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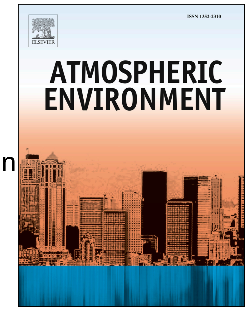

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Assessment of discrepancies between bottom-up and regional emission inventories in Norwegian urban areas

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Abstract

This study shows the capabilities of a benchmarking system to identify inconsistencies in emission inventories, and to evaluate the reason behind discrepancies as a mean to improve both bottom-up and downscaled emission inventories. Fine scale bottom-up emission inventories for seven urban areas in Norway are compared with three regional emission inventories, EC4MACS, TNO_MACC-II and TNO_MACC-III, downscaled to the same areas. The comparison shows discrepancies in nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$ and PM_{10}) when evaluating both total and sectorial emissions. The three regional emission inventories underestimate NO_x and PM_{10} traffic emissions by approximately 20-80% and 50-90%, respectively. The main reasons for the underestimation of PM_{10} emissions from traffic in the regional inventories are related to non-exhaust emissions due to resuspension, which are included in the bottom-up emission inventories but are missing in the official national emissions, and therefore in the downscaled regional inventories. The benchmarking indicates that the most probable reason behind the underestimation of NO_x traffic emissions by the regional inventories is the activity data. The fine scale NO_x traffic emissions from bottom-up inventories are based on the actual traffic volume at the road link and are much higher than the NO_x emissions downscaled from national estimates based on fuel sales and based on population for the urban areas. We have identified important discrepancies in $PM_{2.5}$ emissions from wood burning for residential heating among all the inventories. These discrepancies are associated with the assumptions made for the allocation of emissions. In the EC4MACs inventory, such assumptions imply high underestimation of $PM_{2.5}$ emissions from the residential combustion sector in urban areas, which ranges from 40 and 90% compared with the bottom-up inventories. The study shows that in three of the seven Norwegian cities there is need for further improvement of the emission inventories.

Keywords

Emission inventories; benchmarking system; urban scale; downscaled emissions; bottom-up emissions

1. Introduction

Air pollution in Europe is a political and social concern since mid-twentieth century. In December 2013, the European Commission adopted a Clean Air Policy Package that consists of an updated programme with i) new air quality objectives up to 2030, ii) a proposal for revised National Emission Ceiling Directive, and iii) a proposal for a new directive to reduce emissions from medium-sized installations. Air pollution in urban areas is becoming a priority. Among the reasons are that around 70% of the global population is estimated to live in urban areas by 2050 (UN, 2014), urban air pollution is linked to 1 million premature death in developed countries (UN, 2016), and cities contribute to 70% of global greenhouse gas emissions (UN, 2011). Consequently, a priority focus exists on developing solutions for the environmental sustainability of urban areas.

Air quality plans are nowadays being developed in urban and regional areas where air quality does not comply with the limit values established by Air Quality Directives (2008/50/EC). Air quality models are essential tools to support policy formulation by evaluating the possible impact of local and regional emission abatement options on air quality and human health (Thunis et al., 2016a). Therefore, there is a need for better understanding the air quality model uncertainties and ensure they are fit-for-purposes. The uncertainties mostly relay on the input data, such as meteorology, boundary conditions and, emissions, the latter been pointed out as the most uncertain among them (Russel & Dennis, 2000; Viaene et al. 2013).

Emission inventories are developed at local, regional and national scales, with methods that very much depend on the purpose, emission source intensity and input data availability. The EMEP/EEA emission inventory guidebook (EMEP/EEA, 2013) supports the official reporting obligations under the Convention on Long-range Transboundary Air Pollution (LRTAP) and the National Emission Ceilings Directive (NEC 2001/81/EC). The guidebook states that emissions can be estimated at different levels, which are expressed as three tiers of increasing complexity. Accordingly, tier 1 is based on statistical activity rate and default emissions factors; tier 2 uses more specific information, e.g. specific emission factors per type of process or technology; and tier 3 involves greater level of disaggregation of activity data and emissions factors than tier 2. The selection of the tier will depend on data availability and the importance of the source. Apart from direct measurements of specific emissions, which usually are scarce and only available for large point sources, emission inventories at regional and local scale are built based on two types of methods, namely “top-down” and “bottom-up”. In both cases, emissions are estimated as the product of an activity (A) and the corresponding emission factor (EF). The most significant difference is the spatial aggregation of activity data. In “top-down” methods, activity data is collected at regional or national level and then distributed on space or gridded based on different types of ancillary data (e.g. population density, land cover data). Whilst in “bottom-up” methods, the activity data is collected at a finer spatial scale (e.g. point source, road links, households) and thereafter aggregated at the required spatial resolution.

The spatial resolution of emission inventories is crucial for air pollution dispersion applications and related studies such as population exposure, health and ecosystem impact assessments or the evaluation of programmes for emission reductions in urban areas. For instance, Denby et al. (2011) identified systematic errors when the assessments at European level are based on the typical chemical transport model resolution of about 50 km. Regional emission inventories are available at a relatively coarse resolution for urban scale exposure and assessment purposes. For instance, the EMEP emission grid is approximately 50 x 50 km (available at http://www.ceip.at/) and the new EMEP grid will be available at 0.1° x 0.1° longitude – latitude resolution. Other regional emission inventories are built based on downscaling the EMEP national emission inventory, usually with the help of source-specific spatial distribution proxies. Examples of downscaled emission inventories are TNO_MACC (Kuenen et al., 2014) or EC4MACs (Bessagnet et al., 2016), available at approximately 7 km x 7 km, or the Danish emission inventory available at 1 km x 1 km resolution (e.g. Pjeldrup and Gyldenkærne, 2011). The development of bottom-up emission inventories is demanding and requires significant amount of input data and resources. Therefore, there is an increasing use of downscaled emission inventories as input data for air quality modelling activities at urban scale. The comparison or benchmarking of bottom-up and downscaled emission inventories may contribute to the better understanding of urban emissions, the identification of inconsistencies and the improvement of emission inventories at urban scale.

Our study is part of the development of a Norwegian Air Quality Urban Planning Tool, and it is performed in the framework of FAIRMODE; the Forum for Air Quality Modelling created for exchanging experience and results from modelling in the context of the Air Quality Directive (AQD). The FAIRMODE network intends to support model users at administrative levels in their policy-related model applications by establishing tools, databases and methods to enhance harmonization and promote good modelling practices among Member States. Our study is carried out in the working group on emissions focussing on the understanding and improvement of urban emissions inventories. In addition, an Emission Benchmarking Tool (ΔEmis tool) was developed (Thunis et al. 2016b; Guevara et al., 2016), and is employed in this study to facilitate the comparison between emission inventories.

The aim of our study is to contribute to the understanding and improvement of urban emissions through the evaluation of inconsistencies between bottom-up emission inventories developed for air quality assessment at the urban scale and regional downscaled emission inventories. Previous studies have already pointed out discrepancies between bottom-up and top-down emission inventories (e.g. Denier van der Gon et al., 2011; Timmermans et al., 2013). The novelty of our study lies on the usefulness of the benchmarking tool that allows emission experts at administrative level evaluate the accuracy of emission data at urban scale. Our study shows with a practical example how the comparison of emission inventories compiled through different approaches increases the understanding of emission processes and the accuracy of the emission data. The use of the FAIRMODE ΔEmis tool is demonstrated to be a powerful tool to identify the inconsistencies and to further evaluate the reasons behind them in order to ultimately improve both bottom-up and downscaled emission inventories. The outcome from our study is essential for the improvement of emission inventories and therefore their subsequent applications such as in urban and regional air quality forecasting systems (e.g. Marécal et al., 2015) or other applications.

2. Emission inventories

2.1. Urban bottom-up emission inventories

We have selected seven urban areas that are currently part of the development of a Norwegian Air Quality Urban Planning tool and of the Improved City Air forecasting system in Norway (Ødegaard et al., 2013). The selected geographical domains represent different areas in Norway. Oslo domain consists of an area of about 38 km x 27 km including parts of ten municipalities and representing the most populated of the seven selected areas. Bergen (16 km x 27 km), Trondheim (14 km x 16 km), and Stavanger (14 km x 25 km) are the most populated urban areas in Norway after Oslo. Drammen domain covers an area of about 23 km x 22 km and includes a small town that has experienced a fast shift from being an industrial town to an awarded city for its environmental and urban development. Nedre Glomma is a metropolitan region (29 km x 22 km) located at the southeast of Norway and centred between two towns Fredrikstad and Sarpsborg. Grenland is a district in the south (16 km x 23 km) that encompasses the biggest industrial park of Norway and the central location of the petrochemical industry.

Emissions from different sectors have been compiled for all seven Norwegian urban areas following primarily bottom-up approaches, except in the case of Drammen where area sources are estimated according to a downscaling approach that combines EMEP emissions with land cover data (CORINE land cover 2006). The main sectors are traffic, both on-road and non-road, residential combustion, industrial combustion and shipping. Based on regular validation processes by comparing air dispersion modelled results with observations, and on the share of traffic emissions in the urban areas, the inventories are commonly used as representative for the years 2012 or 2013. An overview of the timeliness of the data used for the different cities and sectors is given in Table 1.

For all seven locations, on-road traffic is regularly updated according to the reference year of the emission inventory. Emissions are calculated based on the line emission model included in the AirQUIS system (Slørdal et al. 2008). The emission model takes into account: i) "static traffic data" which refers to the physical characteristics of the road network (e.g. road type, width, length, gradient); ii) "dynamic traffic data" that refers to the amount of traffic (e.g. average daily traffic, ADT); and iii) "road vehicle distribution". The type of vehicle includes two levels of detail, i) the vehicle class (e.g. light duty vehicle-LDV, heavy-duty vehicle-HDV, buses), and ii) the technology class (e.g. Euro class). For each road link and type of road, the different variables are provided and emissions (g*s/m) are estimated based on the daily traffic (ADT), the percentage of emission calculated for each vehicle class within a vehicle category and a basic emission factor from the Handbook Emission Factors for Road Transport (HBEFA, 2010). The basic emission factors are corrected based on the ageing of the vehicle, as a function of the mileage, and factors that relate to the road gradient and speed dependency. The Norwegian Road Administration provides most of the input data such as average daily traffic, the speed (i.e. speed limit of the road segment), and the vehicle distribution (LDV vs HDV). Other data such as the vehicle technology class is obtained from regional statistics (OFV, 2013). Non-exhaust emissions of PM_{10} and $PM_{2.5}$ due to re-suspension are calculated for six of the geographical domains based on the percentage of studded tyres, heavy-duty traffic, traffic speed, number of vehicles and road wetness. In Oslo however, it is calculated based on the NORTRIP model (Denby et al., 2013a, 2013b).

Emissions from area or point sources are relatively outdated and some of the sources such as residential heating and non-road mobile combustion are over a decade old (Table 1). Emissions from area sources were estimated by Statistics Norway and following the same methodology that it is currently used for reporting the official national emissions (Statistics Norway, 2014). Emissions from wood burning for residential heating used in our study are based on bottom-up estimates at fine resolution (e.g. district level; Finstad et al., 2004a, 2004b), and not such estimates are available for updated years. Emissions from wood burning were determined by the product of the amount of wood consumed per type of technology (i.e. open fireplace, wood stove produced before 1998 and wood stove produced after 1998) based on surveys and the corresponding emission factors, established based on measurements for Norwegian conditions (SINTEF, 2013). An attempt to update wood burning emissions for official national estimates downscaled to the urban areas has existed, and thereafter tested with air dispersion models. The results showed a large overestimation of PM pollution levels when comparing with observations. Denier van der Gon et al. (2015) obtained similar outcomes, highlighting the need for updating and harmonizing official estimates for wood burning emissions. For this reason, bottom-up wood burning emissions relatively outdated are still used to represent current situation in urban areas.

Emissions from large point sources are officially reported to the Norwegian Environment Agency and they are linked to the corresponding geographical position. In the case of industrial emissions that cannot be linked to a stack or large point source, they are distributed spatially based on surrogate data at the municipality level, e.g. employment figures in the industrial sector (Norwegian Environment Agency, 2016). Emissions from non-road mobile sources include emissions from construction machinery, tractors, households and gardening. Emissions were estimated by Statistics Norway based on the number of registered machinery or equipment in each municipality, and the corresponding fuel sales. In the case of machinery from the industrial and construction sectors, emissions were estimated based on the diesel consumption according to the statistics from the industrial sector. Emissions from shipping in Bergen, Stavanger and Trondheim are from Statistics Norway and were calculated based on the sale of marine fuels for both national and international sea transport and using average emission factors. For Oslo, the shipping emission inventory was developed following a tier 3 approach based on the activity data provided by the Port of Oslo, and specific emission factors for the different types of vessels (López-Aparicio et al., 2014; 2016).

In this study we focus on the five largest contributing sectors in Norwegian urban areas in terms of emission total; on-road traffic, wood burning for residential heating, industry, shipping and non-road mobile combustion sources. To facilitate the comparison with downscaled emission inventories, we have classified and aggregated the bottom-up emissions into SNAP sectors (Selected Nomenclature for Air Pollutants; CEIP, 2016) as indicated in Table 1. Small subsectors that are not included in the discussion are i) non-wood residential heating, ii) commercial heating, iii) airport and iv) railways.

Emissions from these subsectors are only available, when applicable, for Oslo, Bergen, Stavanger and Trondheim. Even though the contribution from these subsectors to total urban emissions is below 5% for both NO_x and particulate matter (PM), we have included them in the corresponding SNAP sector, i.e. SNAP2 for non-wood residential heating and stationary commercial heating, and SNAP8 for emissions from airport and railways. We aim at the best possible completeness of the SNAP sectors in the urban areas.

Table 1: Overview of the reference years of the main emission sectors in the emission inventories.

Urban areas	On-road Traffic	Residential Heating	Shipping	Off-road mobile combustion	Industry
Bergen	2012	2003	1995/1998	1995/1998	1995/1998
Drammen	2012	2012	n.a.	2012	2012
Grenland	2012	1998	n.a.	n.a.	1991
Nedre Glomma	2012	2012	n.a.	n.a.	2012
Oslo	2013	2002	2013	1995	2013
Stavanger	2012	1998	1995/1998	1995/1998	1995/1998
Trondheim	2012	2005	2005	2005	2005
SNAP sectors	SNAP7	SNAP 2	SNAP 8	SNAP 8	SNAP 3-4

2.2. Downscaled emission inventories

We selected EC4MACS (2007), TNO_MACC-II (2009), and the newly improved version TNO_MACC-III (2011) as downscaled regional inventories at European level. For detailed information about these inventories, we refer to Kuenen et al., (2014) and Bessagnet et al., (2016). These inventories are widely used in European Air Quality applications and have supported air quality inter-comparison exercises (e.g. AQMEII project, Forkela et al., 2015). Emissions in the regional inventories are distributed in macro-sectors: 1) energy industries; 2) non-industrial combustion; 3) industrial combustion; 4) production processes; 7) road transport; and 8) non-road mobile combustion sources, as the relevant sectors for our study, and classified according to the SNAP nomenclature (CEIP, 2016). In TNO_MACC-II and TNO_MACC-III, sectors SNAP3 and SNAP4 are merged. The three regional emission inventories are developed based on officially reported emissions to the Convention for Long-Range Transboundary Air Pollution (CLRTAP; http://www.unece.org/env/lrtap/welcome.html), and completed with emissions at the country level from GAINS model (Amann et al., 2011) or EDGAR (JRC, 2011). In TNO_MACC-II and TNO_MACC-III, officially reported emissions (CEIP and EEA) were the primary data source for EU Member States and EFTA countries, and GAINS for former Soviet Union countries and some Balkan countries. For Norway, TNO_MACC emission inventories are based on officially reported data for all compounds (i.e. CH_4, CO, NH_3, NMVOC, NO_X, PM_{10}, $PM_{2.5}$ and SO_2). The emission data is then spatially disaggregated to a finer spatial resolution following different downscaling techniques. The gridding of emissions in the three regional emissions inventories is downscaled according to different assumptions, using the proxies summarized in Table 2.

Emissions from point sources in TNO_MACC-II and III and their geographical locations are taken from The European Pollutant Release and Transfer Register (E-PRTR database) and combined with TNO's own point source database. In the case of Norway, emissions from point sources are from the E-PRTR. In EC4MACs inventory, emissions from point sources are taken for the previous European Pollutant Emission Register (EPER) and combined with artificial land use data.

Emissions associated to non-industrial combustion plants (SNAP2) are mainly allocated according to total population density. The SNAP2 sector consists of i) commercial / institutional stationary combustion; ii) residential combustion; iii) stationary combustion associated with agriculture, forestry or fishing; and iv) other stationary. In Norway, around 98% of emissions in SNAP2 sector are from residential combustion, most of it from biomass (i.e. wood burning). TNO_MACC-II and TNO_MACC-III use internal approaches based on population and wood availability. In EC4MACs, emissions from biomass burning are allocated with coefficients defined based on population density by Terrenoire et al. (2015). These coefficients were defined at a French bottom-up study that established that PM emissions per inhabitant sharply decrease when the population density increase.

Table 2: Overview of the proxies employed for gridding emissions by sector in the three regional emission inventories. TNO_MACC (2007; Denier van der Gon, et al, 2010)

	TNO-MACC_II	TNO-MACC_III	EC4MACS
Ref	Kuenen et al., 2014	(pers. commun.)	Bessagnet et al., 2016; Denier van der Gon (2010)
Year	2003 - 2009	2000 - 2011	2009
SNAP1	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	EPER and Artificial Landuse
SNAP2	Total population and Wood use map	TNO internal estimates (Population and wood availability)	Dissagregated based on population (Terrenoise et al., 2015)
SNAP3	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	TNO_MACC (2007); E-PRTR and TNO PS database
SNAP4	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	Artificial Landuse
SNAP5	E-PRTR, TNO PS database or Urban Population		Artificial Landuse
SNAP6	Total population		Artificial Landuse
SNAP7	TRANSTOOLS network and Total population		TNO_MACC (2007); Road Network and Partly population
SNAP8	TNO PS database, Rail map, Shipping map, Arable land, Total population	Shipping; methodology improved, estimated differently per sea	TNO_MACC (2007); Rail map, Inland and coastal waterways, Arable land, Population
SNAP9	E-PRTR, Rural population or Total population		TNO_MACC (2007); E-PRTR and Population
SNAP10	Livestock map, Arable land, Total population		TNO_MACC (2007); Livestock map, Arable land, Total population

The emissions in the merged SNAP3 (Combustion in manufacturing industry) and SNAP4 (Production processes) sectors in the TNO_MACC emission inventories are distributed based on the information from the E-PRTR database, the TNO internal point source database and population. The TNO_MACC-III introduces an improvement in the distribution of industrial diffusive emissions (i.e. industrial emissions that cannot be linked to an E-PRTR facility), and they are allocated based on industrial land use data from the CORINE classification instead (*personal communication*). This improvement regarding TNO_MACC-II was introduced to avoid an over-allocation of industrial emissions in urban areas. In EC4MACs, EMEP emissions were re-gridded into a finer model domain based on the TNO-MACC spatial distribution for SNAP3 and on artificial land use area for SNAP4. TNO_MACC emission inventories distribute emissions in SNAP5 and 6 based on total or urban population, whereas EC4MACs does it by using artificial land use data at 1 km resolution. Regarding SNAP sectors 7, 8, 9 and 10, EC4MACS based the distribution of emissions on TNO_MACC spatial distribution. Thus, on-road transports (SNAP7) is distributed based on the TRANSTOOL network (JRC, 2005) for interurban traffic emissions and population density for urban traffic emissions, and the remaining sectors (SNAP8, SNAP9 and SNAP10) based on population or the corresponding land cover maps (Table 2).

3. Benchmarking tool: methodology for comparison of emission inventories

For the comparison of bottom-up and downscaled emission inventories, we used the Δ-Emis tool (Thunis et al., 2016b; Guevara et al., 2016). Δ-Emis is an IDL-based tool designed to screen and benchmark emission inventories, and especially to support the comparison of bottom-up and top-down emission estimates at city, regional, and country scale. The tool was originally designed as a flagging system to identify inconsistencies in emission inventories, and evaluate the reasons for these inconsistencies in order to improve the emission inventories. The benchmarking was mainly carried out based on the direct comparison of a bottom-up inventory (BUP) to the downscaled emission inventory (TOD) in the macro-sectors and pollutants pairs for the seven model domains (i.e. Bar-Plot in the Δ-Emis tool). The evaluation is supported by the used of the "diamond" diagram (Thunis et al., 2016b), also available in the Δ-Emis tool, aiming at getting additional insights in possible explanations for discrepancies between emissions over the selected areas. The diamond diagram is designed to identify discrepancies in the inventories and allows an informed evaluation of whether differences between inventories can be mostly related to differences in the use of emission factors or in the choice of activity data. For more details about the theory behind the diamond diagram and its interpretation, we refer to Thunis et al. (2016b).

4. Results and Discussion

A preliminary comparison of urban NO_x emissions estimated according to bottom-up methods and emissions, for the same areas, according to the 3 downscaled regional emission inventories shows a lack of consistency among all the urban areas. However, PM_{10} and $PM_{2.5}$ emissions in TNO_MACC-II are generally higher than in the BUP. Other studies has reported similar differences when comparing total downscaled emissions with bottom-up estimates (Kuenen et al. 2010; Maes et al. 2009). In other to shed light on the causes of discrepancies, an evaluation at the sector or subsector level is needed, as total values could also be affected by compensation of errors, i.e. overestimations and underestimations in different sectors. This section presents an evaluation of emissions for on-road transport (SNAP7), residential combustion sector - wood burning (SNAP2), non-road mobile sources and machinery (SNAP8) and industry (SNAP3 and SNAP4).

4.2. On-road transport sector

The benchmarking shows similar BUP/TOD ratio for SNAP7 (on road transport) in each area when comparing with the three TODs (Figure 1). As previously described, $TOD_{EC4MACs}$ is based on TNO_MACC (Table 2) and thus explains this similarity. For the seven areas, NO_x and PM_{10} emissions in the BUPs are higher than in the three TODs.

The BUP_{PM10} to TOP_{PM10} ratios are above a factor 2. The reason of this discrepancy is on non-exhaust PM emissions due to re-suspension that is accounted for in the BUPs, whereas officially reported emissions to the CLRTAP from Norway only include automobile tyre wear, brake wear and road abrasion as non-exhaust emissions in SNAP7. The importance of including re-suspension as a subsector in the official reporting of emissions is highlighted in our study, as we underestimate national emissions of PM. For instance, in Oslo emissions from re-suspension account for about 34% of total road transport PM_{10} emissions. Moreover, cities exposed to icing and de-icing conditions, and the use of studded tyres, experience recurrent exceedances of PM limit values (Amato et al., 2014 and references therein). The evaluation of measures targeting at resuspension are therefore needed, and consequently re-suspension needs to be accounted for in emission inventories.

BUP_{NOX}/TOD_{NOX} ratios are a factor above 2 for Drammen, Nedre Glomma and Oslo. For $PM_{2.5}$ however, $BUP_{PM2.5}$ and $TOD_{PM2.5}$ seem to show similar emission values except for Drammen where BUP is much higher than TOD. The reason behind the different results obtained for Drammen is not clear and additional effort need to be put in the evaluation of this emission inventory. A higher share of diesel vehicles in BUP than in TODs could explain the higher BUP_{NOX} than TOD_{NOX}, and similar $BUP_{PM2.5}$ and $TOD_{PM2.5}$. NO_x traffic emissions in Oslo are very much due to diesel vehicles, as 92% of total NO_x emissions are associated with heavy duty vehicles, buses and diesel light duty vehicles (i.e. passenger cars and other light duty vehicles), and barely 8% is associated with gasoline passenger cars. In TNO_MACC-II and TNO_MACC-III, NO_x traffic emissions in Oslo domain associated with diesel vehicles are around 86% and 90%, respectively. The share diesel versus gasoline seems to be similar among the inventories. The reason behind discrepancies in NO_x emissions may be then in the activity data, as emission factors in BUP and in the Norwegian national emissions (Statistic Norway, 2014), and therefore in the TOD, are from HBEFA. In Norway, national emission are estimated following a Tier 3 according to EMEP/EEA (2013) guidebook and based on fuel sold, number of vehicles per category, and driving patterns (Statistics Norway, 2014; Norwegian Environment Agency, 2016), whereas the emissions in BUPs are based, among other variables, on the amount of traffic per road link expressed as average daily traffic (ADT).

Traffic emissions for the four most populated urban areas are plotted on diamond diagrams (Figure 2) in order to shed light on possible reasons of inconsistencies between BUPs and TODs. The comparison is carried out with TNO_MACC-III as it closest represents the year of the BUPs. The X axis of the diamond diagram represents the emission factor ratio (ef_BUP/ef_TOD) while the Y axis represents the activity data ratio (A_BUP/A_TOD). As a result, the distance from the X and Y origin provide information on the deviations made in terms of emission factor and activity, respectively (Thunis et al., 2016).

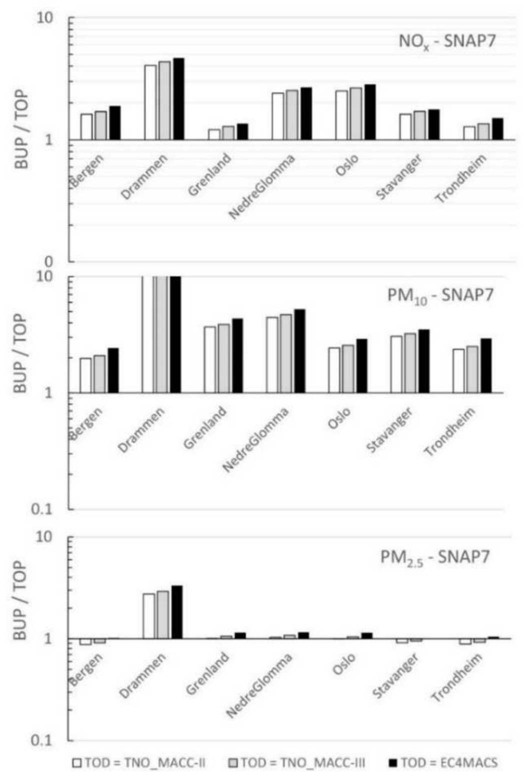

Figure 1: Ratios of emissions of NO_x, PM_{10} and $PM_{2.5}$ from bottom-up inventories (BUP) to downscaled emissions for the SNAP7 (Road Transport).

The disposition of the symbols representing NO_x, PM_{10} and $PM_{2.5}$ emissions from traffic (TRA in Figure 2) indicates that there may be inconsistencies in term of the emission factors as they are spread on the horizontal axis (Thunis et al., 2016b). The $ef\_BUP_{PM10}/ef\_TOD_{PM10}$ for the four model domains are calculated to be ≥1, and higher than $ef\_BUP_{PM2.5}/ef\_TOD_{PM2.5}$. These values indicate overestimations of EF_{PM10} in the BUPs. This supports previous observation regarding the existence of resuspension when we estimate emissions of PM_{10} in the BUPs.

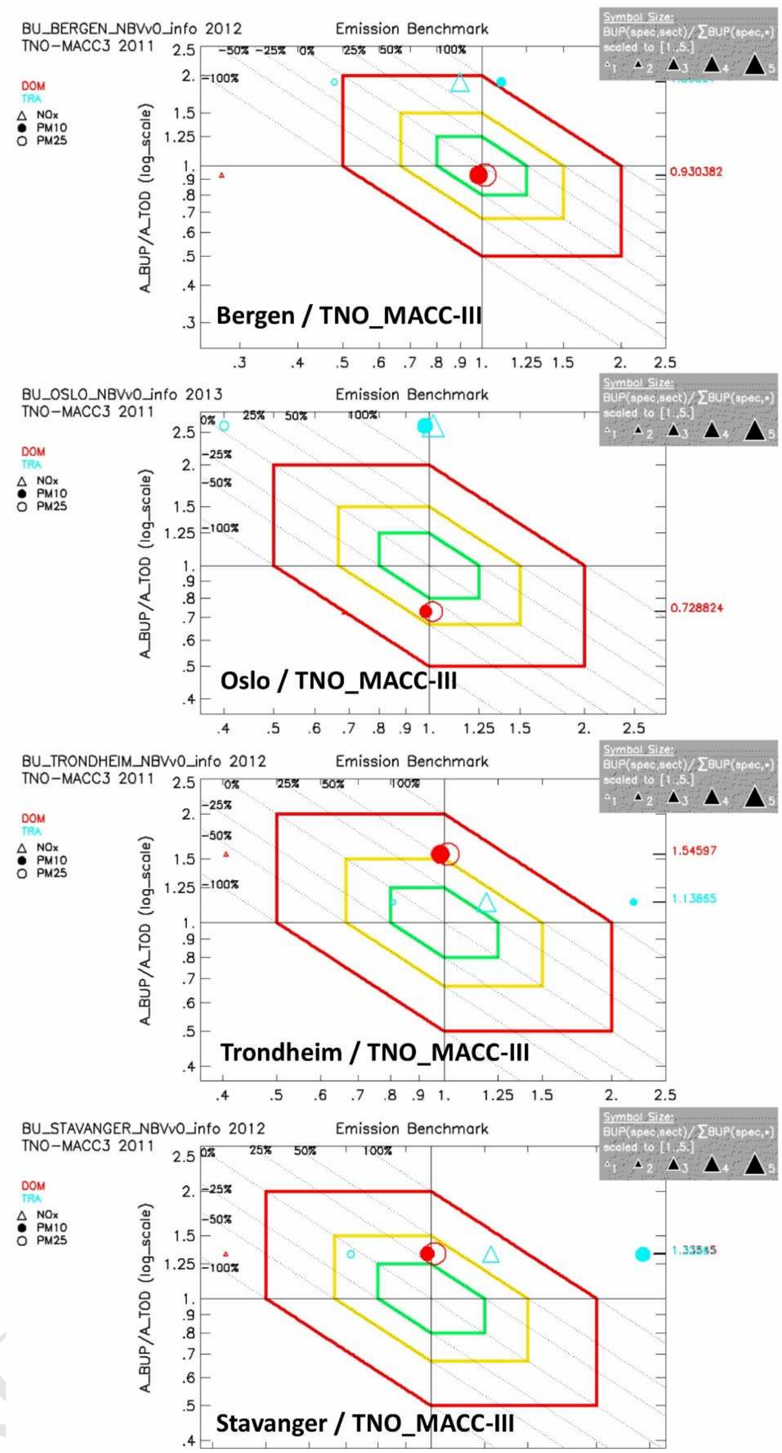

Figure 2: Diamond diagrams for Bergen, Oslo, Stavanger and Trondheim benchmarked against TNO_MACC-III.

Traffic emissions are plotted on the area that indicates higher activity in the BUP than in the $TOD_{TNO\_MACC-III}$, especially for Bergen and Oslo (Figure 2). The lack of detailed information about the location of emissions, and the method used to disaggregate traffic emissions entail discrepancies on activity for urban areas as shown by the diamond diagram. As previously stated, TNO_MACC uses the TRANSTOOL road network and population data to allocate interurban and urban traffic emissions, respectively. This is because TRANSTOOL focuses on interurban transport and only considers motorways and main roads. The percentage of total traffic emissions that TNO_MACC assigns to urban traffic based on population is underestimated. The highest differences would be observed for the areas with highest urban road network density, as it is the case of Oslo and Bergen (Figure 2). This source of uncertainty has been previously stated in Ferreira et al. (2013). Similarly Maes et al. (2009) established that the downscaling approach poorly reproduced the spatial surrogates for on-road transport. BUPs inventories are more likely capturing the spatial variations within the urban area, since the road network used to estimate the emissions at the road link level is more detailed, includes more updated traffic variables (e.g. ADT) and contains secondary and local roads along with the motorways and main roads.

4.3. Residential combustion sector _ wood burning

Emissions from non-industrial combustion plants (SNAP2) in Norway are mainly associated with the residential sector and due to wood burning, as it is the second most important heating source after electricity (http://www.iea.org/). The comparison of $BUP_{PM2.5}$ with the three TOPs for the residential combustion sector shows several discrepancies (Figure 3). Emissions from area sources in Drammen are downscaled according to an approach based on EMEP emissions and land cover data for residential heating, emissions are calculated to be higher than in EC4MACs, TNO_MACC-II and TNO_MACC-III.

The comparison with TNO_MACC-II shows that $PM_{2.5}$ emissions in the BUPs are lower, whereas the comparison with TNO_MACC-III shows that BUP and $TOD_{TNO\_MACC-III}$ are similar or $BUP_{PM2.5}$ is slightly higher (i.e. Stavanger and Trondheim; Figure 3). These differences reflect the modifications introduced in TNO_MACC-III with respect to TNO_MACC-II, which show that emissions from wood burning in urban areas have been reduced with the implementation of a new approach.

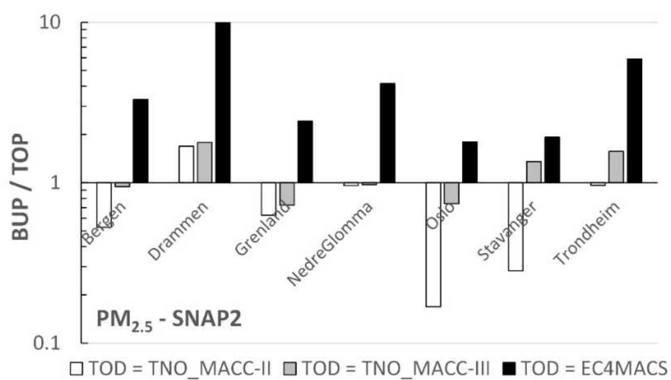

Figure 3: Ratios of $PM_{2.5}$ emissions in BUP to $PM_{2.5}$ emissions in TOD for the SNAP2, Non-industrial combustion (top left).

The comparison of BUPs with EC4MACs shows opposite results, as $PM_{2.5}$ emissions in the BUPs are calculated to be much higher than emissions resulting from the downscaling, and the ratio of BUP to $TOP_{EC4MACs}$ reaches factors between 2 and 7. EC4MACs assumes that emissions from wood burning sharply decreases with population density and therefore these emissions are allocated in sparsely populated areas. This assumption is based on a bottom-up study carried out in France and thereafter it was extrapolated to the whole Europe (Terrenoire et al., 2015; Bessagnet et al., 2016). This assumption is valid for some European countries such as France, where the main heating sources in urban areas are electricity and natural gas, while wood burning is mostly used as heating in rural areas. However, this assumption is not valid for Norway, where wood burning is generally used as heating source also in urban areas. Domestic wood burning has been reported to be an important anthropogenic source of PM emissions in Nordic cities, and contributor to PM pollution levels. For instance, in Oslo (Norway), Lycksele (Sweden), Gävle (Sweden) and Helsinki (Finland), local domestic wood burning emissions have been estimated by source apportionment and measurements to contribute by 30-50%, 40-80%, 5-30% and 14%, respectively, to urban background concentration levels in winter (see review in Denby et al., 2009). For these reasons, it is fair to conclude that EC4MACs underestimates PM emissions from wood burning for residential combustion in urban areas in Scandinavia and Finland.

The diamond plot shows that PM_{10} and $PM_{2.5}$ emissions from wood burning based on BUPs and $TOD_{TNO\_MACC\text{-}III}$ are consistent in Bergen (Figure 2). The benchmarking performed for Stavanger and Trondheim indicates that activities may be higher in the BUP emission inventories, whereas for Oslo is slightly lower. As indicated at the beginning of this paper, emissions from wood burning are a decade old in the BUPs and the years are not consistent among the urban areas. Results for Stavanger, Oslo and Trondheim refer to 1998, 2002 and 2005, respectively (Table 1), whereas TNO_MACC-III emissions are based on 2011 activity data. Wood burning activity depends on the climatic conditions, thereby long and cold winters will result in higher wood consumption over the consumption during shorter and milder winters. In addition, the uncertainties in wood burning emission estimates are high, for instance in Oslo it has been reported to be around 50% (Denby et al., 2009). Wood burning is therefore one of the sectors that needs a special attention, and regular updates to best represent the reference year are required. Figure 4 shows time series for biomass consumption and $PM_{2.5}$ emissions from residential heating in Norway from 1998 to 2014. Differences are observed from year to year on annual emission values, and they may be explained by different meteorological winter conditions. Norway has significant climate variations as it covers a span of 13 degrees of latitude, thus annual national average temperature or wood consumption would very much smooth the local variations. Variations from year to year may be higher at local scale such as in urban areas. Based on our knowledge of emissions from the residential heating in Norwegian urban areas and on the outcomes from the benchmarking, emissions in TNO_MACC-III may represent better local scale in the selected Norwegian urban domains than TNO_MACC-II and EC4MACs.

4.4. Non-road mobile sources and machinery

In Norway, non-road mobile sources and machinery (SNAP8) contribute to around 20% of the total national NO_x emissions. Figure 4 shows the time series for NO_x emissions from SNAP8 and the corresponding subsectors, and a decrease is observed from 1999 to 2014, specially significant from 2008. The biggest contributing subsectors is shipping, followed by national fishing and non-road mobile sources associated with industry and construction. The two latest subsectors have not experienced a significant change with time, whereas shipping exhibits a pronounced decrease.

The BUPs for the seven norwegian cities are not consistent regarding the completeness of emissions representing SNAP8 neither the year of reference. For instance, both Grenland and Nedre Glomma lack emissions from non-road mobile sources such as machinery in the construction and industrial sectors, and shipping is missing in Drammen, Grenland and Nedre Glomma. The incompleteness in the BUPs would explain the marked differences observed in total emissions with TODs (Table 3). The benchmarking exercise shows that emissions from non-road mobile sources based on BUP are lower than those reported by the TODs for both NO_x and PM_{10} (Figure 5, left panel). The BUP_{NOX}/TOP_{NOX} ratios are between 0.3 and 0.5 for most of the urban areas, and in Trondheim the ratio BUP_{NOX} to TOP_{NOX} reaches around 0.1. BUP_{PM10}/TOD_{PM10} ratios show higher inconsistencies reaching values around 0.2 or even below 0.1 in the case of Trondheim and TOD_{TNO_MACCs}. An hypothesis to explain these differences lie on the bottom-up emission inventories, as they are more than a decade old when even complete, i.e. in Bergen, Oslo, Stavanger and Throndheim (Table 1). However, emissions from non-road mobile combustion sources have significatly decreased along time (Figure 4). Hereby, the comparison between BUP and more updated TODs would result on the opposite result, BUP > TOD.

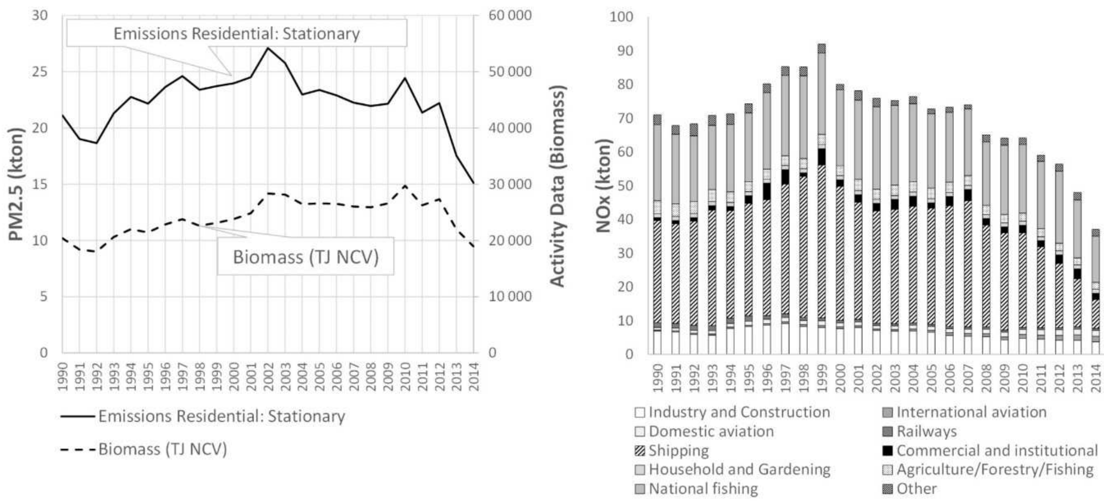

Figure 4: $PM_{2.5}$ emissions from residential sector in Norway from 1990 to 2014 and the corresponding activity data (left) and NOx emissions from non-road mobile sources and machinery (SNAP8) and corresponding subsectors (right).

The most probable cause would be the proxis used for allocating and gridding emissions in the TODs as part of the downscaling processes. For instance, mobile machinery associated with the manufacturing industry and other mobile souces are allocated based on total population. This results in an over-allocation of emissions in urban areas. In Norway, non-mobile sources associated with construction and industries is the third biggest contributing subsector to SNAP8 (Figure 4), therefore an over-allocation may results in significant differences as those observed in our results. At the beginning of this chapter we indicated that total emissions of PM in TODs are reported to be higher than total PM emissions in BUPs. Higher PM emissions from SNAP8 will contribute to the total overestimation of emissions in urban areas.

4.5. Diverse industry

Emissions from the industrial sector are low in all the analysed urban areas except for Grenland, which holds an industrial complex with several large point sources. In Bergen and Oslo, NO_x emissions from the industrial sectors are much lower in the BUP than in TNO_MACC-II and EC4MACs (Figure 5). Emissions from SNAP3 and SNAP4 sectors that cannot be linked to a specific E-PRTR facility (i.e. diffuse emissions) are merged in TNO_MACC-II and gridded based on total population. This approach results in an over-allocation of industrial emissions in urban areas, which has already been pointed out in previous studies (Guevara et al., 2014). The improved TNO_MACC-III addressed this issue, and diffusive industrial emissions are distributed based on the industrial classification from the CORINE land cover map (Table 2). Consequently, $BUP_{NOx}/TOD_{NOx\ (TNO\_MACC\text{-}III)}$ ratio approaches 1 for most of the urban areas. In EC4MACs, emissions from SNAP3 and SNAP4 are distributed according to TNO_MACC and artificial land-use, respectively. This approach seems to show consistent results, and similar to those reported by TNO_MACC-III for some of the domains. In Oslo domain, the ratio BUP_{NOx} to TOD_{NOx} is very low. To our knowledge, there are no important industrial sources in Oslo geographical domain, and the contribution from those existing is almost negligible to NO_2 pollution levels. There may still be an over-allocation of industrial emissions in populated areas. Dios et al., (2012) pointed out about the inaccuracy of the E-PRTR information, i.e. total amount of emissions released and geographical location, but the evaluation of the E-PRTR for Oslo does not seem to show inaccurate results. However, CORINE land cover dataset for Oslo shows large areas classified as industrial land uses. These areas are mainly commercial and storage facilities located in the urban area and clearly distinguishable from residential areas. Therefore, the use of

CORINE land cover to allocate diffuse emissions is the reason for an over-allocation of industrial emissions in urban areas.

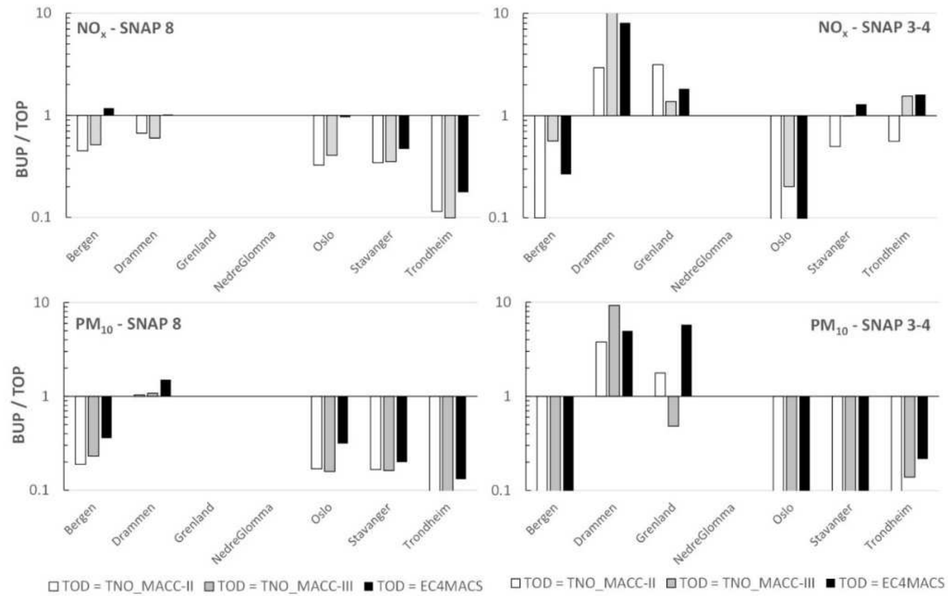

Figure 5: Ratios of NO_x and PM_{10} emissions in BUPs to emissions in TODs for the SNAP8, Non-road transport (left) and SNAP3+4, industry (right).

It is also important to highlight that CORINE land cover data is from 2006, and therefore it may not register some of the urban transitions from industrial to more environmentally friendly urban areas. This may be the case of Drammen, were BUP emissions as area sources are calculated based on downscaling approaches using CORINE land cover as ancillary data. The results show that Drammen is a very industrial urban area, which does not correspond with the current situation. BUP_{PM10}/TOD_{PM10} shows very low values and below 0.1 for most of the urban domains. The BUP considers $PM_{2.5}$ emissions equal to PM_{10}, and therefore emissions of the PM coarse fraction are set to zero. The $BUP_{PM2.5}/TOD_{PM2.5}$ ratios are similar to those obtained for PM_{10}, or slightly closer to 1 (no shown in figure). Assuming that emissions of the PM coarse fraction is zero involves that we underestimate PM_{10} emissions from the industrial sector in the BUP. Industry is a minor contributor to emissions and to air pollution levels, thus we do not expect that it will affect the total emissions or the subsequent evaluation.

The distribution of emissions from industry and on-road transport is very much based on a tier 1 according to EMEP/EEA (2013) guidebook, as it uses population or land cover as proxies to allocate emissions. The results obtained in our study indicate that tier 1 involve high uncertainties and in most of the cases an over allocation of emissions in highly populated areas.

5. Conclusions

This paper presents the comparison between seven bottom-up emission inventories for seven urban areas in Norway and three downscaled regional emission inventories (EC4MACS, TNO_MACC-II and TNO_MACC-III). The comparison focuses on NO_x, PM_{10} and $PM_{2.5}$ emissions and on on-road transport, residential combustion, non-road transport and industry sectors. Our study shows the benefit of comparing emission inventories developed according to different approaches in order to improve emissions in urban areas.

Total emissions of NO_x and PM from downscaled emission inventories are in general not similar to bottom-up emission inventories defined for the same urban areas. Discrepancies in the on-road transport sector are prevalent among the selected areas, and downscaled emission inventories usually underestimate both PM_{10} and NO_x emissions. Non-exhaust emissions due to resuspension is probably the main reason of discrepancies for PM_{10}, which is included in the Norwegian bottom-up emission inventories, but it is not in the regional estimates for the country. Re-suspension is an important source that needs to be taken into account as part of the design of programmes to reduce population exposure to PM levels above limit values. This is especially relevant in urban areas exposed to icing and de-icing conditions, and with the use of vehicles with studded tyres. National official emissions reported to UNECE by Norway does not include this subsector, but automobile tyre wear, brake wear and road abrasion. This is one of the limitations of the use of downscaled official emission inventories for air quality modelling at urban or regional scale.

NO_x emissions from on-road transport are estimated to be much higher by means of bottom-up methods than from downscaling are. National emissions from on-road transport are estimated following a tier 3 approach based on fuel sales, vehicle fleet composition and driving patterns. The disaggregation of emissions from on-road transport in urban areas in regional emission inventories is performed based on population. This proxy entails lower activity and therefore an underestimation of traffic emissions in the urban area. This phenomenon occurs especially in urban areas characterized by high urban road network density. The bottom-up approaches are more likely capturing the spatial variations within the urban area, as several variables are defined as unique values at the road link level. Therefore, on-road traffic emissions from the seven bottom-up emission inventories are likely more accurate than traffic emissions from downscaled regional emission inventories. A way forward in the developing and improving of regional and global emission inventories would be the nesting of bottom-up inventories for urban areas, along with the improvement of the current European road network information.

The benchmarking shows significant discrepancies on the estimates of wood burning emissions according to bottom-up and downscaled approaches. The proxies selected for the spatial allocation of emissions are the main reason behind the discrepancies. In EC4MACS, an approach developed from a study in France was then extrapolated to the whole Europe. This assumption is not valid for countries as Norway, as it results in a significant underestimation of $PM_{2.5}$ emissions from wood burning in urban areas. This can be the case for other European countries in northern latitudes where wood burning is very much used as heating source in urban areas. Wood burning for residential heating depends on local conditions, economy or even cultural factors. Our study shows the importance of local knowledge on the selection of assumptions and proxies for the spatial allocation of emissions. Thus, it is important to investigate the possibility of including knowledge and studies at local level in the development of European regional emission inventories. In addition, wood burning activity depends on the climatic conditions; therefore, we identify the need for regular updates of the wood burning sector in the seven bottom-up emission inventories to best represent the reference year.

Other sectors such as diffusive industrial emissions and non-road mobile combustion sources shows important discrepancies. One of the reasons is the incompleteness of some of the bottom-up emission inventories, especially for two urban areas (i.e. Nedre Glomma and Grenland). Another reason for discrepancies is the use of population or land cover as ancillary data. The use of population results in an overestimation of emissions in populated areas such as cities. Land cover has shown to be an improvement in the case of diffusive industrial emissions. However, the relatively outdated land cover data does not reflect the fast urban development experienced in some urban areas from industrial cities to more environmentally friendly populated areas. This can be the case of one of the bottom-up emission inventories, i.e. Drammen, which area sources are developed according to downscaling processes using land cover data. There is a need for new sources and ways of acquiring ancillary data that represent current conditions in urban areas experiencing fast urban planning and developments.

The benchmarking carried out here has strengthened our trust on the urban emission inventories for Oslo, Bergen, Stavanger and Trondheim. For the three other Norwegian cities, this study shows the need for further improvement of the urban emission inventories: in Grenland and Nedre Glomma there are missing sources from the off-road sector, while the inconsistencies identified in Drammen make recommendable a revision of the inventory methodology used to compile the urban scale inventory. The study also shows how the data from the regional emission inventories cannot be readily used in Norway, as there are important missing sources in particular from resuspension, road traffic and biomass burning in the downscaled emissions if intended for use in urban areas.

The discrepancies found between downscaled and bottom-up emission inventories may have significant implications for their subsequent use in for instance exposure assessments or the evaluation of policy measures. Hence, the assimilation of bottom-up emission estimates and its local ancillary data by downscaled regional emission inventories may improve the quality of the regional inventories, and their subsequent applications.

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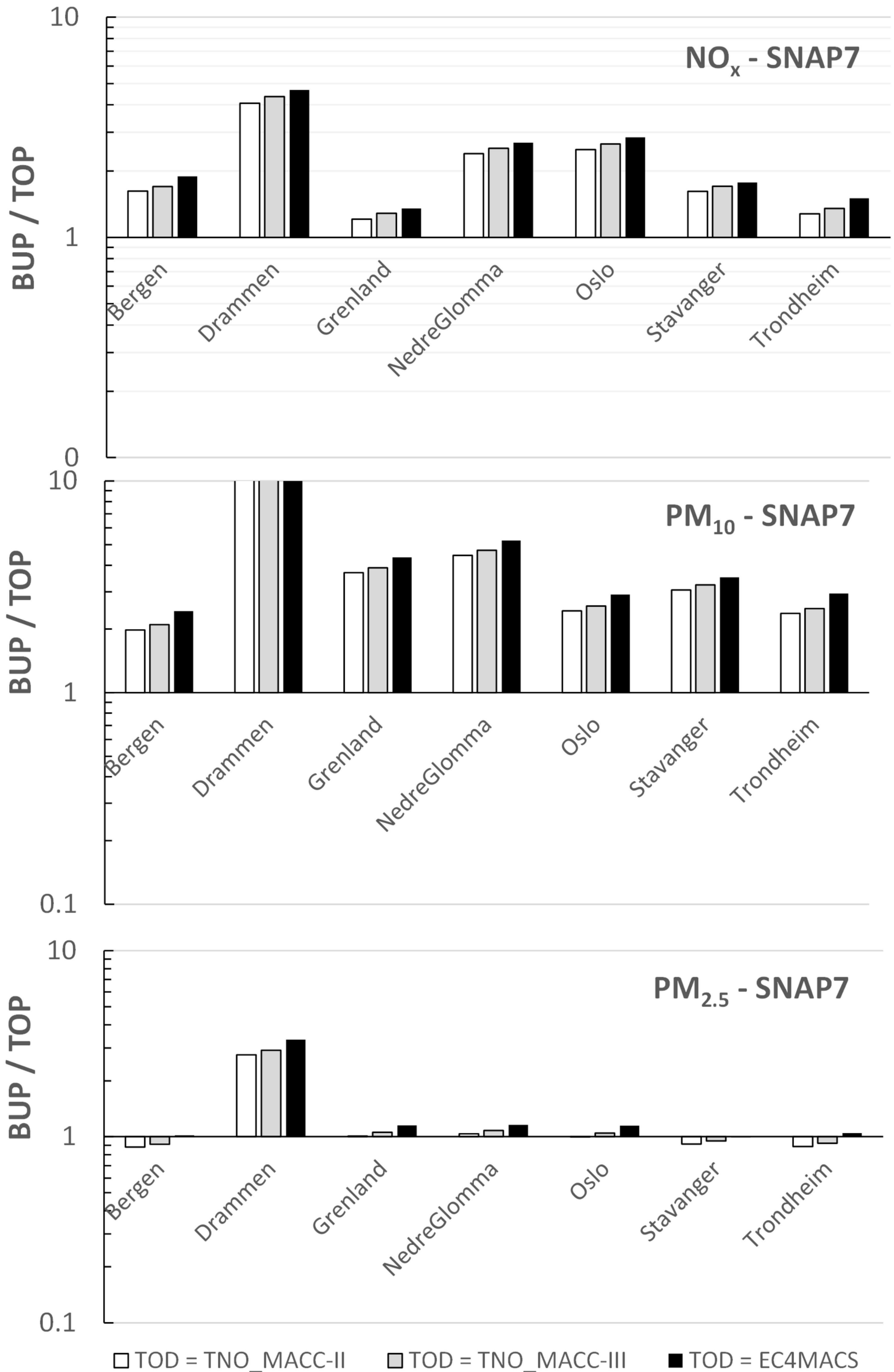
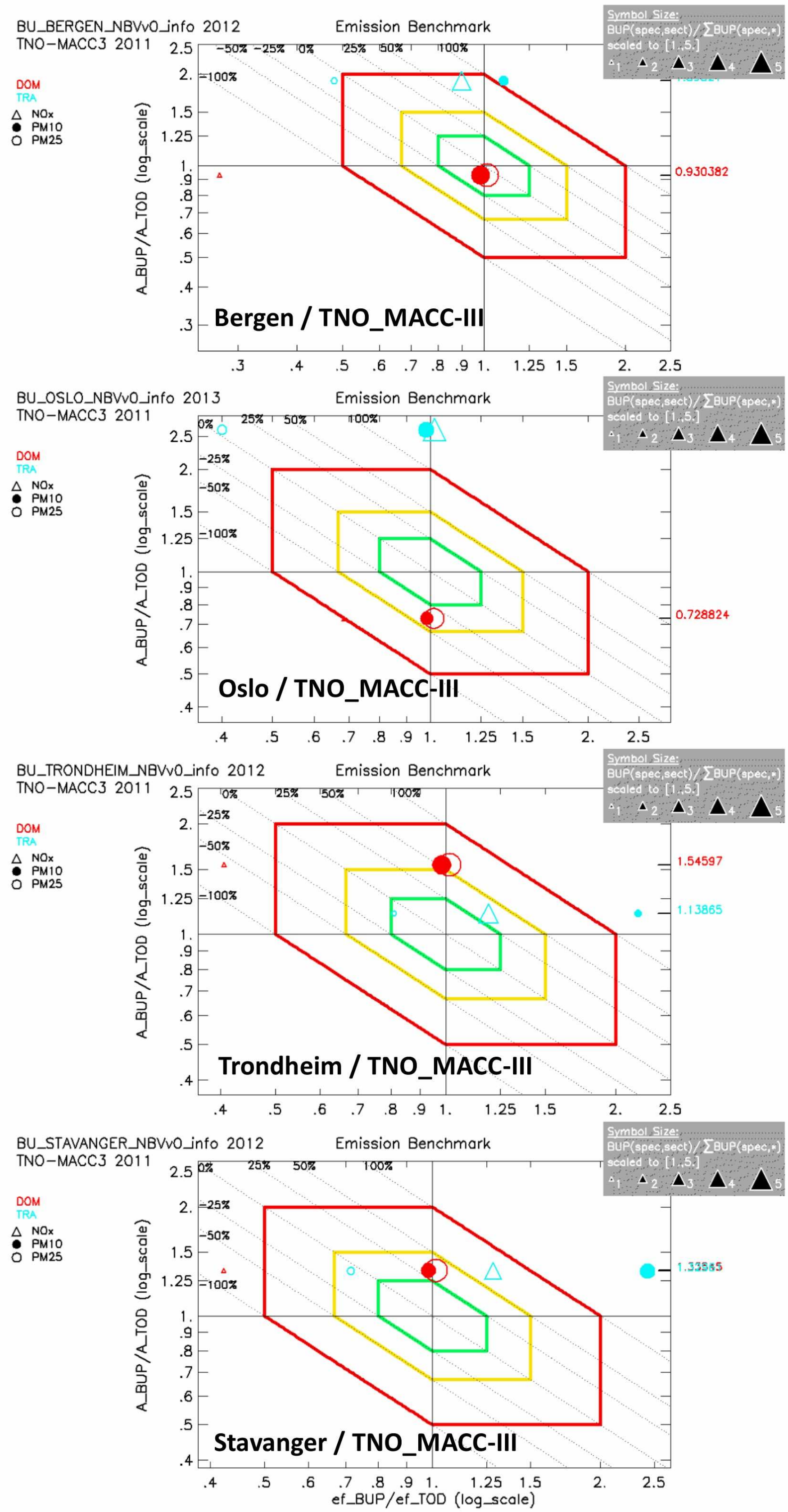
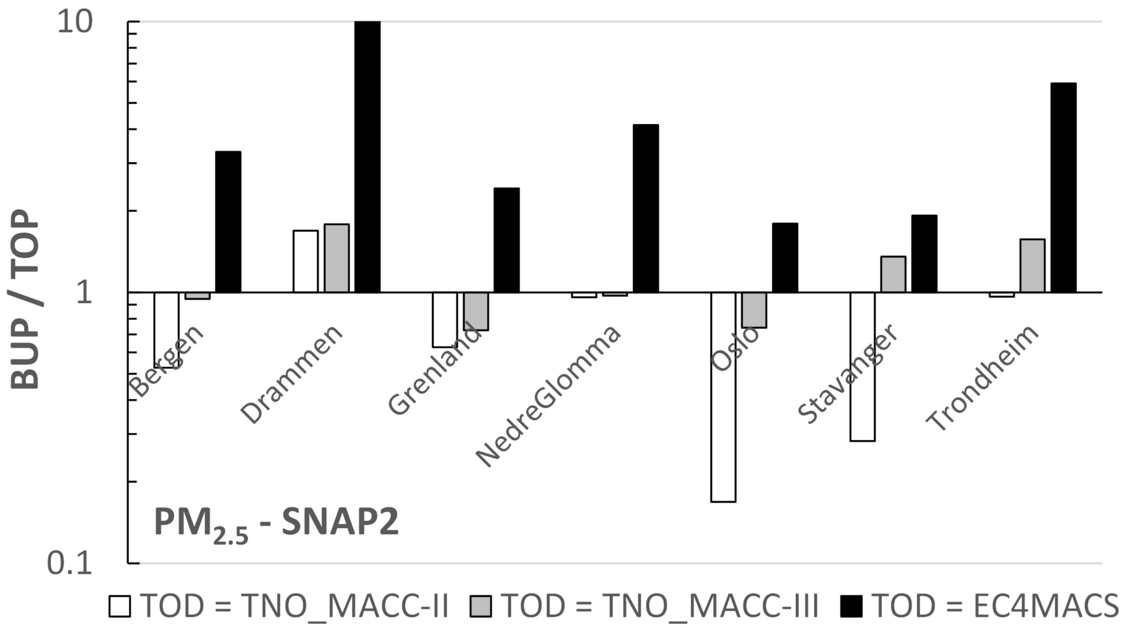
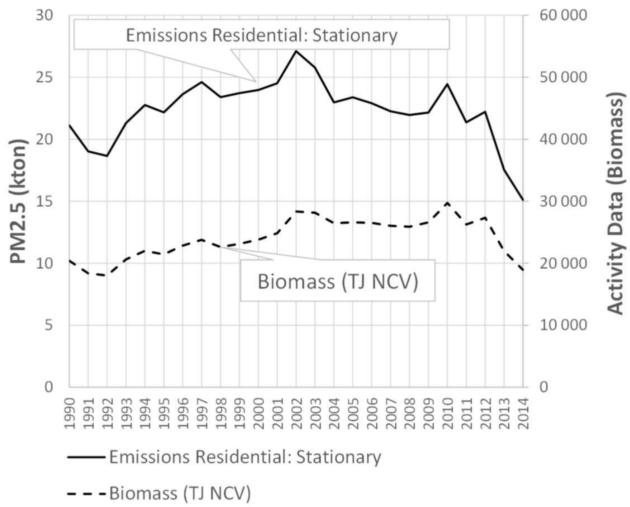
Urban areas	On-road Traffic	Residential Heating	Shipping	Off-road mobile combustion	Industry
Bergen	2012	2003	1995/1998	1995/1998	1995/1998
Drammen	2012	2012	n.a.	2012	2012
Grenland	2012	1998	n.a.	n.a.	1991
Nedre Glomma	2012	2012	n.a.	n.a.	2012
Oslo	2013	2002	2013	1995	2013
Stavanger	2012	1998	1995/1998	1995/1998	1995/1998
Trondheim	2012	2005	2005	2005	2005
SNAP sectors	SNAP7	SNAP 2	SNAP 8	SNAP 8	SNAP 3-4

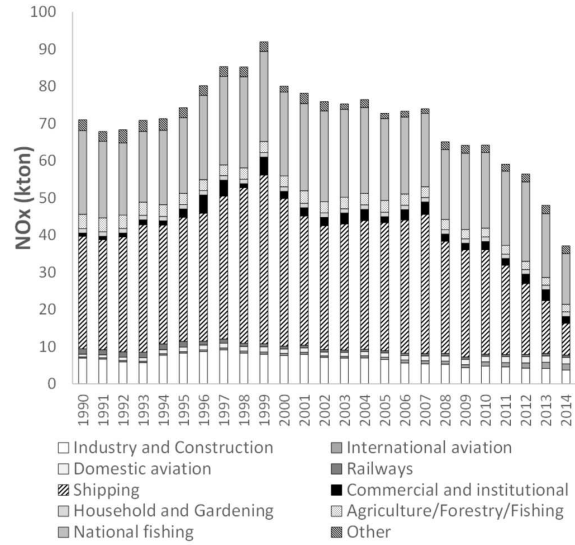
	TNO-MACC_II	TNO-MACC_III	EC4MACS
Ref	Kuenen et al., 2014	(pers. commun.)	Bessagnet et al., 2016; Denier van der Gon (2010)
Year	2003 - 2009	2000 - 2011	2009
SNAP1	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	EPER and Artificial Landuse
SNAP2	Total population and Wood use map	TNO internal estimates (Population and wood availability)	Dissagregated based on population (Terrenoise et al., 2015)
SNAP3	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	TNO_MACC (2007); E-PRTR and TNO PS database
SNAP4	E-PRTR, TNO PS database	Improved based on bottom up data and Industrial land cover	Artificial Landuse
SNAP5	E-PRTR, TNO PS database or Urban Population		Artificial Landuse
SNAP6	Total population		Artificial Landuse
SNAP7	TRANSTOOLS network and Total population		TNO_MACC (2007); Road Network and Partly population
SNAP8	TNO PS database, Rail map, Shipping map, Arable land, Total population	Shipping; methodology improved, estimated differently per sea	TNO_MACC (2007); Rail map, Inland and coastal waterways, Arable land, Population
SNAP9	E-PRTR, Rural population or Total population		TNO_MACC (2007); E-PRTR and Population
SNAP10	Livestock map, Arable land, Total population		TNO_MACC (2007); Livestock map, Arable land, Total population

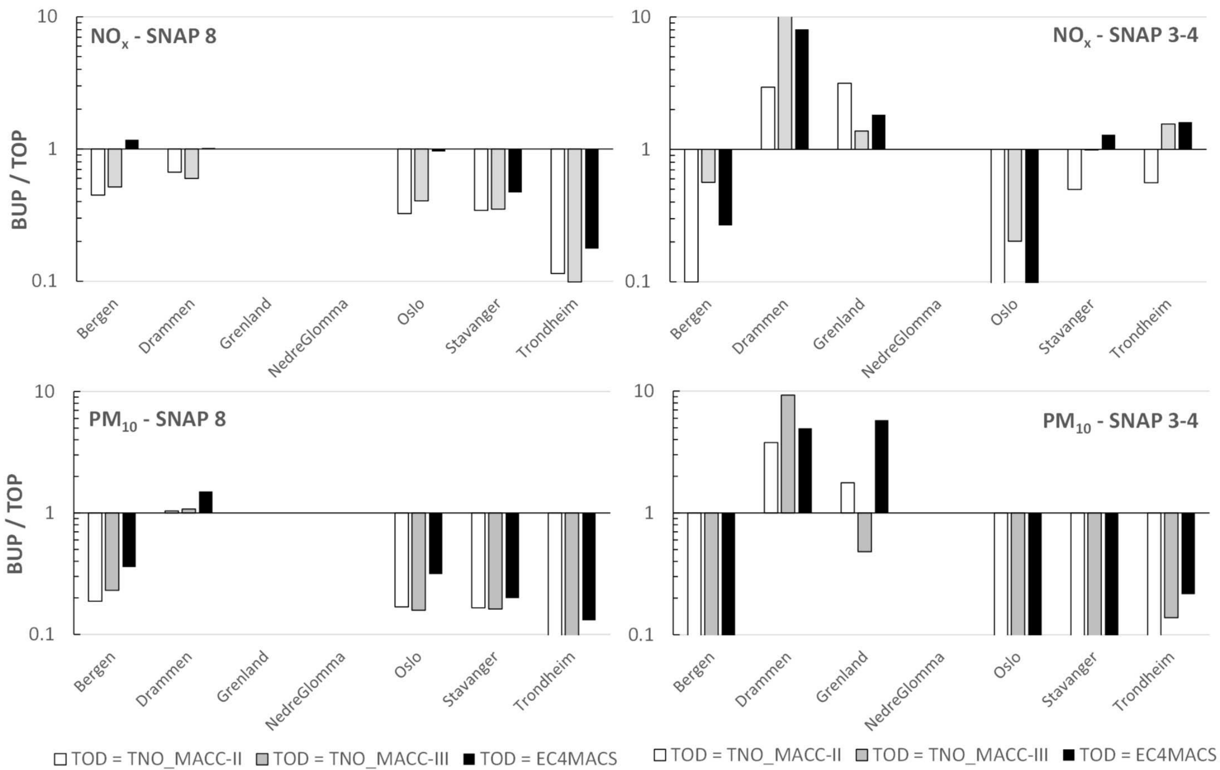

NOx - SNAP7
PM10 - SNAP7
PM2.5 - SNAP7
BUP / TOP
10
1
0
0.1
Bergen
Drammen
Grenland
NedreGlomma
Oslo
Stavanger
Trondheim
TOD = TNO_MACC-II
TOD = TNO_MACC-III
TOD = EC4MACS


BU_BERGEN_NBVv0_info 2012
TNO-MACC3 2011
Emission Benchmark
Symbol Size:
BUP(spec,sect)/∑BUP(spec,*)
scaled to [1.,5.]
DOM
TRA
NOx
PM10
PM25
A_BUP/A_TOD (log_scale)
0.930382
Bergen / TNO_MACC-III
BU_OSLO_NBVv0_info 2013
TNO-MACC3 2011
Emission Benchmark
0.728824
Oslo / TNO_MACC-III
BU_TRONDHEIM_NBVv0_info 2012
TNO-MACC3 2011
Emission Benchmark
1.54597
1.13865
Trondheim / TNO_MACC-III
BU_STAVANGER_NBVv0_info 2012
TNO-MACC3 2011
Emission Benchmark
Stavanger / TNO_MACC-III
ef_BUP/ef_TOD (log_scale)


10
1
0.1
BUP / TOP
Bergen
Drammen
Grenland
NedreGlomma
Oslo
Stavanger
Trondheim
PM2.5 - SNAP2
TOD = TNO_MACC-II
TOD = TNO_MACC-III
TOD = EC4MACS


Emissions Residential: Stationary
Biomass (TJ NCV)
PM2.5 (kton)
Activity Data (Biomass)
Emissions Residential: Stationary
Biomass (TJ NCV)


NOx (kton)
Industry and Construction
Domestic aviation
Shipping
Household and Gardening
National fishing
International aviation
Railways
Commercial and institutional
Agriculture/Forestry/Fishing
Other


NO$_x$ - SNAP 8
NO$_x$ - SNAP 3-4
PM$_{10}$ - SNAP 8
PM$_{10}$ - SNAP 3-4
BUP / TOP
10
1
0.1
Bergen
Drammen
Grenland
NedreGlomma
Oslo
Stavanger
Trondheim
TOD = TNO_MACC-II
TOD = TNO_MACC-III
TOD = EC4MACS

Highlights

- The capability of a benchmarking system to improve emission inventories is shown.
- The regional emission inventories cannot be readily used in urban areas in Norway.
- Regional emission inventories underestimate NOx and PM10 urban traffic emissions.