European Commission

HORIZON 2020

Milestone M14 (M3.3)

Top-down and bottom-up estimation of city scale emission inventories

RI URBANS

RI-URBANS

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

By

BSC, TNO & NOA

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

TNO innovation for life

26th September 2023

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

Milestone M18 (M3.3): Top-down and bottom-up estimation of city scale emission inventories

Authors: Marc Guevara & Oriol Jorba (BSC), Jeroen Kuenen (TNO), Eleni Athanasopoulou & Nasia Kakouri (NOA)

Work package (WP)	WP3 Improving modelling and emission inventories for policy assessment using advanced observation-based methodologies
Milestone	M14 (M3.3)
Lead beneficiary	BSC
Means of verification	Emission inventories compared
Estimated delivery deadline	M24 (30/09/2023)
Actual delivery deadline	26/09/2023
Version	4.0
Reviewed by	WP3 leaders
Accepted by	RI-URBANS Project Coordination Team
Comments	This document provides the results of an emission intercomparison exercise performed between the downscaled European-wide inventories developed as part of T3.2 and independent bottom-up inventories collected for a total of 13 urban areas, including 10 RI-URBANS pilot cities. The comparison assesses the consistency between local city and regional NOx, NMVOC, PM10 and PM2.5 emission estimates for the road transport and residential/commercial combustion sectors, both in terms of total annual emissions and their spatial distribution at 1x1km^2 resolution. The results of this intercomparison are meant to provide feedback to TNO and NOA, which are responsible for the development of a European gridded anthropogenic emission inventory (M13 (M3.2), D18 (D3.3)) and of the downscaling methodology and tool, which provides 1x1km^2 zooms over the pilot cities D17 (D3.2), respectively.

Table of Contents

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

1. About this document

This document provides the results of an emission intercomparison exercise performed between the 1x1km2 downscaled European-wide inventories developed as part of T3.2 and independent bottom-up emission inventories for a total of 13 urban areas, including 10 RI-URBANS pilot cities. The comparison assesses the consistency between local city and regional NOx, NMVOC, PM10 and PM2.5 emission estimates for the road transport and residential/commercial combustion sectors, both in terms of total annual emissions and their spatial distribution.

This milestone M14 (M3.3) addresses T3.2 on enhancing quality and completeness of emission inventories constructed to support urban air quality modelling activities in WP3 (T3.3 and T3.4). The results of this intercomparison are meant to provide feedback to TNO and NOA, which are responsible for the development of a European gridded anthropogenic emission inventory (M13 (M3.2), D18 (D3.3)) and of the downscaling methodology and tool, which provides 1x1km^2 zooms over the pilot cities D17 (D3.2), respectively.

This is a public document, available in the RI-URBANS website (https://riurbans.eu/work-package-3/#milestones-wp3). The document will be distributed to all RI-URBANS partners for their use and submitted to European Commission as an RI-URBANS milestone M14 (M3.3).

2. Description of the emission inventories

2.1 Downscaled European-wide emission inventories

The RI-URBANS European-wide gridded emission inventory developed by TNO uses the CAMS-REG emission inventory version 5.1 as a basis (Kuenen et al., 2022). A couple of specific modifications of the CAMS-REG-v5.1 emission inventory have been made for RI-URBANS (see milestone report M3.2 for more details):

- Road transport emissions from CAMS-REG are excluded and replaced with a consistent bottom-up inventory.
- PM10 and PM2.5 small combustion emissions from CAMS-REG are excluded and replaced with a consistent bottom-up “science-based” estimate which takes into account the condensable component of PM in a consistent and complete manner (Denier van der Gon et al., 2015).
- Particle numbers (in the size range 10-325 nm) have been estimated for all sources.

The emissions provided in this dataset have 2018 as a reference year and a spatial resolution of 6x6km^2 over the European domain, including the RI-URBANS pilot cities. Emissions are reported per species and sector following the GNFR nomenclature. For the purpose of the intercomparison, the emissions from road transport (GNFR categories F1-F4) were aggregated to GNFR F (road transport as a whole).

High resolution 1x1km^2 emission inventories were derived for the pilot cities combining the RI-URBANS European-wide gridded inventory with a downscaling methodology tool developed by NOA, which is largely based on the existing GIS-based tool UrbEm (Ramacher et al., 2021) and is further optimized as described in D3.2. We refer to this dataset as CAMS-REG-UrbEm.

Additionally, we also considered the 1x1km^2 downscaled uEMEP emission inventory for 2018, developed by MetNo using as a basis the official data submission to the EMEP Centre on Emission Inventories and Projections and sector-

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

specific spatial emission proxy data, as described in Mu et al. (2022). For this inventory we only considered emissions for the road transport sector, as the original EMEP PM emissions from the residential/commercial combustion sector (GNFR_C) are replaced by the same TNO bottom-up estimates considered in the RI-URBANS European inventory. Original uEMEP emissions are distributed at 0.25x0.25km^2 resolution, but for this exercise they were aggregated to 1x1km^2 in order to compare to CAMS-REG-UrbEm.

2.2 Local bottom-up emission inventories

Figure 1 and Table 1 indicate the location and main characteristics of the local bottom-up emission inventories compiled for the intercomparison exercise. The collected dataset allows covering all the RI-URBANS pilot cities except for Bucharest (for which no bottom-up inventory is available), as well as Madrid, London and Hamburg.

The local emission inventories were either downloaded from the corresponding open data repository or made available to BSC by the research centres and institutions responsible for their development. Note that for some cities (i.e., Milan, Bologna, Paris, Madrid) the local inventories were only available at the municipality level and therefore comparisons at the grid level could not be made. Note that the local inventories that are reported at a spatial resolution finer than 1x1km^2 (i.e., Helsinki, Zurich) where aggregated to a 0.01x0.01º regular lat-lon WGS84 grid for compatibility. For the majority of local inventories, the base year is equal (2018) or very close (2019, 2017) to the one considered in the European-wide inventories.

For some cities and sectors, certain species had to be removed from the intercomparison as the emissions were not reflecting the same activities and sources considered in the CAMS-REG-UrbEm GNFR_F (road transport) and GNFR_C (other stationary combustion activities) categories, as detailed in Table 1.

Table 1. *Summary of local bottom-up emission inventories considered.*

Pilot city	Year	Spatial resolution	Sectors & pollutants	Provider
Amsterdam	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC (1), PM10, PM2.5)	RIVM
Central Athens area	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	NOA
Barcelona	2019	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	BSC
Birmingham	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Defra & BEIS
Bologna	2017	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Arpa Emilia-Romagna
Hamburg	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Helmholtz-Zentrum Hereon
Helsinki	2019	0.25x0.25km^2 & road link	Road transport (NOx, PM2.5) Residential (PM2.5)	FMI
London	2018	1x1km^2	Road transport (NOx, PM10, PM2.5) Residential (NOx (2), PM10, PM2.5)	Madrid City Council
Madrid	2019	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Greater London Authority
Milan	2019	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Arpa Lombardia
Paris	2018	Paris city, metropolis, Ile-de-France	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC (3), PM10, PM2.5)	Airparif
Rotterdam	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC (1), PM10, PM2.5)	RIVM
Zurich	2015	0.01x0.01km^2	Road transport (NOx, NMVOC, PM10)	UGZ

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

			Residential (NOx, NMVOC, PM10)	

(1) Excluded since emissions from non-residential/commercial facilities are included
(2) Excluded since commercial combustion emissions are reported in another sector (industrial combustion emissions)
(3) Excluded since residential use of solvent emissions are included in the same sector

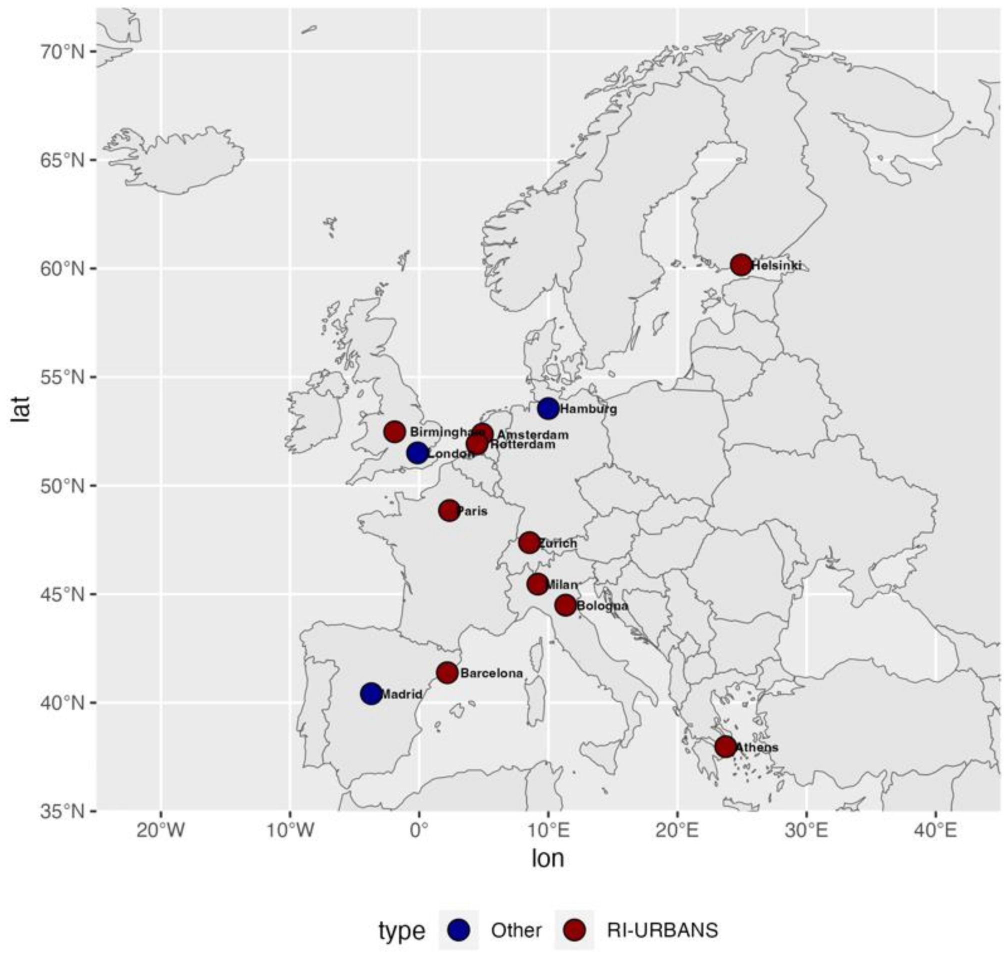


Figure 1*. Cities for which bottom-up emission inventories were collected. Red dots indicate RI-URBANS pilot cities while blue dots indicate extra cities that were added to the comparison.*

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

3. Emission intercomparison

This section presents the results of the intercomparisons performed between the downscaled and bottom-up emission inventories in each one of the selected cities and for each of the targeted pollutant sectors; road transport and residential/commercial combustion emissions. These two sectors are the main contributors to total NO_x and PM2.5 European emissions, respectively.

Gridded emissions are reported at approximately 1x1km^2 resolution in all cases, but the definition of the domains slightly change between datasets: in CAMS-REG-UrbEm, emissions are reported in a 0.01x0.01 deg. regular lat-lon WGS84 grid, in uEMEP emissions are reported in a 0.01x0.01º ETRS89 LAEA projected grid, while for the local inventories several projections are considered (e.g., 1x1km2 British national grid for Birmingham, 1x1km^2 National Triangle Coordinates grid for Amsterdam and Rotterdam). As a result, a grid-to-grid comparison cannot be performed between inventories, but rather a visual comparison of the spatial patterns reported by each dataset.

The comparison of total emissions is performed considering the grid cells that intersect with the boundaries of each city, which are defined as the boundaries of the municipality where the city is located.

3.1 Road transport

Figure 2 to Figure 10 show the results of the intercomparisons performed between road transport gridded emission inventories for the cities of Amsterdam, Athens, Barcelona, Birmingham, Hamburg, Helsinki, London, Rotterdam and Zurich. All nine figures follow the same scheme: the top part presents a comparison between total annual road transport NO_x, NMVOC, PM10 and PM2.5 emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and the corresponding local emission inventory (referred to with the name of the provider), while the bottom part shows the spatial distribution of the road transport NOx emissions [t/year·cell] reported by each inventory as well as the administrative borders considered for the comparisons. Figure 11 summarizes the comparison between total annual road transport NO_x, NMVOC, PM10 and PM2.5 emissions in the remaining cities (i.e., Bologna, Madrid, Milano, Paris) for which gridded data was not available. Summary scatterplots showing the relationship between local bottom-up and CAMS-REG-UrbEm NO_x and PM2.5 road transport emission estimates per city are shown in Figure 12.

The same pattern is observed in almost all cities when looking at NO_x results: CAMS-REG-UrbEm tends to report lower emissions than the local inventories, while uEMEP results are more in line with the bottom-up estimates (Figure 12). Athens, Hamburg and Bologna are the cities that present the largest differences between CAMS-REG-UrbEm and the local bottom-up inventories (i.e., -76%, -61% and -55%, respectively). The respective differences between uEMEP and local NO_x inventories are 19% , -31% and -50%. Similarly, the differences observed between CAMS-REG-UrbEm and the bottom-up estimates in Helsinki, Birmigham, Barcelona, Rotterdam and Amsterdam (differences ranging between -32% and -45%) are considerably higher than those between the local inventories anduEMEP values (differences ranging between -12% and 13%, except for 50% for Barcelona). Zurich and Madrid are the only two cities where CAMS-REG-UrbEm reports larger emissions than the local estimates (+20% and +42%, respectively). uEMEP also report larger emissions than the local dataset for Zurich (+32%), but results of both are consistent for Madrid (-3.8%).

It should be noted that the low emission masses from the road sector of the CAMS-REG inventory is also regarded a source of CTM NOx underestimations in European cities (Kuik et al., 2018; Ramacher et al., 2021). Tuning factors of 2 to 3 (used as NOx Road transport annual emission multipliers) seem to considerably improve model performance for Berlin, Athens and Hamburg.

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

The large discrepancies between CAMS-REG-UrbEm and the local NO_x inventories could be related to the share of the road type split between highway and non-highway (i.e., urban and rural) emissions that is assumed in the CAMS-REG approach for spatially distributing national emissions to grid level (Kuenen et al., 2022). The method considers traffic intensity as a direct proxy but might not correctly take into account detailed traffic parameters such as levels of congestion, which tend to be higher in urban areas.

For PM10 and PM2.5, CAMS-REG-UrbEm tends to allocate less emissions when compared to the local bottom-up inventories, as see for NOx. Largest discrepancies both in relative and absolute terms are observed in Hamburg, Barcelona and London (around -75% and between 500t/year and 2000t/year for PM10), where the local estimates include resuspension emissions, a source that is not considered in the CAMS-REG-UrbEm inventory. Interestingly, in Madrid the differences between PM10/PM2.5 emissions reported by CAMS-REG-UrbEm and the local estimates (-2%/7%) are much lower than those for NOx (42%) (Figure 12), indicating that the discrepancies cannot be attributed to a single issue, and in this case could be driven by the road transport NO_x emission factors considered in each inventory.

Regarding the spatial distribution of NO_x emissions, important differences are observed between CAMS-REG-UrbEm, uEMEP and the local emission inventories. In the CAMS-REG-UrbEm emission maps main urban corridors, road rings and city access roads are in general much less marked than in the results reported by uEMEP and the local inventories. Five clear examples of that are the cities of Amsterdam (Figure 2), Birmingham (Figure 5), Helsinki (Figure 7), London (Figure 8) and Rotterdam (Figure 9). The discrepancies observed between CAMS-REG-UrbEm and local estimates could be caused by a combination of three factors:

1) <u>The under-allocation of NO_x emissions in urban areas in CAMS-REG_v5.1</u>. As discussed above, CAMS-REG-UrbEm tends to report less NO_x total annual emissions within the urban areas than the local inventories. Therefore, less emissions are available to allocated across the urban grid cells.
2) <u>The spatial proxies used to distribute the original CAMS-REG_v5.1 emissions</u>. The analysis of the spatial distribution of the CAMS-REG_v5.1 inventory at its native resolution (6x6km^2) already indicates that grid cells intersecting with main urban corridors and road rings are not always the ones reporting the largest emissions, as the case for the local, bottom-up inventories (and uEMEP). An example of that is illustrated in Figure 13, where the CAMS-REG_v5.1 NO_x emissions at 6x6km^2 for the cities of Helsinki and London are shown. The grid cells that intersect with the main ring road (Ring I and III in Helsinki and motorway M25 in London) report much lower emissions (i.e., 2-3 times lower) than other grid cells located in the inner-city centers. Here it should be noted that the 6x6km^2 cells are representing a rather large region with a range of different roads, hence it's difficult to draw direct conclusions from such mismatches. However, in the framework of CAMS, further investigation into this issue has been initiated with the aim of improving future CAMS-REG inventories and (if possible under the time constraints) the updated Ri-URBANS emission inventory (D3.3, due in January 2024).
3) <u>The spatial proxies used in UrbEm to downscale the CAMS-REG_v5.1 emissions</u>. The UrbEm tool downscales the original CAMS-REG_v5.1 road transport emissions to 1x1km^2 using the OpenStreetMaps (OSM) road links tagged as motorway, trunk, primary, secondary and tertiary roads. Weight factors are applied as a function of the length and number of lanes per road type. The resulting weight factors per road type indicate low differences between e.g., tertiary and motorway roads as compared to the weight factors considered by uEMEP (Mu et al., 2022), which could indicate an under allocation of emissions to main roads. For this reason, sensitivity tests have been implemented and further discussed in Sect. 4.

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

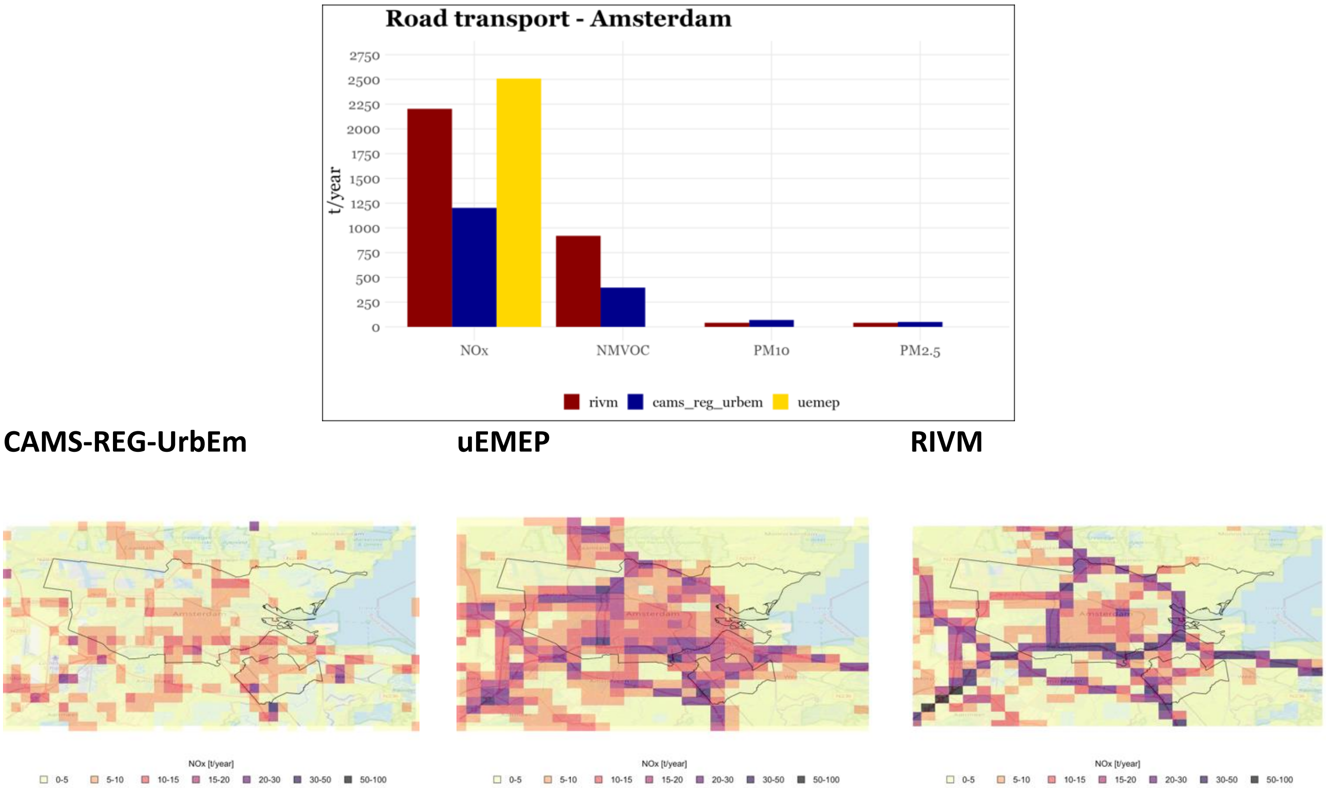


Figure 2*. Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and RIVM for Amsterdam*

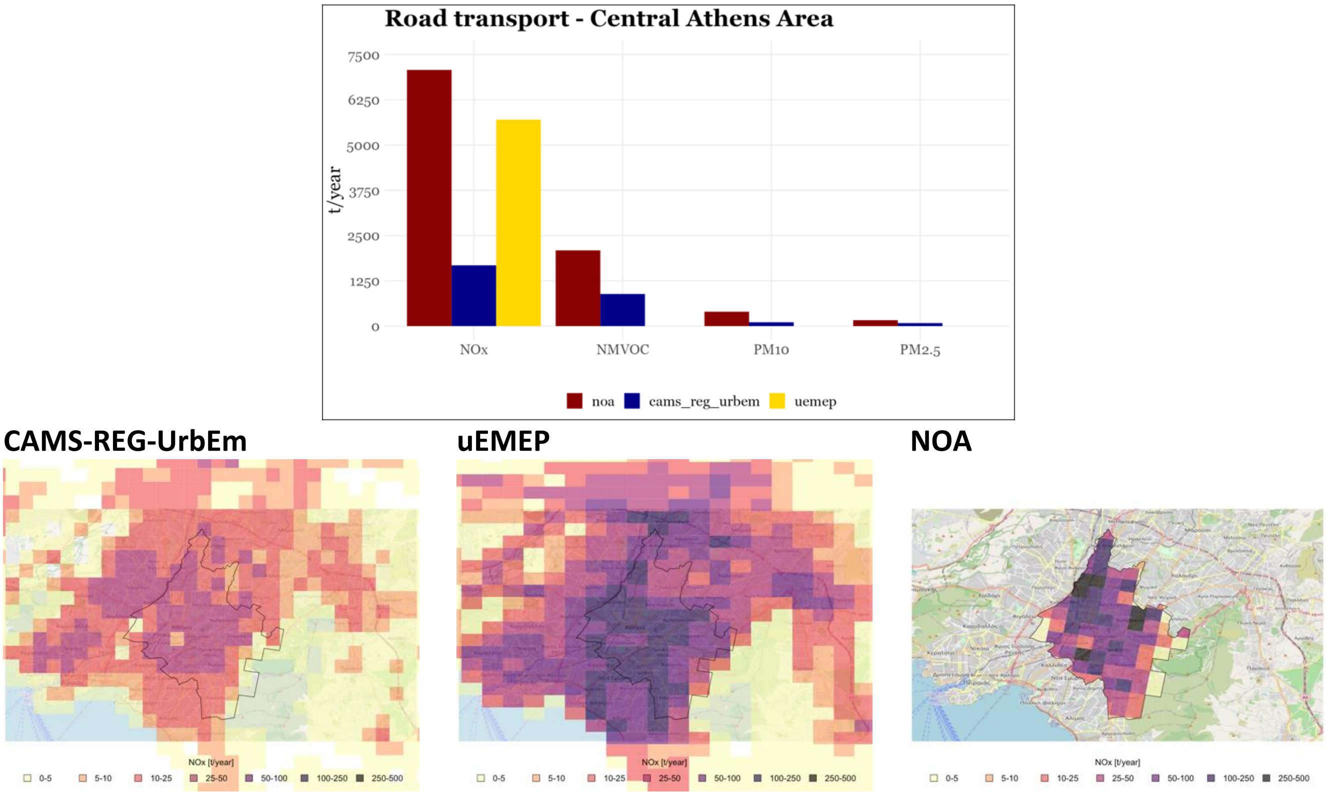


Figure 3. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and NOA for Athens*

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

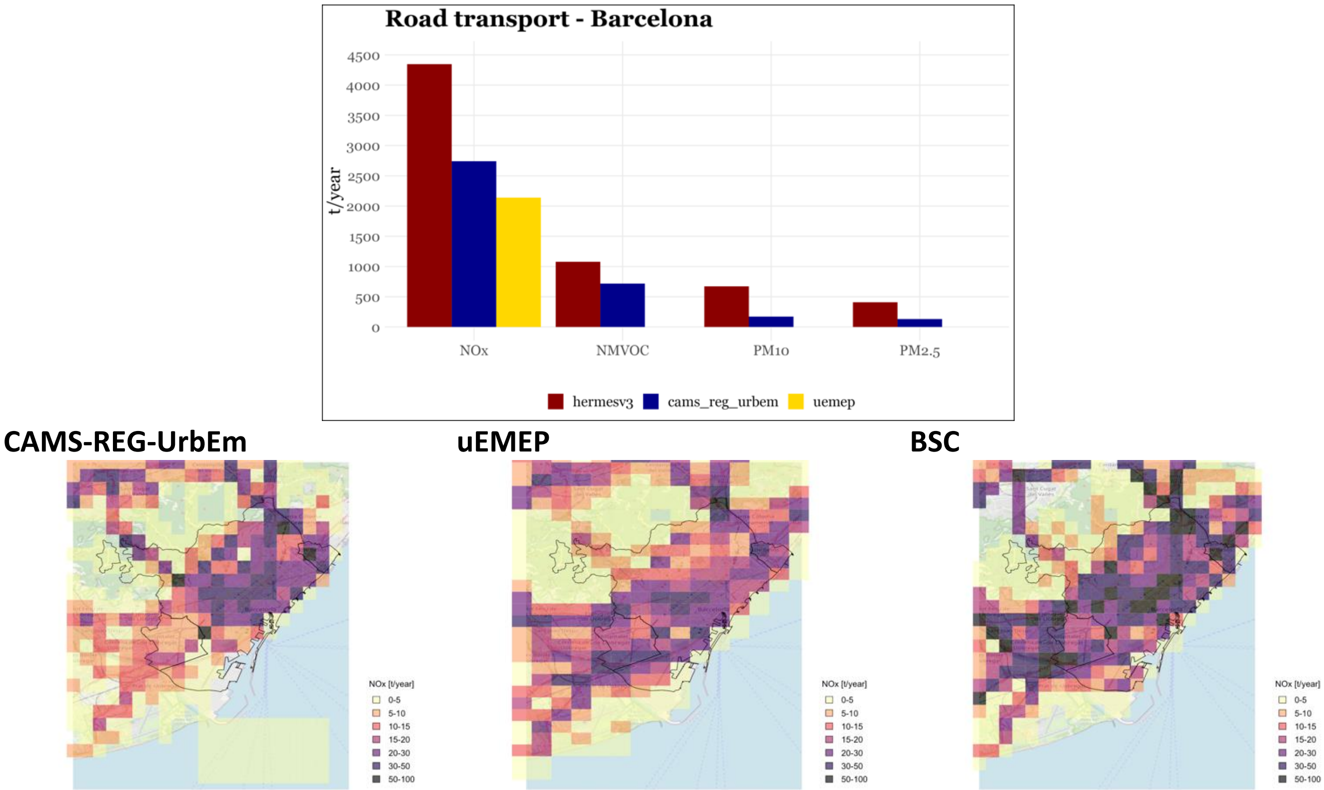


Figure 4. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and BSC for Barcelona*

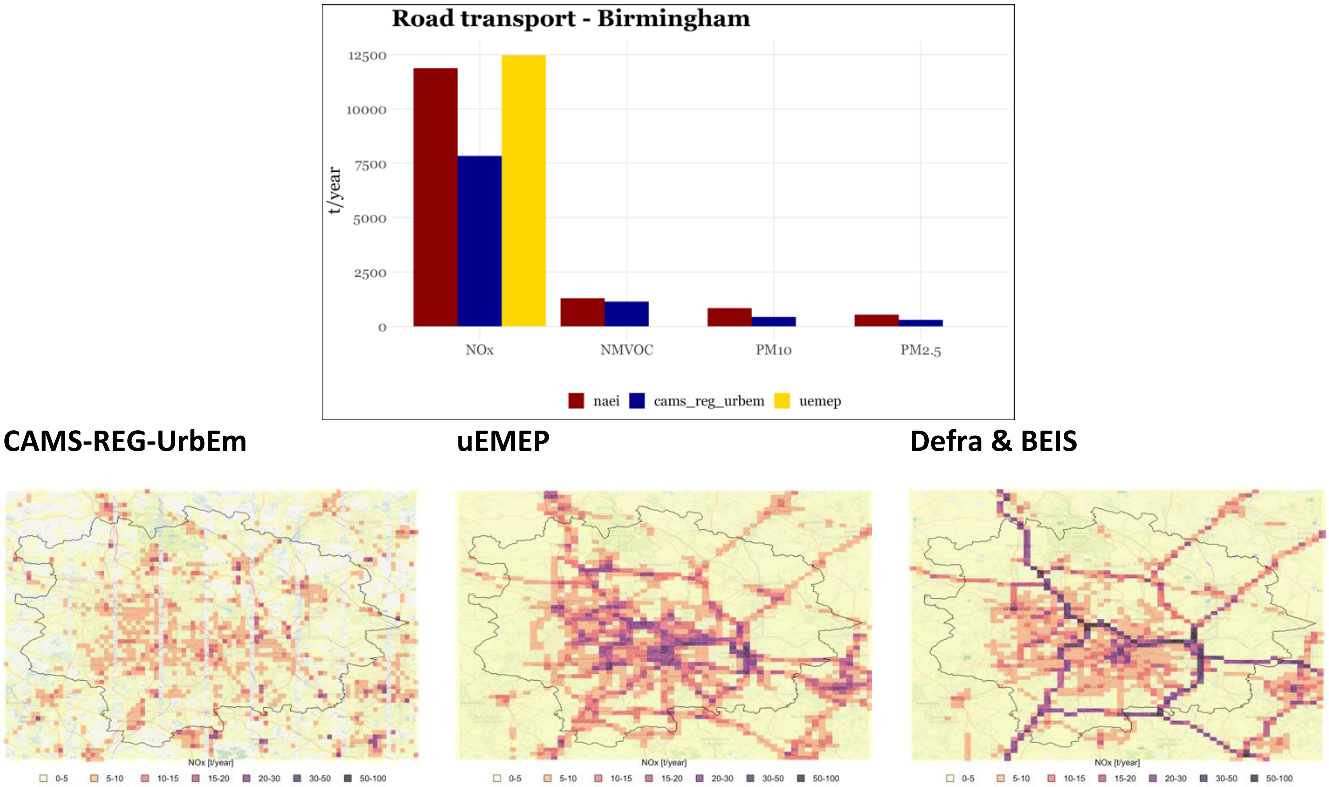
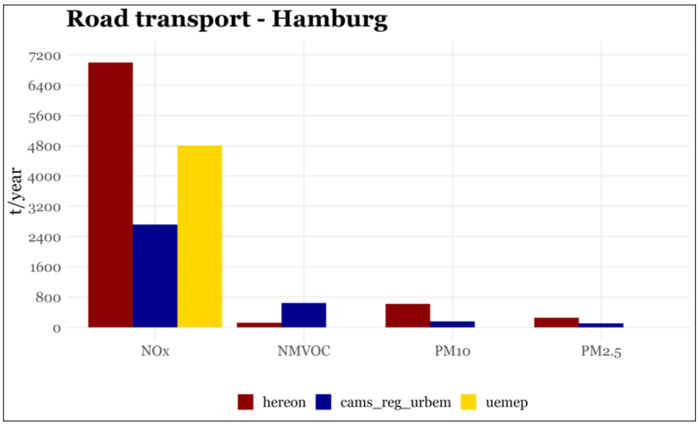
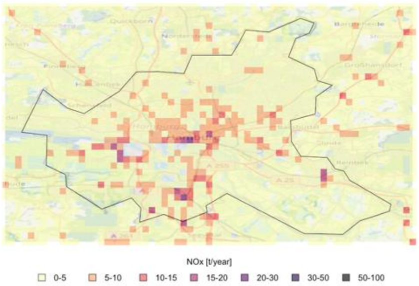


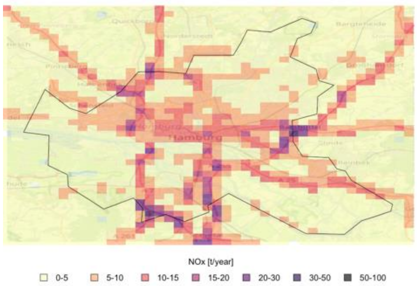
Figure 5. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and Defra/BEIS for Birmingham*

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



CAMS-REG-UrbEm **uEMEP** **HEREON**





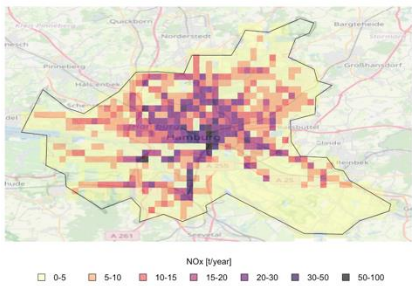
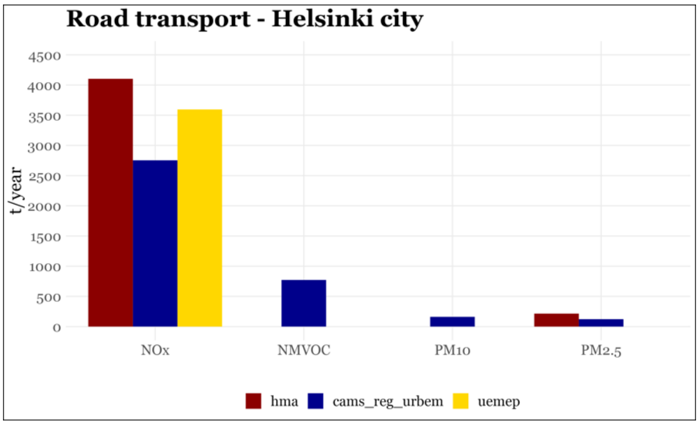
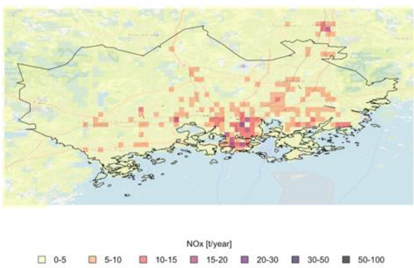
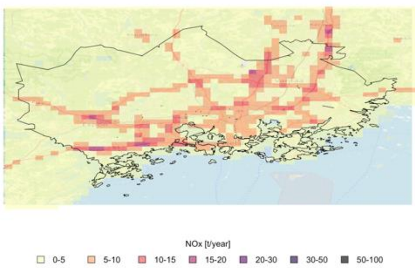


Figure 6. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded* NO_x *(bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and HEREON for Hamburg*



CAMS-REG-UrbEm **uEMEP** **FMI**





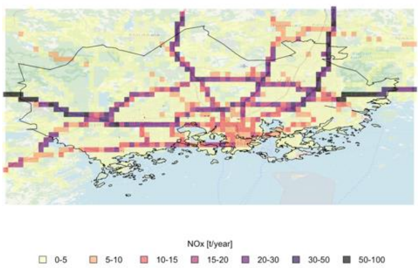
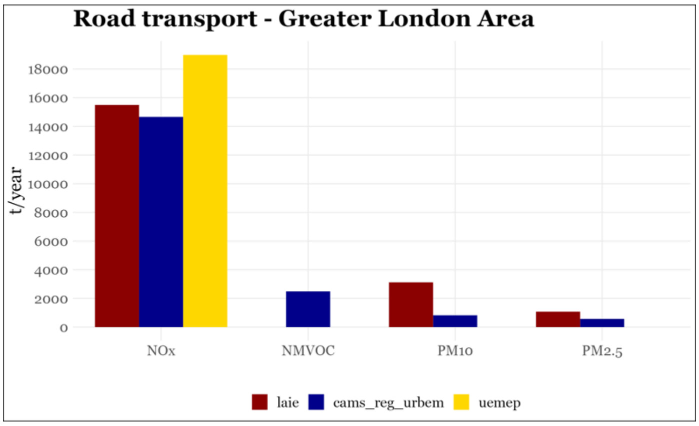


Figure 7. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded* NO_x *(bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and FMI for Helsinki*

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



CAMS-REG-UrbEm **uEMEP** **LAEI**

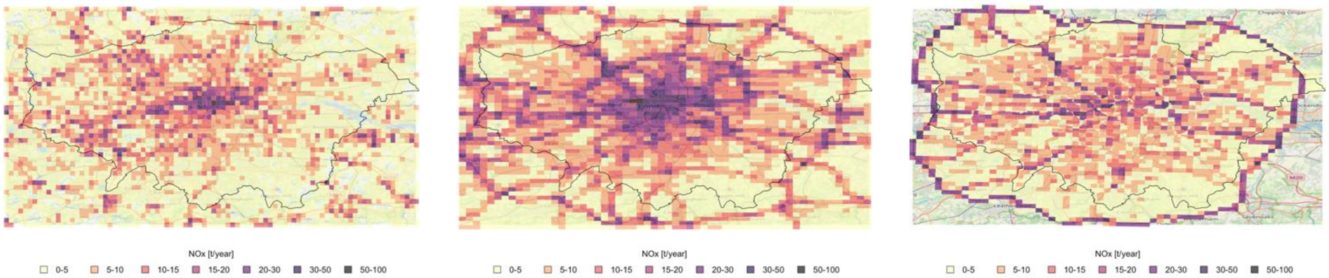
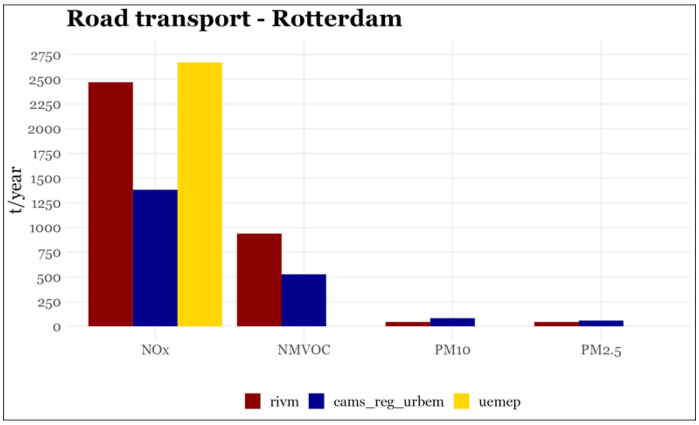


Figure 8. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and LAEI for London*



CAMS-REG-UrbEm **uEMEP** **RIVM**

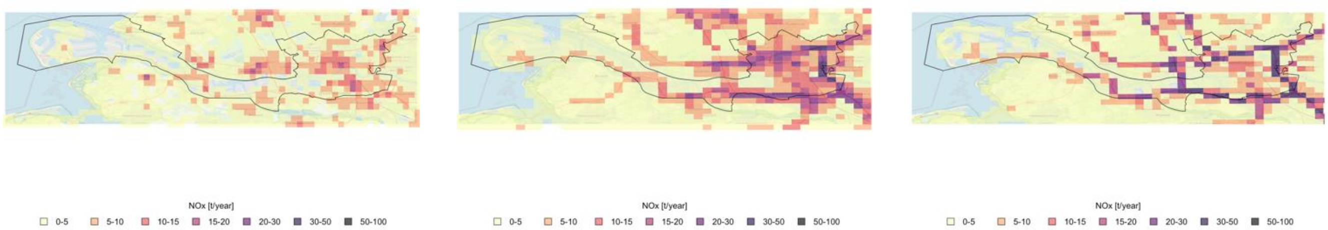


Figure 9. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and RIVM for Rotterdam*

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

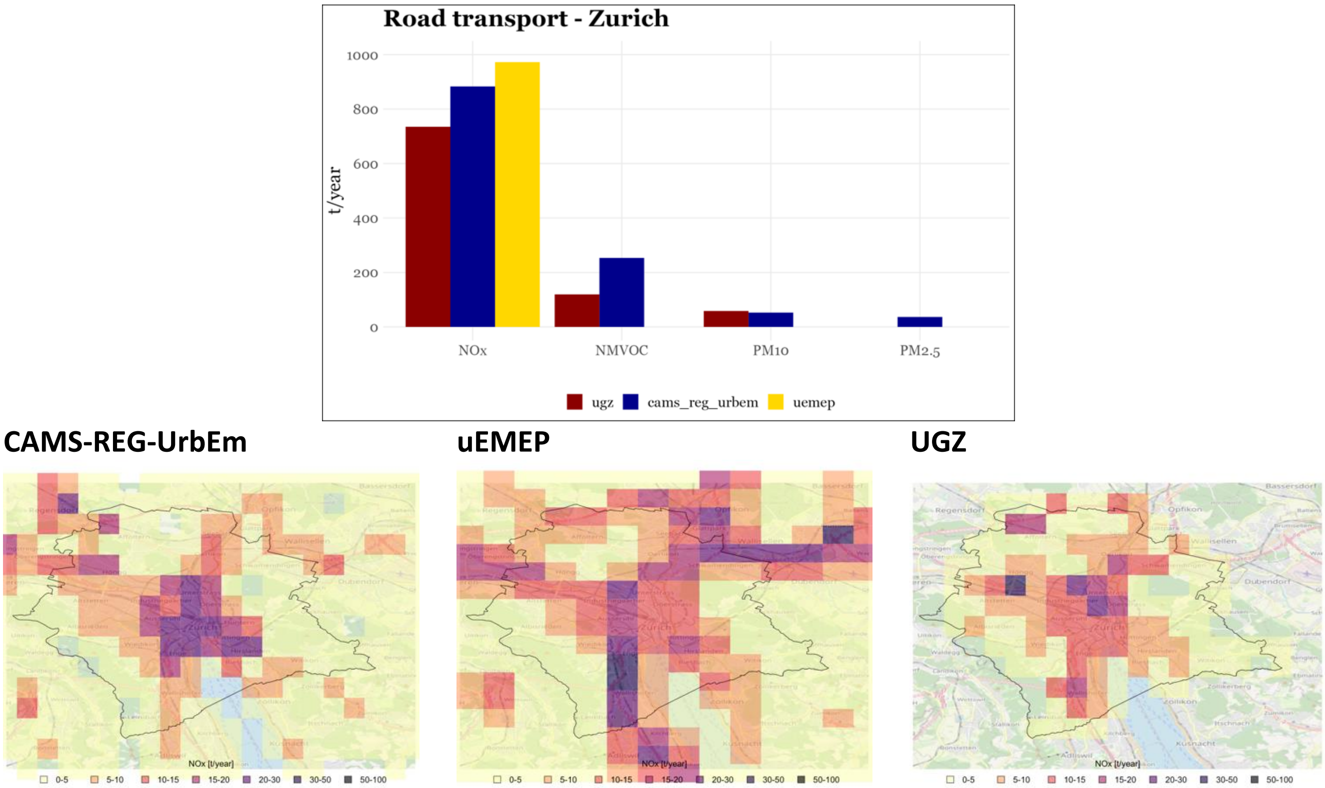


***Figure 10**. Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and UGZ for Zurich*

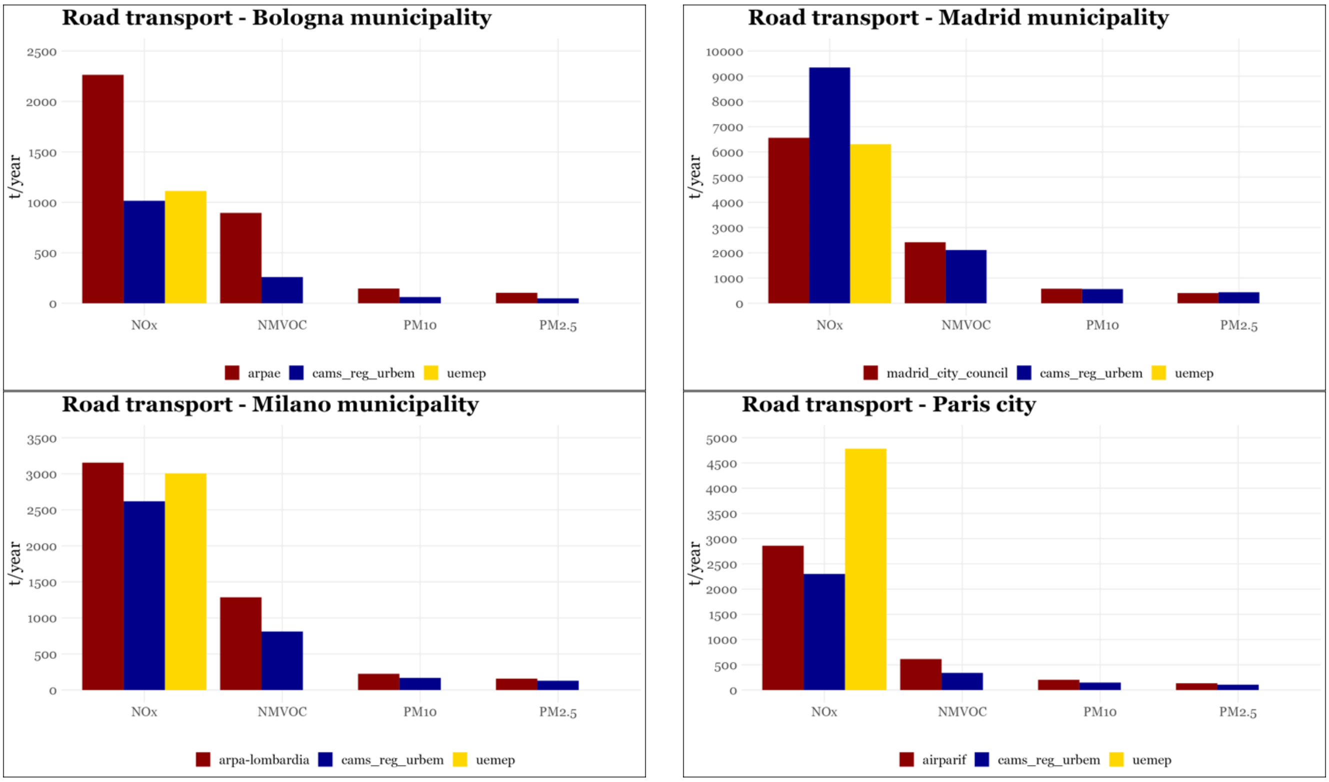


***Figure 11**. Comparison between annual NOx, NMVOC, PM10 and PM2.5 road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and the corresponding local inventories for the cities of Bologna, Madrid, Milano and Paris*

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

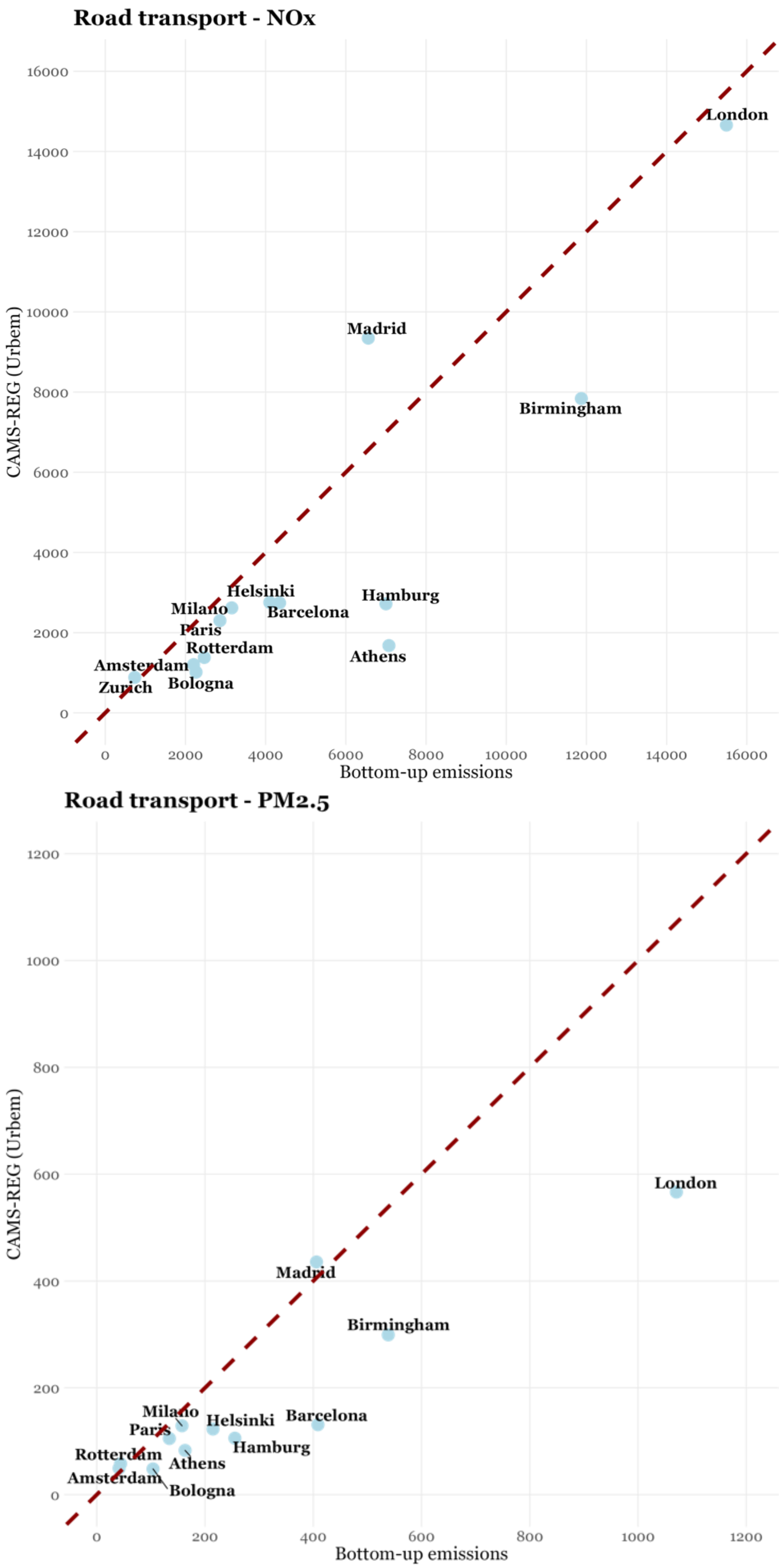
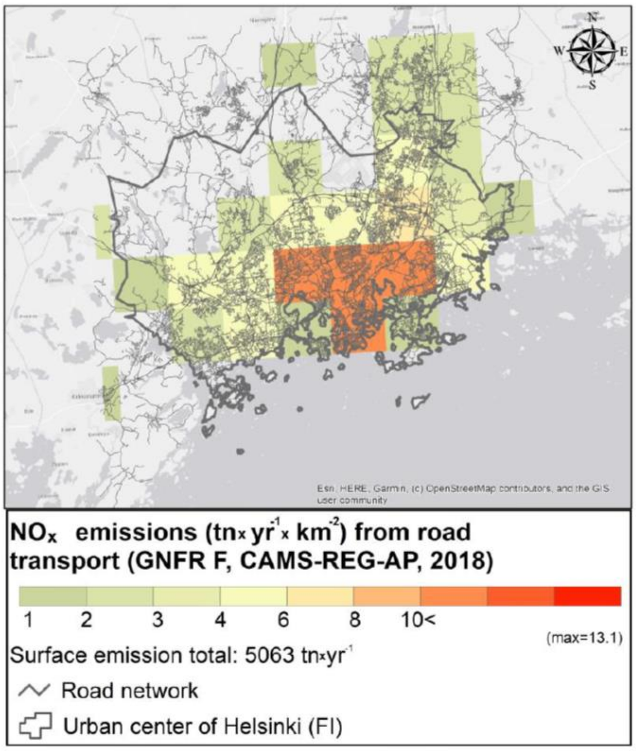
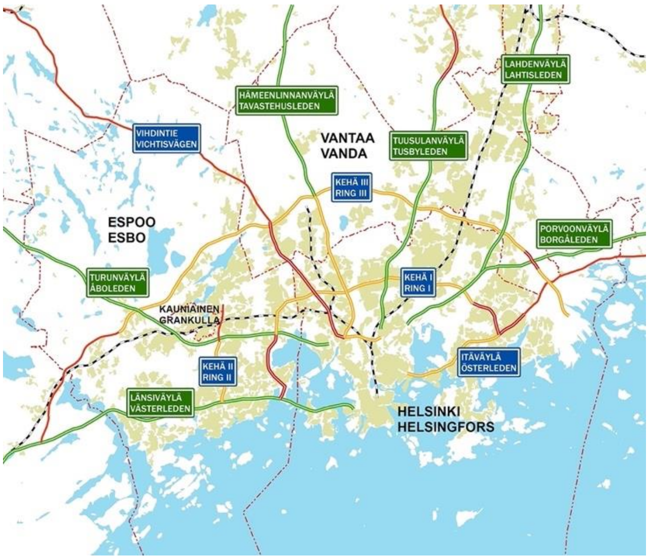


Figure 12*. Scatterplots showing the relationship between local bottom-up (X-axis) and CAMS-REG-UrbEm (Y-axis) NO_x (top) and PM2.5 (bottom) road transport emission estimates per city (light-blue dots). Lines of equalities are represented with the dashed dark red lines.*

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





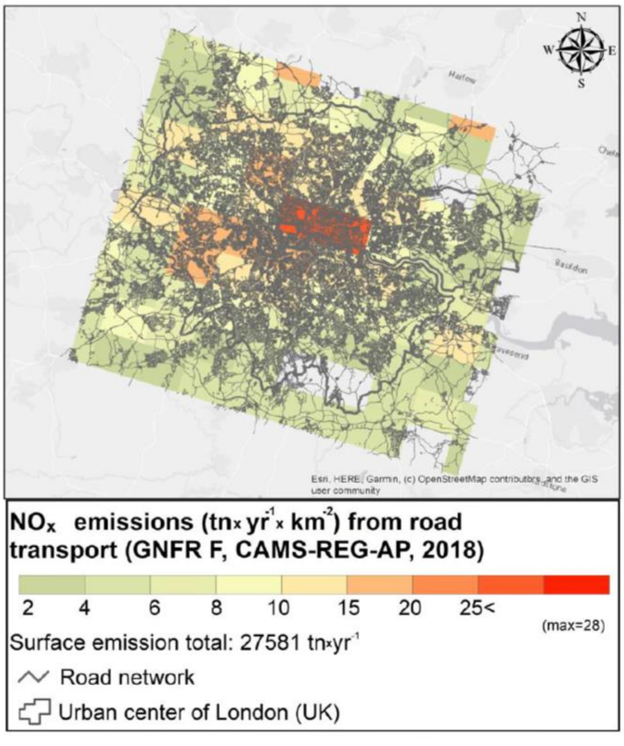


Figure 13. *Spatial distribution of original CAMS-REG_v5.1 NO_x road transport emissions [t/y·km^2] at 6x6km^2 for the cities of Helsinki and London, and maps of the main access and ring roads in the Helsinki (Migro) and London areas (British Department for Transport)*

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

3.2 Residential and commercial combustion

Figure 14 to Figure 22 show the results of the intercomparisons performed between residential and commercial combustion, gridded emission inventories for the cities of Amsterdam, Athens. Barcelona, Birmingham, Hamburg, Helsinki, London, Rotterdam and Zurich. All nine figures follow the same scheme: the top part presents a comparison between total annual residential and commercial NO_x, NMVOC, PM10 and PM2.5 emissions [t/year] reported by CAMS-REG-UrbEm and the corresponding local emission inventory (referred to with the name of the provider), while the bottom part shows the spatial distribution of the residential and commercial combustion PM2.5 emissions [t/year·cell] (PM10 in the case of Helsinki) reported by each inventory as well as the administrative borders considered for the comparisons. Figure 23 summarizes the comparison between total annual residential and commercial combustion NO_x, NMVOC, PM10 and PM2.5 emissions in the remaining cities (i.e., Bologna, Madrid, Milano, Paris) for which gridded data was not available. Summary scatterplots showing the relationship between local bottom-up and CAMS-REG-UrbEm NO_x and PM2.5 emission estimates per city are shown in Figure 24.

Discrepancies between CAMS-REG-UrbEm and bottom-up NO_x emissions are in general much lower than the ones reported for road transport (see Sect. 0). Depending on the city, CAMS-REG-UrbEm reports higher or lower emissions, the largest differences occurring in Amsterdam (37%) and Hamburg (-42%). In contrast, significant discrepancies are observed when comparing PM2.5 emissions. In Birmingham, London, Athens and Paris, CAMS-REG-UrbEm reports between -60% and -90% less emissions, while in Madrid, Helsinki and Barcelona, the emissions reported by the downscaled inventories are between 1.5 and 4.5 times larger than the bottom-up estimates. Residential and commercial PM2.5 emissions are mainly driven by residential wood combustion activities (Denier van der Gon et al., 2015) and therefore most of the discrepancies observed are linked to specific components of this source, including mainly:

- Spatial allocation of domestic wood burning: the amount of wood that is burned in urban areas for space heating purposes can significantly vary from one country (or region) to another as a function of socioeconomic and legislation factors (e.g., ban on wood burning stoves). In the CAMS-REG_v5.1 inventory, residential wood combustion emissions are spatially distributed in a consistent way across Europe, using a proxy map that considers the urban/rural population density with a higher weight for wood use for a rural person and (local) availability of wood. The use of this proxy matches the local bottom-up inventories in cities such as Bologna, Milano or Hamburg. While in these cases the differences between downscaled and bottom-up PM2.5 emissions is generally low (< 20%), the proxy fails to match the local bottom-up inventories in other cities such as Barcelona (difference of a factor of 4.5), where natural gas is by far the main fuel used for residential combustion activities.
- Emission factors: As described in section 0, the CAMS-REG_v5.1 inventory estimates PM emissions from residential wood combustion emissions making use of emission factors that include the condensable fraction, which can be an order of magnitude higher than the emission factors that inly consider solid particles. Moreover, it should be noted that there are other factors besides the inclusion of organic condensable that can create important discrepancies between the emission factors used in the regional and bottom-up emission inventories, including: the appliance type splits considered (e.g., old versus new stoves, open fireplaces), assumption on burning practices, and wood characteristics (e.g., type of wood, dry/wet wood) (Simpson et al., 2020). An example of this type of discrepancy is observed in Helsinki, were both the regional and bottom-up inventories consider emission factors including condensables, but discrepancies between total PM2.5 are very large, the regional inventory reporting almost 3 times more emissions.

Note that other aspects than the ones listed above can also be causing the discrepancies observed between the downscaled and bottom-up PM2.5 emissions. For example, in the case of London, the large discrepancy observed

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

(-65%) is mainly related to the fact that the bottom-up inventory for this city includes emissions from commercial cooking activities, which are not included in the CAMS-REG_v5.1 inventory, neither in the official estimates that are reported to EMEP.

It should be noted that these discrepancies do not necessarily mean that the CAMS-REG dataset is not correct in each of these cases. For instance, for Athens the use of the CAMS-REG emissions in CTM modelling shows consistency to in-situ aerosol measurements during wintertime (Athanasopoulou et al, 2017), suggesting that the CAMS-REG emissions represent the real emissions relatively correct.

Part of the explanation in the discrepancies observed may also be the different cultural aspects with regard to wood burning, as well as local measures to reduce wood use impacts (awareness raising, fleet renewal or even local bans). These may substantially influence the local situation, whereas the CAMS-REG inventory uses a consistent approach across all of Europe.

In terms of spatial distributions, the patterns reported by the downscaled regional and bottom-up inventories are generally in line. It’s worth noting how in Helsinki both the regional and bottom-up inventory tend to locate most of the PM2.5 emissions outside of the city center, indicating than other sources of energies than wood (e.g., natural gas, electricity) are used for heating purposes in the inner city (Figure 19). In Amsterdam and Rotterdam (Figure 14 and Figure 21) the bottom-up inventory reports hotspots in isolated grid cells that are not observed in the European downscaled inventories. In the case of Rotterdam, most of these hotspots are in the port area, where the presence of residential or commercial combustion activities is in principle low. We hypothesize that the bottom-up inventories constructed by RIVM in these two cities are including some emission sources related to (industrial) activities in the harbour area, that may be wrongfully attributed to the GNFR_C sector. This issue will be further investigated together with the Dutch inventory provider (RIVM).

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

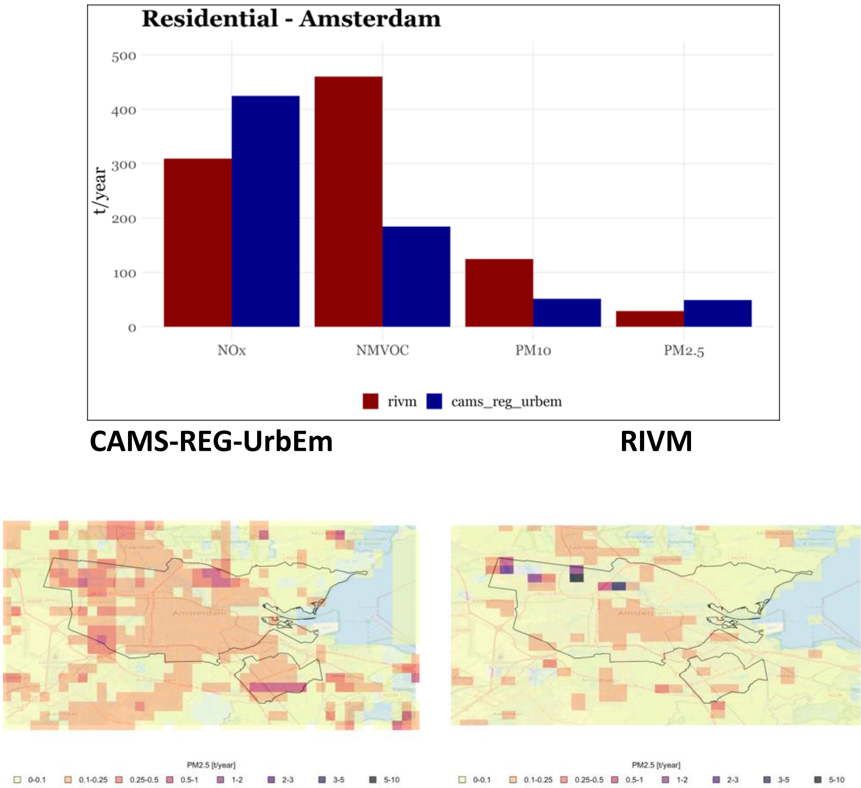


Figure 14. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and RIVM for Amsterdam*

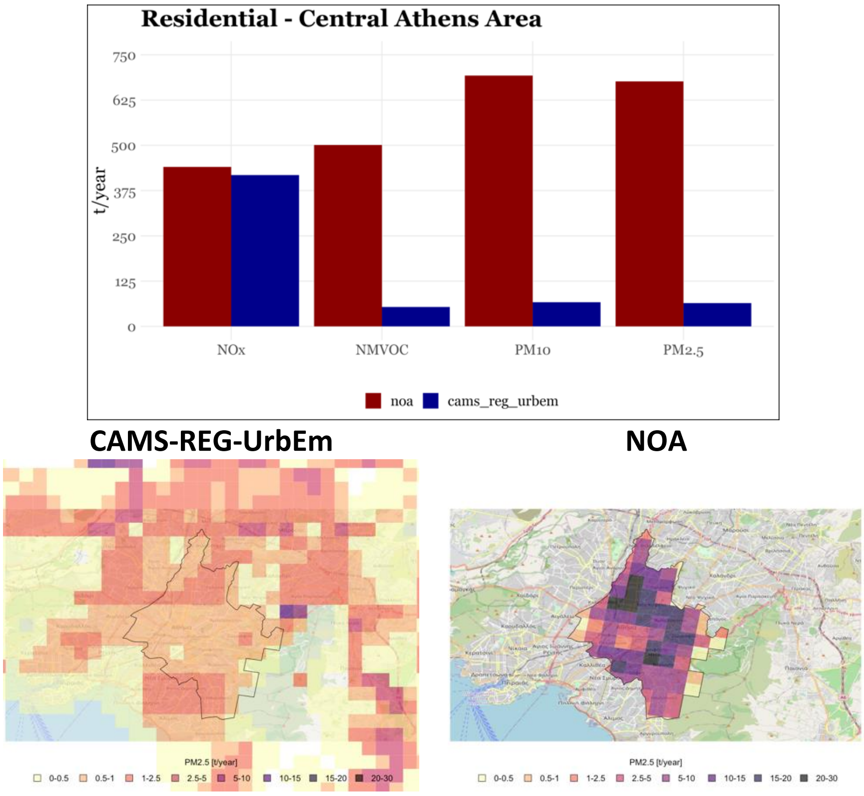


Figure 15. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and NOA for Athens*

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

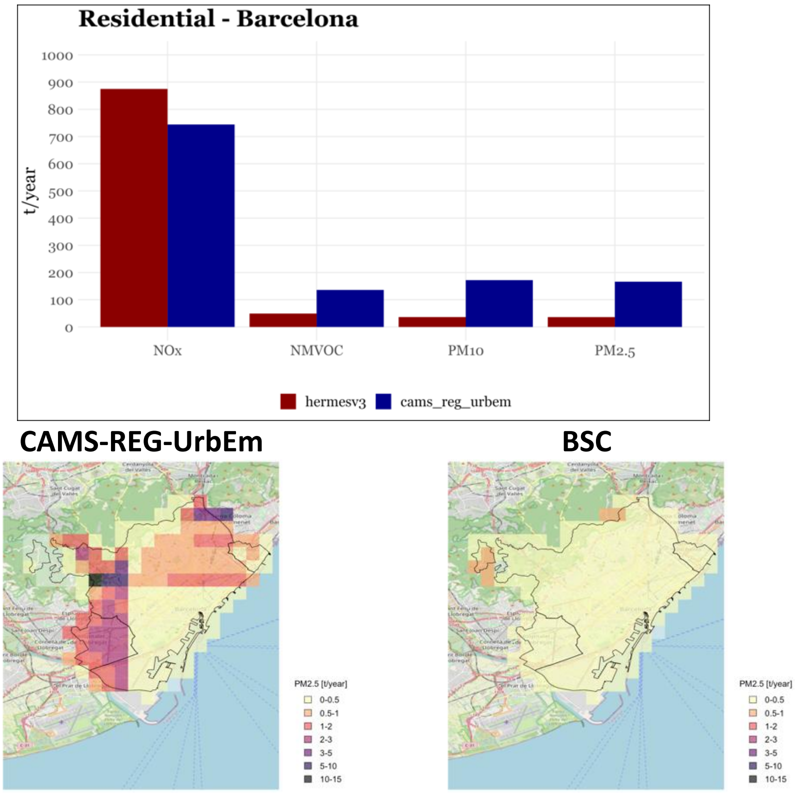


Figure 16. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and BSC for Barcelona*

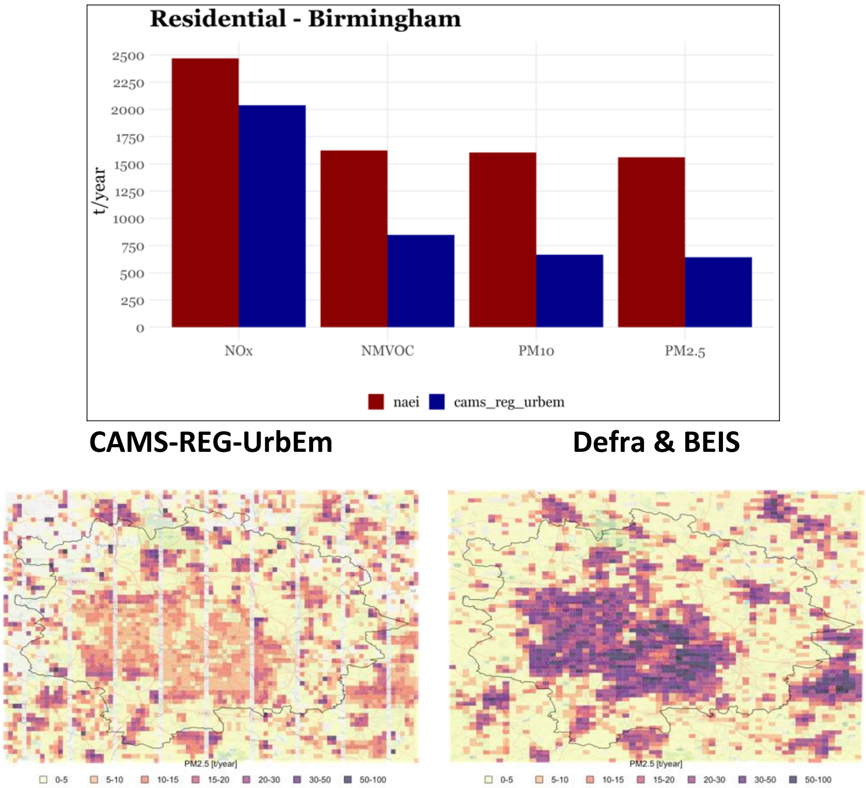
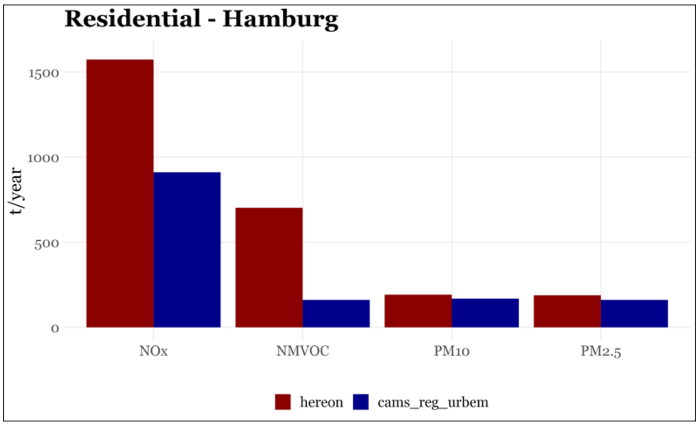


Figure 17*. Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and Defra for Birmingham*

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



CAMS-REG-UrbEm **HEREON**

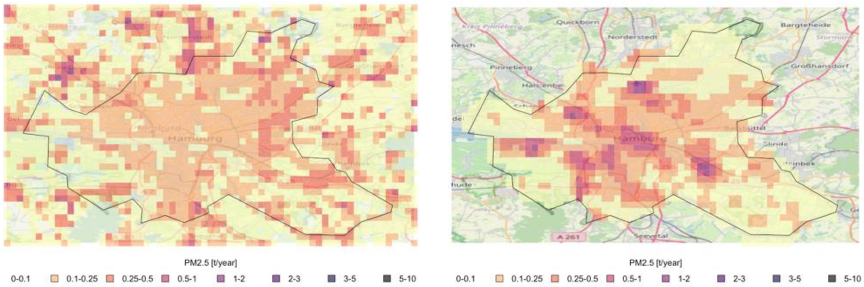
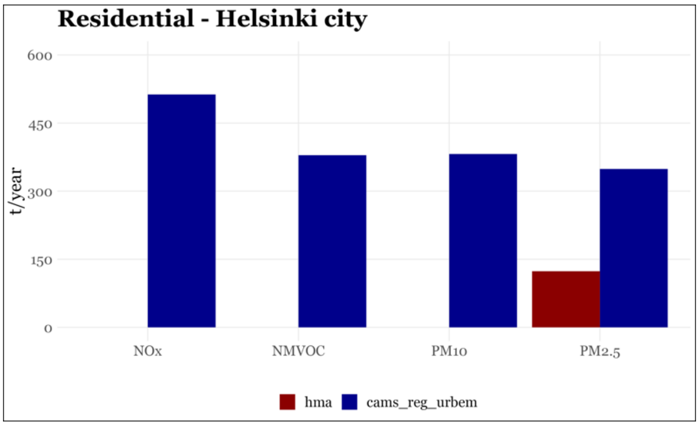


Figure 18. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and HEREON for Hamburg*



CAMS-REG-UrbEm **FMI**

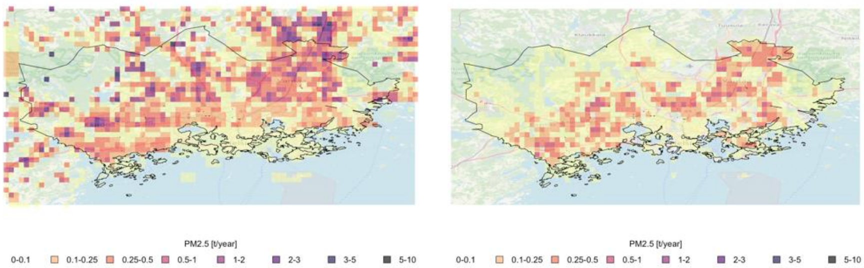
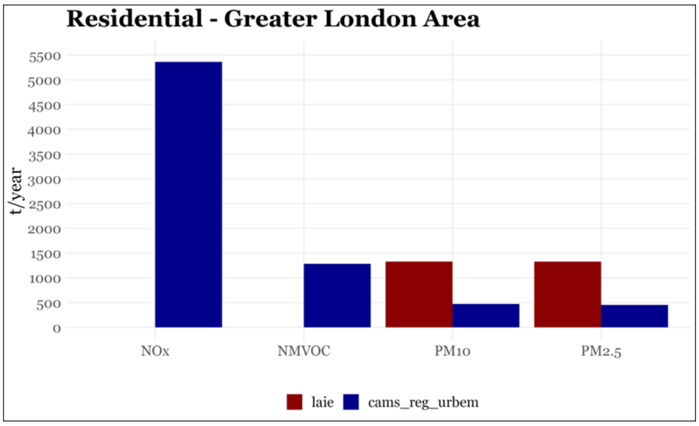


Figure 19. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and FMI for Helsinki*

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



CAMS-REG-UrbEm **LAEI**

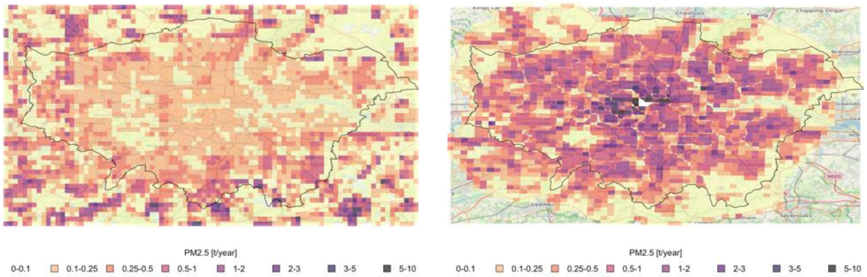
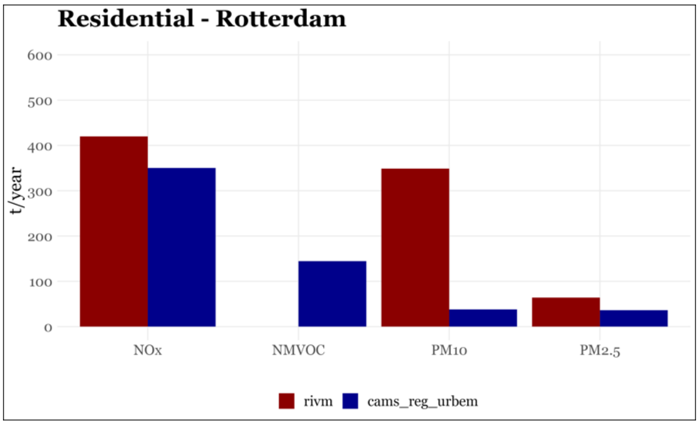


Figure 20. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and LAEI for London*



CAMS-REG-UrbEm **RIVM**

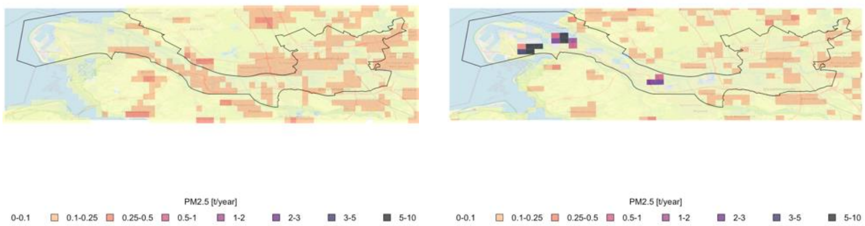


Figure 21. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM2.5 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and RIVM for Rotterdam*

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

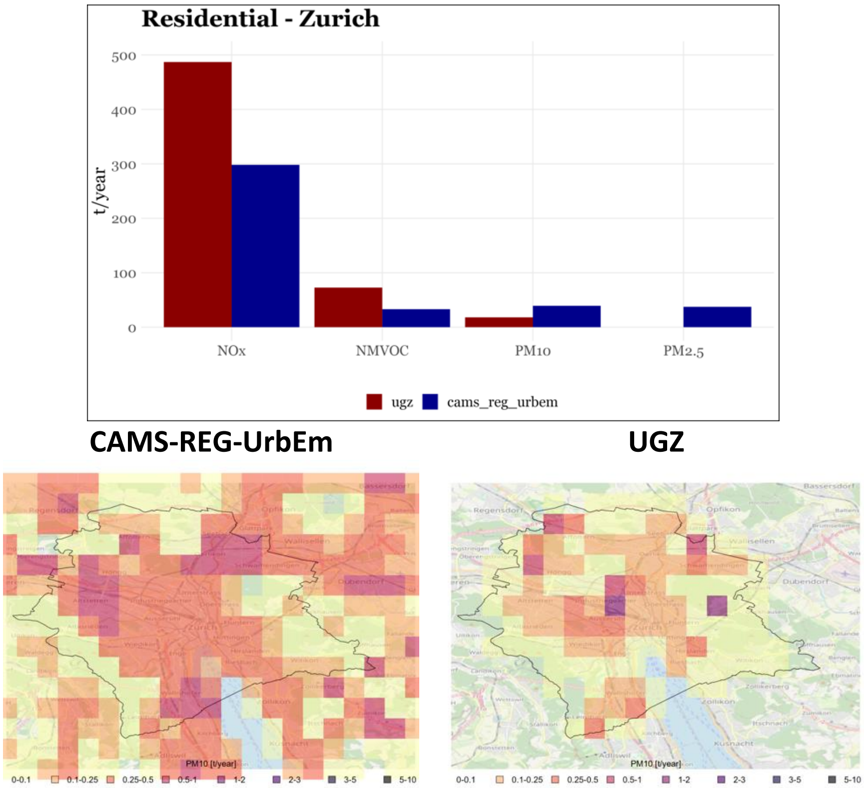


Figure 22. *Comparison between annual NOx, NMVOC, PM10 and PM2.5 (top) and gridded PM10 (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and UGZ for Zurich*

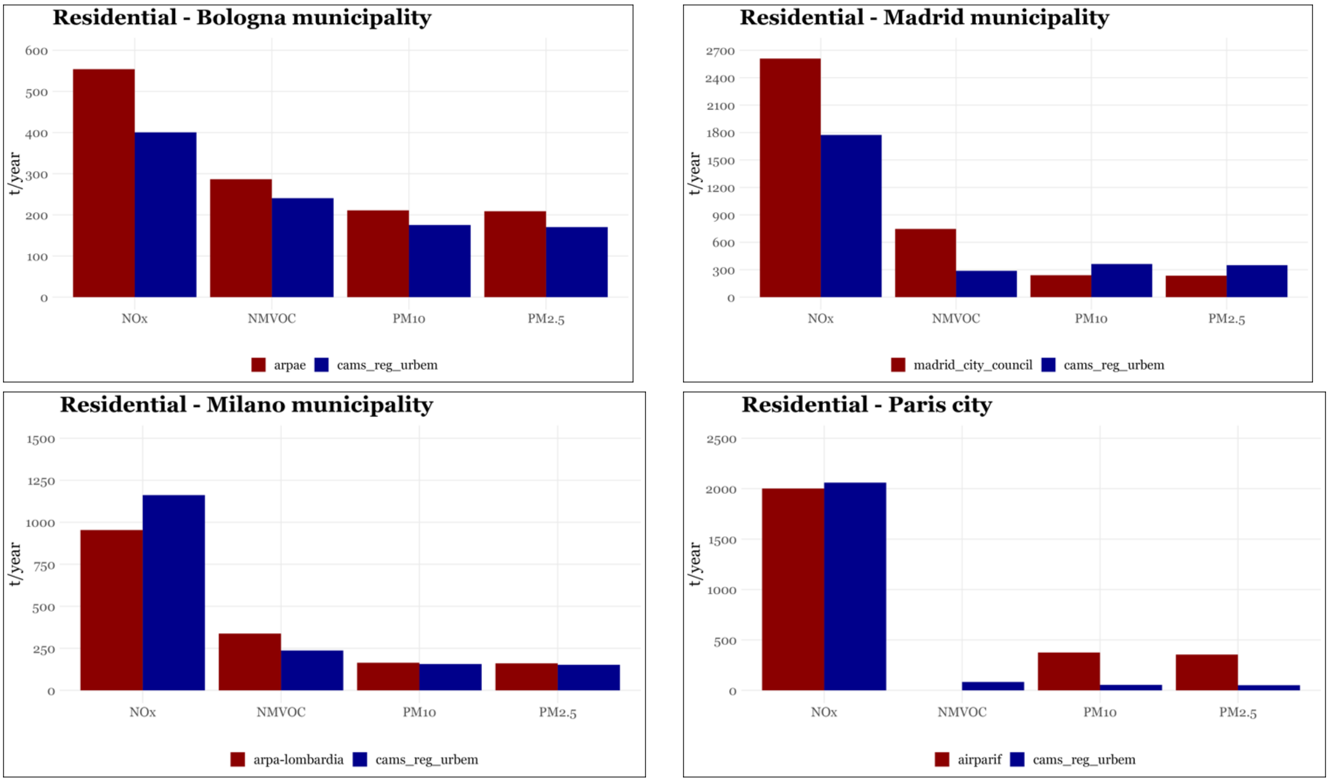


Figure 23*. Comparison between annual NOx, NMVOC, PM10 and PM2.5 residential emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and the corresponding local inventories for the cities of Bologna, Madrid, Milano and Paris*

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

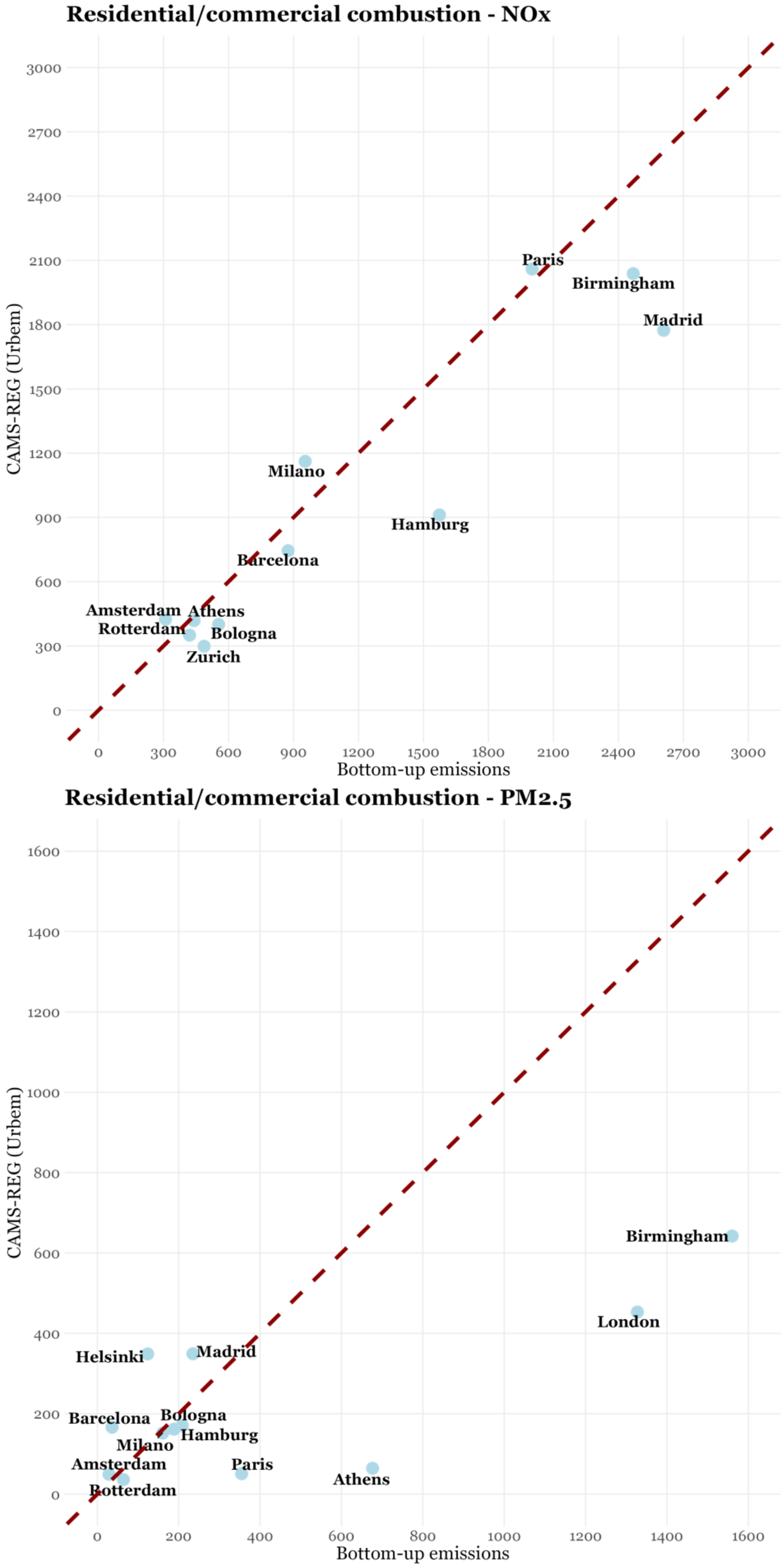


Figure 24. *Scatterplots showing the relationship between local bottom-up (X-axis) and CAMS-REG-UrbEm (Y-axis) NO_x (top) and PM2.5 (bottom) residential emission estimates per city (light-blue dots). Lines of equalities are represented with the dashed dark red lines*

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

4. Sensitivity tests

Based on the results obtained from the intercomparison exercise for road transport emissions, several sensitivity tests were performed to assess the impact of road type on the UrbEm downscaling methodology (3rd potential reason of spatial discrepancies, as discussed in Sect. 3.1). . The default weight factors considered for each OSM road type were first modified and then replaced according to relevant published information (Mu et al., 2022) (Table 2). Note that in most road segments UrbEm applies the number of lanes tagged automatically by the OSM database. In cases where segments lack this tag, the weights applied are these provided in Table 2, which are largely in consistency to the prevailing OSM tags per road type. As evident, the weight factors used as input are not directly comparable, because their normalization occurs in a later step in the UrbEm code. However, large discrepancies can be observed between factors. In the default dataset, the weight factors assumed for residential roads are between 2.5 and 3 times lower than the ones assumed for motorways, whereas in the case of Mu et al., (2022) the differences between these two road types are much larger (almost a factor of 20).

Table 2 *Spatial distribution weight factors per OSM road type considered by default in the UrbEm tool and reported by Mu et al., (2022).*

OSM road type	Default weight factors (# of lanes)	weight factors by Mu et al. (2022)
Residential	1 (one way) / 2 (two way)	0.049167
Tertiary	1 (one way) / 2 (two way)	0.098333
Secondary	2 (one way) / 4 (two way)	0.295000
Primary	2 (one way) / 4 (two way)	0.491667
Motorway	3 (one way) / 5 (two way)	0.983333
Trunk	3 (one way) / 5 (two way)	0.983333

The sensitivity tests were run for three cities, Amsterdam, Rotterdam and London. Figure 25 shows the road transport CAMS-REG-UrbEm downscaled NOx emissions [t/year·cell] obtained with the default and Mu et al., (2022) OSM weight factors, as well as the gridded emissions reported by the corresponding local inventories. It is observed that the spatial patterns of the CAMS-REG-UrbEm results obtained using the Mu et al., (2022) weight factors are in general slightly closer to the ones reported by the corresponding local inventory, as main urban corridors appear more marked than when using the default weight factors. Nevertheless, importance discrepancies are still observed, which may be due to the under-allocation of NO_x emissions in urban areas and main urban corridors in the original CAMS-REG inventory, as discussed previously in Sect. 0.

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

CAMS-REG-UrbEm (default)	CAMS-REG-UrbEm (Mu et al., 2022)	Local bottom-up inventory

Figure 25. *Gridded NO_x annual road transport emissions [t/year] reported by CAMS-REG-UrbEm using the default and Mu et al. (2022) open street map road type weight factors, and by the local inventories for Amsterdam, London and Rotterdam.*

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

5. Conclusions

This document provides the results of an emission intercomparison exercise performed between the downscaled European-wide inventories developed as part of T3.2 (CAMS-REG-UrbEm) and independent bottom-up inventories collected for a total of 13 urban areas, including 10 RI-URBANS pilot cities. The comparison assesses the consistency between local city and regional NOx, NMVOC, PM10 and PM2.5 emission estimates, both in terms of total annual emissions and their spatial distribution. The work focusses on the road transport and residential/commercial combustion emission sectors, which are the main contributors to total NO_x and PM2.5 European emissions, respectively. For NOx road transport emissions, a third independent European downscaled inventory which is based on the official EMEP emissions (uEMEP) is also considered.

The main conclusions of the intercomparison exercise are as follows:

Road transport emissions

- **CAMS-REG-UrbEm consistently reports lower NO_x road transport emissions than the local inventories, differences ranging between -76% and -32% for most of the cities**. The discrepancies are much lower when local inventories are compared to the uEMEP inventory, ranging mostly between -50% and -19%.
- The under-allocation of NO_x traffic emissions reported by CAMS-REG-UrbEm could be related to the method considered in the CAMS-REG inventory to split emissions between road types (highway, urban and rural) at national level combined with the relevant spatial distribution method for these road types. This is because the current approach does not take into account traffic parameters such as levels of congestion, which tend to be higher in urban areas. **Therefore, the method to split emissions between different road types in a country (urban, rural, highway) in CAMS-REG should be reviewed and revised as appropriate.**
- **For PM10 and PM2.5 road transport emissions, CAMS-REG-UrbEm also reports less emissions when compared to the local bottom-up inventories**. The largest discrepancies are observed in cities where the local estimates include resuspension emissions (e.g., London, Barcelona), a source that is not considered in the official reported emissions considered by the CAMS-REG inventory.
- **Regarding the spatial distribution of NO_x emissions, important differences are observed between CAMS-REG-UrbEm, uEMEP and the local emission inventories**. In the CAMS-REG-UrbEm emission maps main urban corridors, road rings and city access roads are in general much less marked than in the results reported by uEMEP and the local inventories.
- The discrepancies between CAMS-REG-UrbEm and local spatial pattern estimates are likely caused by uncertainties in the spatial proxies used to: **1) distribute the original CAMS-REG_v5.1 emissions at the European 6x6km^2 grid and 2) to downscale them at higher resolution (1x1km^2) with the UrbEm tool.**
    - Regarding the first point, an analysis of the spatial patterns reported by original 6x6km^2 CAMS-REG emissions in London and Helsinki indicates that the grid cells intersecting with main urban corridors and road rings are not always the ones reporting the largest emissions. While this is not necessarily wrong, a further investigation into these issues would be recommended.
    - Concerning the second point, the sensitivity test performed to analyse the impact of modifying the UrbEm downscaling methodology for road transport emissions indicates that the current default weight factors considered in the tool to distribute emissions across open street map road types should be reviewed. This change is therefore implemented and now added to the improvements of the UrbEm tool in the frame of RI-URBANS.

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

Residential and commercial combustion emissions

- **Discrepancies between CAMS-REG-UrbEm and bottom-up NO_x emissions are in general much lower than the ones reported for road transport**.
- In contrast, **significant discrepancies are observed when comparing CAMS-REG-UrbEm and bottom-up PM2.5 emissions, the differences being heterogenous across cities**. For instance, in Birmingham, London, Athens and Paris, CAMS-REG-UrbEm reports between -60% and -90% less emissions, while in Madrid, Helsinki and Barcelona, the emissions reported by the downscaled inventories are between 1.5 and 4.5 times larger than the bottom-up estimates.
- These **heterogeneous discrepancies** are linked to several components of the residential wood combustion emissions, **including mainly the emission factors used** (i.e., inclusion or not of condensables, appliance type splits considered, assumption on burning practices, and wood characteristics) **and the spatial proxies considered to allocate wood combustion emissions** (e.g., population density, proximity to wood).
- The uncertainties in these two parameters are very large, as they can heavily vary from one country to another as a function of socioeconomic and legislation factors (e.g., ban on wood burning stoves in cities). While local inventories may have access to the required data to reflect these characteristics in the resulting bottom-up emissions, it is much difficult to reflect them in the original CAMS-REG inventory, as it applies an homogeneous estimation and spatial distribution of emissions across the entire European domain.
- **In terms of spatial distributions, the patterns reported by the CAMS-REG-UrbEm and bottom-up inventories are generally in line**, indicating that the proxy considered by UrbEm (i.e., population density) is adequate to perform a downscaling of the original CAMS-REG inventory.

The results of these intercomparison exercise will be presented during the RI-URBANS 2nd science meeting and shared with the bottom-up emission inventory providers to gather their feedback. In addition, complementary city-scale CTM applications in the RI-URBANS pilot cities –utilizing the CAMS-REG-UrbEm database- will provide NOx, PM2.5 and PM10 timeseries for comparison with in situ concentration measurements, thus for a direct evaluation and potentially optimization of the RI-URBANS emission algorithms and datasets. In the framework of CAMS, further investigation into some of the issues identified in the present work (i.e., under allocation of NO_x road transport emissions in urban areas) has been initiated with the aim of improving future CAMS-REG inventories and (if possible under the time constraints) the updated Ri-URBANS emission inventory (D3.3, due in January 2024).

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

6. References

Denier van der Gon, H. A. C., Bergström, R., Fountoukis, C., Johansson, C., Pandis, S. N., Simpson, D., and Visschedijk, A. J. H.: Particulate emissions from residential wood combustion in Europe – revised estimates and an evaluation, Atmos. Chem. Phys., 15, 6503–6519, https://doi.org/10.5194/acp-15-6503-2015, 2015.

Kuenen, J., Dellaert, S., Visschedijk, A., Jalkanen, J.-P., Super, I., and Denier van der Gon, H.: CAMS-REG-v4: a state-of-the-art high-resolution European emission inventory for air quality modelling, Earth Syst. Sci. Data, 14, 491–515, https://doi.org/10.5194/essd-14-491-2022, 2022.

Mu, Q., Denby, B. R., Wærsted, E. G., and Fagerli, H.: Downscaling of air pollutants in Europe using uEMEP_v6, Geosci. Model Dev., 15, 449–465, https://doi.org/10.5194/gmd-15-449-2022, 2022.

Ramacher, M.O.P.; Kakouri, A.; Speyer, O.; Feldner, J.; Karl, M.; Timmermans, R.; Denier van der Gon, H.; Kuenen, J.; Gerasopoulos, E.; Athanasopoulou, E. The UrbEm Hybrid Method to Derive High-Resolution Emission City-Scale Air Quality Modeling. Atmosphere 2021, 12, 1404. https://doi.org/10.3390/atmos12111404.

Simpson, D., H. Fagerli, A. Colette, H. Denier van der Gon, C. Dore, M. Hallquist, H.C. Hansson, R. Maas, L. Rouil, N. Allemand, R. Bergström, B. Bessagnet, F. Couvidat, I. El Haddad, J.G. Safont, F. Goile, A. Grieshop, I. Fraboulet, Å. Hallquist, J. Hamilton, K. Juhrich, Z. Klimont, Z. Kregar, I. Mawdsely, A. Megaritis, L. Ntziachristos, S. Pandis, A.S.H. Prévôt, S. Schindlbacher, M. Seljeskog, N. Sirina-Leboine, J. Sommers, S. Åström: How Should Condensables Be Included in PM Emission Inventories Reported to EMEP/CLRTAP? EMEP Technical Report MSC-W 4/2020, Available at: https://emep.int/publ/reports/2020/emep_mscw_technical_report_4_2020.pdf (last accessed July 2023), 2020.

Kuik, F., Kerschbaumer, A., Lauer, A., Lupascu, A., von Schneidemesser, E., and Butler, T. M.: Top–down quantification of NO_x emissions from traffic in an urban area using a high-resolution regional atmospheric chemistry model, Atmos. Chem. Phys., 18, 8203–8225, https://doi.org/10.5194/acp-18-8203-2018, 2018.

Athanasopoulou, E., Speyer, O., Brunner, D., Vogel, H., Vogel, B., Mihalopoulos, N., and Gerasopoulos, E.: Changes in domestic heating fuel use in Greece: effects on atmospheric chemistry and radiation, Atmos. Chem. Phys., 17, 10597–10618, https://doi.org/10.5194/acp-17-10597-2017, 2017.

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