Simulation of primary and secondary pollutants in the streets: using multi-scale modelling to estimate population exposure in urban areas

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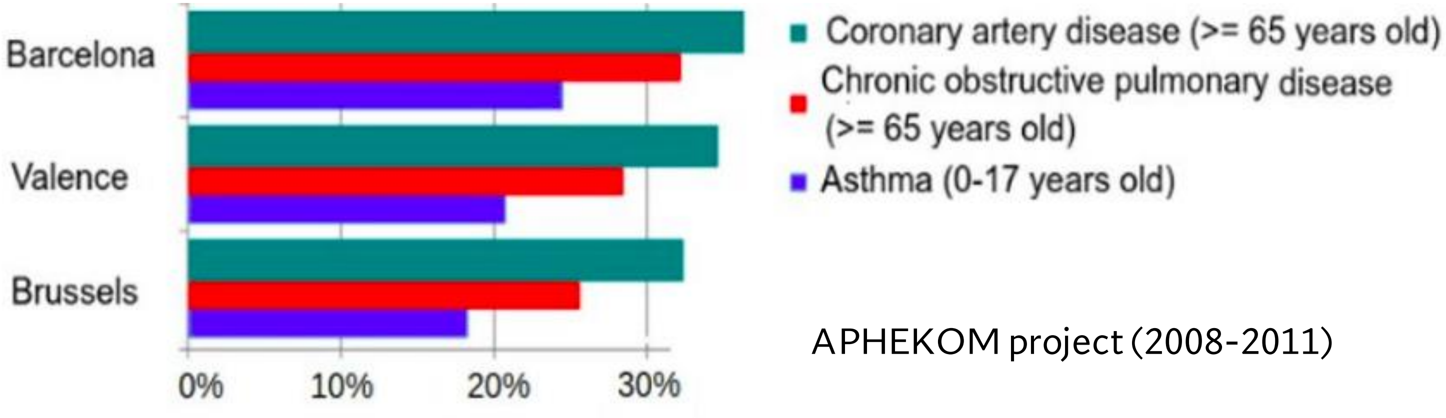
Introduction

- Atmospheric pollution: responsible for 7 million deaths worldwide per year (World Health Organization)
- Different pollutants present different sanitary impacts
  - Nitrogen dioxide: affects the respiratory system, causing asthma (Kowalska et al. 2020)
  - **Black carbon**: affects the cardiovascular system, and can impact the fetus development (Ali et al. 2020)
  - **Organics**: affect the respiratory and cardiovascular system, and may cause cancer (Nault et al. 2020)
- High concentrations of those pollutants observed in urban areas, especially near streets



APHEKOM project (2008-2011)

- Importance of reducing pollutant concentrations in streets, where populations are exposed

Introduction

- Different sources of atmospheric pollutants: **primary and secondary pollutants**

Primary pollutants

- Directly emitted in the atmosphere
- Different sectors (industry, residences, road traffic)

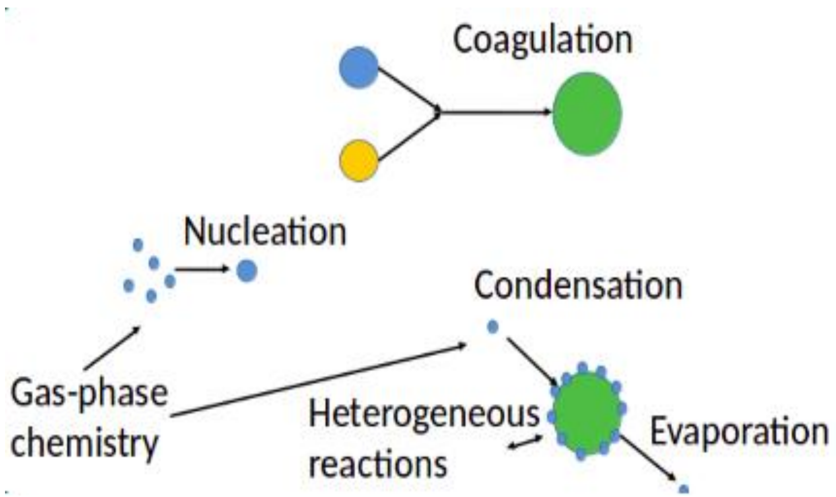
- Estimated using emission factors

- traffic **exhaust emissions**: fuel combustion
  .relatively well-known in Europe

- traffic **non-exhaust emissions**: tyre, brake and road wear; resuspension
  . high uncertainties in the literature
  . resuspension emission factors may not respect the mass balance over the street surface

Secondary pollutants

- Formed in the atmosphere from physical and chemical reactions



- Pollutants can be primary and secondary
- Examples: NO_2, $PM_{2.5}$, organics, inorganics

- **Importance of representing pollutant emissions (primary) and the formation of secondary pollutants**

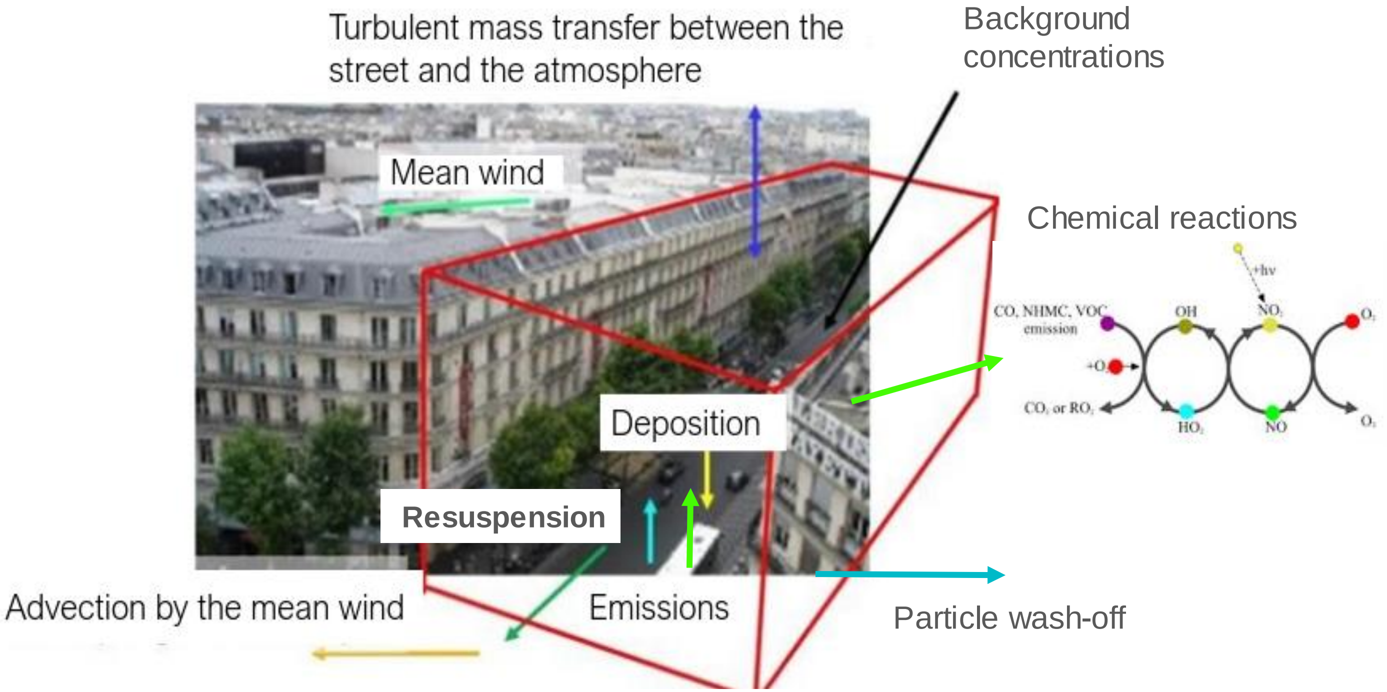
Introduction

- **Urban areas: different processes - regional and local spatial scales**

Urban background
(regional scale
spatial resolution *km*)

Mass transfer
between streets
and background

**Streets where
populations are exposed**
(local scale - spatial
resolution *tens of m*)



Introduction

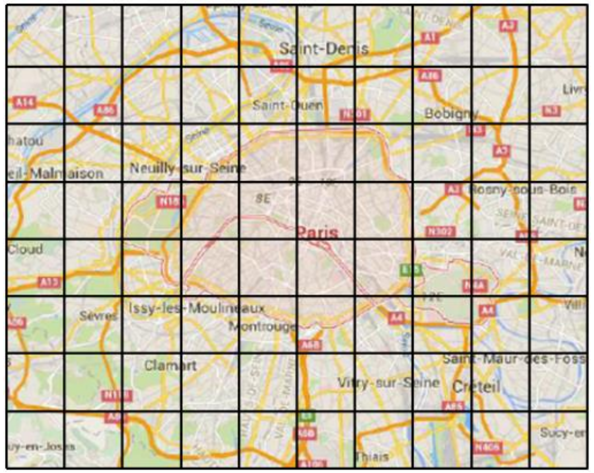
- **Air-quality models**: Important tools to estimate pollutant concentrations

Regional-scale models – Polair3D (Mallet et al 2007)

- Transport and chemistry, with secondary pollutants
- Concentrations averaged over each grid cell
  - Urban background concentrations
  - Fail to represent the high concentrations observed in streets

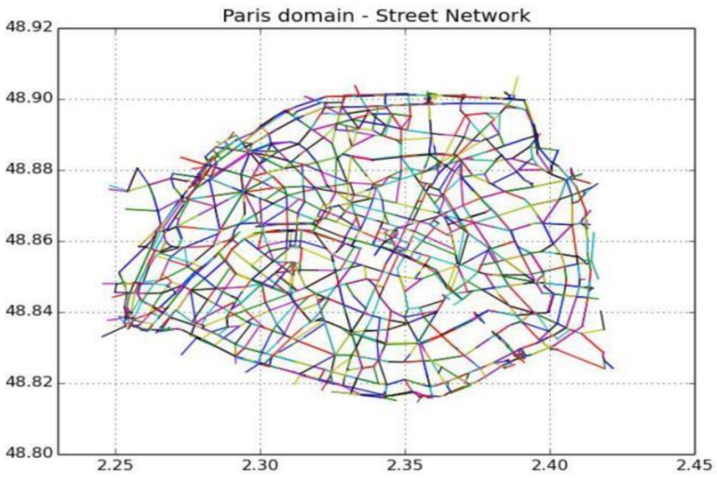
Local-scale models – MUNICH (Kim, et al 2018; Lugon et al 2021)

- Represent the high concentrations in streets
- Take into account background concentrations and traffic emissions
- They often adopt important simplifications
  - determination of background concentrations
  - no chemistry, no secondary compounds
  - underestimating or neglecting non-exhaust emissions



One-way coupling

Background concentrations



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

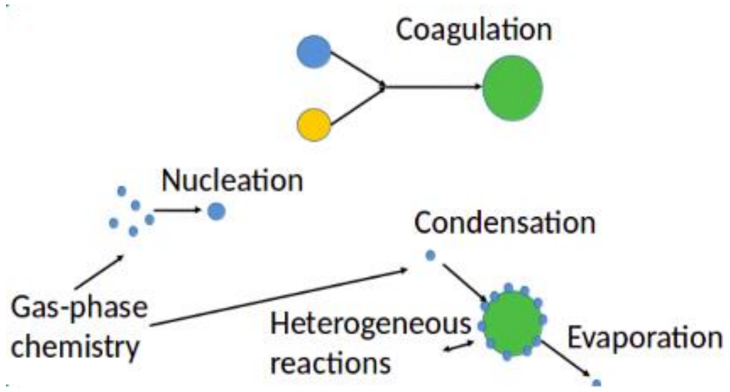
- **Formation of secondary particles:** chemical module SSH-aerosol (Sartelet et al., 2020)

  Gas-phase chemistry: formation of secondary gas-phase compounds:

  - NO_2, condensables (i.e. nitric acid, semi-volatile compounds)

  Particle dynamics:

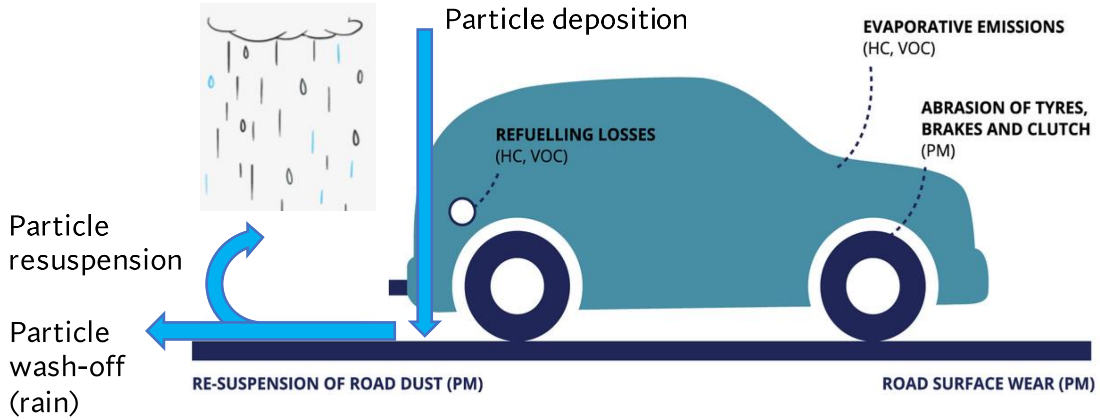
  - nucleation, coagulation, condensation/evaporation



- **Non-exhaust emissions:** resuspension estimated strictly respecting the mass balance over the street surface

  Mass on the street surface:

  particle deposition, wash-off and resuspension

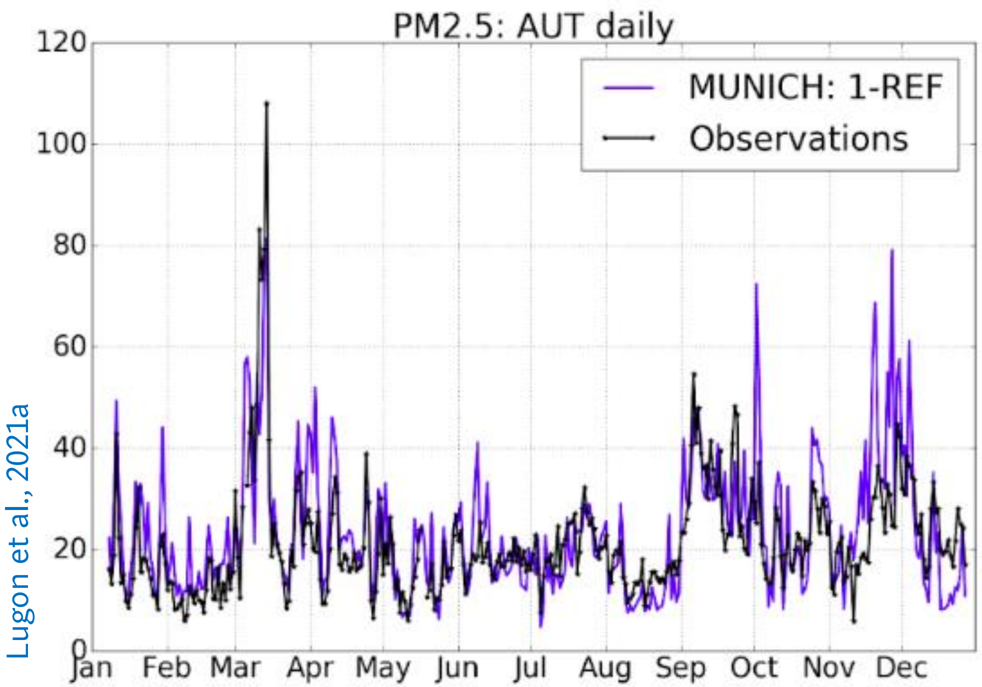


Model of
Urban
Network of
Intersecting
Canyons and
Highways

- **Model validation – particle concentrations and chemical composition**

- Multi-scale simulations performed in Paris over 2014

Lugon et al., 2021a



$PM_{2.5}$ daily-concetrations in a street

Observed and simulated $PM_{2.5}$ chemical composition in the streets

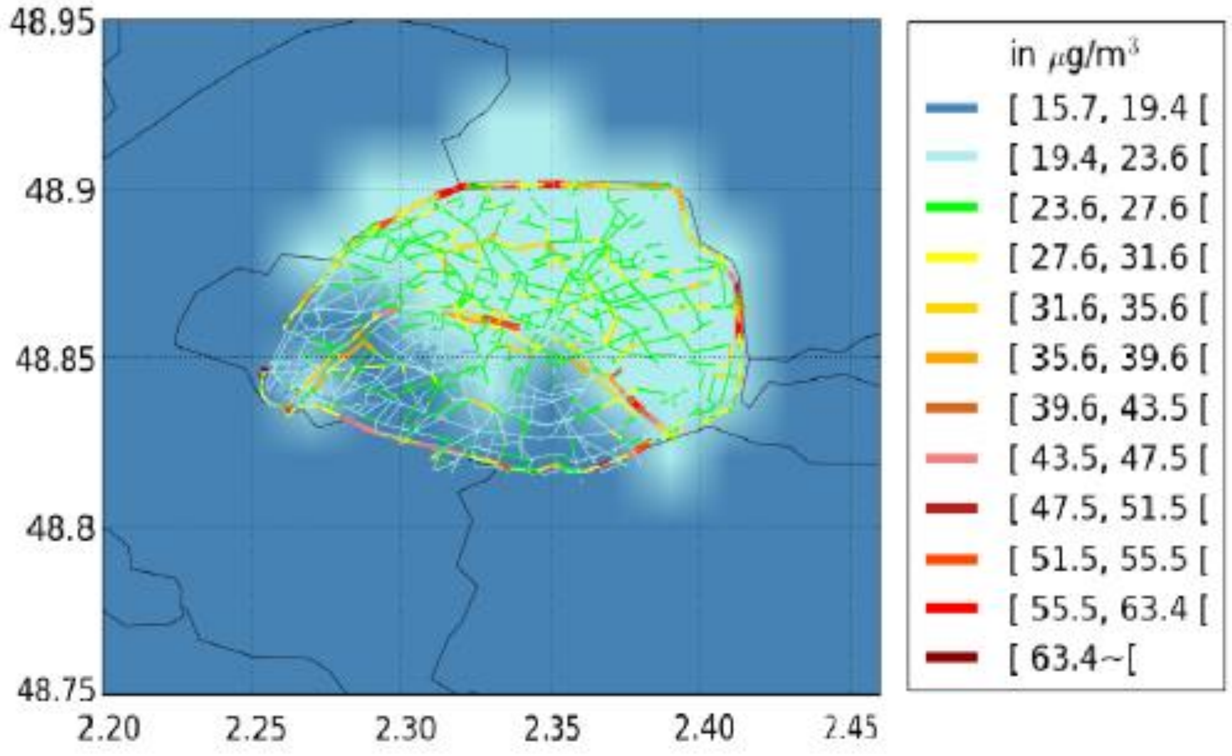
Chemical compound	AIRPARIF report	MUNICH
Black carbon (BC)	27.0%	22.5%
Sulphate (SO_4)	7.0%	7.8%
Nitrate (NO_3)	12.0%	10.0%
Ammonium (NH_4)	6.0%	5.6%
Organic matter	39.0%	36.4%
Sea salt (Na + Cl)	1.0%	1.3%
Dust and others (DU)	7.0%	16.4%

Lugon et al., 2021b

- Meet strict performance criteria often used to evaluate simulations

• Pollutant concentrations in the streets and in the urban background

- Concentrations of health-related pollutants are higher in the streets than in the urban background



Annual-average $PM_{2.5}$ concentrations in 2014

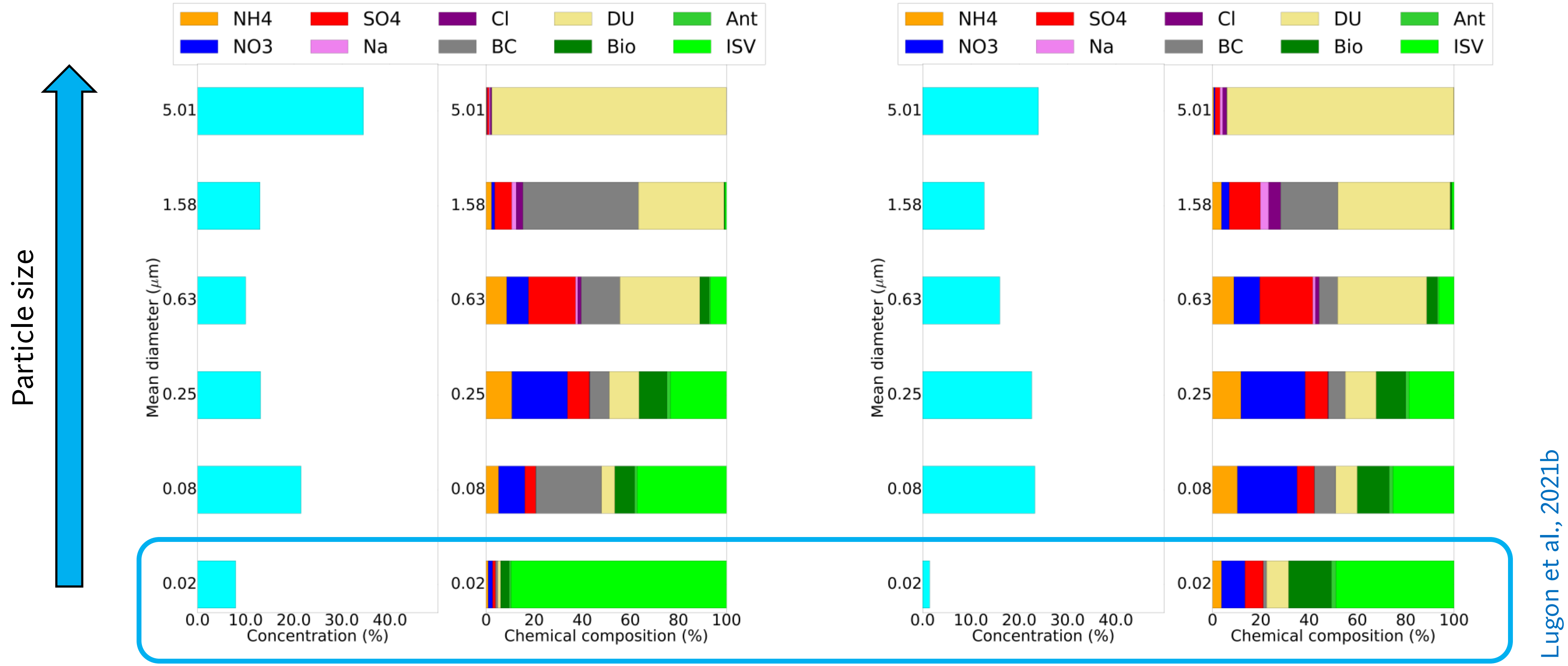
Ratio between annual-average concentrations in the streets (C_{st}) and in the urban background (C_{bg})

Chemical compound	C_{st}/C_{bg}
Nitrogen dioxide (NO_2)	2.0
Black carbon (BC)	3.0
Organic particles	1.8

Lugon et al., 2021a

• Particle size distribution and chemical composition

- Smaller is the particle, higher is its penetration in the human organism – severe sanitary impacts
- Organic particles (green color): high reactivity in the human organism – severe sanitary impacts

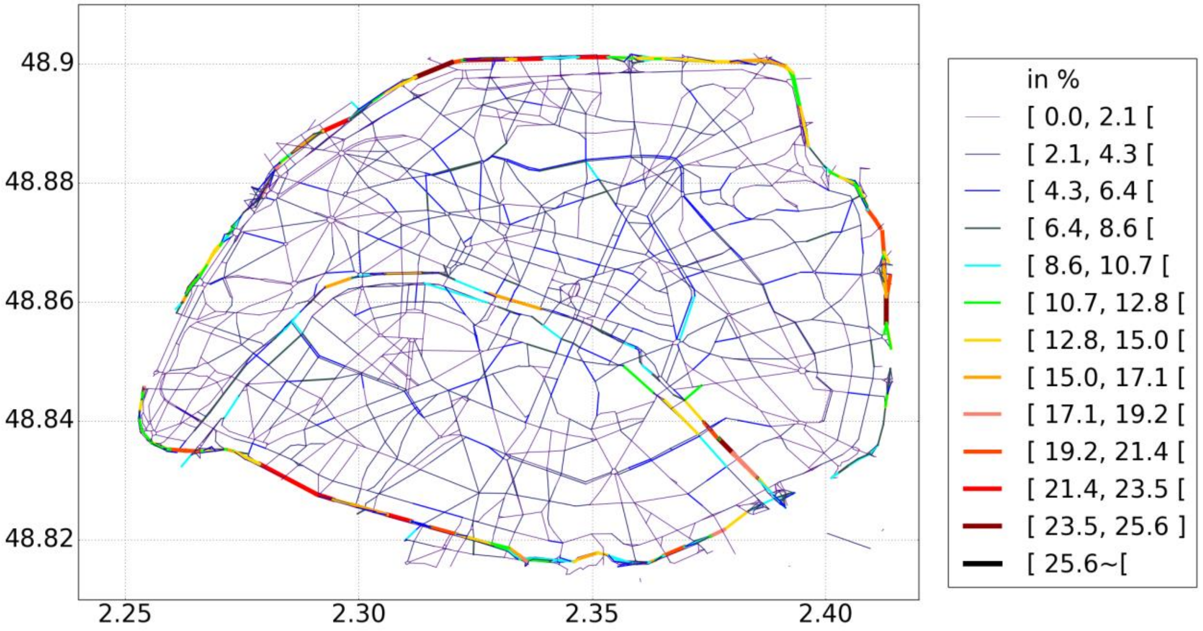


Simulated particle chemical composition in the streets (left panel) and in the urban background (right panel)

- Particles in the streets may have more health impact than those from the urban background

- **Influence of ammonia traffic emissions**

- Ammonia from traffic emissions (emitted especially by recent vehicles)
- Gas-phase chemistry: increase of nitric acid and nitrate concentrations (condensables)
- Ammonia condenses with nitric acid: formation of ammonium nitrate



Lugon et al., 2021b

Influence of ammonia traffic emissions on inorganic $PM_{2.5}$ concentrations

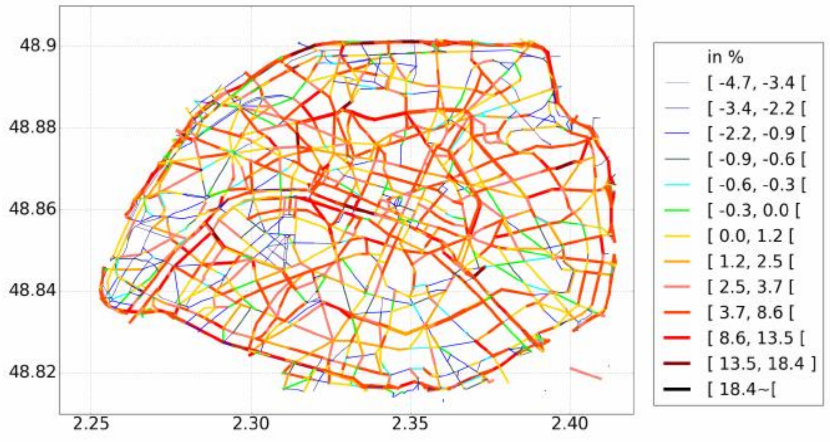
- Average increase of 3.1% of $PM_{2.5,inorganic}$, reaching 26% in high traffic streets

- **Influence of secondary aerosol formation (gas-phase chemistry + aerosol dynamics)**

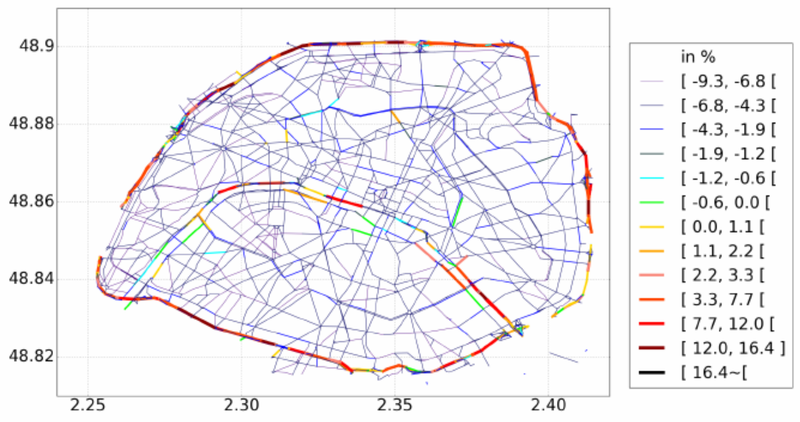
- Influence of processes linked to aerosol formation in streets on $PM_{2.5}$: maximal average impact of 18%, reaching 27% in the morning (rush-hours)

- Inorganic particles: higher concentrations in streets with high traffic emissions

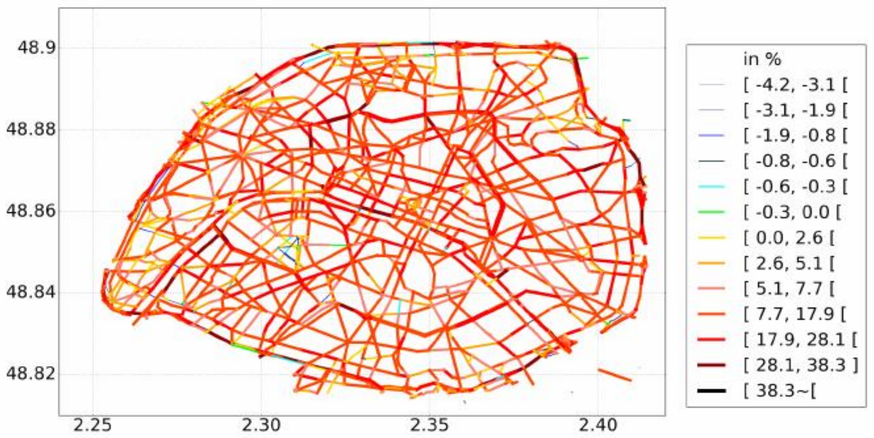
- Organic particles: higher concentrations over the whole street network



$PM_{2.5}$



$PM_{2.5}$ inorganic



$PM_{2.5}$ organic

Lugon et al., 2021b

- **Sensitivity tests with different tyre-wear emission factors based on measurements observed in the literature**

- Great variability between particle non-exhaust emissions observed in the literature

. Emission factors, size distributions and chemical compositions

Sim. 1 – European guidelines EMEP: Emission $factor_{tyre,BC}$ = 1.36 µg.vkm^{-1}

Sim. 2 – Boulter (2005), Luhana et al. (2004): Emission $factor_{tyre,BC}$ = 20.8 µg.vkm^{-1}

- Investigation the importance of particle resuspension

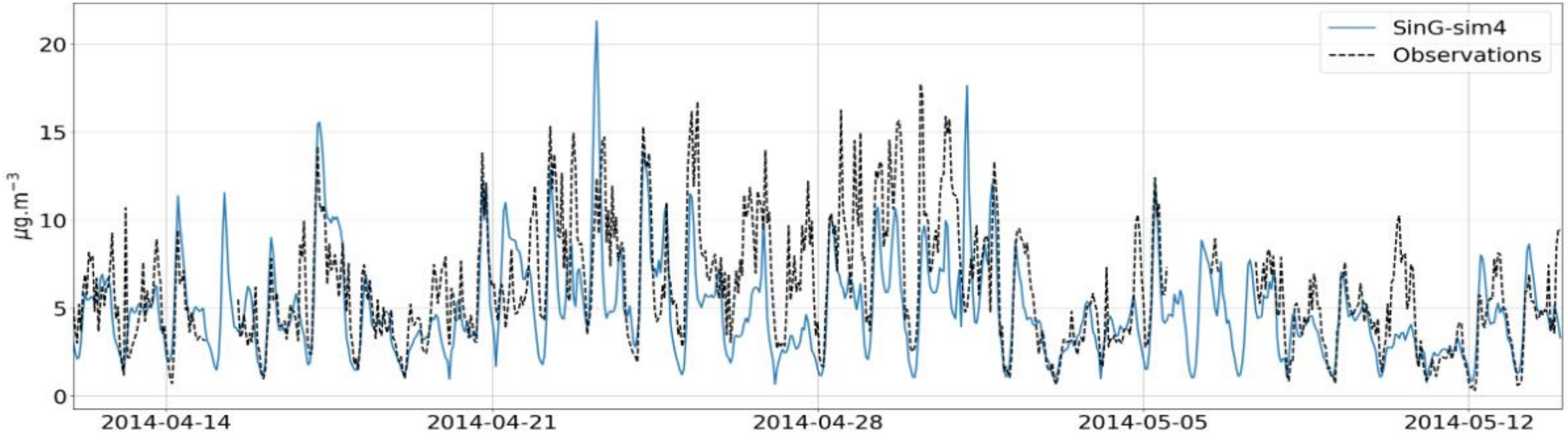
Sim. 3 – Sim. 2 without particle deposition (representing maximal resuspension)
All deposited particles are resuspended – no deposited mass on the street surface

• Sensitivity tests with different tyre-wear emission factors observed in the literature

	obs [µg.m⁻³]	sim [µg.m⁻³]
1	**6.07**	**1.74**
2	**6.07**	**4.91**
3	6.07	4.92

- Black carbon emissions following the European guidelines are not high enough to justify the high black carbon concentrations observed in the streets (Sim. 1)

- Good representation of black carbon in streets using higher tyre wear emission factors based on observations in the literature (Sim. 2)



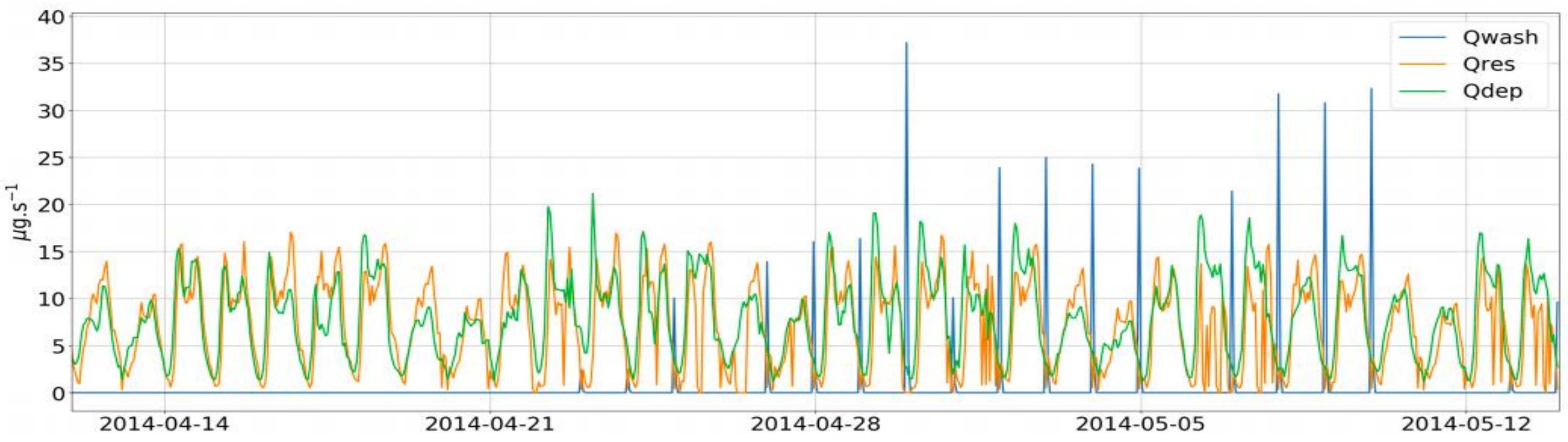
Lugon et al., 2020

Sim. 1 – European guidelines (EMEP)
Sim. 2 – Boulter (2005), Luhana et al. (2004)
Sim. 3 – Sim. 2 without particle deposition (maximal resuspension)

- **Sensitivity tests with different tyre-wear emission factors observed in the literature**

  - Resuspension does not influence much black carbon concentrations here (Sim. 2 x Sim. 3)
    . Resuspension is limited by particle deposition, which is low

	obs [µg.m^{-3}]	sim [µg.m^{-3}]
1	6.07	1.74
2	**6.07**	**4.91**
3	**6.07**	**4.92**



Lugon et al., 2020

Sim. 1 – European guidelines (EMEP)
Sim. 2 – Boulter (2005), Luhana et al. (2004)
Sim. 3 – Sim. 2 without particle deposition (maximal resuspension)

Conclusions

- Importance of reducing pollutant concentrations in streets – where populations are exposed
  - . Use of multi-scale simulations to calculate pollutant concentrations in the streets (MUNICH model)
  - . Good representation of particle concentrations and chemical composition
  - . Particles in the streets may have more health impact than those from the urban background

- Secondary particles have an important contribution in streets (reaching up to 27% on $PM_{2.5}$ concentrations depending on the street and the time of the day)
- Tyre-wear abrasion may contributes to black carbon concentrations in streets
- Resuspension does not contribute much to black carbon concentrations in streets here

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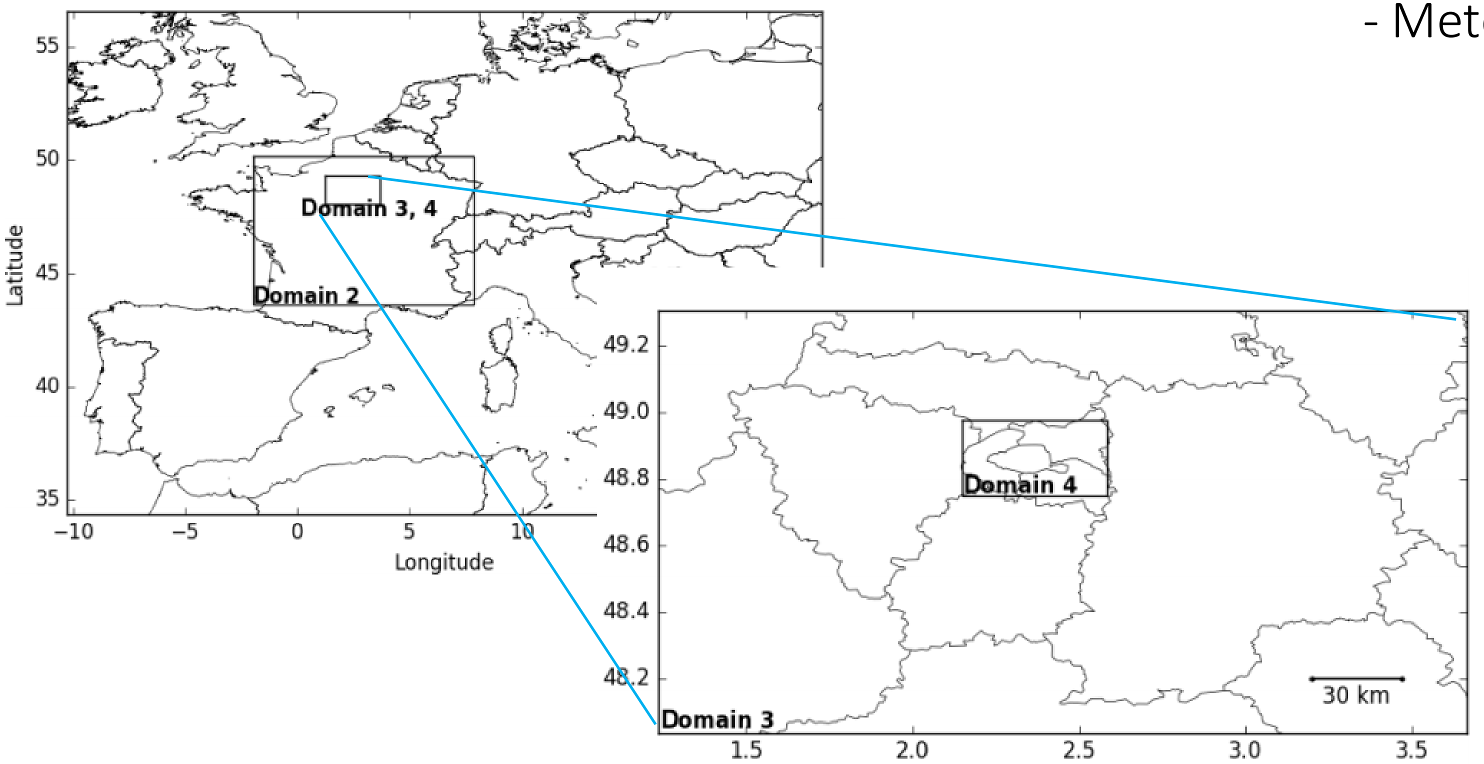
Setup of simulations:

Regional scale – input data for Polair3D

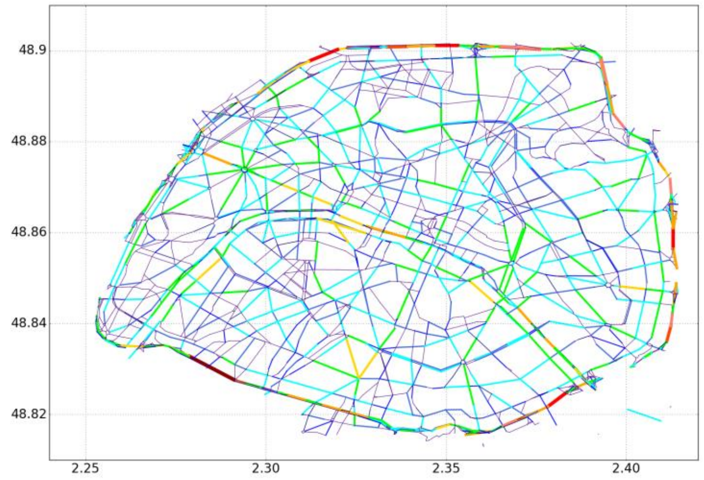
- Initial and boundary conditions: nesting from Polair3D
- Emissions: Airparif (2012 and 2014/ANSES for traffic)
- Spatial resolution of 1km x 1km
- Meteorological data: WRF model simulation

Local scale – input data for MUNICH model

- Street network with the main streets of Paris (~3800)
- Emissions per street: Airparif (2014/ANSES)
- Background concentrations computed by the regional-scale model Polair3D
- Meteorological data: WRF model simulation



Regional-scale simulated domains



NO_2 emissions in the Parisian street network