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UrbEm: a method and tool to refine regional emission inventories for urban atmospheric studies

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Abstract: As cities are growing in size and complexity, the estimation of air pollution exposure requires detailed spatial representation of air pollution levels. Intra-urban atmospheric studies require up-to-date and credible emission inventories. The Copernicus Atmosphere Monitoring Service (CAMS) provides consistent and quality-controlled information on anthropogenic emissions from Europe in the spatial resolution of 0.1 x 0.05 degree (lon/lat). The UrbEm method and tool applies a prompt and effective approach to spatially refine these emissions for any European city (or area). In particular, a top-down approach is built upon the CAMS-REG-AP database of anthropogenic air pollution emissions, creating added-value products of road transport emissions (line sources), mass emitted from industrial units (point sources) and surface emissions attributed at a grid of 1 km resolution. The disaggregation is based on publicly available, well-established, contemporary gridded datasets, which provide high resolution, suitable sector-specific proxies per source category, such as population density from Global Human Settlement (GHS), land use categories from Copernicus Land Monitoring Service (CLC 2018) and road networks from OpenStreetMap. In this work, the downscaling approach is applied in 9 diverse European Urban Centers and the improvements of the spatial disaggregation of CAMS emissions are comparatively examined.

Keywords: air pollution, emissions, urban air quality, Chemistry Transport Modelling

1. Introduction

While air pollution is considered as one of the world's largest environmental health threats emission inventories constitute essential components in understanding its sources and developing mitigation strategies (Kuenen et al., 2021), especially when it comes to the urban and intra-urban scale (Ramacher et al., 2021). Emission inventories are separated by their spatio-temporal variation to bottom-up and top-down and have a valuable contribution to three-dimensional atmospheric chemistry transport model (CTM) systems (Matthias et al, 2018).

A bottom–up approach primarily depends on gathering local activity estimates over a specific area of interest. Top-down approaches, on the other hand, spatially distribute emission totals according to gridded proxies (Ramacher et al., 2021). While bottom–up emission inventories offer greater precision (Dios et al., 2012), they can be less consistent when applied to larger regions and more time-consuming and resource-intensive than top-down inventories (Andreão et al., 2020). However, top-down inventories have their limitations too. They rely on a limited number of measurements and assumptions about emissions sources, which can lead to significant uncertainties in the estimates (Cifuentes et al., 2021).

This study introduces UrbEm, an innovative approach for creating high-resolution ($1km^2$) emission inventories over any European region (Ramacher et al., 2021). UrbEm consists a hybrid approach that combines existing, reliable emission datasets and geospatial proxies, including JRC's Global Human Settlement Layer, CLM Corine Land Cover, E-PRTR data and OSM data. By downscaling the CAMS-Reg-AP regional emission inventory for the year 2018, with a spatial resolution of 0.1 x 0.05 degree (lon/lat), UrbEm aims to produce fine-resolution emission inventories for 9 European Urban Centers with varying geographical and meteorological conditions. These high-resolution emission data could be used to support city-scale CTM applications and demonstrate good performance against measurements (Ramacher and Karl, 2020) and other available bottom-up inventories.

2. Data and Methodology

This section provides a brief overview of the updated UrbEm approach, along with some methodological enhancements described in detail by Ramacher et al. (2021). The process is fully automated and includes a user-friendly interface that enables the detailed mapping of industrial (point) sources, residential, agricultural, and other (area) sources, as well as the added-value option of transport (line) sources for any European city or area.

Annual emission totals are obtained from the Copernicus Atmospheric Monitoring Service (CAMS) using the CAMS-REG-AP v5.1 database for 2018, which provides information on a variety of pollutants (CH4, CO, NH3, NMVOC, NOX, PM10, PM2.5 and SO2) from different emission sources, including transportation, industry, agriculture, and more. CAMS-REG-AP v5.1 database has a horizontal spatial resolution of 0.1 x 0.05 degree (lon/lat).

To disaggregate the emissions data, publicly available gridded datasets are used, including the Global Human Settlement Layer (GHSL 2015), the Copernicus Land Monitoring Service (CLC 2018), the European Pollutant Release and Transfer Register (E-PRTR 2019), and the Open Street Map project (OSM). These datasets, as well as their combinations when needed, provide suitable proxies for each GNFR category.

As illustrated in Figure 1 the anthropogenic activities with the GNFR classification, are combined with the corresponding proxies for each source, including population density, land type categories (e.g., industrial, agriculture), and road networks. In the case of 4 GNFR categories (Fugitive, Solvents, Waste, and Agriculture), an alternative sector-specific proxy is activated as a backup, when the initial proxy doesn't provide information for the spatial distribution of a coarse cell. This additional step could further improve the downscaling procedure.

Figure 1. Spatial datasets used to disaggregate each anthropogenic activity. More information on all spatial datasets used can be found in Ramacher et al. (2021).

Anthropogenic Activity (GNFR source categories)	**Spatial Proxy (Dataset Source)**	**Alternative Spatial Proxy (Dataset Source)**
Public power (A)	Polygons hosting Public Power installations (E—PRTR and CLC 2018) combined with Land type characterized as 'Industry' (CLC 2018)	
Industry (B)	Polygons hosting installations of mineral or chemical industries and of production (and processing) of wood, paper, metals, animal and vegetable (E—PRTR and CLC 2018) combined with Land type characterized as 'Industry' (CLC 2018)	
Other Stationary Combustion (C)	(Residential) population Density (GHS-POP 2015)	
Fugitive (D)	Land type characterized as 'Industry' (CLC 2018)	(Residential) population Density (GHS-POP 2015)
Solvents (E)	(Residential) population Density (GHS-POP 2015)	Land type characterized as 'Industry' (CLC 2018)
Road transport (F)	Areas: 1) (Residential) population Density (GHS-POP 2015) 2) Road Network (OSM) consisting of motorways, trunks, primary, secondary, tertiary and residential roads, and their links Lines: Major Road Network (OSM) consisting of motorways, trunks, primary and secondary roads, and their links	
Shipping (G)	Land type characterized as 'Ports' (CLC 2018) combined with Ferry routes (OSM)	
Aviation (H)	Land type characterized as 'Airports' (CLC 2018)	
Non-road transport (I)	Land type characterized as 'Non-Road Mobile Sources' (CLC 2018) relevant to agricultural, industrial, and construction activities combined with Railway Network (OSM) consisting of rail and tram	
Waste (J)	Polygons hosting waste management installations (E—PRTR and CLC 2018) combined with Land type characterized as 'Arable land' (CLC 2018) to allocate open waste	(Residential) population Density (GHS-POP 2015)
Agriculture Livestock (K)	Land type characterized as 'Agriculture' (CLC 2018)	(Residential) population Density (GHS-POP 2015)
Agriculture Other (L)	Land type characterized as 'Agriculture' (CLC 2018)	(Residential) population Density (GHS-POP 2015)

To refine the downscaling methodology of the gridded datasets, several spatial processes are carried out per selected area (Ramacher et al., 2021). These include aggregating all spatial data to a fine resolution of 1 km², masking the geographical data according to the area extent, reclassifying initial analytical information when necessary, and projecting all spatial datasets to the appropriate coordinate system (e.g., WGS84). The high-resolution grid cells, deriving from the spatial proxies, are then verified per coarse cell separately so that the spatial distribution information of the coarse CAMS-REG grid is retained in the sector-specific proxy grids, which follow the urban domain definition.

Additional enhancements have been implemented to better distribute emissions for shipping, road and non-road transport sources. Specifically, rail and tram information from OSM data is combined with agriculture and industry information from CORINE (LULC) to better distribute off-road emissions. Offroad railway consists one of the 4 subsectors of non-road transport sources, while offroad agriculture and industry consist the major ones. To achieve this, railway line information is spatially joined with agriculture and industry LULC data, resulting in an enhanced spatial proxy.

Similarly, to improve the distribution of shipping emissions, ferry route data based on OSM's ferry key element are combined with port areas from LULC. This is accomplished by spatially joining ferry route (line) information with port LULC data, resulting in an improved spatial proxy.

Last but foremost, road transport emissions are among the most significant sources of emission inventories. As emphasized by Ramacher et al. (2021), line source emissions from the road transport sector, such as those provided by UrbEm, can be particularly useful for urban-scale CTMs, such as EPISODE-CityChem (Karl et al., 2019), which can provide more accurate air quality simulations. However, this may not be the case for the majority of CTMs.

The latest improvement of UrbEm enables the spatial distribution of road transport emissions in 2 ways, that are particularly useful for generating area source emissions while omitting line sources. In particular, this version of UrbEm allows the creation of area emissions with the use of either population density or OSM road data. The latter option is determined based on the number of lanes each road segment has. This improvement enables UrbEm to more accurately distribute road transport emissions by selecting 10 road types from OSM and reclassifying them into motorway, trunk, primary, secondary, tertiary, and residential types. The calculations are performed per grid cell. Along this line, road transport emissions are distributed to areas based on major road networks instead of where the population resides.

3. Results

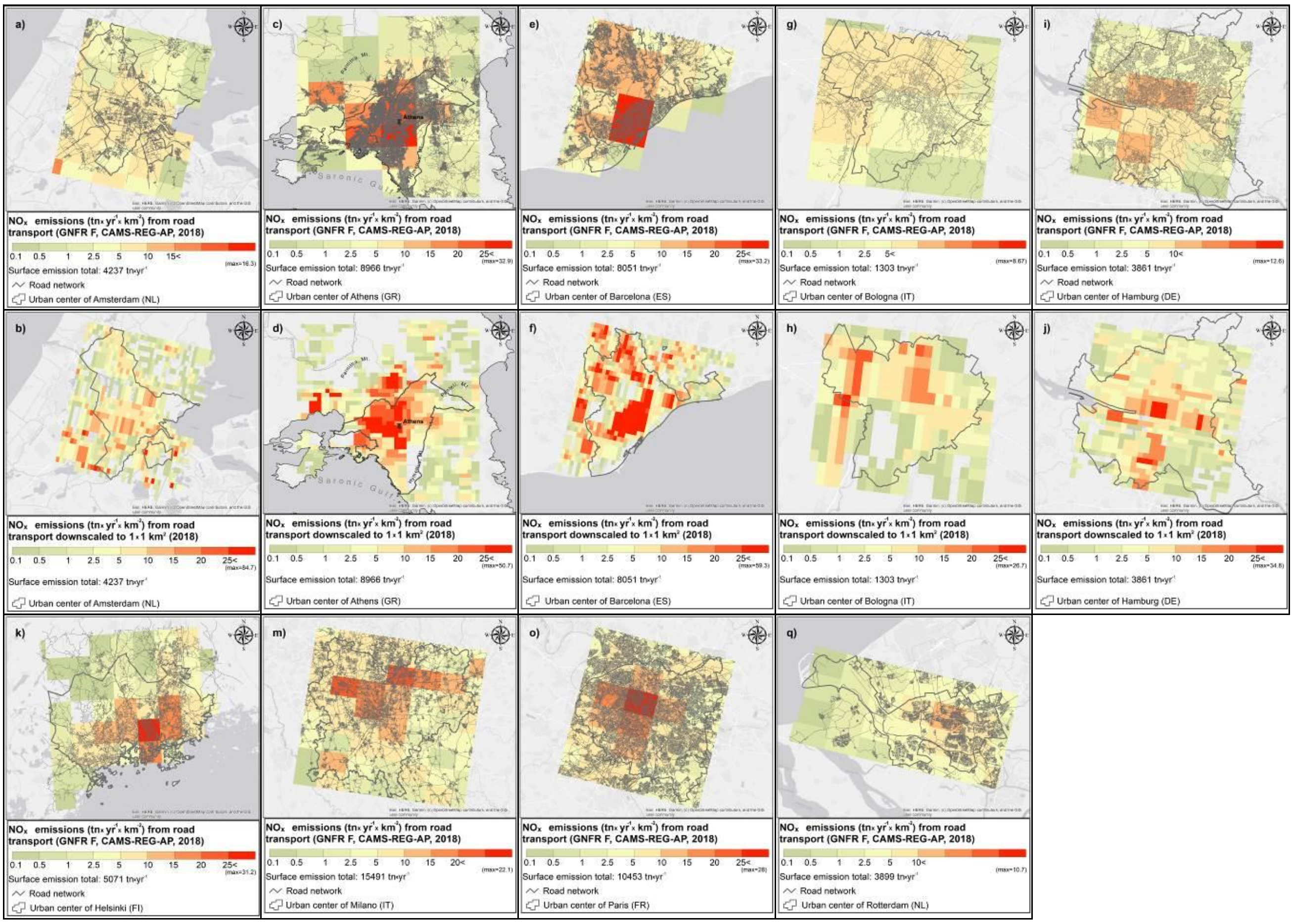
This section focuses on the latest improvement in road network emissions. Figure 2 displays representative maps of 9 European Urban centers, showing the annual emission rates from the road network as provided by CAMS (a, c, e, g, I, k, m, o and q) and by the UrbEm approach (b, d, f, h, j, l, p and r). The most common pollutant (NOx) emitted from road network sources, including gasoline-fueled cars, was selected.

The developed method provides the advantage of distributing the vehicle emissions by following the road network even in a gridded format. This input is valuable since conventional regional CTMs may not be able to properly account for street canyon circulation and dispersion. As a result, it enables a more accurate spatial distribution of emissions in more suitable locations. It is highlighted that ensuring mass consistency between the two datasets is still maintained for each domain.

With respect to absolute numbers for all urban centers., it seems that a homogeneous distribution of NOx emissions gives an average maximum of approximately 25 – 40 tn km^{-2} yr^{-1}, while this ranges in most cases from 2.5 to 20 tn km^{-2} yr^{-1}, given the selected proxy to reallocate this mass.

Urban centers of Athens, Barcelona, Milan, Paris and Helsinki exhibit higher emission values compared to other regions, even from the original CAMS database. This observation could be attributed to their dense road network, which may lead to increased traffic-related air pollution. On the other hand, the urban centers of Amsterdam, Rotterdam and Bologna have less dense road network and exhibit lower emission values compared to aforementioned urban centers. However, the meteorological conditions (precipitation, humidity and temperature) and the local characteristics (topography, elevation and proximity to water bodies and coasts) of these regions seem to differ.

To obtain a better understanding of the results, the quantitative spatial deviations between the two datasets (CAMS and UrbEm) for all cities were also examined. In particular, the total number of 1x1 cells, where road emissions were allocated by the original CAMS, but resulted in zero emissions with UrbEm, were calculated for each urban center separately. This comparison enables us to determine the impact of using UrbEm for emissions allocation as it solely allocates emissions to the OSM network. As expected the improvement rates were higher for cities with denser road networks, ranging from 2-34%, while cities with sparser road networks showed a range of 6-27%. Athens, Helsinki, and Barcelona underwent an additional procedure that masked land emissions by the coastline if coastal parts were included in the domain, resulting in higher improvement rates of 34%, 31%, and 13%, respectively.



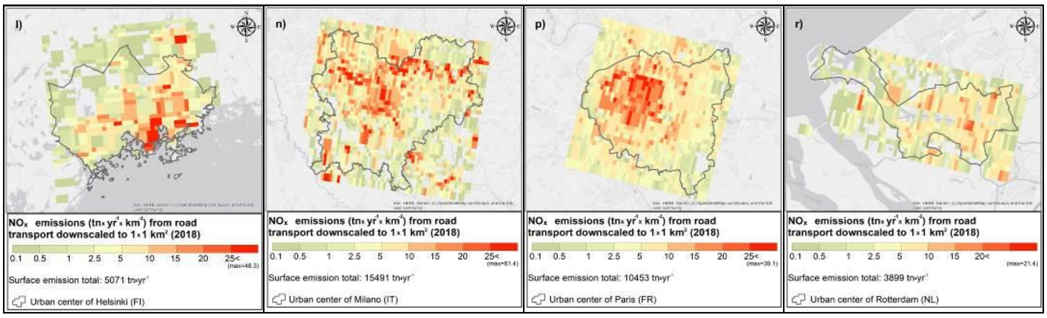


Figure 2. Annual emission fields for the urban centers of Amsterdam (a, b), Athens (c, d), Barcelona (e, f), Bologna (g, h), Hamburg (i, j), Helsinki (k, l), Milano (m, n), Paris (o, p), Rotterdam (q, r) from road traffic as originally provided by CAMS (upper maps corresponding to a, c, e, g, I, k, m, o and q) and by the improved UrbEm approach (lower maps corresponding to b, d, f, h, j, l, p and r). Advanced road network including motorway, trunk, primary, secondary, tertiary and residential road types used for the spatial disaggregation of CAMS toward the 1 km by 1 km grid are shown on the maps representing original CAMS data.

4. Discussion

Managing air quality (AQ) at an urban scale using regional emission inventories can be difficult, but UrbEm offers a credible solution for European cities without bottom-up emission inventories. UrbEm is an innovative approach that downscales gridded regional emissions using sector-specific spatial proxies based on a range of open-access, geospatial datasets. This approach can be applied to any European area, providing methodological homogeneity across different cities.

To demonstrate one of UrbEm's latest enhancements, the spatial distribution of road network emissions combined with the improved analytical road network proxy from OSM for 9 European urban centers was calculated. As a result, significant improvements in the representation of local features, particularly emission hotspots were noted. Specifically, as observed urban centers with denser road networks seem to have greater improvements.

A quantitative comparison of emissions distribution in 1 km2 cells was attempted under both scenarios (CAMS and UrbEm), which supported the conclusion that areas with denser road networks experienced a greater improvement. However, it is essential to consider other factors, such as meteorological conditions, that may also have an impact on the results.

As a future work, we plan to expand even more the automation of the entire workflow, minimize the need for location-specific refinements, and ensure efficient temporal processing per city. Moreover, as UrbEm evolves, two valuable enhancements would be to create high-resolution grids with different orientations and non-rectangular cells.

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