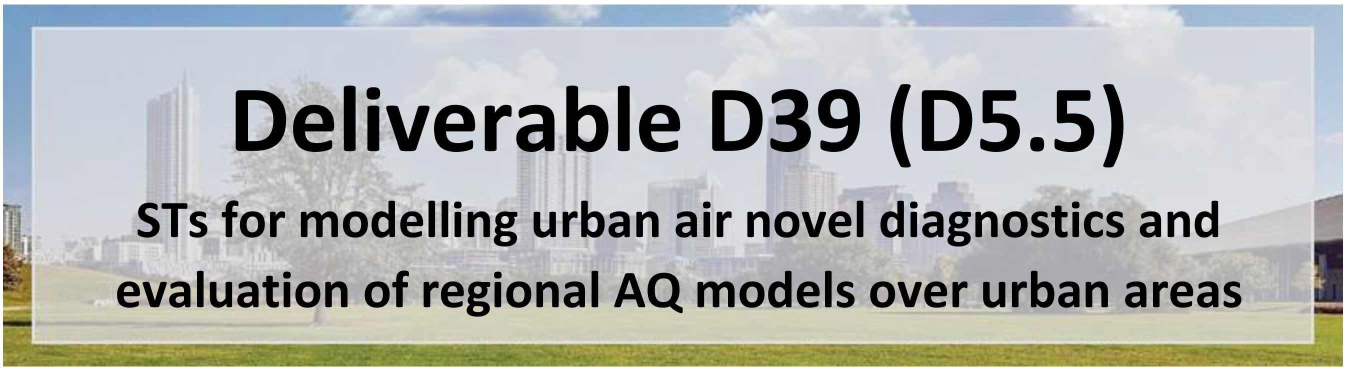

# Deliverable D39 (D5.5)

## STs for modelling urban air novel diagnostics and evaluation of regional AQ models over urban areas

## RI-URBANS

## Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS (GA n. 101036245)

**By**

**INERIS, FORTH, METNO, TNO, CNRS & FZJ**

***29th September 2025***

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# Deliverable D39 (D5.5): STs for modelling urban air novel diagnostics and evaluation of regional AQ models over urban areas

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| | |
|---|---|
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| **Accepted by** | Project Coordination Team |
| **Comments** | This report summarises the progress achieved in the RI-URBANS project to developing regional models relevant at urban scale, and the associated evaluation practices against observational data. We focus on air quality parameters of interest for health indicators and policy support. The main focus is on source apportionment of both sectoral and geographic (local or long range) for (i) particulate matter (PM) mass (including PM constituents such as organic matter and equivalent black carbon), (ii) Ultra fine particles (UFP), (iii) oxidative potential (OP). We also cover the use of vertical profiling data to validate regional models in urban areas. |

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# 1 About this document

This deliverable summarises the progress achieved in the RI-URBANS project to **developing regional models** relevant at urban scale, and the **associated evaluation practices** against observational data. We focus on air quality parameters of interest for health indicators and policy support. The main focus is on source apportionment of both sectoral and geographic (local or long range) for (i) particulate matter (PM) mass (including PM constituents such as organic matter and equivalent black carbon), (ii) Ultrafine particles (UFP), (iii) oxidative potential (OP). We also cover the use of vertical profiling data to validate regional models in urban areas.

For each of these quantities, we review the maturity of modelling systems in delivering research or operational information and we propose a synthesis of available observation data, also differentiating the monitoring data flows available in routine measurement or only through limited field campaign, for short periods or historical time series. For each of those, we highlight relevant evaluation strategies by proposing state of the art quality control procedures, extended, when possible, to the release of user-friendly interfaces and tools for uptake by relevant users.

This is a public document that will be distributed to all RI-URBANS partners for their use and submitted to the European Commission as the RI-URBANS deliverable D39 (D5.5) This document can be downloaded at https://riurbans.eu/work-package-5/#deliverables-wp5.

# 2 Black Carbon

This section focuses on the modelling and evaluation of Black Carbon (BC), Element Carbon (EC) and equivalent Black Carbon (eBC). BC and EC are primary particulate pollutants generated by incomplete combustion processes. They represent the same atmospheric product, EC from a thermochemical classification and BC from optical classification. eBC can be defined as the mass concentration of BC as indirectly determined by light absorption techniques such as filter-based absorption photometers. More information on specific terminology can be found in Petzold et al. (2013).

## 2.1 Regional Modelling

### 2.1.1 Modelling methodologies

Most state-of-the-art regional chemistry-transport models (CTMs) include the representation of EC as inert passive aerosol tracers directly prescribed from emission inventories. In the emission inventories, EC is either directly specified as a single emitted source from corresponding activity data and emission factors or inferred from primary particulate emissions using a prescribed country and/or sector dependent EC/PM ratio. Even if in some cases, the actual emission factors are measured using aethalometer data and therefore correspond to eBC (and indirectly to BC), those are considered as EC in the emission inventories.

Being considered an inert aerosol species, it is straightforward to differentiate emission sources of EC to perform Source Apportionment (SA). The most relevant distinction is to tag residential or transport source, or solid or fossil fuels, in order to match the definition in observational data (see Deliverable D3 (D1.3) “Report on source apportionment studies and recommendations for source apportionment procedures”.

### 2.1.2 Available Modelling Products

The Copernicus Atmosphere Monitoring Service (CAMS) (Peuch et al., 2022; Colette et., 2025) produces on an operational basis forecast and analysis model results for EC, including the source apportionment of residential emissions (ECres), and total EC (ECtot) which includes all other sources including but not limited to traffic. These modelling products are available for public use on the Atmosphere Data Store (https://ads.atmosphere.copernicus.eu/datasets).

## 2.2 Observation data

### 2.2.1 Monitoring Methodologies

EC can be monitored using thermo-optical analysers operated either off-line using (pre-burn quartz) filters or continuously, as with the SUNSET Field Analyzer. BC can be monitored with aethalometers and subsequently converted to Equivalent Black Carbon (eBC). There are different approaches to convert BC to eBC that are detailed in Deliverable D1 (D1.1) “Guidelines, datasets of non-regulated pollutants inc. metadata, methods”[1]. In a nutshell, BC to eBC conversion relies on a factor which can be either (i) prescribed by the instrument manufacturer or from the literature, or (ii) derived from independent EC observations that are collected locally thereby offering the possibility to use a conversion factor which varies in space and time. It is also possible to infer the source apportionment of measured BC with aethalometers by making use of multi-wavelength measurements and taking benefit of the spectral dependence of light absorption by brown carbon co-emissions (especially for solid fuel combustion processes). The major methodologies to achieve this are detailed in Deliverable D3 (D1.3) “Report on source apportionment and recommendations for source apportionment procedures". Recommendations are also provided in EYE-CLIMA (https://eyeclima.eu/products/public-reports/).

### 2.2.2 Available Observations

The number of available measurement for BC/EC/eBC has increased sharply in the recent years. And this trend is expected to continue as BC is now included as a reglementary pollutant (to be monitored at supersites) by the Ambient Air Quality Directive revised in 2024 (“Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe”, https://eur-lex.europa.eu/eli/dir/2024/2881/oj).

In the framework of RI-URBANS, 11 pilot sites have monitored continuously BC. The corresponding data have been processed and converted to eBC, including the fractional part of solid and liquid fuel (eBCsf and eBClf respectively) using the methodology described in Milestone M5 (M1.6) “Data management for online source apportionment ST”. They are available for further use from the ACTRIS Data Center (EBAS: ebas.nilu.no) repository. Data can be visualized on the following interface “ACMCC Network Visualization Tool”.

Historical dataset of ambient eBC and EC measurements covering the 2006-2022 period is described in Deliverable D1 (D1.1) “Guidelines, datasets of non-regulated pollutants inc. metadata, methods” and available in a Zenodo repository (https://doi.org/10.5281/zenodo.7982201). Concentration time series are available for 53 sites in Europe. There were intensive measurement campaigns in the years 2018/2019 in the framework of the COLOSSAL Cost Action, so that the measurement density is larger for that period. Instrumental and operational settings provide the source contributions from biomass burning and traffic (eBCsf and eBClf). Savadkoohi et al. (2023) present a comprehensive description and analysis of this dataset.

Currently, the eBC data from 25 ACTRIS National Facilities are delivered to Copernicus (and made available for related operational services) in Near Real Time (NRT) as part of the CAMS2_21 service. In that context, NRT means

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[1] https://riurbans.eu/wp-content/uploads/2022/10/RI-URBANS_D1_D1_1.pdf
https://riurbans.eu/wp-content/uploads/2024/07/RI-URBANS_D3_D1_3.pdf

with a delay of about 3 hours. Going forward, more recurrent observations will be made available in the ACTRIS framework but also from regulatory reporting of European Member States following the new requirements in the ambient air quality directive issued in 2024. The ACTRIS and CAMS2_21 eBC datasets are derived uniformly from filter-absorption measurements, following the guidance provided by CAIS/ECAC, the ACTRIS Topical Centre for Aerosol In Situ measurement (https://www.actris-ecac.eu/particle-light-absorption.html#Guidelinesand), and made available through the EBAS/ACTRIS NRT data portal (https://ebas-nrt.nilu.no/). eBC source apportionment products (namely eBCsf and eBClf) can be derived for the same station following state-of-the-art data treatment procedures as defined within the corresponding RI-URBANS service tool (ST11[2]) The data issued from the national reporting will be processed at national levels, ideally using harmonized methodologies and taking advantage of RI-URBANS guidance documents, and made available publicly on EEA AQ e-reporting system for both NRT (as up-to-date as for the PM analysers, i.e. 3 to 6hrs delay) and as validated data delivered in September of the following year.

## *2.3 Evaluation and Quality Control*

In the framework of RI-URBANS, a methodology to confront models and observations was developed based on the COLOSSAL Cost Action data collected in the year 2018 and simulations from 8 CAMS regional CTMs. This evaluation method was implemented in a demonstrator using NRT data from CAMS (11 CTMs currently operational) and RI-URBANS pilot sites (hereinafter referred to as "EvaNRT-BC") for a chosen date (hourly timestep). eBC concentration observations obtained from AE33 aethalometers were converted from BC by applying a harmonization factor (H) equal to 1.76 (Yus-Diez et al., 2021) which is one of the methods recommended by RI-URBANS (D1 (D1.1)) cited in 2.2.1) and by ACTRIS (https://www.actris-ecac.eu/particle-light-absorption.html#Guidelines). The resulting eBC was subsequently directly compared to modelled EC. The proposed EQC methodology includes consistent comparison between modelled EC and observed eBC at hourly timestep, including source apportionment of solid and liquid fuel based on and the source-specific Absorption Angstrom Exponents (AAE) values from Zotter et al. (2017). Information on the data processing of NRT measurements from aethalometers is documented in Milestone M5 (M1.6) "Data management for online source apportionment ST". Moreover, the evaluation was transposed into the Model Quality Indicator framework proposed in the FAIRMODE Guidance Document on Modelling Quality Objectives and Benchmarking (Janssen et al., 2022) which accounts for respective model and observation uncertainties. The detailed presentation of "EvaNRT-BC" as well as the resulting EQC diagnostics are illustrated in Deliverable D19 (D3.4) "High resolution mapping over European urban areas". The "EvaNRT-BC" demonstrator is available in a user-friendly interface in the form of a public Jupyter notebook (**Figure 1**), which users can adapt to their needs, by substituting to their own model or observation sources. The associated code is freely available on the following Zenodo repository https://doi.org/10.5281/zenodo.16812466 (Guion et al., 2025).

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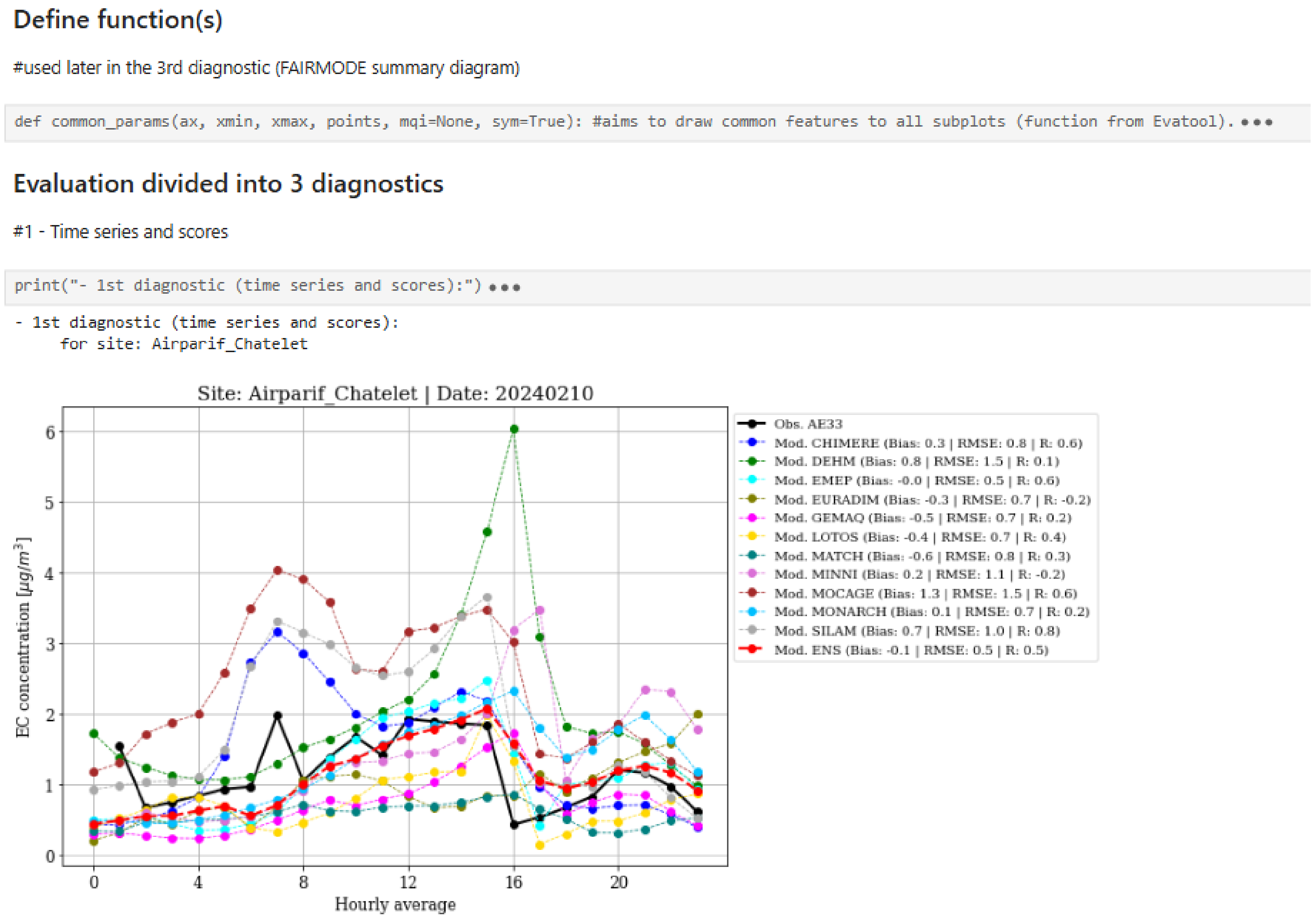
[2] https://riurbans.eu/wp-content/uploads/2025/02/ST11.pdf



Define function(s)

#used later in the 3rd diagnostic (FAIRMODE summary diagram)

```
def common_params(ax, xmin, xmax, points, mqi=None, sym=True): #aims to draw common features to all subplots (function from Evatool).•••
```

Evaluation divided into 3 diagnostics

#1 - Time series and scores

```
print("- 1st diagnostic (time series and scores):")•••
```

```
- 1st diagnostic (time series and scores):
     for site: Airparif_Chatelet
```

***Figure 1**. The open source interactive EvaNRT-BC online jupyter notebook allows user to compare operational CAMS modelled EC to eBC NRT data using well established quality control procedures.*

## 2.4 *Synthesis on Evaluation of Regional CTMs*

In order to summarize the key source of information to evaluate eBC and related source apportionment, either in terms of modelling or observational source, the various type of data available are presented in Table 1.

**Table 1.** For both models (top) and observation (bottom), the available sources of information are listed as well as the time period covered and their operational/research character level.

| | Intercomparison experiment | Reanalysis | Analysis and forecasts |
|---|---|---|---|
| **Model** | CAMS_61 Project | CAMS production | CAMS production |
| Research | Yes (2018, available upon request to the project coordinator[3]) | | |

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[3] https://atmosphere.copernicus.eu/sites/default/files/custom-uploads/CAMS-5thGA/day2/Fagerli%20H_Met%20Norway_Chemistry%20aerosol%20modelling.pdf

**RI-URBANS (www.RIURBANS.eu) is supported by the European Commission under the Horizon 2020 – Research and Innovation Framework Programme, H2020-GD-2020, Grant Agreement number: 101036245**

| | | | |
|---|---|---|---|
| Operational | | Yes (from 2020, available on the ADS[4]) | Yes (available on the ADS) |

| | Historical dataset | NRT production |
|---|---|---|
| **Observations** | RI-URBANS compiled dataset | ACTRIS (EBAS) |
| Research | Yes (2006-2022, see link above) | / |
| Operational | / | Yes (from 2022, see link above) |

# 3 Organic Aerosol

Positive Matrix Factorization (PMF) is traditionally used to source apportionment analysis using of organic aerosol concentrations of PM1 based on the ACSM data. The contribution estimated with this method are generally expressed in terms of HOA (Hydrocarbon like organic aerosol), BBOA (Biomass Burning Organic Aerosol) and OOA (Oxygenated Organic Aerosol). Comparison between PMF and chemistry-transport model (CTM) results can help to evaluate and improve results of organic aerosol models.

## 3.1 Regional Modelling

### 3.1.1 Modelling methodologies

The difficulty with a PMF/CTM comparison resides on how to match PMF results with the organic aerosol species simulated by the CTMs. A first comparison was performed with an ensemble of 4 models (CAMX, CHIMERE, EMEP and LOTOS-EUROS) in D19 (D3.4) “High resolution mapping over European urban areas”[5] based on a methodology typically used in modelling studies:

- BBOA is defined as the sum of primary particulate organic aerosol (POA) from biomass burning
- HOA is the sum of POA from other sources
- OOA is the sum of all other organic compounds. For the models that considered POA to be semi-volatile, the secondary compounds formed from the oxidation of the primary SVOC are accounted for in OOA. EMEP also considered that some POA emitted by forest fires were directly counted in the OOA fraction.

The comparison showed that there is a great variability of treatment of organic aerosols by models with some models taking account the semi-volatile properties of POA and some other models assuming non-volatile POA. These differences lead to very different results and seem to indicate the need for high or moderate OA complexity models that account for the necessary processes (in particular to consider the semi-volatile properties of POA).

The methodology used for the comparison raises several issues in relation with the matching between observed HOA, BBOA and OOA and the species simulated by the models. Part of the biomass burning primary aerosols can indeed be classified as HOA as it consists of long chain carbons (for example resinic acids) while another part could be highly or moderately oxidized and be classified as OOA. In addition, the different types of aerosols constituting biomass burning organic aerosols can behave differently in the atmosphere than levoglucosan (corresponding to the ACSM signal m/z60 used to discriminate BBOA by the PMF) due to differences in the gas/particle partitioning

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[4] https://ads.atmosphere.copernicus.eu/

[5] https://riurbans.eu/wp-content/uploads/2024/04/RI-URBANS_D19_D3_4.pdf

or aging processes. Therefore, BBOA contribution estimated by the PMF from ACSM is likely missing part of the organic aerosols from biomass burning.

### 3.1.2 Available Modelling Products

There is no operational modelling system delivering detailed organic aerosol composition at this stage. Most operational modelling groups are presently using very simplified scheme in the forecast and may not be able to tag HOA, BBOA and OOA. To achieve this, it is still necessary to rely on research activities to perform simulations with more complex SOA scheme which may impact significantly the CPU time.

## 3.2 Observation data

### 3.2.1 Monitoring Methodologies

The non-refractory $PM_1$ (NR-$PM_1$), including organic aerosols (OA), is measured continuously and in near real-time using the Aerosol Chemical Speciation Monitor (ACSM) — either the Quad-ACSM or ToF-ACSM — or the Aerosol Mass Spectrometer (AMS). The operation and quality control of these instruments are detailed in the RI-URBANS Guideline document (ST3[6]).

These instruments provide concentration and error matrices (mass spectra and time series) for OA, which are used for source apportionment (SA) of OA. The most commonly used method is Positive Matrix Factorization (PMF) with the ME-2 engine solver. This approach allows the identification of the main sources of OA at various receptor sites. A harmonized protocol for OA source apportionment was developed by Chen et al. (2022), using both seasonal PMF and rolling PMF for long-term measurements. More details on the methodologies and recommendations can be found in the RI-URBANS document (ST10[7]). Such harmonized and publicly available information are extremely useful for use in model evaluation.

### 3.2.2 Available Observations

Considering ACTRIS, RI-URBANS Pilots and other supersites, there are overall multiple PM observation datasets (See Annex A and also the overview compiled for Europe as part of the CAMEO Project, Zhang et al. 2025) suitable for PMF. A single database gathering all the observations is not (yet) available and data availability is dependent on individual requests to data providers.

Historical datasets of NR-$PM_1$ species, including OA, from 2011 to 2023 for 35 sites — comprising 26 urban background, 5 suburban, 3 traffic, and 1 remote background site — have been provided to RI-URBANS by AQMNs, ACTRIS, and other research institutes. These datasets are described in the RI-URBANS Service tool 3 document.

Within the framework of the COST COLOSSAL Action, datasets from 22 stations, including OA source contributions for the years 2018–2019, are openly available in the publication by Chen et al. (2022), using harmonized methodologies at the European level using the rolling PMF method).

As part of the RI-URBANS framework, NRT OA SA has been maintained for 13 sites during the pilot phase. Rolling PMF analyses have also been conducted for these sites in parallel to compare with the NRT data. The methodology is described in Deliverable D5 (D1.5) “NRT Source Apportionment Service Tools for submicron carbonaceous matter (final)”. The NRT results and rolling PMF analyses will be made available after publication (Petit et al., in prep).

## 3.3 Evaluation and Quality Control

Comparing model results to Positive Matrix Factorisation (PMF) data is complex due to the required complexity of OA models and ambiguous matching with observed species. Nonetheless, the comparison can help to evaluate the

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[6] https://riurbans.eu/wp-content/uploads/2025/04/ST3.pdf

[7] https://riurbans.eu/wp-content/uploads/2025/02/ST10.pdf

model results and can provide for future model developments. Harmonisation of PMF analysis is recommended to facilitate comparisons with model results over multiple sites.

The work completed in RI-URBANS and documented in D19[8] demonstrated the feasibility of near-real-time comparison between Regional CTMs models and ACSM PMF for OA at RI-URBANS pilot sites. Such comparisons were proved useful to perform a quality control of the temporal variability of models and observations. The example of Figure 2 shows for instance that all 4 CTMs exhibit a two-peak daily cycle for BBOA, while the ACMS observed BBOA cycle as a main peak only at night, and not in the morning, which is expected due to the more frequent use of wood burning for residential heating at night (Guevara et al., 2025). However, some challenges raised by the required complexity of OA models (which are not available at present in operational setting) and ambiguous matching with observed species remain to be addressed to make a wider and more quantitative use of this comparison.

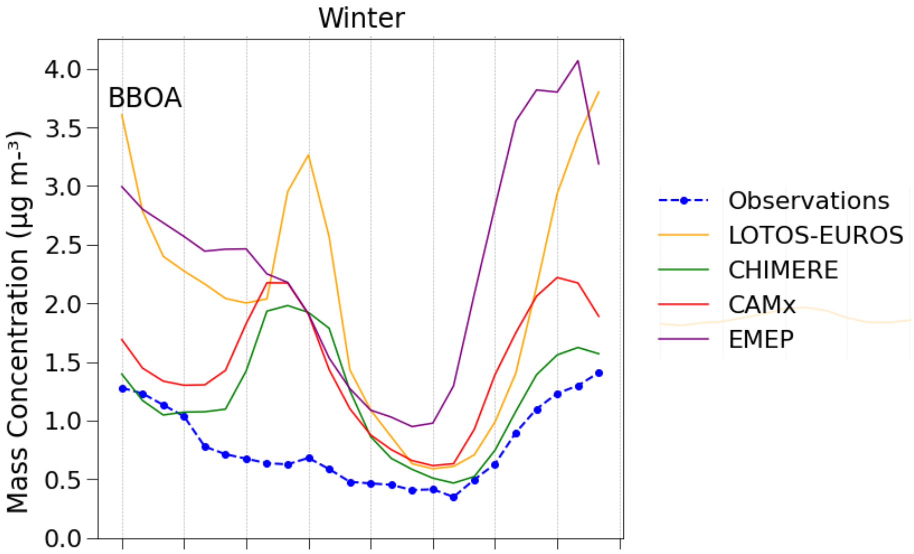

***Figure 2.*** *Winter diurnal cycle of BBOA estimated by the PMF and simulated by the four air quality models (LOTOS-EUROS, CHIMERE, CAMx and EMEP). Figure taken from D19[4].*

## *3.4 Synthesis on Evaluation of Regional CTMs*

In order to summarize the key source of information to evaluation organic aerosol and related source apportionment, either in terms of modelling or observational source, the various type of data available are presented in Table 2.

**Table 2.** For both models (top) and observation (bottom), the available sources of information are listed as well as the time period covered and their operational/research character level.

| Model | CAMX<br>(D19 method) | CHIMERE<br>(D19 method) | EMEP<br>(D19 method) | LOTOS-EUROS<br>(D19 method) |
|---|---|---|---|---|
| Research | Yes | Yes | Yes | Yes |
| Operational | No | No | No | No |
| Publicly available | No (Upon request) | No (Upon request) | No (Upon request) | No (Upon request) |

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[8] https://riurbans.eu/wp-content/uploads/2024/04/RI-URBANS_D19_D3_4.pdf

Observations

| | Historical datasets | Historical datasets | NRT data |
|---|---|---|---|
| Source | COST COLOSSAL compiled dataset | RI-URBANS compiled dataset | RI-URBANS pilot phase (13 sites, 2023) |
| Research | Yes | Yes | No |
| Operational | No | No | No |
| Publicly available | Chen et al. (2022) (https://doi.org/10.5281/zenodo.6522811) | Not yet (on request) | Not yet (article in preparation). Rolling PMF results for 2023 for 13 sites could be provided and used for research purposes after publication. |

# 4 Sector apportionment of PM Mass

This section focuses on the sectoral source apportionment of total PM mass, either $PM_{2.5}$ or $PM_{10}$. The source apportionment of the PM components EC and OC are discussed in the previous two chapters. Geographical source apportionment of PM mass is not considered here because of the absence of information on geographical origin from observational methods.

## 4.1 Regional Modelling

### 4.1.1 Modelling methodologies

Sector apportionment within CTMs relies on methods which can be split into two subgroups:

1. Tagging based methods which provide PM contributions for air quality assessments. These methods keep track of the origin of air pollutants throughout a model simulation. Results are valid for current atmospheric conditions. By definition the sum of all contributions equals the total concentration, and the sum of individual contributions equals the combined contribution. In case of strong non-linearities influencing the relationship between emissions and concentrations, the contributions cannot directly be translated to a potential emission reduction impact.
2. Sensitivity/brute-force (BF) based methods which provide potential impacts of emission reductions on PM concentrations for air quality planning. These methods provide the concentration change resulting from a specific emission reduction (ER) converted by factor 100/ER. In case of strong non-linearities influencing the relationship between emissions and concentrations, the emission impact cannot always be extrapolated to emission reductions other than the one applied and the potential impacts from individual sources cannot be summed to provide a combined impact and/or the total concentration.

Under the second category we can also identify modelling tools that represent the complex relationship between emissions and concentrations by simplified functions. The Air Control Toolbox (ACT, Colette et al., 2022) tool uses polynomial functions trained on a set of scenario runs to provide estimates for the potential impact of emission reductions on the air pollutant concentrations. SHERPA (Pisoni et al., 2024) assumes a bell-shaped function representing the dependence of the concentration change on the distance to the location of the emission reduction and combines this with source-receptor relationships derived from a set of emission reduction scenario runs.

The relatively new local fractions (LF) methodology (Wind and van Caspel, 2025) which calculates the derivative of the concentration with respect to an emission change (dC/dE) at the current concentration can be considered similar to a brute force methodology with very small emission reductions.

### *4.1.2 Available Modelling Products*

The Copernicus Atmosphere Monitoring Service (Peuch et al., 2022) produces on an operational basis hourly sector apportionment of PM for main European cities from the ACT tool based on the CHIMERE model which will in the near future be extended by source apportionment from a tagging method in the LOTOS-EUROS model. These modelling products are available (visually and for downloads) (2023 – now) for public use on the CAMS policy support website (https://policy.atmosphere.copernicus.eu/). In addition, hourly wildfire and natural (seasalt, dust) contributions to PM10 are available from the CAMS regional air quality service for public use on the Atmosphere Data Store (ADS, https://ads.atmosphere.copernicus.eu/).

The TNO operational apportionment service (TOPAS) produces on an operational basis daily sector apportionment of PM for main European cities and EEA observational sites from the LOTOS-EUROS model with its tagging approach. This modelling product is available for the past 6 weeks (visually) and recent years (visually and for downloads) (2023-2024) for public use on the TOPAS website (https://airqualitymodeling.tno.nl/topas/topas-eu/).

The Joint Research Centre (JRC) provides offline yearly averaged sector allocation information from the SHERPA tool for a base year. The products can be accessed with an EU login through the SHERPA dashboard (https://aqm.jrc.ec.europa.eu/Section/Sherpa/). Pre-processed PM2.5 sector allocations from SHERPA for European cities for 2021 and 2023 are available from the urban PM2.5 urban atlas on the JRC air quality modelling website (https://aqm.jrc.ec.europa.eu/Section/Sherpa/Background)

EMEP MSC-W provides yearly country-to-country source-receptor matrices for PM2.5 and PM10 (and other reported compounds) based on brute force simulations with the EMEP model (possibly from the local fraction method in the future). The products are provided through the website (https://emep.int/mscw/mscw_moddata.html).

## ***4.2 Observation data***

### *4.2.1 Monitoring Methodologies*

Source attribution based on observational data is performed through the application of receptor modelling (RM). Positive Matrix Factorisation (PMF) is currently the most applied receptor modelling method within Europe for PM which looks for internal correlation in PM composition observations from filter measurements. This analysis yields several factors that in some cases can be attributed to source sector categories. Other factors represent contributions from combined sectors, such as commonly obtained (secondary) nitrate-rich and sulphate-rich factors.

### *4.2.2 Available Observations*

PMF datasets are available from a range of projects, campaigns and/or (national) programmes. Most of the datasets cover a period of several months up to 2 years. At a few locations longer timeseries of PMF PM source attribution data is available, these include the Spanish sites of Barcelona and Montseny (CSIC), the French site of Grenoble (university of Grenoble) and four sites in the Italian Po Valley (ARPAE, Scotti 2021). A harmonised PMF set derived with the same solution criteria and settings has been produced by CSIC/University of Grenoble/INERIS/ARPA Lombardia) for the cities of Barcelona (2000,2019,2021), Grenoble (2013), Milan (2017-2019). The dataset is described in ST10.

In the Annex A we provide an overview of PMF datasets which are either published or found through direct contact with the associated institutes within RI-urbans and other European projects. Datasets are usually not freely accessible but can be requested through direct contact with the data providers. Memorandum of Understandings are an option to foster collaboration and exchange CTM and PMF datasets.

## 4.3 Evaluation and Quality Control

Comparing model results to Positive Matrix Factorisation (PMF) data is complex due to differences in each PMF dataset characteristics (sampling, analysed chemical components, solution criteria) and difficulty in isolating sources. It requires thorough analysis of the PMF profiles and geochemistry expertise to identify its potential match with CTM sources.

Harmonisation of PMF analysis is recommended to facilitate comparisons over multiple sites and interpretation of the data. More detailed modelled source attribution for subsectors can help to better match with the PMF factors. Note that in principle only modelled source contributions (from tagging approaches) are directly comparable to PMF source contributions while modelled potential impacts are not when it includes also secondary PM influenced by non-linear effects.

Comparisons performed in the context of RI-urbans (Pekel et al., 2025) and other studies within e.g. the EU project CAMEO (Zhang et al., 2025) illustrate that quantitative comparisons are feasible for PMF profiles with clear tracer species, i.e. residential biomass combustion, sea salt and to some extent dust (can contain mixing of natural and anthropogenic dust) while for other sources more qualitative comparisons can provide valuable insights for both PMF and CTM development and emission inventories. This holds for e.g. traffic, shipping and industry. Agriculture is usually not captured with PMF since its source contributions are dominated by secondary PM which mainly ends up in combined secondary PMF factors (nitrate-rich).

## 4.4 Synthesis on Evaluation of Regional CTMs

In order to summarize the key source of information to evaluate PM mass and related source apportionment, either in terms of modelling or observational source, the various type of data available are presented in Table 3.

**Table 3.** For both models (top) and observation (bottom), the available sources of information are listed as well as the time period covered and their operational/research character level.

| | **Historical trend** | **Historical campaigns** | **Recent NRT** |
|---|---|---|---|
| Model (& method) | LOTOS-EUROS (tagging), EMEP (BF), CHIMERE (ACT) | LOTOS-EUROS (tagging, BF, surrogate modeling), EMEP (BF and LF), CHIMERE (ACT)and many CTM models | CHIMERE (ACT)<br>(soon also LOTOS-EUROS (tagging)) |
| Research | Yes | yes | yes |
| Operational | No | From 2023 | yes |

| | **Historical trends** | **Historical campaigns** | **Recent NRT** | **Harmonised datasets from multiple locations** |
|---|---|---|---|---|
| Observations | Grenoble, Barcelona, Po Valley | Projects campaigns, e.g. RI-urbans, LIFE-Remy, SOURCES, PM-Ost | Not available | RI-urbans dataset |
| Research | On request | On request | no | On request |
| Operational | no | no | no | no |

# 5 Oxidative Potential

Aerosol Oxidative Potential (OP) has been associated with cell damage/oxidative stress in laboratory experiments and acute short-term outcomes in cohorts and is hypothesized to be one of the drivers of the association between particulate matter (PM) exposure and morbidity. Commonly used techniques for quantifying aerosol OP are through the analysis of dithiothreitol (DTT) and ascorbic acid (AA) OP assays, each being sensitive to different aerosol components.

In the RI-URBANS project, first attempts at European and city-scale model-to-measurement were made, focusing on model skill with respect to observation, as well as on the impact of modelling assumptions on total simulated OP. To this end, model results from the LOTOS-EUROS, EMEP MSC-W and Urban EMEP (uEMEP), and the CHIMERE models were evaluated on a European scale.

For policy applications, our general recommendation is that modelling and measurement groups first work towards a harmonized PMF framework, to bring together model-to-measurement source evaluations. Evaluating the model's capability to simulate OP using source-specific intrinsic OP values from the harmonized dataset then follows as a second step. As a third step, model assumptions on, for example, chemical aging and sources of secondary aerosol can be tested. Currently, such developments are required to build confidence in the reliability of (policy-relevant) modelling OP products.

## 5.1 Regional Modelling

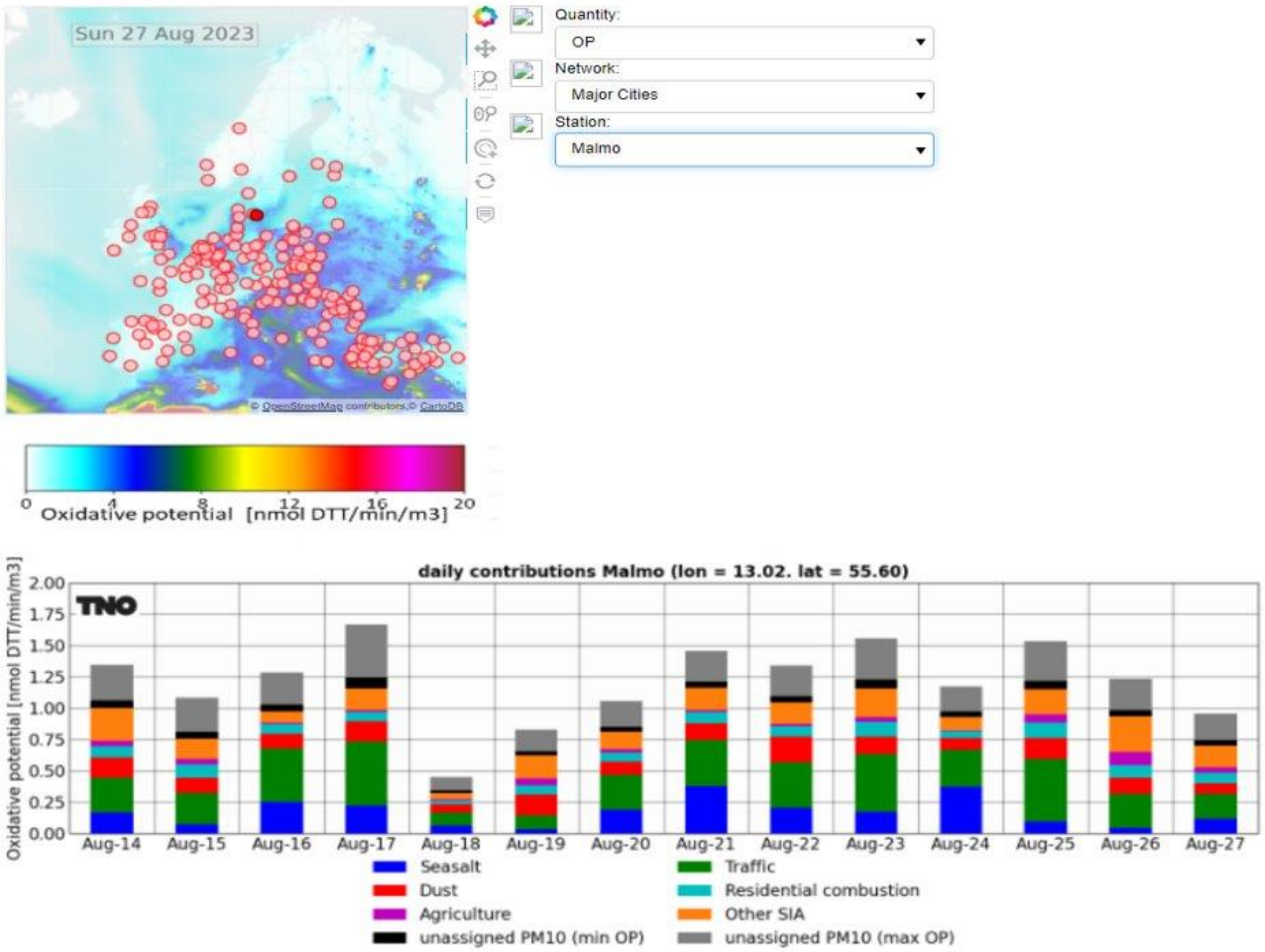
### 5.1.1 Modelling methodologies

The current state of the art methodologies to derive source specific OP values are based on the OP apportionment works of Weber et al. (2021) and Daellenbach et al. (2020). As described in Section 5.2.1 (observational data), the latter two works provide source-specific (intrinsic) OP coefficients that can be applied to modelled output concentrations to estimate total modelled OP.

OP modelling is currently still at a research stage, while first attempts and prototypes were made a.o. as part of the RI-URBANS project (see Figure 3). In these attempts modelled source contributions are multiplied by the source specific OP values mentioned above which are derived from observations.  Other recent literature results using this approach are given by Pekel et al. (2025) and Vida et al. (2025).

For an operational implementation of OP modelling, the methodologies require further model-to-measurement development and evaluation (reflecting also on Ch. 5), as well as requiring further research investigating the applicability of the (linear) intrinsic OP values on a European scale. The latter is especially important for producing European-scale OP maps. For policy applications, such maps can for example be used to investigate the impact of emission control strategies on OP exposure. Concrete future required developments for the purpose of improving OP model capabilities are:

- Availability of source specific OP values across Europe with better representativeness of different environments (e.g., rural, urban, marine remote, traffic)
- Source specific OP values for more source sectors (e.g. agriculture)
- Improvements of some source sector modelling/emissions as well as improved representations of secondary aerosol formation processes in models in general
- Taking into account aging of seasalt (currently OP from aged seasalt is used)


Quantity: OP

Network: Major Cities

Station: Malmo

***Figure 3.** Prototype of source apportionment of OP tool (not available online yet)– based on current TOPAS (https://airqualitymodeling.tno.nl/topas/topas-eu/).*

### *5.1.2 Available Modelling Products*

Currently no OP modelling products are available through open access, given that the model methodologies are still in a research phase. Nevertheless, the modelling groups participating the RI-URBANS project (LOTOS-EUROS, CHIMERE, EMEP MSC-W) are willing to share OP modelling results (time series, maps) upon request.

## *5.2 Observation data*

### *5.2.1 Monitoring Methodologies*

As mentioned above, two commonly used OP measurement methodologies are based on the DTT and AA assays. AA-depletion in AA-assays is sensitive to oxidative potential of transition metals, and very few other specific organic or other reactive species DTT-depletion in DTT-assays is caused by the interactions with the thiol and a wide range of reactive species (transition metals and quinones) and free radicals. Both probes represent the main categories of non-enzymatic lung anti-oxidant categories (DTT a surrogate of Gluthatione, and Ascorbic acid, a natural lung anti-oxidant).

AA and DTT-depletion (being the measure of OP) are measured in a lab setting based on samples taken from (daily mean) PM filter measurements.

Weber et al. (2021) and Daellenbach et al. (2020) combined OP observational with positive matrix factorization (PMF) analysis to estimate observationally derived source-specific (intrisic) OP values. This was achieved by multi-linear regression, resulting in sets of (linear) intrinsic OP values for both $OP^{DTT}$ and $OP^{AA}$. The Weber et al. (2021) dataset focuses mostly on urban measurements in France, while the Daellenbach et al. (2020) dataset combined urban and rural OP measurements from four stations in Switzerland.

### *5.2.2 Available Observations*

The lack of readily available OP measurement data is largely the result of much of the analysis still being in a research phase. However, OP measurements from the four sites in Switzerland discussed in Daellenbach et al. (2020) are available for download from https://doi.org/10.5281/zenodo.4048589 (last access, July 2025).

As part of the RI-URBANS project, OP data from the Weber et al. (2021) dataset, OP measurements from eight sites in Switzerland, and OP measurements from an urban site in Barcelona, were distributed as part of a Memorandum of Understanding (MoU) agreement between modelling project partners (CHIMERE/CNRS-LISA, SILAM, EMEP-MSCW) and IGE (Institut des Géosciences de l'Environnement). This data can be requested by contacting the IGE Atmospheric Chemistry group (https://pmall.fr/contact/).

While there are also several other studies investigating single (or a limited number of local) OP measurement sites (e.g., Vörösmarty et al. 2023; Cesari et al. 2025), to our knowledge, such data is only available upon request. For an evaluation of the modelling capabilities to simulate OP on a European scale, a database containing measurements from all such different sources would be hugely beneficial and recommendable.

## *5.3 Evaluation and Quality Control*

OP measurement quality control has been the subject of several recent publications (e.g., Dominutti et al., 2024), as well as being part of the RI-URBANS project. Current efforts focus on the repeatability of OP measurements between labs, for example through the introduction of harmonized and simplified measurement protocols.

## *5.4 Synthesis on Evaluation of Regional CTMs*

In order to summarize the key source of information to evaluate OP and related source apportionment, either in terms of modelling or observational source, the various type of data available are presented in Table 4.

**Table 4.** For both models (top) and observation (bottom), the available sources of information are listed as well as the time period covered and their operational/research character level.

| Model | EMEP MSC-W | LOTOS-EUROS | CHIMERE |
|---|---|---|---|
| Research | Yes | Yes | Yes |
| Operational | No | No (only offline) | No |
| Publicly available | Upon request | Upon request | Upon request |

| Observations | RI-URBANS/IGE MoU (23 stations) | Daellenbach et al. (2020) (4 stations) |
|---|---|---|
| Research | Yes | Yes |
| Operational | No | No |
| Publicly available | Upon request | Yes |

# *6 Ultrafine particles (UFP)*

Ultrafine particles (UFP) have significant impacts on human health and the environment. They are involved in cytotoxic, genotoxic, brain disorders and oxidative stress processes. Due to their small size, they can penetrate deeper in the human body than larger particles, where they lead to respiratory, cardiovascular and neurological diseases. They also interact with radiation and contribute to cloud condensation nuclei, thus affecting climate. UFP are emitted by fuel and biomass combustion sources and are also formed by nucleation. The recent decades instrumentation has been developed to enable measurement of UFP number concentration in the atmosphere on regular basis.

The new Ambient Air Quality Directive (AAQD, 2024/2881/CE, published in November 2024), aims to tighten air pollution limits and address emerging pollutants. The Directive emphasizes pollutants such as black carbon (BC), ultrafine particles (UFPs), and ammonia, for which strict observational requirements are introduced.

In RI-URBANS, an effort was made to develop UFP emission estimates and model UFP on European and city levels. Regional and city level models (PMCAMx-UF, CHIMERE/MUNICH/SSH-aerosol) have been developed in that purpose.

## *6.1 Regional Modelling*

### *6.1.1 Modelling methodologies*

To perform UFP simulations, primary emissions of UFPs are needed as well as explicit consideration of new particle formation in the atmosphere (nucleation and growth). Models can vary in the UFP emission inventories used, in the representation of aerosol size distribution as well as in the parameterisation of nucleation.

Emission inventories from the different anthropogenic activity sectors are necessary to perform UFP simulations. In RI-URBANS, PMCAMx-UF is used with the RI-URBANS number emission inventory developed by TNO, whereas CHIMERE/MUNICH/SSH-aerosol is used with either bottom-up or top-down inventories using the methodology presented in Sartelet et al. (2022) and Park et al. (2024) to estimate number emissions from mass.

The methodology defined in the ST15: Emission Inventories for Regional and Urban Scale Modelling and Applications may be used to downscale the lower spatial resolution emission inventories, like EMEP and CAMS, to higher resolution over cities. UFP emission inventories have been developed by TNO in RI-URBANS in a horizontal spatial resolution of 0.1°×0.05° (lat-lon) which is equivalent to roughly 6×6 $km^2$ over central Europe, while the area emissions for the European domain are generated at a spatial resolution of 36×36 $km^2$ following the PMCAMx-UF grid. High resolution 1×1$km^2$ emission inventories can be derived for the pilot cities based on this dataset using the downscaling methodology tool developed by National Observatory of Athens (NOA) (D17 (D3.2)).

For multi-scale simulations down to the street-scale, hourly road-network emissions are also needed, as detailed in ST12: Deterministic Urban Modelling: PM and PN. To distribute PM2.5 emissions in the modelled particle size sections, first emissions of particles in the range PM0.1-PM1 and PM0.01-PM0.1 are estimated using the PM1/PM2.5 and PM0.1/PM1 ratios given in Sartelet et al. (2022) for each activity sector. The emissions in each of the size ranges: PM0.01-PM0.1, PM0.1-PM1, and PM1-PM2.5 are distributed amongst the model size sections with an algorithm that conserves mass and number (Park et al. 2024).

PMCAMx-UF simulation of the aerosol microphysics is handled by the updated version of the Dynamic Model for Aerosol Nucleation (DMANx), which includes the processes of condensation, evaporation, nucleation, and coagulation assuming an internally mixed aerosol (Patoulias et al., 2015). DMANx includes the TwO-Moment Aerosol Sectional (TOMAS) algorithm, which tracks both mass and number concentrations simultaneously and can use the desired nucleation theory to simulate particles starting from nuclei sizes. The aerosol size distribution is described with 41 size sections starting from 0.8 nm diameter (Jung et al., 2006). The sensitivity of the results to the nucleation parameterization is discussed in Patoulias et al. (2025).

Both CHIMERE and MUNICH models are coupled with the 0D chemical module SSH-aerosol (Sartelet et al., 2020), which includes the state-of-art representations of aerosol dynamics, such as condensation/evaporation, coagulation and nucleation. The size distribution is discretized into sections and internal mixing of particles is assumed in the 3D simulations. Further details on the methodology are provided in ST16: Ultrafine Particle Modelling.

### 6.1.2 Available Modelling Products

Regional models simulate UFP can provide as diagnostics the aerosol number concentration at the model aerosol sizes. Common output is N10, i.e. number concentration for particles larger than 10 nm, which is a proxy for UFP concentrations since larger particles are only a few in number. A source apportionment method has been also developed for PMCAMx-UF which produces information on the sources of UFP.

## 6.2 Observation data

### 6.2.1 Monitoring Methodologies

Within RI-URBANS methodologies related to UFP measurements have been harmonized and a scientific synthesis of Pan-European observations has been performed. Concise recommendations on the measurements of UFPs in urban environments have been made in D46 (D6.1).

The prEN 16976:2023 document describes a standard method for determining the particle number concentration (PNC) in ambient air by using a Condensation Particle Counter (CPC) operated in the counting mode. The lower limit of the measured particle size range is set to be 10 nm and thus identical to Mobility Particle Size Spectrometer (MPSS) measurements (see CEN/TS 17434). In air quality monitoring networks where MPSS will be used for determining the particle size distribution a CPC may be used for QA purposes for the MPSS data.

The methodology used to determine UFP is CPC, where particles are enlarged by condensation growth and then subjected to optical detection by scattered light. The MPSS used to measure particle number size distribution (obligatory particle size range 10-800 nm) consists of a bipolar diffusion charger, a differential mobility analyser (DMA) and a Condensation Particle Counter (CPC).

### 6.2.2 Available Observations

In RI-URBANS, Trechera et al. (2023) compiled existing UFP-PNSD measurements in urban Europe(Figures 4 and 5) for a joint evaluation according to (i) the instrumental and methodological approaches implemented; (ii) the comparison of urban concentrations across Europe; (iii) the identification of similarities and major differences; and (iv) the evaluation of relationships with other pollutants, such as BC, PMx (PM10, PM2.5, PM1), and gaseous pollutants ($SO_2$, $NO_x$, $O_3$, CO), and with meteorological parameters.

RI-URBANS (www.RIURBANS.eu) is supported by the European Commission under the Horizon 2020 – Research and Innovation Framework Programme, H2020-GD-2020, Grant Agreement number: 101036245

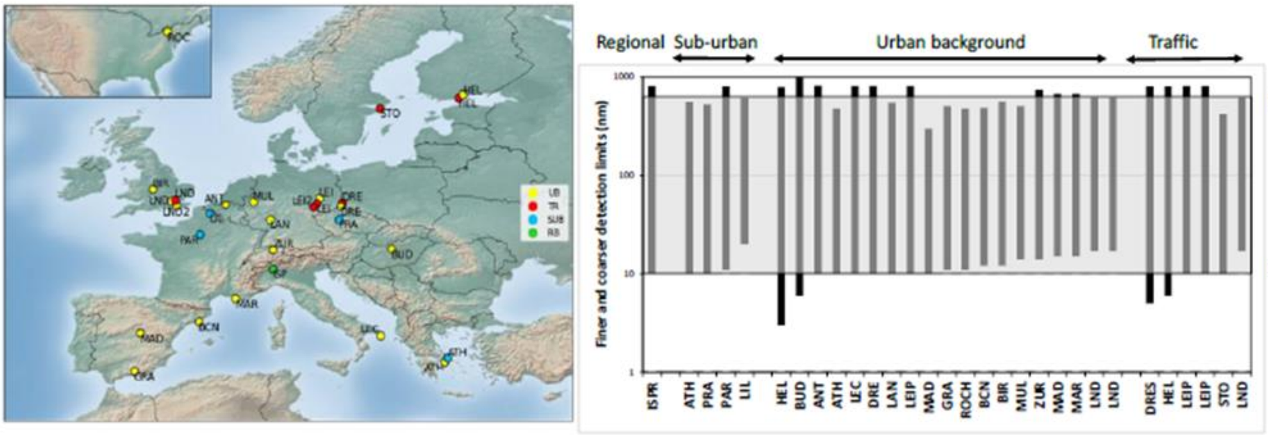


***Figure 4**. Left: Location of the cities supplying data on particle number concentrations and size distributions for the present study and the type of stations. UB, Urban background; TR: Traffic; SUB: Suburban background; RB: Regional background. Right: Particle size detection limits of PNSD measurements and recommended ones for CEN (10-800nm). Modified from Trechera et al (2023).*

Only 18/29 datasets had >70% data availability in 2017-2019 and 7/29 had data availability of <50%. This deficiency reflects the complexity of the UFP-PNSD measurements and the need for detailed supervision and frequent instrumentation maintenance. Example of daily and seasonal variability of UFP in Urban locations is shown Figure 5, where further details can be found. Observations are also available from the Ri-Urbans pilot cities.

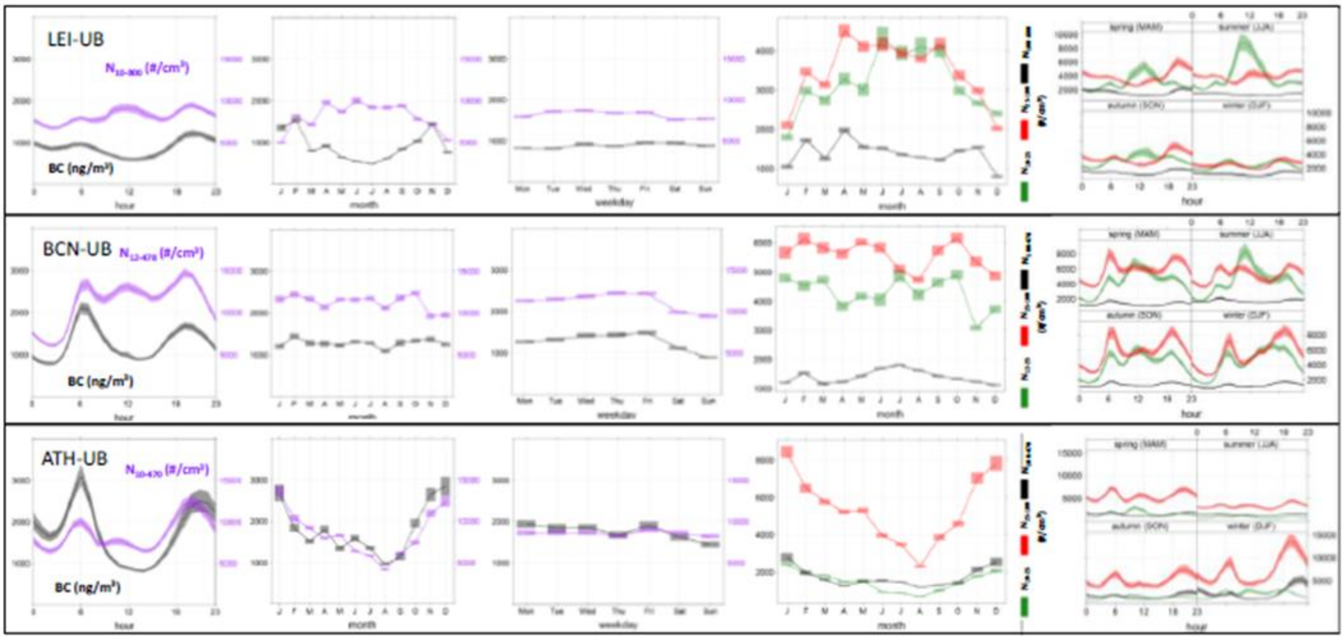


***Figure 5**. Daily and seasonal patterns of UFP and BC for three Urban background stations in South Europe: LEI_UB, BCN_UB and ATH_UB. Figure from Trechera et al. (2023).*

## 6.3 Evaluation and Quality Control

Summertime daily simulated concentrations obtained with CHIMERE/SSH-aerosol at Barcelona (Figure 6), Madrid and Ispra stations are particularly close to observations in these stations, with mean fraction error below 30% and more than 95% of the data with less than a factor of 2 difference from the observations, highlighting the robustness of this approach.

Comparison of the predictions of PMCAMx-UF using a 1×1 km$^2$ grid size with the observations from Demokritos/ Athens, shows that the model performs well for most of July, with a few days overestimating the number concentration (Figure 7). For the month of January, the model underpredicts the number concentration for most days, indicating that further improvement is needed in particular in the emission database.

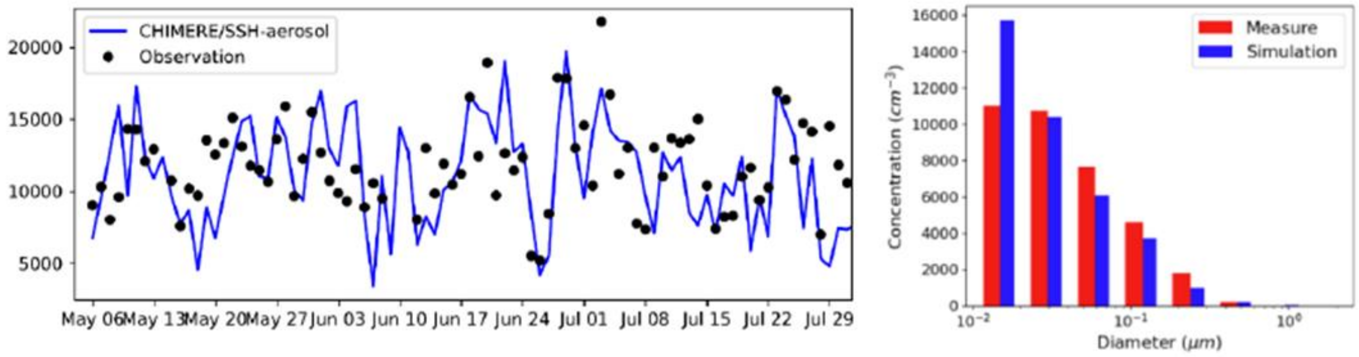


***Figure 6***. *CHIMERE/MUNICH/SSH-aerosol model to data comparison of N10 concentrations simulated over Barcelona, Spain. The left panel illustrates the total N10 temporal evolution and the right panel the number concentration per size section [in cm$^{-3}$].*

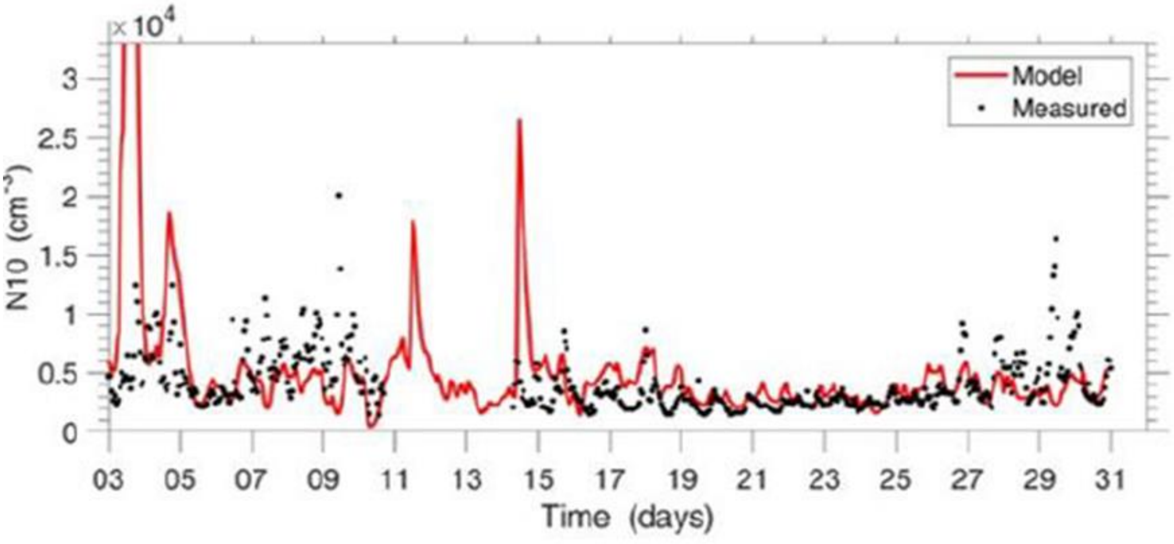


***Figure 7.*** *Comparison of the measured N10 concentration in Demokritos with the predictions of PMCAMx-UF at high grid resolution for July 2019.*

## 6.4 Synthesis on Evaluation of Regional CTMs

For UFPs, in RI-Urbans we have developed a multi-scale modelling framework that predicts the number concentration and size distribution of UFPs across Europe, in both urban and rural areas. Combined with population maps, UFP modelling can be used to assess population exposure to UFPs. In addition, UFP modelling can provide information on the sources of the predicted number concentration and size distribution of UFPs. Monitoring of UFPs (number and size distribution) has recently been legislated by the EU and the modelling tool developed contributes to the identification of UFP sources and locations where high levels of UFPs occur. UFP modelling also provides useful information for the selection of UFP monitoring sites and assists stakeholders in making decisions to reduce UFP levels and the resulting human exposure, thus providing an opportunity to explore mitigation measures for UFP. A case study for the year 2019 has shown the ability of this framework to identify sources of UFP and estimate the seasonal variability of their contribution (details are provided in D3.5) and the sensitivity of predicted UFP to different rate parameterizations has been investigated in Patoulias et al. (2025).

**Table 5.** For both models (top) and observation (bottom), the available sources of information are listed as well as the time period covered and their operational/research character level.

| Model | PMCAMx-UF | CHIMERE/MUNICH | LOTOS-EUROS |
|---|---|---|---|
| Research | Yes | Yes | Yes |
| Operational | No | No | No |
| Publicly available | Upon request | Upon request | Upon request |

| Observations | RI-URBANS |
|---|---|
| | 29 datasets with long term records[9] |
| Research | Yes |
| Operational | No |

## 7 Vertical Profiles

Regional scale chemistry-transport models increased in horizontal resolution in the recent past, so that models covering the whole European scale can now also be relevant for urban background air quality. This is the case in particular for the Copernicus Atmosphere Monitoring Service Regional System, whose ENSEMBLE has been shown to meet the Model Quality Objectives to be achieved in the context of regulatory application under the Ambient Air Quality Directive (2024/2881) following the FAIRMODE recommendations (Gauss et al., 2024)[10].

The validation of the vertical structure of regional models in urban areas is not as advanced. The CAMS Evaluation and Quality Control Service includes several indicators about tropospheric atmospheric composition, but it is essentially based on ozone and CO vertical profiles (sounding or commercial aircraft through the IAGOS programme, Figure 8). Total columns of NO2 are assessed by comparison to satellite data (typically TROPOMI NO2 on board Sentinel 5P), but with no possibility to assess vertical gradients and structures.

In that context, the emergence of Nitrogen Oxides measurements in the IAGOS programme, offers a very precious perspective to assess models in relation to an important urban air quality pollutant. In particular in the context where the joint assimilation of surface in situ $NO_2$ and satellite total columns is increasing.

### 7.1 Regional Modelling

#### 7.1.1 Modelling methodologies

Most urban scale and machine learning land use regression models only cover the surface layer. As a consequence, the vertical structure of the atmosphere is only relevant to deterministic chemistry-transport models.

#### 7.1.2 Available Modelling Products

The Copernicus CAMS Regional Service provides (Colette et al., 2025) operational air quality forecasts and analyses at 10km resolution over Europe. The vertical resolution differs between the eleven models of the ensemble, but

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[9] https://riurbans.eu/wp-content/uploads/2025/04/ST1.pdf

[10] https://atmosphere.copernicus.eu/sites/default/files/custom-uploads/EQC-regional/JJA-2024/CAMS283_2021SC2_D83.1.4.1-2024Q3_202410_ENSEMBLE_EQC_Report_v1.pdf

they are all delivered on a common list of 10 vertical levels: surface, 50m, 100m, 250m, 500m, 750m, 1000m, 2000m, 3000m, and 5000m above ground. The results are available as quick view maps[11] as well as numerical data through an API[12].

## 7.2 Observation data

### 7.2.1 Monitoring Methodologies

The IAGOS (in service Aircraft for a global observing system) Research Infrastructure conducts atmospheric composition measurement on board commercial aircrafts. Including the earlier phases of the project, measurement dating as far back as 1995 are now available to the scientific community.

A package monitoring NO, $NO_2$, and total NOx has been recently developed[13] and it is now included in the payload of the Lufthansa, Iberia, China Airlines, and recently Air France aircraft contributing to the IAGOS Research Infrastructure.

Such data started to be available in 2015, now it is about 21 vertical profiles of NO, $NO_2$, and NOx that are collected during descent every week above European airports. The data are available from the IAGOS public database (http://www.iagos.org) where the user can access validated profiles with a 6 to 12 months delay, as well as consolidated products such as climatologies. Preliminary data can be accessible on request on certain conditions by contacting the PI (at Julich, DE).

### 7.2.2 Available Observations

The IAGOS data are available for public use as per https://www.iagos.org/iagos-data/

## 7.3 Evaluation and Quality Control

The IAGOS NOx profile data (Figure 8) are not yet used in the operational CAMS Evaluation and Quality Control. But considering the recent development of this measurement, it will soon be possible to add these diagnostics together with the ozone CAMS/IAGOS validation already undertaken on a regular basis.

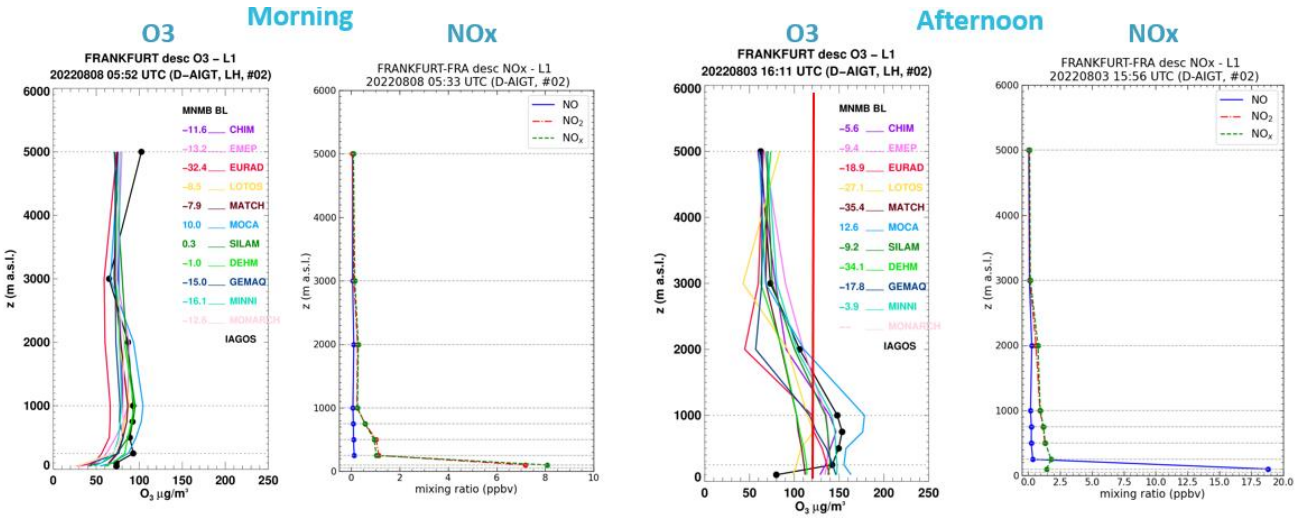

***Figure 8.*** *Comparison of vertical profiles between CAMS regional models and IAGOS ozone and NOx measurement. Courtesy: CNRS, CAMS 2024 General Assembly.*

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[11] https://atmosphere.copernicus.eu/european-air-quality-forecast-plots

[12] Ads.atmosphere.copernicus.eu

[13] https://www.iagos.org/iagos-core-instruments/package2b/

## 8 Summary and Outlook

This Deliverable (RI-Urbans D39 (D5.5)) constitutes a Service Tools reviewing evaluation practices for regional air quality (AQ) models tailored for urban environments, focusing on novel diagnostics and source apportionment techniques. The report assesses the maturity and performance of chemistry-transport models (CTMs) and corresponding routine or research grade observations for key health-relevant pollutants and indicators: **Black Carbon (BC)**, **Organic Aerosols (OA)**, **Particulate Matter (PM)**, **Oxidative Potential (OP)**, and **Ultrafine Particles (UFP), as well as their source apportionment**. It integrates observational data from supersites, pilot cities, and European networks, and compares operational and research model outputs with harmonized datasets using advanced evaluation tools and frameworks. The document also explores vertical profiling using IAGOS aircraft data to validate modelled $NO_x$ and ozone concentrations. A strong emphasis is placed on harmonizing methodologies for source apportionment and quality control, enabling better alignment between models and measurements with the ultimate aim to assess model reliability and robustness to underpin air quality policies.

The deliverable highlights the need for **operational integration** of advanced diagnostics such as OP and UFP into routine AQ modelling. These developments aim to strengthen the policy relevance of AQ models and support the implementation of the revised Ambient Air Quality Directive (2024/2881/CE), ultimately contributing to healthier urban environments across Europe. Future work beyond RI-URBANS will focus on:

- Expanding **source-specific OP coefficients**
- Improving secondary aerosol representation in operational models.
- Enhancing **UFP emission inventories** and multi-scale modelling frameworks.
- Leveraging **vertical profile data** for improved urban model validation.
- Promoting **harmonized PMF protocols** to support model-to-measurement comparisons.

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## 10 ANNEX A: Overview of available PM PMF source apportionment datasets

| Country / Area | Locations | Institute | campaign/project | Period | nr of stations | Publication |
|---|---|---|---|---|---|---|
| France | Multiple stations | University Grenoble | a.o. SOURCES | 2012-2019 (depends on location) | 15 | (Weber et al., 2019) |
| France | Metz | Atmo Grand-Est, LSCE | | 2015-2017 | 1 | (Petit et al., 2019) |
| Spain | Barcelona and Montseny | CSIC- Idaea | | 1-1-2018 to 31-3-2019 | 2 | (in ’t Veld et al., 2023) |
| Spain | Barcelona and Montseny | CSIC- Idaea | | 2009-2018 | 2 | (in ’t Veld et al., 2021) |
| Germany | 9 stations Eastern Germany | TROPOS | PM-Ost | Sep 2016-march 2017 | 10 | (Timmermans et al., 2022) |
| Germany | Melpitz | TROPOS | | 2019-2020 | 2 | (van Pinxteren et al., 2024) |
| Germany | Stuttgart, Gartringen, Freiburg | LUBW | | 2017-2018 | 3 | (Schwarz et al., 2019) |
| Italy | Lombardi / Milan | CSIS-IDAEA, ARPAE Lombardia | LIFE REMY/ RI-urbans | 2017-2019 | 2 | Not Published |
| Italy | Emilia Romagna, Po Valley (San Pietro Capofiume, Bologna, Rimini, Parma) | ARPAE Emilia Romagna | | April 2013 - October 2017 | 4 | (Scotto et al., 2021) |
| Italy | Lecce | | | 2013-2014 & 2016-2017 | 1 | (Giannossa et al., 2022) |
| Italy | Lecce, aradeo | ISAC-CNR | | feb 2010 - aug 2014 | 3 | (Guascito et al., 2023) |
| Italy | Tuscany | National Institute of Nuclear Physics (INFN | | nov 2013 - jan 2015 | 2 | (Lucarelli et al., 2019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Switzerland | Switzerland | EMPA | | June 2018 - May 2019 | 5 | (Grange et al., 2021) |
| Netherlands | Ijmuiden, Beverwijk, Wijk aan zee | RIVM - GGD Amsterdam | | 2017-2019 | 3 | (Mooibroek et al., 2022) |
| Netherlands | Multiple sites | RIVM | | 2013-2014 | 5 | (Mooibroek et al., 2016) |
| Netherlands | Multiple sitez | RIVM | | 2007-2008 | 5 | (Mooibroek et al., 2011) |
| Greece | Patras | FORTH/ICE-HT & University of Patras | | 2019 | 1 | (Manousakas et al., 2020) |
| Greece | Thessaloniki | University Western Macedonia | | 2011-2012 | 1 | (Saraga et al., 2019) |
| Greece | Athens | | | 2013-2014 | 2 | (M. Manousakas et al., 2021) |
| Europe | Multiple sites | | | Jan 2014 – Dec 2015 | 11 | (Almeida et al., 2020) |
| Belgium | Wallonia | ISSEP | SPECIMEN | May 2014- April 2016 | 4 | (Maenhaut et al., 2016) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **OA PMF** | | | | | | |
| France | ATOLL, Lille | | | 2016-2020 | 1 | Chebaicheb et al. 2023 |
| France | Multiple sites | | | 2015-2021 | 12 | Chebaicheb et al., in prep. |
| Espagne | Palau Reial, Barcelona | | | | | Via et al. 2021 |
| Italy | Bologna | | | | | Paglione et al. 2020 |
| Cyprus | CAO, Nicosia | | | | | Christodolou et al. 2023 |
| Greece | Demokritos, Athens | | | | | Zografou et al. 2022 |
| Ireland | Dublin | | | | | Lin et al. 2021 |
| Spain | Granada | | | | | - |
| Germany | Hohenpeissenberg | | | | | - |
| Romania | INOE, Bucharest | | | | | Mărmureanu et al. (2020) |
| Poland | Krakow | | | | | Tobler et al. 2021 |
| UK | Marylebone road, London | | | | | Chen et al. in prep. |
| UK | N-Kensington, London | | | | | Chen et al. in prep. |
| France | Longchamp, Marseille | | | | | Chazeau et al. 2022 |
| Italy | Milano | | | | | - |
| Italy | Padova | | | | | - |
| France | SIRTA, Paris | | | | | Zhang et al. 2019 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Estonia | Tartu | | | | | Chen et al. 2022 |
| Lithuania | Vilnius | | | | | Pauraite et al. 2022 |
| Switzerland | Zurich | | | | | Chen et al. 2022 |
| Europe | Multiple sites | | COST COLOSSAL ACTION | 2014-2020 (depends on location) | 22 | Chen et al. 2022 |