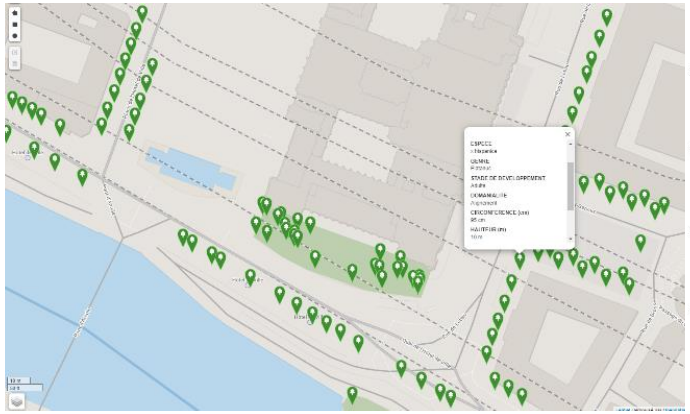


Urban climate model
(Masson 2000; Lemonsu et al, 2012 Redon et al, 2017; 2020)

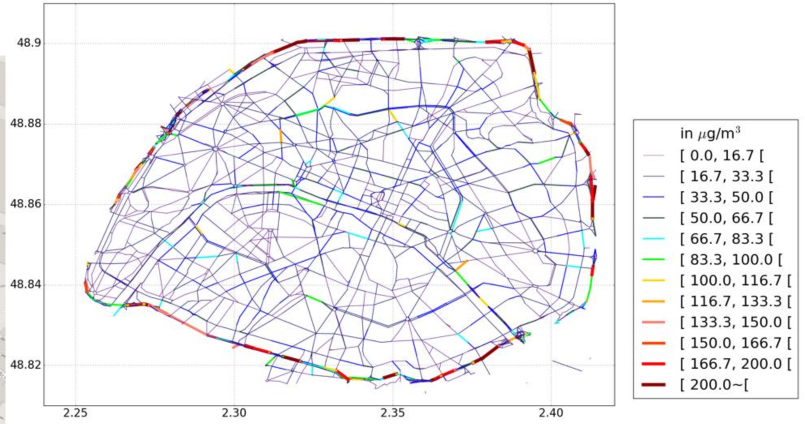


Tree hydraulic model
(Tuzet et al., 2017)

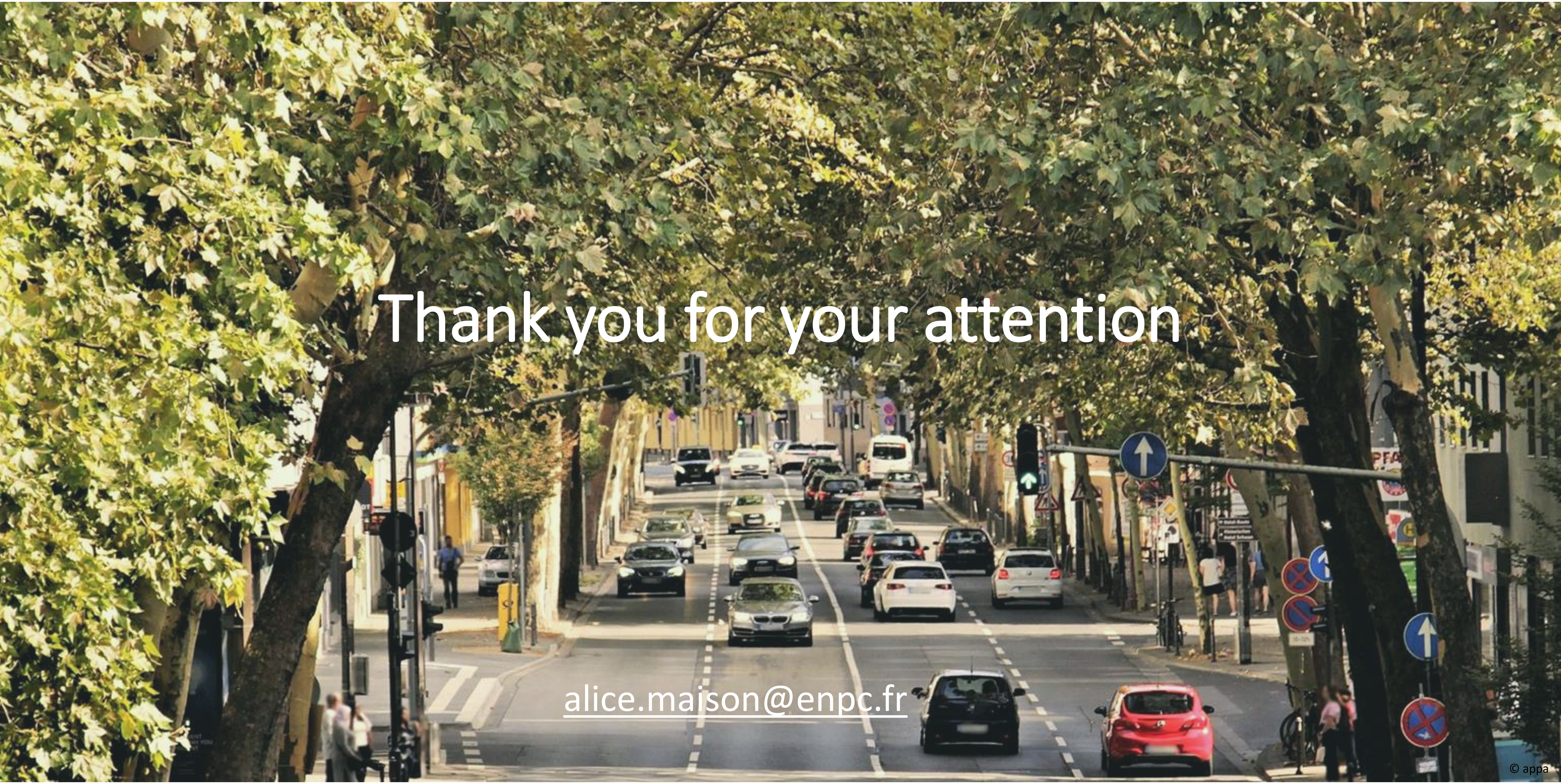
- Simulations for the **streets of the full city of Paris**
  - → using the city tree database
- Compare simulation results to measurements



https://opendata.paris.fr/explore/dataset/les-arbres



NO_2 concentrations simulated in the streets of Paris with MUNICH (Lugon et al., 2020).



Thank you for your attention

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Meteorological data